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GPHS - RTGs

In Support of the

Cassini RTG Program

**Addendum
to the
Final Technical
Report**

Document No. RR18

**1 May 1998
through
31 December 1998**

December 1998

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**GPHS-RTGs in
Support of the
Cassini Mission**

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**1 May 1998
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Space Power Programs

**Addendum to
Final Technical Report**

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Foreword

The Cassini GPHS-RTG Program Final Technical Report (document No. RR18) describes program activities during the contract period 11 January 1991 through 30 April 1998.

This Addendum to the Cassini GPHS-RTG Program Final Technical Progress Report describes activities performed during the period 1 May 1998 through 31 December 1998, including effort reflecting contract modification M058. These activities include Earth Gravity Assist (EGA) reentry and related analyses which are detailed in Part A, and effort related to the installation of CAGO equipment within Lockheed Martin's Building 100 facility in Valley Forge, PA, which is detailed in Part B.

Final Technical Report

***Addendum
Acronyms***

Final Technical Report Addendum

Acronym List

3DOF	Three Degree-of-Freedom
6DOF	Six Degree-of-Freedom
ABL	Atmospheric Boundary Layer
BRV	Ballistic Reentry Vehicle
BSM	Benkley-Schulman Model
CAGO	Contract Acquired Government Owned
CCDF	Complementary Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CIR	Coincident Impact Release
DOT	Department of Transportation
ECW	Equilibrium-Catalytic Wall
EDM	Electrical Discharge Machining
EGA	Earth Gravitational Assist
FOS	Face-On-Stable
FSAR	Final Safety Analysis Report
FWPF	Fine Weave Pierced Fabric
GIS	Graphite Impact Shell
GPHS	General Purpose Heat Source
INSRP	Interagency Nuclear Safety Review Panel
IUS	Inertial Upper Stage
JHU/APL	Johns-Hopkins University/Applied Physics Laboratory
LA-AFB	Los Angeles Air Force Base
LAS	Loading Assembly Station
LASEP-T	Launch Accident Scenario Evaluation Program - Titan IV
LHS	Latin Hypercube Sampling
LM	Lockheed Martin
LORAN	Langley Optimized Radiative Nonequilibrium
LTNE	Local Thermodynamic Nonequilibrium

Final Technical Report Addendum
Acronym List (Cont'd)

MBW	Mass-Balance (Wall) Boundary
MC	Monte Carlo
MET	Meteorological Sub-Panel
MVP	Model Validation Program
NWS	National Weather Service
PST	Pacific Standard Time
RACER	Reacting, Ablating, Chemical Equilibrium/Nonequilibrium with Radiation
ReSP	Reentry Sub Panel
RHU	Radioactive Heating Units
RPS	Radioisotope Power Systems
RSS	Root-Sum-Square
RTG	Radioisotope Thermoelectric Generator
SEB	Surface Energy Balance
SEM	Scanning Electron Microscope
SPARRC	Space Accident Radiological Release and Consequence
SRM	Solid Rocket Motor
THT	Transient Heat Transfer

Part A

Earth Gravity Assist (EGA) Reentry and Related Analyses

Section A1

Surface Energy Balance (SEB) Investigations

SECTION A1

SURFACE ENERGY BALANCE (SEB) INVESTIGATIONS

The conventional form of the SEB formulation for an ablating, chemically reacting surface in hypersonic flight was first devised in late 1950's when research began on the concept of using ablative materials for the heat protection of reentry vehicles. Independent studies by Cohen, Bromberg, and Lipkis (Reference A1-1) and Bromberg and Lipkis (Reference A1-2) complemented the pioneering work of Lees (Reference A1-3). Scala and Sutton (Reference A1-4) followed these studies and developed a more general SEB expression.

The surface energy balance is the link between flowfield solutions and the transient-heating analysis. In the Cassini EGA reentry analysis procedure performed for the Final Safety Analysis Report (FSAR), three flowfield solutions are obtained for three specified surface temperatures at selected points along the trajectory. The surface temperature (or temperature distribution) is an input boundary condition for the flowfield computation. The actual surface temperature, and its variation along the trajectory, is unknown when the flowfield solutions are obtained. The surface and in-depth temperature history is subsequently obtained in the transient-heating analysis by iteratively solving the SEB. At each temperature iteration, the ablation-rate and total heat-flux tables (obtained from the flowfield solutions as a function of surface temperature) are interpolated to obtain terms in the SEB. Iteration continues until the temperature distribution satisfies the SEB.

Lockheed Martin employed the conventional SEB in the early stages of the development of an aerothermodynamic technique for EGA reentry. However, the Lockheed Martin model was extended and became the first technique to include nonequilibrium ablation (Knudsen-Langmuir vaporization) together with the imposition of an equilibrium, fully catalytic surface boundary condition, in a nonequilibrium flow solver. Because of these unique features in the early Lockheed Martin model, the validity of the conventional SEB for these boundary conditions was investigated. This investigation led to the development of a new SEB formulation (References A1-5 through A1-11).

This new SEB was used to compute the recession and surface temperature histories of the GPHS module along the steep, intermediate, and shallow trajectories. These results were

presented in the FSAR (Reference A1-12). In their review of the FSAR, INSRP/ReSP (Reference A1-13) made the following statement objecting to the new LM SEB formulation, which they referred to as the "ad hoc surface energy balance".

"The ReSP has identified and documented two errors in the ad hoc surface energy balance used for the FSAR carbon ablation calculations. The first error double counts the energy flux due to diffusion. The second error occurs when the carbon species mass and energy fluxes at the Knudsen layer edge, determined by the computational fluid dynamics calculations, are replaced (thereby neglecting homogeneous reactions) by values from terms in the ad hoc surface energy balance."

Consequently, as described in Section 6 of the main body of this report, the GIS (nonspinning) recession and temperature histories were computed using both the conventional SEB advocated by INSRP and the new LM SEB. In general, use of the conventional SEB leads to significantly more recession. For example, on the intermediate trajectory the predicted recession of the nonspinning GIS is about 0.10 inches using the LM SEB (out of a total FWPF thickness of 0.168 inches). However, use of the conventional SEB results in about 0.15 inches of recession, which is approaching burn-through.

Due to the importance of the SEB in predicting recession, LM performed an independent internal review of the SEB. This effort is described in Section A1.1.

An improved chemical/flowfield formulation, described in Section A1.2, was developed to resolve the ambiguity in the direction that this energy is released. This new approach removes the modeling assumption of an instantaneous transition to an equilibrium composition. Further, the governing gas-dynamic equations are integrated across the homogeneous reaction region. Finally, the energy transferred to the surface is obtained by directly solving energy conservation for a small, but finite, gas volume adjacent to the surface.

A1.1 INDEPENDENT SEB REVIEW

An independent review of the Lockheed Martin SEB was performed by Dr. Frank Kampas, Lead Cassini Project Engineer for Source Term Analysis and Risk Integration. The results of his review are described below.

The LM SEB model (referred to here as the Bhutta-Daywitt model) has three regions adjacent to the ablating surface, as shown in Figure A1.1-1. These regions are a Knudsen-Langmuir layer, a chemical-equilibrium layer and a non-equilibrium layer, in order of increasing distance from the surface. The gas temperatures in the Knudsen-Langmuir and chemical equilibrium layers are assumed to be constant and equal. The concentrations of chemical species are assumed to be constant within each layer, but not equal, as shown in Figure A1.1-2. In other words, there is a discontinuous change in the concentrations in the chemical species at the interface between the Knudsen-Langmuir layer and the chemical equilibrium layer. Furthermore, the thicknesses of the Knudsen-Langmuir and chemical equilibrium layers are assumed to be zero. In other words, the limit of the layer thicknesses going to zero is taken in constructing the mathematical representation of the model.

Figure A1.1-1. Bhutta-Daywitt Model

Figure A1.1-2. Temperatures and Concentrations

A1.1.1 Discussion of LM SEB Model

Examination of the model assumptions, before taking the limit of zero layer thicknesses, reveals a problem. The heat flux within the Knudsen-Langmuir and within the chemical-equilibrium layers is identically zero because the temperature and chemical concentrations are constant within these layers (see Equation A1-1).

$$q = -k \frac{\partial T}{\partial z} + \rho \sum_{i=1}^{NS} h_i D_i \frac{\partial C_i}{\partial z} \quad [A1-1]$$

In Equation A1-1, q is heat flux in the z direction, k is the thermal conductivity, T is the temperature, NS is the number of chemical species, h_i is the enthalpy of species i , ρ is the density, D_i is the diffusion constant of species i and C_i is the mass fraction of species i .

Zero heat flux in the two layers is non-physical since there must be a heat flux from the ablating surface. It is not clear whether or not the non-physical nature of the model is removed in the limit of the two layers having zero thickness. This determination could only be made by assuming that the temperatures and concentrations are not constant and determining if their derivatives disappear in the limit of zero layer thicknesses.

A1.1.2 Conclusions of Independent SEB Evaluation

Some of the assumptions underlying the model appear to be non-physical. The effect of these assumptions can only be tested by constructing a more general model.

A1.2 SEB COMPARISONS USING IMPROVED GIS CFD APPROACH

To better understand the nonequilibrium flow over an ablating carbon surface, a simplified (reduced) carbon-air system is used to analyze the near-wall ablation and nonequilibrium species mass balances. A new nonequilibrium mass-balance boundary condition is used for each chemical species at the ablating wall, and results are compared with the corresponding predictions based on a catalytic wall assumption. The new mass-balance boundary conditions are derived from first principles and impose the strict conservation of mass for each individual species at the wall. Based on the new nonequilibrium formulation and using the conservation of total energy in a small control volume at the ablating carbon surface and the adjacent gas phase, a new Surface Energy Balance equation has been derived (see

Section A.3.2). This section discusses the results of two sample calculations that compare the predictions of the new SEB formulation based on the improved CFD analysis with the corresponding predictions based on the approach used in the FSAR analysis (Reference A1-12) and the approach advocated by INSRP/ReSP (Reference A1-13).

The first sample case involves the flowfield and ablation predictions for the diffusion-controlled surface oxidation of a carbon cylinder using a simplified 9 species (O , N , N_2 , O_2 , NO , C , CO , CO_2 and CN) and 19-reaction chemical model. The flow conditions consist of a 20 kft/sec flow over a carbon cylinder at an altitude of 200 kft and a wall temperature of 2000 °R. For this case, a detailed analysis of the near wall region is given in Section A.3.5, and shows that the mass of each species is conserved. Furthermore, for the diffusion-controlled-oxidation conditions considered, the surface oxidation process is almost completely fed (controlled) by the mass diffusion process. Results of the SEB comparisons show that, while the new nonequilibrium wall-ablation and mass-balance model predicts higher ablation rates, the in-depth heat conduction is less and somewhat offsets the effects of the higher ablation rate.

The second sample case involves the nonequilibrium carbon-sublimation limit, and considers that flow over the GIS at the peak-heating conditions (147 kft altitude) along the intermediate reentry trajectory ($\gamma = -20^\circ$). In this case the flowfield chemistry is modeled using a 19 species (O , N , N_2 , O_2 , NO , C , C_2 , C_3 , CO , CO_2 , CN , N^+ , O^+ , N_2^+ , O_2^+ , NO^+ , C^+ , CO^+ and e^-) and 44-reaction chemical model. For this case also, the results of the new SEB show that the predicted surface-ablation rate is higher, however, the corresponding in-depth heat conduction is less and somewhat offsets the effects of the higher ablation rate.

Nonequilibrium Species Mass-Balance at the Wall and Resulting Surface Energy-

Balance Equation: The nonequilibrium species-mass-balance boundary conditions at the ablating wall have been derived in detail in Section A.3.2, and are imposed on a small control volume at the wall. The height of this control volume (Δ_w) is equal to half the grid cell height at the wall. It is important to note that the conservation of mass and energy above this half-cell interface is implied by the finite-difference form of the governing conservation equations applied at the first grid point off the wall. Thus, with the additional mass and energy

conservation equations imposed on the half cell at the wall, the global conservation of mass and energy is strictly satisfied from the wall out into the freestream. The species composition at the wall is determined using the constraint of conservation of species mass in this control volume at the wall. The resulting nonequilibrium species-mass-balance boundary condition have been derived in Section A.3.2 as

$$(\rho v C_s - \dot{m}_s^{inj}) = J_s + \dot{\omega}_s \Delta_w \quad [A1-2]$$

where $\dot{m}_s^{inj}$ is the mass of the species 's' being injected or consumed by the ablating wall, J_s is the diffusion mass flux of species 's', ρ is the density, v is the velocity, and C_s is the species mass fraction at the cell interface at $y=\Delta_w$. The rate at which the species 's' is produced/consumed per unit volume in this control volume at the wall is $\dot{\omega}_s$.

The conservation of energy in this small control volume is coupled with the surface ablation process to form a Surface Energy Balance and determine the in-depth heat conduction. This energy balance is given in detail in Section A.3.2 and produces the following expression for the in-depth heat conduction (Q_s):

$$Q_s = \left[k \frac{\partial T}{\partial y} + \sum h_s J_s \right]_{\Delta_w} + Q_r - \left([\rho v h_0]_{\Delta_w} - \dot{m}_w h_{surface} \right) - \epsilon \sigma (T_w^4 - T_\infty^4) \quad [A1-3]$$

where $h_{surface}$ is the enthalpy of the solid carbon surface, h_0 is the total enthalpy, Q_r is the radiation heat flux to the wall, T_w is the wall temperature, and T_∞ is the freestream temperature.

The corresponding in-depth heat conduction based on the SEB model used in the FSAR (Reference A1-12) is

$$Q_s = \left[k \frac{\partial T}{\partial y} + \sum h_s J_s \right]_w + Q_r - \left(\sum \dot{m}_s h_s - \dot{m}_w h_{surface} \right) - \epsilon \sigma (T_w^4 - T_\infty^4) \quad [A1-4]$$

and assumes an equilibrium-catalytic wall. The corresponding in-depth heat conduction based on the SEB model advocated by INSRP/ReSP (Reference A1-13) is

$$Q_s = \left[k \frac{\partial T}{\partial y} + \sum h_s J_s \right]_w + Q_r - \dot{m}_w (h_w^{EQ} - h_{surface}) - \epsilon \sigma (T_w^4 - T_\infty^4) \quad [A1-5]$$

where the ablating surface is also assumed to be equilibrium catalytic, and h_w^{EQ} is the enthalpy of the resulting equilibrium mixture at the wall.

Sample Diffusion-Controlled Oxidation Case and Discussion: The effects of the new nonequilibrium species-mass-balance boundary conditions (MBW) were evaluated by comparing with the corresponding predictions of an equilibrium catalytic wall (ECW). The case considered for analysis was the stagnation streamline flow over a carbon cylinder reentering the Earth atmosphere at a speed of 20 kft/sec at an altitude of 200 kft. The wall temperature is assumed to be 2000°R, and the radius of the sphere was 0.775 inch. At this temperature it was envisioned that nonequilibrium sublimation effects would be negligible and a diffusion-controlled surface oxidation environment will exist. To simplify the chemical system involved, a 9-species carbon-air chemical system (O, N, N₂, O₂, NO, C, CO, CO₂ and CN) governed by 19 gas-phase reactions was assumed to be adequate. Numerical calculations were done along the stagnation streamline using equilibrium (ECW) as well as nonequilibrium (MBW) wall boundary conditions.

For this case, detailed surface mass balances obtained using the nonequilibrium mass-balance boundary conditions are summarized in Section A.3.5. In general, the results show that, while individual species have diffusion mass flux to or away from the ablating wall, the net mass diffusion to the wall summed over all species is zero. In short, the total mass entering the shock-layer due to surface-ablation effects (0.0038 lbm/ft²-sec) must be carried away from the wall into the shock layer by only the mass convection effects. To satisfy the global conservation of total mass, there should be no net loss or gain of mass due to mass diffusion effects and chemical reactions. By summing over all species, it is also shown in Section A3.5 that the predictions based on the new nonequilibrium species-mass-balance boundary conditions also satisfy the global conservation of mass at the ablating wall.

Having satisfied the conservation of species mass as well as the total mass at the wall, the conservation of total energy is done on the small control volume at the ablating surface to determine the amount of in-depth heat conduction (Q_s). The resulting surface energy balance is given by Equation [A1-2], and the numerical results of the new SEB at the stagnation point are shown in Figure A1-1. Figure A1-1 also includes similar calculations of the in-depth heat conduction based on the SEB model used in the FSAR (Reference A1-12) and the one advocated by INSRP/ReSP (Reference A1-13). Equations (A1-3) and (A1-4) represent these FSAR and INSRP/ReSP SEB models, respectively. The results show that the computations based on the new nonequilibrium mass-balance boundary conditions (MBW) result in a higher surface ablation rate ($0.0038 \text{ lbm/ft}^2\text{-sec}$) than the corresponding equilibrium-catalytic wall case ($0.0006 \text{ lbm/ft}^2\text{-sec}$). However, the resulting in-depth heat conduction ($268 \text{ BTU/ft}^2\text{-sec}$) is significantly lower than either the FSAR SEB model ($318 \text{ BTU/ft}^2\text{-sec}$) or the INSRP/ReSP SEB model ($309 \text{ BTU/ft}^2\text{-sec}$). It should be noted that both FSAR and INSRP/ReSP SEB formulations use the same equilibrium catalytic wall assumption. In general, it is observed that the effects of a higher surface-ablation rate predicted using the new nonequilibrium species mass-balance boundary conditions are somewhat mitigated by the significantly lower in-depth heat conduction. In other words, due to the lower in-depth heat conduction, the surface heats up less and, thus, the final surface recession is also not so high.

Sample Sublimation Case and Discussion: The effects of the new nonequilibrium species-mass-balance boundary conditions (MBW) were evaluated by comparing with the corresponding predictions of an equilibrium catalytic wall (ECW). The case considered for analysis was the stagnation streamline flow over the GIS at peak-heating conditions (147 kft and 51 kft/sec) along the intermediate reentry trajectory ($\gamma=-20^\circ$). CFD calculations were done for wall temperatures of 7500°R , 7600°R , 7650°R , and 7675°R . For this case, the surface temperature predicted by the transient heating analysis is approximately 7625°R . At these surface temperatures the heterogeneous surface-oxidation effects are negligible, and nonequilibrium sublimation effects predominantly drive the surface ablation process. In these

Mach 19 Flow Over an Ablating Carbon Cylinder

(Comparison of the Indepth Heat Conduction based on Various SEB Models)
 $V_\infty = 20$ kft/s, Altitude=200 kft, 2-D Cylinder, $R_n = 0.775$ inch, $T_w = 2000$ °R, No Gas Radiation,
 Simplified 9-Species and 19-Reaction Carbon-Air Chemical System ($N, N_2, O, O_2, NO, C, CO, CO_2, CN$)

Figure A1-1. Comparison of Various SEB Models and the Predicted In-Depth Heat Conduction at the Stagnation Point for the Sample Diffusion-Controlled Oxidation Case

GIS flowfield calculations, the flowfield chemistry is modeled using a 19 species ($O, N, N_2, O_2, NO, C, C_2, C_3, CO, CO_2, CN, N^+, O^+, N_2^+, O_2^+, NO^+, C^+, CO^+$ and e^-) and 44-reaction chemical model and gas radiation effects have been included. Numerical calculations were done along the stagnation streamline using the new MBW boundary conditions at the ablating wall, and comparisons have been made with the earlier post-FSAR analyses described in Section 6.5.3.3.3 which used ECW approximation.

Figure A1-2 shows the predicted surface-ablation rate using the improved CFD approach with nonequilibrium species-mass-balance boundary conditions (MBW) and post-FSAR predictions based on an equilibrium-catalytic wall (ECW). The results show that the new CFD analysis predicts about 30% higher ablation rate than the earlier predictions. However, as shown in Figure A1-3, the predicted in-depth heat conduction with the improved

GIS: Nonequilibrium vs Equilibrium Catalytic Wall (Stagnation-Point Surface-Ablation Rate)

Figure A1-2. Comparison of Predicted Surface-Ablation Rate at the Stagnation Point for the Sample Sublimation Case

CFD approach is about 21% lower than that predicted using the earlier LM predictions [LM (FSAR) SEB] and about 26% lower than that predicted using the SEB advocated by INSRP/ReSP [INSRP (FSAR) SEB]. The results of the transient heating analysis and surface recession predictions for the GIS are discussed in detail in Section A5.1. However, briefly speaking, the reduced in-depth heat conduction offsets the effects of the higher surface ablation rate because the converged surface temperature predicted by the transient-heating analysis is somewhat lower. Due to these compensating effects, along the intermediate trajectory, the final predicted recession of the GIS using the improved CFD approach is within 3% of the earlier predictions (see Section A5.1).

Figure A1-3. Comparisons of Various SEB Models and the Predicted In-depth Heat Conduction at the Stagnation Point for the Sample Sublimation Case

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Section A2

EGA Uncertainty Evaluations

SECTION A2

EGA UNCERTAINTY EVALUATIONS

The computation of the aerothermodynamic environment and material response of the GPHS module and GIS requires the coupled solution of the nonequilibrium, chemically reacting flowfield with nonequilibrium hot gas radiation. Necessarily, the application of computational fluid dynamic (CFD) techniques to the high temperature, high velocity, extremes of EGA reentry, even with the most sophisticated modeling, will entail uncertainty.

Cassini GPHS-RTG FSAR Approach: The details of the systematic approach used to evaluate uncertainty and variability in the CFD analyses have been presented in the FSAR (Reference A2-1), Appendix E, Section E.3.1.4. In this approach, uncertainty and variability are defined as:

- **Parameters and Uncertainty:** '*Parameters*' are quantities whose '*nominal*' values, based, directly or indirectly, on measured data, need to be specified in a computational analysis. Any ambiguity in establishing their '*nominal*' value will be called '*uncertainty*'. Examples of such CFD parameters are shock-layer viscosity and thermal conductivity, species enthalpies, reaction rates, sublimation vapor pressures, species radiation properties, etc.
- **Variables and Variability:** '*Variables*' represent naturally occurring phenomenon and possible variations in them will be called '*variability*'. Examples of such CFD variables are freestream temperature, freestream density, freestream velocity, freestream composition, freestream turbulence, orientation for a random tumbling case, etc.

In the FSAR, a total of seventeen uncertainty parameter groups and one variability parameter group were investigated. These parameter groups were chosen in order to encompass all likely sources of uncertainty and variability. The uncertainty parameters groups, listed below, were assessed using a combination of RACER/LORAN-C computations, empirical relations, and results from the literature.

- species convergence,
- choice of sublimation species,
- element diffusion data,
- thermodynamic equilibrium assumption,
- reaction-rate data,
- third-body efficiency matrix,
- species enthalpy data,
- species viscosity,
- species thermal-conductivity,

- species diffusion,
- absorption/emission coefficients,
- spectrum data,
- radiation convergence,
- tangent-slab approximation,
- equilibrium catalytic wall assumption,
- species vapor-pressure data, and
- drag coefficient (effect of freestream velocity at a specified altitude)

For each group, the uncertainty in surface heat flux and ablation rate, due to uncertainty in the parameters, was determined. All estimates reported in the FSAR were generated for the GPHS module.

The only significant variability parameter is the atmospheric model. In the FSAR, the effects of departures of the freestream density from the Standard Atmosphere were estimated using the correlation of $\rho_{\infty} V_{\infty}^3$ with heating. It was concluded that variability of the freestream density could result in $\pm 5\%$ variability in the surface heat flux and ablation rate.

The final result of the uncertainty and variability analyses reported in the FSAR was that:

"The combined effect of all M-type (biased) uncertainties in the net heat flux to the wall and the ablation rate is approximately -15% (where a minus sign indicates an over-prediction). A +2% margin has been added to this bias for conservatism. Based on this bias estimate, the most probable value of the net heat-transfer rate and the ablation rate is approximately 0.85 times their nominal values. The root sum-square of all U-type uncertainties around this most probable value is approximately $\pm 15\%$, and the additional effect of variability is approximately $\pm 5\%$."

Updated Approach: In their review of the FSAR, INSRP/ReSP (Reference A2-2) contended that the uncertainty should be higher and that the bias of -15% overstated the conservatism of the approach. They acknowledged that time did not permit the use of detailed RACER/LORAN-C computations to evaluate all uncertainty parameters. However, they expressed reservations in the uncertainty results that were obtained using approximate techniques. Nevertheless, INSRP/ReSP employed an approximate computational method as a basis to judge the RACER/LORAN-C results.

In this updated analysis, effort is focused on refining the FSAR uncertainty and variability estimates and applying them to the GIS. Emphasis has shifted to the GIS because the GPHS module was determined to structurally fail (and release the GISs) for most reentry path angles ($|\gamma| \geq 16^\circ \pm 4^\circ$).

In addition to re-evaluating the largest contributors to uncertainty and improving estimates by performing full RACER/LORAN-C computations, additional candidate uncertainty parameters have been identified and evaluated. Most importantly, the INSRP/ReSP contention that a reasonable bias in the volumetric radiative emission prediction is +100% (that is, the radiative emission prediction could be too small by a factor of 2), was assessed in detail. As described in Section A2.1, the large radiation bias assigned by INSRP was found to be excessive for modern techniques such as LORAN.

A2.1 RADIATION UNCERTAINTY

In an independent review performed by Professor Leland Carlson, a member of the Texas A&M Aerospace Engineering Department, the approach cited by INSRP/ReSP (Reference A2-2) to arrive at its estimate of a 'factor of two' underprediction for radiative heating was investigated. Professor Carlson reviewed the theoretical techniques and experiments cited by INSRP/ReSP and the relevance of the experiments and the validity of the theoretical methods used by INSRP/ReSP as applied to the GPHS and GIS reentry environment were evaluated. Further, the radiative heat transfer prediction technique used by Lockheed Martin and embodied in RACER/LORAN-C were reviewed and assessed. Finally, refined uncertainty estimates associated with the radiative heating were developed. Professor Carlson's report on these topics (Reference A2-2a) is summarized in Section A2.1

A2.1.1 Critique of INSRP/ReSP's Method of Approach and Cited Experimental Data

INSRP/ReSP used a flowfield and radiation model to assess the accuracy of the Lockheed Martin predictions. They noted that theoretical techniques similar to theirs, when compared to experimental data, indicated that theory overpredicted radiative emission rates, sometimes by a factor of two, at conditions similar to those which would be encountered by Earth entry of the GPHS modules. They then drew the conclusion that the Lockheed Martin technique could be expected to reasonably underpredict the radiative emission by a factor of two. Their approach and conclusions will be reviewed in this section.

The use of an approximate stagnation-point model to assess the accuracy of FSAR computations seems reasonable, particularly considering that the INSRP/ReSP model included, approximately, radiative cooling by using a fourband equilibrium radiation model. However, while the INSRP/ReSP model in some manner included diffusion and wall mass

transfer, it did not include the effect of ablation products in the radiation model. In addition, it is believed that the INSRP/ReSP model was inviscid, and the inviscid solution was subsequently used in the Fay-Riddell formula to obtain convective heating. Further, the model was for a spherical stagnation point and the results were approximately corrected for a flat-faced stagnation point. While such an approach should give an indication of the uncertainty of the FSAR computations, results obtained from it should be viewed as qualitative approximations. Encouragingly, the INSRP/ReSP approximate results agreed quite well with the FSAR results. However, INSRP/ReSP nevertheless concluded that the Lockheed Martin radiative results could be low by a factor of two.

To address these issues, several of the INSRP/ReSP statements (Reference A2-2) will be taken individually and commented upon.

"The notable lack of flight data or ground test experimental data for validation of convective and radiative heating calculations at the extremely high entry velocities of VVEJGA reentries was not fully acknowledged."

There definitely is a lack of radiative emission and/or radiative heating data corresponding to air temperatures above 16,000°K. Nerem et al. (References A2-3 through A2-6) did obtain some stagnation point and reflected shock data at temperatures in the 16000-18000°K range, but most measurements are at 16000°K and below. Examples are bow shock measurements by Thomas and Menard (Reference A2-7), stagnation-point data by Gruszczynski and Warren (Reference A2-8), and reflected shock data of Wood et al. (Reference A2-9). The GPHS steep trajectory point 6 cited by Lockheed Martin (Reference A2-10) shows equilibrium temperatures on the order of 18000°-20000°K. However, most theoretical models including four-band (Reference A2-11), five-band (Reference A2-5), eight-band (Reference A2-12), RADEQUIL (Reference A2-13), LORAN (Reference A2-14), etc. were designed using theories such that they could be accurate up to 20000°K, given appropriate species input data. Thus, while it is true that little experimental data exists at the temperatures and conditions of interest, it is believed that appropriate theory is available to develop reasonable and adequate radiation models for the present conditions of interest. The available experimental data and comparison to various radiation models are discussed later in this section.

"Radiation heating rates are much greater than convective heating rates during the EGA entries..."

At peak heating points this statement is definitely true; but at early times during the entries, particularly on the shallow trajectories, the convective heating rate is higher. The impact of radiative heating on total heat load needs to be examined for the entire trajectory. The point is --"errors" in radiative heating do not have as great a total impact on recession rate as would be indicated by only looking at peak heating conditions. Lockheed Martin (Reference A2-2) took into account the relative contributions of radiative and convective heating, integrated over the entire heat pulse. It was found that radiative heating is about one-half of the total flux for the GPHS shallow trajectory and even less for the GIS on the intermediate trajectory. INSRP/ReSP also stated that high radiative heating leads to high ablation rates which results in reduced convective heating rates. This statement is probably true; but it overlooks the fact that ablation products can be highly absorbing and thus also reduce the radiative heating to the wall.

"It is not clear that emission at wavelengths below about 1300 Å has been included in the FSAR modeling. No independent estimate has been made of the possible error in radiation flux that could result from neglecting this shorter wavelength emission."

The wavelength of 1300Å corresponds to 9.5 eV and so INSRP/ReSP is wondering about radiation with energies greater than 9.5 eV, i.e. radiation in the ultraviolet (UV) and vacuum ultraviolet (VUV). LORAN, like RAD/EQUL, covers radiative processes from 0.68 eV (from 18235 Å) up to 16.5 eV (down to 751 Å). Thus, LORAN adequately covers the UV and VUV. There is essentially no known air radiation of interest outside this range, although the eight-step model (Reference A2-12) actually goes to 31 eV. Thus, the INSRP/ReSP concern is a moot point; radiation in this region was properly included in RACER/LORAN-C. The validity of LORAN and LORAN-C will be discussed later in this section.

"The INSRP/ReSP believes that the volumetric emission rate and related radiation transport in the shock and boundary layers of the GPHS and GIS are the largest uncertainty sources in EGA reentry heating rate predictions."

Later in this section an attempt will be made to justify and estimate the accuracy of LORAN as a radiation model. However, it can reasonably be asserted that the radiation model and method of computing the radiation transport is not a major source of error. Based upon

several studies conducted by this Carlson, if a set of temperatures and species concentrations are used in the radiation model, in this case LORAN, the resultant radiation, absorption, and radiative transport will be very similar to that computed by other models given the same flowfield information. Therefore, the greatest potential for error in the radiative heating solution is not in the radiation modeling, but in the flowfield solution used as input to the model.

INSRP/ReSP asserts that the model of Page (Reference A2-11) was compared with others by Wood et al. (Reference A2-9) and found to agree reasonably closely. This statement is true as can be seen in Figure A2-1. However this comparison is for an isothermal layer 1cm thick. The key word here is isothermal. In other words, radiative cooling was not included in these predictions. It is not clear whether or not absorption was included in the computations and comparisons on this figure, or if instead the results presented are for a thin-gas computation. In any event, it is true that the various models agree quite well and what divergence that exists between the models shown is, at the most, on the order of 30-40% and nowhere near a factor of two.

INSRP/ReSP then notes that Wood et al. compared their theoretical predictions with experimental data and found that at high temperatures, roughly above 12,000°K, that the theories overpredicted the experimental data (see Figures A2-2 and A2-3) by as much as a factor of two. This disagreement existed both for total radiation intensity measurements and for measurements through a quartz window. The latter would only measure the visible and infrared radiative intensity. The reflected data corresponded to stagnation-point flight conditions of 9.5 to 14 km/sec at an altitude of 43 km., and pressures in the reflected shock region ranged from 2.2 to 6 atmospheres. The theoretical predictions shown by Wood however were "calculated assuming a uniform gas at the thermodynamic conditions computed from the Rankine-Hugoniot equations and an LMSC thermochemical equilibrium computation" (Reference A2-9). The key here is that the technique which overpredicted the experimental data at the higher temperatures assumed a uniform gas (i.e., isothermal and with constant chemical composition) based upon thermochemical equilibrium. These predictions all assumed that the reflected shock conditions were based upon complete

Figure A2-1. Comparison of Various Theories at the Conditions of Wood Shock-Tube Experiments (from Reference A2-9)

equilibrium in all regions of the shock-tube flow -- both behind the incident wave and the reflected wave. The possible effects of radiative gasdynamic coupling (i.e., radiation cooling) were not included. Wood et al. estimated that cooling could only account for at most a 10% decrease because they did not observe what they felt were significant decreases in their transient heat-transfer (THT) gage heat-flux measurements with time. As will be shown, they may have been wrong in this estimate.

Figure A2-2. Comparison of Wood et al.'s Total-Intensity Experimental Data with their Theoretical Predictions (from Reference A2-9)

In 1968, Golobic and Nerem (Reference A2-6) published measurements of radiative heat transfer on the end wall of a shock tube where the radiating flow was generated by a reflected shock wave. Their measurements used a sapphire window between the flow and the gage; and, thus, the measured radiation only included the visible and infrared ($1700\text{\AA}$ to $60000\text{\AA}$) parts of the spectrum. They compared their results to several radiation models for the reflected shock region. These models, which were non-gray and included emission and absorption, used only two steps to represent the entire radiating spectrum; and they excluded

Figure A2-3. Comparison of Experimental Data of Wood et al. Obtained through a Quartz Window (i.e., Visible Plus Infrared) with their Predictions (from Reference A2-9)

cooling effects due to radiation losses. The resulting values overpredicted the reflected shock-tube measurements by as much as a factor of two for the higher shock velocities. Thus, they observed the same discrepancy between theory and experiment as Wood et al. Consequently, Knott, Carlson, and Nerem (Reference A2-5) in 1969 developed a new five-step radiation absorption coefficient model and incorporated it into an equilibrium reflected-shock code that included radiation cooling. This absorption coefficient model was designed to include all of the important processes expected in the reflected-shock region associated with the experiments. As shown on Figure A2-4, the results with the new model predicted end-wall radiative heat transfer values in the middle of the measured shock-tube data over

Figure A2-4. Comparison of Golobic and Nerem Reflected Shock Tube Data with Various Radiation Computations that Exclude and Include Absorption and Radiative Cooling (from Reference A2-5)

the entire velocity range. As can be seen, results were also presented which included and excluded radiative cooling. Without radiative cooling, the predictions for the visible plus infrared end wall radiative heating were about a factor of two high. Obviously, radiative cooling explained the Golobic and Nerem data.

Today, most investigators also believe that radiative cooling explains the Wood data and its lack of agreement with theory as shown on Figures A2-2 and A2-3. It appears that Wood et al. took their measurements about 5 μsec after shock reflection. As shown on Figure A2-5, the reflected-shock temperature profile predicted by Carlson (Reference A2-15) for the Knott, Carlson, and Nerem paper (Reference A2-5) drops rapidly from its immediate post shock

Figure A2-5. Reflected-Shock Temperature Profiles Including Radiation Cooling
 (from Reference A2-15)

value. Based upon equilibrium computations, the reflected-shock theoretical equilibrium temperature would have been slightly over $17000^\circ K$ for the conditions shown (Reference A2-16). However, as shown on the Figure A2-5, the temperature in the reflected-shock zone by five microseconds would have dropped to about $16000^\circ K$. This cooling significantly changed the end-wall heat transfer in the Golobic and Nerem experiments; and it would also change a measurement, such as that of Wood, which measured radiative heating or intensity across the reflected shock region. Thus, it would appear, that radiative cooling is probably the explanation of the factor of two difference between the data of Wood et al. and their presented theory (which agreed with the Page model on Figure A2-1) for at least the visible

and infrared spectral regions. It would seem logical to expect similar cooling effects on the total emission results.

Nicolet (Reference A2-13) in 1970 took the results of Wilson and Nicolet (Reference A2-17) and their detailed studies of radiative processes and absorption coefficients and developed the RAD/EQUIL model. In his report, Nicolet compared results predicted by RAD/EQUIL including a radiative-cooling estimate and the data of Wood et al. for the visible and infrared region. His predictions, shown in Figure A2-6, fall right through the mean of the Wood data.

Based upon these comparisons, it is believed that the explanation of the factor of two overprediction in the Wood data is simply a lack of inclusion and understanding of the importance of radiative cooling at the time Wood et al. published their results. Thus, it is not appropriate to conclude that radiation modeling theory is incapable of predicting the Wood results. In fact, the work of Knott, Carlson, and Nerem and of Nicolet demonstrates that the Wood data can be accurately predicted.

The INSRP/ReSP report concluded that *"a factor of 2 higher volumetric emission rate is considered a reasonable uncertainty..."* and they used this conclusion in their overall assessments. They arrived at this conclusion by noting that *"When the INSRP/ReSP radiation model is compared with that of Page, the latter (i.e., Page) is about a factor of two higher for total emission over the range of pressures and temperatures of greatest Cassini interest."*

This statement is confusing because the INSRP/ReSP model was based upon the work of Page and the panel does not further explain the statement. However, it is possible that they were comparing emission predictions using the Page model (for example, using Figure A2-1) at Cassini conditions with the INSRP/ReSP computations. Since the emission predictions, such as those in Figure A2-1, did not include radiative cooling and the INSRP/ReSP computations appear to have included radiation cooling, a factor of two difference would be likely based upon the above discussion of cooling effects at these temperatures. Thus, it is possible that this discrepancy is due to an inappropriate comparison.

Figure A2-6 Comparison of Shock Tube Data of Wood with Predictions from RAD/EQUIL
 (from Reference A2-13)

There are a couple of other reasons why INSREP/ReSP might have wanted to state an uncertainty of a factor of two. During the Apollo program, there was great concern about radiative heating, particularly the amount associated with the ultraviolet and vacuum ultraviolet. However, the heat shield had to be designed during the period when there was only limited knowledge and data about the visible plus infrared and almost no data for the ultraviolet and vacuum ultraviolet regimes. Thus, it was common to use large safety factors, on the order of two; and it was generally assumed at the time that radiative heating estimates were potentially in error by a factor of two. (The Apollo heat shield probably had a safety factor of at least four.) Later, with the theoretical work of Olstad, Wilson, Nicolet, and Page et al., and the experimental data of Golobic and Nerem and Wood, considerable progress was

achieved. Some experimental data was also obtained in the Fire II flight (Reference A2-18). In general, theory developed during this period had less variance than shock-tube data. Nevertheless, the concept remained among most people that radiation was not known within a factor of two. Many members of INSRP/ReSP may recall those adventurous and uncertain times and therefore intuitively believe that radiation cannot be predicted within a factor of two.

The INSRP/ReSP report also states that *"other factors ... not modeled in the theory"* might influence the predictions, but the report does not indicate what factors.

Possibly, INSRP/ReSP was thinking of the limitations of the four-band model of Page (Reference A2-11) and what it included. As noted, in their approximate studies it appears they used the Page model for their radiation computations. However, LORAN (Reference A2-14) contains all of the features of RAD/EQUIL (Reference A2-13) and actually improves and extends what RAD/EQUIL includes. Furthermore, LORAN-C extends LORAN to include the radiative effects of ablation products. Thus, it is hard to imagine what important radiative phenomena were not included in LORAN. What phenomena were included in LORAN, and what were excluded, will be discussed later, and the impact of those choices will be assessed. Further, the theoretical basis for RAD/EQUIL, and thus LORAN and LORAN-C, is more extensive than the model of Page, particularly in the detailed treatment of lines in the infrared, ultraviolet, and vacuum ultraviolet (Reference A2-14).

So again -- Why did INSRP/ReSP conclude that a factor of two higher was reasonable? First, as mentioned, it could be due partially to a general uneasiness about this entire area by many people. This uneasiness arises because of the small volume of data, particularly in the ultraviolet and vacuum ultraviolet regions of the spectrum. To put this problem in perspective, the data and theoretical predictions need to be separated out into those for the visible and infrared (i.e., below 6.2 eV or above 1700 or 2000 Å) and those for the ultraviolet and vacuum ultraviolet (above 6.2 eV and below 2000 Å).

In general, radiation models such as RAD/EQUIL result in excellent predictions of radiative heat transfer or emission data taken in the visible and infrared. Knott (Reference A2-19) compared results using the five-step model (Reference A2-5), including radiation cooling, with Nerem's stagnation-point (Reference A2-3) and reflected shock-tube data and obtained

excellent correlation. The stagnation data comparison is shown in Figure A2-7. Likewise, predictions using RAD/EQUIL went right through the middle of both Nerem's shock-tube stagnation-point data and the Wood et al. Reflected-shock data when cooling was included (Reference A2-13). Further, as discussed below, most radiation models such as LORAN agree with AVCO shock-tube spectral emission data taken in the visible and/or infrared region. While not as consistent, probably due to the methods of determining the flowfield, most radiative schemes compare closely with the Fire II flight visible and infrared measurements. Wood et al. Also compared their theory to the data of Nerem and in general overpredicted his measurements. Again, this overprediction was probably due to not including radiation-cooling effects.

On the other hand, Wood also compared their theory to the experimental data of Thomas and Menard (Reference A2-7), which was obtained on the front face of a cylindrical model. The theory was, surprisingly, below these measurements. This discrepancy is puzzling since Thomas and Menard, in their article (Reference A2-7) compare their data with Nerem (Reference A2-3), and the two sets of data agree almost perfectly. Thus, it is difficult to reconcile the Wood et al. results.

In a thorough survey paper, Sutton (Reference A2-20) also compared predictions made with his version of RAD/EQUIL, called RADICAL, with a variety of shock-tube data. His predictions compared well with the data of Nerem in the visible plus infrared, but they were below the Thomas and Menard data. On the other hand, Sutton's model yielded results identical with the theories of Wood et al. shown on Figures A2-1 and A2-2. Thomas and Menard believed the difference might be due to N- radiation, but Sutton investigated this possibility and estimated that even if N- radiation existed it would only increase the emission by 25% -- not a factor of two. Sutton also obtained good agreement with Hoshizaki's experimental results (Reference A2-21). For the Gruszczynski and Warren (Reference A2-8) data, his computed values were about 50% below their total measurements. However, the predicted trend was in agreement with the measurement variation, both with and without quartz windows. Thus, his variation prediction was correct for the visible plus infrared and the total spectrum. Further, his results predicted the difference between the radiation from

Figure A2-7(a). Comparison of Radiatively Cooled Prediction with Nerem Stagnation- Point Data (from Reference A2-19)

Figure A2-7(b). More Comparisons of Radiative Cooled Predictions with Nerem Stagnation-Point Data (from Reference A2-19)

the visible and infrared region and the total radiation correctly. This type of agreement implies that either Sutton, who assumed chemical equilibrium, did not properly model the Gruszczynski and Warren (Reference A2-8) flowfield conditions or that there was a consistent data reduction error in the Gruszczynski and Warren results. The Sutton model also correctly predicted the visible plus infrared light-gas gun data of Page and Arnold (Reference A2-22), and the reflected shock data of Nerem and Golobic (Reference A2-6) when he included simulated cooling. For the data of Wood et al. (Reference A2-9), Sutton's prediction is consistently high at the higher incident shock velocities (i.e., higher temperatures). However, it is believed he did not include radiative cooling in this comparison. Sutton also compared his predictions to constricted arc data available for air and nitrogen both with and without quartz windows. He obtained good agreement, although there appears to be some question about interpreting constricted arc data.

Sutton also compared his predictions with the Fire II experiment and the Apollo 4 data. In general, he obtained amazingly good predictions. Thus, based upon the results and comparisons presented in his survey paper, it would appear that the methods and modeling used in RADICAL (or RAD/EQUIL) should give very good estimates for radiative heating over a wide range of conditions.

Finally, based upon considerable experience with several techniques, almost all good radiation models agree with each other in the visible and infrared. As will be determined below in the review of RACER/LORAN, the differences in these predictions in the visible and infrared is about 10%. Since shock-tube data has much wider scatter than 10%, it would appear that at least for the visible and infrared, that radiation can be predicted more accurately than it can be measured. In this respect, it should be noted that many shock-tube experiments have had the data presented for all data points. Nerem (Reference A2-3), however, used an averaging technique to average data points at similar conditions, and, as can be seen on Figure A2-7, the resultant data had less scatter and also was very close to the theoretical predictions.

Thus, while the INSRP/ReSP panel may have felt some uneasiness about data available in the visible and infrared, it probably was due to the data scatter in the shock-tube measurements and not to deviations between various models.

In the ultraviolet and vacuum ultraviolet, which can be thought of as looking at total-intensity/heat-transfer measurements, there is a definite lack of experimental radiation data. The only two sets of measurements associated with total radiant intensity or heat transfer are those of Wood et al. (Reference A2-9) (discussed above) and those due to Gruszczynski and Warren (Reference A2-8). Unfortunately, while the prediction of Wood et al. was above their reflected-shock measurements for incident shock speeds of 7.5 km/sec and higher (temperatures above 13000⁰K), the Wood predictions for the total-spectrum Gruszczynski and Warren measurements are low for incident shock speeds from 8.5 km/sec to 9.5 km/sec. The latter data were taken at the stagnation point of a flat-faced cylinder in the incident-shock flowfield after the passage of the incident shock. Since a shock forms around the cylinder, the conditions are similar to those for the reflected-shock region. Note that Nerem's data (Reference A2-3) was taken at the stagnation point of hemisphere cylinders. Unfortunately, a comparison of Nerem's and Gruszczynski and Warren's data from the visible and infrared zones indicates that the latter's data is consistently above that of Nerem. Nicolet also compared predictions using RAD/EQUIL with the Gruszczynski and Warren data and his prediction was also low and at the bottom of the data scatter region of the Gruszczynski and Warren data.

The unfortunate part about the Gruszczynski and Warren and the Wood et al. total heat-transfer data is that they are about a factor of two different. This fact may be part of the reason the INSRP/ReSP wanted to assign a factor of two uncertainty. It should be noted, however, that both the Wood prediction and the Nicolet RAD/EQUIL prediction are in reasonable agreement with the Gruszczynski and Warren data for measurements made behind a quartz window (and hence only in the visible and infrared). Also, the Gruszczynski and Warren data for the quartz window case are close to similar measurements of Nerem behind a sapphire window. Thus, it would appear that the Gruszczynski and Warren data for the visible and infrared is in reasonable agreement with other data and with theoretical predictions. However, the Gruszczynski and Warren total prediction is not. At this point,

there is no explanation for the difference between the Gruszczynski and Warren and Wood et al. data. However, it should be noted that the Gruszczynski and Warren data was for a limited number of data points (on the order of 10) and that no theory has ever agreed with it. As discussed throughout this section, considerable progress has been made in the past thirty years in the development of accurate, detailed radiation models and in viscous nonequilibrium chemistry flow solvers; and results obtained with these models should be more accurate than the difficult to obtain experimental data of Gruszczynski and Warren or Wood et al. Thus, even though the two experiments disagree by a factor of two, it does not follow, and in fact would be inappropriate, to assert that the uncertainty in radiative heating predictions is a factor of two.

In summary, it is believed that predictions by modern radiation models, such as LORAN and RAD/EQUIL should give values within 10% or so for the visible and infrared portions of the spectrum. For the ultraviolet and vacuum ultraviolet, there may be a greater uncertainty and it may be reasonable to treat present predictions as a lower limit. However, it would appear, based upon the above discussion, that a factor of two is excessive. First, the primary area of uncertainty in the ultraviolet and vacuum ultraviolet is in the 8-10 (or 11) eV range. This situation is shown in Figure A2-8. This figure displays stagnation-point radiative heating (Reference A2-23) as a function of energy for a 16 km/sec vehicle at 80 km altitude. (Note: The spectral variation of radiative heating is shown in two different forms on this figure. In the top graph, the radiation heating is shown on a linear scale and quickly displays which regions of the spectrum contribute to the stagnation radiative heating. However, it does not indicate which contributions are due to lines and which is continuum. The lower graph uses a logarithmic scale and shows the details of the lines.) This result was obtained using a local thermodynamic nonequilibrium radiation model based upon RAD/EQUIL and NEQAIR (References A2-23 and A2-24). In general, the emission or radiative heating from continuum processes is well understood; and with models like LORAN or RAD/EQUIL, it can be well predicted. In addition, as shown on Figure A2-8, above 12 eV the line radiation is heavily absorbed in line centers, although there is some emission in the line wings. However, between 8 - 11 eV, the lines are not significantly self absorbed. Thus, for that region the

Figure A2-8. Gally's 16/80 QR Results. Top is Usual Presentation. Bottom Shows Details of Lines. Notice Absorption by Line Centers above 10eV. (from References A2-23 and A2-24)

radiation prediction could depend upon the accuracy of the available line data and the way the lines are treated in a model. It should be noted that RAD/EQUIL attempted to treat these lines very accurately and properly and to include all of them. Previous band models (References A2-5, A2-11, and A2-12) only included so called "dominant" lines or line groups; and therefore, they will not be as accurate as RAD/EQUIL. LORAN, which is based upon RAD/EQUIL for atomic processes, actually improved the treatment of lines. Note that for Cassini conditions, there are essentially no molecules and the radiative processes are all atomic in origin.

Later in this section, the results of some simple investigations will be presented in an attempt to determine the effect of "uncertainties" in the 8-10eV region. It should be noted that an uncertainty of a factor of 2 in the 8-10 eV region might have a much smaller effect on the overall radiative heat transfer.

A2.1.2 Review of Theoretical Techniques Used by INSRP/ReSP

In this section the theoretical techniques utilized by INSRP/ReSP will be reviewed. (The experiments cited by INSRP/ReSP and used in developing their conclusions were discussed above.) In particular, attention will be paid to the relevance and validity of the models applied by INSRP/ReSP to the GPHS and GIS cases. In their approximate model, INSRP/ReSP made several assumptions. These are stated and commented upon in the following paragraphs.

A2.1.2.1 Equilibrium Air Shock Layer

This assumption should be a qualitative approximation for most of the critical conditions, such as peak heating, associated with the GPHS entry trajectory. The stagnation-streamline temperatures and species profiles shown in the FSAR, Volume II (Reference A2-1), specifically Figures E 4-8, E 4-13, and E 4-14, are, except for a small region immediately behind the shock front and the "viscous" and ablation layer immediately adjacent to the wall, all indicative of a radiation coupled shock layer that is close to chemical and thermal equilibrium. However, radiative heating is very sensitive to chemical composition; and the fact that the middle of the flow is only near chemical equilibrium and the ablation layer is probably in nonequilibrium could cause the radiative heating to be significantly different from that predicted using an equilibrium approach. As shown in Section A.3.2, the flowfield along the stagnation line for the GIS (at 147 kft and 51 kft/sec) never reaches chemical equilibrium. Thus, the assumption of an equilibrium-air shock layer is approximate and results obtained using such an assumption should be viewed as qualitative.

A2.1.2.2 Radiation Based on a Four-Band Model

INSRP/ReSP states that their radiation model is based upon the work of Kivel and Bailey (Reference A2-25) and Page et al. (Reference A2-11). The Kivel and Bailey model was one of the first radiation models associated with reentry phenomena. Basically, it developed analytical expressions for spectral absorption coefficients under assumptions that resulted in a smeared structure and a continuous distribution of radiation over the wavelength of certain types of band radiation. The model concentrated primarily, it is believed, on molecular band systems. However, it does contain some of the important f-numbers for various radiative

processes and perhaps INSRP/ReSP used those values in their model. The Kivel and Bailey model was the earliest such model, and while it used the best data available at the time, by the mid-1960's it was apparent that the model overestimated the radiance at high temperature even in the visible and infrared portions of the spectrum. This condition is shown in Figure A2-9 from Reference A2-3, which compares several mid-sixties radiance models.

Page et al. (Reference A2-11) developed in 1968 a four-band absorption coefficient model for air which was designed to be used in radiatively coupled solutions. They compared their four-band model with various experimental data. It agreed with Nerem's (Reference A2-3) stagnation-point shock-tube data for the visible plus infrared within better than 30% (their

Figure A2-9. Comparison of Radiance Models (from Reference A2-3)

claim), and with Hoshizaki (Reference A2-21) (also only in the visible and infrared) except it was somewhat high at temperatures above 12000⁰K. They also used it to predict the reflected shock tube total emission data of Wood et al. (Reference A2-9) and achieved good agreement up to temperatures around 13000⁰K. Above that temperature, the Page model prediction was always higher than the emission data of Wood et al.

While the four-band approach is a reasonable approximation, it has its limitations. In 1969 Knott and Nerem (References A2-5 and A2-19) developed a five-band model; and in 1971 Olstad created an eight-step model. The four- and five-step band models were designed to accurately predict equilibrium stagnation point conditions and reflected shock conditions, and they give excellent results for those situations, which covered pressures from two to about twenty atmospheres. However, later studies (Reference A2-26 and A2-27) indicated that two- and five-step models, and thus presumably four-step models, were inadequate for many conditions of interest; and that at a minimum an eight-step model should be used.

The inadequacy of band models led Nicolet (Reference A2-13) to develop the RAD/EQUIL (sometimes called RADICAL) radiation model. The RAD/EQUIL model is extremely detailed and based upon the best information available at the time. As discussed above, and thoroughly demonstrated by Sutton (Reference A2-20) and Gally (References A2-23 and A2-24) RAD/EQUIL and models based upon it usually yield very accurate predictions and excellent agreement with experimental measurements.

Almost all of these radiation models use essentially the same molecular and atomic radiation constants as initial input. The primary differences are in how the basic information is used to compute absorption coefficients and black-body function values. In the band models, the detailed information is averaged over a certain wavelength and then correlated as a function of temperature and species concentrations. In contrast, in RAD/EQUIL the entire spectrum is essentially treated in detail with only limited grouping of closely spaced lines into effective lines. It should be noted that the strength of the RAD/EQUIL model is (1) its attention to detail and (2) its treatment of atomic-line and atomic-continuum radiation. As a result, it probably does a better job of properly modeling and accounting for atomic phenomena than

any other model. Note that all of the models discussed in this section so far were for thermal and chemical equilibrium gas compositions, usually air or nitrogen.

Later Park (Reference A2-28) developed the NEQAIR radiation model. NEQAIR, which was developed to handle nonequilibrium conditions associated with high altitude aero-assisted entry profiles at speeds of 9-10 km/sec, primarily concentrated on molecular processes; and it included techniques for handling local thermodynamic and chemical nonequilibrium situations. While it included atomic-line and continuum processes, these may not have always been modeled as well as the molecular processes. To handle local thermodynamic nonequilibrium (LTNE), NEQAIR included a quasi-steady state (QSS) approach to compute non-Boltzman excited-state populations. In equilibrium situations, NEQAIR yields results very similar to RAD/EQUIL, particularly for the visible and infrared regions of the spectrum dominated by molecular processes and infrared line emission.

Subsequently, the chemical and thermal nonequilibrium radiation model, LORAN, was developed by Hartung (nee Chambers) (References A2-14 and A2-29). Starting with RAD/EQUIL and NEQAIR, Hartung retained the good features of each, improved the treatment of lines and the computation of radiative transfer, and utilized throughout the spectrum the QSS approach for determining excited-state populations under nonequilibrium conditions. LORAN was specifically designed for LTNE situations and, because of its improvements, should yield excellent results for equilibrium flows.

Simultaneously with LORAN, RADTHERM was developed by Carlson and Gally (References A2-23 and A2-24). It was also based upon RAD/EQUIL and NEQAIR, and it too was designed to handle chemical and thermal nonequilibrium situations. However, while it retained the local thermodynamic equilibrium approaches of RAD/EQUIL for atoms and of NEQAIR for molecules, it accounted for LTNE by using correction factors that could be computed using known concentrations of species.

In summary, the Page four-band radiation model used by INSRP/ReSP probably provides a reasonable estimate of radiation phenomena if the flow is in equilibrium. But it is not as detailed, or as accurate, as later more sophisticated models such as RAD/EQUIL, LORAN, or RADTHERM. Thus, results obtained using it could be in error, particularly at higher

temperatures where the details of line radiation become more important, and under conditions of nonequilibrium. It should be noted that for many points on potential Cassini entry trajectories, reasonable amounts of chemical nonequilibrium exist behind the shock front and in the viscous ablation-products layer near the wall. This situation is particularly true for the shallower trajectories in which the GPHS module would spend more time at higher altitudes with lower freestream density.

A2.1.2.3 Fay-Riddell Stagnation Point Heating

This similarity solution approach does include conductive and diffusive heating. The INSRP/ReSP report, however, assumed an equilibrium shock layer; and the composition used in the Fay-Riddell solution would be an equilibrium composition at the wall temperature. The FSAR indicates on Figure E.4-25 wall temperatures of 4000-4600 °K. Figure E.4-8 in the FSAR shows that the temperature rises rapidly to over 10000°K very near the wall. The experiences of Gally and Carlson (References A2-23 and A2-24) indicate that in the region near the wall, significant nonequilibrium can occur even if most of the shock layer is in equilibrium or near equilibrium. In other words, chemical nonequilibrium phenomena can be significant both in the immediate post shock front region and in the region adjacent to the vehicle surface. This latter nonequilibrium phenomena could affect the accuracy of the convective heating predictions obtained by the INSRP/ReSP using the Fay-Riddell correlation formula. Thus, their convective heating results, while probably in the ballpark, could contain significant error, particularly when ablation products are present.

In discussing Figures 9.9 and 9.10 of Reference A2-1, the INSRP/ReSP report criticized the FSAR results for convective heating by saying that the FSAR convective predictions always increased with time. Actually, the last point shown in Figure 9.9 has a decrease and therefore may be displaying the same trend as the INSRP/ReSP computations but at a delayed time. (The results in Figure 9.10 terminate prior to peak convective heating.) This delay could be due to nonequilibrium phenomena, which is accounted for in the FSAR results but not in the INSRP/ReSP approach.

A2.1.2.4 Simplifying Assumptions for the Momentum Solution

The approach used by the INSRP/ReSP to simplify the momentum equation should be adequate for an approximate solution, as should the two-dimensional inviscid stagnation-point approach. It is similar to approaches used in other approximate solutions to the hypervelocity stagnation-line problem (Reference A2-26).

A2.1.2.5 Exact Solution of 1-D Energy Equation with Convection, Diffusion, Prescribed Radiation, and Wall Mass Transfer

This appears to be the Page stagnation line model (Reference A2-11) with diffusion and wall mass-transfer terms added in some fashion. Since the INSRP/ReSP indicates that the method iterates to solve for radiation/mass transfer coupling, this technique should yield a qualitative approximate solution.

In general, it appears that the INSRP/ReSP approximate theoretical approach should give an estimate of the convective and radiative heating conditions associated with Earth entry of the GPHS module and the GIS. However, their usage of an equilibrium gas, four-band radiation model, and an approximate solution technique could lead to significant errors. This possibility is enhanced by the high temperatures and possible existence of significant chemical nonequilibrium, not only immediately behind the shock front but also in the ablation products layer near the surface. These phenomena could importantly affect the radiation, particularly line radiation in the ultraviolet. It is interesting to note that the INSRP/ReSP total heating results, shown in Figures 9.8, 9.9, and 9.10 of the INSRP/ReSP report (Reference A2-2), agree with the FSAR results within about 12 to 24% at conditions near peak heating (or the last point in the case of the steep trajectory). Such agreement lends significant credence to the far more sophisticated and detailed technique used by Lockheed Martin and presented in the FSAR.

In comparing the INSRP/ReSP and FSAR results, it is important to keep in mind several distinct differences in the approaches. The GPHS analyses techniques reported in the FSAR treat the three-dimensional features of the module. The INSRP/ReSP technique only applies to the stagnation point. In particular, the RACER/LORAN-C solutions provide GPHS front and side-face heating rate distributions. In addition, the solutions in the FSAR show that the highest heating rates and maximum ablation occurs at the small-radius edge of the front face;

and not at the stagnation point. The RACER/LORAN-C results are supplied to a three-dimensional, transient, in-depth heating code that includes a moving boundary capability to track recession. The transient-heating results are then supplied to a three-dimensional, nonlinear, thermo-structural analysis code. Thus, the RACER/LORAN-C approach is significantly more sophisticated and detailed than the approximate technique used by the INSRP/ReSP.

A2.1.3 Review of the Radiation Prediction Technique in Racer/Loran-C and Assessment of Its Validity for GPHS and GIS Analyses

In this section, the various assumptions and models used in RACER/LORAN-C that might have an influence on the subsequent radiative heat transfer predictions will be reviewed. An attempt will also be made to evaluate the radiation uncertainties determined by Lockheed Martin. The various assumptions and models will be discussed individually in the following paragraphs.

A2.1.3.1 The LORAN (LORAN-C) Radiation Model

The objective of the sub-section is to establish the accuracy and applicability of the LORAN-C model as developed and utilized by Lockheed Martin.

Olynick et al. (Reference A2-30) recently developed a modified radiation model, called NOVAR. This model is based upon LORAN but contains some significant differences relating to spectral discretization of atomic lines, the choice of flow points used to compute the radiation, and the choice of population distributions for the excited molecular and atomic states. In their paper discussing their model they state that *"In the course of developing the NOVAR algorithm, it was found that if an identical flow solution and excited-state population distribution were used as an input for both ..., then the differences between the calculated radiation properties were small. Specifically, they found for equilibrium air at two atmospheres and at 10,000°K,"* the percent difference between the calculated emission coefficients is on the order of 2-3% or less."

Greendyke and Hartung (Reference A2-31) in their studies of the radiative heat transfer for the Fire II vehicle compared predictions obtained using NEQAIR in an uncoupled fashion with those computed from LORAN with radiative coupling turned off. They also compared these

predictions with the Fire II data and with LORAN radiatively coupled predictions. The NEQAIR and LORAN uncoupled results were identical for the entire flight radiation emanating from the visible and infrared regions (i.e. below 6.2 eV). However the uncoupled NEQAIR and LORAN predictions for the total absorbed radiative flux disagree. At the peak radiative heating point, the difference is about 16% with the uncoupled LORAN value being lower. Since the two radiation models agreed below 6.2 eV, this result implies that the difference is due to treatments in the ultraviolet and vacuum ultraviolet spectral regions. Uncoupled total-heating predictions by NEQAIR and LORAN were also compared. These comparisons assumed the gas to be radiatively thin (i.e., nonabsorbing) since the NEQAIR results were computed with that assumption. The flowfield solutions were identical for the two models and the maximum difference occurred at peak heating and was about 7.5%. Greendyke and Hartung also demonstrated that coupled and uncoupled as well as NEQAIR and LORAN radiation results agreed when the flow was equilibrium. For Fire II, full equilibrium would occur at a time when the temperatures were low enough that radiation cooling would not be expected to be important.

Hartung (Reference A2-29) also compared NEQAIR and LORAN for shock-tube and Fire II cases. Good agreement with shock-tube emission intensity data taken by AVCO for the spectral regime between 2000 and 20000 Å was shown for both NEQAIR and LORAN. Comparisons between NEQAIR and LORAN visible and infrared radiative heating (0.31 –5.4 eV) predictions for Fire II at 1634 sec. and 1637.5 sec. were compared and agreed not only in magnitude but also with respect to the origin of the radiation (i.e. atomic line, atomic continuum, or molecular band). The resultant wall radiative flux differences between the two models was only 3% and 6%, respectively.

Hartung et al. (Reference A2-32) studied the radiative heat transfer to a Mars return aerobrake at 12.883 km/sec and 65 km altitude. The shock layer at this condition was essentially in equilibrium. Wall radiative heat-transfer predictions were obtained using the standard nonequilibrium version of LORAN and an equilibrium LORAN, and the heat-transfer values from the two models were within 2 to 8% of each other around the body. This agreement validates using LORAN in a near-equilibrium situation even though it was designed for local thermodynamic nonequilibrium conditions. Hartung also compared the

uncoupled LORAN prediction with an uncoupled prediction computed by RAD/EQUIL. The two heating values agreed within 4%. This result establishes that at near-equilibrium conditions LORAN agrees closely with RAD/EQUIL.

In another paper (Reference A2-33), Gnoffo, Hartung and Greendyke examined solutions for a lunar transfer vehicle in near-equilibrium conditions. A comparison was shown for full spectrum, radiatively coupled, stagnation-point radiative heating predictions obtained by a nonequilibrium radiation model (the LORAN/LAURA codes), and an equilibrium radiation model (the RAD/EQUIL/RIFSP codes). The predicted values were respectively, 29 and 30 W/cm². These values, which are within 4% of each other, again tend to validate LORAN for near-equilibrium shock layers. Spectral results showing comparisons between NEQAIR and LORAN for Fire II at 1643 sec and a lunar transfer vehicle case were also presented. These indicated that NEQAIR predicts considerably more radiation in the ultraviolet and vacuum ultraviolet than LORAN. Agreement between the two radiation models in the visible and infrared regions was reasonable overall, although details differed somewhat. The total differences were on the order 20% for the LTV and perhaps more for the Fire II case.

The origin of this difference is unknown, but it does indicate that if there is any significant uncertainty in the LORAN model, it probably is in the spectral region above 8eV. It should be noted that this statement would also apply to RAD/EQUIL. It should further be noted that radiative heating results using NEQAIR have never been compared to available total intensity data (References A2-8 and A2-9). Thus, unlike RAD/EQUIL, there is essentially no verification for the NEQAIR model in the vacuum ultraviolet or ultraviolet regions of the spectrum. Since LORAN is based upon RAD/EQUIL, and RAD/EQUIL has been favorably compared to total radiation data, it is suspected that the differences in the ultraviolet and vacuum ultraviolet is due to some unknown feature of NEQAIR and that LORAN is the more accurate of the two radiation models. It should be noted that other investigators also believe that NEQAIR needs improvement in the ultraviolet and vacuum-ultraviolet regions (Reference A2-33a).

In a study primarily devoted to the influence on nonequilibrium radiative heating of various dissociation and vibrational-translational energy exchange models, Hartung, Micheltree, and

Gnoffo (Reference A2-34) compared NEQAIR and LORAN at three Fire II flow conditions. At these flight points, the stagnation region shock layer ranged from complete nonequilibrium to about half equilibrium. For all three points, the stagnation-point radiative heating predicted by LORAN and NEQAIR agreed within 12% for the spectral range of 0.31 to 6.2 eV, which again verifies the theoretical accuracy of LORAN in predicting radiation from the visible and infrared portions of the spectrum.

Based upon the studies discussed so far in this section, it would appear that for the visible and infrared that a reasonable uncertainty in the LORAN predictions would be, at the most, 10-12%. Different radiation models such as RAD/EQUIL, LORAN, and NEQAIR agree well in this spectral range and predictions agree well with experimental data when cooling is included. Further, the disagreement between the various radiation models is less than the data scatter in the shock- tube and flight experiments.

A feature which can affect the uncertainty of a radiation model is the accuracy with which it includes and models the emission and absorption characteristics of the dominant radiators in the flowfields of interest. In the FSAR it was determined that the primary species affecting radiation emission and absorption about the GPHS were N^+ , O^+ , C^+ , C , N , and CO . The major emitters were N^+ , O^+ , C and C^+ and the major absorbers were N , CO , N_2 and C_3 . This result was determined by examining the radiation output from LORAN-C at the sixth point of the GPHS steep trajectory with individual species removed from the computation. By comparing the results with a species removed with the complete results, it was felt that the influence of a given species could be determined.

However, examination of the LORAN-C input file indicates that bound-free (i.e. continuum) and line radiation was only included for N , O and C ; and for N^+ , O^+ , and C^+ only free-free radiation was included. However, for molecules all major bands were included. Since line radiation was not included for ions, the above statement as to the major emitters and absorbers requires some explaining.

The explanation is as follows. LORAN-C treats emission and absorption separately since it calculates the population of the excited states of all species using the quasi-steady state (QSS) formulation from NEQAIR. Other nonequilibrium radiation methods such as

RADTHERM (References A2-23 and A2-24) use correction factors to account for the deviation from a Boltzman distribution among the atomic electronic states. As shown in the LORAN manual (Reference A2-14), line radiation (bound-bound) absorption involves the number density of the lower state while line emission involves the number density of the upper state. Thus, by excluding a species from the LORAN computation the effect of line radiation for a given species would be excluded.

However, for continuum or bound-free and free-bound processes, the situation is a little different. Free-bound radiation from atoms is essentially photo-deionization, i.e., $N^+ + e^- = N + h\nu$. The absorption coefficient used by LORAN for this process involves the number density of the atom, N ; but the emission coefficient utilizes the number density of the associated ion, N^+ , and the electron number density. Thus, if N^+ is excluded from the LORAN-C computation, the effect of photo-deionization free-bound emission involving N^+ would be excluded. Hence, the statements in the FSAR imply that N^+ and O^+ and C^+ have considerable free-bound photoionization emission and that C has considerable line emission (and perhaps absorption). The statement concerning absorption implies bound-free and line absorption by N along with band absorption by CO , N_2 , and C_3 .

This review of dominant radiators determined that LORAN-C does not include line radiation for atomic ions. This exclusion needs to be considered in the estimate of uncertainty. It should be noted that RAD/EQUIL typically only includes two N^+ lines and no O^+ lines. The two often included are around 13.453 eV and 11.424 eV. The one at 13.45 eV is probably not important compared to the continuum radiation and other line radiation from N prevalent in that vicinity. The line near 11.42 eV might be more important since N lines in this region do not tend to be strongly self-absorbing.

LORAN-C also does not include the free-bound continuum for atomic ions, i.e. photodeionization of $N^{++} + e^- = N^+ + h\nu$. This process is not normally considered in radiation models since even at the extreme conditions considered here, N^{++} would not be present in significant amounts. Similar comments should apply to O^{++} and C^{++} free bound continuum deionization processes.

The FSAR statements concerning primary radiators and absorbers could cause some confusion. Usually, most investigators consider photo-deionization, i.e., free-bound processes, to be radiatively associated with the atom and not the ion. Thus, while these continuum processes are included in most radiation models they are called "atomic continuum" instead of being associated with the ions. Also, in some cases processes involving N- are also included. However, in general the latter, which can also be termed free-bound, is not included in most radiation models.

At the conditions of interest for this study, the primary radiation should be due to atomic continuum (deionization) emission and absorption, free-free processes involving ions, and line radiation. All of these processes are included in LORAN-C except for line radiation from ions.

The reason given for not including N+ and O+ etc. lines in radiation models such as RAD/EQUIL or LORAN is usually the lack of appropriate data. However, it is noted that in the original article by Wilson and Nicolet (Reference A2-17) that some of the data for these lines was included. Thus, it perhaps might be possible to include them in LORAN-C in future studies.

For a Cassini GPHS reentry, the degree of ionization at Steep Point 6 and at Shallow Max Heating is on the order of 46 to 50%, pressures can be as high nine atmospheres, and temperatures are above 17000⁰K. The question naturally arises -- Is line radiation from ions important at these conditions and how much uncertainty is introduced by its omission from the LORAN-C model? In the Nerem and Golobic (Reference A2-6) reflected-shock experiments, theoretical temperatures around 17270⁰K and pressures of 22.6 atmospheres were obtained. At these conditions the degree of ionization was about 29%. In the Wood (Reference A2-9) reflected-shock experiments the maximum theoretical temperatures were probably around 16075⁰K at 5.99 atmospheres, which would yield a degree of ionization of 36%. These values are from shock-tube computations assuming equilibrium temperatures and compositions (Reference A2-16).

When radiation cooling is properly included, the Wood and Nerem-Golobic experiments agree quite well with theoretical predictions which do not include ion line radiation. Thus, for

those conditions, it would appear that ion line radiation is not significant, at least in the visible and infrared portions of the spectrum (0 -- 6.2 eV), and it would appear reasonable to draw a similar conclusion for the current conditions of interest. While the agreement between models and the total intensity Wood data probably implies a similar conclusion concerning radiation from the ultraviolet and vacuum ultraviolet, the lack of additional total radiation data, when compared to the seeming abundance of data in the visible plus infrared, makes such a conclusion more tenuous. Thus, the only major possible uncertainty due to ion lines is the potential effect in the ultraviolet and vacuum ultraviolet regimes.

In the visible plus infrared, there have been some new values obtained for the radiative cross sections associated with the $N_2^+(1-)$ band system and the $N_2(2nd\ positive)$ system. As discussed by McGough (Reference A2-35), it is now believed that these cross sections are 10% and 15% lower, respectively. Since these changes would lower the total radiative heating, and since molecular species are essentially absent for the GPHS reentry conditions of interest, these new values are not considered pertinent and indicate the present predictions in the visible and infrared should be adequate and perhaps conservative. The only disturbing feature concerning the visible and infrared region is that local thermodynamic nonequilibrium, multi-temperature, and chemical nonequilibrium coupled predictions by Gally and Carlson (Reference A2-24) and by McGough (Reference A2-35) always seemed to underpredict the radiation for the Fire II experiment in the 0 -- 6.2eV range. However, other models assuming equilibrium (Reference A2-20) did quite well. Thus, the error in the nonequilibrium calculations might be more due more to the treatment of local thermodynamic nonequilibrium than any inherent uncertainty in the radiation modeling for the visible and infrared.

In an attempt to further determine the uncertainty due to the LORAN-C radiation model, a highly approximate stagnation-line model (Reference A2-26) was applied at conditions of interest for GPHS entry. This model includes, in an approximate fashion, nonequilibrium chemistry, local thermodynamic nonequilibrium effects on radiation, equilibrium chemistry, and radiation cooling; and it uses a modified eight-step radiation model (Reference A2-12) which closely matches RAD/EQUIL. This stagnation-line model, however, does not include any effects due to ablation. For near-equilibrium conditions and when shock detachment

distances are closely matched, this model yields reasonable agreement with the equilibrium results of Sutton and Hartung (Reference A2-37) as shown in Table A2-1.

At first, the last condition appears to be in considerable error. However, for the 16/60 case the shock layer has a considerable non-equilibrium region; and it would be anticipated that the Sutton prediction which assumes equilibrium would be high. Hence, the fact that the approximate computation is lower is in the correct direction and has the proper trend. Thus, this approximate model should give a reasonable indication of trends and effects and help to determine the uncertainty in the FSAR radiation results.

Table A2-1 -- Comparison of Approximate Model Radiative Heating Results with Equilibrium Predictions by Sutton and Hartung (Reference A2-36)

	Sutton Solution	Approximate Solution	Difference
Velocity (km/sec)	14	14	
Altitude (km)	42	42	
Delta (cm)	1.028	0.98	
QR (watts/sq. cm)	20444	22076	7.98%
Velocity (km/sec)	16	16	
Altitude (km)	48	48	
Delta (cm)	0.922	0.906	
QR (watts/sq. cm)	17260	17988	4.2%
Velocity (km/sec)	16	16	
Altitude (km)	60	60	
Delta (cm)	0.90	0.98	
QR (watts/sq. cm)	3478	2619	24.7%

Application of this approximate model to the shallow trajectory point (16.4 km/sec at about 58.5 km) for the GPHS yielded a shock detachment distance of 0.93 cm and a QR_{total} of 3932 watt/sq. cm. The effective nose radius was estimated to be $R_{GPHS}/0.3$. The FSAR prediction for this case was a shock layer thickness of about 1.7 cm and a QR of approximately 2270 watts/sq. cm. out of 2600 watts/sq. cm total stagnation point heat load. Since the approximate model does not include ablation, it should predict a thinner shock layer and a higher heat load. Flowfield and stagnation point radiative heat transfer results for this case

are shown in Figures A2-10 and A2-11. In Figure A2-10, EPS is the degree of ionization and T is the heavy body temperature. Note that for this case the approximate solution indicates a significant amount of chemical nonequilibrium in the region immediately behind the shock front.

Figure A2-10. Approximate Solution at Peak Radiative-Heating Point on Shallow Trajectory for GPHS

The steep trajectory, point 6, for the GPHS is at 16.82 km/sec at about 43 km. Sutton and Hartung's (Reference A2-36) equilibrium prediction (without ablation) at 14 km/sec at 42 km for a 1.028 cm shock layer is 20440 watts/sq. cm. The FSAR results show about a 1.85 cm shock layer with a QR of about 36600 watts/sq. cm at the stagnation point. The approximate model predicted a 0.95 cm shock layer and a stagnation QR of 92434 watts/sq. cm. Again, at first, the approximate model looks incorrect; but it does not include ablation. Examination of the FSAR results shows that 20-25% of the shock layer is heavily influenced by ablation products. Also, the dQR/dx gradient shows a significant decrease at 0.3 cm from the wall and actually goes negative at 0.2 cm. Thus, the ablation layer is significantly absorbing radiation and reducing the radiative heat load to the wall. In the approximate computation,

Figure A2-11. GPHS Stagnation-Point Radiative Heating for Shallow Trajectory Case vs. Energy

the "cool" wall boundary layer only affected about 0.02 cm of the flow next to the wall. Examination of the variation of the approximate solution with freestream velocity, i.e. solutions at 14, 16, and 17 km/sec at 42 km, indicates it has the correct velocity dependence for a non-ablating case. Thus, it appears that a possible explanation for the difference between the FSAR prediction and the present approximate result is due to ablation; although many other factors such as the modeling of the gas properties, approximations in the model itself, etc. might also contribute to the different predictions. In spite of these differences, it is believed that the approximate model can serve as a basis for estimating the consequences of some of the potential uncertainties in the radiation model. Results from the approximate model for the steep trajectory, point 6, are shown in Figures A2-12 and A2-13, with T and EPS as defined for Figure A2-10.

In the above discussion, it was established that the error in the visible plus infrared regime was probably no greater than 12%. This spectral region includes molecular radiation, atomic continuum radiation, and infrared line radiation in the 0 to 6.2 eV range.

Figure A2-12. Approximate Stagnation-Line Solution for GPHS Steep-Trajectory, Point 6

Figure A2-13. GPHS Stagnation-Point Radiative Heating from Approximate Solution. Steep-Trajectory, Point 6

For the ultraviolet and vacuum ultraviolet range above 6.2eV, there is also reasonable agreement between predictions by different radiation models with the Wood total spectrum data if cooling is taken into account. In addition, in the ultraviolet and vacuum ultraviolet the theory for continuum radiation is very well founded and the error, if the pertinent processes are included, should be small. Thus, the primary source of error should be in the treatment of ultraviolet and vacuum ultraviolet lines. The errors can come about from the f-numbers (radiative cross sections), line widths, and line shapes. Also, many previous models lumped various closely spaced lines together into effective lines; and there can be an error associated with such convenient lumping. Hartung, in the development of LORAN, improved upon the approach used in RAD/EQUIL, included the details of many more lines, and improved upon the treatment of line shapes. Thus, LORAN should give even better results than RAD/EQUIL.

Examination of a typical radiative heat transfer stagnation-point result from Gally (Reference A2-23) shows that in the vacuum ultraviolet above 11-12 eV that the line centers are strongly self absorbing. However, there are measurable contributions to the radiative heating from the line wings and lines cannot be totally ignored in this spectral region. This center absorption and emitting line wings can be seen in Figure A2-8. It is believed that any error in line treatment in this region, especially considering the magnitude of the background continuum, should have only a small effect on the overall stagnation-point heating.

However, for the 7-11 eV range, sometimes termed the ultraviolet, any error in the treatment of lines by a radiation model could be important since the lines in this region are not particularly self-absorbing. While the continuum and lines in this region have been well studied and documented, the effect of any error in this region should be investigated. Consequently, the approximate model has been used to investigate the effect an arbitrary factor of two error in radiation cross section in this region would have on the stagnation-point radiative heating. It should be noted that this approach does not imply that the uncertainty in radiation cross sections in this region is a factor of two. It is simply an attempt to create some type of safe upper bound. The result is as follows:

**Table A2-2 – Changes Due to a Factor of Two in Radiative Cross Section
 in the Region 6.88 eV to 10.97 eV**

<u>Case</u>	<u>Change in Total Stagnation-Point Radiative Heating</u>
Shallow Trajectory Point	+10%
Steep Point 6	+16%

It should be noted that for the shallow case, the vacuum ultraviolet (above 11 eV) and visible plus infrared (below 7eV) contributions to radiative heating were essentially unchanged while the ultraviolet portion was increased about 93%. However, for the steep point the vacuum ultraviolet was actually reduced about 13%, the visible plus infrared part was effectively unchanged, and, as expected, the ultraviolet was increased 51%. Obviously coupling phenomena are important.

To further estimate the uncertainty possibly associated with inaccurate radiation data, two additional approximate calculations were carried out. These again used a factor of two increase in the radiative cross section for the 6.88 to 10.97 eV range and also increased the radiative cross section in the visible and infrared regions of the spectrum by 10%. The first factor is probably the maximum possible error while the second is based upon differences between theories and between theories and experiment in the visible and infrared. The radiative heating for the shallow trajectory was increased 12% over the original value and the radiative heating for the steep trajectory point was increased 19.5%. The changes in the various spectral regions were similar to those obtained in the first uncertainty test involving only the 6.88 to 10.97 eV.

Based upon experimental data, comparisons of theory with experiments, and results obtained with the approximate solution, it is believed that a reasonable uncertainty for the radiation modeling is no greater than 20%. Further, considering the scatter in experimental data and the lack of significant flight data other than Fire II, this uncertainty should be always in the positive direction. Thus, it is suggested that the uncertainty in radiative heat transfer associated with absorption/emission coefficients and species spectrum data be changed from the FSAR assigned value of $\pm 20\%$ to a value of $+20\%$. Expressed as an uncertainty in the total heat flux integrated over the trajectory, the recommended uncertainty is $+10\%$, rather than $\pm 10\%$ as shown in Table 5.5-1 of Volume II in the FSAR.

A2.2 EFFECTS OF FREESTREAM DENSITY VARIABILITY

The effects of season and latitude on atmospheric density are shown in Figure A2-14. Summer and winter density profiles at 60°-latitude vary by more than $\pm 30\%$ from the 1966 Standard Atmosphere (Reference A2-38). As shown in Figure A2-14, departures from the Standard are largest at high altitudes and tend to diminish at lower altitudes. The density profiles at 60°-latitude shown in Figure A2-14 are the mean of summer and the mean of winter measurements. The summer and winter means approach the Standard as the latitude approaches the equator. The 95% range of all observed densities at 60°-latitude is approximately $\pm 20\%$ about the mean in winter and $\pm 15\%$ about the mean in summer.

Figure A2-14. Density Variability as Percent Deviation from the 1966 Standard Atmosphere

In order to refine the FSAR estimate for the effects of freestream density variability, coupled RACER/LORAN-C solutions were obtained for the GIS on the intermediate trajectory using the summer and winter 60°-latitude atmospheres. The intermediate trajectory ($\gamma = -20^\circ$) was selected because it resulted in the smallest margin (highest GIS heatshield recession). Trajectories were first generated for the GPHS module in each atmosphere. GIS release altitudes were determined based on the g-loading on the GPHS module. Structural analyses in the FSAR showed that the GPHS module would fail on the

intermediate trajectory when the axial acceleration reached 194 g. Using this criteria, the GIS release altitude (160kft) in the Standard Atmosphere was found to be lower (154 kft) in the 60⁰-winter atmosphere and higher (165 kft) using the 60⁰-summer atmosphere. The GIS intermediate trajectory for each atmospheric model is shown in Figure A2-15. The trajectory is shown from the release altitude down to 80kft (below 80kft, heating is insignificant because the velocity has fallen to less than 3kft/sec). The corresponding freestream density along this trajectory for each atmospheric model is shown in Figure A2-16.

Figure A2-15. Effect of Atmospheric Density Variability on the GIS Intermediate Trajectory

RACER/LORAN-C computations of the GIS were performed for each atmosphere at 147 kft. This altitude was chosen because it is near peak-heating conditions (in the Standard Atmosphere) and because the departure of the density from the Standard Atmosphere is still large. As shown in Figure A2-14, at lower altitudes the summer and winter density profiles tend to approach the Standard Atmosphere.

Figure A2-16. Latitude and Seasonal Density Variability along the GIS Intermediate Trajectory

In addition to freestream conditions, RACER/LORAN-C analyses require the specification of a wall temperature. The wall temperature history is determined by a transient-heating analysis. In lieu of generating the matrix of solutions that is needed to compute the surface temperature history for each atmosphere (this would require RACER/LORAN-C solutions for several altitudes and several wall temperatures at each altitude), a common wall temperature was used for both the winter and summer analyses. A wall temperature of 7675°R at 147 kft had been determined from the previous transient-heating analysis, with Standard Atmosphere properties, as documented in Section 6.5 of this report.

The freestream conditions and the RACER/LORAN-C solutions for the surface heating and ablation rate at the GIS stagnation point (nonspinning) for each atmosphere are presented in Table A2-3.

Table A2-3 Effect of Freestream Density Variability

GIS Intermediate Trajectory, Altitude = 147 kft, Wall Temperature = 7675°R

	∞ (SLUGS/ FT ³)x10 ⁶	V_{∞} (KFT/SEC)	$\dot{q}_{cond}$ (BTU/FT ² - SEC)	$\dot{q}_{diff}$ (BTU/FT ² - SEC)	$\dot{q}_{rad}$ (BTU/FT ² - SEC)	p_{stag} (LB/FT ²)	$\dot{q}_{total}$ (BTU/FT ² - SEC)	$\dot{m}$ (LBM/FT ² - SEC)
SUMMER 60° LATITUDE	4.882	48.774	1215	5539	5036	10916	11790	0.2316
STANDARD	4.171	51.023	1120	5007	4975	9612	11102	0.2433
WINTER 60° LATITUDE	3.299	53.914	823	4854	4725	9011	10402	0.2483

The column labeled $\dot{q}_{total}$ is the sum: gas-conduction ($\dot{q}_{cond}$) + diffusion ($\dot{q}_{diff}$) + radiation ($\dot{q}_{rad}$).

The GPHS module was previously analyzed under similar conditions on the intermediate trajectory. The total heat flux for the GPHS was close to the results shown for the GIS in Table A2-3. However, radiation was the dominant component of the heat flux (87% of the total) to the GPHS module. In contrast, radiation at the GIS stagnation point is only about 45% of the total.

Seasonal and latitude effects are summarized in Table A2-4, which shows differences expressed as a percent deviation from the Standard Atmosphere.

Table A2-4. Percent Deviation from Standard Atmosphere Solution

GIS Intermediate Trajectory, Altitude = 147 kft, Wall Temperature = 7675°R

	ρ_{∞}	V_{∞}	$\dot{q}_{cond}$	$\dot{q}_{diff}$	$\dot{q}_{rad}$	p_{stag}	$\dot{q}_{total}$	$\dot{m}$
SUMMER 60° LATITUDE	+17.0	-4.4	+8.5	+10.6	+1.2	+13.6	+6.2	-4.8
WINTER 60° LATITUDE	-20.9	+5.7	-26.5	-3.1	-5.0	-0.5	-6.3	+2.1

As shown in Table A2-4, in the winter atmosphere at 147kft the freestream density is 20.9% lower, and the resulting freestream velocity is 5.7% higher, relative to the Standard Atmosphere trajectory. Compared to the Standard Atmosphere solution, the total heat flux is 6.3% lower and the ablation rate is 2.1% higher in the winter atmosphere. A relation of the form, $\rho_{\infty}^n V_{\infty}^m$, is often used to approximate the heat flux. In the winter atmosphere, heat flux is lower, even though the velocity is slightly higher, because the dramatically lower density dominates the V_{∞}^m term. As expected, the effects of the summer atmosphere are opposite of the winter atmosphere solution. In the summer environment the freestream density is 17% higher than the Standard Atmosphere. This results in a 4.4% reduction in the freestream velocity. The heat flux is higher by 6.2% and the ablation rate has decreased by 4.8%.

The wall temperature for these cases, 7675°R, was obtained from a transient heating analysis for the Standard Atmosphere trajectory. The temperature will change slightly for the winter and summer atmospheres that will, in turn, change the heat flux and ablation rate. In lieu of performing the transient heating analysis,

- The lower heat flux (-6.3%) for the winter atmosphere would tend to decrease the wall temperature (below 7675 °R). This, in turn, would reduce the +2.1% ablation rate and increase the heat flux. So that, in a transient analysis, $\dot{q}_{total}$ will be approximately -5% or less and $\dot{m}$ will be on the order of +1%.
- Similarly, the higher heat flux (+6.2%) for the summer atmosphere would tend to increase the wall temperature and hence increase the -4.8% ablation rate, which would then

decrease the heat flux. A transient heating analysis would thus yield a $\dot{q}_{total}$ of approximately +5% and an accompanying $\dot{m}$ on the order of -3%.

In summary, these results show that the FSAR estimate for density variability effects of $\pm 5\%$ on the heat flux and $-/+5\%$ on the ablation rate is very reasonable.

A2.3 EFFECTS OF DRAG COEFFICIENT UNCERTAINTY

The representation of the drag characteristics of the GPHS module and GIS cylinder is based on wind-tunnel tests. This data is used in both six-degree-of-freedom (6DOF) and three-degree-of-freedom (3DOF) flight-dynamic codes to compute the flight trajectory and load history. For these configurations, the estimated uncertainty in the drag coefficient measurement could be as high as $\pm 5\%$. This estimate is higher than the $\pm 2\%$ typical of aerodynamically shaped slender bodies because of the greater potential for sting interference. In addition, ground-test facilities cannot fully simulate the flight-test environment. In particular, real-gas effects including nonequilibrium reacting flow phenomena are not duplicated in the wind tunnel. Previous studies of the space shuttle and other vehicles have shown that wind-tunnel drag may be low by as much as 10%.

To establish limits on the effects of uncertainty in the drag coefficient, two trajectories bounding the nominal were computed. In both cases, the GIS is assumed to be broad-side stable. This assumption is based on motion studies that showed the GIS will rapidly stabilize in this orientation (see Section A4). In the maximum drag scenario, the GPHS is assumed to be oriented in the face-on-stable attitude. A bounding case is constructed by adding a measurement uncertainty of +5% to a real-gas bias of +10%. In the minimum drag scenario the GPHS module is assumed to tumble. The bias effect (which only serves to increase the drag coefficient) is neglected and a -5% measurement uncertainty is assumed.

Figure A2-17 shows the GIS portion of the nominal, maximum and minimum drag coefficient trajectories. The GIS is released from the GPHS module based upon a g-load GPHS failure criteria that was previously established in the FSAR using nonlinear thermostructural analyses. As shown in Figure A2-17, the highest altitude of GIS release occurs for the maximum drag trajectory.

Figure A2-17. Effect of Drag Coefficient Uncertainty on the GIS Intermediate ($\gamma = -20^\circ$) Trajectory

RACER/LORAN-C GIS stagnation-point computations were performed at 147 kft on all three trajectories. This altitude is near-peak heating for the nominal drag coefficient history. The RACER /LORAN-C results are compared in Table A2-5.

In Table A2-6 the RACER /LORAN-C results for the minimum and maximum drag coefficient cases are listed as a percent difference from the nominal case. Although the freestream velocity varies by only $\pm 3\%$ due to drag differences, the effect on heating ($+15.8\% / -10.7\%$) is more dramatic. The individual components of the total heat flux are affected in a complex, coupled fashion. For the minimum drag case, a decrease in the ablation rate leads to a higher total heat flux. Conversely, for the maximum drag case, the higher ablation rate results in a lower total heat flux.

Table A2-5. Effect of Drag Coefficient Uncertainty

GIS Intermediate Trajectory, Altitude = 147 kft, Wall Temperature = 7675°R

	V_{∞} (KFT/SEC)	$\dot{q}_{cond}$ (BTU/FT ² -SEC)	$\dot{q}_{diff}$ (BTU/FT ² -SEC)	$\dot{q}_{rad}$ (BTU/FT ² -SEC)	p_{stag} (LB/FT ²)	$\dot{q}_{total}$ (BTU/FT ² -SEC)	$\dot{m}$ (LBM/FT ² -SEC)
MAXIMUM C_D	49.502	763	4940	4215	9057	9918	0.2542
NOMINAL C_D	51.023	1120	5007	4975	9612	11102	0.2433
MINIMUM C_D	52.634	1245	5650	5959	10229	12855	0.2249

The column labeled $\dot{q}_{total}$ is the sum: gas-conduction ($\dot{q}_{cond}$) + diffusion ($\dot{q}_{diff}$) + radiation ($\dot{q}_{rad}$).

Table A2-6. Percent Deviation from Nominal Drag Coefficient Solution

GIS Intermediate Trajectory, Altitude = 147 kft, Wall Temperature = 7675°R

	V_{∞}	$\dot{q}_{cond}$	$\dot{q}_{diff}$	$\dot{q}_{rad}$	p_{stag}	$\dot{q}_{total}$	$\dot{m}$
MAXIMUM C_D	-3.0	-31.9	-1.3	-15.3	-5.8	-10.7	+4.5
MINIMUM C_D	+3.2	+11.2	+12.8	+19.8	+6.4	+15.8	-7.6

These results are based on imposing the wall temperature of 7675°R from the transient-heating solution of the nominal-drag trajectory. Transient-heating analyses of the minimum and maximum drag trajectories would yield different wall temperatures (colder for the maximum drag trajectory and hotter for the minimum drag trajectory). This compensating effect greatly reduces the percent differences obtained using a constant wall temperature

(the compensating effect is demonstrated in Section A5.1). As a result, the effects of drag uncertainty are estimated to be approximately $\pm 6\%$ on the total heat flux and $\pm 6\%$ on the ablation rate. This uncertainty is twice that estimated in the FSAR. The FSAR estimate was based on empirical approximations rather than RACER/LORAN-C computations.

A2.4 EFFECTS OF THE SHOCK-PRECURSOR

At EGA reentry velocities, the hot shock layer radiates energy beyond the bow shock into the freestream. Part of this radiative energy is absorbed and causes measurable pre-shock ionization. Since a portion of this ionized freestream is subsequently convected into the shock layer, there is a possibility that a radiative-cooled coupled shock-layer solution that does not include the precursor might overestimate the amount of radiative cooling, and, consequently, underestimate the surface radiative heat transfer. In the FSAR, this phenomenon was not addressed because it was assumed to be negligible compared to the large radiative heat transfer rates from the shock layer. INSRP/ReSP agreed that shock-precursor effects were probably small (Reference A2-2), but objected because no supporting evidence was cited. To address this concern, Prof. Leland Carlson (Texas A&M) has performed a review of shock precursor experiments and analyses, and has established an estimate of this effect on the EGA reentry of the GPHS/GIS (Reference A2-39). His results are summarized in this section.

The possibility that shock-precursor effects could be important was of concern in the 1960s in the Apollo program (Reference A2-40), in the 1970s in the studies for Galileo probe (Reference A2-41), and in the 1990's for flows about aero-assisted entry vehicles (Reference A2-42). Since Galileo involved entry into the hydrogen atmosphere of Jupiter, Jovian precursor studies are not directly relevant for EGA reentry.

In 1968 Lasher and Wilson (Reference A2-40) investigated the effect of the precursor on the radiative heating to a 5 ft (1.5 m) radius reentry body. Their one-dimensional analysis assumed that the shock layer and the precursor were uncoupled, considered only that portion of the precursor within a distance of one characteristic body dimension, and ignored geometric attenuation effects. While the shock-layer radiation was determined with reasonable spectral detail using an early version of the RAD/EQUIL code (later incorporated

in the LORAN code), the absorption properties of the cool freestream were determined using two models. The first model, termed Model A, included O₂ and N₂ photoionization resulting from photons having energy greater than 12.1 eV; and the second model, called Model B, considered only N₂ photoionization caused by photons with energies above 15.6eV. No details of the resulting precursor were presented.

Lasher and Wilson subsequently approximated the effect of precursor absorption on vehicle radiative heating by estimating the change in the radiation loss parameter. In other words, they estimated the decrease in radiative cooling due to the precursor. This approximate approach yielded the results shown in Table A2-7 for a 5 ft. (1.5 m) radius vehicle at 200 Kft. (60.96 Km).

Table A2-7. Shock-Precursor Estimates of Lasher and Wilson

Velocity		Increase in Radiative Heating	
Kft/sec	Km/sec	Model B	Model A
50.	15.24	2%	12%
55.	16.76	3%	15%
60.	18.28	6%	25%
65.	19.81	10%	30%

Based upon these results, Lasher and Wilson concluded that precursor effects were "relatively unimportant" in the computation of radiative heat transfer to a vehicle for speeds below 60Kft/sec (18.28 km/sec). For the GIS on the intermediate ($\gamma = -20^\circ$) trajectory, near peak-heating conditions occur at 51 Kft/sec (15.55 Km/sec) at an altitude of 147 Kft (44.81 Km). About one-half of the total heat flux to the surface of the GIS for these conditions is due to radiation. The radiative heating component of the total heat flux diminishes rapidly along the trajectory as the GIS velocity decreases. The Lasher and Wilson results would appear to indicate that precursor effects on the GIS total integrated heat flux should be small. However, in making such an evaluation, it must be recognized that the Lasher and Wilson analysis was very approximate, that it was for a much larger vehicle at a higher altitude (200 Kft), and that it did not include geometric attenuation.

In their studies (References A2-42 and A2-43) of precursor phenomena, Stanley and Carlson modeled the precursor in great detail and also included in the electron-electronic energy equation radiative terms to properly account for the effects of absorption and emission of radiation on the individual energy modes of the gas. Their radiation model was a modified version of the RADTHERM (Reference A2-24) code that not only included chemical and thermal nonequilibrium phenomena, but also accounted for additional radiation phenomena that are important in the precursor region (Reference A2-42). For example, for N_2 , they added the ionization continuum associated with the ground and first three excited states ($h\nu > 8.24\text{eV}$), the Lyman-Birge-Hopfield (L-B-H) molecular band ($4.77\text{eV} < h\nu < 9.78\text{eV}$), and the dissociation continuum adjoining the L-B-H molecular band ($h\nu > 9.78\text{eV}$). They also included geometric attenuation. While Stanley and Carlson's work was limited, in that the freestream was assumed to be nitrogen and not air, they did compare their results with the shock tube data of Omura and Presley (References A2-44 and A2-45); and for the dominant precursor within three body radii their results were in good agreement with their data.

Stanley (References A2-42 and A2-46), whose work is probably one of most detailed and complete precursor studies conducted, investigated the stagnation region and precursor of a 7.55ft (2.3m) radius vehicle at velocities of 32.8 Kft/sec to 52.5 Kft/sec (10 to 16 Km/sec) and altitudes between 236 Kft and 262 Kft (72 and 80 Km). Some detailed results (Reference A2-46) for the precursor for the 52.5 Kft/sec (16 Km/sec) cases are shown in Figure A2-18.

As shown in Figure A2-18a, the heavy-particle temperature increase is less than one percent (only a few degrees). However, the electron-electronic temperature increase (Figure A2-18b) is from a freestream temperature on the order of 200^0K to $3500\text{--}4300^0\text{K}$. This temperature increase is potentially significant for two reasons. First, it may indicate a significant change in the immediate pre-shock conditions and thus affect the post-shock conditions. Second, electron-electronic temperature changes only slightly across the shock front; and it is the controlling temperature for many chemical reactions. Thus, an enhanced pre-shock electron-electronic temperature might affect the post-shock nonequilibrium zone. It should be noted that the density and velocity of the gas in the precursor were found to be constant and unaffected by the absorption of radiation.

(a) Heavy Particle Temperature Distribution

(b) Electron/Electronic Temperature Distribution

Figure A2-18. Changes in the Freestream due to Shock-Precursor Effects
 (from Reference A2-46)

(c) Electron/Electronic Energy Distribution

(d) Total Enthalpy Distribution

Figure A2-18. Changes in the Freestream due to Shock-Precursor Effects
 (From Reference A2-46) (Cont'd)

(e) Pressure Distribution

(f) N_2 Mass Fraction Distribution

Figure A2-18. Changes in the Freestream due to Shock-Precursor Effects
 (from Reference A2-46) (Con'td)

(g) N_2^+ Mass Fraction Distribution

(h) N Mass Fraction Distribution

Figure A2-18. Changes in the Freestream due to Shock-Precursor Effects
 (from Reference A2-46) (Cont'd)

(i) N^+ Mass Fraction Distribution

(j) e^- Mass Fraction Distribution

Figure A2-18. Changes in the Freestream due to Shock-Precursor Effects
 (from Reference A2-46) (Concluded)

However, as shown on Figure A2-18c, while the electron-electronic energy increases in the precursor to a value on the order of 10^9 ergs/gm, the total enthalpy (Figure A2-18d) is on the order of 10^{12} ergs/gm; and its increase due to precursor phenomena is less than 0.2%. Thus, the amount of radiative energy absorbed in the precursor is small compared to the total energy in the freestream.

Figure A2-18e shows that there is about a 10% increase in the freestream pressure due to the precursor; but in hypersonic flow the freestream pressure has very little effect on the magnitude of the post-shock pressure (in the hypersonic limit, the post-to-pre-shock pressure ratio $\rightarrow \infty$). In this case the freestream pressure ranges from 10.7 dynes/cm² at 80 km to 41.9 dynes/cm² at 72 km, but the post shock pressure is on the order of 10^4 dynes/cm². Thus, the pressure change due to the precursor is insignificant.

The remaining plots in Figures A2-18f through A2-18j show various species mass fraction variations in the precursor. These plots indicate that the dominant chemical reaction far from the shock front is photoionization of atomic nitrogen but that near the shock, photoionization of molecular nitrogen is most important. Thus, there is some measurable ionization and free-electron formation due to absorption of radiation in the precursor region; although the ionization level appears to be less than one percent. For air, this ionization would probably be associated with the species O_2^+ and N_2^+ . Since seed electrons are needed for the electron-impact ionization of N and O, which are the dominant ionization reactions behind the shock front, there is a possibility that the precursor ionization could lead to more rapid ionization immediately behind the shock front.

To investigate the effect of the precursor on the shock layer, Stanley iterated between the shock-layer solution and the precursor solution. His studies determined that in all cases investigated that the precursor had a negligible effect on the shock-layer solution and produced no measurable change in the radiative heat transfer to the body. All differences in temperature and species concentrations between solutions, including and excluding precursor effects, were confined to the first few computational spatial points in the shock layer.

As shown by Stanley, the primary effect of the precursor is the increase in electron-electronic temperature and the creation of free electrons via photoionization in front of the vehicle shock wave. While Stanley's results indicated these did not affect post-shock phenomena or radiative heat transfer, there is the remote possibility that these changes could be more important at lower altitudes. The seed electrons and enhanced electron-electronic temperature might cause the electron temperature to increase slightly faster and for electron-impact ionization to occur more rapidly in the nonequilibrium zone behind the shock front. However, these changes would only be detectable in a multi-temperature nonequilibrium computation. In the RACER/LORAN-C codes (Reference A2-10) employed in the GPHS/GIS analyses, a one-temperature model is used. This approach will lead to a higher electron temperature, a faster ionization rate, and higher radiative heating than would be predicted by a multi-temperature model. Thus, the usage of RACER/LORAN-C should account for any of the small effects that might be caused by the absorption of radiative energy in the precursor.

Another indication that the shock precursor has a minimal effect on surface radiative heat transfer can be found in shock tube data. As detailed in Reference A2-47, when theoretical computations properly model radiation and chemistry phenomena and include radiation cooling, the resultant radiative heat transfer predictions, which do not include precursor effects, are in good agreement with stagnation point and reflected shock radiative heat transfer. If precursor effects were significant, such agreement would not be expected.

Based upon the detailed results of Stanley and experimental data, precursor effects would have little or no effect on the radiation heat transfer to the GPHS/GIS for EGA reentry conditions. Further, the results of Lasher and Wilson should be considered as an extreme upper limit. While it could be argued that Stanley's results are for nitrogen, and thus his results should be compared to Model B of Lasher and Wilson, Lasher and Wilson themselves stated that the "true coupling effect of the precursor probably lies somewhere between the results represented by "... their two absorption models".

Based upon Stanley's detailed analysis and the high altitude conditions for his study, and considering that RACER/LORAN-C employs a one-temperature model, the shock-precursor has a negligible effect on the GPHS and GIS total integrated heat flux and recession.

A2.5 Effects of Carbon Vapor Pressure and Vaporization Coefficient Uncertainty

The severe EGA reentry conditions generate very high temperatures in the carbon-carbon fine-weave pierced-fabric (FWPF) heatshield. Because EGA peak heating occurs at high altitudes, the surface pressure is very low compared to the pressure on conventional ballistic reentry vehicle (BRV) nosetips at peak heating. For example, BRV stagnation pressures can exceed 200atm with surface temperatures in excess of 4500⁰K. In contrast, on the shallow trajectory the face-on-stable (FOS) GPHS aeroshell surface temperature rises above 4000⁰K with a stagnation pressure of 0.9atm. On the steep trajectory, the FOS GPHS surface temperature approaches 4600⁰K (at 9atm) prior to structural failure. The released GIS surface temperature would also reach nearly 4600⁰K (at 18atm) on the steep trajectory if it were oriented broadside to the flow and did not spin. The same non-spinning, broadside GIS orientation on the intermediate trajectory results in peak surface temperatures around 4200⁰K (at 4.6atm).

Unlike existing flowfield codes, in RACER the flowfield is strongly coupled to the carbon ablation model. For sublimation, which is the dominant carbon ablation mechanism at these high temperatures, the mass flux of C, C₂ and C₃ gas species is given by the Knudsen-Langmuir relation:

$$\dot{m}_s^{sub} = \alpha_s \sqrt{M_s / (2\pi RT_w)} (p_s^v - p_s) \quad [A.2-1]$$

where the subscript, $s = 1, 2, \text{ or } 3$ denotes the carbon molecule, M_s is the molecular weight of species s , R is the gas constant, and T_w is the specified wall temperature. At each iteration for each point on the surface, RACER computes the species partial pressure, p_s , from the gas mixture and the species vapor pressure, p_s^v , from a curve-fit of JANAF (Reference A.2-48) data.

In RACER, the vaporization coefficients, α_s , are from the measurements of Zavitsanos and others at 2700⁰K (Reference A.2-49). The values, $\alpha_1 = 0.24$, $\alpha_2 = 0.5$, and $\alpha_3 = 0.023$, have been widely used and are now considered standard. However, uncertainty in the carbon-

species vapor pressure and vaporization coefficients increases with increasing surface temperature.

In a three-year experimental and theoretical study, Baker et al. (References A2-50, A2-51, and -52)) found fault with the JANAF data and instead endorsed the high-temperature carbon species thermochemical properties computed by Lee and Sanborn (Reference A2-53) and by Leider et al. (Reference A2-54). Baker et al. referred to these computations and measurements as the "Livermore" data. Furthermore, they formulated a nonlinear Knudsen-layer model, "... by assuming that the carbon vapor can be represented by a single, albeit fictitious, species..." (Reference A2-55). The vapor pressure of this fictitious species was set equal to the sum of the carbon C_1 through C_7 vapor pressures from the "Livermore" data. Baker et al. also determined a temperature-dependent vaporization coefficient $\alpha(T_w)$ for their fictitious single carbon species.

Unfortunately, this fictitious-species formulation is of no use in a finite-rate, chemically reacting flowfield code, such as RACER, which requires the vaporization coefficient and vapor pressure of each carbon species. Any assumption made in order to use the single fictitious species approach, such as assuming that the sublimation species is composed entirely of C_3 , would probably introduce even more uncertainty.

Using an approximate technique, INSRP/ReSP (Reference A2-2) compared ablation predictions using the JANAF thermochemistry with predictions based on the "Livermore" data. They concluded that, with their technique, the "Livermore" thermochemistry resulted in about 10% more ablation. Further, they estimated that mechanical erosion could add another 10%. Mechanical erosion refers to the removal of small particles by surface "scrubbing" due to flow shear forces (as opposed to spallation caused by internal stresses).

In the FSAR, the effect of uncertainties in C_1 , C_2 and C_3 vapor pressure was determined by comparing RACER ablation-rate predictions (based on JANAF data) and estimates using Zavitsanos's vapor-pressure data (Reference A2-56). These studies led to an estimate of $\pm 10\%$ uncertainty in the ablation rate. Mechanical erosion was not considered because arc-jet tests of high-quality FWPF have shown no definitive evidence to support inclusion of this mechanism.

Combining and weighing the FSAR results with the ReSP assessment, we now estimate uncertainty in the ablation rate is:

- Methodology bias of +10% (that is, an underprediction due to JANAF thermochemistry and possibly slight erosion effects) and
- Unbiased uncertainty of +/-10% due to uncertainty in both the JANAF and "Livermore" data at high temperatures.

A2.6 EFFECTS OF UNCERTAINTIES IN REACTION-RATE DATA

Uncertainties in reaction-rate data and third-body efficiencies were investigated in some detail in the FSAR. In this section, new rate information (published after the release of the FSAR) is examined.

Bose and Chandler (Reference A2-57) performed a detailed quasi-classical trajectory study of the first Zeldovich reaction, $N_2 + O \rightarrow NO + N$. This reaction is the primary source of NO in most hypersonic flowfields, especially under rarefied flow conditions. The forward rate proposed by Bose and Chandler is larger, especially at high temperatures, than the Blottner rate model (Reference A2-58) used in the FSAR. However, RACER/LORAN-C computations for the GIS at near peak-heating conditions showed that the effect of the new Bose and Chandler rates on the total surface heat flux and the ablation rate was negligible.

The post-shock flowfield is strongly affected by the electron-impact ionization reactions of atomic nitrogen (N) and oxygen (O). The resulting chemical composition of the post shock region also directly affects the gas radiation and heat flux to the ablating wall. For the electron-impact reactions, the rate data of Dunn and Kang (Reference A2-59) was used for all GPHS solutions in the FSAR and all GIS solutions in the Section 6.5.3.3.3 of this report.

The electron-impact reactions of atomic nitrogen (N) and oxygen (O) are

The Dunn and Kang rate data for these reactions is,

$$K_{f1} = 1.1 \times 10^{32} T^{-3.14} \exp(-168200/T)$$

$$K_{b1} = 2.2 \times 10^{40} T^{-4.5}$$

$$K_{f2} = 3.6 \times 10^{31} T^{-2.81} \exp(-158500/T)$$

$$K_{b2} = 2.2 \times 10^{40} T^{-4.5}$$

Carlson and Gally (Reference A2-23, A2-24, and A2-39) concluded that the Dunn and Kang rates are too slow and derived new rates based on the theory of Kunc. The Carlson and Gally rates are,

$$\begin{aligned}K_{r1} &= 5.08 \times 10^{16} \exp(-121000/T) \\K_{b1} &= 3.97 \times 10^{24} T^{-1.5} \exp(48000/T) \\K_{r2} &= 6.35 \times 10^{15} \exp(-106200/T) \\K_{b2} &= 1.62 \times 10^{24} T^{-1.5} \exp(51800/T)\end{aligned}$$

The effects of the electron-impact reactions were studied for the near peak-heating altitude of 147 kft along the intermediate GIS reentry trajectory ($\gamma = -20^\circ$) at a wall temperature of 7600°R. Computations were performed using the stagnation-streamline version of the new RACER code. Figures A2-19a through A2-19c show the results using the different electron-impact reaction data sets.

Figure A2-19a shows the mass-fraction profiles of N and N⁺ along the stagnation streamline for the computations based on the rates of Dunn and Kang and the corresponding recommendations of Carlson. The shock-layer temperature profiles are also shown in this figure, and include the effects of radiation cooling. The results show that the rate data of Carlson predicts much more ionization of N in the post-shock region. This ionization and the resulting radiation cooling decrease the post shock-layer temperature. Figure A2-19b shows the corresponding mass-fraction profiles of O and O⁺. In this case the rate data of Dunn and Kang shows larger ionization of O than the predictions based on the rate data of Carlson. In general, Figure A2-19c shows that, for the peak-heating conditions considered, the electron-impact reaction rate data of Carlson results in about a 10% reduction in the post-shock temperature. The heat flux to the ablating wall due to gas conduction and mass diffusion effects is reduced by about 6%. This reduction is offset by the wall heat flux due to gas radiation which is increased by about 6%. The surface ablation rate is reduced by about 2%. Thus, although the electron-impact reaction rates of N and O have a significant effect on the post-shock temperature, gas compositions and gas radiation, the effects on the wall ablation process are small.

Figure A2-19a. Effects of Electron-Impact Ionization Reactions on the Near-Wall Concentrations of N

Figure A2-19b. Effects of Electron-Impact Ionization Reactions on the Near-Wall Concentrations of O

Figure A2-19c. Effects of Electron-Impact Ionization Reactions on the Wall Heat Flux and Surface Ablation Rate

These results show that the electron-impact reaction rates of Dunn and Kang, which were used in the FSAR analysis and are also used the new GIS CFD analysis, are slightly more conservative in predicting the surface recession effects. These results also support the FSAR uncertainty estimate of $\pm 2\%$ for reaction rate data and third-body efficiencies.

As discussed in Section A3, the improved RACER code incorporates new rates for the dissociation of C_2 and C_3 . Compared to the rates used in the FSAR and post-FSAR analyses described in Section 6.5.3.3.3 of this report, computations at a constant wall temperature show that the new rates significantly affect the ablation rate and total heat flux. However, transient-heating analyses (Section A5-1) show that these differences are compensating and result in different wall temperature histories, but nearly identical recession histories.

A2.7 OTHER UNCERTAINTIES PARAMETER GROUPS

The uncertainty parameter groups, shown below in Table A2-8, were examined in the FSAR and reviewed again as part of this study. The "Type" designation refers to an unbiased uncertainty, denoted as "U", or a methodology bias, denoted as "M". As shown in Table A2-8, this review found no need to change the FSAR estimates.

Table A2-8. Uncertainty Estimates Unchanged from the FSAR

Parameter Group	Type	Uncertainty(%) (FSAR)	Uncertainty(%) (Updated)
Species Convergence	U	~ 0	~ 0
Choice of Sublimation Species	M	~ 0	~ 0
Element Diffusion Data	M	~ 0	~ 0
Species Enthalpy Data	U	~ 0	~ 0
Species Viscosity, Thermal-Conductivity, and Diffusion Data	M	-5	-5
Radiation Convergence	M	+5	+5

Other uncertainty parameter groups were examined and their estimated uncertainty contributions were increased. The methodology bias associated with the assumption of thermodynamic equilibrium, i.e., with the use of a single-temperature model, was estimated to be -5% in the FSAR (where the minus sign denotes that the method is conservative, that is, overpredicts recession and total heat flux). This estimate is probably reasonable, however, for some GPHS and GIS flight conditions a single-temperature model is more appropriate. In addition, the comparison in the FSAR of one- and two-temperature results did not include the effects of ablation products. Lacking a direct comparison of models for an ablating GIS, this favorable bias (-5%) has been discounted. Instead, no bias (~0%) will be used.

In the FSAR, the assumption of an equilibrium catalytic wall led to a methodology bias estimate of -10%. The improved RACER code eliminates the need for this assumption. Furthermore, results with the new RACER code show that the Lockheed Martin surface energy balance (SEB) used in the FSAR and accurately accounts for the distribution of

energy released by the equilibrium reactions. That is, the bias usually associated with this assumption is due to the use of the traditional SEB advocated by INSRP/ReSP. Therefore, this methodology bias has been set to 0% (i.e., made less conservative).

The use of a tangent-slab approximation for radiation transport computations was estimated to cause a -2% methodology bias. This estimate has been maintained for the cylindrical GIS, but set to 0% for the flat-face GPHS configuration.

New uncertainty parameter groups were identified and evaluated as part of this study. The effects of grid size and solution convergence tests in the RACER code were described in the FSAR. An unbiased uncertainty has been added to account for possible errors due to these effects. For the GPHS this uncertainty is estimated to be $\pm 5\%$. The estimate for the GIS, $\pm 3\%$, is less because of the use of a finer grid (more points between the body and the shock).

Another potential source of uncertainty arises in REKAP when it performs interpolations of the RACER/LORAN-C ablation rate and heat flux tables (stored as functions of wall temperature and altitude). The accuracy of this interpolation is maximized by using logarithm functions that closely follow the change in ablation rate with wall temperature. Therefore, an uncertainty of $\pm 5\%$ should bound potential interpolation errors.

A new parameter group labeled, "Miscellaneous," was added to encompass other uncertainties that don't fall into the FSAR groups or the other groups added in this study. This group includes weather erosion which can be important for conventional reentry vehicles. However, for GPHS/GIS EGA reentry, at the altitude of the highest cloud encounter, the module/GIS is falling at its terminal velocity. At this velocity, the effects of rain, snow, or ice particle impact would be negligible.

Another potential source of uncertainty that was reviewed under the "Miscellaneous" category involves electromagnetic effects. This issue could arise because the Navier-Stokes equations that are solved by RACER neglect electromagnetic coupling. However, for reentry flowfields, even at EGA conditions, the Navier-Stokes equations have been shown to accurately model all significant flow phenomena.

Finally, although the nonequilibrium chemistry set in RACER is extensive (19-species, 44-reactions), it is conceivable that additional reactions would yield a more accurate model. For example, Crowell (Reference A2-60), includes C_2N in an equilibrium reaction set. Park (Reference A2-33a) speculates that the formation of C_3N_2 is possible under reentry conditions. However, the rates for C_2N and C_3N_2 reactions at high temperatures are not known.

An uncertainty estimate of $\pm 5\%$ for the "Miscellaneous" parameter group has been added to the FSAR uncertainties.

A2.8 UPDATED UNCERTAINTY AND VARIABILITY ESTIMATE

The components of the updated uncertainty and variability estimate are shown in Table A.2-9.

The updated unbiased (U-type) uncertainty estimates, together with the variability estimate, are combined using a root-sum-square (RSS) approach as described in the FSAR. The only variability term involves the freestream conditions. Uncertainties can potentially be reduced, for example, if new methods could be devised to obtain more accurate, high temperature data. However, variability can not be reduced because it depends on the atmospheric conditions during the accidental reentry.

In general, the updated biased uncertainties (M-type), unbiased uncertainties, and variability estimates have been exaggerated towards favoring GIS burnthrough. In particular, transient-heating analyses would show that estimates yielding higher heat flux and lower ablation rates, or lower heat flux and higher ablation rates, will be compensating.

The FSAR estimate of uncertainty in predicted ablation for the GPHS was: $M = -17\%$ (overprediction methodology bias), $U = \pm 12.8\%$ (unbiased uncertainty plus variability).

Based on the results of this study, the GPHS estimate of uncertainty in predicted ablation has been revised upward. The new estimate is: $M = +20\%$, $U = \pm 4.5\%$

**Table A2-9. Summary of Uncertainty and Variability Components for
Flowfield/Radiation Predictions**

<u>Input Parameter Group</u>	<u>Type</u>	<u>Uncertainty/Variability (%)</u>
• Species Convergence	U	~ 0
• Choice of Sublimation Species	M	~ 0
• Element Diffusion Data	M	~ 0
• Thermodynamic Equilibrium Assumption	M	~0
• Reaction-Rate Data and Third-Body Efficiency Matrix	U	+/- 2
• Species Enthalpy Data	U	~ 0
• Species Viscosity, Thermal-Conductivity, and Diffusion Data	M	- 5
• Absorption/Emission Coefficients and Species Spectrum Data	M	+ 10
• Radiation-Flowfield Coupling Convergence	M	+ 5
• Tangent-Slab Approximation	M	(GIS) - 2 (GPHS) ~ 0
• Equilibrium-Catalytic Wall Assumption	M	~ 0
• Carbon Species Vapor-Pressure Data, Vaporization Coefficients, and Mechanical Erosion	U M	+/- 10 +10
• RACER/LORAN-C Grids and Convergence	U	(GIS) +/- 3 (GPHS) +/- 5
• Interpolation of RACER/LORAN-C Solutions by REKAP (Transient-Heating Analysis)	U	+/- 5
• Shock Precursor	U	~ 0
• Drag Coefficient	U	+/- 6
• Miscellaneous (Includes Choice of Species and Reactions)	U	+/- 5
<u>Input Variable</u>		
• Freestream Density	U	+/- 5

Uncertainty and variability estimates for the GIS were not derived in the FSAR. The results of this study have now provided these estimates for the GIS: $M = +18\%$, $U = \pm 15.0\%$

The effect of these estimates on the likelihood of GIS survival to ground impact can be determined by computing the worst-case GIS recession. Combining the methodology bias ($+18\%$) with the maximum unbiased uncertainty ($+15\%$) for the most stressing GIS trajectory ($\gamma = -20^\circ$), and neglecting the mitigating effect of spin on recession yields:

$$0.105 \text{ inch (predicted recession)} \times 1.33 \text{ (Maximum uncertainty plus variability)} = \underline{0.140 \text{ inch recession}}$$

The FWPF heatshield on the GIS is 0.167 inch thick, so that margin remains even for the worst-case recession.

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Section A3

Improved GIS CFD Analysis

SECTION A3

IMPROVED GIS CFD ANALYSIS

The following sections give a brief overview of the carbon surface-ablation process under hypersonic reentry conditions, and provide a detailed summary of the new computational algorithm that has been developed to accurately simulate the associated nonequilibrium flow and ablation processes.

A3.1 OVERVIEW OF THE CARBON SURFACE-ABLATION PROCESS

The high-speed reentry flow over an ablating carbon surface consists of a finite-rate reacting gas mixture of several species and several chemical reactions. The resulting surface ablation process during reentry is in fact a direct consequence of some very complex interaction between the subliming and oxidizing solid carbon surface and hot shock-layer gases surrounding it. In general, as shown in Figure A3-1, the ablation process involves heterogeneous surface oxidation as well as nonequilibrium sublimation. In heterogeneous oxidation, the solid carbon directly reacts with the available oxygen at the ablating surface to form CO and CO₂, which then enter the hot gas phase and react with the other chemical

Figure A3-1. Schematic of the Carbon Surface-Ablation Process.

species in the shock layer. With nonequilibrium sublimation, when the surface temperature is high enough, the solid carbon directly sublimates in the form of C, C₂ and C₃ species. Upon entering the hot shock-layer flow, these sublimation products dissociate and/or react with the other air species and ablation products. The resulting gas composition at the wall, in turn, affects the rate at which the carbon surface is oxidizing and/or subliming. In general, the shock-layer flow and the surface ablation processes are intrinsically coupled to each other in a highly nonlinear manner.

A3.2 OVERVIEW OF THE IMPROVED CFD ANALYSIS APPROACH

Compared to the CFD approach used in the earlier FSAR (Reference A3-1) analysis the main features of the new CFD approach

- (a) Eliminate the imposed constraint of Equilibrium-Catalytic Surface
- (b) Eliminate the modeling constraint of an infinitesimally-thin homogeneous reaction zone at the surface (i.e., instantaneous change from nonequilibrium sublimation/surface-oxidation to equilibrium conditions at the surface)
- (c) Eliminate the ambiguity about the direction in which the energy is released during the instantaneous transition from nonequilibrium sublimation/ surface-oxidation conditions to equilibrium conditions

In order to eliminate the aforementioned analytical limitations, we

- (a) Use the nonequilibrium species-mass-balance boundary conditions
- (b) Integrate the continuum gas-dynamics equations across the homogeneous reaction zone at the surface
- (c) Obtain the energy transferred to the ablating surface from the actual energy conservation of a very small but finite gas volume adjacent to the ablating surface.

A3.2.1 CFD Equations and Boundary Conditions

The governing CFD equations consist of six (6) coupled fluid-dynamics equations given below

- (a) Conservation of Mass (Continuity) Equation (1)
- (b) Conservation of Momentum Equations (3)
- (c) Conservation of Total Energy Equation (1)
- (d) Equation of State of the reacting gas mixture (1)

In addition, there are (NS-NE) number of nonequilibrium chemistry equations, representing the

- (a) Conservation of Element Mass Equations (NE)
- (b) Conservation of Species Mass Equations (NS-NE)

where NS is the total number of chemical species and NE is the total number of elements being considered.

In addition to these fluid dynamics equations we have two more equations representing the

- (a) Surface Ablation-Rate ($\dot{m}_w$) Equation (1)
- (b) Surface Energy-Flux ($\dot{Q}_w$) Equation (1)

The boundary conditions for the coupled fluid-dynamics equations remain unchanged from the FSAR approach and consist of the following six constraints

- (a) No wall slip ($u_w = v_w = 0$)
- (b) Specified surface blowing ($\rho_w v_w = \dot{m}_w$)
- (c) Specified surface temperature (T_w)
- (d) Equation of state ($p_w = Z \rho_w T_w$)
- (e) Zero body-normal pressure gradient ($\left[\left(\frac{\partial p}{\partial n}\right)_w = 0\right]$)

The boundary conditions for the nonequilibrium chemistry equations in our new CFD approach are significantly different from the earlier FSAR analysis approach. These boundary conditions consist of the mass-balance boundary conditions for the NE number of element conservation equations, and nonequilibrium species-mass-balance boundary conditions for (NS-NE) number of molecular species boundary conditions. The element mass-fraction boundary conditions used are essentially unchanged from the FSAR approach, and are based on the conservation of element mass at the ablating wall and include the effects of mass convection and diffusion. The new nonequilibrium species-mass-balance boundary conditions are based on imposing a full conservation of nonequilibrium species mass at the ablating carbon surface, and include the effects of species mass convection, diffusion and production/consumption effects at the ablating wall.

As far as the carbon surface-ablation rate is concerned, we model both the nonequilibrium sublimation effects as well as the heterogeneous surface oxidation effects. In general, we use a nonequilibrium sublimation model for high-temperature and high-ablation reentry conditions, and a heterogeneous surface-oxidation model for the low-temperature and low-ablation reentry conditions.

As far as the surface energy flux is concerned, unlike the earlier FSAR analysis, in the new CFD approach it is determined from actual conservation of energy for a small but finite gaseous control volume at the wall.

A3.2.2 Nonequilibrium Chemistry Boundary Conditions

As mentioned before, the nonequilibrium chemistry boundary conditions consist of the element boundary conditions and the nonequilibrium species boundary conditions. As far as the element boundary conditions are concerned, they remain unchanged from the FSAR approach and, as shown below in Figure A3-2, they represent the conservation of element mass over a small control volume at the ablating surface.

Figure A3-2. Element Mass-Balance at the Ablating Wall

This conservation of element mass can be represented as

$$\text{Convection of element mass away from the wall} = \text{Diffusion of element mass to the wall}$$

Using the expressions given in Figure A3-2 for the various components, we get

$$(\rho v E_e - \dot{m}_w E_e^{inj}) = J_e \quad [A3-1]$$

The nonequilibrium species-mass-balance boundary conditions used in the new CFD approach represent a significant departure from the equilibrium-catalytic wall boundary conditions used in the FSAR analysis. The species mass balance equations are derived in a manner quite similar to the element mass balance boundary conditions except that, as shown in Figure A3-3, the nonequilibrium species boundary conditions also include the potential effects of species production/ consumption due to the gas-phase chemical reactions.

Figure A3-3. Nonequilibrium Species-Mass-Balance at the Ablating Wall

This nonequilibrium species-mass-balance can be represented as

$$\text{Convection of species mass away from the wall} = \text{Diffusion of species mass to the wall} = \text{Production of species mass at the wall due to chemical reactions}$$

Using the expressions given in Figure A3-3 for the various components, we get

$$(\rho v C_i - \dot{m}_i^{inj}) = J_i + \omega_i \Delta y \quad [A3-2]$$

A3.2.3 Carbon Surface Ablation Modeling

In the new CFD approach, a combined nonequilibrium sublimation and heterogeneous surface-oxidation approach is used which is essentially the same as the one used in the FSAR analysis. In this combined approach the total surface ablation rate is a sum of the oxidation and sublimation effects; i.e.,

$$\dot{m}_w = \sum \left(\dot{m}_i^{sub} + \dot{m}_i^{oxd} \right) \quad [A3-3]$$

The nonequilibrium sublimation model used is only dominant under high-temperature and high-ablation reentry conditions and is based on the following Knudsen-Langmuir relations (for C, C₂, and C₃ species)

$$\dot{m}_i^{sub} = \alpha_i \sqrt{\frac{m_i}{2\pi m_u T_w}} (p_i^{vap} - p_{wi}) \quad [A3-4]$$

The heterogeneous surface-oxidation model is important only under low-temperature and low-ablation reentry conditions. In this model we use Blottner's oxidation-probability approach (Reference A3-3) which can be summarized as

Mass flux of carbon atoms from the surface due to surface collisions of O or O ₂ molecules	=	Oxidation Probability of O or O ₂	x	Collision mass flux of O or O ₂ molecules with the surface
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Although this heterogeneous-oxidation model is the same as the one used in the earlier FSAR analysis, it makes a significant difference when it is used in conjunction with the new nonequilibrium mass-balance boundary conditions. When, combined with the new species mass-balance boundary conditions at the ablating wall, the diffusion-controlled oxidation limit is automatically modeled in the correct manner. This is in significant contrast to equilibrium-

catalytic wall boundary condition where there is no way to impose a balance between the mass diffusion and surface oxidation effects.

A3.2.4 Determination of the Surface Energy Flux

The surface energy flux to the ablating surface is determined using the conservation of total energy over the small control volume at the ablating surface. It should be realized that the new nonequilibrium species mass-balance already imposes the conservation of species as well as the total mass over this small control volume. This conservation of total energy is represented as follows:

Using the expressions given in Figure A3-4 for the various components,

$$\dot{Q}_w = k \frac{\partial T}{\partial y} + \sum \rho h_i D_i \frac{\partial C_i}{\partial y} + \dot{Q}_r + \left(\sum \dot{m}_i^{inj} h_i^{inj} + \frac{1}{2} \rho_w v_w^3 \right) - \rho v h_0 \quad [A3-5]$$

Figure A3-4. Gas-Phase Energy Balance at the Ablating Wall

A3.2.5 Surface Energy Balance Equation

With the new CFD formulation the conservation of species and total mass are satisfied over a small gaseous control volume at the ablating surface. Furthermore, the heat flux to the ablating surface is determined by satisfying the conservation of total energy over this control

volume. As shown in Figure A3-5, a new surface-energy-balance equation is derived by applying the conservation of total energy over a small control volume at the ablating carbon surface.

Figure A3-5. Energy Balance at the Ablating Carbon Surface

The surface energy balance of Figure A3-5 can be written as

$$k_s \left(\frac{\partial T}{\partial y} \right)_s = \dot{Q}_w - \left(\sum \dot{m}_i^{inj} h_i^{inj} + \frac{1}{2} \rho_w v_w^3 \right) - \sigma (T_w^4 - T_\infty^4) + \dot{m}_w h_s \quad [\text{A3-6}]$$

By combining with the expression for $\dot{Q}_w$ we obtain the following expression for the in-depth heat conduction

$$k_s \left(\frac{\partial T}{\partial y} \right)_s = \left[k \frac{\partial T}{\partial y} + \sum \rho D_i h_i \frac{\partial C_i}{\partial y} \right]_{y=\Delta_w} + \dot{Q}_r - \left([\rho v h_0]_{y=\Delta_w} - \dot{m}_w h_s \right) - \sigma (T_w^4 - T_\infty^4) \quad [\text{A3-7}]$$

The above expression is in fact the new Surface Energy-Balance equation based on our new nonequilibrium species mass-balance and surface heat-flux formulations for the ablating surface.

The corresponding Surface Energy-Balance equation based on the previous FSAR approach (Reference A3-1) is

$$k_s \left(\frac{\partial T}{\partial y} \right)_s = k \frac{\partial T}{\partial y} + \sum \rho D_i h_i \frac{\partial C_i}{\partial y} + \dot{Q}_r - \left(\sum \dot{m}_i h_i^{inj} - \dot{m}_w h_s \right) - \sigma (T_w^4 - T_\infty^4) \quad [\text{A3-8}]$$

where the ablating surface is assumed to be equilibrium catalytic. The corresponding Surface Energy-Balance equation based on INSRP/ReSP formulation (Reference A3-2) is

$$k_s \left(\frac{\partial T}{\partial y} \right)_s = k \frac{\partial T}{\partial y} + \sum \rho D_i h_i \frac{\partial C_i}{\partial y} + \dot{Q}_r - \dot{m}_w (h_w^{EQ} - h_s) - \sigma (T_w^4 - T_\infty^4) \quad [\text{A3-9}]$$

where the ablating surface is also assumed to be equilibrium catalytic, and h_w^{EQ} is the enthalpy of the equilibrium mixture at the ablating wall.

A3.3 EQUILIBRIUM REACTION FACTOR (ϕ_s) FOR A CHEMICALLY REACTING SPECIES

A finite-rate reacting gas mixture is usually composed of several species and several chemical reactions with varying reaction rates. This is especially true for a nonequilibrium ablating flow situation where the ablating species (such as various forms of carbon) react with each other and the available air species at the wall to form numerous other ablation products. Since there is a tremendous variation in the rates at which the various reactions among these species are occurring, it is not difficult to imagine that not all species may approach or depart from its limiting equilibrium state at the same time. In short, it is unrealistic to imagine a reacting mixture as a single entity that is either in equilibrium, nonequilibrium or a frozen state. Rather, this definition has to be further reduced to a species level and in turn consider the equilibrium, nonequilibrium or frozen state of each individual species.

Classically, the state of the chemical reaction in a mixture is represented in the form of a Damkohler number (D) defined as $D = t_f/t_c$, where t_f is the characteristic time scale of the flow and t_c is the characteristic time scale for a chemical reaction. A Damkohler number of order one or less indicates nonequilibrium chemistry. For example, as the ambient freestream air passes through the bow shock the high post-shock temperatures trigger dissociation and ionization reactions. If these reactions are fast, relative to the flow velocity, then $t_c \ll t_f$ and the flow is in equilibrium. However, for a reacting gas mixture composed of several air species and ablation products, it is hard to establish a representative reaction time for the mixture.

The finite-rate chemically-reacting RACER code has been used to predict the reentry flowfield for the accidental Earth reentry of the GPHS and GIS modules during the Earth swingby of the Cassini Spacecraft (Reference A3-1). In the improved CFD approach for predicting the nonequilibrium reentry flowfield and surface-ablation rate for the GIS the reaction state of each reacting species 's' has been characterized in the form of an Equilibrium Reaction Factor (ϕ_s). This Equilibrium Reaction Factor (ϕ_s) is defined such that it can be computed at any point in the flowfield and is always bounded between 0 and 1. The lower limit of $\phi_s = 0$ represents the frozen reaction limit, the upper limit of $\phi_s = 1$ represents the equilibrium reaction limit. The range between $0 < \phi_s < 1$ represents the nonequilibrium reaction regime.

The species Equilibrium Reaction Factor has been determined using the modified RACER code for conditions of GIS reentry along the intermediate trajectory ($\gamma = -20^\circ$). As mentioned before in Section A3.2, these improved CFD calculations also include new nonequilibrium species mass-balance boundary conditions instead of the equilibrium-catalytic wall boundary conditions used in the Cassini FSAR and in post-FSAR calculations described in Section 6.5.3.3.3 of this report. The results obtained at this peak-heating condition indicate that all significant species are in chemical nonequilibrium and sufficiently far from an equilibrium-reaction limit. In fact, the wall species concentrations are very different from assuming an equilibrium reaction state at the wall. The predicted nonequilibrium reacting-gas mixture at the wall has a much higher enthalpy at the wall than an equivalent equilibrium mixture. This lead to the conclusion that INSRP/ReSP's assumption of chemical equilibrium across the

shock layer and at the wall (see Reference A3-2) is not appropriate and would lead to the prediction of higher surface ablation rates by under-predicting the gas enthalpy at the ablating surface.

A3.3.1 Equilibrium Reaction Factor

Consider the following partial differential equation representing Conservation-of-Mass Equation for a species 's' for 2-D/axisymmetric flows.

$$\frac{\partial}{\partial \xi_i} [\rho U_i C_s] + \epsilon \frac{\partial}{\partial \xi_i} \left[\frac{m_0 \rho D_i}{J} \frac{\partial C_s}{\partial \xi_i} \right] = \frac{\omega_s}{J} \quad [\text{A3-10}]$$

where, ξ_i represents the curvilinear coordinates ξ_1 and ξ_2 , U_i is the Contravariant Velocity in the ξ_i coordinate direction, ' J ' is the Jacobian of the curvilinear transformation, and ' m_0 ' is a metric quantity. This equation is composed of a convection gradient term, a diffusion gradient term, and a net species production rate (ω_s). In fact, the net species production term is the difference between the production of species 's' dictated by its local production-related reactions and the consumption of species 's' from its local consumption related reactions. The location production rate of species 's' is denoted by ω_s^+ and the local consumption of species 's' by ω_s^- so that the net local production of species 's' is $\omega_s = (\omega_s^+ - \omega_s^-)$.

The governing differential equation representing the conservation of mass of a species 's' can also be easily visualized as the conservation of fluxes over a small unit differential volume in the curvilinear coordinates. The dimensions of this differential control volume in the curvilinear space are $\Delta \xi_1 = \Delta \xi_2 = 1$. The transformation Jacobian ' J ' represents the inverse of the volume of this differential curvilinear element. Now, the convective gradient term for this differential curvilinear control volume can be written as the difference between the total species mass entering the differential control volume due to convective effects (F_s^+) and the total species mass leaving the differential control volume due to convective effects (F_s^-). Similarly, the convective gradient term can be written as the difference between the total species mass entering the differential control volume due to mass-diffusion effects (J_s^+) and the total species mass leaving the differential control volume due to diffusion effects (J_s^-). In this control volume representation of the differential equation of conservation of species mass can be written as

$$J[F_s^+ - F_s^-] + J[J_s^+ - J_s^-] = [\omega_s^+ - \omega_s^-] \quad [A3-11]$$

Now, the relative dominance of the production and consumption terms determine whether a species is in a frozen, nonequilibrium or equilibrium state. This is accomplished by defining

$$\phi_s = \frac{\frac{1}{2}(|\omega_s^+| + |\omega_s^-|)}{\left[|J|(|F_s^+| + |J_s^+|) + \frac{1}{2}(|\omega_s^+| + |\omega_s^-|) \right]} \quad [A3-12]$$

In the frozen limit, there is no chemical production and consumption of the species 's' (i.e., $\omega_s = \omega_s^+ = \omega_s^- = 0$) and $\phi_s = 0$. In the equilibrium limit the chemical rates are infinite and, while the species production and consumption rates are infinite, there is no net production of the species 's'. In other words, in the equilibrium reaction limit $\omega_s^+ = \omega_s^- \rightarrow \infty$ and $\omega_s = (\omega_s^+ - \omega_s^-) = 0$. Thus, the species Equilibrium Reaction Factor (ϕ_s) is unity in the true limit of chemical equilibrium.

A3.3.2 Sample Results and Discussion

The species Equilibrium Reaction Factors were computed for the peak-heating condition for the GIS reentry at an altitude of 147 kft and a velocity of 51 kft/sec along the intermediate GPHS reentry trajectory ($\gamma = -20^\circ$). The condition chosen corresponds to the peak heating point along this GIS trajectory (see Reference A3-1). Figures A3-6a through A3-6e show sample results for some selected species. Figure A3-6a shows the shock-layer temperature profile and the mass-fraction and Equilibrium Reaction Factor profiles for N_2 and O_2 . The corresponding mass-fraction and Equilibrium Reaction Factor profiles for N^+ and O^+ are shown in Figure A3-6b. Similar profiles for C_2 , C_3 , CO , CO_2 , CN and C^+ are shown in Figures A3-6c, A3-6d, and A3-6e.

Figure A3-6a. Shock-Layer Temperature Profile and Mass Fraction and Equilibrium Reaction Factor Profiles for N_2 and O_2 .

Figure A3-6b. Mass Fraction and Equilibrium Reaction Factor Profiles for N^+ and O^+ .

Figure A3-6c. Mass Fraction and Equilibrium Reaction Factor Profiles for C_2 and C_3 in the Near-Wall Region.

Figure A3-6d. Mass Fraction and Equilibrium Reaction Factor Profiles for CO and CO₂ in the Near-Wall Region.

Figure A3-6e. Mass Fraction and Equilibrium Reaction Factor Profiles for CN and C+ in the Near-Wall Region

In general, these results show that, under these conditions, *all of the species of any consequence are in nonequilibrium and far from equilibrium*. In regions where some species' Equilibrium Reaction Factors approach unity, these species are in negligible concentrations and, thus, have little or no effect on the overall gas behavior. In particular, keeping all other aspects of the computational model the same, the assumption of equilibrium chemistry at the wall results in a gas mixture at the wall that has a significantly lower enthalpy. Due to this much lower enthalpy at the assumed equilibrium mixture at the wall, the assumption of equilibrium catalysis at the wall leads to a much higher ablation rate.

A3.4 EFFECTS OF SOME CHEMICAL REACTIONS ON THE FLOWFIELD SOLUTION

The high-speed reentry flow over an ablating carbon surface consists of a finite-rate reacting gas mixture of several species and several chemical reactions. The gas chemistry and the surface ablation process are intrinsically coupled to each other because the composition of the gas mixture at the ablating wall strongly dictates the surface ablation rate and the composition of the ablating carbon species. For the hypersonic reentry flows characterizing the accidental Earth reentry of the Cassini GPHS module and the subsequent release of the

fuel-containing GIS, the gas chemistry in the near-wall region is strongly affected by the reaction rates of the carbon dissociation reactions. This section investigates the carbon-dissociation reaction rates of Blottner (Reference A3-3) and Park (Reference A3-4), and concludes that the rates of Park should be adopted in the new GIS CFD analysis.

A3.4.1 Reaction-Rate Data and Discussion

The flowfield predictions of the FSAR were based on the carbon dissociation reaction rates of Blottner (Reference A3-2). These reaction rates represented the best and most reliable data available at that time.

The dissociation reactions of C_2 and C_3 are

For these carbon dissociation reactions, the forward reaction rate data of Blottner (Reference A3-3)

$$K_{f1} = 4.5 \times 10^{18} \, T^{-1} \exp(-70930/T)$$

$$K_{f2} = 1.6 \times 10^{16} \, T \exp(-87480/T)$$

was compared with the more recent rate data of Park (Reference A3-4)

$$K_{f1} = 4 \times 10^{14} \exp(-70930/T)$$

$$K_{f2} = 4 \times 10^{14} \exp(-87480/T)$$

The reaction rates used in the FSAR for the C_2 and C_3 dissociation reactions were based on the forward reaction rates of Blottner. While the backward reaction rate for the C_2 dissociation was also based on that suggested by Blottner, the backward reaction rate for the C_3 dissociation reaction was estimated using the equilibrium constant approach of Park (Reference A3-5). Blottner's backward reaction rates were based on his estimates of the equilibrium constant using the species partition-function data available to him. However, our computations of equilibrium species composition using Blottner's equilibrium constant for the C_3 dissociation reaction did not agree with those predicted using the free-energy minimization approach of McBride et al. (Reference A3-6). However, with a revised equilibrium constant for the C_3 dissociation reaction computed using the Park (Reference A3-5) approach, the

predicted equilibrium composition was found to be in good agreement with the corresponding predictions based on the equilibrium approach of McBride et al.

Since the earlier FSAR computational approach used a chemical equilibrium assumption at the ablating wall, having the correct equilibrium constant was sufficient. However, in the new and improved GIS CFD analysis described in Section A3.2, there is no longer a constraint to this equilibrium assumption and instead a new nonequilibrium species mass-balance approach is used at the ablating wall. With this new approach, the species composition at the wall is significantly impacted by the accuracy of the actual forward and backward reaction rates and not just the accuracy of the equilibrium constant represented by them. While Blottner had documented both the forward and backward reaction rates for the C_2 and C_3 dissociation reactions, Park (Reference A3-4) only gave the forward reaction rates. The backward reaction rates corresponding to the forward reaction rates of Park were estimated using the equilibrium constants for these reactions. The equilibrium constant used for the C_2 dissociation reaction was based on the forward and backward rate data of Blottner. For the C_3 dissociation reaction, we used the equilibrium constant computed by Lewis (Reference A3-7) using the approach recommended by Park (Reference A3-5). As mentioned before, we had established the accuracy of these equilibrium constants by comparing with the free-energy minimization approach of McBride et al. (Reference A3-6).

A3.4.2 Some Sample Results and Discussion

The effect of the carbon dissociation reactions was studied for the peak-heating altitude of 147 kft along the intermediate GIS reentry trajectory ($\gamma = -20^\circ$) at a wall temperature of 7600 °R. Computations were performed using the stagnation-streamline version of the new RACER code. Figures A3-7a and A3-7b show the results of the computations using the Blottner and Park reaction rates for the dissociation of C_2 and C_3 .

Figures A3-7a and A3-7b show the near-wall concentrations of the carbon species C, C_2 and C_3 . The results show that the Blottner reaction rates for the dissociation of C_2 and C_3 predict significantly less dissociation of C_3 resulting in an excessive amount of available C_3 at the

Figure A3-7a. Effects of Carbon Dissociation Reactions on the Near-Wall Concentrations of C, C_2 and C_3 .

Figure A3-7b. Effects of Carbon Dissociation Reactions on the Wall Concentrations of C, C_2 and C_3 and Surface Ablation Rate.

wall. On the other hand, the reaction rates of Park (Reference A3-4) predicted that most of the C_3 and C_2 dissociate into C. In general, Figure A3-7b shows that the dissociation rates of Blottner predict 70% less C and 106% more C_3 at the ablating wall. The C_2 composition differs by about 20%, with Blottner's rates under-predicting the amount of C_2 available at the wall. The amount of free C, C_2 , and C_3 available at the wall affects the rate at which these species sublime from the solid carbon surface. Thus, the wall chemistry has a direct effect on the predicted surface ablation rate. As a result of these differences in the near wall chemistry for this peak-heating case, the computations based on the Blottner rates under-predict the surface ablation rate by 30%. However, the corresponding reduction in the surface-heating rate offsets the effects of this higher ablation rate on the Surface Energy Balance (SEB) and the in-depth heat conduction. This compensating effect was confirmed by performing a transient-heating analysis (see Section A5.1). The reaction rates of Park (Reference A3-4) were considered to be more reliable because, in addition to being used in the NASA Mission Studies (Reference A3-3), they produced results that were more consistent with observations. In Reference A3-4 Park noted that, while the ablating gases are primarily composed of C_3 , this mixture quickly decomposes in the hot gas phase to form C. Figures A3-7a and A3-7b show that the predictions based on the Park's rates are more consistent with such an observation. Thus, unlike the earlier FSAR analysis, in the new GIS CFD computations we have adopted the C_2 and C_3 dissociation rates of Park (Reference A3-4).

A3.5 A SIMPLIFIED CARBON ABLATION CASE AND SPECIES MASS BALANCES AT THE ABLATING WALL

To better understand the nonequilibrium flow over an ablating carbon surface, a simplified (reduced) carbon-air system is used to analyze the near-wall ablation and nonequilibrium species mass balances. A new nonequilibrium mass-balance boundary condition is used for each chemical species at the ablating wall, and results are compared with the corresponding predictions based on a catalytic wall assumption. The new mass-balance boundary conditions are derived from first principles and impose the strict conservation of mass for each individual species at the wall. Sample calculations are carried out for the diffusion-controlled surface oxidation over a carbon cylinder using a 9 species (O , N , N_2 , O_2 , NO , C , CO , CO_2 and CN) and 19 reaction chemical model. Detailed analysis of the near wall region

shows that the mass of each species is conserved, and it is shown that for the conditions considered the surface oxidation process is almost completely fed (controlled) by the mass diffusion process.

The wall boundary conditions are imposed on a small control volume at the wall. The height of this control volume (Δ_w) is equal to half the grid cell height at the wall. It is important to note that the conservation of mass and energy above this half-cell interface is implied by the finite-difference form of the governing conservation equations applied at the first grid point off the wall. Thus, with the additional mass and energy conservation equations imposed on the half cell at the wall, the global conservation of mass and energy is strictly satisfied from the wall out into the freestream. The species composition at the wall is determined using the constraint of conservation of species mass in this control volume at the wall. The resulting nonequilibrium species-mass-balance boundary conditions are given in Section A3.2 by Equation [A3-2].

A3.5.1 Sample Results and Discussion

The effects of the new nonequilibrium species-mass-balance boundary conditions (MBW) were evaluated by comparing with the corresponding predictions of an equilibrium catalytic wall (ECW). The case considered for analysis was the stagnation streamline flow over a carbon cylinder reentering the earth atmosphere at a speed of 20 kft/sec at an altitude of 200 kft. The wall temperature was assumed to be 2000°R, and the radius of the sphere was 0.775 inch. At this temperature it was envisioned that nonequilibrium sublimation effects would be negligible and a diffusion-controlled surface oxidation environment will exist. To simplify the chemical system involved, a 9-species carbon-air chemical system (O, N, N₂, O₂, NO, C, CO, CO₂ and CN) governed by 19 gas-phase reaction was assumed to be adequate. Numerical calculations were done along the stagnation streamline using equilibrium (ECW) as well and nonequilibrium (MBW) wall boundary conditions. The results of these calculations are summarized in Figures A3-8a through A3-8e.

Figure A3-8a. Near-Wall Concentration Profiles of N and N_2 and the Corresponding Surface Mass Balance

Figure A3-8a shows the details of the near-wall concentration profiles of N and N_2 along with the shock-layer temperature profile. In general, compared to the equilibrium-catalytic wall (ECW) assumption, the nonequilibrium mass-balance boundary conditions (MBW) predict a 13% decrease in the N_2 available at the wall. The concentration of N increases dramatically from nearly zero with an ECW to nearly 7% with an MBW boundary condition at the wall. Figure A3-9a also shows that, with the nonequilibrium species-mass-balance boundary conditions (MBW), N and N_2 reach the ablating surface by diffusion mass flux and are carried back into the shock layer by equivalent mass convection effects. Furthermore, both ECW and MBW boundary conditions predict a definite edge of the near-wall region at a distance of $0.1 R_n$ from the ablating surface where the shock-layer temperature is around $7500^\circ K$. At this location the equilibrium as well as nonequilibrium wall boundary conditions predict almost identical levels of N and N_2 . In the region bounded by the wall and $0.1 R_n$, the ECW boundary conditions force the N and N_2 concentrations to rapidly reach prescribed equilibrium

Figure A3-8b. Near-Wall Concentration Profiles of O and O₂ and the Corresponding Surface Mass Balance

Figure A3-8c. Near-Wall Concentration Profiles of CO and CO₂ and the Corresponding Surface Mass Balance

Figure A3-8d. Total and Species Mass Balance at the Stagnation Point

compositions at the wall resulting in large concentration gradients. On the other hand, the nonequilibrium mass-balance boundary conditions result in a much more gradual change in concentrations of N and N₂, and the predicted concentration gradients (diffusion fluxes) in the near-wall region are much less compared to the equilibrium-catalytic wall case. The reasons for this becomes clear when evaluating the mass balance at the wall where the diffusion mass flux of N and N₂ toward the wall has to be equal to the small convective mass flux of these species from the wall (0.00025 lbm/ft²-sec for N and 0.00235 lbm/ft²-sec for N₂, see Figure A3-8a). The resulting diffusion fluxes (equivalently the concentration gradients) of N and N₂ at the wall are also small and, thus, the concentration levels in the near wall region tend to not change too much from their values at the edge of the near-wall region at 0.1 R_n. In short, for the nonequilibrium species-mass-balance boundary conditions (MBW), the species concentrations at the edge of the near-wall region have a strong effect on the species concentrations at the abating surface.

Figure A3-8b shows the near-wall profiles and surface mass balance of O and O₂. Similar to the previously discussed results of N and N₂, the new nonequilibrium species-mass-balance

boundary conditions also tend to reduce the concentration gradients of O_2 in the near-wall region. However, O continues to have a strong concentration gradient in the near-wall region. The species mass balance at the wall shows that the concentration gradients of O are preserved because the rate at which O is consumed at the wall in the heterogeneous surface-oxidation process is in fact supported by the rate at which O diffuses to the wall. Thus, the strong concentration gradient of O in the near-wall region is needed to support its mass diffusion to the wall. Furthermore, Figure A3-8b shows that the oxygen needed at the wall for the heterogeneous surface-oxidation process arrives there almost solely by the diffusion of O and, hence, the justification for calling this process the diffusion-controlled oxidation limit. There is almost no contribution of O_2 to the surface oxidation process. Actually, the rate at which O diffuses to the wall ($0.00946 \text{ lbm/ft}^2\text{-sec}$) is more than the rate at which it is consumed at the wall in the heterogeneous surface oxidation reactions ($0.00944 \text{ lbm/ft}^2\text{-sec}$) because a small amount of O ($0.00002 \text{ lbm/ft}^2\text{-sec}$) is also to be carried back into the shock layer by the convection process at the ablating wall. In short, the new nonequilibrium species-mass-balance boundary conditions also inherently include all the mass flux effects needed to accurately support a diffusion-controlled oxidation limit.

Figure A3-8c shows that CO_2 is the major by-product of the heterogeneous surface oxidation process. The predictions based on the new nonequilibrium species-mass-balance boundary conditions (MBW) show that the amount of CO_2 produced by the heterogeneous surface-oxidation process ($0.0122 \text{ lbm/ft}^2\text{-sec}$) is predominantly carried away from the wall into the shock-layer by mass diffusion effects ($0.0112 \text{ lbm/ft}^2\text{-sec}$) and the remaining ($0.0010 \text{ lbm/ft}^2\text{-sec}$) is transported into the shock layer by mass convection effects. Most importantly, Figure A3-8c shows that the mass fraction of CO_2 needed to satisfy such a detailed mass balance at the ablating surface is only 0.06, and not the 0.265 mass fraction suggested by equilibrium-catalytic wall model.

Figure A3-8d summarizes the complete mass balance at the ablating wall obtained using the nonequilibrium mass-balance boundary conditions. The results show that, while individual species have diffusion mass flux to or away from the ablating wall, the net mass diffusion to the wall summed over all species is zero. In short, the total mass entering the shock-layer due to surface-ablation effects ($0.0038 \text{ lbm/ft}^2\text{-sec}$) must be carried away from the wall into

the shock layer by only the mass convection effects. To satisfy the global conservation of total mass, there should be no net loss or gain of mass due to mass diffusion effects and chemical reactions. Figure A3-8d shows that, when summed over all species, the predictions based on the new nonequilibrium species-mass-balance boundary conditions also satisfy the global conservation of mass at the ablating wall.

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Section A4

Coupled GPHS/GIS 6-DOF Analyses

SECTION A4

COUPLED GPHS/GIS 6-DOF ANALYSES

A series of coupled GPHS module/GIS 6-DOF Monte Carlo simulations were performed to determine the flight dynamic behavior of the GPHS module and GIS, particularly as it is related to their respective thermal environments and thermal response.

The flight behavior is affected by the dynamic conditions (angular rates and attitude) at GPHS removal during spacecraft demise or breakup, the reentry state condition (flight path angle and velocity), the aerodynamic characteristics, and the dynamic conditions at GIS removal from a breached GPHS aeroshell.

A 1000 trial Monte Carlo analysis has been completed for the intermediate EGA trajectory entry condition ($\gamma = -20$ deg). The analysis includes the correlated set of 1000 GIS Monte Carlo trials (which are "one-to-one" continuations of the module trials following the predicted module failure/GIS release). The EGA intermediate flight reentry is utilized because it represents the worst-case aerothermal environment (combination of heat flux magnitude and heating duration).

A4.1 GPHS AERODYNAMICS

The GPHS aerodynamic data consist of a subsonic set and a supersonic/hypersonic set and assumes an non-ablated shape. The subsonic data and hypersonic dynamic damping derivatives (pitch and roll) were supplied by JHU/APL in 1986.

The hypersonic data was reduced by Lockheed Martin Missiles and Space (then GE) in 1986 based on Mach 10 wind tunnel test conducted by JHU/APL. A complete set of force and moment coefficients (C_x , C_y , C_z , C_m , C_n , C_l) as functions of total angle of attack and aerodynamic roll angle (ϕ) was generated and documented in a report to C. T. Bradshaw (Reference A4-1).

A4.2 INITIAL CONDITIONS FOR THE GPHS AND GIS

The 1000 GPHS trials are developed from random draws of the following parameters:

- Initial total angle-of-attack, δ : Uniform distribution between 0 and 90 degrees.
- Initial aerodynamic roll angle, f : Uniform distribution between ± 180 degrees.

- Initial roll rate, P: Normal distribution with zero mean and ± 50 RPM ($3-\sigma$).
- Initial pitch rate, q: Normal distribution with zero mean and ± 50 RPM ($3-\sigma$).
- Initial yaw rate, r: Normal distribution with zero mean and ± 50 RPM ($3-\sigma$).

These initial angular body rate and orientation distributions are based on earlier studies of Cassini spacecraft breakup performed by JPL. JPL characterized (Reference A4-2) the spacecraft breakup as "...the maximum expected angular rate for the spacecraft is approximately 50 RPM which is expected to damp aerodynamically to as low as 1 RPM early in reentry".

In general the flight dynamics of the module will affect the heat flux distribution across the module surfaces and therefore the rate of heatshield ablation. In addition the angular rates at module failure/GIS removal are transferred to the GIS as initial conditions and will affect its subsequent flight dynamic/thermal response behavior.

The module or GPHS is failed based on the attainment of a critical deceleration (aerodynamic drag load). Once this deceleration level is achieved the GIS is assumed to be released with the angular rates and orientations of the module as illustrated in Figure A4-1. The corresponding GIS Monte Carlo samples are continued through their respective heat pulse. The failure aerodynamic loads are 195 Gs and 340 Gs for a face-on stable module and random tumbling module, respectively, as given in the Cassini GPHS-RTG FSAR.

A4.3 CHARACTERIZATION OF DYNAMICS FOR GPHS

In performing the Monte Carlo assessment the primary objective is the determination of the statistical distribution associated with the module's thermal response (i.e., Is the module effectively responding as tumbling or face-on stable?). The rigid body dynamic flight behavior of the module directly affects this thermal response. If the module maintains a purely face-on stable orientation the face presented to the wind (velocity) vector will experience the maximum heating and ablation possible. Similarly, as the module tumbles the heating with respect to any given face will vary approximately as a cosine of the angle between the face and the velocity vector. The heating distribution is determined by computing a hot-wall,

Figure A4-1. Definition of GIS Initial Conditions

convective, heat flux to each module face based on the velocity normal to that face. Similarly, an approximate radiation heat flux is computed (Reference A4-3) and correlated/corrected to the detailed calculations derived from RACER/LORAN-C. The total heat flux (convective plus radiation) is integrated over the flight and compared to the pure face-on value. Each face then experiences an integrated heat flux as a percentage of the face-on stable level for each Monte Carlo trial. This data is available for statistical post-processing.

The reference integrated heat flux (where the integrated heat flux is referenced to the final pure face-on stable integrated heat flux value) for each module face, for a sample trial (trial number 2 of the Monte Carlo set), is shown in Figure A4-2. (Module face numbers are defined in Figure A4-1) Similarly, Figures A4-3 and A4-4 show the corresponding total angle-of-attack and roll rate history, respectively, for this sample. As can be seen the heat load is distributed primarily on the broad faces of the module (faces numbered 1 and 4) with very

Figure A4-2. GPHS Reference Heating to Each Face – Trial 2

Figure A4-3. GPHS Angle of Attack Response – Trial 2

Figure A4-4. GPHS Roll Rate and Stability Bounds – Trial 2

little on the edge faces (numbered 2, 3, 5, and 6). For this example the maximum heating to any given face is approximately 45% of the pure face-on stable value. This result is expected in that the module exhibits static stability at angles-of-attack in which the broadside faces are normal to the velocity vector ($\delta = 0$ and 180°).

The FSAR indicated that for reentry flight path angles shallower than -16° the GPHS will survive regardless of whether it is face-on stable or tumbling. For flight path angles steeper than -21° the GPHS will fail structurally whether it is face-on stable or tumbling. Further for flight path angles between -16° and -21° the GPHS will survive if tumbling motion prevents any face from receiving more than 35% of the total integrated heat flux. Therefore it can be said that the case presented above (trial 2) is effectively a face-on stable case.

As can be seen in Figure A4-3 the module initially stabilizes with the flow broadside to face 1 (zero angle of attack). At approximately 5 seconds the module tumbles and, relatively quickly, re-stabilizes with face 4 normal to the velocity vector (180 degree angle of attack).

Again, at about 7 seconds the module tumbles and shortly re-stabilizes with face 1 again broadside.

Blunt reentry bodies (such as the planetary probes Pioneer Venus, Galileo, and Viking) which are both statically and dynamically stable can exhibit instability at moderate spin rates. This characteristic is due in part to the pronounced negative lift coefficient slope developed because of the high axial force of the blunt body. The conditions leading to instability can be developed as discussed below. The angular equation of motion for a rigid body (with zero trim) can be represented as a second order differential equation:

$$\ddot{\zeta} + (a+ib)\dot{\zeta} + (c+id)\zeta = 0 \quad [A4-1]$$

where, $\zeta = \alpha + i\beta$,

α is the angle - of - attack and

β is the angle - of - sideslip

This equation is similar to that for a viscously damped oscillator but with complex coefficients. Essentially the a term affects the rate of growth or decay of the amplitude of oscillations and the c term defines the frequency of oscillations. The effects of the complex coefficients are reversed in that the b term affects frequency and the d term affects the damping. (It can be noted that for zero roll rate the complex coefficients drop out and you are left with an equation that corresponds to a harmonic oscillator.) The solution of this equation is assumed to take the form of,

$$\zeta = R \exp(\lambda + i\omega) \quad [A4-2]$$

or,

$$\zeta(t) = \left(\frac{\omega_e}{\omega_0}\right)^{1/2} \left\{ R_{lo} \exp\left[\int (i(-\Delta\omega - \omega_0) + (\lambda_0 + \Delta\lambda)) dt\right] + R_{ho} \exp\left[\int (i(-\Delta\omega + \omega_0) + (\lambda_0 - \Delta\lambda)) dt\right] \right\} \quad [A4-3]$$

where,

$$\Delta\omega = -P \left(1 - \frac{A}{2B}\right),$$

$$\text{of, } \omega_0 = \left[\frac{-q_\infty S d}{B} C_{m\alpha} + \left(\frac{PA}{2B}\right)^2 \right]^{1/2}, \text{ Basic body frequency.}$$

$$\omega_h \text{ (high frequency)} = -\Delta\omega - \omega_0, \text{ and } \omega_l \text{ (low frequency)} = -\Delta\omega + \omega_0$$

$$\lambda_0 = \frac{-q_\infty S}{2V} \left[\frac{C_{L\alpha}}{m} - \frac{d^2}{2B} C_{mq} \right], \text{ Damping ratio.}$$

$$\Delta\lambda = \frac{q_\infty S}{V} \left(\frac{PA}{4\omega_0 B} \right) \left[\frac{C_{L\alpha}}{m} + \frac{d^2}{2B} C_{mq} \right],$$

and R_{ho} and R_{lo} are the initial magnitudes of the high and low frequency components of angle-of-attack.

To assure convergence or stability the real elements, $\lambda + \Delta\lambda$, and, $\lambda - \Delta\lambda$, must be negative.

Therefore, solving for the condition at which this criteria is met leads to:

$$P_s \leq \left(\frac{2B}{A} \right) \left(\frac{-q_\infty S C_{m\alpha}}{2md C_{L\alpha} C_{mq}} \right)^{1/2} \left(C_{L\alpha} - \frac{md^2}{2B} C_{mq} \right) \quad [A4-4]$$

which provides a stability bound defined by a roll rate limit.

The sample case above initially stabilized with face 1 normal to the flow (broadside). The module then begins to spin-up until the roll rate is achieved at which the module is dynamically unstable (represented by the dashed line in Figure A4-4 – a prediction based on the roll rate stability bound equation for P_s). When the module goes unstable it begins to tumble and the roll rate drops allowing it to re-stabilize, this time with face 4 normal to the velocity vector. This behavior may, and will, reoccur multiple times.

A4.4 CHARACTERIZATION OF THE DYNAMICS FOR THE GIS

The GIS, a right circular cylinder, characteristically exhibits two static trim conditions, broadside (90° angle of attack) and near end-on (approximately 22° angle of attack). The GIS has no inherent roll torque mechanism and will maintain whatever roll rate is imparted to it at separation from the failed GPHS.

It is assumed that motion is imparted as shown in Figure A4-1. The spin rate will be sufficiently high, to mitigate recession, if at least one revolution is completed within the heat pulse (3 to 4 seconds) or approximately 100 deg/sec. Therefore, for the purposes of this analysis, for GIS roll rates greater than 100 deg/sec the GIS may be considered "spinning", less than 100 deg/sec will indicate a "non-spinning" GIS.

A4.5 MONTE CARLO RESULTS

Figure A4-5 shows a histogram of the GPHS integrated heating (maximum for all faces) binned as a percentage of the pure FOS value for the Monte Carlo runs. As can be seen approximately 64% of the trials yield face heating 35% or more of the pure FOS and can therefore be considered effectively face-on stable (FOS).

A histogram of the GIS roll rate is illustrated in Figure A4-6. All of the trials exhibit roll rates between ± 8000 deg/sec. In order to determine the fraction of the trials that can be considered non-spinning Figure A4-7 expands the distribution of roll rate between ± 100 deg/sec. It can be seen that approximately 50 samples have roll rates less than 100 deg/sec, or 5% of the total trials (1000). Therefore 5% of the GIS can be termed "non-spinning."

None of the samples in the 1000 GIS trials stabilized "end-on." As illustrated in Figure A4-8, 75% of the GIS trials stabilized broadside within one second of release from the failed GPHS. Similarly, 88% stabilized broadside in less than 3 seconds.

Figure A4-5. Comparison of Maximum Integrated Heating to any Given Face to Hypothetical Pure Face-On-Stable Value

Figure A4-6. GIS Roll Rates

Figure A4-7. Histogram of GIS Roll Rates between ± 100 deg/sec

Figure A4-8. GIS Convergence Time to within ± 25 Degrees of Broad Side Stable

References for Section A4

- A4-1 Bradshaw, C. T., "Reentry Trajectory Characteristics of the GPHS Configuration C", PIR No. 1986-32-007, 16 June 1986.
- A4-2 Letts, W., Lockheed Martin, Private communication with Angus McDonald, NASA-JPL, October 1998.
- A4-3 Tauber and Sullivan, Journal of Spacecraft and Rockets, Vol. 28, No. 1, January-February 1991.

Section A5

**LM/INSRP EGA
Predictions Comparison**

SECTION A5

LM/INSRP EGA PREDICTIONS COMPARISON

A5.1 UPDATED ABLATION PREDICTIONS

Surface ablation and heating computations were performed for a non-spinning, broad-side stable, GIS on the intermediate reentry trajectory ($\gamma = -20^\circ$) using the improved CFD analysis approach with the new nonequilibrium species-mass-balance boundary conditions (see Section A3.2). For the conditions considered, nonequilibrium-sublimation effects dominate the surface ablation process. The flowfield chemistry is modeled using a 19 species (O, N, N₂, O₂, NO, C, C₂, C₃, CO, CO₂, CN, N⁺, O⁺, N₂⁺, O₂⁺, NO⁺, C⁺, CO⁺ and e⁻) and 44-reaction chemical model. Except for the carbon (C₂ and C₃) dissociation reactions, the reaction-rate data used for these 44 reactions is the same as used for the FSAR calculations (Reference A5-1) and the post-FSAR calculation described in Section 6.5.3.3.3 of this report. As discussed in Section 3.2, the rate data used for the carbon (C₂ and C₃) dissociation reactions in this improved CFD approach are based on the forward rate data of Park (Reference A5-2). These modifications were incorporated into the RACER flowfield code used for the earlier FSAR and post-FSAR analyses.

Nonequilibrium flowfield predictions with coupled ablation and radiation were performed using the modified RACER code for several temperatures at seven altitudes (160 kft, 155 kft, 147 kft, 138 kft, 125 kft, 114 kft, and 102 kft) along the trajectory. Using the approach outlined in Section A3.2, Surface Energy Balance (SEB) computations were performed for each of these flowfield solutions to compute the corresponding in-depth heat conduction (Q_s). The surface-ablation rate (m_w) and in-depth heat-conduction (Q_s) results of these calculations were put together in the form of 2-D tables using wall temperature (T_w) and the flight altitude (Alt.) as the independent variables; i.e., $m_w(T_w, \text{Alt.})$ and $Q_s(T_w, \text{Alt.})$. This tabular database is provided to the REKAP transient heat-conduction code (Reference A5-3), which then computes the surface temperature and surface recession of the GIS as it reenters along the prescribed reentry trajectory.

Figure A5-1a compares the surface-ablation rate predictions of the modified RACER code (using the improved CFD approach of Section A3.2 and the nonequilibrium species-mass-balance boundary conditions) with the earlier predictions in Section 6.5.3.3.3 of this report based on an equilibrium-catalytic wall approximation. The results shown in Figure A5-1 are for a constant wall temperature of 7600°R along the intermediate trajectory, and indicate that the improved CFD approach predicts almost a 30% higher surface ablation rate. However, Figure A5-1b shows that the corresponding in-depth heat conduction (Q_s) computed using the surface energy balance (SEB) of Section A3.2 is about 26% lower than the corresponding Final Report predictions based on an equilibrium-catalytic wall. In fact, Figure A5-1 shows that the predicted in-depth heat conduction (Q_s) is the highest for the post-FSAR predictions using the INSRP advocated SEB (see Section A5.3.2), and the lowest for the predictions based on the modified CFD. This lowering of the in-depth heat conduction (Q_s) is important because it lowers the final surface temperature of the GIS. The surface-ablation rate corresponding to this lower surface temperature is also lower, and the predicted surface recession of the GIS is not significantly affected. In summary, the adverse effects of the

Figure A5-1a. Effect of Improved CFD Analysis on the Predicted Surface-Ablation Rate for the GIS Reentry along the Intermediate Trajectory

Figure A5-1b. Effect of Improved CFD Analysis and Various SEB Models on the In-Depth Heat-Conduction Rate for the GIS Reentry along the Intermediate Trajectory

Higher surface-ablation rate predicted using the new and improved CFD approach are mostly compensated by the lower in-depth heat conduction predicted for these cases.

The enthalpy of the gaseous mixture at the wall has a direct influence on the SEB. Figure A5-1c shows that the enthalpy of the gaseous mixture at the wall based on a chemical equilibrium assumption (H_w^{EQ}) is significantly lower than the enthalpy of the wall gas mixture based on a nonequilibrium species-mass-balance boundary condition (MBW). It can be easily seen from the Surface Energy Balance equations given in Section 3.2 (Equations A.3-7 and A.3-9) that the larger the enthalpy of the wall mixture, the larger the amount of energy carried by convection effects from the wall into the surrounding nonequilibrium gas phase. Consequently, the smaller is the amount of in-depth energy (Q_s) conducted to the ablated carbon surface.

Figure A5-1c. Effect of Improved CFD Analysis on the Predicted Gas Enthalpy at the Ablating Wall for the GIS Reentry along the Intermediate Trajectory

The surface temperature predictions of the REKAP transient heat-conduction code are shown in Figures A5-2a, and the corresponding surface-recession history is shown in Figure A5-2b. The time in seconds shown in these figures is the time from the RTG breakup and release of the GPHS module. The GPHS aeroshell failure and the GIS release occur at 5.8 sec. These figures also include the post-FSAR predictions from Section 6.5.3.3.3 of this report based on an equilibrium-catalytic-wall (ECW) approximation and the corresponding Lockheed Martin and INSRP-advocated Surface Energy Balance formulations labeled "LM (FSAR) SEB" and "INSRP SEB". The surface temperature results of Figure A5-2a show that the GIS surface temperature predicted using the improved CFD formulation, labeled "LM SEB", is typically lower than that predicted using equilibrium-catalytic-wall approximation. The peak surface temperature is about 7750°R and occurs around 1.4 sec after GIS release (or 7.2 sec after RTG break up). At 9.2 sec, the GIS surface temperature predicted using the improved CFD

approach ("LM SEB") is about 7300°R. The corresponding prediction in the earlier Final Report analysis ("LM (FSAR) SEB") is 7500°R and that of the INSRP-advocated SEB ("INSRP SEB") is about 7700°R. The heat pulse ends at around 5 sec after GIS release (or 10.8 sec after RTG breakup). At the end of the heat pulse at 10.8 sec, the predicted GIS surface temperature is about 6800°R, which is about 3% lower than that predicted using the INSRP SEB (See Section 6.5.3.3.3 of this report). The corresponding prediction of the Lockheed Martin SEB model used in the FSAR and post-FSAR analysis is about 4% lower. In general, over the intermediate GIS trajectory, effects of the various SEB formulations on the GIS surface temperature are within 6%.

Figure A5-2a. Effect of Improved CFD Analysis and Various SEB Models on the Predicted Surface Temperature of the GIS (Non-Spinning) along the Intermediate Reentry Trajectory

Figure A5-2b. Effect of Improved CFD Analysis and Various SEB Models on the Predicted Surface Recession of the GIS (Non-Spinning) along the Intermediate Reentry Trajectory

The corresponding surface-recession history of the GIS along the intermediate trajectory is shown in Figure A5-2b. These results clearly show that the surface recession predicted with the improved CFD approach ("LM SEB") is within about 4% of that predicted earlier using the Lockheed Martin SEB ("LM (FSAR) SEB"). However, both these GIS surface-recession predictions are substantially lower than that predicted using the INSRP-advocated SEB model ("INSRP SEB"). At the end of the heat pulse at 10.8 sec, the previous SEB ("LM (FSAR) SEB") resulted in a surface recession of 0.97 inch and the improved CFD approach ("LM SEB") yields comparable recession of 1.01 inch. In contrast, the corresponding recession predicted using the INSRP-advocated SEB model ("INSRP SEB") is approximately 0.15 inch. The total thickness of the FWPF heatshield is 0.167 inch. In short, the present results substantiate the earlier Lockheed Martin predictions and show that, along the intermediate reentry trajectory ($\gamma = -20^\circ$), about 42% of the heatshield for a non-spinning GIS is still intact at the end of the heat pulse.

A5.2 RELEASE STATISTICS

The section provides updated fuel release estimates based on the modified CFD GIS and coupled module/GIS 6-DOF simulations described in Sections A2 and A4. Of interest is the distribution of GPHS module end states, given reentry, and the potential release types that could lead to health consequence. A detailed description of the end states and release types used in the EGA consequence analysis is given in Section 6.6.4.

An updated EGA event tree is shown in Figure A5.2-1 incorporating in the shaded symbols revisions from the event tree included in Section 6 of this report. The probability of face-on-stable module orientation is revised upwards from 0.4 to 0.7 based on preliminary evaluation of the coupled module/GIS 6-DOF simulations described in Section A4. Final 6-DOF evaluations produced a slightly lower probability of 0.64.

Also changing in the event tree from the prior version is the probability of GIS retention following aeroshell failure. This probability is reduced from 0.25 (for FOS) and 0.5 (for non-FOS modules) to 0.0 based upon consideration of the forces exerted on the GISs during an aeroshell breach. Event tree branches following "No GIS Release" have been removed due to the 0.0 probability "No GIS Release."

The orientation of the GPHS at failure will, most probably, be face-on to the flow, particularly since the maximum aerodynamic loads across the surface are experienced at this attitude, and the breach point will most likely occur at or near the stagnation point. Once the aeroshell is breached it is expected that the cavity containing the two GISs will rapidly pressurize due to ram air injection resulting in catastrophic structural failure. It is therefore expected that the GIS, following failure, will not be retained by the GPHS aeroshell. The determination and modeling of the failure event is extremely complex and well beyond the intended scope of these analyses. However, a complete and catastrophic aeroshell failure is likely and the assumption of no GIS retention has been adopted.

Figure A5.2-2 provides a comparison of end state probabilities from the FSAR and the updated reentry analysis (values given in parenthesis). Of significance is the increase in the clad melted probability for reentry angles above the critical angle 21 degrees. The updated analysis predicts that virtually all GISs released from failed aeroshells (99%) would survive

Figure A5.2-1. Updated Variability EGA Event Tree (Cont'd)

Figure A5.2-1. Updated Variability EGA Event Tree (Cont'd)

Figure A5.2-1: GPHS Module End State Event Tree

reentry but the clads would be melted. As a result, the end state B (or GIS-OK – Clad-OK) with potential fuel release upon rock impact is no longer applicable. Given reentry, the updated total probability a GPHS module will be in end state A (Intact Aeroshell) or end state C (GIS-OK – Clad Melt) will be 13% and 87%, respectively. In-air failure of the GISs is predicted to have a less than 0.1% probability.

In order to predict the distribution of release types that could lead to health consequences, the SPARRC/LHS analysis process was used to draw a number of modules breaching, in-air or upon ground impact in affected latitude bands as defined by the 500 km swingby plan (Section 6.4.2 of this report). This sampling takes into account the various probabilities including, module end states, reentry angle, impacted latitude band, and Earth's surface characteristics. Table A5.2-1 provides the number of employed trials and the results in terms of contribution of release types leading to health consequences. For end state GIS-OK-Clad-Melt, it is predicted that an average of 14 modules would release fuel on soil and nearly 2 modules would release fuel on rock. This represents an increase of about a factor of 5 when compared to the FSAR results. The number of modules associated with the in-air release of fine fuel particles due to GIS failure is reduced from 1.68 to less than 1. This failure mode only appears in 14% of reentry simulations, as opposed to 89% predicted previously for the FSAR.

For comparison with INSRP results (Reference A5-4), the above results were sorted for shallow and steep reentry. Tables A5.2-2 and A5.2-3 provide the conditional probability of each end state and the expected number of GPHS modules leading to health consequences. Of significance, INSRP predicted a high probability of GIS failure for any steep reentry, and as a result, in-air fuel release becomes the pre-dominant release type in their assessment. For shallow reentry, INSRP predicted that some GPHS modules could experience sufficient degradation during reentry to produce non-zero probabilities for the end states aeroshell failure and GIS-OK-Clad-Melt. In contrast, both the FSAR results and the updated GIS analysis predict that the GISs would be more likely to survive reentry, producing fuel release only upon ground impact. For that reason, the conditional probability of consequence, given reentry, is lowest for the updated GIS analysis because of the requirements of impact either on soil or rock surfaces.

Table A5.2-1. Contribution of Release Types Leading to Health Consequences

Release type	Number of Associated Trials		Probability of Occurrence Given Consequence from Any Release Type		Mean Number of Failed Modules	
	FSAR	Updated Analysis	FSAR	Updated Analysis	FSAR	Updated Analysis
Intact Module on Rock	3,578	3,578	0.0442	0.1014	0.1	0.2
GIS OK - Clad OK on Rock	2,451	0	0.1656	0	0.35	0
GIS OK - Clad Melt on Soil	5,769	6,748	0.4044	0.8274	3.17	14.35
GIS OK - Clad Melt on Rock	2,723	4,313	0.1820	0.529	0.34	1.73
GIS Failed - large Particles on Soil	2,980	65	0.2131	0.0112	0.31	0.01
GIS Failed - Large Particles on Rock	359	7	0.0253	0.0013	0.03	1.32×10^{-3}
GIS Failed - Fine Particles - Air release	7,779	606	0.8882	0.1372	1.68	0.14
All Types	12,416	10,548				

Table A5.2-2. Conditional Probability of Module End States from Various Analyses

Reentry Angle	Module End State	FSAR	Updated Analysis	SER
Shallow ($\gamma < 16$ deg.)	Intact Module	1.0	1.0	0.473
	GIS OK - Clad OK	0.0	0.0	0.237
	GIS OK - Clad Melt	0.0	0.0	0.237
	GIS Failed In air	0.0	0.0	0.0
Steep ($\gamma > 16$ deg)	Intact Module	0.047	0.024	0.0
	GIS OK - Clad OK	0.569	0.0	0.0
	GIS OK - Clad Melt	0.359	0.975	0.315
	GIS Failed In air	0.026	0.001	0.685

Table A5.2-3. Expected Number of GPHS Modules with Fuel Release Leading to Consequence

Reentry Angle	Release Type	FSAR	Updated Analysis	SER
Shallow ($\gamma < 16$ deg.)	Intact Modules Or Intact GIS	2.6	2	4
	On Rock			
	GIS with Clad Melted on Rock/Soil	0	0	8.5
	GIS Failed With In-air Release	0	0	0
Steep ($\gamma > 16$ deg.)	Intact Modules Or Intact GIS	0.38	0.02	0
	On Rock			
	GIS with Clad Melted on Rock/Soil	3.6	17.6	4
	GIS Failed With In-air Release	1.7	0.15	36
Mean Conditional Probability of Consequence Given Reentry		0.8	0.4	0.7

References for Section A5

- A5-1 "Final Safety Analysis Report (FSAR), GPHS-RTGs in Support of the Cassini Mission," Lockheed Martin, November 1996.
- A5-2 Park, C., "Review of Chemical-Kinetic Problems of Future Mars Missions, I: Earth Entries," *Journal of Thermophysics and Heat Transfer*, Vol. 7, No.3, July-September 1993, pp. 385-398.
- A5-3 Gordon, P., "Analysis of One-Dimensional Heat Conduction Computer Program," General Electric Company, SSL-MSD, TIS No. RR663D10, March 1966.
- A5-4 Supporting Technical Studies prepared for the Cassini Mission – Interagency Nuclear Safety Review Panel – Safety Evaluation Report – PSSP Report, Section 7.1.9 and RIUA Report, Section 5, October 1997.

Section A6

SPARRC Validation (Titan 34D-9)

SECTION A6

SPARRC VALIDATION (TITAN 34D-9)

This section describes validation studies done with the PUFF/SATRAP analysis models used for the Cassini Mission FSAR and FSAR Addendum against the accident characteristics identified following the launch of the Titan 34D9 at Vandenberg AFB on the California central coast on 18 April 1986. The key sources of information for this accident included two reports related to hazardous plume definitions associated with rocket launch accidents (References A6-1 and A6-2) and a video tape (Reference A6-3) of the accident. An Aviation Week & Space Technology article at the time of the accident (Reference A6-4) also provided some information about the vehicle and the accident sequence. The main source of plume rise information was a JANNAF conference paper and associated faxed data from Larry Mendenhall of Logicon (Reference A6-5). This work was focused on three key areas that affect nuclear consequence estimation. The first is the liquid fireball plume rise, which is estimated using the PUFF code. The second is the solid rocket motor (SRM) fragment fire plume rise, which is also estimated using the PUFF code. This plume comes from the ground-based fire after fall back of the SRM fragments. The third area is cloud transport characteristics. Each of these analyses was first performed using the original Cassini models and evaluation approach. In addition to the Cassini model approach several sensitivity studies were performed to investigate the effects of model changes on prediction capabilities.

A6.1 DESCRIPTION OF 18 APRIL 1986 LAUNCH ACCIDENT

The Titan 34D9 accident occurred 8.77 seconds after the launch at an elevation of 252 m (Reference A6-1). The launch occurred at 11:45 am PST. The weather was clear and the surface winds were blowing from the north/northwest, which would blow surface pollutants across the western edge of the peninsula and out to sea along the coast. The surface winds were blowing at speeds in the range of 5 to 8 m/sec. The lowest altitude temperature inversion was detected approximately 48 m above ground level (agl) at 10:45am. This height (referred to as a mixing height) is referenced to the pad level which is ~120 m (Reference A6-5) above mean sea level. In the following two sections a more detailed description of the

accident characteristics that are pertinent to accident modeling are summarized and the details of the meteorological conditions at the time of the event are also provided.

A6.1.1 Titan 34D9 Launch Vehicle and 18 April 1986 Accident Description

The 34D9 launch vehicle had two liquid propellant motors and two strap-on solid booster rockets. This launcher used only the solid rocket boosters at launch. The boosters were nominally to be separated at approximately 120 seconds into the mission which is when the first stage engine is ignited. The stage 2 engine is not ignited until 273 seconds into the launch and it is used to carry the payload to its final orbit location. According to Kevin Rudolph of LMA-Denver, there was no transstage or IUS (i.e., stage 3) on this mission. The accident appeared to be caused by the explosion of one of the solid rockets at 8.77 seconds (Reference A6-1) into the mission. Within milliseconds of this explosion, the self destruct system on the other booster and main engines destroyed the rest of the system. The spacecraft and compartment 2a which contains the avionics of the launch vehicle remained intact and sent telemetry until impact on the ground at 28 seconds into the mission. The liquid propellant is A-50 for both core motors and the oxidizer is N_2O_4 . The propellant types and inventories are summarized in Table A6-1. Heats of combustion used for this analysis are provided in the last column.

Table A6-1. 34D9 Accident Estimated Propellant Characteristics

Titan 34D Rocket Stage	Engine/Rocket Description	Propellant/Mass (lbm)(a)	Oxidizer/Mass (lbm)(a)	Propellant Heat of Combustion (BTU/lbm of propellant)
Stage 1	Aerojet	A-50 / 101827	N_2O_4 / 191983	~21300(b)
Stage 2	Aerojet	A-50 / 24739	N_2O_4 / 43934	~21300(b)
SRMs	United Technologies	AP PBAN Al / 928696 (61953 burned prior to accident)	N_2O_4 / 16848 (for thrust vector control)	~2637(c)
SV	Lockheed	Not Available	Not Available	Not Available

a) Reference A6-1 b) Reference A6-6 and c) Reference A6-2

The radius of the area within which SRM fragments landed (referred to as SRM fragment footprint) was estimated from video footage and still photographs (Reference A6-1) to be 4360 ft (1329 m). Video footage indicated a dense burning zone of approximately 0.44 of this value or 585 m. If the ratio adopted in the Cassini FSAR Addendum is used (0.5), then a dense burning zone of 664 meters would be obtained. This compares to 909 meters for the dense burning zone diameter or the full footprint diameter of 1818 m as estimated by fits to the FALLBACK code footprint predictions as a function of mission elapsed time for the Cassini Mission. It is not clear why the FALLBACK code predicted a 37% larger footprint diameter, but it could be related to the differences between 34D9 SRM and the Titan IVB SRMU characteristics or just model predictive capability.

A6.1.2 Meteorological Data and Conditions

The meteorological data for Vandenberg was obtained from figures in Reference A6-5. The data that was used for this study was from the rawinsonde 1/2 hour prior to the launch and 1.25 hours after the 10:45am launch. The 10:15am PST and the 12:01pm PST rawinsonde data was extracted from the plots of Reference A6-5 and converted to numerical tables for use with PUFF and SATRAP. The cloud location data was from the GOES-6 satellite as taken from Reference A6-5. It was noted by Mendenhall that these two rawinsonde data sets were taken at two different locations. The 10:15 rawinsonde was taken approximately 5km northeast of the launch pad. The 12:01 rawinsonde was taken 14km northeast of the launch site. Figures A6-1, A6-2 and A6-3 plot the wind direction, the wind speed, and the atmospheric temperature for these two data sets. The nearest temperature inversion to the ground in the two temperature profiles are at 34 m (agl) and 84 m (agl) for the 10:15 and 12:01 soundings; respectively. At the time of the launch the first inversion layer was estimated to be 48 m (agl).

A6.2 INTERPRETATION OF GOES-6 INFRARED PICTURES RELATIVE TO WIND SPEED AND DIRECTION DATA

Infrared images taken after 50 minutes of transport time indicate the presence of six clouds. Table A6-2 summarizes the estimated direction of transport, distance traveled and velocities of these clouds. Obviously this analysis is very crude but serves the purpose of providing an

Figure A6-1. Wind Direction Versus Elevation for 34D9 Event

Figure A6-2. Wind Speed Versus Elevation for 34D9 Event

Figure A6-3. Atmospheric Temperature Vertical Profile for the 34D9 Event

Table A6-2. Estimated Cloud Directions, Velocities and Heights

Cloud Number from IR Image	Direction (vector)	Direction (vane)	Displacement on Figure (cm)	Estimated Meters of Horizontal Motion (m)*	Estimated Velocity (m/sec) displ./raw. **	Estimated Elevation (m from sea level)	Estimated Elevation (m from ground level)
1	324.5	144.5	.5	8620	2.87/1.9	2200	2080
2	303	123	.2	3448	1.15/2	2250	2130
3	301	121	.8	13791	4.6/6.0	1400	1280
4	254.5	74.5	.24	4137	1.38/2.4	900	780
5	216.5	36.5	.6	10343	3.45/2.5 ---/3.0	625 2400	505 2280
6	178.5	358.5	.8	13791	4.6/3.0	375	255

*17239.29m/cm

**First velocity is based on displacements and the second velocity is read from rawinsonde data plot.

analytical basis for estimating the vertical position of the clouds based on wind direction and speeds. This analysis uses only the 10:15 PST rawinsonde for simplification and because

the 12:01 PST data set was taken almost 15 km away from the pad. It is not clear that the second sounding is applicable for the time period of interest.

Cloud 5 could be at either 505m or 2280 meters of elevation based on the wind direction and speed information. However, video evidence indicates that the upper-most cloud is moving to the north/northwest and not to the south/southwest. Thus, the lower elevation of 505m was assigned to this cloud. Mendenhall also saw this problem with cloud 5 and appears to have also come to the same conclusion since his estimate of the cloud top was 2180m agl.

A6.3 PUFF ANALYSIS RESULTS

The following two subsections document the analysis cases run using the PUFF code for the liquid fireball and the ground based fire plume.

A6.3.1 PUFF Liquid Fireball Analyses

PUFF was run to simulate the plume rise for the liquid fireball using two different modeling approaches. The first is the Cassini liquid fireball model which was described in Section C.14.4, Volume II, Book 2 of the GPHS-RTG Cassini FSAR (Reference A6-6). This model took the following form:

$$Q=3.26 \times 10^6 \times W \times 0.33$$

where W (lbm) - is the total amount of liquid propellant and oxidizers for the fireball of interest, and 0.33 - is the derating factor applied to account for unburned fuel from Reference A6-2. The second model used the historical DOT (Reference A6-7) heats of combustion to estimate the energy released during the explosion and applies estimated burn fractions and radiation loss fractions.

From the energies listed in the first column of the top portion of Table A6-3 it can be seen that the Cassini formulation without application of the 0.33 derating factor predicts a significantly lower (~66% lower) total energy released due to combustion than a model based on DOT heats of combustion as reported in Table A6-1. The Cassini model is based on a calculation done by Mat Sagartz of Sandia for Bruce Broughton (Reference A6-8). The effective heat of combustion per lbm of A-50 from this memo is 9523.7 BTU/lbm of A-50 and 10428 BTU per

Table A6-3. 34D9 Titan 18 April 1986 Accident - PUFF Plume Rise Predictions

Date:12Nov98 Time:01:30pm		Location: /home/astro20/deane/asterx/cassini/Puff_34D9_Nov98_Sum.as														
PUFF INPUTS		Energy in Stage (J)	Radiation Loss Fraction	Fraction Burned	Adjustment For Pre-Accident Burn	PUFF Energy to Drive Plume Rise (J)	Overall Energy Reduction Factor	Calibration Factor								
First Stage																
Cassini Formulation		9.578e+11	0	0.33	No	3.16e+11	0.330	N/A								
100% Propellant Burned		2.880e+12	0.33	1	No	1.93e+12	0.670	N/A								
33% Propellant Burned		2.880e+12	0.33	0.33	No	6.37e+11	0.221	N/A								
10% Propellant Burned		2.880e+12	0.33	0.1	No	1.93e+11	0.067	N/A								
Second Stage																
Cassini Formulation		2.239e+11	0	0.33	No	7.39e+10	0.330	N/A								
100% Propellant Burned		5.558e+11	0.33	1	No	3.72e+11	0.670	N/A								
33% Propellant Burned		5.558e+11	0.33	0.33	No	1.23e+11	0.221	N/A								
10% Propellant Burned		5.558e+11	0.33	0.1	No	3.72e+10	0.067	N/A								
Combined Stages 1 and 2 Fireballs																
Cassini Formulation		1.182e+12	0	0.33	No	3.90e+11	0.330	N/A								
100% Propellant Burned		3.436e+12	0.33	1	No	2.30e+12	0.670	N/A								
33% Propellant Burned		3.436e+12	0.33	0.33	No	7.60e+11	0.221	N/A								
10% Propellant Burned		3.436e+12	0.33	0.1	No	2.30e+11	0.067	N/A								
100%burned No Rad Loss		3.436e+12	0	1	No	3.44e+12	1.000	N/A								
SRM Fire Plume																
Original Cassini Est.		1.650e+12	0.34	1	Yes	9.18e+09	0.006	0.00843								
Upd Calib. w/Real Met. Data**		2.411e+12	0.34	0.99	Yes	1.85e+10	0.008	0.01172								
Upd Calib.w/Radar Data**		2.411e+12	0.34	0.99	Yes	4.57e+10	0.019	0.02903								
PUFF RESULTS		PUFF Final Elevation (m)(agl)	PUFF Initial Elevation (m)(agl)	PUFF Rise (m)(agl)	Fraction of PUFF Rise to Stabilized Height	Cloud Center (m)(agl)	Cloud Diameter (m)	Initial Fireball Diameter (m)	Cloud Top (m)(agl)	Cloud Bottom & Stem Top (m)(agl)	Stem Center (m)(agl)	Stem Bottom (m)(agl)	Sigma xyz Cloud (m)	Sigma xy Stem (m)	PUFF Final Time (min)	Percent Difference Cloud Center From Avg
Combined 34Stages 1 and 2 Fireballs																
34D9 with Cassini Formulation		2121.2	252	1869.2	0.88	1896.9	999	233.8	2396.4	1397.4	824.7	252.0	249.8	58.5	5.0	-11.8
100% Propellant Burned(33%rad. loss)		2518.2	252	2266.2	0.88	2246.3	1386.4	422.6	2939.5	1553.1	902.5	252.0	346.6	105.7	3.8	4.5
33% Propellant Burned(33%rad. loss)		2263.6	252	2011.6	0.88	2022.2	1134.2	292.2	2589.3	1455.1	853.6	252.0	283.6	73.0	4.7	-5.9
10% Propellant Burned(33%rad. loss)		2031.5	252	1779.5	0.88	1818.0	925.2	196.2	2280.6	1355.4	803.7	252.0	231.3	49.0	5.5	-15.4
100%burned No Radiation Loss		2608.5	252	2356.5	0.88	2325.7	1504.4	483.2	3077.9	1573.5	912.8	252.0	376.1	120.8	3.7	8.2
Gould/Gayle Model 100%W		N/A	N/A	N/A	N/A	2552.1	1709.9	612.7	3407.1	1697.2	974.6	252.0	427.5	153.2	N/A	18.7
Gould/Gayle Mod. 14.9%W		N/A	N/A	N/A	N/A	1199.8	803.9	330.0	1601.8	797.9	524.9	252.0	201.0	82.5	N/A	-44.2
Estimated Accident or "Experimental" Values																
Photographic Evidence(Logicon) Mendenhall									2180							
Estimated Actuals(Logicon)Mendenhall's Paper/Fax Wind Direction/Speed									2380-2580							
Estimated Cloud Heights and Dimensions(LMA estimated from Video)						2170	620	175	2480							
Aviation Week Estimate									2318							
Best Estimate Based Upon Cloud Position at 50minutes Wind Speed and Directions						2130										
Average "Experimental" (E) Estimates Based on Wind and Video Evidence						2150	429	175	2364							
Average "Experimental" to Calculated (E/C) Ratios																
E/C Ratios for 34D9 with Cassini Formulation						1.13	0.43	0.75	0.99							
E/C Ratios for 100% Propellant Burned(33%rad. loss) Case						0.96	0.31	0.41	0.80							
E/C Ratios for 33% Propellant Burned(33%rad. loss)						1.06	0.38	0.60	0.91							
E/C Ratios for 10% Propellant Burned(33%rad. loss)						1.18	0.46	0.89	1.04							
E/C Ratios for 100%burned No Radiation Loss						0.92	0.29	0.36	0.77							
Gould/Gayle Model 100%W						0.84	0.25	0.29	0.69							
Gould/Gayle Mod. 14.9%W						1.79	0.53	0.53	1.48							
SRM Fire Cylindrical Plume Model Data																
Cassini Calib./Formula for 34D9		474.0	0	474.0	0.88*	417.1	909.6									
Upd Calib. w/Real DeltaII Met. Data**		751.9	0	751.9	1	751.9	909.6									
Upd Calib.w/DeltaII Radar Data**		848.6	0	848.6	1	848.6	909.6									
Photographic Evidence(Logicon) Mendenhall						-580										
Estimated Actuals(Logicon)Mendenhall's Paper/Fax Wind Direction/Speed						<700										
Dense burning zone (Video Evidence/Knight&Prince) (.44to.5x1328.9m(full dia))							585-664						156			
* SPARRC Shell applies .88 erroneously here																
**Updated calibration from Delta II analysis. This is a verification analysis.																

lbm of MMH or hydrazine. This compares to the 21300 BTU/lbm of hydrazine and assumed applicable to A-50 used for the alternate model calculations for the 34D9 analysis. This alternate model is based on the historical DOT values as used by HNUS (Reference A6-9). At this time the reason for the differences in the heats of combustion provided by the Sandia (Reference A6-8) and the DOT references are not obvious. A recent review of Prince and Banning report (Reference A6-2) by Haskin (Reference A6-10) showed reasonably close agreement of the Prince and Banning heats of explosion with the DOT values.

Only the combined stage 1 and 2 fireball was investigated using PUFF for this study due to video evidence that showed no indication of separate fireballs. The first case used the Cassini energy available to drive plume rise formulation. The next four cases use the DOT combustion energies for estimating the energy available to drive PUFF plume rise analysis. The first of the DOT-based cases assumed 100% of the material burned and 33% radiation losses. The next two cases assumed 33% and 10% burned, respectively, and both used 33% radiation losses. The 0.33 radiation loss factor for the alternate model analysis is based on the 0.34 value identified for SRMU fires (Reference A6-11) rounded to 1/3 or 0.33 for liquid fireballs. The 33% burn fraction case was run to be consistent with the Cassini model but with the radiation loss term included. This value is in the range listed of 0.1 to 0.4 (Reference A6-12) for a Titan vehicle. The burn fraction of 10% is based on Reference A6-13. The final case assumed 100% of the stage 1 and 2 propellants were burned and that the no radiation losses occurred. This 100% burned and no radiation loss case was investigated because this case was found to give the best prediction of the plume rise following the 17 January 1997 Delta II accident at CCAS (Reference A6-14).

The PUFF plume rise and initial and final diameter results are shown in the middle of Table A6-3. The Cassini PUFF model under-predicted the plume rise by approximately 12%. The case with 100% of propellant burned and with 33% radiation losses provides the best fit to the average plume rise estimate for the accident. The plume rise for this case is ~2246 m agl and the average estimate from the photographic and wind evidence is ~2150 m. This case over-predicted the plume rise by 4.5% as shown in the last column of the PUFF results in Table A6-3. The best fit would be between the 100% burn and the 33% burned propellant cases. All of the cases are well within the $\pm 25\%$ assigned to the accuracy of the PUFF code

plume rise model by Boughton as documented in the Cassini GPHS-RTG FSAR Volume III, Book 2, Appendix J. In the Cassini Risk Assessment a +30% bounded normal distribution was applied to the PUFF predicted rise height. According to Mendenhall the REEDM code predicted a 2200m rise for the 34D9 plume. With the Cassini energy available to drive plume rise, the PUFF code slightly under-predicted the plume rise and it appears to over-predict the size of the initial and the final fireball/plume diameters as noted in the experimental-to-calculated ratio section of Table A6-3. The problem with this initial and final diameter comparison is that the video evidence or visual part of the cloud does not account for the heated boundary of the cloud. These diameters are also important to the Cassini process because they are used to define the initial Gaussian plume sigma x, y and z parameters which set the initial cloud size characteristics for the SATRAP code. A better approach would be to compare the calculated cloud dimensions to those found in the infrared GOES-6 data. Cloud 2 in the IR image was estimated to be the highest cloud and it has an estimated diameter of 6.9 km. This estimated cloud diameter falls within the range of fast diffusion regime predicted by the long range transport model (Reference A6-15) as used by SATRAP code. Thus, the final diameters being predicted by PUFF and the SATRAP code seem to be reasonable.

The Gould (Reference A6-16) plume rise and Gayle (Reference A6-17) fireball diameter model were also applied to the 34D9 fireball for comparison purposes to historic modeling approaches. The second Gould/Gayle case in Table A6-3 represents the Cassini scale back approach (Reference A6-18) identified for fireballs that occur between 170 ft and 3800 ft. Because the 34D9 event occurred at 828 ft or 525 m, a reduction factor of 0.22 would be applied. For consistency, the 0.67 radiation loss factor was also applied in this case for both the plume rise analysis and the initial diameter analysis. The Gould model over-predicted the plume rise for the full fuel/oxidizer mass input case but under-predicted the rise when the Cassini air blast reduction factor and radiation loss terms were included.

A6.3.2 SRM Ground Based Fire PUFF Plume Rise Results

At the bottom of Table A6-3 the SRMU two plume rise estimates were re-run using the updated range for the energy calibration factor as developed in Reference A6-13. The heat of combustion of 2637 BTU/lbm for this analysis came from Reference A6-2 and the fraction burned of 0.99 comes from Reference A6-19. The first case is the original calibration check case as documented in the Cassini FSAR Addendum in Table 5.2-1, page 5-13. The other two cases are the updated cases using the final Delta II calibration (Reference A6-14) and the energy associated with the 34D9 solid propellant (Reference A6-2). These two results are slightly higher than the estimates made by Mendenhall for the ground based plume rise of 580m. It should be noted that the code modifications proposed by Haskin (Reference A6-20) will eliminate the need for this calibrated energy input assumption for ground based SRM fire plume rise estimates in the future.

A6.4 SATRAP CLOUD TRANSPORT EVALUATIONS

The SATRAP code was run in the cloud trajectory mode for a selected set of the PUFF analysis cases. Only the upper cloud was traced. No tail clouds were evaluated. The SRM best estimate plume center location was also evaluated. The selected cloud definitions that were traced are defined as follows:

Case Letter	Description	Cloud Center (m)
a)	DOT Model 10% propellant burned 33% radiation Loss	1818
b)	Cassini Model	1897
c)	DOT Model 33% propellant burned 33% radiation Loss	2022
d)	DOT Model 100% propellant burned 0% radiation Loss	2326
e)	Gould Model without elevation dependent derating factor	2552
f)	Best Estimate SRM ground based plume center	290

Figure A6-4 shows the center line traces for these clouds for 1hr and 20 minutes of tracking time using only the 10:15 am PST rawinsonde data. Figure A6-5 shows the traces when the 12:01 rawinsonde is used to provide an interpolated wind field. It was concluded from the plots in Figure A6-6 that the use of the second rawinsonde data set tends to turn the cloud too soon and it is suspected that there is either data missing in the 12:01 PST rawinsonde or it is not a good assumption to apply the profile taken 15 km from the launch pad location.

Figure A6-4. One Hour and 20 Minute Cloud Traces Using the 10:15 PST Rawinsonde

Figure A6-5. One Hour and 20 Minute Cloud Traces Using Two Rawinsondes

The best estimate for the elevation of the liquid fireball or upper cloud center is between 2130 m (GOES-6 basis) to 2170 m (video basis). Figures A6-6 and A6-7 show these two elevation traces for 50 and 120 minutes which correspond to the GOES-6 pictures from the Mendenhall report. An 1818 m cloud was also traced using the 10:15am PST rawinsonde. These two trace plots demonstrate that the 2130 m is the most likely elevation for the liquid fireball. The 2170 m elevation is too high. The lower elevation trace confirms that the clouds 1 and 3 in IR image are at lower elevations than cloud 2 which is the plume cap cloud.

Figure A6-6. 50 Minute Cloud Traces Using the 10:15 am PST Rawinsonde

A6.6 Conclusions and Recommendations from 34D9 Evaluations

Applying the energy available to drive plume rise as used for the FSAR and FSAR Addendum leads to a model predicted plume rise that is too low for the 34D9 accident. The alternate model based on the DOT or databook heats of combustion should be used in the future. Using 2130 m as the best estimate for the liquid fireball plume cap center location, a best estimate total energy reduction or derating factor based on the current PUFF model for this

Figure A6-7. 110 Minute Cloud Traces Using the 10:15 am PST Rawinsonde

34D9 analysis is shown in Figure A6-8 to be 0.437. For an assumed 33% radiation loss fraction then the best estimate propellant burn fraction would be 0.652. The PUFF results for the 34D9 accident appear to be very reasonable. Based on the 34D9 case no PUFF code modifications would be recommended at this time. However, when the results of the earlier Delta II analysis (Reference A6-13) are included it might be wise to include the k_r and α parameters as identified by Haskin (Reference A6-19) as uncertainty parameters rather than constants as was assumed in the Cassini FSAR analyses. The k_r parameter is used to set the initial diameter of the fireball and the α parameter is the air entrainment parameter. In general the PUFF comparison with the 34D9 data was in better agreement than found in the Delta II comparisons.

Figure A6-8. PUFF Plume Rise Height Versus Energy Reduction Factor

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Section A7

Assessment of SPARRC Conservatism in EGA Reentry Consequence Analyses

SECTION A7

ASSESSMENT OF SPARRC CONSERVATISMS IN EGA REENTRY CONSEQUENCE ANALYSES

The models used for health consequence predictions in the Cassini GPHS-RTG FSAR included several conservatisms which tended to cause consequences to be over-predicted. These conservatisms were adopted either to allow simplified analysis methods or due to a lack of field data which might support a more nominal assumption. This section describes evaluations of several conservatisms that were included in the FSAR consequence analysis of an inadvertent Earth Gravitational Assist (EGA) reentry accident. The first conservatism evaluated was the use of an urban resuspension model independent of the population density class in which the source term was released. The results of employing a rural resuspension (as a bounding case) are summarized in Section A7.1. The second conservatism evaluated was the assumption that when an intact GIS containing melted clads impacts on soil that the fuel release height is 0.5 meters. It is possible that this type of release would be contained within the crater caused by the impact and would not be released as a plume. The effect on consequence predictions of assuming such impacts would result in GIS burial is summarized in Section A7.2. The third conservatism evaluated was the assumption that when a GIS is released in-air from a breached module that the two GIS assemblies impact the Earth side-by-side. The effect on consequence predictions of assuming GISs released from the same module can land in differing locations (with potentially differing population densities) is summarized in Section A7.3.

A7.1 RESUSPENSION FACTORS

The purpose of this study was to evaluate the impact of using the rural resuspension model for the 800 km Earth swingby EGA consequence analysis rather than the urban resuspension model that has been assumed in the previous 800km EGA analyses (Reference A7-1). Reentry characteristics from an 800 km Earth swingby are as defined in the updated JPL Earth Swingby Plan (Reference A7-2). [The currently anticipated Earth swingby has been adjusted from 800 km to 1157 km (Reference A7.2a) to reflect the actual launch date (15 October 1998).] The JPL reentry data used for this analysis was obtained by email (Reference A7-3). This analysis used an event tree definition of state probabilities

(Reference A7-4) which included post-FSAR GIS 6-DOF analyses as described in Section 6 of this report.

A7.1.1 Resuspension Model Background

Urban resuspension was selected originally for use in consequence analyses regardless of population density of areas evaluated as a simplification in analysis method which also provided an upper bound. In the 800km EGA analysis (Reference A7-1) the probability of an urban impact was 0.0554. Consequence in this impact class constituted 24% of the mean health effects when using the urban resuspension model only. Figure A7.1-1 shows the different resuspension factors for the two (rural and urban) models. The urban resuspension model has a higher initial resuspension rate and a slower decay rate. Both models use the same long-term resuspension factor of 1×10^{-9} . For more details on the two resuspension models see the Cassini GPHS-RTG FSAR Volume III, Book 2, Appendix I, page V.III I-41 for rural conditions and page V.III I-47 for urban conditions. Urban is normally defined within the SATRAP model of SPARRC as more than 100 persons per square kilometer.

A7.1.2 Effects of Rural Resuspension Assumption on Key Consequence Measures

To evaluate the impact of resuspension model on predicted consequences, the 800 km EGA swingby analysis was re-run using the rural resuspension model for all population densities. It is recognized that the rural assumption will be non-conservative; however it can be used to bound the consequence analysis from the low side. The previous 800 km analysis (Reference A7-1) bounded the consequence on the high side. The rural resuspension assumption should reduce the health effects and dose consequence measures since there is less material resuspended with this model as indicated by Figure A7.1-1. This effect is confirmed by the summary results provided in Table A7.1-1. Table A7.1-1 compares the Cassini GPHS-RTG FSAR Supplement 500 km EGA results and the previous 800 km urban resuspension results with the 800 km EGA results with the rural resuspension model applied. The results in Table A7.1-1 indicate the greatest effect of using the rural resuspension model is to reduce the mean maximum individual dose for an 800 km swingby by approximately 75%. The mean 50-year health effects without de-minimis are reduced by 30%. The mean 50-year health effects with de-minimis are reduced by 42%. Land area contaminated to above $0.2 \mu\text{Ci}/\text{m}^2$ is unchanged at 21 km^2 .

Figure A7.1-1. - Comparison of Urban and Rural Resuspension Models

Table A7.1-1. Effects of Rural versus Urban Resuspension Model on 800 km EGA

ACCIDENT CASE	PROBABILITY OF FAILURE	CONDITIONAL PROBABILITY OF FUEL RELEASE	MEAN HEALTH EFFECTS WITHOUT DE-MINIMIS	MEAN HEALTH EFFECTS WITH DE-MINIMIS	MEAN MAXIMUM INDIVIDUAL DOSE (REM)	MEAN LAND AREA WITH $>2 \mu\text{Ci/sq. m}$ (km^2)
500km Urban FSAR Event Tree	8.0×10^{-7}	0.76	140	26	650	19
800km Urban Uses updated Event Tree Probabilities	6.2×10^{-7}	0.51	91	60	1780	21
800km Rural Uses updated Event Tree Probabilities	6.2×10^{-7}	0.51	64	35	439	21
Percentage Change 800km (R-U)/U*100	No change	No change	-29.7	-41.7	-75.3	No change

Figure A7.1-2 compares the 50-year health effects CCDFs for the two 800 km cases. There is little difference in these two CCDFs for consequences below 100 persons. Figure A7.1-3 shows the contribution of the eight final event tree end states to the overall health effects CCDF for an 800 km swingby using the rural resuspension model. The contribution to the mean health effect from each end state is provided in Table A7.1-2, which also provides the FSAR Supplement results along with the original 800 km urban resuspension only results (Reference A7-1) for comparison. The occurrence probability and the number of modules releasing for each end state are unchanged from those reported in Table 6.7.2-2 of the main body of this report for the original 800km analysis using urban resuspension.

Figure A7.1-2. Comparison of Health Effects with Urban and Rural Resuspension for 800 km EGA Swingby Reentry

Figure A7.1-3. End State Contributions to Total Health Effects for an 800 km EGA Swingby Reentry Analyzed with a Rural Resuspension Model

As noted previously the biggest change in the consequence occurs in the mean maximum individual dose. This mean dose decreases from 1789 rem to 439 rem or 75% for an 800 km swingby. The CCDFs for this consequence measure are plotted in Figure A7.1-4 for both urban resuspension and rural resuspension models. The CCDFs for the number of persons exposed to selected dose levels are provided in Figure A7.1-5. The mean number of health effects during an 800 km EGA from doses above 400 rem or 0.2 Gy decreases from 27.9 to 7.4 or from 30% to 11% of the total health effects. The CCDFs for the health effects due to doses above 400 rem or 0.2 Gy are provided in Figure A7.1-6 for the FSAR Supplement and the 800 km urban and rural EGA analyses.

A7.1.3 Conclusions and Recommendations

In the urban resuspension 800 km EGA analysis case, only 22 of the 91 mean health effects or latent cancer fatalities occurred in urban conditions. For the rural resuspension 800 km EGA analysis case, 12 of the 64 mean health effects or latent cancer fatalities occurred in

Table A7.1-2. Comparison of Consequence Contributions by End State between the 500 km FSAR Supplement EGA and the 800 km Post Supplement (PFSAR) EGA Analyses Assuming Urban and Rural Resuspension

Release Type	Contribution to Mean Health Effects* 500km EGA FSAR Suppl.**	Contribution to Mean Health Effects* 800km EGA PFSAR-Urban	Contribution to Mean Health Effects* 800km EGA PFSAR-Rural	Percentage Contribution to Health Effects* 500km EGA FSAR Suppl.	Percentage Contribution to Health Effects* 800km EGA PFSAR-Urban	Percentage Contribution to Health Effects* 800km EGA PFSAR-Rural
All Types	136.9	90.8	63.6	100.00	100.00	100.00
Intact Module on Rock	4.98e-04	6.34e-04	3.96e-04	0.00	0.00	0.00
GIS OK - Clad OK on Rock	1.84e-02	1.04e-02	7.71e-03	0.01	0.01	0.01
GIS OK - Clad Melt on Soil	19.4	49	24.9	14.17	53.96	39.14
GIS OK - Clad Melt on Rock	3.8	12.3	9.4	2.78	13.55	14.85
GIS Failed on Soil	2.91	0.61	0.44	2.13	0.67	0.69
GIS Failed on Rock	8.23e-02	6.8e-03	3.46e-03	0.06	0.01	0.01
GIS Failed - Air Release	110.6	28.8	28.8	80.79	31.72	45.30

*50 year without De-minimis

** The FSAR Supplement 500km flyby EGA analysis assumed the Urban Resuspension Model

Figure A7.1-4. Comparison of 800 km EGA Maximum Individual Dose CCDFs for Urban and Rural Resuspension Models

Figure A7.1-5. CCDFs for 800 km EGA Swingby Using the Rural Resuspension Model for the Number of Persons Exceeding the Indicated Dose Level

Figure A7.1-6. CCDFs for Health Effects from Doses above 400 rem or 0.2 Gy

urban conditions. Thus, 74 health effects represents the best estimate for an 800 km EGA reentry assuming that the correct resuspension was used for each population class (i.e., 64-12+22). This represents a 19% reduction in the health effects compared to use of the urban resuspension model only. The mean risk would also be reduced by 19% when appropriately applying the rural or urban resuspension models based on population density – reduced from 2.87×10^{-5} to 2.32×10^{-5} . The evaluation of conservatisms in selecting resuspension models described in this section is further detailed in Reference A7-6.

A7.2 GIS BURIAL UPON SOIL IMPACT

The purpose of this sensitivity study is to document the impact on the 800 km EGA reentry consequence analysis of assuming that GIS assemblies which contain melted clads will be buried when impacting on soil. This analysis also assumes the rural resuspension model in all SPARRC runs. This analysis was compared against the previous 800 km EGA analyses (Reference A7-1), which used the conservative urban resuspension model as done for the FSAR analyses. The source term available for atmospheric transport from buried GIS

assemblies was set to a value of less than 10^{-12} grams to approximate a 0 mass release. The 800 km EGA swingby reentry characteristics are as defined in the updated JPL Earth Swingby Plan (Reference A7-2). The JPL reentry data used for this analysis was obtained by email (Reference A7-3). This analysis also used an event tree definition of state probabilities (Reference A7-4) which included post-FSAR GIS 6-DOF analyses as described in Section 6 of this report.

A7.2.1 GIS-OK Cladding Melt Impacting on Soil Source Term Background

The source term for an intact GIS with melted clads impacting on soil is a point estimate as defined in the Cassini FSAR Vol. II Book 1 (pg. V.II 5-104). The full 603.94 grams PuO_2 inventory (from the two GISs) was assumed to be released at a height of 0.5 meters with a 1 meter sigma for the Gaussian plume dispersion calculation in the baseline FSAR analyses. This assumption was used because it was believed to be conservative and there was little or no information on release characteristics for this type of impact available in the safety testing database. It is possible that the GIS could bury itself on impact but it is not known how much of the fuel would be released from a partially ablated GIS containing melted clads during impact. It is possible that some fuel could be elevated by the plume generated by the impact. The GIS burial assumption would essentially "zero" out the health effects from this end-state. Thus, the case being documented here represents a lower bound of the health effects from the GIS-OK clad melt end-state for soil impacts.

A7.2.2 Effects on Key Consequence Measures of Assuming Burial for GIS-OK Clad Melt Impacts on Soil

The effective burial assumption should reduce the health effects, dose, and land contamination area consequence measures since there is significantly less material available to be dispersed. These effects are confirmed by the summary results provided in Table A7.2-1. Table A7.2-1 compares the FSAR Supplement 500 km EGA swingby reentry results and the previous 800km urban resuspension results (Reference A7-1) with the 800km flyby EGA results with the rural resuspension model (Reference A7-6) both with and without the GIS-OK clad melt burial assumption. The results in Table A7.2-1 indicated the greatest effect

**Table A7.2-1. Effects of GIS-OK Clad Melt Buried on Soil Impact
for 800 km EGA Reentry Results**

ACCIDENT CASE	PROBABILITY OF FAILURE	CONDITIONAL PROBABILITY OF FUEL RELEASE	MEAN 50yr HEALTH EFFECTS WITHOUT DE-MINIMIS	MEAN 50yr HEALTH EFFECTS WITH DE-MINIMIS	MEAN MAXIMUM INDIVIDUAL DOSE (REM)	MEAN LAND AREA WITH $>2 \mu\text{Ci/sq. m}$ (km^2)
500km Urban FSAR Event Tree	8.0×10^{-7}	0.76	140	26	650	19
800km Urban Uses updated Event Tree Probabilities	6.2×10^{-7}	0.51	91	60	1780	21
800km Rural(R) Uses updated Event Tree Probabilities	6.2×10^{-7}	0.51	64	35	439	21
800km Rural with GIS-ok Clad Melt on Soil Buried(B) w/Updated Event. Tree Prob.	6.2×10^{-7}	0.51	39	9.9	201	7.4
Percentage Change 800km (B-R)/R*100	No change	No change	-39	-72	-54	-65

of using the buried GIS assumption is to reduce the 800 km swingby, rural resuspension health effects with de-minimis by 72%. This is due to the fact that air releases, which tend to be below the de-minimis threshold now contribute 74% of the mean consequence. The mean land area contaminated to levels $>0.2 \mu\text{Ci/m}^2$ is reduced by 65% due to the smaller source term associated with the GIS-OK Clad Melt on soil end-state. The mean maximum individual dose is also reduced by approximately 54%. The mean 50-year health effects without de-minimis are reduced by 39%. These reductions represent the lower bound on these consequence measures since the fuel may be released but not transported. If no remediation had occurred and the impact site were disturbed at some later time some resuspension of the material might occur which would increase the consequences relative to those listed for the burial case.

Figure A7.2-1 compares the 50-year health effects CCDFs for the three 800 km cases shown in Table A7.2-1. There is little difference in these CCDFs for consequences below 100 persons. Figure A7.2-2 shows the contribution of the 8 event tree end states to the overall

Figure A7.2-1. Comparison of Health Effects CCDFs with Urban Resuspension and Rural Resuspension with/without GIS-OK Clad Melt Burial on Soil Impact

Figure A7.2-2. End State Contributions to Total Health Effects with Rural Resuspension and GIS-OK Clad Melt Burial on Soil Impact

CCDF. Air releases dominate health effects, following by the GIS-OK clad melt on rock end-state. The contribution to the mean health effects from each end state is provided in Table A7.2-2. This table compares the two rural resuspension cases with and without GIS-OK Clad Melt burial assumed on soil impact to the FSAR Supplement results along with the original 800 km urban resuspension results (Reference A7-1).

The mean maximum individual dose decreases from 439 rem to 201 rem or 54% when adopting the buried GIS assumption. The CCDFs for the maximum individual dose are plotted in Figure A7.2-3. The CCDFs for the number of persons exposed to selected dose levels is provided in Figure A7.2-4. The mean number of health effects during an 800 km EGA swingby reentry from doses above 400 rem or 0.2 Gy decreases from 7.4 to 1.2 or from 11% to 3% of the total health effects. The CCDFs for the health effects due to doses above 400 rem or 0.2 Gy are provided in Figure A7.2-5 for the FSAR Supplement analysis and the three 800 km urban and rural EGA analyses.

Land contamination as shown in Table A7.2-1 is reduced by 65% for the 800 km EGA swingby due to the effective burial assumption. Figure A7.2-6 compares the CCDFs of the land area contaminated to levels $>0.2 \mu\text{Ci}/\text{m}^2$ for the various EGA consequence analyses. Figure A7.2-7 shows the land contamination CCDFs for selected contamination levels assuming GIS-OK clad melt burial on soil impact.

Table A7.2-2. Comparison of Consequence Contributions by End State between the 500 km FSAR Supplement EGA and the 800 km Post Supplement (PFSAR) EGA Analyses Assuming Urban Resuspension and Rural Resuspension with GIS-OK Clad Melt Burial on Soil Impact

EGA Sensitivity Case	Contribution to Mean Health Effects* 500kmEGA FSAR Suppl.**	Contribution to Mean Health Effects* 800kmEGA PFSAR Urban	Contribution to Mean Health Effects* 800kmEGA PFSAR Rural	Contribution to Mean Health Effects* 800kmEGA PFSAR Rural Soil*** Buried	Percent Contribution to Health Effects* 500kmEGA FSAR Suppl.**	Percent Contribution to Health Effects* 800kmEGA PFSAR Urban	Percent Contribution to Health Effects* 800kmEGA PFSAR Rural	Percent Contribution to Health Effects* 800kmEGA PFSAR Rural Soil*** Buried
Release Type								
All Types	136.9	90.8	63.6	38.7	100.00	100.00	100.00	100.00
Intact Module on Rock	4.98e-04	6.34e-04	3.96e-04	3.96e-04	0.00	0.00	0.00	0.00
GIS OK - Clad OK on Rock	1.84e-02	1.04e-02	7.71e-03	7.71e-03	0.01	0.01	0.01	0.02
GIS OK - Clad Melt on Soil	19.4	49	24.9	0.0	14.17	53.96	39.14	0.00
GIS OK - Clad Melt on Rock	3.8	12.3	9.4	9.4	2.78	13.55	14.85	24.40
GIS Failed on Soil	2.91	0.61	0.44	0.44	2.13	0.67	0.69	1.13
GIS Failed on Rock	8.23e-02	6.8e-03	3.46e-03	3.46e-03	0.06	0.01	0.01	0.01
GIS Failed - Air Release	110.6	28.8	28.8	28.8	80.79	31.72	45.30	74.44

*50 year without De-minimis

** The FSAR Supplement 500km flyby EGA analysis assumed the Urban Resuspension Model

***GIS-OK with Clad Melt Endstate Impacting on Soil is Effectively Buried (Source Term Multiplied by 1e-15)

Figure A7.2-3. Comparison of Maximum Individual Dose CCDFs Using Urban Resuspension and Rural Resuspension with and without GIS-OK Clad Melt Burial on Soil Impact

Figure A7.2-4. CCDFs for the Number of Persons Exceeding the Indicated Dose Level, Assuming GIS-OK Clad Melt Burial upon Soil Impact

Figure A7.2-5. CCDFs for the Health Effects from Doses above 400 rem or 0.2 Gy

Figure A7.2-6. Comparison of Land Contamination CCDFs

Figure A7.2-7. Comparison of Land Contamination CCDFs at Selected Contamination Levels, for 800 km EGA Swingby Assuming GIS-OK Clad Melt Burial upon Soil Impact

A7.2.3 GIS-OK Clad Melt Burial on Soil Impact Conclusions and Recommendations

Because this analysis was performed using the rural resuspension model, the results provide a lower bound on the health effects. The exact result would require that urban and rural resuspension be used in accordance with the population density associated with the impact. The likelihood of burial and its characteristics have not been studied as a part of this sensitivity study. Further investigations of burial characteristics as related to soil type and moisture content and supporting test data would be needed to support the application of this assumption in any future nuclear safety assessment.

A7.3 GIS INDEPENDENT IMPACTS

In the EGA analysis performed for the Cassini GPHS-RTG FSAR (References A7-5 and A7-7), side-by-side GIS impacts were assumed for ground releases associated with GIS impacts on soil or rock. For each GIS impact simulation, the non-separated GISs from a GPHS module are assumed to have a unique plume footprint affecting one population density

class at the location of impact. This report provides the results of a sensitivity study carried out for the effects of independent GIS impacts, assuming that:

1. All modules with GIS-OK clad melt failure mode would release their GISs during reentry,
2. The same atmospheric dispersion conditions apply for the releases from the two GISs, but
3. Different population density classes could be impacted.

The effects of GIS impacts at separate locations were determined for several consequence measurements including health effects, individual dose, and land contamination. The sensitivity study was carried out for the 500 km EGA swingby analyzed in the Cassini GPHS-RTG FSAR (Reference A7-5) and the 800 km EGA swingby reentry that includes updates of reentry probabilities, reentry sequence event tree, and resuspension model (References A7-4 and A7-6).

A review of the EGA reentry event trees (References A7-4 and A7-8) shows that modules descending in a Non-Face-On-Stable (Non-FOS) condition, at reentry angle $|\gamma| > 21^\circ$, or in a Face-On-Stable (FOS) condition, for $|\gamma| > 16^\circ$, will suffer an aeroshell breach and potentially release GISs which would see heat fluxes sufficient to melt the Ir fuel cladding. Both conditions are categorized as EGA steep reentries. As shown in Table A7.3-1, under most steep reentry conditions, the majority of GPHS modules breach and have their GISs released before ground impact. Given the higher probability of GIS release, adopting an assumption of independent GIS impacts should have the greater impact for the 800 km swingby.

Since within a SPARRC simulation, GIS separation only affects the multinomial sampling for the combination of breaching GISs and population density classes and the scaling of consequences, a complete rerun of the SPARRC EGA analysis was not necessary. The outputs from the first level EGA analysis were modified as follows:

- Sampled values for latitude band, reentry angle, impacted cell and surface atmospheric condition were conserved.
- The predicted number of GPHS modules in GIS-OK clad melt failure mode was doubled to account for the GIS separation effect. Values of other failure modes and their respective normalized consequence results were conserved.

Table A7.3-1. Conditional Probability of the GIS-OK-Clad-Melt Failure Mode and Relative Fraction of GIS Release

Steep-Reentry	Non-FOS ($\gamma > 21$ deg.)		FOS	
	Conditional Probability	Relative Fraction	Conditional Probability	Relative Fraction
500-km Swingby	0.049	50%	0.713	94%
800-km Swingby	0.499	98%	0.749	94%

- Normalized consequence results of individual GPHS modules with the GIS-OK clad melt failure mode were substituted with appropriate results from the analysis of a single GIS.

Once the first level EGA analysis results were modified, post-processing was performed using the multinomial sampling and scaling approach to derive the new set of results.

Tables A7.3-2 and A7.3-3 summarize the new consequence results obtained for the 500 km and 800 km swingby cases, respectively. The following conclusions can be obtained for the effects of GIS separation:

Table A7.3-2. Effects of GIS Separation on Mean Values of the 500 km EGA Consequence Analysis

Consequence Results	Percentile Value	500 km Swingby		
		Non-Separated GIS	Separated GIS	Change
50 yr. Health Effects w/o de minimis	5 th Percentile	4	3	-3%
	50 th Percentile	109	109	0%
	95 th Percentile	357	361	1%
	99 th Percentile	482	497	3%
	Mean	137	138	1%
Max. Individual Dose (rem)	5 th Percentile	4.4×10^{-5}	4.4×10^{-5}	0%
	50 th Percentile	3.0×10^{-4}	3.0×10^{-4}	0%
	95 th Percentile	3.2×10^3	2.4×10^3	-9%
	99 th Percentile	4.9×10^3	3.2×10^3	-35%
	Mean	652	441	-32%
Land Contamination $> 2 \mu\text{Ci}/\text{m}^2$ (km ²)	5 th Percentile	0	0	0%
	50 th Percentile	0	0	0%
	95 th Percentile	46	68	48%
	99 th Percentile	70	95	36%
	Mean	19	23	21%

Table A7.3-3. Effects of GIS Separation on Mean Values of the 800 km EGA Consequence Analysis

		800 km Swingby		
		Non-Separated GIS	Separated GIS	Change
50 yr. Health Effects w/o de minimis	5 th Percentile	5.8×10^{-3}	6.2×10^{-3}	7%
	50 th Percentile	40	40	0
	95 th Percentile	199	204	3%
	99 th Percentile	338	349	3%
	Mean	64	64	0%
Max. Individual Dose (rem)	5 th Percentile	4.5×10^{-5}	4.5×10^{-5}	0%
	50 th Percentile	75	50	-33%
	95 th Percentile	1.4×10^3	687	-51%
	99 th Percentile	4.9×10^3	4.8×10^3	-2%
	Mean	439	291	-33%
Land Contamination > 2 $\mu\text{Ci}/\text{m}^2$ (km^2)	5 th Percentile	0	0	0%
	50 th Percentile	9	13	44%
	95 th Percentile	85	128	50%
	99 th Percentile	124	166	34%
	Mean	21	30	43%

The 50-year health effects results are virtually unchanged due to the fact that while the health effects from individual releases decrease, there are more impacts occurring in high population density class areas. The conditional probability of release in population density class above 175 pers./ km^2 increased from 8 to 11% when adding the independent GIS impact assumption.

Adopting independent GIS impacts reduces the mean value of maximum individual dose about 32% in both EGA cases. Figure A7.3-1 shows the CCDF plots of the maximum individual dose from different EGA cases. The upward shift in the highest maximum individual doses when including GIS separation reflects the predominant contribution of the GIS-OK clad melt end state. (It should be noted that, for the 500 km EGA swingby reentry GIS separation was not assumed for end states in which the GISs remain (with unmelted clads) within a breached aeroshell until Earth impact.)

Figure A7.3-1. Comparisons of Maximum Individual Dose for EGA Reentry Cases with and without GIS Separation

The mean value of land area contaminated above $0.2 \mu\text{Ci}/\text{m}^2$ increases about 21% and 43% for the 500 km and 800 km EGA swingby, respectively, when including GIS separation. This reflects the increased number of individual footprints at ground impact. A stronger influence from GIS separation is found for the 800 km swingby reentry because a higher average number of GPHS modules failing and leading to GIS-OK clad melt end states is predicted (6.9 vs. 3.2 modules). Figure A7.3-2 provides the CCDF plot of the land contamination.

Overall, the conservatism of assuming side-by-side GIS impacts is most pronounced for the 800 km EGA swingby reentry, due to the higher probability of survival to ground impact for GISs released from breached modules.

References for Section A7

- A7-1 Memo from Nelson A. Deane to Larry DeFillipo, "800km EGA Flyby Analysis Using Final Updated GIS Failure and Clad Melt Probabilities," (Cassini Memo. No. 547A), 23 October 1997.
- A7-2 "Cassini Earth Swingby Plan Supplement," JPL D-10178-3, Jet Propulsion Laboratory, 19 May 1997.

Figure A7.3-2. Comparison of Land Contamination above $0.2 \mu\text{Ci}/\text{m}^2$ for EGA Reentry Cases with and without GIS Separation

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A7-3 E-mail, from Troy D. Goodson to Calin Eftimie, "Data for Latitude Distributions, etc.," 10 June 1997.

A7-4 Tobery, Wayne, "Reentry Event Sequence Diagram Review," (Cassini Memo No. 478) Rev. A, 11 September 1997.

A7-5 Cassini GPHS-RTG Final Safety Analysis Report Supplemental Analyses, Lockheed Martin CDRL C.3, May 1997, Section 3.

A7-6 Deane, Nelson A., "Analysis of the 800 km EGA Using the Rural Versus the Urban Resuspension Model," (Cassini Memo. No. 604), 7 October 1998.

A7-7 Cassini GPHS-RTG Final Safety Analysis Report, Lockheed Martin CDRL C.3, Volume III, Book 1, November 1996, Section 4.4.

A7-8 Cassini GPHS-RTG Final Safety Analysis Report, Lockheed Martin CDRL C.3, Volume II, Book 1, November 1996, Section 5.4.4.

Section A8

SPARRC/EMERGE Comparisons

SECTION A8

SPARRC/EMERGE COMPARISONS

Ten test cases were performed in which atmospheric dispersion predictions from the SATRAP module of the LM SPARRC code were compared against the TetraTech-NUS EMERGE code. Specifically, the atmospheric dispersion calculations which provide ground-level concentrations for radiological consequence prediction were compared. Similarly to SATRAP in the Cassini analysis, EMERGE was used by TetraTech-NUS to predict the consequences resulting from the near-range transport of the RTG fuel in the Galileo and Ulysses nuclear safety analyses. Applicable scenarios are releases in launch accidents or ground releases in reentry accidents. At the beginning of the Cassini GPHS-RTG Program, a comparison of the two models was made with the same test cases (Reference A8-1). However, it was felt that the difference in cloud diffusion models used by SATRAP and EMERGE had influenced strongly the results and the interpretation of other modeling effects was quite difficult. At that time, SATRAP used the energy dissipation rate model, while EMERGE used the Pasquill-Gifford model. For this comparison, the same set of ten test cases was re-analyzed with SATRAP, using the Pasquill-Gifford model, formulated by Briggs for rural conditions (Reference A8-2). The same model was adopted for the Cassini GPHS-RTG FSAR consequence analysis.

Table A8-1 summarizes the atmospheric dispersion conditions and the source term description for each test case. Combined with the similarity in dispersion model, these simplified release conditions facilitate the interpretation of differences in code predictions. All test cases have a unit source term (1 Ci) and assumes a uniform wind field. The Pasquill stability classes considered for atmospheric diffusion include neutral (D), slightly stable (E) and extremely unstable (A) conditions. Four particle sizes (0.32-, 3.2-, 32- and 300 μm) were selected to define the single particle source cloud for the various test cases. Table A8-2 provides their respective gravity settling velocity and deposition velocity as implemented in SATRAP for the atmospheric transport analysis. Note that the settling velocity is used to predict the time-dependent elevation of the cloud center, while the deposition velocity is used

Table A8-1. Test Cases for Atmospheric Dispersion Analysis

Case Title	Physical Diameter (μm)	Stability Class	Mean Wind Speed (m/s)	Inversion Height (m)	Source Term (Ci)	Release Height (m)	Initial σ _y (m)	Initial σ _z (m)
P1	0.32	D	7	1500	1	100	25	13
P2	3.2	D	7	1500	1	100	25	13
P3	32	D	7	1500	1	100	25	13
E1	0.32	E	2	200	1	100	25	13
E2	3.2	E	2	200	1	100	25	13
E3	32	E	2	200	1	100	25	13
A1	0.32	A	5	1500	1	100	25	13
H4	300	A	5	1500	1	3000	75	75
G1	0.32	A	5	1500	1	4	2	2
M2	3.2	E	2	200	1	500	25	13

Table A8-2. Characteristics of Particle Sizes

Size (μm)	Settling Velocity (cm/s)	Deposition Velocity (cm/s)	Example
0.32	0.005	0.037	Smog
3.2	0.33	0.41	Industrial Dust
32	29	29	Spray Can
300	558	558	Coarse Sand

for the calculation of depletion to the ground. Two key outputs of the atmospheric dispersion analysis, integrated air concentration (in $\mu\text{Ci}\cdot\text{s}/\text{m}^3$) and ground deposition concentration (in $\mu\text{Ci}/\text{m}^2$) at the plume centerline were extracted from the two models for comparison. The EMERGE results are from previous TT-NUS transmittals (References A8-3 and A8-4).

Figure A8-1 shows the integrated air concentrations from SATRAP and EMERGE for the releases into neutral atmospheric conditions for cases P1, P2, and P3. Air concentration values are nearly identical for the small and medium particles (0.32 and 3.2 μm), but are about a factor of 2 higher with SATRAP. This difference is attributed to the plume reflection at ground level implemented in SATRAP. For the large particle (32 μm), SATRAP predicts a much shorter footprint than EMERGE and two peak concentrations at about 1.2 km and 2.4 km downwind. The peak concentration from EMERGE is at the 1581 m grid point. Figure A8-2 shows the ground deposition results from the two models. In general, ground deposition has the same profile as integrated air concentration, but the effect of particle size is seen in

Figure A8-1. Comparison of Integrated Air Concentration – Cases P1, P2 and P3

Figure A8-2. Comparison of Ground Deposition – Cases P1, P2, and P3

the SATRAP results. The trajectory of the 32 μm cloud center, as presented in Figure A8-3, confirmed that the peak ground concentration as provided by SATRAP is near the 2.4 km downwind distance, corresponding to the cloud center landing position.

Figures A8-4 and A8-5 show test results from cases E1, E2, and E3, representing releases into a slightly stable atmospheric condition. For the 0.32 and 3.2 μm particle sizes, the air concentration profiles are nearly identical but are slightly higher from SATRAP. Because the deposition velocity of EMERGE varies with downwind distance (Reference A8-5), the ground concentration profiles of these two particles differ from the air concentration. Due to high depletion at the beginning of transport, ground concentrations from EMERGE exhibit a slope steeper than the corresponding air concentrations. For this low wind speed condition (2 m/s), the 32 μm particle size cloud lands 700 m downwind (see Figure A8-6). The results from EMERGE reflect the lack of calculation grid points below that range. Again, SATRAP predicts a smaller horizontal diameter for the final position of this large particle cloud.

Figure A8-3. Trajectory of Cloud Center - Cases P1, P2, and P3

Figure A8-4. Comparison of Integrated Air Concentration – Cases E1, E2 and E3

Figure A8-5. Comparison of Ground Deposition – Case E1, E2 and E3

Figure A8-6. Trajectory of Cloud Center - Case E1, E2, and E3

Case A1 is used to compare the release of small particles in an extremely unstable atmospheric condition. As shown in Figure A8-7, both SATRAP and EMERGE predict fast cloud diffusion with a peak concentration between 400 and 500 m downwind. Similar to previous cases, ground reflection of the diffusing cloud and deposition velocity contribute to the difference in air concentration. The profiles from both SATRAP and EMERGE display a change in slope at about 60 km, indicating cloud capping at the mixing height. For this particular case, the ground concentrations from EMERGE are about 2 to 3 orders of magnitude higher than those from SATRAP.

Figure A8-7. Comparison of Integrated Air Concentration and Ground Deposition – Case A1

In case G1, because the source cloud is released 4 m above ground and in an extremely unstable atmospheric condition, ground deposition occurs early and cloud diffusion to large dimensions is quite fast. As shown in Figure A8-8, SATRAP predicts the peak concentration to occur 100 m downwind. The fixed grid system of EMERGE can only provide results at distances above 700 m but shows the same trend with a peak concentration at the first grid point. With a height of release lower than case A1 (4 m vs. 100 m), the difference in ground

Figure A8-8. Comparison of Integrated Air Concentration and Ground Deposition – Case G1

concentrations is somewhat reduced, ranging from 1 to 2 orders of magnitude. However, for near-range transport (less than 1 km), the ground concentrations from SATRAP increase while those from EMERGE decreases.

Case H4 represents a release of very heavy particles at high altitude. Figure A8-9 shows a large difference in cloud width predicted by the two models. As shown in Figure A8-10, the cloud center lands between 2 and 3 km downwind and thus both models give a peak concentration at that range. However, EMERGE does not provide air concentration values for grid points that are downwind further than 4138 m but predicted to have ground deposition.

Figure A8-9. Comparison of Integrated Air Concentration and Ground Deposition – Case H4

Figure A8-10. Trajectory of Cloud Center - Cases A1 and H4

For test case M2, close agreement was obtained between SATRAP and EMERGE for both integrated air concentration and ground deposition in long range transport. Figure A8-11 shows the low concentrations from both models, with peak values between 60 to 70 km. Figure A8-12 indicates that the cloud center remains above the 200 m mixing height after 100 km advection. Note that for the Cassini GPHS-RTG risk analysis, this release would not produce any ground concentration because the small $3.2\ \mu\text{m}$ particle is released at nighttime, above the nocturnal mixing height. In such a case, any fumigation to the ground would only occur in the late morning with the rise of the convective mixing height.

Figure A8-11. Comparison of Integrated Air Concentration and Ground Deposition – Case M2

Based on the above results, it can be concluded that:

- Overall, SATRAP and EMERGE provide air concentration results within a factor of 2 to 10 for releases of small and medium particles in neutral and stable atmospheric conditions. This difference is mainly due to the modeling of cloud reflection at ground level adopted in SATRAP for mass conservation (Reference A8-5). Reflection is not considered for heavy particles or large deposition velocities.

Figure A8-12. Trajectory of Cloud Center - Case M2

- Large differences occur in ground deposition results, especially for unstable atmospheric conditions. The deposition velocities used by EMERGE are estimated to be larger than those from SATRAP by about a factor of 5 to 30, depending on the particle size and stability class. Also, the deposition velocity decreases with transport distance in EMERGE, while it remains constant in SATRAP. The deposition velocity adopted in EMERGE is dependent on the rate of plume growth during atmospheric transport.
- Close agreement was obtained between the two models for small particles released at high altitudes, above the mixing height, in stable atmospheric conditions.
- The flexible grid system in SATRAP provides more information for the near-range ground concentrations of releases at low altitudes or in unstable atmospheric conditions.
- Some test cases have significant differences for the large particles, at 32 μm and above, but their effects on radiological consequences should be small because of low inhalability.

References for Section A8

- A8-1 Letter from D. Damon to B. Bartram, "Test Cases for Model Comparison", GE Letter No. XL-T26-920014, 16 April 1992.
- A8-2 Briggs, G. A, Diffusion Estimation for Small Emissions, ATDL Contribution file No. 79, Atmospheric Turbulence and Diffusion Laboratory, 1973.
- A8-3 Letter from B. Bartram to D. Damon documenting the test results from EMERGE, HNUS letter no. MPM-92-122, 1 June 1992
- A8-4 Facsimile from H. Firstenberg to D. Damon/C. Ha for correction of results of cases E1, E2, E3, A1, H4, G1 and M2, 30 November 1992.
- A8-5 Hanna, S. R., G. A. Briggs and R. P. Hosker, Jr., Handbook on Atmospheric Diffusion, Sec. 4, DOE-TIC-11223, 1982.

Section A9

RHU/RPS Risk Integration Methodology

SECTION A9

RHU/RPS RISK INTEGRATION METHODOLOGY

A9.1 BACKGROUND

Risk distributions have historically been independently calculated for RHUs (Radioactive Heating Units) and the RPSs (Radioisotope Power Systems) common to a mission. These distributions are then combined into an overall risk distribution. An improved procedure for accomplishing this task in future risk assessments is described here.

A9.2 COMBINING DISTRIBUTIONS REPRESENTING VARIABILITY

The risk distributions for the RHUs and RPSs may either be distributions reflecting variability or both variability and uncertainty, depending upon the process used to generate them. The procedure for combining distributions representing variability only is presented first, since the procedure for combining distributions representing variability and uncertainty is an extension of the procedure for distributions representing only variability.

Cumulative consequence distributions for the RHU and RPS are formed by sorting the ordered pairs by consequence and then performing a running sum of the probabilities. The two cumulative distribution functions are then combined by adding the consequences at given cumulative probabilities. This can be carried out by interpolating the distribution functions at selected values of cumulative probability. The process is illustrated in Figure A.9-1. Note that the two distributions have different cumulative probability values for zero consequence, representing different conditional probabilities of release.

The steps shown in the figure are 1) inversion of the distributions to make the cumulative probability the independent variable, 2) summation of the consequences at given cumulative probability levels, and 3) inversion to convert the result to a cumulative probability distribution.

A9.3 COMBINING DISTRIBUTIONS REPRESENTING VARIABILITY AND UNCERTAINTY

A distribution representing both variability and uncertainty can be represented as a set of variability distributions. Distributions of this form can be combined in a straight-forward manner. If the distributions are not in this form, they must be converted to a set of variability distributions representing the uncertainty. For example, if the distribution is given as a

Figure A.9-1. Combination of Two Variability-Only Distributions

variability distribution and a distribution of consequence multipliers, a Monte Carlo calculation can generate a set of variability distributions representing the uncertainty. These calculations must be performed simultaneously for all the distributions to be combined if the uncertainties are deemed to be correlated. Otherwise the calculations are performed separately.

Once the sets of variability distributions have been generated, they are individually combined using the method described previously for variability distributions. Each variability distribution from one source of risk (the RPS for example) is combined with a variability distribution from the other source of risk (the RHUs) to form a set of distributions representing the combined risk. The resulting set of distributions can then be converted into a set of variability distributions at definite confidence levels using a sort. The cumulative distributions are converted to a matrix of cumulative probabilities at a series of cumulative probability values (by interpolation) and sorted so that the resulting distributions do not intersect. The result is a set of cumulative distributions at definite confidence levels.

Section A10

**Atmospheric Transport
Validation Studies**

SECTION A10

ATMOSPHERIC TRANSPORT VALIDATION STUDIES

A series of atmospheric transport validation studies were performed prompted by comments on the Cassini GPHS-RTG FSAR analysis methodology as documented in the Interagency Safety Review Panel's Meteorological (MET) Subpanel report (Reference A10-1). An initial response to the MET comments was prepared as documented in Reference A10-2. Several of the MET comments were identified for further evaluation using currently available meteorological data and resources. These issues are:

- 1) Effects of Additional Wind Towers Data,
- 2) Adequacy of Latin Hypercube Sampling,
- 3) Adequacy of Weather-Day Cluster Sampling,
- 4) Effects of Weather-Day Cluster Sampling,
- 5) Effects of Self-Induced Rainout,
- 6) Effects of Sparse Upper Air Data, and
- 7) Nocturnal Stable Boundary Layer.

Studies performed for each of these issues are described in Sections A10.1 through A10.7, respectively.

A10.1 EFFECTS OF ADDITIONAL WIND TOWERS DATA FROM MVP

This section describes the results of the adaptation of the Cassini GPHS-RTG FSAR weather processing methods to utilize the Model Validation Program's (MVP) (Reference A10-3) meteorological data and the subsequent comparison of the FSAR 20-tower windfield to the MVP 41 tower windfield. MVP is a program sponsored by the Titan System Program Office of the Space and Missile Systems Center at LA-AFB. MVP spanned a broad range of meteorological conditions (Reference A10-4), wherein each session in the Model Validation Program occurred at different times during the year. Each data collection period is referred to as a session. The four MVP data collection periods or session time frames are listed below:

Session 1: 13 July to 1 August 1995

Session 2: 1-18 November 1995

Session 3: 26 April to 9 May 1996

Session 4: 14-31 May 1997

The focus of this analysis was to compare atmospheric transport as predicted by windfields generated with the 20-tower data set used for the FSAR to transport based on the 41-tower data set available from the Model Validation Program for Session 2. INSRP (Reference A10-5) questioned

- 1) the use of only 20 towers versus some 53 possible towers, and
- 2) that the 20-tower set would provide valid windfields for the SPARRC model used for low level transport (SATRAP).

This sensitivity study addresses these two issues. HNUS (now TetraTech-NUS) performed the tower selection process and it is described in Reference A10-6. The main reasons given by HNUS for eliminating towers were 1) lack of a 54 meter data set, 2) suspicions regarding data quality, 3) data quantity reduction, and 3) judgement as to importance in predicting cloud motion from complex 40. The adequacy of the HNUS screening/elimination process is addressed in the following sections.

A10.1.1 Selected MVP Session

Session 2 was selected for this analysis because its time frame is typical of the October-December Cassini primary launch window. Around 20 tests were performed during Session 2. Two of the tests performed (Reference A10-7), were identified as being night releases of SF₆. These tests are:

MVP Test Number 220 on 13 November 1995 (Releases from 2004 hrs-2234 hrs),

MVP Test Number 222 on 14 November 1995 (Releases from 1902 hrs-2132 hrs).

Meteorological data from MVP was supplied in Reference A10-7 for test 220. This MVP data is the basis for the assessment of the methods employed during the Cassini FSAR risk analysis to generate the transport windfield. Additional data files for test 220 (Reference A10.-8) were also provided for this test.

A10.1.2 Data Processing

The Cassini wind/receptor processing codes and shells were modified to enable the conversion of MVP data to binary input files for the SATRAP consequence analysis. The MVP data consisted of 5-minute average data from 41 towers. The Cassini weather processing tools were modified to create the 15-minute average data consistent with the FSAR process. The MVP buoy data was not used for additional wind vector measurements because it appears that this wind data was not collected for the session two days applicable to tests 220 and 222.

There were 5 rawinsonde soundings on the 13th at 6am, 9am, 12noon, 3pm, and 6pm. There were 4 soundings on the 14th at 6am, 12noon, 3pm, and 6pm. The rawinsonde data from the MVP database contained more information at the sounding elevations than was supplied by HNUS for the Cassini GPHS-RTG FSAR. Figures A10.1-1 and A10.1-2 show the wind speed, direction, temperature, and potential temperature profiles for 13 November 1995 at 12pm. At noon the first temperature inversion occurs at approximately 1850m.

A tower 313 database similar to that used for FSAR analyses, including the mixing height, had to be derived from the available MVP multitower data sets prior to running the analysis. The National Weather Service (NWS) rawinsonde data from Vero Beach, Daytona Beach and Orlando which was originally part of the mixing height calculation in the FSAR analysis was not purchased for this study nor was it part of the MVP data sets. The data required to generate the tower 313 database were obtained from the MVP rawinsonde and multiple tower data sets. The Cassini multiple tower database generator was altered to select the data for tower 313 from the multiple tower ASCII inputs to create the intermediate 313 binary tower database. The parameters that were found to be unavailable in the MVP multitower database included the precipitation rate, the mixing heights, and the ambient air pressure. Since the precipitation rate was set to zero in the FSAR process, the same value was assigned for the MVP process. Mixing height generation tools were modified to evaluate the MVP data at KSC and over the ocean. An average ambient air temperature above the ocean was determined and then applied in the thermal mixing height calculation above the ocean.

Figure A10.1-1. Wind Speed and Direction from 1200pm MVP Rawinsonde

Figure A10.1-2. Temperature and Potential Temperature from 1200pm MVP Rawinsonde

The time histories of the calculated mechanical and thermal mixing heights for KSC for the two MVP days are shown in Figure A10.1-3. The mechanical mixing height is depicted by (diamonds) and thermal mixing height is depicted by (triangles) in Figure A10.1-3. The SATRAP code uses the larger of the two values depending on the time of day. The Orlando and Daytona Beach NWS station mixing heights were not calculated for this analysis since these data were not part of the MVP data sets. Thus, no interpolation over land could be done in this validation study as was done in the FSAR analysis. The ambient air pressure parameter was found to be available on the buoy data and was used to create the pressure time history for the MVP weather-day data set generation.

A10.1.3 Wind Field Assessment

Grid point vectors were calculated for the 200 km x 200 km grid computation domain using both the MVP and the FSAR tower sets to provide a qualitative assessment of windfield differences. Figure A10.1-4 plots the location of the towers used for these evaluations. The two windfield vectors sets were superimposed at 0000, 0700 and 1400 hours of 13 November 1995 as shown in Figures A10.1-5, A10.1-6 and A10.1-7. The elevation for these vector comparison plots is 16.5 meters. The solid black vectors in these figures represent the windfield as calculated from the MVP tower set. The gray or dashed vectors are from the FSAR tower set. It should be noted that towers 417, 709, and 1609 of the FSAR data set were not part of the MVP multitower data sets. MVP tower 509 was substituted for FSAR tower 709 and MVP tower 0415 was substituted for FSAR tower 417. No substitution was made for tower 1609. The tower numbers shown in Figures A10.1-5, A10.1-6, and A10.1-7 are the FSAR set plus the two substitutes. The scale for the vectors is shown in the bottom left hand corner of each of these figures. The MVP tower 006 is also shown in these figures because it is another "detailed" tower like towers 110 and 313 used in the FSAR analysis. The differences in the wind fields shown in Figures A10.1-5, A10.1-6 and A10.1-7 at 16.5 meters represent the biggest differences in the two cases. At higher elevations there are fewer towers to provide data and eventually the rawinsondes define the wind. Since the FSAR process called for the use of all available rawinsonde data the MVP and FSAR processes for upper level winds above 200 m are no different.

Figure A10.1-3. 13 and 14 November 1995 Cassini FSAR Model Mixing Heights Versus Time

Figure A10.1-4. Location of MVP and FSAR Wind Towers

Figure A10.1-5. Comparison of MVP/FSAR Wind Vectors at 16.5m at 0000Hr for 951113

Figure A10.1-6. Comparison of MVP/FSAR Wind Vectors at 16.5m at 0700Hrs for 951113

Figure A10.1-7. Comparison of MVP/FSAR Wind Vectors at 16.5 m at 1400 Hours for 951113

To get a sense of the time history of the differences associated with the two windfield modeling approaches, the wind speed and direction at three of the wind stations not part of the FSAR set were compared against the FSAR tower set projections for that location. MVP Tower 0022 on the northern coastline was selected for comparison because of the large differences in vector field projection seen in Figure A10.1-6. MVP tower 1500, which is an inland tower position, was selected because it appears to provide the best projection. With the other two towers covering the range of differences, tower 311, which is near the launch site, was selected to represent the potential impact of application of one wind field over the other on releases located near the launch pad. Figures A10.1-8 and A10.1-9 look at the time history for tower 0022. Winds for that tower are clearly under predicted. The time axis in these figures is the day's date. Figure A10.1-8 shows both the measured and projected wind magnitude (m/s) and direction (vane). Figure A10.1-9 is the difference between measurement and projection. Figures A10.1-10 and A10.1-11 are the wind vector time histories for tower 1500. Winds for that tower are generally over predicted. Figures A10.1-12 and A10.1-13 are the wind vector time histories for tower 311. Reasonably good agreement was found for this location.

Figure A10.1-8. Comparison of FSAR Wind Projection at MVP Tower 0022 at 16.5 m

Figure A10.1-9. Difference Between MVP Tower 0022 at 16.5 m and FSAR Projection

Figure A10.1-10. Comparison of FSAR Wind Projection at MVP Tower 1500 at 16.5 m

Figure A10.1-11. Difference Between MVP Tower 1500 at 16.5 m and FSAR Projection

Figure A10.1-12. Comparison of Cassini Wind Projection at MVP Tower 311 at 16.5 m

Figure A10.1-13. Difference Between MVP Tower 311 at 16.5 m and FSAR Projection

A10.1.4 Impact on Consequence Analysis

To investigate the impact on consequences of the different MVP and FSAR windfields a series of sensitivities were run in both windfields on 13 November 1995. Releases were made at 20, 100 and 500 meters using a 100m σ_x , σ_y , and σ_z . Release times were at 3am and 12noon. The mass of the release was 0.01grams and the particle size was 0.74 mm. The clouds were tracked for 10 hours or until each was depleted. The cloud center trace plots for these cases are shown in Figures A10.1-14 and A10.1-15. The only visible difference in the traces is in the 20-meter release case. This would be expected since this cloud will spend all of its transport time within the wind layer corresponding in altitude to the additional towers. For the 3am 20 meter release case the FSAR windfield blows the cloud down the Banana River while the MVP windfield blows the cloud along the east coast of Merritt Island. The mixing height at 3am and 12 noon was estimated to be 250 m and 1450 m. Thus, the 20 and 100-meter release cases are below the mixing height for the 3am cases and all releases are below the mixing height for the noon cases. Table A10.1-1 shows the impact on key consequence measures. Because the release mass is small the land area contaminated to 0.2, 0.6, 1.2 and 2.4 $\mu\text{Ci}/\text{m}^2$ are all zero. To get an estimate of the impact on land contamination, the maximum land contamination level for each case was recorded along with the area contaminated as shown in the last two columns of Table A10.1-1. As expected the windfield has the largest impact on the low level or 20 m release consequences. The 50-year health effects from the FSAR windfield were lower by 81%, 3%, and 0% for the 20 m, 200 m and 500 m releases at 3am relative to the MVP windfield analysis; respectively. It should be noted that the 3:00am release at 500 m exited the grid without producing any health effects in both windfields because it was released above the mixing height and never reached the ground prior to exiting the grid. (Off-grid effects were not evaluated during this study.) For the 12-noon release at 20 meters the Cassini process over-predicted the consequence by 2% and there was little or no change for the 100 and 500 m release cases. Thus, the largest consequence differences occur for clouds released at the lowest level because this is where the differences in the windfields occur when more wind towers are available.

Figure A10.1-14. Cloud Traces in MVP and FSAR Windfields at 3am

Figure A10.1-15. Cloud Traces in MVP and FSAR Windfields at 12pm

Table A10.1-1. Comparison of Key Consequence Measures Using the FSAR and MVP Tower Sets

Type Of Analysis	Time of Release	Elevation of Release (m)	1st Year	50 Year	1st Year	50 Year	50 Year	50 Year	50 Year	50 Year	50 Year	Land Contamination >X microCi/sq. m				Maximum	Land
			Health	Health	Health	Health	Health	Health	Health	Maximum	Maximum					Surface	Area
			Effects	Effects	Effects	Effects	Effects	Effects	Effects	Potential	Individual					Contamin.	Contamin.
			w/o De-minimis	With De-minimis	Residents	Workers	Spectators	Dose	Dose	Dose	Dose	X >0.2	X >0.6	X >1.2	X >2.4	(microCi/ sq. m)	to Max. Level (sq. km)
Cassini Towers	3am	20	8.39e-03	1.11e-02	4.69e-03	4.74e-03	1.03e-02	7.06e-04	8.78e-05	8.06e-02	4.98e-02	0	0	0	0	2.0e-03	1.89e-02
	3am	100	7.95e-03	1.10e-02	7.40e-04	7.40e-04	1.02e-02	8.07e-04	8.99e-06	2.15e-03	2.15e-03	0	0	0	0	8.0e-05	2.50e-01
	3am	500	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0	0	0	0	0.0e+00	0.00e+00
	12pm	20	4.37e-03	6.09e-03	2.67e-05	2.67e-05	6.05e-03	3.69e-05	2.64e-06	5.83e-03	4.96e-03	0	0	0	0	2.0e-04	2.12e-01
	12pm	100	2.59e-03	3.64e-03	1.71e-05	1.71e-05	3.56e-03	7.46e-05	2.57e-06	6.68e-03	4.99e-03	0	0	0	0	2.0e-04	3.08e-02
	12pm	500	1.60e-03	2.09e-03	0.00e+00	0.00e+00	2.09e-03	1.25e-06	2.11e-06	5.30e-04	5.30e-04	0	0	0	0	2.0e-05	5.43e+01
MVP Towers	3am	20	4.13e-02	5.84e-02	3.71e-02	3.86e-02	5.80e-02	4.01e-04	1.25e-05	8.86e-02	8.86e-02	0	0	0	0	2.0e-03	6.43e-03
	3am	100	8.22e-03	1.13e-02	6.32e-04	6.32e-04	1.05e-02	8.06e-04	8.99e-06	2.17e-03	2.17e-03	0	0	0	0	8.0e-05	2.50e-01
	3am	500	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0	0	0	0	0.0e+00	0.00e+00
	12pm	20	4.35e-03	5.96e-03	4.81e-05	4.81e-05	5.92e-03	3.50e-05	2.84e-06	5.87e-03	5.00e-03	0	0	0	0	2.0e-04	2.41e-01
	12pm	100	2.59e-03	3.64e-03	1.71e-05	1.71e-05	3.56e-03	7.54e-05	2.57e-06	6.69e-03	4.93e-03	0	0	0	0	2.0e-04	3.70e-02
	12pm	500	1.61e-03	2.09e-03	0.00e+00	0.00e+00	2.08e-03	1.25e-06	2.11e-06	5.84e-04	5.84e-04	0	0	0	0	2.0e-05	1.15e+02
Percentage Difference Between Cassini and MVP Data Sets(C-MVP)/MVP*100																	
	3am	20	-79.7	-80.9	-87.4	-87.7	-82.2	76.4	599.4	-9.0	-43.7	No Diff.	No Diff.	No Diff.	No Diff.	0.0	194.1
	3am	100	-3.3	-2.9	17.1	17.1	-3.1	0.1	0.0	-0.6	-0.6	No Diff.	No Diff.	No Diff.	No Diff.	2.2	2.0
	3am	500	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.	No Diff.
	12pm	20	0.5	2.2	-44.6	-44.6	2.2	5.4	-6.8	-0.8	-0.8	No Diff.	No Diff.	No Diff.	No Diff.	0.0	-12.1
	12pm	100	-0.0	-0.0	-0.2	-0.2	0.0	-1.1	0.0	-0.1	1.4	No Diff.	No Diff.	No Diff.	No Diff.	0.0	-16.7
	12pm	500	-0.3	0.1	No Diff.	No Diff.	0.1	-0.0	-0.0	-9.2	-9.2	No Diff.	No Diff.	No Diff.	No Diff.	0.0	-52.9
Ratio of MVP Process to Cassini Process Values (MVP/C)																	
	3am	20	4.92	5.25	7.92	8.14	5.61	0.57	0.14	1.10	1.78	1	1	1	1	1.00	0.34
	3am	100	1.03	1.03	0.85	0.85	1.03	1.00	1.00	1.01	1.01	1	1	1	1	1.00	1.00
	3am	500	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	12pm	20	0.99	0.98	1.81	1.81	0.98	0.95	1.07	1.01	1.01	1	1	1	1	1.00	1.14
	12pm	100	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	0.99	1	1	1	1	1.00	1.20
	12pm	500	1.00	1.00	1	1	1.00	1.00	1.00	1.10	1.10	1	1	1	1	1.00	2.13

A10.1.5 Conclusions and Recommendations

Obviously more data on any given day will usually give a more precise answer for that day. However it should not be concluded from this analysis of a single day that these differences would always be of the same magnitude. As pointed out on this particular day the large differences that occurred for the release from 20 meters at 3am was primarily the result of passing over a different set of receptor grids. The MVP trace was primarily over land and the Cassini trace was over water. In a real accident scenario the majority of the source term would be engulfed in one or more fireballs and elevated above this lower surface level. Thus, releases that are purely in the lowest surface levels are unlikely. Because many trials (i.e., 900 per case for variability only and 1500 trials for variability plus uncertainty cases) were evaluated for the FSAR, such fine refinements at the surface level would not be expected to significantly affect the mean consequences nor key distribution percentile values. The need for slightly more precise analysis in the windfield at the lowest elevations has to be traded-off against the cost of processing more data in a probabilistic risk assessment. Based on this limited assessment and previous FSAR assessments done for the NWS weather station data, the 20 tower data set selected by HNUS was more than adequate to estimate the potential consequences of a Cassini launch pad area accident.

A10.2 MONTE CARLO SAMPLING VERSUS LATIN HYPERCUBE SAMPLING (LHS)

The purpose of this sensitivity study was to quantify the impact of using fuel and weather-day clusters and LHS sampling on the Cassini FSAR results. This analysis was performed to respond to INSRP Meteorology (MET) Subpanel comments (Reference A10-1) and Risk Integration and Uncertainty Analysis Subpanel comments (Reference A10-9) as follows:

MET-Subpanel:

Adequacy of meteorological clustering not demonstrated.

Risk Integration and Uncertainty Analysis Subpanel:

LHS observations are of unequal probability potentially invalidating

SPARRC/LHS results

The LHS fuel and meteorological clustering was demonstrated to adequately capture both source term and weather variability by comparison to the Cassini scaling model which evaluated all day and source term combinations as shown in Appendix B of Volume III, Book 2 of the Cassini GPHS-RTG FSAR. The Cassini LHS observations are equally likely as required by the LHS code process. However the runs made within each observation are not equally likely due to the clustering or stratification process used. This clustering process assured that the most risk significant combinations were not ignored in the sampling process. Another way of showing the adequacy of the LHS cluster approach has been demonstrated whereby the analysis is performed without either fuel or weather-day clusters and using a Monte Carlo Sampling process rather than the LHS process. This analysis is documented in the following sections.

A10.2.1 Case Selection Background

Cassini FSAR case 1.1 (Total Boost Vehicle Destruct) was selected for this analysis because it was the dominant contributor to the Cassini launch related consequences and risk. Only the simulation of case 1.1 with no SRMU coincident impact releases (CIR) was evaluated for this study because it requires fewer analyses than if the with-CIR analysis is performed. Case 1.1 with no CIR (also designated as case 1.1z) has 1868 fuel or source term release records from 17656 LASEP-T trials. There are approximately 28 different times that could be sampled from any 1 of 150 weather-days in the database based on the 15-minute average wind data in the 7-hour launch window. Thus, there are greater than 4.203×10^6 possible combinations of source term, launch day, and time to be randomly sampled for this one Cassini launch accident case. The LHS code provides an option for Monte Carlo Sampling which was used for this analysis. The fuel source term clusters were merged into a single population for sampling and the weather-day clusters were also merged into a single population for the random or Monte Carlo sampling process. Thus, the results from this analysis have no Latin Hypercube sampling effects or clustering effects associated with the fuel source term or weather-days.

A10.2.3 Case 1.1 no CIR Monte Carlo Analysis Results

The Monte Carlo results are compared to the baseline FSAR Addendum analysis results for this case in Table A10.2-1. An additional comparison to the case 1.1 re-run results (Reference A10-10) and the Monte Carlo results is also provided in Table A10.2-2. The mean of the Monte Carlo case is lower in the range of 16 to 18 percent depending on what baseline case is taken as shown in Tables A10.2-1 and A10.2-2. The Monte Carlo case was run twice with 2000 trials each. Each set was based on a different seed. These cases were constructed using the repetition option of LHS which is inherent to the LHS/SPARRC Rev. 3 shell. The means of these two samples were calculated separately and combined. The means of the first 900 trials of each Monte Carlo observation set was also calculated for comparison to the 900 trial/30 observation Cassini LHS process.

Table A10.2-1. Case 1.1 Comparison of the Monte Carlo and the Cassini LHS with Clusters Analysis Done for the FSAR Addendum 50-Year Health Effects without de-minimis

Mean or Percentile Distribution Values	Cassini LHS with Clusters Analysis (30 observations or 900 trials)	Random Monte Carlo (MC) Sampling with No Clusters (4000 trials)	% Difference (MC-LHS)/LHSx100
Mean	6.84×10^{-2}	5.64×10^{-2}	-18
5th	4.54×10^{-5}	3.91×10^{-5}	-14
50th	6.90×10^{-3}	3.67×10^{-3}	-47
95th	1.69×10^{-1}	1.77×10^{-1}	+4
99th	1.23	7.97×10^{-1}	-36
Maximum	41.7	12.8	-69

Figure A10.2-1 is a plot of the mean 50-year health effects estimated as a function of the number of trials performed. The 900 Monte Carlo trial cases plotted here represent the first 900 trials processed from the each of the 2000 trial runs. The 4000 trial point is the composite of the two 2000 trial runs. The LHS result that is plotted is based on the Reference A10-10 case 1.1 re-run that corrected minor bugs in the LHS/SPARRC preliminary Rev. 3 code. The LHS process mean would be expected to be higher than the Monte Carlo

**Table A10.2-2. Case 1.1 Comparison of the Monte Carlo and the Cassini LHS with Clusters Analysis Done to Identify the Impact Relative to Case 1.1 Re-Run Results
50-Year Health Effects without de-minimis**

Mean or Percentile Distribution Values	Cassini LHS with Clusters Analysis (30 observations or 900 trials)	Random Monte Carlo (MC) Sampling with No Clusters (4000 trials)	% Difference (MC-LHS)/LHSx100
Mean	6.67×10^{-2}	5.64×10^{-2}	-16
5th	5.91×10^{-5}	3.91×10^{-5}	-34
50th	7.12×10^{-3}	3.67×10^{-3}	-48
95th	1.64×10^{-1}	1.77×10^{-1}	+7
99th	1.18	7.97×10^{-1}	-32
Maximum	43.5	12.8	-71

Figure A10.2-1. Case 1.1z No CIR 50-Year Mean Health Effects versus Number of Observations

mean since the LHS and the source term and weather-day clustering process assures that high source terms are sampled with weather-days that produce high consequences. Thus, the most risk significant combinations are not missed in the LHS sampling process as may have occurred in the Monte Carlo samples. The LHS analysis process achieves a comparable mean with approximately 1/4 of the processing time.

The health effects and land contamination CCDFs are compared in Figures A10.2-2 and A10.2-3, respectively. The baseline case used for these comparisons is the Reference A10-10 re-run case. CCDFs for the LHS process include more of the tail of the distribution than the Monte Carlo based CCDF as would be expected from a stratified or cluster sampling approach as used in the Cassini FSAR analysis. Figure A10.2-4 compares the 900 trial Monte Carlo, the 2000 trial Monte Carlo and the 4000 trial Monte Carlo CCDFs with that of the Reference A10-10 re-run case. Figures A10.2-5, A10.2-6 and A10.2-7 provide comparisons of the Addendum LHS case with the Monte Carlo case results.

A10.2.4 Conclusions

The conclusions from this Monte Carlo and LHS analysis comparison are:

- 1) the Cassini analysis process is valid,
- 2) the LHS sampling approach combined with the clustering analysis provided an efficient computational process to define the:
 - a) mean and
 - b) distribution parameters for the Cassini launch accident consequence measures, and
- 3) the LHS clustering approach used approximately 1/4 of the computation time of the Monte Carlo analysis to get comparable results.

Figure A10.2-2. Comparison of LHS and Monte Carlo 50-Year Health Effects CCDFs without de-minimis

Figure A10.2-3. Comparison of LHS and Monte Carlo Land Contamination CCDFs

Figure A10.2-4. Comparison of LHS and Monte Carlo 50-Year Health Effects CCDFs for Selected Sample Sets

Figure A10.2-5. Comparison of Monte Carlo (MC), Case 1.1 Re-Run (Rev3f), and Addendum (Add) 50-Year Health Effects CCDFs

Figure A10.2-6. Comparison of Monte Carlo and Addendum LHS 50-Year Health Effects CCDFs

Figure A10.2-7. Comparison of Monte Carlo and Addendum LHS Land Contamination CCDF Results

A10.3 ADEQUACY OF WEATHER-DAY SAMPLING

In its review report of the Cassini GPHS-RTG FSAR, the INSRP Meteorology subpanel has identified the approach adopted by Lockheed Martin for sampling of meteorology conditions for launch accident analyses as inadequate. The sampling of the 10 different weather-day clusters was believed to undersample geographic sectors associated with population centers, resulting into an underestimate of the health effects consequence. While the basis for weather-day clustering has been discussed using a comparison of health effects from a series of tests in the Cassini FSAR (Vol. III, Book 2, Appendix C), the actual sampling for the dominant accident case 1.1 (Total Boost Vehicle Destruct) was further verified, using trajectory plots of the cloud center of released source terms. The results of this verification are discussed here.

For accident case 1.1, which without coincident impact release contributes 64% to the mean health effects of launch accidents, the consequence analysis process used 30 different LHS observations, equivalent to 900 accident simulations. Due to the difference in stabilized height of the solid and liquid propellant fire plumes, each accident simulation usually involves three different source term release heights for the start of transport analysis. These heights correspond to centers of the liquid propellant fireball, the solid propellant fire plume and the fraction of the stem that rises above the solid propellant fire plume. A trajectory trace was generated for 0.05 μm particles from simulations which predicted release heights close to pre-selected nominal values. These small particles have the longest airborne time of the 13 particle sizes analyzed by SPARRC.

Figures A10.3-1 and A10.3-2 show the trajectories processed for the release height at 200 m and 500 m, respectively. In the first case, the average release height is 175 m, with 288 out of 900 releases at 200 ± 50 m. Similarly for the second case, the average release height is 487 m with 275 releases at 500 ± 50 m. Typical of wind variability at low elevations, the trajectories at 200 m elevation display a more complex pattern than those at 500 m. The sampled wind fields display characteristics such as on-shore, off-shore, and wind reversal. But most importantly, both graphs show the plume trajectories densely cover all geographic sectors, except for near the North-West direction at the 500 m level. If the actual plume width

**Figure A10.3-1. Case 1.1 without Coincident Impact Release -
Trajectories for Cloud Centers with Release Height about 200 m**

was taken into account, the ground-level surface of this sector would be covered by the overlapping footprints. Moreover, the high population density areas along the North-West coast line such as Daytona Beach are well covered by many plume traces. Thus, based these findings it is concluded that the sampling process of 10 weather-days clusters is adequate for the risk analysis.

**Figure A10.3-2: Case 1.1 without Coincident Impact Release -
Trajectories for Cloud Centers with Release Height about 500 m**

A10.4 EFFECT OF WEATHER DAY CLUSTER SAMPLING

The purpose of this sensitivity study is to compare the predicted consequences using the LHS weather-day cluster sampling process versus using all 150-days in the Cassini weather-day database. The case was evaluated as a result of the following INSRP Meteorology Subpanel comment (Reference A10-11):

"The adequacy of the meteorological clustering was not demonstrated. The selection of clusters based on wind direction toward and away from population centers appears arbitrary and appears to lead to serious under sampling of meteorological conditions in some sectors. The adequacy of the clustering technique is not supported in the FSAR by comparison of health effects determined for the same source under conditions for all database days and health effects determined for weighted cluster sample convolution."

The objective of this comparison is to further demonstrate the adequacy of the Cassini LHS 30 observation sampling of the weather-day clusters as defined in the Cassini FSAR (Reference A10-12). The weather-day clusters used in the Cassini analysis utilized wind direction relative to population concentrations including on-shore and off-shore categories. These two categories represent the first level of consequence based clustering. The second level of consequence based clustering is by high population zones for onshore wind directions. An additional level of categorization was the definition of a minimum consequence cluster and maximum consequence cluster. These clusters grouped the maximum and minimum consequence days based on sensitivities studies using each of the key LASEP-T release types (Reference A10-13). These two clusters were defined to assure adequate sampling of the risk significant weather-days without significantly biasing the mean. These two clusters also capture in an integrated fashion the meteorology characteristics that lead to high and low consequence without having to further break down the weather-day clusters into stability classes and wind speed. Further breakdown would have lead to a process with computation times that exceeded the Cassini FSAR analysis schedule requirements. The ability of the Cassini wind categorization technique to reasonable cluster consequences was demonstrated in Volume III, Book 2, Appendix C.5.2 of the Cassini FSAR. The analysis reported here provides additional confirmation of this consequence clustering ability by computing means and CCDF characteristics for selected key consequence measures from a fixed type 3-source term (release into a spacecraft propellant fireball) at a fixed release time.

A10.4.1 Background for the Case Evaluated

The single source term for this analysis was selected to be the nearest type 3 source term to the average type 3 release mass of 14.47 grams from the case 1.1 re-run (Reference A10-10). A type 3 analysis was selected because in Cassini case 1.1 with no coincident impact release (CIR) this release type made up approximately 90% of the releases sampled by LHS. The nearest type 3 release to this mean mass was LASEP-T trial number 6069, which has a total mass of 14.4 grams of PuO_2 . The mission elapsed time for this release record was determined to be 22.8277 seconds. Because this is less than the 25-second cutoff time to exclude the solid propellant burning plume from transport calculations, such a plume was calculated for all trials. A 3:00am release or accident time was also assumed for all trials in this study. This source term was then run for all 150 days in the database and also run using 1, 5, 10, 15, 20, and 30 LHS observations of the ten weather-day clusters.

A10.4.2 Comparison of 150-Day to LHS Results

The mean values of the key consequence measures, 50-year health effects without and with de-minimis, maximum individual dose, and land area contaminated to $>0.2\mu\text{Ci}/\text{m}^2$ are summarized in Table A10.4-1. The percentage difference between the various LHS observation number cases (i.e., 1, 5, 10, 15, 20, and 30) and the 150-day best estimate case is also shown in Table A10.4-1. The 50-year mean health effects without de-minimis is 2.5% higher using the 30 observation (300-day) LHS sample as compared to the 150-day best estimate, while the with de-minimis prediction is 4.3% higher than the 150-day sample. The mean maximum individual dose is underestimated by the 30 LHS observation case by 2.9% and the mean land contamination is 2.3% higher than the 150-day sample case.

The mean values of the 50-year health effects without and with de-minimis, maximum individual dose and land area contaminated to $>0.2\mu\text{Ci}/\text{m}^2$ are plotted versus the number of LHS observation in Figures A10.4-1 through A10.4-4, respectively. For all consequence measures the 30-observation case is within 5% of the best estimate using all 150 days of the database. Figure A10.4-5 is a comparison of the full variability in the 50-year health effects for case 1.1 without coincident impact releases to the 150-day variability associated with the

Table A10.4-1. Comparison of 150-Day Results versus the Number of LHS Observations for Key Consequence Measures

Number of LHS Observations	Mean 50 Year Health Effects w/o De-minimis	Mean 50 Year Health Effects With De-minimis	Mean Maximum Individual Dose to > 1 Person (rem)	Land Contaminated to >.2Micro Ci/sq m (sq km)
1	1.950e-01	9.477e-02	1.332e-02	3.610e+00
5	1.286e-01	4.796e-02	1.021e-02	3.777e+00
10	1.064e-01	3.175e-02	1.075e-02	3.815e+00
15	1.003e-01	2.904e-02	1.116e-02	4.073e+00
20	9.784e-02	2.823e-02	1.233e-02	4.019e+00
30	9.792e-02	2.838e-02	1.259e-02	3.933e+00
All 150 days	9.553e-02	2.721e-02	1.297e-02	3.846e+00
Percentage Difference From All 150 Day Run				
1	104.1	248.3	2.7	-6.1
5	34.6	76.2	-21.3	-1.8
10	11.3	16.7	-17.1	-0.8
15	5.0	6.7	-14.0	5.9
20	2.4	3.8	-5.0	4.5
30	2.5	4.3	-2.9	2.3
All 150 days	N/A	N/A	N/A	N/A

Figure A10.4-1. Compare Mean 50-Year Health Effects without de-minimis for All 150 Days and as a Function of the Number of LHS Observations for a Typical Type 3 Release

Figure A10.4-2. Comparison of Mean 50-Year Health Effects with de-minimis for All 150 Days and as a Function of the Number of LHS Observations for a Typical Type 3 Release

Figure A10.4-3. Comparison of Mean Max. Individual Dose for All 150 Days and as a Function of the Number of LHS Observations for a Typical Type 3 Release

Figure A10.4-4 Comparison of Mean Land Area Contaminated to $>0.2 \mu\text{Ci}/\text{m}^2$ for All 150 Days and as a Function of the Number of LHS Observations for a Typical Type 3 Release

Figure A10.4-5. Comparison of Case 1.1z_no CIR and LASEP Trial 6069 50-Year Health Effects Variability CCDFs

type 3 LASEP-T trial 6069 at 3:00am. Figure A10.4-5 puts the single source term case into perspective relative to the Cassini results for case 1.1. Figure A10.4-6 compares the 150-day and 30 LHS observation CCDFs for the 50-year health effects without de-minimis.

The 30 LHS sample case is compared in Figure A10.4-6 to the 150-day case because 30 observations were typically used in the Cassini FSAR pre-launch and early launch phase accident analyses. The tails of the CCDFs are slightly different because in the 150-day case the maximum health effects day is 891010 which was not sampled in the 30 LHS observation case. The weather-day 891010 (10 October 1989) is part of cluster 8, which has 56 possible days; thus it is not unreasonable that this day was not sampled in a 30 LHS observation analysis.

Figure A10.4-6. Comparison of LASEP Trial 6069 150-Day Case and 30 LHS Observation Case
 50-Year Health Effects Variability CCDFs

Normally this day would have been expected to be in the high consequence cluster, number 9. It is suspected that it was not in cluster 9 because the average release type source term analysis for all days was not re-evaluated when the SRMU plume modeling was incorporated into the SPARRC modeling process for the FSAR Addendum. The cluster analysis was based on the original SPARRC modeling assumptions of no SRMU plume effects. This analysis was not redone because it was felt to be a small effect as demonstrated by these results.

Table A10.4-2 provides a detailed comparison of the 150-day case results to the 15 and 30 LHS observation cases. The 30 observation case means for all of the key consequence measures shown are within 10% of the 150-day results with the exception of worker health effects, which is within 20%. For the 15-observation case all of the means are within 10% with the exception of worker health effects and maximum individual dose which are within 20%.

A10.4.3 Conclusions

The comparison of the 150-day variability case to 30 LHS observations of the Cassini weather-day clusters case shows good agreement for the means and distribution percentiles. This study further demonstrates that the Cassini weather-day clustering and LHS sampling processes are reasonable and adequate for the task. This conclusion was also supported previously by the two 2000 trial Monte Carlo evaluations that did not use Latin Hypercube Sampling (LHS), fuel clusters, or weather-day clusters as documented in Section A10.2 (see also Reference A10-14) and the adequacy of the sector sampling was also demonstrated by plotting the trajectories of all 900 trials for case 1.1z as documented in Section A10.3 (see also Reference A10-15).

Table A10.4-2. Comparison of Key Consequence Measure Distributions for the 150-Day Variability Case and the 15 and 30 LHS Weather-Day Cluster Observation Cases

Key Consequence Measures															
Mean/ Quantile	Prob. of Failure (POF)	Probabilit of Release (Case1.12)	1st Year	50 Year	1st Year	50 Year	50 Year	50 Year	50 Year	50 Year	50 Year	Land Contamination >X microCi/sq. m			
			Health Effects w/o De-minimis	Health Effects w/o De-minimis	Health Effects With De-minimis	Health Effects With De-minimis	Health Effects Resident	Health Effects Worker	Health Effects Off-grid	Maximum Potential Dose (rem)	Maximum Individual Dose>1pers (rem)	X >0.2 (sq km)	X >0.6 (sq km)	X >1.2 (sq km)	X >2.4 (sq km)
150 Day LASEP-T Trial Number 6069 Variability															
Mean	4.19e-03	0.1058	6.26e-02	9.55e-02	2.26e-02	2.72e-02	8.15e-02	2.79e-03	1.12e-02	2.17e-02	1.30e-02	3.85e+00	2.59e+00	2.09e+00	1.66e+00
5th	N/A*	N/A	N-A**	2.30e-03	N-A	6.11e-08	1.02e-05	1.43e-05	8.00e-04	2.66e-03	2.36e-03	2.60e+00	1.97e+00	1.61e+00	1.35e+00
50th	N/A	N/A	N-A	6.00e-02	N-A	4.90e-03	4.15e-02	5.71e-04	1.08e-02	1.17e-02	5.00e-03	3.53e+00	2.50e+00	2.03e+00	1.61e+00
95th	N/A	N/A	N-A	3.12e-01	N-A	1.27e-01	3.09e-01	1.19e-02	2.65e-02	7.52e-02	3.79e-02	5.80e+00	3.48e+00	2.66e+00	2.12e+00
99th	N/A	N/A	N-A	4.24e-01	N-A	2.43e-01	3.83e-01	2.27e-02	3.44e-02	1.23e-01	7.52e-02	8.40e+00	4.47e+00	3.27e+00	2.47e+00
max	N/A	N/A	5.14e-01	8.79e-01	2.95e-01	3.58e-01	N-A	N-A	N-A	1.52e-01	N-A	N-A	N-A	N-A	N-A
15 LBS Observations of 10 Weather Day Clusters															
Mean	4.19e-03	0.1058	6.51e-02	1.00e-01	2.39e-02	2.90e-02	8.70e-02	2.25e-03	1.11e-02	2.19e-02	1.12e-02	4.07e+00	2.66e+00	2.15e+00	1.70e+00
5th	N/A	N/A	N-A	2.29e-03	N-A	1.78e-07	1.02e-05	1.49e-05	9.90e-04	2.38e-03	2.38e-03	2.57e+00	1.95e+00	1.66e+00	1.34e+00
50th	N/A	N/A	N-A	6.04e-02	N-A	5.94e-03	4.95e-02	6.15e-04	1.04e-02	1.20e-02	4.99e-03	3.54e+00	2.48e+00	2.04e+00	1.59e+00
95th	N/A	N/A	N-A	3.29e-01	N-A	1.70e-01	3.14e-01	6.71e-03	2.61e-02	6.79e-02	3.07e-02	6.37e+00	3.62e+00	2.88e+00	2.31e+00
99th	N/A	N/A	N-A	4.24e-01	N-A	1.95e-01	3.83e-01	1.76e-02	2.99e-02	1.03e-01	4.85e-02	1.27e+01	7.42e+00	5.98e+00	4.25e+00
max	N/A	N/A	2.84e-01	4.91e-01	2.10e-01	2.59e-01	N-A	N-A	N-A	1.47e-01	N-A	N-A	N-A	N-A	N-A
30 LBS Observations of 10 Weather Day Clusters															
Mean	4.19e-03	0.1058	6.40e-02	9.79e-02	2.30e-02	2.84e-02	8.46e-02	2.26e-03	1.11e-02	2.17e-02	1.26e-02	3.93e+00	2.62e+00	2.12e+00	1.67e+00
5th	N/A	N/A	N-A	2.30e-03	N-A	6.66e-08	9.54e-06	1.43e-05	9.90e-04	2.66e-03	2.36e-03	2.60e+00	1.97e+00	1.60e+00	1.34e+00
50th	N/A	N/A	N-A	6.03e-02	N-A	4.90e-03	4.43e-02	6.18e-04	1.06e-02	1.20e-02	5.80e-03	3.58e+00	2.48e+00	2.04e+00	1.60e+00
95th	N/A	N/A	N-A	3.29e-01	N-A	1.70e-01	3.14e-01	7.24e-03	2.65e-02	7.26e-02	3.07e-02	6.24e+00	3.62e+00	2.86e+00	2.22e+00
99th	N/A	N/A	N-A	4.24e-01	N-A	1.95e-01	3.83e-01	1.76e-02	3.68e-02	1.23e-01	7.52e-02	1.08e+01	4.52e+00	3.33e+00	2.79e+00
max	N/A	N/A	2.84e-01	4.91e-01	2.10e-01	2.59e-01	N-A	N-A	N-A	1.47e-01	N-A	N-A	N-A	N-A	N-A
Percentage Difference[(15obs-150day)/150day*100]															
Between 15 LBS Observation Case and 150 Day Case															
Mean	0.0	0.0	4.1	5.0	5.8	6.7	6.7	-19.6	-1.1	0.8	-14.0	5.9	2.8	2.7	2.4
5th	N/A	N/A	N/A	-0.7	N/A	190.5	0.0	4.3	23.7	-10.6	0.9	-1.2	-1.0	3.1	-0.7
50th	N/A	N/A	N/A	0.7	N/A	21.2	19.2	7.6	-4.1	3.0	-0.2	0.3	-0.8	0.5	-1.2
95th	N/A	N/A	N/A	5.5	N/A	33.7	1.6	-43.5	-1.5	-9.8	-19.0	9.8	4.0	8.3	9.0
99th	N/A	N/A	N/A	0.0	N/A	-19.7	0.0	-22.5	-13.1	-16.1	-35.5	51.2	66.0	82.9	72.1
max	N/A	N/A	-44.7	-44.1	-28.8	-27.7	N/A	N/A	N/A	-3.4	N/A	N/A	N/A	N/A	N/A
Percentage Difference[(30obs-150day)/150day*100]															
Between 30 LBS Observation Case and 150 Day Case															
Mean	0.0	0.0	2.3	2.5	2.0	4.3	3.8	-19.1	-1.2	-0.0	-2.9	2.3	1.2	1.2	0.9
5th	N/A	N/A	N/A	0.0	N/A	8.9	-6.4	0.0	23.7	0.0	0.0	0.0	0.0	-0.6	-0.7
50th	N/A	N/A	N/A	0.6	N/A	0.0	6.7	8.1	-1.9	3.0	15.9	1.4	-0.8	0.5	-0.6
95th	N/A	N/A	N/A	5.5	N/A	33.7	1.6	-39.1	0.0	-3.4	-19.0	7.6	4.0	7.5	4.7
99th	N/A	N/A	N/A	0.0	N/A	-19.7	0.0	-22.5	6.9	0.0	0.0	28.6	1.1	1.8	13.0
max	N/A	N/A	-44.7	-44.1	-28.8	-27.7	N/A	N/A	N/A	-3.4	N/A	N/A	N/A	N/A	N/A

*N/A Not Applicable

**N-A Not Available

This study also shows that if pressed for processing time, the 15-observation case could also provide a reasonable estimate of the means to within $\pm 20\%$ and percentile values for most cases to within approximately $\pm 40\%$. However, this should probably be demonstrated for a complete analysis case rather than just one release type.

A10.5 EFFECTS OF SELF-INDUCED RAINOUT

In the Cassini risk analysis, wet deposition was not considered for launch accident scenarios. Because the health effects and land contamination would increase significantly in areas affected by wet deposition and the overall consequence results of the simulation could be under-estimated, a sensitivity study was conducted to assess the effect of self-induced rainout. Rainout is the removal process by in-cloud condensation associated with the lifting of warm moist air to high altitudes during plume rise. Washout, the other removal process, is associated with precipitation scavenging of particles by collision with the falling raindrops of a coincidental rain during plume transport. Taking into account the launch constraint that precludes launch in the presence of rain within five nautical miles, washout is considered as a low probability event and will not be discussed.

The work of Carhart and Policastro (Reference A10.5-1) related to the simulation of self-induced rainout from tactical nuclear explosions is used as guidance for this sensitivity study. Among the reported results, the fraction of radioactivity deposition as a function of relative humidity and yield are of interest. The results for the first 30 minutes of transport are considered applicable to the initial rainout from launch accident fire plumes and are reproduced in Table A10.5-1 for information. Assuming conservatively that a high relative humidity applies to all launch accident environments, the value of 11% is used for wet deposition in this sensitivity study.

Table A10.5-1. Percent of Total Initial Radioactivity Deposited at 30 Minutes after Detonation as a Function of Yield and Relative Humidity (Reference A10.5-1)

Yield	Relative Humidity			
	90%	75%	50%	20%
30KT	8.5	9.1	1.2	None
50KT	9.1	10.9	5.2	0.0
100KT	11.0	8.6	6.8	0.1

Three simulations of accident case 1.1 – without coincident impact release, including the mean-, median-, and 99th percentile cases for 50-year health effects were re-analyzed with wet deposition simulation. A set of clouds corresponding to 11% of the source term mass were added to the existing configuration, using the fireball height as release height but with the particle fall velocity set at 206 cm/s, equivalent to a 0.5 mm diameter raindrop. Studies of rain spectra have shown that the peak frequencies usually occur between 0.5 and 1.0 mm diameters (Reference A10.5-2). It should be noted that particles of bin 9 and above (larger than 34.3 μm) are unaffected by the wet removal process because of their high fall velocity. The consequence results from simulations with and without rainout effects are presented in Table A10.5-2 for comparison. As shown, the initial wet deposition due to rainout has a decreasing effect on the health effects of workers and residents. This is due to the low population density in the near-range surrounding the launch pad. Land contamination above 0.2 $\mu\text{Ci}/\text{m}^2$ remains nearly unchanged. The large mass fraction of source term of particles above bin 9, which are unaffected by rainout, dominates the land contamination and therefore the addition of the rainout fraction has not affected the results. Examination of ground deposition patterns from various simulation isopleths show that the difference between cases with and without rainout is small. Thus, from these results it can be concluded that rainout tends to decrease the health effect results in the launch site vicinity and the consequence results for postulated launch accidents as provided in the Cassini GPHS-RTG FSAR are appropriate.

Table A10.5-2. Consequence Results from Simulations with and without Self-Induced Rainout

Simulation	Results	Without Rainout	With Rainout	Difference (%)
Mean case of 50-year health effects	Total 50-year health effects w/o de minimis	7.06×10^{-2}	6.29×10^{-2}	-10.9
	Workers 50-year health effects w/o de-minimis	5.80×10^{-3}	5.2×10^{-3}	-10.3
	Residents 50-year health effects w/o de-minimis	6.48×10^{-2}	5.77×10^{-2}	-10.9
	Land contamination $> 0.2 \mu\text{Ci}/\text{m}^2 (\text{km}^2)$	8.02	8.00	~ 0
Median case of 50-year health effects	Total 50-year health effects without de-minimis	6.17×10^{-3}	5.49×10^{-3}	-11
	Workers 50-year health effects without de-minimis	1.02×10^{-4}	9.65×10^{-5}	-5.4
	Residents 50-year health effects without de-minimis	6.07×10^{-3}	5.39×10^{-3}	-11.2
	Land contamination $> 0.2 \mu\text{Ci}/\text{m}^2 (\text{km}^2)$	3.80	3.80	~ 0
99 th percentile case of 50-year health effects	Total 50-year health effects w/o de-minimis	1.48	1.35	-9
	Workers 50-year health effects w/o de-minimis	1.02×10^{-1}	9.1×10^{-2}	-11
	Residents 50-year health effects w/o de-minimis	1.38	1.26	-8.4
	Land contamination $> 0.2 \mu\text{Ci}/\text{m}^2 (\text{km}^2)$	30.7	30.4	-1

A10.6 EFFECTS OF SPARSE UPPER AIR DATA

For the risk analysis at the launch site, upper air wind data (above 150 m) from daily rawinsondes were converted into a database supporting the standard simulations performed with the SPARRC model SATRAP. A routine rawinsonde is a data collection pertaining to wind velocity, temperature, and pressure from a balloon release once or twice daily. While upper air layers have less variation in wind vectors as compared to the surface layer, there is a concern that an artificial wind shear could be introduced by the time interpolation of the sparse data.

For this study, simulations from accident case 1.1 - without coincidental impact release (referred to as case 1.1z) were reviewed. Note that accident case 1.1 contributed 76% of the phase 1 early launch risk. In modeling the plume trajectory, the more wind vector data points available for the wind field, the more accurate the model. Multiple rawinsondes give the transport model more information to calculate the wind field and interpret the particle cloud's

path from the release site over a given period. Typically rawinsondes are available once a day, at 24-hour intervals. The days with multiple rawinsondes can be used to compare with specific time point values of the interpolated wind field model from the routine limited set of data. Also, the consequence results from a typical particle cloud distribution, dispersed in wind fields generated by both minimum and multiple rawinsonde data sets can be compared.

For this risk analysis case1.1z was used in the comparison because it is the dominant contributor to consequence in the early launch phase. From the 900 simulations of the variability-only analysis, it was found that eight sampled weather-days had multiple rawinsondes available. Table A10.6-1 shows the weather- days and their rawinsondes.

Table A10.6-1. List of Selected Weather-Days with Multiple Rawinsondes

Dates	Number of Cases	Multiple Rawinsondes
25 Oct 91	12	6
11 Oct 90	30	7
30 Oct 90	3	7
6 Nov 90	6	7
15 Nov 90	6	7
18 Oct 89	12	8
17 Oct 89	9	9
12 Oct 87	12	11

Due to the combination of sampled accident time and source terms, the eight weather-days listed above supported a total of 90 accident simulations. This led to 180 runs to provide the minimum and full rawinsonde case output. For the Cassini FSAR risk analysis, the minimum rawinsonde set consisted of three samples over a three-day period. A full rawinsonde has the same first and last samples, yet also includes the multiple rawinsondes for the middle (target) day. The differences in trajectory and dispersal in the wind fields generated by both the minimum and multiple rawinsonde data sets were assessed with trajectory plots and the consequence results were compared. The 50-year health effects - without de-minimis for each rawinsonde set was recorded and the percentage difference between the two values derived.

A. With multiple rawinsonde, cloud passing along shore

B. Without multiple rawinsonde, cloud path offshore along coast.

**Figure A10.6-1. Comparison of Plume Center Traces.
Example of Maximum Difference on Health Effects**

A. With multiple rawinsondes

B. Without multiple rawinsondes

**Figure A10.6-2. Comparison of Plume Center Trace.
Example of Minimum Difference on Health Consequence Results**

Figure A10.6-1 illustrates an example of significant difference in terms of health consequence between the minimum and multiple rawinsonde consequence outcomes. In Figure A10.6-1A, with multiple sets of upper air data, the source term clouds pass over the heavily populated coastal region. In Figure 1B, with limited rawinsonde data, the cloud path is offshore and thus has a significant decrease in health effects. Figure A10.6-2 shows a case where wind shear is insignificant, the cloud path remains unchanged with the multiple rawinsonde data, and therefore the variation in health effects is minimum.

Figure A10.6-3 presents the distribution of health effects difference in terms of percentage for the 90 cases analyzed. The average difference between the minimum and full rawinsonde data sets is 8.7 %, with an average deviation of 32.3%. If the two outlier cases are removed, the average difference between the minimum and full sets of rawinsonde data reduces to 1.1% with an average deviation of 21.9%. The mean 50-year health effects for the minimum and multiple rawinsondes are 0.81 and 0.96, respectively.

Figure A10.6-3. Plot of Percentage of Health Effects Difference between Minimum and Multiple Rawinsondes

Except for some limited extreme cases where significant differences can be explained by onshore and off shore flows, as demonstrated in Figure A10.6-1, the majority of simulations differed by less than 1% between the minimum and multiple rawinsonde data sets. This can be explained in part by the short time interval from the early rawinsonde to the simulated launch time which was between 0:00am to 7:00am. Also, when the cloud path is offshore, the effect of wind shear is irrelevant because there are no population centers affected by the cloud footprint. In conclusion, the difference in consequence predicted from the two methods of analysis, with the minimum and full set of rawinsondes, is considered to be small and the analysis as adopted for Cassini is judged to be adequate.

A10.7 NOCTURNAL STABLE BOUNDARY LAYER

The nocturnal boundary layer, an important parameter in launch accident transport analysis, was evaluated for the Cassini GPHS-RTG FSAR from the surface temperature and wind data, using the Benkley-Schulman Model (referred herein as BSM - Reference A10.7-1). Because detailed temperature profiles were not available at the time of preparation of the meteorology database, for the FSAR an approximated model formula, recommended by the same authors, was adopted. In its review of the FSAR, (Reference A10-1) the INSRP MET panel considered this model to be inappropriate and suggested that a different method based on the height of the ground-based inversion temperature should be considered. With the recent acquisition of additional data from TT-NUS (Reference A10.7-2), an investigation was carried out to assess the suggested method and to compare with the FSAR results as well as the rigorous BSM results. It should be pointed out that, previously TT-NUS had provided two databases, one with a fixed 500 m mixing height for all weather-days (Reference A10.7-3) at the beginning of the Cassini program and another with evaluated ground-based inversion heights (Reference A10.7-4) before the analyses of the FSAR. Due to limited time availability for processing, the mixing height values from the latter database were not used for the Cassini FSAR but were retrieved in this study for comparison with the BSM results.

Before going into detail of the analysis, it is useful to define the atmospheric boundary layer. The Atmospheric Boundary layer (ABL) is defined as the near-ground layer of the troposphere influenced by surface forcings with a time scale of one hour or less. The surface forcings include phenomena such as heat transfer, frictional drag, evaporation and terrain

induced flow modification. The ABL height is quite variable, ranging from hundreds of meters at nighttime to one or two kilometers at mid-day. Since the ABL is where surface emitted pollutants disperse and eventually become well-mixed, it is commonly known as the mixing height in dispersion meteorology. During daytime, the ABL is structured with a unique mixed layer, usually convectively driven by heat transfer from warm ground surfaces and radiative cooling from the top of the cloud layer. At nighttime, it subdivides into a stable boundary layer adjacent to the ground and an upper layer called a residual layer. Within the stable boundary layer, turbulence is mostly suppressed and the emitted pollutants disperse relatively little in the vertical direction. If injected in the residual layer, the pollutants rarely disperse down to the ground because of limited turbulence at low levels and they can be advected for long distances until being reached by the rising daytime mixed layer.

Predictions of the nocturnal mixing height with BSM was based on the temperature and wind data measured at two levels, $z_1 = 3.8$ m and $z_2 = 16.6$ m, using the formula:

$$h = a \frac{u_*}{f} \quad [\text{A10.7-1}]$$

Where $a = 0.185$, f is the Coriolis parameter, and u_* is the mean friction velocity for the time interval of interest. The friction velocity was evaluated with:

$$u_* = \frac{k u_1 - k \beta \frac{g}{T_0} \frac{\Delta \bar{\theta}_1}{\Delta \bar{u}} z_1}{\ln(z_1/z_0)} \quad [\text{A10.7-2}]$$

where:

$k = .35$, $\beta = 4.7$, $g = 9.81 \text{ m/s}^2$, $z_1 = 3.8 \text{ m}$, $z_0 = 0.01 \text{ m}$, $\Delta \bar{\theta}_1$ is the difference in potential temperature, $\Delta \bar{u}$ is the difference in wind speed, and T_0 is the ambient temperature in Kelvin. As shown, the model requires wind speed and temperature to be known at two levels, preferably about 10 m apart to represent the surface layer data. Lacking these measurements, Benkley and Schulman suggested using the wind as a logarithmic profile and reduced Equation [A10.7-1] to:

$$h \approx C\bar{u} \quad [A10.7-3]$$

In the above formula, the wind speed is computed for a 3-hour average and the constant C is equal to 90 for best fitting their experimental data. Equation [A10.7-3] was used for the FSAR.

The wind and temperature data from towers 313 and 110 were received for this study, with tower 110 located about one km from the Cassini launch pad (40). Examination of the data revealed tower 313 usually provided a lower surface temperature at the 3.8 m level, and thus appeared to confirm that its lowest collection level is in a hollow. For that reason, data from tower 110 were used for evaluating the friction velocity. Tower 313, which has the highest level of measurement (150m), was used for potential inversion height. Using Equation [A10.7-2], the friction velocity was evaluated with temperature and wind measurements average over a half-hour. If the data of a weather-day were found to induce uncharacteristically low or negative values for the friction velocity ($u_* < 0.025$ m/s), that weather-day was eliminated. Any unstable temperature gradients ($\Delta\bar{\theta}_i < 0$) are assumed to be an artifact of the averaging process at separate levels and a neutral condition is used.

Tables A10.7-1 and A10.7-2 show the comparison of different mixing heights calculated with different models for October 1990 and 1991. Derived from the early rawinsonde profiles, the ground-based inversion heights from TT-NUS do not correlate with the 3:00am inversion height from tower data. While the rawinsonde data can only provide a one time point measurement, the tower data are limited by the maximum measurement height of the tower, and thus the latter values are always less than 150 m. But most importantly, this method of evaluating the nocturnal boundary layer with the inversion height leaves many days without values. Table A10.7-3 shows a significant number of weather-days without any inversion height, especially in 1987. Comparison of the approximate values as used in the FSAR and the values from BSM shows an average of difference about -6% and -20% for 1990 and 1991, respectively. In general, usage of the 3-hour average wind speed instead of evaluation of the friction velocity has led to a slight over-estimate of the mixing height.

Table A10.7-1. Comparison of Mixing Height Values for October 1990

Day	Mixing Height From FSAR (m)	Inversion Height from TT-NUS (m)	Inversion Height From Tower Data (m)	Mixing Height From BSM (m)	Δ (TTNUS - FSAR)	Δ (BSM - FSAR)
3-Oct	280		32	316		12.90%
4-Oct	293	52	31	360	-82.25%	22.77%
5-Oct	195	209	21	109	7.18%	-44.10%
6-Oct	270			265		-1.68%
7-Oct	376	43	16	447	-88.56%	18.86%
8-Oct	414		23	458		10.58%
9-Oct	593		22	632		6.61%
10-Oct	600		23	698		16.27%
11-Oct	553		62	600		8.41%
12-Oct	493		77	294		-40.30%
13-Oct	251			283		12.91%
14-Oct	280	41		109	-85.36%	-61.07%
15-Oct	182		31	38		-79.35%
16-Oct	347	93	38	338	-73.20%	-2.62%
17-Oct	406		25	447		10.08%
18-Oct	247		32	327		32.39%
19-Oct	230		24	109		-52.61%
20-Oct	512			392		-23.36%
21-Oct	213	109		371	-48.83%	74.00%
22-Oct	359			436		21.45%
23-Oct	235	39		218	-83.40%	-7.23%
24-Oct	268			196		-26.79%
25-Oct	312		1	338		8.30%
26-Oct	458		14	501		9.48%
27-Oct	330	156		338	-52.73%	2.40%
28-Oct	280	99		153	-64.64%	-45.50%
29-Oct	306	204		218	-33.33%	-28.76%
30-Oct	385	57	42	305	-85.19%	-20.72%
Average	345	100		332	-62.76%	-5.95%

Table A10.7-2. Comparison of Mixing Height Values for October 1991

Day	Mixing Height from FSAR (m)	Inversion Height from TT-NUS (m)	Inversion Height from Tower Data (m)	Mixing Height From BSM (m)	Δ (TTNUS - FSAR)	Δ (BSM - FSAR)
1-Oct	603		55	632		4.85%
2-Oct	271	202	31	101	-25.46%	-62.85%
3-Oct	240	208		218	-13.33%	-9.16%
7-Oct	497		20	294		-40.78%
8-Oct	559		25	480		-14.20%
9-Oct	452		45	349		-22.83%
10-Oct	202		24	66		-67.32%
11-Oct	221	246		207	11.31%	-6.29%
12-Oct	261	63		294	-75.86%	12.76%
13-Oct	262	356		174	35.88%	-33.43%
17-Oct	299	193		251	-35.45%	-16.15%
22-Oct	166	49	19	62	-70.48%	-62.39%
23-Oct	292			259		-11.16%
24-Oct	494	105		506	-78.74%	2.49%
25-Oct	493		282	515		4.43%
26-Oct	331	44		398	-86.71%	20.36%
27-Oct	409	50	44	395	-87.78%	-3.52%
28-Oct	232	46		80	-80.17%	-65.66%
30-Oct	538			473		-12.17%
31-Oct	259	117		205	-54.83%	-20.87%
Average	354	141		269	-46.80%	-20.20%

Table A10.7-3. Number of Days without Inversion Height from TT-NUS Database

Oct-87	23
Oct-88	15
Oct-89	17
Oct-90	17
Oct-91	10
Oct-92	9
Oct-93	12
Nov-90	4
Nov-91	11
Nov-92	15
Nov-93	8

In order to compare more closely the FSAR values to the BSM results, separate scatter plots were created with a linear regression fit for October 1990 and 1991. Figures A10.7-1 and A10.7-2 show the relationship between the BSM results and the FSAR values. Although the slope of the linear fit is less than one, a positive offset value is applicable to the FSAR results, indicating that the approximate formulation based solely on wind speed [Equation A10.7-3] tends to over-estimate the stable boundary layer. The data were found to be well correlated, with a Pearson factor r at 0.83 and 0.90 for the 1990 and 1991 data, respectively.

Figure A10.7-1. Comparison of FSAR Mixing Height to the Predictions Using Detailed Tower Data – October 1990

Figure A10.7-2. Comparison of FSAR Mixing Height to the Predictions Using Detailed Tower Data – October 1991

The FSAR mixing height values were further reviewed with an examination of values for all 150 weather-days estimated for 3:00am. Figure A10.7-3 shows only four extreme cases that exceed 600 m and an average height about 328 m. This average value is typical for nocturnal conditions. It should be pointed out that, most of the launch accident simulations involved large plumes from a solid fuel propellant fire, and in such conditions, the potential source terms are injected above and below the mixing height. It is believed that over-estimating the mixing height in those simulations tends to produce conservative consequence results because more source terms (below the mixing height) would be subject to near-range transport effects.

Figure A10.7-3. FSAR Mixing Height Values Evaluated at 3:00am

Most authors recognize that prediction of the nighttime ABL has proven to be more difficult and less reliable than the daytime ABL height. Direct measurements with acoustics sounder and lidar, which are not available for most routine meteorological observations, are considered as the only reliable means. Based on data taken from the Great Plains Experiment, the results from Hanna (Reference A10.7-5) show that the ground-based inversion height has no significant correlation with the equilibrium ABL height. Yu (Reference A10.7-6) compared various nocturnal boundary layer models and concluded that the ground-

inversion height has no significant correlation with the equilibrium ABL height. Yu (Reference A10.7-6) compared various nocturnal boundary layer models and concluded that the ground-based inversion height exhibits the least correlation with the various measured heights. In a critical assessment of different models proposed for the stable boundary layer, Arya (Reference A10.7-7) recommended three models, one of which very similar to the one proposed by Benkley and Schulman. He used the coefficient a in Equation [A10.7-1] equal to 0.142 instead of 0.185. Arya also concluded that the inversion height based on either the discontinuity of the temperature gradient or on the extent of cooling height from the ground is a poor measure of the nocturnal mixing height. Garret (Reference A10.7-8) found that the Benkley-Schulman model, while relying only on surface temperatures and wind values measured from routine observations, could provide good results, comparable to other sophisticated models of the National Weather Service.

From the above findings, it can be concluded that:

1. Due to the lack of detailed input data, the values of the nocturnal boundary layer as used in the FSAR analyses are slightly over-estimated but not unreasonable. The average value of the mixing height, evaluated at 328 m for all weather-days at 3:00am, is typical for nighttime regime. Out of 150 weather-days, only 4 days have a mixing height exceeding 600 m due to the approximate formula.
2. Given more surface temperature data, the Benkley-Schulman model can be applied with an average input from several wind stations to estimate the surface friction velocity. Routine observations at wind towers have not focused on the actual gradient temperature but separately collect data at various levels, and thus the averaging process can introduce spurious inputs to the model.
3. The ground-based inversion height as suggested by INSRP is not a good measure of the nocturnal boundary layer. It is not practical for the obvious reason that, in situations where there is no inversion, the boundary layer cannot be evaluated.

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Part B

Facilities Transition

PART B

FACILITIES TRANSITION

Due to the Lockheed Martin Corporation plans to discontinue the lease of Building B, equipment, tools, and supplies felt to be necessary for maintaining key thermoelectric capabilities and support engineering development work were temporarily stored in eighteen locked and sealed trailers at the end of 1997. A meeting was held with Facilities representatives in March 1998 to develop plans for setting up these capabilities in the Building 100, King of Prussia Lockheed Martin facilities. At that meeting, the Facilities representatives proposed usage of certain areas in the M8500/M8600 section of the first floor and several additional rooms in the U8600/U8400 laboratory areas. These recommendations were based on surveys of the equipment while still installed in Building B and detailed requirements and priorities as identified by the Space Power Program Office. The areas selected were to become available in the near future, would minimize the renovation/equipment utility installation requirements and additionally had some clean room facilities that are costly to construct new. As these areas were relatively contiguous and near the planned Space Power Program Office area in U8620, an agreement was made to have the Facilities organization proceed with detailed planning and obtaining of cost estimates.

On 20 April 1998, building renovation activities started in the M8500/M8600 area. Equipment installations and renovations were completed by 30 September 1998. Checkout of the equipment and processes occurred during and following completion of the installations. A review was performed for operational, safety, and preventive maintenance readiness of the equipment. Certain processes not expected to be immediately used were given a less rigorous startup evaluation.

Capabilities include seven life test furnaces, four Denton vacuum chambers for component testing, a complete Metallography Lab, a Scanning Electron Microscope (SEM), a Machine Shop including Electrical Discharge Machining (EDM) capability, specialized hydrogen firing and brazing equipment, sputtering equipment, a Materials Engineering R&D Lab, air firing and vacuum bake out equipment, and other lab and shop areas needed to support power generator fabrication, inspection, assembly, and testing. Support areas such as Tool Control,

Stockroom, Receiving, and Receiving Inspection were established. A decision was made early on to forgo installation of the Plating Facility as an immediate need at this juncture has not materialized. The Plating Line equipment was placed in temporary storage until a final determination is made. Table B-1 lists a breakdown of the shop and laboratory areas that have been established in Building 100. Figure B-1 shows a layout of the first floor shops and laboratories.

A concerted effort was made to utilize, wherever possible, existing room configurations, HVAC, and utility distributions to minimize the installation costs for the equipment.

A separate element of this project was associated with the fact that Building 800, one of the out buildings at the same site, was to be dismantled to make way for a new road. Lockheed Martin Corporation agreed to remove one of the Loading and Assembly Stations (LAS) with associated equipment and reinstall and check it out in the Building 100 Space Power area. Modifications to the lab area to allow the LAS equipment installation were provided under the Cassini GPHS-RTG Program. The equipment has been installed and checkout of the LAS was nearing completion at the time of this report.

Table B-1. Breakdown of Space Power/Laboratory Areas

LOCATION	SHOP/LAB AREA DESCRIPTION	AREA (SQ FT)
M8539	BACK AISLE, ADD'L COMPONENT TEST	912
M8537	COMPONENT TEST	982
M8533	LIFE TEST	864
M8529	LAS PROCESSING (FORMERLY BLDG 800)	1008
M8527	SLICING	375
M8523	WAFERING / GRINDING	450
M8521	MACHINE SHOP	1056
M8500	MAIN AISLE	582
M8524	EDM MACHINING	522
M8532	RECEIVING INSPECTION	932
M8538	SCANNING ELECTRON MICROSCOPE (SEM)	448
M8526	CLEANROOM DRESSING ROOM	144
M8639	TEST / MAINTENANCE STOCKROOM	588
M8635	EHS ASSEMBLY LAB	648
M8635	EHS AIR OVEN / VACUUM FURNACES	504
M8625	SYSTEM VII VACUUM FURNACE	100
M8623	PARTS DEBURRING	110
M8621A	CLEANROOM CARGO ENTRANCE	160
M8621B	FOIL AND CLOTH FAB	880
M8621C	PARTS CLEANING	288
M8621D	FINAL ASSEMBLY CLEANROOM	247
M8613	MET LAB	1072
M8304	INCOMING MATERIAL RECEIVING AREA	528
U8447-57	STOCKROOM	1824
U8428	TOOL CONTROL	460
U8609	ENGINEERING R & D	1596
U8613	HAYES FURNACE / SPUTTERING	1067
U8623	MRB / CONFIGURATION CONTROL	420
U8619	INPROCESS INSPECTION	912
	TOTAL SHOP / LAB AREAS	19679

Figure B.1. Layout of the Shops and Laboratories (First Floor - Building 100)