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Aerospace Nuclear Safety Program

PIONEER F/SNAP 19 HEAT SOURCE ABLATION STUDIES

by D. W. CONN

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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FORWARD

The work reported herein was conducted by the Applied Physics Laboratory Aeronautics Division for the Atomic Energy Commission, Safety Branch, Space Nuclear Systems Office. Activities of the Aeronautics Division are under the general supervision of Dr. William H. Avery. The Project Engineer for the Aerospace Nuclear Safety Program is James C. Hagan.

ABSTRACT

A series of studies were conducted to assess the ablation performance of the Pioneer F/SNAP 19 heat source for various analytical thermochemical and mechanical erosion models. One of the specific objectives of this study was to evaluate the oxidation cut-off concept employed in past reentry safety analyses versus more physically representative oxidation models. It also afforded an opportunity to obtain a gross assessment of heat shield performance for oxidation models representative of the graphite mass loss data measured at (a) General Electric and (b) NASA Langley Research Center. These studies were extended to investigate the effects of different graphite sublimation models on heat shield performance and attempted to consider "mechanical erosion" effects heretofore omitted in reentry safety analyses.

Finally, uncertainties present in current graphite ablation predictive techniques and specifically, within the recommended model of these studies are discussed and demonstrated in terms of heat source ablation performance.

SUMMARY

A series of studies were conducted to assess the reentry ablation performance of the Pioneer F/SNAP 19 heat source for various analytical thermochemistry and mechanical erosion models. Results of the oxidation studies indicated the simple oxidation cut-off model used in Teledyne-Isotope's safety analysis can be justified only if the cut-off temperature is specified at about 1500°F. This specification essentially equates the model to the Fast Rate model (Fig. 2) and will predict slightly conservative (higher) oxidation losses when compared to APL's currently recommended Moderate Rate oxidation model. The oxidation studies further indicated a significant amount of heat shield recession can be attributed to oxidation during subsonic reentry (typically, 50 to 55 mils for shallow reentries). A gross model (Very Slow Model, Figure 2) of NASA Langley's oxidation data was evaluated against the Moderate Rate model (which represents G.E. data) for effects on heat shield performance for an orbital decay reentry. The results indicated a 50% reduction in predicted heat shield recession for the Very Slow model. The NASA Langley data and G.E. data are currently in conflict and, from this gross comparison, can yield substantial differences in predicted heat shield performance. The mechanical erosion effect resulted in total heat shield recession varying from a 25% increase over thermochemical predictions to prompt ablation failure.

Uncertainties within the APL recommended model include formulation solely on the basis of experimental ATJ ablation data

and absence of pressure effects in the mechanical erosion model. Uncertainties of a more basic nature concern the true kinetic mechanisms of carbon oxidation and the thermodynamic characteristics of the higher order carbon vapor species forming during sublimation at elevated temperatures. APL's model has assumed a conservative position in light of limitations and/or uncertainties within the available data. Significant refinements in graphite ablation modelling will require (a) extended experimental research to precisely define the fundamental aspects of carbon oxidation and vaporization and (b) an extended experimental data base for graphite materials of current interest in heat source designs.

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I. INTRODUCTION

The oxidation cut-off concept has been used both by Sandia and Teledyne-Isotopes in their Pioneer F SNAP 19 heat source reentry safety analyses. It has been indicated by both Sandia⁽¹⁾ and APL⁽²⁾ that this approach for determining oxidation effects can lead to significant differences in predicted graphite recession as well as moderate differences in structural impact temperature depending upon the choice of the cut-off temperature. This memo reports on a study that evaluated the cut-off concept by examining more physically representative oxidation models for several Pioneer F heat source reentries. It also permitted an opportunity to obtain a gross assessment of the effects on heat shield performance for oxidation models representative of (a) the G.E. experimental graphite mass loss data⁽³⁾ and (b) the NASA Langley data of Maahs⁽⁴⁾ and Miller/Sutton⁽⁵⁾. Additionally, the study was extended to investigate the effect of widely varying graphite sublimation models on heat shield performance and attempts to consider "mechanical erosion" effects heretofore omitted in reentry safety analyses.

II. OXIDATION STUDIES

A. Oxidation Cut-Off Concept

The continuous curve in Figure 1 depicts the classical oxidation rate profile experienced by a reactive surface under boundary layer influences and is characterized by reaction rate controlled, transitional and diffusion-limited oxidation regimes. Although the precise shape of this rate profile, which suggests a simple Arrhenius kinetic behavior, can be argued in light of current investigations (e.g., Maahs⁽⁶⁾ and Baron and Bernstein⁽⁷⁾), it does serve to indicate the basic regimes that should be considered in an oxidation model. The oxidation cut-off concept represents a simplification of this profile as illustrated by the dashed lines in Figure 1. This simplified model indicates that above a specified surface temperature, oxidation proceeds at a diffusion limited rate whereas below it, oxidation is inhibited. The basic weakness of this model is the general lack of criteria for selection of a cut-off temperature.

B. Oxidation Models

Perini⁽⁸⁾ has recently conducted a survey on both the theoretical and experimental aspects of graphite ablation. A result of this survey was a compilation of experimental oxidation data for ATJ graphite as shown in Figure 2. The oxidation mass loss data have been normalized by the corresponding diffusion limited rate, m_D . The literature showed ATJ to be the only artificial grade of graphite that was extensively tested over the total oxidation regime. Data on the POCO graphites (current heat shield materials for RTG heat sources) were piecemeal and generally

lacked supporting data to permit normalization in the manner shown in Figure 2. The compilation can be described by two basic sets of data within the rate controlled and transitional oxidation regimes; that is, the data set owing basically to the investigations at G.E.⁽³⁾ and the data set from the investigations at NASA Langley^(4,5). These sets of data are conflicting and have been a continuing subject for discussion at past Pioneer F nuclear safety review meetings. The NASA Langley data represent a portion of the data base that has led Maahs⁽⁶⁾ to suspect that kinetic controlling mechanisms may be prominent in determining graphite oxidation losses at temperature levels previously thought to be solely diffusion-limited. To date, the causes for the differences in these data sets have not been resolved.

Figure 2 also includes several classical oxidation models that bracket the experimental data. Specifically, the "Fast" Rate model provides a left hand extremum, the "Very Slow" Rate a right hand extremum while the "Moderate" Rate model provides a reasonable representation of the large data set measured at G.E. One of the recommendations resulting from the APL survey⁽⁸⁾ was to use the Moderate Rate model to predict oxidation behavior for graphite. This recommendation is not to be interpreted as a refutation of the NASA Langley data but rather one which models a data base that yields greater ablation predictions. This is in keeping with the general philosophy of conservatism for reentry safety analyses when confronted with uncertainties (in this instance, experimental oxidation data).

It was decided to evaluate the Fast, Moderate and Very Slow oxidation models for a common Pioneer F heat source reentry. The orbital decay reentry was selected for this purpose since heat shield surface temperatures are limited to the oxidation regime, (i.e., less than 5000°F). An evaluation of this type is meaningful for the following considerations:

(1) Oxidation sensitivity can be established between APL's current recommended Moderate Rate Model and the extreme Fast Rate Model.

(2) The Very Slow Rate Model is a gross representation of the NASA Langley oxidation data. Therefore, a comparison of this model with the Moderate Rate Model will give an indication of the sensitivity on heat shield oxidation response resulting from the conflicting data sets of G.E. and NASA Langley.

(3) Finally, a comparison of the Fast and Slow Rate Models will index the bounds on heat shield oxidation response as dictated by the currently observed range of experimental graphite oxidation data.

C. Thermal Model and Surface Energy Balance

The thermal model shown in Figure 3 is a one-dimensional cross section of the Pioneer F heat source at the windward, mid-span, stagnation location for a flat leading, side-on-stable reentry attitude. This model considered temperature dependent thermal properties, a fixed gap distribution and a specific fuel power level

as defined in the T-I thermal analyses. The model is intended solely to assess the effect on ablation response of the various oxidation models previously discussed in Subsection B. The resulting temperature data should be viewed solely on a comparative basis rather than per se since the model is void of circumferential conduction effects.

The general surface energy balance for this study is shown in Figure 4 and is modeled after the phase interface control volume concept of Spalding⁽⁹⁾. With exception of the surface enthalpy fluxes, the indicated energy components are self explanatory (see Nomenclature). Solid carbon represents the transferred substance at the interface, being introduced into the control volume in its solid state at the rate, $\dot{m}_L$, and removed at a rate $\dot{m}_L^*$, due to particulate erosion, and at $\dot{m}_S$ in a gaseous state due to thermochemical transformation. Consequently, the resulting enthalpy flux, $\dot{m}_S h_S$, results from the heterogeneous reaction of solid carbon with boundary layer oxidants wherein (a) h_S is the resulting sensible and chemical enthalpy of the reaction products based on equilibrium thermochemistry and (b) $\dot{m}_S$ is the mass loss rate based on the oxidation models of Figure 2. Equilibrium surface thermochemistry solutions were obtained from the EST⁽¹⁰⁾ and/or NOTS⁽¹¹⁾ computer codes for the simplifying assumptions of unity Lewis Number and equal specie diffusion coefficients. These thermochemistry data were utilized in solving the governing surface energy balance and resulting in-depth thermal response of the heat source model via the CMA code⁽¹²⁾.

D. Results and Discussion

The results of the orbital decay reentry analysis are summarized in Table 1 in terms of the heat source's critical design parameters, i.e., total heat shield recession, clad member peak temperature and strength member impact temperature. A comparison of heat shield recession histories during the heat pulse and terminal phases of reentry is shown in Figure 5. The Fast and Moderate Rate oxidation models do not yield substantial differences in either predicted recession or structural temperatures. The Fast model predicted 4% greater total recession than the Moderate model due to (a) earlier initiation of oxidation during reentry and (b) continued operation in the diffusion limited regime during terminal reentry. This small difference would be even further reduced for steeper reentries due to faster surface temperature transients. It is noted in this figure that a significant amount of recession (.055") occurs during the subsonic terminal phase of reentry.

The Very Slow oxidation model causes a 50% reduction in recession from the levels predicted for the Fast and Moderate models. Although a portion of this difference can be attributed to the oxidation model's flatter profile, the principal effect is shown in Figure 5 to be the inhibition of oxidation during the final 200 seconds of flight. This, of course, relates to the termination of oxidation effects at or below approximately 2100°F as defined by this model. It is of interest to note that a 2100°F surface temperature occurs at approximately Mach 1 with

the Fast and Moderate Rate models. Consequently, if a 2100°F cut-off temperature was specified for an oxidation cut-off model (as considered in the T-I analyses), the entire subsonic recession profile shown in Figure 5 would be unaccounted for within the analysis. This illustrates the hazard of over-specifying a cut-off temperature when employing an oxidation cut-off model.

Table 1 indicates a negligible effect from the various oxidation models on predicted peak clad temperatures. However, the Very Slow model results in predicted strength member impact temperatures 90 to 100°F lower than the other models which again points to the absence of surface oxidation effects during terminal reentry. Figure 6 compares the strength member temperature and heat shield surface temperature histories during terminal reentry for the Fast and Very Slow Rate oxidation cases. The divergence in temperature response of the strength member results from differences in radial heat transfer during cool-down due to significant differences in the response of the shield's surface temperatures. The shield temperature resulting from the Very Slow model continues to decay due to an absence of exothermic heating to the surface attributable to carbon oxidation. On the other hand, exothermic heating from the Fast model sustains surface temperatures at significantly higher levels. It is noted that the surface temperature for the Fast model remains at a sufficient level to sustain carbon oxidation at a diffusion limited rate throughout the entire reentry flight period. This is an important observation since an identical behavior would

be obtained from an oxidation cut-off model if the cut-off temperature is specified at a sufficiently low value. It is further noted that the rapid kinetics of the Fast Rate model results in a profile which approximates an oxidation cut-off model at a cut-off surface temperature of about 1500°F. Consequently, it would appear the cut-off oxidation concept can be justified in heat source reentry analyses if the cut-off criterion is specified at a temperature level of about 1500°F rather than at the higher levels as employed in past safety analyses. The 1500°F criterion would essentially equate the cut-off model to the Fast Rate model and, as noted from this study, will predict slightly higher oxidation losses than obtained from the recommended Moderate Rate model.

III. SUBLIMATION STUDIES

A. Sublimation Models

APL's survey⁽⁸⁾ of graphite ablation behavior also included the sublimation regime. The experimental ATJ data of Lundell and Dickey⁽¹³⁾ were the only quality graphite data found within the sublimation regime for a stagnation pressure range synonymous with heat source reentries. This data set is also shown in Figure 2 for a 1 atmosphere pressure level. The data set has been used by APL as the basis for selection of a recommended sublimation model. In that Lundell and Dickey observed mechanical erosion effects during ablation of their test specimens, it is reasonable to expect thermochemical predictions of sublimation to be somewhat less than the measured data for comparable surface temperature and pressure conditions. On this basis, APL has currently selected a JANAF (69) equilibrium model to provide thermochemical predictions⁽⁸⁾. This model is shown in Figure 2 to fall slightly below the experimental data in the sublimation temperature range. Figure 2 also indicates the Scala model⁽¹⁴⁾ compares reasonably well with the JANAF model except at the extreme temperatures. The thermochemical model of Dolton, et. al.⁽¹⁵⁾ represents an extreme for determining sublimation rates and is shown in Figure 2 to vastly overpredict Lundell and Dickey's experimental data set. It was decided to investigate heat shield performance for a typical superorbital reentry (i.e., a 8°/40K fps initial flight condition) for both the Dolton and JANAF thermochemical sublimation models. The

same heat source thermal model and surface energy balance as described in Figures 3 and 4 were considered in these studies.

B. Results and Discussion

Figure 7 compares recession profiles for a $-8^{\circ}/40\text{K}$ fps superorbital reentry resulting from (a) the three oxidation models discussed in Section II coupled with the APL recommended JANAF sublimation model and (b) the APL recommended Moderate Rate oxidation model coupled with the conservative Dolton sublimation model. Differences in recession for Curves 1, 2 and 3 do not occur until the heat shield experiences cool-down. The effects of the different oxidation models are the same as previously discussed for the orbital decay analysis. Note once again the small differences in recession resulting between the Fast and Moderate oxidation models. Furthermore, the use of a 2100°F cut-off temperature would again eliminate the entire subsonic recession region. The discrete effects of the various oxidation models on recession are not sizable during the early period of the heat pulse (35 to 40 second) due to rapid surface temperature transients. Comparison of Curve 4 with Curve 2 (the APL recommended total thermochemistry model) illustrates the effects of the different sublimation models. The large sublimation rates occurring with the Dolton model (e.g., at 50 seconds) leads to eventual burn through of the heat shield. The comparison emphasizes the point that rational criteria must be used in selecting a thermochemistry model (Lundell and Dickey's experimental data set in this case) rather than merely choosing the extreme conservative model for

ablation calculations. The use of Dolton's sublimation model for the Pioneer F heat source ablation analyses would have probably identified a substantial V-X ablation failure space.

C. Mechanical Erosion Models

The results of Figure 7 are based on thermochemical recession predictions only. This analysis was extended to include mechanical erosion effects in the manner suggested by Lundell and Dickey⁽¹³⁾. Specifically, the data set of Lundell and Dickey was reduced to a 'mechanical erosion' component by predicting, via the JANAF (69) model, the thermochemical component at each data point's respective temperature and pressure condition. Therefore, to provide proper context, mechanical erosion is defined herein as the difference between measured data and the currently recommended thermochemical model predictions. This scheme is discussed in further detail in (8). The resulting reduced data are shown in Figure 8 and do not indicate any discernible pressure effect over the pressure range of the test series (i.e., .5-4 atm). Consequently, a curve fit through the data was determined solely as a function of surface temperature⁽⁸⁾ and is defined as Model 1 in Figure 8. It should be noted, however, that this model appears to be statistically biased at the extreme temperatures ($>3750^{\circ}\text{K}$) since (a) there is a paucity of data in this region and (b) the existent high temperature data were collected solely at the higher pressure test conditions. Therefore, an alternate mechanical erosion model (simple step function) was additionally examined which assumed the mechanical

erosion component to remain fixed at a constant level with surface temperature as dictated by the lower pressure conditions. This model is defined as Model 2 in Figure 8. These models were subsequently incorporated into the ablation analyses to address the "mechanical erosion" effect.

D. Results and Discussion

The $-8^{\circ}/40\text{K}$ reentry was re-analyzed to include the effects of mechanical erosion Models 1 and 2. The results of this analysis are shown by the recession profiles in Figure 9. The comparative effects between Model 1 and Model 2 on total recession are not particularly significant for this reentry. However, the general effect of mechanical erosion on total recession is substantial, amounting to 25% of the predicted thermochemical recession at time of impact. It is of interest to note for this particular reentry that the heat shield burns through at approximately the time of impact for the Model 1 case and constitutes a boundary condition for ablation failure of the Pioneer F heat source in V- β space.

Heat shield surface temperatures for the $-8/40\text{K}$ reentry did not reach levels to permit discrimination of the two mechanical erosion models. Consequently, a more severe reentry was analyzed to examine the effects of higher surface temperatures on mechanical erosion. Figure 10 presents a similar comparison of recession profiles for a severe $-12^{\circ}/42\text{K}$ reentry. This comparison shows total recession to have an alarmingly high sensitivity to the mechanical erosion models and specifically relates to the questionable high temperature

region (3750 to 4000°K) previously discussed in Figure 8.

Ablation failure occurs within the sublimation period of flight for Model 1 since surface temperatures exceed 7000°R (3880°K) and corresponding mechanical erosion rates are equivalent or in excess of predicted thermochemical rates. The heat shield survives the sublimation period for the less severe Model 2 and does not indicate failure until approximately time of impact (oxidation burn through). The important conclusion to be drawn from this analysis is that the introduction of the mechanical erosion effect, a refinement heretofore neglected in nuclear reentry safety analyses, has in turn introduced a new element of uncertainty into reentry analyses. Once again, in keeping with a conservative policy for safety analyses, APL is inclined to favor the more severe Model 1 to assess mechanical erosion effects. However, it is abundantly clear that more experimental data are required to clarify the 'erosion' effect at the higher surface temperatures for pressure conditions of interest (i.e., $P_s \sim 0-5$ atm).

IV. ABLATION MODEL UNCERTAINTIES

It has been indicated in this report and elsewhere⁽⁸⁾ that APL currently favors (a) the Moderate Rate oxidation model (Figure 2), (b) the JANAF(69) sublimation model (Figure 2) and mechanical erosion Model 1 (Figure 8) to predict ablation behavior of graphite. It has further been shown that these models have been founded on a seemingly rational application of available experimental graphite ablation data. Furthermore, where uncertainties appear within the data, a conservative posture has been taken in selecting models for reentry safety ablation analyses. At this point, it might prove worthwhile to discuss these uncertainties in somewhat further detail.

A. Oxidation Modelling

It has been previously indicated in Section II that the graphite oxidation data measured at General Electric and at NASA Langley are in conflict. The contradiction of these data sets has currently led to the selection of a model (Moderate Rate) representative of the G.E. data simply by virtue of its more conservative nature. The comparison of recession losses between the Moderate and Very Slow Rate models in Table 1 showed significant differences in ablation performance as constituted by these data sets. Although the Very Slow Model is admittedly a very gross representation of the Langley data, these results indicate substantial gains to be realized in heat shield performance should one choose to implement the Langley data. However, justification for this data basically involves knowing the true kinetic mechanism(s)

relating to carbon oxidation and it is herein that uncertainty currently exists. An evaluation of a substantial body of experimental graphite oxidation data has led Maahs^(4,6) to surmise that kinetic mechanisms may persist to very high surface temperatures and are alien to the Arrhenius form generally assumed in oxidation studies. These investigations of Maahs merit serious consideration. Unfortunately, research of this type has not been pursued to the extent where a universal kinetic mechanism can now be identified with carbon oxidation. Maahs' recommendation of using a specific rate expression that provides correlation with the experimental data of Golovina and Khaustovich is made categorically for all artificial graphites. However, it is well known that oxidation characteristic vary for different grades of graphite due to such effects as impurity levels, binder to particle ratio, porosity, etc. Although Maahs' investigations are acknowledged and encouraged, it does not appear that the recommended rate expression resulting from these studies to date has sufficient substance to supplant the Arrhenius based oxidation model as recommended by APL⁽⁸⁾ for reentry safety analyses. One other area of uncertainty related to the oxidation studies of this report centers about the current model being dictated solely on the basis of observed data for ATJ graphite. As previously mentioned, oxidation characteristics vary for different graphitic materials due to inherent differences in microstructure. Consequently, model refinement becomes contingent upon acquiring a similar data base for the graphites being considered in heat source designs (i.e., POCO grades currently,

possibly carbon/carbon composites in the future) to permit evaluation of rate constants, etc. as required for any presumed kinetic mechanism. It should be noted that a limited amount of oxidation data for the Pioneer F shield material, POCO AXF-Q1, became available from Teledyne-Isotopes toward the conclusion of this study. These data have been included in Figure 2 and show good agreement with the currently recommended Moderate Rate model at these lower temperatures. However, it is too limited a data base to validate the model for this particular graphite grade.

B. Mechanical Erosion and Sublimation Modelling

It was indicated in Section III that the inclusion of mechanical erosion effects in reentry analyses has introduced still another uncertainty which merits consideration. Based on Lundell and Dickey's data set as a reference, the resulting mechanical erosion Model 1 has been formulated on the basis that pressure effects are not influential at the lower pressure levels (0-5 atm) and is in conformance with Lundell and Dickey's observations. It was shown in Figure 10 that this supposition leads to severe ablation losses in evaluating the Pioneer F heat source performance as opposed to a simple-minded erosion model (Model 2) that was intended to represent low pressure conditions. Intuitively, it does not appear that the pressure parameter should be neglected in the pressure range for current heat source reentries solely on the basis of the reduced data resulting from Lundell and Dickey's investigations. On the contrary, pressure levels provide an index to the aerodynamic forces acting on the body which are a prime impetus in removing particulate matter. Clearly,

resolution of this pressure effect is tied to acquiring a larger data base, particularly at conditions of high surface temperature and low pressures where the recommended erosion model is currently biased. Once again, it is of importance to acquire sublimation data specifically for graphites being considered in heat source designs. Ideally, sublimation is considered to be strictly a surface mechanism and consequently independent of graphite microstructure. Realistically, it is related to microstructure due to sub-surface sublimation effects resulting from macro and micro-pore distributions within the material.

Although the uncertainty of pressure effects on mechanical erosion modelling has been directly demonstrated in terms of this Pioneer F study, there is an underlying uncertainty of a more basic nature that additionally requires consideration. At this time, there is no universal quantitative model for determining mechanical erosion effects as a function of both graphite microstructure and the thermochemical environment. Furthermore, it does not appear hopeful that such a model will be forthcoming in the reasonably near future. Consequently, mechanical erosion models probably will continue to be formulated from reduced experimental data in the manner previously described in Subsection III,C. Therefore, model refinement for determining mechanical erosion behavior becomes contingent upon accurate definition of the basic thermochemical sublimation process. It has long been observed that vaporization of carbon results in a multicomponent mixture of carbon vapor species as opposed to a vapor with a singular molecular structure (e.g., $C_1(g)$). The JANAF (69) model employed in this study considers carbon vapor species C_1 through C_5 constrained to a condition of thermochemical equilibria.

Whereas the heats of formation and thermodynamic functions of species C_1 and C_2 issued by JANAF are generally accepted, there is dispute regarding the properties for C_3 . The C_3 specie is of critical importance in modelling the graphite sublimation process since (a) it is a very active molecule during carbon vaporization over a broad temperature range and (b) generally provides the foundation for estimating the thermodynamic properties for C_4 and higher order carbon species (e.g., the method of Pitzer and Clementi⁽¹⁶⁾). The rationale for the JANAF C_3 thermodynamic functions and resultingly, the estimations for C_4 and C_5 , is that they provide good correlation with the experimental equilibria vapor pressure data of Drowart, et. al⁽¹⁷⁾ obtained in the limited temperature range of 2000 to 3000°K. The uncertainty regarding this model, or any model for that matter, relates to the verity of the thermodynamic functions extended to temperatures in excess of 3000°K. Another uncertainty of perhaps lesser importance is the absence of higher order molecular species (i.e. C_6 and above) in the model. Inclusion of these species again would require estimation of the molecular properties based principally on the C_3 characterization. The excellent review on carbon vaporization by Palmer and Shelef⁽¹⁸⁾ further indicates that the influence of C_6 and C_7 in an equilibrium system does not appear significant until temperatures are in excess of 4500°K. This temperature condition would be in excess of surface temperatures currently associated with heat source reentries (approximately $\leq 4000^\circ\text{K}$). There is also the question of whether kinetics are prominent in the formation of these higher order species (i.e. $T \leq 4000^\circ\text{K}$) which in turn introduces uncertainties currently registered with available

evaporation coefficient data. At any rate, the presence of kinetic influences would act to further reduce the concentrations of higher order species at the surface temperature levels of current interest. Although these higher order species do not appear to be significant for heat source ablation, experimental data are required to validate this premise.

In reviewing the above uncertainties, one might ask how they effect the results of this study? By forcing total recession (i.e. thermochemical and mechanical) to approximately match the Lundell and Dickey data as indicated in this study, it becomes important to understand what percentage of this data is attributable to thermochemical effects. If it can be shown that the uncertainties result in a larger thermochemical loss than predicted by the current JANAF (69) model, the effect should be to reduce surface temperatures due to larger endothermic energy considerations in the surface energy balances. A reduction in surface temperature would act to reduce the mechanical erosion component as currently indicated in Model 1 (Figure 8) and enhance ablation performance. It is intuitively felt that any subsequent changes to APL's currently endorsed sublimation model would behave in the above manner and thereby reduce predicted ablation losses.

C. Summary

The discussion of uncertainties in this section has attempted to provide recognition that the state of the art in graphite ablation modelling has by no means achieved a final, glorious state. These discussions clearly indicate that further broad refinements in ablation modelling are contingent upon the following considerations:

1. An extended experimental ablation data base in both the oxidation and sublimation regimes is necessary for the graphitic materials currently being considered in heat source designs. Low pressure sublimation data are particularly important for assessing pressure effects on mechanical erosion modelling at the extreme surface temperature conditions.

2. Highly controlled experimental research remains necessary to acquire a basic definition of (a) the kinetic mechanisms of carbon oxidation and (b) the thermodynamic and kinetic characteristics of higher order molecular carbon vapor species. Specifically, the work of Maahs has provided a fresh insight to carbon oxidation at elevated temperatures and should be pursued on recognition of the potential gains to be realized in heat source ablation performance. Furthermore, carbon vaporization research should be particularly directed toward (a) refining the heats of formation data for species C_3 through C_7 as well as (b) validating their thermodynamic functions at temperatures in excess of $3000^\circ K$ for immediate benefits in refining heat source sublimation calculations.

V. PIONEER F HEAT SOURCE ABLATION FAILURE STUDY

The effects of uncertainties inherent within current graphite ablation models can further be dramatized by extending the sublimation studies of Section III in superorbital V- δ space. The limited studies of Section III identified an ablation failure mode for the Pioneer F heat source for certain prompt reentries based on APL's current recommended ablation model. It was later indicated in Section IV that the recommended ablation model implies a posture of conservatism in view of current uncertainties regarding graphite ablation behavior. This section addresses a brief follow-on study which attempted to define a V- δ ablation failure boundary for the Pioneer F heat source based on APL's current ablation model (i.e., Moderate Rate oxidation, JANAF (69) sublimation and Model 1 mechanical erosion models).

A. V- δ Failure Space

A total of 15 superorbital reentries were examined using the thermal structural model and surface energy balance defined previously in Section II (Figures 3 and 4). The resulting vertical failure boundary shown in Figure 11 was derived from the criterion of total heat shield recession at approximately time of impact. The multiple skin region had previously been identified as an ablation failure zone in Teledyne-Isotope's safety analysis⁽¹⁹⁾. Consequently, the skip boundary constitutes a lower boundary for the purposes of this study. The upper boundary in this region is dictated by the heat shield's thermal stress failure boundary. Since this study has been conducted on the basis of nominal analyses

(as opposed to error analyses with variation of parameters), the nominal $V-\delta$ maximum stress plots determined by Teledyne-Isotopes (Fig. IV-88, Ref. 19) were used in defining a stress failure boundary. Teledyne-Isotopes indicated in the final Pioneer F safety review that stress calculations should be increased by 10% to account for various factors not previously considered in their stress calculations. On the basis of the nominal $V-\delta$ stress map and the 10% correction factor, a relocated stress failure boundary was estimated and is shown in Figure 12. The region encompassed by the thermal stress failure boundary, ablation failure boundary and the multiple skip boundary represents the $V-\delta$ space yielding ablation failure of the heat shield during prompt reentry. Based on trajectory conditions at the time of heat shield failure, a fuel capsule melt failure boundary was estimated as shown in Figure 12. Unfortunately, time did not permit the boundary to be substantiated via analyses prior to the Pioneer F World Hazard Review Meeting. The melt failure boundary tacitly implies that the fuel capsule is immediately released to the atmosphere upon heat shield failure. The terminal or release conditions associated with the 15 ablation analyses are summarized in Table 2. The cross-hatched $V-\delta$ space to the right of the melt boundary provides an estimate of the region yielding atmospheric fuel release due to an ablation failure mode. This nominal failure space was reported at the World Hazard Review Meeting.

B. Discussion

The failure space resulting from heat shield ablation failures during reentry have been derived on the basis of nominal analyses. To remain consistent with the Teledyne-Isotope's safety analyses, this failure mode should be evaluated on the basis of an error analysis in the manner conducted for the heat shield thermal stress failures. Although time did not permit such an analysis prior to the final Pioneer F safety review meeting, some observations can be made regarding the possible outcome.

In constructing an error analysis, one must be conscious not only of the uncertainties related to data per se (e.g., thermal properties) but also to uncertainties related to technique. Consequently, an ablation error analysis must not only consider many of the uncertainties addressed by Teledyne-Isotopes in their thermal stress analysis but also give prime attention to the uncertainties related to ablation modelling as discussed in Section IV. It is clear that consideration of the modelling uncertainties would act to shift the ablation failure boundary to the right in Figure 12 and thereby reduce fuel release probabilities. This can be illustrated by isolating attention to the mechanical erosion effect. One could have chosen mechanical erosion Model 2 rather than Model 1 (Figure 8) to perform the failure study. It could be argued that this model more closely reflects reentry conditions since, as indicated in Table 2, maximum stagnation pressures within the V-8 failure space of interest generally do not exceed two atmospheres. An indication of the outcome using Model 2 can be obtained from the

results for the -12/42K reentry previously discussed in Figure 10. This figure shows ablation failure to shift to approximately time of impact for the Model 2 mechanical erosion behavior and intimates the ablation failure boundary in Figure 11 probably shifts to the 42K velocity coordinate. It follows that any additional variation considered for ablation modelling uncertainties (for example, an oxidation model reflecting the NASA Langley data) will further shift this boundary and reduce the V- δ failure space and associated fuel release probabilities. In view of the large sensitivities associated with these uncertainties (e.g., mechanical erosion models in Figure 10) it is reasonable to expect that ablation failures predicted for the Pioneer F heat source by an error analysis should be minimal and not significantly alter the atmospheric fuel release probabilities reported by Teledyne-Isotopes. However, in conclusion, the thrust of this exercise is not so much related to the discussion of Pioneer F heat source failure probabilities per se as it is to re-emphasizing the need to resolve the uncertainties related to graphite ablation predictive techniques through extended experimental investigations. It should be recognized that within our current framework of knowledge regarding graphite ablation behavior, consideration of these uncertainties in future error analyses of heat source systems will be largely subjective and may well be of more critical importance than indicated herein for the Pioneer F system. The other alternative, of course, is to adhere to a conservatively oriented ablation model (as currently considered by APL) and incorporate existing uncertainties as penalties into the design of future heat source assemblies.

VI. CONCLUSIONS

A series of studies were conducted to assess the ablation performance of the Pioneer F/SNAP 19 heat source for various analytical thermochemistry and mechanical erosion models and was supplemented with a discussion on uncertainties currently contained within the APL model and with graphite ablation predictive techniques in general. Conclusions from these studies are as follows:

A. Oxidation Studies

1. The simple oxidation cut-off model can be justified for estimating oxidation rates if the cut-off temperature is specified at about 1500°F. This specification will essentially (a) equate the cut-off model to the Fast Rate oxidation model (Figure 2) which slightly over-predicts recession and (b) predicts equivalent structural temperatures when compared to the current recommended Moderate Rate model results.

2. A significant amount of heat shield recession results from graphite oxidation during the subsonic period of reentry (typically, 50 to 55 mils for shallow reentries). A portion or all of this subsonic recession may well be omitted in an ablation analysis utilizing an oxidation cut-off model if a cut-off temperature is over-specified (e.g., 2100°F).

3. The Very Slow Rate model, which is a very gross representation of the NASA Langley data, results in about a 50% reduction in predicted heat shield recession from the value predicted by the G.E. derived Moderate Rate model for an orbital decay reentry. This crude comparison serves to illustrate the

substantial differences in ablation performance that can result from these conflicting data sets.

B. Sublimation and Mechanical Erosion Studies

1. Mechanical erosion is an important consideration in assessing heat shield ablation performance that has, heretofore, been omitted in nuclear reentry safety analyses. These studies have shown this effect to result in added recession during sublimation conditions that ranged from (a) a 25% increase over thermochemical predictions to (b) prompt ablation failure of the heat shield for various superorbital reentries.

2. The pressure effect on mechanical erosion is not currently included in the mechanical erosion model and has indications of being a decisive factor in determining graphite ablation for high energy reentries.

3. The sublimation model proposed by Dolton et al represents an ultra-conservative thermochemical model in terms of the Lundell and Dickey data and lead to premature heat shield ablation failure for the Pioneer F heat source.

C. Ablation Model Uncertainties

1. The current APL graphite ablation model is based on a seemingly rational application of available experimental ablation data and assumes a conservative position in the selection of the oxidation and mechanical erosion models in view of current uncertainties within the available data.

2. Uncertainties within the APL model includes formulation on the basis of solely ATJ graphite experimental data and the absence of pressure effects in predicting mechanical erosion.

Basic uncertainties relative to graphite ablation models in general concern the imprecise knowledge defining the kinetic mechanism(s) of carbon oxidation and the thermodynamic functions and kinetic behavior of higher order carbon vapor species formed during sublimation.

3. Significant refinements in graphite ablation predictive techniques for heat source reentry analysis are contingent upon:

(a) acquiring an extended experimental ablation data base in both the oxidation and sublimation regimes for graphite materials currently being considered in heat source designs; wherein, particular emphasis should be directed toward low pressure data at elevated surface temperature to resolve pressure effects on mechanical erosion.

(b) extending experimental research in the areas of carbon oxidation kinetics and carbon vaporization at elevated temperatures.

D. Ablation Failure Study

1. The combined analyses of 15 superorbital reentries using APL's current graphite ablation model identified a Pioneer F heat source ablation failure boundary in V- θ space that commenced at the multiple skip boundary and extended essentially along the 40K velocity coordinate. The failure criteria was selected as heat shield burn through at approximately time of impact.

2. The large sensitivity of graphite ablation to changes in the mechanical erosion and oxidation models (as displayed in these studies) suggests that an error analysis which addressed

these uncertainties would yield minimal fuel release probabilities and not significantly alter the probabilities reported by Teledyne-Isotopes.

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VIII. NOMENCLATURE

c_p	=	Specific heat at constant pressure
D_{12}	=	Binary diffusion coefficient
h	=	Combined sensible and chemical enthalpy, $h = \int c_p dT + h^\circ$
h°	=	Heat of formation at 298°K
k_i	=	Species mass fraction
k	=	Thermal conductivity
$\dot{m}$	=	Mass loss rate per unit area
$\dot{m}^*$	=	Mass loss rate due to particulate erosion
$\dot{q}$	=	Heat transfer rate per unit area
$\dot{s}$	=	Recession rate
t	=	Time
T	=	Temperature
V	=	Flight velocity
y	=	Distance normal to surface
γ	=	Flight angle
ρ	=	Density
$\int \dot{s} dt$	=	Total recession

Subscripts

c	=	Convective transfer
i	=	Chemical species; inertial frame of reference
int	=	Solid conduction transfer
L	=	Reference state (e.g., solid)
S	=	Transferred state due to chemical transformation
$rad\ in$	=	Radiation transfer to surface
$rad\ out$	=	Radiation transfer from surface

TABLE 1
EFFECTS OF OXIDATION MODELS ON REENTRY THERMAL PERFORMANCE
PIONEER F HEAT SOURCE

RE ENTRY ~ ORBITAL DECAY, 400K FT. RE ENTRY ALTITUDE
 SIDE ON (PLAT LEADING) TRIM
 INIT TEMPS ~ NOMINAL OPERATION
 MODE

<u>OXIDATION MODELS</u>	1-D <u>HEAT SHIELD RECESSION,</u> <u>INCHES</u>	
	IMPACT $\int_0^{\text{IMPACT}} \dot{A} dt$	$t @ T_s = 2100^\circ F$ $\int_0^{\text{IMPACT}} \dot{A} dt$
FAST RATE	.192	.135
MODERATE RATE	.184	.131
VERY SLOW RATE	.092	.092
	1-D <u>STRUCTURAL TEMPERATURE,</u> <u>$^\circ F$</u>	
	PEAK, CLAD	IMPACT, STRENGTH MEMBER
FAST RATE	3387	2916
MODERATE RATE	3380	2921
VERY SLOW RATE	3379	2829

* TEMPERATURES SHOULD BE VIEWED ON A COMPARATIVE BASIS
 SINCE A 1-D ANALYSIS OVER PREDICTS HEAT SOURCE
 CAPSULE TEMPERATURES BY 10-12%.

Table 2
SUMMARY OF ABLATION FAILURE STUDY
PIONEER F HEAT SOURCE

Conditions: Thermochemistry Model: Moderate Rate, JANAF(69) Sublimation
Mechanical Erosion: Model No. 1
Attitude: Flat Leading, Side on Stable, Initial Altitude: 400K ft.
Initial Temperature: Nominal Operational Mode

Trajectory	F/S/B	Thermal Conditions					$Pt_{s_{max}}$ (atm)	$\theta_{q_{max}}$ (sec)
		θ (sec)	S(in)	V(fps)	Z(ft)	q/q_{max}		
-6 x 37K fps	S	396	.237	256	0			
-6 x 39K fps	B	459	.283	269	2935			
-6 x 40K fps	F	501	.283	2667	191950	~0	.28	80
-8 x 40K fps	B	295	.283	258	0			
-9 x 39K fps	S	273	.252	256	0			
-9 x 41K fps	F	173	.283	519	36840	~0	1.3	46.2
-9 x 43K fps	F	52.5	.283	26185	134700	.615	1.6	42.9
-12 x 40K fps	B	206	.283	300	10050			
-12 x 42K fps	F	37.6	↓	25070	121270	.615	2.0	32.9
-12 x 44K fps	F	32.3	↓	34335	140655	.973	1.9	30.5
-14 x 39K fps	S	223	.266	256	0			
-14 x 44K fps	F	42.5	.283	7130	87875	.019	2.40	28.2
-16 x 39K fps	S	212	.271	256	0			
-16 x 41K fps	F	35	.283	9490	88500	.035	2.40	25.2
-16 x 43K fps	F	25	.283	32290	127290	.94	3.60	23.4

Code:

F/S/B ~ Failure in flight/Survived thru impact/Failure at approx. time of impact
S ~ Total heat shield recession
 $Pt_{s_{max}}$ ~ Stagnation pressure, time of maximum erosion rate
 q/q_{max} ~ Terminal heating rate normalized by maximum heating rate
 θ ~ Flight time from initial reentry at 400K ft.
 $\theta_{q_{max}}$ ~ Time of maximum convective heating rate
Z ~ Altitude

OXIDATION CUT-OFF CONCEPT

FIGURE 1

11/16/71

Figure 2. Comparison of Graphite Thermochemical Ablation Models and Experimental Data

FIGURE 3

SURFACE ENERGY BALANCE

$\dot{q}_{rad, in} \sim$ SHOCK LAYER RADIATION (INVISCID, NON-GRAY, SELF ABSORPTION, RADIATIVE COOLED SHOCK LAYER) VIA CALLIS (REF 22)

$\dot{q}_c \sim$ CONVECTIVE TRANSFER { (DETRA, KEMP AND RIDDELL CORRELATION)
($M \geq 5 \sim$ SIBULKIN)

$\dot{q}_{rad, out} \sim$ SURFACE RADIATION

$\dot{q}_{int} \sim$ SOLID CONDUCTION TRANSFER

$\dot{m}_L h_L \sim$ ENTHALPY FLUX OF CARBON (TOTAL ABLATION RATE)

$\dot{m}_L^* h_L \sim$ ENTHALPY FLUX OF CARBON (MECHANICAL ABLATION RATE)

$\dot{m}_s h_s \sim$ ENTHALPY FLUX OF VAPORIZED SPECIES (THERMOCHEMICAL ABLATION RATE)

FIGURE 4

PIONEER F HEAT SOURCE
THERMOCHEMICAL RECESSION PROFILES
RE ENTRY ~ ORBITAL DECAY
ATTITUDE ~ SIDE ON STABLE

FIGURE 5

PIONEER F HEAT SOURCE
COMPARISON OF COMPONENT TEMPERATURES FOR DIFFERENT
OXIDATION MODELS

REENTRY ~ ORBITAL DECAY
 ATTITUDE ~ SIDE ON STABLE

FIGURE 6

PIONEER F HEAT SOURCE
THERMOCHEMICAL RESSION PROFILES
RE ENTRY ~ -8°/40K FPS, 400K FT
ATTITUDE ~ SIDE ON STABLE

FIGURE 7

MECHANICAL EROSION MODELS

EXP. DATA SOURCE ~ LUNDELL & DICKEY (ATJ GRAPHITE)
THERMOCHEM. MODEL ~ MODERATE RATE, JANAF (69) SUBL.

FIGURE 8

PIONEER F HEAT SOURCE
 EFFECT OF MECHANICAL EROSION ON TOTAL RECESSION
 REENTRY ~ 8°/40K FPS, 400K FT
 ATTITUDE ~ SIDE ON STABLE
 CHEMISTRY MODEL ~ MODERATE RATE, JANAF (69) SUBL.

FIGURE 9

PIONEER F HEAT SOURCE
EFFECT OF MECHANICAL EROSION ON TOTAL RECESSION
FOR
SEVERE SUBLIMATION ENVIRONMENT

RE ENTRY ~ -12°/42 K FPS, 400 K FT.

ATTITUDE ~ SIDE ON STABLE

CHEMISTRY MODEL ~ MODERATE RATE, JANAF ('69) SUBL.

FIGURE 10

PIONEER F HEAT SOURCE
ESTIMATED V_i - γ_i BOUNDARY
 FOR
HEAT SHIELD ABLATION FAILURE

THERMOCHEMISTRY MODEL ~ MODERATE RATE, JANAF (69) SUBL.
 MECHANICAL EROSION ~ MODEL 1

FIGURE 11

PIONEER F HEAT SOURCE
ESTIMATED INCREMENTAL V_i - γ_i SPACE (PROMPT REENTRY)
 FOR
ATMOSPHERIC FUEL RELEASE

ABLATION ANALYSIS: I-D, SIDE ON STABLE WITH "MODERATE RATE, JANAF 69
 SUBL." THERMOCHEMICAL MODEL, MECH. EROSION "MODEL 1"

FIGURE 12

* FUEL CAPSULE MELT BOUNDARY ESTIMATED FROM HEAT SHIELD BREAK-UP CONDITIONS; NOT SUBSTANTIATED BY ANALYSIS.

** ESTIMATED THERMAL STRESS BOUNDARY, BASED ON A 10% INCREASE FOR T-Z CALCULATED STRESSES (FIG II-88, PIONEER SAR, VOL II)