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AUTHOR <i>CW Sayles</i> C. W. Sayles	DEPT. & GROUP NO. 731-14	DATE 12-7-65	
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STATEMENT OF PROBLEM Make a parameter survey of the properties and mechanisms affecting the reentry behavior of SNAP fuel particles.			
ABSTRACT: This report gives the results of a parameter survey of the properties and mechanisms affecting the reentry ablation of SNAP fuel particles. The following properties and mechanisms were studied: aerodynamic heating, oxidation, oxide vaporization, metal vaporization, particle emissivity, specific heat, density, velocity, and initial size. These studies were made for particle release altitudes ranging from 170,000 to 228,000 feet.			

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Energy Systems Group
 8900 DeSoto Avenue
 Canoga Park, California 91304

Rockwell
 International

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I. INTRODUCTION

In evaluating the safety hazards associated with orbiting SNAP reactors, it is necessary to describe the behavior of the radioactive fuel during all stages of reentry. When SNAP fuel elements are exposed to the atmosphere they will be heated to their melting temperature (Reference 1). The melted fuel element will be divided into small liquid droplets or particles. These particles will experience further ablation as the reentry process continues.

This report gives the results of a parameter survey of the properties and mechanisms which affect the ablation of reentering SNAP fuel particles. This survey will aid in the planning of experimental work. In this survey, the following properties and mechanisms were studied: aerodynamic heating, oxidation, oxide vaporization, particle emissivity, specific heat, density, velocity, initial size, and metal vaporization. These studies were made at particle release altitudes ranging from 170,000 feet to 228,000 feet.

II. METHOD OF ANALYSIS

A parametric survey was made with two modified versions of a previously developed particle ablation model (References 2 and 3). The previous model, known as VAPAM, was modified to improve its accuracy and versatility. The two modified versions of this model were designated PAM-3 (Particle Ablation Model, #3) and PAM-4 (Particle Ablation Model, #4).

PAM-3 was made by modifying VAPAM to improve the accuracy of the calculations. This was done by the inclusion of a variable time increment. During the initial parts of the temperature transient, the temperature is changing quite rapidly with time. This is seen in an example in Figure 1. As written, the model uses the physical properties at one time to calculate the temperature at the end of the next time

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increment. When the temperature increases rapidly with time, large inaccuracies in the physical properties used might result from this procedure. To remedy this situation, the time interval used is automatically made smaller whenever the change in temperature during a time interval is larger than 2 per cent of the particle temperature.

PAM-4 was developed from PAM-3 by including an option for metal vaporization and a more versatile output format. The same equation is used to express the vaporization rate of the metal as was used to describe the vaporization rate of the oxide (Reference 3). This equation, known as the Langmuir equation, is given by (Reference 4)

$$\dot{Z}_{\max} = P_v \sqrt{\frac{M}{2\pi RT}} \quad \dots(1)$$

It has been shown that Equation (1) reduces to (Reference 13)

$$Z_{\max} = 0.1601 P_v (\text{mm Hg}) \sqrt{\frac{M}{T(^{\circ}\text{R})}} \quad \dots(2)$$

(See Nomenclature for the definitions of all terms used in the equations.)

In Equation (2) it is necessary that the vapor pressure be known. The vapor pressure of zirconium metal expressed in atmospheres is given by (Reference 5)

$$\log P_v = 7.3351 - 0.0002415 T - \frac{31066}{T} \quad \dots(3)$$

In this equation, T is given in degrees Kelvin.

In order to incorporate the effect of metal vaporization into PAM-3 it was necessary to make several changes.

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The current model assumes that metal vaporization can take place only when all of the oxide is removed. The oxide is formed by the oxidation process and removed by vaporization. Within the model, an inventory is kept of the amount of oxide present. When the amount of oxide is found to be zero, vaporization of the metal is allowed. Metal vaporization is allowed for only a fraction of a given time increment. The time increment allowed for metal vaporization is given by the following equation

$$\Delta \theta_m = (1 - \frac{R_o}{Z_o}) \Delta \theta \quad \dots(4)$$

In this equation the fraction (R_o/Z_o) is that portion of the time increment that is spent vaporizing the oxide that has been formed. The remainder of the time increment is available for metal vaporization.

Since the oxidation process is terminated when there is no more metal to be oxidized it is necessary that an inventory of the unoxidized metal be kept. This inventory is a material balance where the material removed by oxidation and by metal vaporization is computed. The equation for this inventory is

$$I_m(\theta) = \frac{4}{3} \pi r_p^3 \rho_p - \int_0^\theta A_s(\theta) R_o(\theta) d\theta - \int_0^\theta A_s(\theta) Z_m(\theta) d\theta \quad \dots(5)$$

To account for metallic vaporization, Equations (2), (3), (4), and (5) were incorporated into the model. In addition to the inclusion of metal vaporization, additional changes were made. These changes were a revised method for obtaining CRT output and a control on metal vaporization.

In the previous models for particle ablation (References 2 and 3), a set of CRT plots were obtained for each case submitted. If a graphical comparison between two cases was desired, it was necessary to replot the

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digital output. This has been changed so that up to six consecutive cases can be compared. With this revision, comparisons can be made for cases where particles have different initial velocities, radii, temperatures, or altitudes.

To allow graphical comparisons to be made between cases with metal vaporization and cases without metal vaporization, an internal control was put on metal vaporization. This control depends on the value of an input number KY. As long as KY is positive or zero, metal vaporization will be considered. If KY is negative, the metal vaporization will be by-passed. The number KY is reduced by "1" at the end of each problem case. As an example, suppose it was desired to compare two cases. The cases were to be identical except that the first was to include metal vaporization and the second was to have no metal vaporization. In this situation, KY would be input as zero. The first problem would then have metal vaporization, and the second would not.

A complete FORTRAN listing of PAM-4 and all of its subroutines is given in Appendix A. A sample set of input data is given in Appendix B. For this sample, the CRT output is shown in Figures 6 through 10.

Most of the parameter survey was made using PAM-3. PAM-4 was used in the study of metal vaporization and to obtain Figures 3 through 10.

The parameter survey was made by assuming a standard set of cases (a different case at different altitudes). Comparisons of final particle radius and fraction remaining unablated were made with the standard cases where one of the properties or mechanisms was changed. These results are presented in Section IV.

III. STANDARD CASES

The standard cases represent an ideal situation, and values were used which do not necessarily represent those most likely to be encountered during reentry. In the standard cases, the reentering particles were assumed to be heated by free molecule aerodynamic heating, oxidation takes place with a free molecule mass transfer mechanism, and each oxygen atom striking the particle underwent the oxidation reaction. The

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emissivity of the standard particle was assumed to be 1.0, the specific heat to be 0.07 Btu/lb °F, and the density to be 375 lb/ft³. The oxide vapor pressure was assumed to follow the relationship given by Hoch, Nakata, and Johnson (Reference 6). In the standard cases there was assumed to be no metal vaporization. The initial size of the particle was determined by the Weber number (Reference 7). (The Weber number is the ratio of the inertial forces to the surface tension forces.) The table below gives the initial velocities and radii for the various altitudes.

TABLE I

Initial Velocities and Sizes for Standard Cases

<u>Altitude</u> <u>Feet</u>	<u>Initial</u> <u>Radius</u> <u>Microns</u>	<u>Initial</u> <u>Velocity</u> <u>Ft/Sec</u>
170,000	500*	14,000
177,000	630	14,200
189,000	688	16,500
203,000	900	18,500
215,000	1195	20,000
228,000	1660	21,400

*Not determined by Weber number.

In all cases the initial temperature of the particle was taken to be 3200°F.

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IV. RESULTS

A. Aerodynamic Heating

To study the effect of aerodynamic heating, cases were compared to situations where the aerodynamic heating was made equal to zero. Since free molecule heating represents the maximum aerodynamic heating, it was not necessary to consider any larger heating rates. Table II gives the comparison of final conditions for the cases with and without aerodynamic heating.

TABLE II

Effect of Aerodynamic Heating on Final Conditions

Altitude	Initial Radius	Final Conditions			
		With Aerodynamic Heating		Without Aerodynamic Heating	
		Radius Micron	Fraction Unablated	Radius Micron	Fraction Unablated
170,000	500	241	0.11289	286	0.1872
177,000	630	349	0.1706	441	0.3421
189,000	688	425	0.2366	602	0.6693
203,000	900	625*	0.3342*	877	0.9262
215,000	1195	940*	0.4865*	1193*	0.9947
228,000	1660	1429*	0.6382*	1660*	0.9997*

*Conditions are not final, but 20 seconds after release.

From Table II it is seen that at the higher altitudes aerodynamic heating plays an important part in the ablation of the particle. At the higher altitudes the oxygen supply, and hence the oxidation rate, is insufficient to provide the heat to keep the particle at temperatures of significant vaporization (Reference 8).

The assumption of free molecule aerodynamic heating is much more realistic than the assumption of no aerodynamic heating. In the future, work should be done to determine the amount that heating is reduced from the ideal free molecule heating.

B. Oxidation

To study the effects of oxidation heating, cases were considered where the oxidation rate was made equal to one half of the standard cases. Since the standard case considers free molecule transport, which gives the maximum oxidation rate, it was not necessary to consider higher oxidation rates.

Table III gives the comparison of the two oxidation rates.

TABLE III
Effect of Oxidation Rate on Final Conditions

Altitude	Initial Radius	Final Condition			
		Standard Oxidation		One-Half Standard Oxidation	
		Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated
170,000	500	241	0.11289	391	0.4779
177,000	630	349	0.1706	515	0.5447
189,000	688	425	0.2366	575*	0.5839*
203,000	900	625*	0.3342*	778*	0.6452*
215,000	1195	941*	0.4865*	1079*	0.7348*
228,000	1660	1429*	0.6382*	1553*	0.8186*

*These conditions are not final, but 20 seconds after release.

From Table III it is seen that this reduction in oxidation rate causes a considerable reduction in the amount of material that is ablated. The reduction in oxidation heating causes a reduction in the equilibrium particle temperature. Although the total amount of oxidation heating is the same, in the standard case oxidation occurs over a shorter time interval. This in turn causes a higher temperature, and hence a more rapid rate of vaporization. In the free molecule flow regime, the assumption in the standard case is a good one. In the near free molecule and transition flow regime, there is a reduction in the oxygen transport rate. To date, little work has been done in determining this transport rate. Some investigators have assumed that the oxidation rate in this region is one-half of the free molecule oxidation (Reference 9). Further work should be done to verify this assumption.

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C. Oxide Vaporization

To study the effect of oxide vaporization, cases using the vapor pressures of Nakata, McKisson, and Pollock (Reference 10) were compared with the standard cases. The standard cases use vapor pressures expressed as the following equation (Reference 6).

$$\log_{10} P = 11.98 - 0.000798 T - 34383/T \quad \dots(6)$$

Nakata, McKisson, and Pollock express their vapor pressure as

$$\log_{10} P = 7.828 - 34020/T \quad \dots(7)$$

In these equations, P is the vapor pressure in atmospheres, and T is the absolute temperature in degrees Kelvin. These relationships for vapor pressure are shown in Figure 2. Table IV gives the comparison of the final conditions when the two vapor pressures are used.

TABLE IV

Effect of Oxide Vapor Pressure on Final Conditions

Altitude Feet	Initial Radius Microns	Final Conditions			
		Reference 6		Reference 10	
		Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated
170,000	500	241	0.11289	358	0.3664
177,000	630	349	0.1706	793	0.4833
189,000	688	425	0.2366	566	0.5568
203,000	900	625*	0.3342	793*	0.6841*
215,000	1195	940*	0.4865*	1146*	0.8819*
228,000	1660	1429*	0.6382*	1647*	0.9754*

*These conditions are not final, but 20 seconds after release.

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It is seen in Table IV that the vapor pressure data of Nakata, and Pollock gives a larger final particle size than does the standard. The data of Nakata, McKisson, and Pollock are more recent measurements and are felt to be better.

D. Emissivity

To study the effect of particle emissivity, cases using an emissivity of 0.8 were compared to the standard cases. The choice of 0.8 was an arbitrary one. It was desired to see how much of a change in final conditions this would make. The effect of emissivity on the final conditions is seen in Table V.

TABLE V

Effect of Emissivity on Final Conditions

Altitude Feet	Initial Radius Microns	Final Conditions			
		Emissivity = 1.0		Emissivity = 0.8	
		Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated
170,000	500	241	0.11829	201	0.06549
177,000	630	349	0.1706	300	0.1083
189,000	688	425	0.2366	377	0.1648
203,000	900	625*	0.3342*	568*	0.2511*
215,000	1195	940*	0.4865*	880*	0.3994*
228,000	1660	1429*	0.6382*	1380*	0.5745*

*These conditions are not final, but 20 seconds after release.

It is seen in Table V that the lower emissivity results in a greater degree of ablation. The lower emissivity gives a higher particle temperature, and this in turn allows a higher vaporization rate. Both the values used (1.0 and 0.8) are higher than the actual emissivity. The-temperature relationship for a particle with an emissivity of 0.8 is seen in Figure 1.

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In studying the effect of specific heat on final particle size, two additional values of specific heat were considered, 0.09 and 0.05 Btu/lb °F. It is felt that these two values bracket those of the fuel alloy and the oxide of the fuel alloy. A comparison of the final conditions for these two specific heats and the specific heat of the standard are shown in Table VI.

TABLE VI

Effect of Specific Heat on Final Particle Conditions

Altitude Feet	Initial Radius Microns	Final Conditions					
		$C_p = 0.05$		$C_p = 0.07$		$C_p = 0.09$	
		Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated
170,000	500	242	0.1142	241	0.11289	240	0.1109
177,000	630	350	0.1722	349	0.1706	348	0.1609
189,000	688	426	0.2384	425	0.2366	423	0.2348
203,000	900	628*	0.3370*	625*	0.3342*	624*	0.3326*
215,000	1195	941*	0.4874*	940*	0.4865*	939*	0.4851*
228,000	1660	1430*	0.6389*	1429*	0.6382	1429*	0.6378*

*These conditions are not final, but 20 seconds after release.

It is seen in this table that the effect of different specific heats is very small when compared to the effects of the previously mentioned parameters. The larger specific heat tends to give more ablation. This is because these particles do not cool as quickly as particles with lower specific heats.

F. Density

In studying the effect of density on final particle size, two additional values of density were considered, 200 lb/ft³ and 450 lb/ft³. Although the real density is known more accurately than these limits, these values were chosen to observe the effect of changes in density. Changes in the density have two main effects upon particle ablation. First, it causes

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a change in total heat capacity of the particle, and this effect is similar to the change in specific heat that was studied above. The second effect is the change in the mass and hence the change in the amount of material that can be oxidized. A comparison of final conditions for these different densities is given in Table VII.

TABLE VII

Effect of Density on Final Particle Conditions

Altitude Feet	Initial Radius Microns	Final Conditions					
		Density=300 lb/ft ³		Density=375 lb/ft ³		Density=450 lb/ft ³	
		Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated	Radius Microns	Fraction Unablated
170,000	500	240.92	0.1132	241.06	0.11289	240.82	0.1122
177,000	630	348.57	0.1698	349.30	0.1706	349.19	0.1701
189,000	687.5	425.52	0.2373	425.32	0.2366	425.46	0.2367
203,000	900	624.33*	0.3335*	624.81*	0.3342*	625.87*	0.3370*
215,000	1195	937.69*	0.4829*	940.08*	0.4865*	940.64*	0.4931*
228,000	1660	1418.25*	0.6232*	1429.49*	0.6382*	1444.41*	0.6579*

*These conditions are not final, but 20 seconds after release.

It is seen that the effect of density is very small compared to the effect of some of the previous parameters studied. At the higher altitudes, more ablation takes place with the less dense particle.

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To study the effect of initial size, some cases were considered where the initial radii were one-half the radii indicated by the Weber number criterion. Also, additional cases were considered to observe the effect of a wider range of particle sizes. The final conditions for these cases are given in Table VIII. The temperature, velocity, radius, and fraction unablated as functions of time for two different particle sizes released at 177,000 feet are given in Figures 3, 4, 5, and 6.

TABLE VIII

Effect of Size Upon Final Particle Condition

Altitude Feet	Initial Radius Microns	Final Radius Microns	Fraction Unablated
170,000	250	120	0.1126
	500	241	0.11289
	1000	482	0.1121
177,000	630**	349	0.1706
	315	174	0.1715
189,000	688**	425	0.2366
	344	212	0.2365
203,000	900**	625	0.3351
	450	312	0.3365
215,000	1195**	918	0.4533
	598	459	0.4560
228,000	1660**	1410*	0.6120*
	840	713	0.6101
	420	357	0.6138
	210	178	0.6096
	105	87	0.5682

*This condition is not final, but 50 seconds after release

**Particle radius determined by Weber number criterion.

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In Table VIII one sees that, for the same release altitude, very nearly the same fraction remains unablated. Therefore, in the future, one need consider only one size of particle per release altitude, and the fraction that remains will be the same for all sizes of particles.

H. Particle Velocity

In studying the effect of velocity, only cases for a particle release altitude of 170,000 feet were considered. The effect of velocity was studied by running cases with initial velocities of 10,000 feet per second and 18,000 per second. (The standard case used an initial particle velocity of 14,000 feet per second.) The temperature, velocity, radius, and fraction unablated as functions of time are given in Figures 7, 8, 9, and 10. In these figures are also shown these functions for particle radii of 250 microns and 1000 microns. The standard case, 14,000 ft/sec. initial velocity and 500 micron initial radius, is represented by the curve. The size and velocity comparisons are represented by the various kinds of points.

In these figures it is seen that the additional velocity greatly enhances the degree of ablation. The additional velocity adds not only additional aerodynamic heating but also contributes to an increase in the oxygen mass flux.

I. Effect of Metal Vaporization on Particle Ablation

To study the effect of metal vaporization on particle ablation, two sets of cases were considered. In one set, the particles were assumed to have no metal vaporization. In this set of cases, the conditions were identical to the standard conditions in a previous parameter study (Reference 3). In the second set of cases, the vaporization of metal was included. The final conditions for these two sets of cases are given in Table IX.

TABLE IX
Effect of Metal Vaporization on Particle Ablation

Altitude (Feet)	Initial Radius	Final Conditions			
		No Metal Vaporization Radius Micron	Fraction Unablated	With Metal Vaporization Radius Microns	Fraction Unablated
170,000	500	241.06	0.11289	239.21	0.1103
177,000	630	349.31	0.1706	347.36	0.1678
189,000	688	425.32	0.2366	423.47	0.2335
203,000	900	624.81*	0.3342	622.75*	0.3309
215,000	1195	922.06*	0.4589	920.03*	0.4559
228,000	1660	1429.49*	0.6382	1427.92*	0.6360

*These conditions are not final, but are 20 seconds after release.

It is seen in this table that, under these conditions, metal vaporization adds very little to the total amount of ablation.

J. Time Increment

A study of the time increment used in the program will give some insight to the accuracy of the model. The use of a time incrementing process is only an approximation. This is because the properties at one temperature and time are used to calculate the properties at the next temperature and time. In the limit as the size of the time increment becomes zero, the solution becomes exact. Since in machine computations this zero time increment is not possible, a finite time increment must be used. In the standard cases, and in all other cases (except for several cases studying the effect of size), the time increment used was 0.02 seconds. With this model, up to 1000 time increments can be used with each problem, and this corresponds to a total time of 20 seconds. In studying the effect of the time increment, the increment was increased to 0.05 seconds and a series of cases were run. In some of the standard cases, ablation was not completed 20 seconds after release,

therefore a comparison of the conditions obtained has been made for 20 seconds after release. Table X gives this comparison.

TABLE X
Effect of Time Increment on Particle Size
20 Seconds After Release

Release Altitude Feet	Initial Radius Microns	Conditions 20 Seconds After Release			
		O = 0.02		O = 0.05	
		Radius	Fraction	Radius	Fraction
		Microns	Unablated	Microns	Unablated
170,000	500	241.06	0.11289	235.43	0.10821
177,000	630	349.30	0.1706	348.31	0.1721
189,000	688	425.32	0.2366	425.54	0.2395
203,000	900	624.81	0.3342	625.44	0.3363
215,000	1195	940.08	0.4865	940.01	0.4862
228,000	1660	1429.49	0.6382	1427.18	0.6350
228,000	105	89.19	0.6160	86.62	0.5682

In this table one sees that the maximum difference in radius is 6 microns and this corresponds to approximately a 4% difference in the fraction that remains unablated.

V. CONCLUSIONS

This report illustrates the effect of several parameters on the amount of fuel particle that remains after reentry at various altitudes. Some parameters, such as total aerodynamic heating, mechanism of oxidation, emissivity, and oxide vapor pressure, are seen to have a great effect on final radius. Others such as density, specific heat, particle size, and metal vaporization are seen to have little effect on the fraction that remains unablated.

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The information obtained in this study will prove to be valuable. This information can form the basis of an influence coefficient study for particle reentry similar to one that has been made for fuel element reentry (Reference 11).

The mechanism of metal vaporization used here is based on the assumption that the vapor pressure relationship for the fuel material is the same as the relationship for zirconium. It is possible that the vapor pressure relationship for unoxidized SNAP fuel material might be different enough to cause a significant change in the effect of metal vaporization. Future experimental determinations of high temperature vapor pressures could give such information.

In the future, this particle ablation model will be further improved by providing more realistic relationships for aerodynamic heating and oxygen mass transfer.

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REFERENCES

1. A. W. Barsell, "Thermo-Physics Technical Note No. 40: Simultaneous Solutions of Transient Hydrogen Redistribution & Heat Transfer in a SNAP Fuel Element", NAA-SR-TDR-10879, December 31, 1964.
2. C. W. Sayles, "Thermo-Physics Technical Note No. 52: Results of a Preliminary Analysis of the Ablation of SNAP Fuel Particles, NAA-SR-TDR 11720, October 29, 1965.
3. C. W. Sayles, "Thermo-Physics Technical Note No. 54: Analysis of the Oxide Vaporization of SNAP Fuel Particles during Reentry Ablation", NAA-SR-TDR-11741, November 15, 1965.
4. L. B. Loeb, The Kinetic Theory of Gases, 3rd Ed. Dover Publications, Inc. New York, 1961.
5. G. B. Skinner, J. W. Edwards, H. L. Johnson, "The Vapor Pressure of Inorganic Substances, V. Zirconium between 1949 and 2054°K", J. Amer. Chem. Soc. 73, 1951.
6. M. Hock, N. Nakata, and H. L. Johnson, "Vapor Pressure of Inorganic Substances XII, Zirconium Dioxide", J. Amer. Chem. Soc. 76, Page 2651 May 1954.
7. R. E. Toews, "Thermo-Physics Technical Letter No. 60: SNAP Fuel Particle Experiment Test Plan", IL to J. W. Baughn, October 12, 1965.
8. C. W. Sayles and H. E. Johnson, "Thermo-Physics Technical Letter No. 58: A Proposal for Experiments to Measure the Vapor Pressure of Oxidized and Unoxidized SNAP Fuel Materials", IL to J. W. Baughn, September 29, 1965.
9. J. M. Bridges and H. G. Hargrove, "Reentry of Fuel Graphite Particles", Proceedings-Aerospace Nuclear Safety, American Nuclear Society, October 1, 1965.
10. M. M. Nakata, R. L. McKisson, and B. D. Pollock, "Vaporization of Zirconium Oxide", NAA-SR-6095, April 15, 1961.
11. L. D. Montgomery and J. E. Arnold, "Thermo-Physics Technical Note No. 47: Probabilities of Initial Ablation of a SNAP 10A Fuel Element for Release Altitudes from 200,000 to 400,000 Feet", NAA-SR-TDR-11560, August 24, 1965.
12. M. Hoffman and W. A. Rhoades, "AICRT 3, A General Code for Display of Digital Data," NAA-SR-MEMO-9069, October 1963
13. R. N. Horten, "An Approximate Solution for the Vaporization of Liquid Droplets Formed During Reentry Ablation," SC-RR-65-138, A print 1965

NOMENCLATURE

A_s	Surface area	L^2
I_m	Metal inventory	M
M	Molecular weight	M
R	Gas constant	F/MLT
R_o	Reaction rate of oxidation	$M/L^2\theta$
r_i	Initial radius	L
P_v	Vapor Pressure	F/L^2
$\dot{Z}$	Vapor formation rate	$M/L^2\theta$
Z_o	Oxide vaporization rate	$M/L^2\theta$
$\Delta \theta_m$	Time increment for metal vaporization	θ
$\Delta \theta$	Time increment of problem	θ
θ	Time	θ
ρ_p	Particle density	M/L^3

APPENDIX A

FORTRAN II LISTING FOR PAM-4

The listing contained here is for PAM-4 and all of its subroutines except AICRT-3. AICRT-3 (Reference 12) is on file with Department 792.

```

C      PARTICLE ABLATION MODEL 4 (PAM - 4) 00000001
C      BY C.W.SAYLES 00000002
C      DEPT. 727-72 00000003
C      SEPT. 1965 00000004
C 00000005
C      THIS PROGRAM SIMULATES THE ABLATION OF SNAP FUEL PARTICLES DURING REENTRY AND THE VAPORIZATION OF BOTH THE OXIDE AND THE METAL. 00000006
C 00000007
C 00000008
C      MAIN PROGRAM 00000009
C      DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9) 00000010
C      1,AT(9),FZ(1000),FZT(1000),FF(9) 00000020
C      2,L0I(100),R0I(100,4),V0I(100,4),T0I(100,4),TI0I(100,4) 00000021
C 00000030
C      COMMON T,V,R,TT,AR,OO,RH0A,RH0P,KX,KY,ND,NS,NC,NF,NG,NX0,NY0,DCX,D0 00000040
C      1CY,XLI,XUI,YLI,YUI,DTI,R0,VO,TO,NTIME,TIME,TI,I,CP,AV,AT 00000041
C      2,VG,FZ,FZT,FF, 00000042
C      3R0I,V0I,T0I,L0I,TI0I,L 00000043
C      WRITE OUTPUT TAPE 6,2 00000045
C      2 FORMAT (1H1,45X,37H PARTICLE ABLATION MODEL - 4 (PAM-4)) 00000047
C      NPR0B = 1 00000050
C      WRITE OUTPUT TAPE 6,4 00000052
C      4 FORMAT (1H0,46X,30H BY C.W.SAYLES DEPT. 727-72) 00000054
C      WRITE OUTPUT TAPE 6,6 00000057
C      1 CALL DATIN (NPR0B) 00000060
C 00000070
C      6 FORMAT (1H ,54X,12H SEPT. 1965 ) 00000075
C      IF (NPR0B - 1) 7,7,9 00000077
C      7 WRITE OUTPUT TAPE 6,8,TT 00000079
C      8 FORMAT (1H-,32X,9A6) 00000080
C      GO TO 11 00000082
C      9 WRITE OUTPUT TAPE 6,10,TT 00000086
C      11 CONTINUE 00000088
C      10 FORMAT (1H1,30X,9A6) 00000090
C      CALL DATPR 00000100
C      PRH0CP = 1.33333*3.14159*RH0P*CP 00000105
C      L = 0 00000106
C      CALL BEGIN (DT,DV,DR) 00000109
C      DO 52 I = 1,NTIME 00000110
C      32 CONTINUE 00000220
C      CALL DVEL(DV) 00000225
C      CALL QAERO(CA) 00000230
C      CALL GRAD(QR) 00000240
C      CALL QOX(QO) 00000250
C      40 CALL QVAP (CR,QO,QV,FZ(I),FZT(I)) 00000260
C 00000261

```

QTOT = QA + QO - QR - QV
CAP = PRHCP*R(1)*R(1)*R(1)

C

DT = QTOT*DTI/CAP

T12 = DT/T(1)

IF (T12 - 0.02) 43,43,42

42 CALL HALFD(DT,DV,DR)

43 CONTINUE

IF (I - 20) 62,62,61

61 IF (MP-10) 63,62,62

62 WRITE OUTPUT TAPE 6,50,I,TI(1),QA,QO,QR,QV,DT

63 MP = MP+1

GO TO 64

MP = 1

64 CONTINUE

50 FORMAT (1H ,I4,7X,F8.4,8X,F12.6,9X,F12.6,F17.6,7X,F12.6,5X,F7.2)

IF (I-NTIME) 68,65,65

C

65 WRITE OUTPUT TAPE 6,66

66 FORMAT (1H0,26H THE FINAL CONDITIONS ARE)

67 WRITE OUTPUT TAPE 6,50,NTIME,TI(NTIME),QA,QO,QR,QV,DT

68 CONTINUE

C

IF (I-NTIME) 51,151,151

51 TI(I+1) = TI(1) + DTI

T(I+1) = T(1) + DT

V(I+1) = V(1) + DV

R(I+1) = R(1) + DR

52 CONTINUE

151 CONTINUE

CALL DATOU

IF (NF - 10) 74,72,72

72 CALL COMP(NPR0B)

74 CONTINUE

NPR0B = NPR0B + 1

GO TO 1

END

SUBROUTINE CATIN(J)

DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),QO(9),TI(1000),AV(9)

1,AT(9),FZ(1000),FZT(1000),FF(9)

C

C

COMMON T,V,R,TT,AR,QO,RH0A,RH0P,KX,KY,ND,NS,NC,NF,NG,NX0,NY0,DCX,D

1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT

2,VG,FZ,FZT

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00000400

00001010

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00001031

00001032

00001040

00001041

00001042

READ INPUT TAPE 5,2,RO,TO,VO,RHOA,VG	00001050
2 FORMAT (5E12.8)	00001060
READ INPUT TAPE 5,4,TT	00001070
4 FORMAT (9A6)	00001080
IF (J-1) 10,10,12	00001085
10 READ INPUT TAPE 5,4,AT	00001093
READ INPUT TAPE 5,4,AV	00001094
READ INPUT TAPE 5,4,AR	00001095
READ INPUT TAPE 5,4,FF	00001096
READ INPUT TAPE 5,4,00	00001097
C	00001100
C	00001101
READ INPUT TAPE 5,6,KX,KY,ND,NS,NC	00001120
6 FORMAT (5I12)	00001130
READ INPUT TAPE 5,6,NF,NG,NX0,,NY0,NTIME	00001140
READ INPUT TAPE 5,8,DCX,DCY,XLI,XUI,YLI,YUI	00001150
READ INPUT TAPE 5,9,RHOP,CP,DTI	00001160
8 FORMAT (6E12.8)	00001170
9 FORMAT (3E12.8)	00001180
12 CONTINUE	00001199
RETURN	00001200
END	00001210
C SUBROUTINE BEGIN	00001501
C THIS SUBROUTINE CALCULATES THE INITIAL CONDITIONS.	00001502
C	00001503
SUBROUTINE BEGIN (DT,DV,DR)	00001510
DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),00(9),TI(1000),AV(9)	00001520
1,AT(9),FZ(1000),FZT(1000),FF(9),	00001521
2L0I(100),R0I(100,4),V0I(100,4), T0I(100,4),TI0I(100,4)	00001522
C	00001530
COMMON T,V,R,TT,AR,00,RHOA,RHOP,KX,KV,ND,NS,NC,NF,NG,NX0,NYC,DCX,D	00001540
1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT	00001541
2,VG,FZ,FZT,FF,	00001542
3R0I,V0I,T0I,L0I,TI0I,L	00001543
C	00001550
I = 1	00001560
V(I) = VO	00001570
T(I) = TO	00001580
R(I) = RO/3.048E05	00001590
TI(I) = 0.0	00001600
CALL DVEL(DV)	00001610
CALL QAERO(CA)	00001620
CALL QGRAD (QR)	00001630
CALL QOX(Q0)	00001640
CALL QVAP (CR,Q0,QV,FZ(I),FZT(I))	00001650

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```

QTOT = QA + QO - QR - QV
1 CAP = 1.33333*3.14159*RHOP*CP*R(I)*R(I)*R(I)
2 DT = QTOT*DTI/CAP
  T12 = DT/T(I)
  IF (T12 - 0.02) 5,5,4
4 TI(I) = 0.0
  CALL HALFD(CT,DV,DR)
  L = 0
  TI(I) = 0.0
5 CONTINUE
  WRITE OUTPUT TAPE 6,7,TI(I),QA,QO,QR,QV,DT
7 FORMAT (1H ,11X,F8.4,8X,F12.6,9X,F12.6,F17.6,7X,F12.6,5X,F7.2)
  TI(I) = DTI
  T(I) = TO + DT
  V(I) = VO + DV
  R(I) = (RO/3.048E+05) + DR
  RETURN
  END
C
C
C SUBROUTINE DATPR
C THIS SUBROUTINE PRINTS SOME OF THE INITIAL DATA.
C
C SUBROUTINE DATPR
  DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)
1,AT(9),FZ(1000),FZT(1000),FF(9)
C
COMMON T,V,R,TT,AR,OO,RHOP,KX,KY,ND,NS,NC,NF,NG,NXO,NYO,DCX,D
1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT
2,VG,FZ,FZT
C
WRITE OUTPUT TAPE 6,2,RO
2 FORMAT (1H-,10X,22H THE INITIAL RADIUS IS,F8.2,8H MICRONS)
C
WRITE OUTPUT TAPE 6,4,VO
4 FORMAT (1H ,10X,33H THE INITIAL PARTICLE VELOCITY IS,F9.1,10H FEET
1/SEC(.))
WRITE OUTPUT TAPE 6,5,TO
6 FORMAT (1H ,10X,36H THE INITIAL PARTICLE TEMPERATURE IS,F7.1,6H DE
1G F)
VI = (RO/3.048E05)**3
VOL = 1.3333*3.14159*VI
CAP = RHOP*VOL*CP
WRITE OUTPUT TAPE 6,7,VOL
7 FORMAT (1H ,10X,31H THE INITIAL PARTICLE VOLUME IS,E16.8,5H CUFT)

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00001680
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00002050
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00002080
00002081
00002090
00002095
00002096
00002098
00002100
00002102
00002103
00002104

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```

WRITE OUTPUT TAPE 6,17,CAP                                00002105
17 FORMAT (1H,10X,43H THE TOTAL HEAT CAPACITY OF THE PARTICLE IS,E1600002106
1.8,10H BTU/CEG F)                                         00002107
WRITE OUTPUT TAPE 6,8,RHQA                                  00002110
8 FORMAT (1H,10X,19H THE AIR DENSITY IS,E14.6,8H LB/CUFT) 00002120
WRITE OUTPUT TAPE 6,9,VG                                    00002122
9 FORMAT (1H,10X,34H THE MEAN AIR MOLECULE VELOCITY IS,F9.2,6HFT/SEC00002125
1C)                                                         00002126
WRITE OUTPUT TAPE 6,10,RHQP                                  00002130
10 FORMAT (1H,10X,24H THE PARTICLE DENSITY IS,F9.3,8H LB/CUFT) 00002140
TIMEN = FLOATF(NTIME)                                       00002150
TIMAX = TIMEN*DTI                                           00002160
WRITE OUTPUT TAPE 6,11,TIMAX                                00002170
11 FORMAT (1H,10X,19H DURATION OF RUN IS,F7.2,4H SEC)     00002180
WRITE OUTPUT TAPE 6,12                                      00002190
12 FORMAT (1H-,10X,5H TIME,12X,12H AEROHEATING,11X,10H OXIDATION,7X,100002200
10H RADIATION,6X,13H VAPORIZATION,7X,3H DT)                00002210
WRITE OUTPUT TAPE 6,14                                      00002220
14 FORMAT (1H,10X,5H SEC,12X,12H BTU/SEC,11X,10H BTU/SEC,7X,100002230
10H BTU/SEC,6X,13H BTU/SEC,6X,6H DEG F)                    00002240
RETURN                                                       00002250
END                                                         00002260

C                                                         00003001
C                                                         00003002
C SUBROUTINE CVEL                                           00003003
C THIS SUBROUTINE CALCULATES THECHANGE IN VELOCITY DURING THE 00003004
C TIME INCREMENT                                           00003005
C                                                         00003006
C SUBROUTINE CVEL(DV)                                       00003010
C DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),GG(9),TI(1000),AV(9)00003020
C 1,AT(9),FZ(1000),FZT(1000),FF(9),                      00003021
C 2L0I(100),R0I(100,4),V0I(100,4), T0I(100,4),TI0I(100,4) 00003022
C                                                         00003030
C COMMON T,V,R,TT,AR,GG,F,TT,RHQP,KX,KY,ND,NS,NC,NF,NG,NXG,NYG,DCX,DJ00003040
C 1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT 00003041
C 2,VG,FZ,FZT,FF,                                           00003042
C 3R0I,V0I,T0I,L0I,TI0I,L                                  00003043
C                                                         00003045
C IF (I - 1) 2,2,4                                         00003050
2 CD = 2.0                                                  00003060
PI = 3.14159                                               00003070
CONS = 3.C*CD*RHQA/(4.0*2.0*PI*RHQP)                      00003080
4 CONSR = CONS*DTI/R(I)                                    00003082
C                                                         00003085
C VL = 1.0/((1.0/V(I))+ CONSR)                             00003090

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C		00003100
C	VL IS REALLY V(I+1)	00003110
C		00003120
	DV = VL - V(I)	00003130
	RETURN	00003140
	END	00003150
	SUBROUTINE FALFC (DT,DV,DR)	00003500
	DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)	00003510
	1,AT(9),FZ(1000),FZT(1000),FF(9),LOI(100),ROI(100,4),VOI(100,4),	00003520
	2TOI(100,4),TIOI(100,4)	00003521
	COMMON T,V,R,TT,AR,OO,RHQA,RHQP,KX,KY,ND,NS,NC,NF,NG,NXO,NYC,DCX,DJ	00003540
	1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT	00003541
	2,VG,FZ,FZT,FF,ROI,VOI,TOI,LOI,TIOI,L	00003542
C		00003550
C		00003552
	L = L + 1	00003557
	LOI(L) = 1	00003558
	LL = 1	00003559
	TOR = T(I)	00003570
	ROR = R(I)	00003580
	WOR = V(I)	00003590
	TIOR = TI(I)	00003595
	DTIOR = DTI	00003596
C		00003600
	K = I - 1	00003604
	S = DT/(0.05*T(I))	00003605
	S = ABSF(S)	00003606
	IF (S - 3.0) 2,3,3	00003607
	2 ISP = 2	00003608
	GO TO 10	00003609
	3 IF (S - 7.0) 4,5,5	00003610
	4 ISP = 5	00003611
	GO TO 10	00003612
	5 IF (S - 13.0) 6,7,7	00003613
	6 ISP = 10	00003614
	GO TO 10	00003615
	7 IF (S - 20.0) 9,9,8	00003616
	8 ISP = 20	00003617
	WRITE OUTPUT TAPE 6,98,DT,T(I)	00003618
	GO TO 10	00003619
	9 ISP = 16	00003620
	10 CONTINUE	00003621
	FISP = FLOATF(ISP)	00003622
	DTI = DTIOR/FISP	00003623
	21 ISPH = (ISP/2) + 1	00003630

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```

D0 40 J =1,ISP
CALL GAERO(CA)
CALL GRAD(QR)
CALL QOX(Q0)
CALL QVAP(DR,Q0,QV,FZ(I),FZT(I))
CALL DVEL(DV)
QTOT = CA + Q0 - QR - QV
CAP = 1.3333*3.14159*CP*R(I)*R(I)*R(I)*RHOP
25 DT = QTCT*DTI/CAP
T(I) = T(I) + DT
R(I) = R(I) + DR
V(I) = V(I) + DV
C
TI(I) = TI(I) + DTI
IF (J-2) 26,24,27
24 IF (ISP -2) 26,31,26
26 T0I(L,LL) = T(I)
R0I(L,LL) = R(I)
V0I(L,LL) = V(I)
TI0I(L,LL) = TI(I)
LL = LL + 1
TIX = TI(I) - DTIOR
WRITE OUTPUT TAPE 6,99,K,J,TIX,QA,Q0,QR,QV,DT
27 CONTINUE
IF (J-ISP) 29,28,29
28 T0I(L,3) = T(I)
R0I(L,3) = R(I)
V0I(L,3) = V(I)
TI0I(L,3) = TI(I)
TIX = TI(I) - DTIOR
WRITE OUTPUT TAPE 6,99,K,J,TIX,QA,Q0,QR,QV,DT
29 CONTINUE
IF (J-(ISP-1)) 31,30,31
30 T0I(L,4) = T(I)
V0I(L,4) = V(I)
R0I(L,4) = R(I)
TI0I(L,4) = TI(I)
TIX = TI(I) - DTIOR
WRITE OUTPUT TAPE 6,99,K,J,TIX,QA,Q0,QR,QV,DT
31 CONTINUE
40 CONTINUE
51 DTI= TI(I) - TIOR
DT = T(I) - TOR
DV = V(I) - VOR
DR = R(I) - ROR

```

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00003635
00003640
00003645
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00003685
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00003695
00003700
00003705
00003707
00003710
00003715
00003720
00003725
00003730
00003732
00003735
00003740
00003745
00003750
00003755
00003760
00003765
00003767
00003770
00003775
00003780
00003785
00003790
00003795
00003800
00003802
00003805
00003810
00003815
00003920
00003925
00003930
00003935

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TI(I) = TIOR

R(I) = ROR

T(I) = TOR

V(I) = VOR

98 FORMAT (1H,10X,15H THE INITIAL DT=F12.2,33H IS LARGER THAN THE

1TEMPERATURE,F12.2)

99 FORMAT (1H,14,13,4X,F8.4,7X,F13.6,8X,F13.6,F17.6,6X,F13.6,F12.2)

RETURN

END

C

C

C

SUBROUTINE QAERO

C

THIS SUBROUTINE CALCULATES THEAERODYNAMIC HEATING RATE USING

C

FREE MOLECULE THEORY.

C

SUBROUTINE QAERO(QA)

DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)

1,AT(9)

COMMON T,V,R,TT,AR,OO,RHOA,RHOP,KX,KY,ND,NS,NC,NF,NG,NXO,NYO,DCX,D

1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT

2,VG

C

Q = 0.5*RHOA*V(I)*V(I)*V(I)

C

C

AT THIS TIME UNITS ARE IN LB

C

Q = Q/(32.2*778.0)

C

C

UNITS ARE NOW BTU/SQFT-SEC

C

PI=3.14159

2 AREA = PI*R(I)*R(I)

4 QA = Q*AREA

RETURN

END

C

C

C

SUBROUTINE GRAD

C

C

SUBROUTINE GRAD EPS = 0.8

C

THIS SUBROUTINE CALCULATES THERADIATIVE HEAT LOSS RATE.

C

SUBROUTINE GRAD(QR)

DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)

00003940

00003945

00003950

00003955

00003980

00003981

00003985

00003998

00003999

00004001

00004002

00004003

00004004

00004005

00004006

00004010

00004020

00004021

00004030

00004040

00004042

00004045

00004050

00004060

00004070

00004080

00004090

00004100

00004110

00004120

00004130

00004150

00004160

00004170

00004180

00005001

00005002

00005003

00005501

00005502

00005003

00005004

00005005

00005010

00005020

88

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```

1,AT(9)                                00005021
C                                       00005030
COMMON T,V,R,TT,AR,GO,RHGA,RHOP,KX,KY,ND,NS,NC,NF,NG,NXG,NYG,DCX,D00005040
1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT 00005041
2,VG                                    00005042
C                                       00005045
EPSIG = 0.4758333E-12                 00005050
TR = T(I) + 459.0                     00005060
Q = EPSIG*TR*TR*TR*TR                 00005070
AREA = 4.0*3.14159*R(I)*R(I)         00005080
QR = Q*AREA                          00005090
RETURN                                00005100
END                                    00005110

C                                       00005501
C                                       00005502
C SUBROUTINE C0X                       00005503
C   THIS SUBROUTINE CALCULATES THEOXIDATION HEAT RATE USING FREE 00005504
C   MOLECULAR GAS FLOW TO THE PARTICLE 00005505
C                                       00005506
SUBROUTINE C0X(Q0)                   00005510
DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),GO(9),TI(1000),AV(9) 00005520
1,AT(9),FZ(1000),FZT(1000)         00005521
C                                       00005530
COMMON T,V,R,TT,AR,GO,RHGA,RHOP,KX,KY,ND,NS,NC,NF,NG,NXG,NYG,DCX,D00005540
1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT 00005541
2,VG,FZ,FZT                         00005542
PIRRP= 3.14159*R(I)*R(I)*RHGA*0.21 00005560
IF (I-1) 2,2,4                      00005570
2 VG2 = 2.0*VG                       00005580
ZMO = 1.3333*PIRRP*R(I)*RHOP/(RHGA*0.21) 00005590
ZM = ZMO                             00005600
4 CONTINUE                           00005610
AMTZ= PIRRP*(V(I)+ VG2)*2.875        00005620
ZM = ZM -AMTZ*DTI                    00005630
IF (ZM) 8,8,6                        00005648
6 Q0= 5150.0 *AMTZ                   00005650
GO TO 10                              00005655
8 Q0 = 0.0                            00005660
10 RETURN                             00005670
END                                   00005680

C                                       00006001
C                                       00006002
C SUBROUTINE DATOU                     00006003
C   THIS SUBROUTINE PRINTS OUT THE DATA AT THE END OF RUN INCLUDING 00006004
C   CRT PLOTS.                         00006005

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C      SUBROUTINE CATOL                                00006006
      DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9) 00006010
      1,AT(9),FZ(1000),FZT(1000),FF(9)                00006021
      2,L0I(100),ROI(100,4),T0I(100,4),V0I(100,4),TI0I(100,4) 00006022
C      COMMON T,V,R,TT,AR,OO,RH0A,RH0P,KX,KY,NO,NS,NC,NF,NG,NX0,NYC,CCX,D00006030
      1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,TIME,TI,I,CP,AV,AT 00006041
      2,VG,FZ,FZT,FF,ROI,V0I,T0I,L0I,TI0I,L          00006042
C      WRITE OUTPUT TAPE 6,1,TT                        00006045
      1 FORMAT (1H1,32X,9A6)                          00006046
      WRITE OUTPUT TAPE 6,2                            00006047
      2 FORMAT (1H0,12X,5H TIME,10X,12H TEMPERATURE,6X,9H VELOCITY,9X,7H 00006050
      1RADIUS,8X,9H FRACTION,7X,9H FRACTION)           00006061
C      WRITE OUTPUT TAPE 6,4                            00006080
      4 FORMAT (1H ,12X,5H SEC,10X,12H DEG F ,6X,9H FT/SEC ,9X,7H M00006100
      1ICRON,7X,11H UNOXIDIZED,5X,10H UNABLATED)      00006110
      L = 1                                             00006111
      DO 34 I = 1,NTIME                               00006113
      R(I) = R(I)*3.048E+05                            00006132
      IF (I - 20) 25,25,21                            00006135
      21 IF (MP-10) 22,25,25                          00006140
      22 MP = MP + 1                                    00006145
      GO TO 26                                          00006150
      25 WRITE OUTPUT TAPE 6,6,I,TI(I),T(I),V(I),R(I),FZ(I),FZT(I) 00006155
C      6 FORMAT (1H ,14,7X,F8.4,6X,F12.2,8X,F10.3,8X,F8.2,8X,F8.6,8X,F8.6) 00006160
      MP = 1                                           00006161
      26 CONTINUE                                     00006162
      IF(L0I(L) - 1) 32,27,32                        00006165
      27 DO 30 LL=1,4                                 00006167
      ROI(L,LL) = ROI(L,LL)*3.048E+05                00006169
      IF (ROI(L,LL) - 0.5) 29,29,28                  00006170
      28 WRITE OUTPUT TAPE 6,129,I,LL,TI0I(L,LL),T0I(L,LL),V0I(L,LL),ROI(L, 00006172
      1LL)                                             00006174
      29 CONTINUE                                     00006176
      L0I(L) = 0                                     00006178
      30 CONTINUE                                     00006179
      L = L + 1                                       00006180
      32 CONTINUE                                     00006182
      34 CONTINUE                                     00006184
      NP = NTIME                                       00006186
      NV = 2                                           00006188

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      IF (NF - 10) 35,35,36
35 CALL AICRT3 (KX,KY,TI,T,NP,ND,NV,NS,NC,TT,OC,AT,1,NG,DCX,DCY,NX0
      1,XLI,XUI,2,C.0,8000.0)
      C
      CALL AICRT3 (KX,KY,TI,V,NP,ND,NV,NS,NC,TT,OC,AV,NF,NG,DCX,DCY,NX0
      1,XLI,XUI,2,C.0,25000.0)
      C
      DR = R(1) - R(NTIME)
      RED = ABSF(DR)/R(1)
      IF (0.01 - RED) 10,12,12
10 CALL AICRT3 (KX,KY,TI,R,NP,ND,NV,NS,NC,TT,OC,AR,NF,NG,DCX,DCY,NX0
      1,XLI,XUI,NYC,YLI,YUI)
12 CONTINUE
      DFZ = FZ(1) - FZ(NTIME)
      IF (DFZ - 0.01) 41,41,31
31 CALL AICRT3 (KX,KY,TI,FZ,NP,ND,2,NS,42,TT,OC,FF,NF,NG,DCX,DCY,2,XL
      1,XUI,2,0.0,1.0)
41 CONTINUE
      DFZT = FZT(1) - FZT(NTIME)
      IF (DFZT - 0.01) 61,61,51
51 CALL AICRT3 (KX,KY,TI,FZT,NP,ND,1,1,44,TT,OC,FF,2,NG,DCX,DCY,2,XLI
      1,XUI,2,0.0,1.0)
61 CONTINUE
      C
129 FORMAT (1H ,I4,2X,I2,3X,F8.4,6X,F12.2,8X,F10.3,8X,F10.4)
36 CONTINUE
      RETURN
      END
      C
      SPECIAL QVAP SUBROUTINE
      C
      THIS SUBROUTINE COMPARES THE EFFECT OF METALLIC VAPORIZATION. IF
      C
      KY = -1, THERE IS NO METALLIC VAPORIZATION. IF KY IS GREATER THAN -1
      C
      THERE IS METALLIC VAPORIZATION. AFTER EACH PROBLEM KY IS REDUCED
      C
      BY 1. THIS SUBROUTINE IS FOR PAM-4. OCT. 4, 1965
      C
      SUBROUTINE QVAP(DR,QOX,QV,FZ,FZT)
      DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)
      1,AT(9),FZ(1000),FZT(1000)
      C
      COMMON T,V,R,TT,AR,OO,RH0A,RH0P,KX,KY,ND,NS,NC,NF,NG,NX0,NYC,DCX,D
      1CY,XLI,XUI,YLI,YUI,DTI,RO,VO,TO,NTIME,ZM,TI,I,CP,AV,AT
      2,VG
      C
      IF (I-1) 1,1,11
      C
      C

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00006190
00006199
00006200
00006205
00006210
00006220
00006230
00006240
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00006580

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1	ZMO = 1.3333*3.14159*R(I)*R(I)*R(I)*RHOP	00006590
	ZOM = 0.0	00006605
	PI = 3.14159	00006606
	IF (KY) 0,7,7	00006610
6	NVAM = 0	00006612
	GO TO 11	00006614
7	NVAM = 1	00006616
11	AMTZ = Q0X / 5150.0	00006618
	CALL VAPOR (VP,T(I))	00006620
	TR = T(I) + 459.0	00006630
C		00006640
C		00006650
C		00006660
	A = 123.22/TR	00006670
	B = SQRTF(A)	00006680
	VRZO = 0.1601*VP*B	00006690
	AREA = 4.0*PI*R(I)*R(I)	00006700
	AVRZ = AREA*VRZO	00006740
C		00006750
	IF (I - 10) 19,19,13	00006762
13	IF (Q0X - 0.000001) 14,14,19	00006764
14	ZM = -1.0E-29	00006766
19	CONTINUE	00006768
	ZOM1 = ZOM + (AMTZ - AVRZ)*DTI	00006770
	IF (ZOM1) 21,21,31	00006772
	IF (NVAM) 28,28,22	00006778
21	AAVRZ = ((ZOM/DTI) + AMTZ)	00006774
	CV = AAVRZ * 1000.0	00006776
22	CONTINUE	00006780
	DTVZM = DTI*AAVRZ/AVRZ	00006784
	CALL VAPZM(VPM,TR)	00006786
	A = 91.2/TR	00006788
	B = SQRTF(A)	00006792
	VRZM = 0.1601*VPM*B	00006794
	AVRZM = AREA*VRZM	00006796
	ZM = ZM - AVRZM*DTVZM	00006798
28	CONTINUE	00006799
	ZOM = 0.0	00006800
	GO TO 41	00006810
31	CV = AVRZ*1000.0	00006820
	ZOM = ZOM1	00006830
41	CONTINUE	00006840
	ZTOT = ZM + ZOM	00006850
	IF (ZTOT) 61,61,51	00006855
51	VNOW = ZTOT/RHOP	00006860

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RNOW = (0.75*VNOW/PI)**0.33333          00006865
DR = RNOW - R(I)                        00006870
FZ = ZM/ZMO                             00006873
FZT = ZTOT/ZMO                          00006874
GO TO 71                                00006878
61 RLAST = R(I)*30.48 E+04              00006880
    TLAST = TI(I)                       00006885
    TEMPL = T(I)                        00006887
    I = NTIME                           00006890
    WRITE OUTPUT TAPE 6,62,RLAST         00006900
62 FORMAT (1H-,12X,48H THE PARTICLE HAS ABLATED TO A RADIUS LESS THAN 00006910
    1N,F11.6,9H MICRONS.)              00006911
    WRITE OUTPUT TAPE 6,63,TLAST,TEMPL  00006920
63 FORMAT (1H,12X,3CH THIS ABLATION OCCURRED AFTER,F9.4,38H SECONDS 00006930
    1,AND THE FINAL TEMPERATURE WAS,F9.2,6H DEG F) 00006931
    FZ = 0.0                            00006935
    FZT = 0.0                           00006940
71 CONTINUE                             00006950
80 CONTINUE                             00006955
    IF (I-NTIME) 90,81,81               00006956
81 KY = KY - 1                          00006957
90 CONTINUE                             00006959
    RETURN                               00006960
    END                                  00006970
C SUBROUTINE VAPOR                       00007000
C   LOG P(ATM) = -34020/T + 7.828       00007001
    SUBROUTINE VAPOR (VP,T)             00007010
    ABTR = T + 459.6                    00007020
    ABTK = ABTR/1.8                     00007030
    PAL = 11.98 -(7.98 E-04)*ABTK - 34383.0/ABTK 00007040
    IF (PAL + 18.0) 10,10,20           00007042
10 PAL = -18.0                          00007046
20 PAT = 10.0**PAL                      00007050
    VP = PAT*760.0                      00007060
    RETURN                               00007070
    END                                  00007080
C SUBROUTINE VAPZM THE VAPOR PRESSURE OF ZIRCONIUM METAL 00007500
    SUBROUTINE VAPZM (VPM,TR)          00007510
C                                         00007515
C SKINNER'S EQU FOR VAPOR PRESSURE    00007518
C                                         00007519
C                                         00007520
    TK = TR/1.8                         00007525
    PAL = 7.3351 +(2.415E-04)*TK        -(31066.0/TK) 00007525
    IF (PAL + 18.0) 10,10,20           00007530
10 PAL = -18.0                          00007540

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20 PAT = 10.0**PAL

VPM

=

PAT*760.0

RETURN

END

C COMP A SUBROUTINE FOR COMPARING RESULTS OF SEVERAL PROBLEMS.

C THIS SUBROUTINE TAKES THE RESULTS OF SEVERAL PROBLEMS AND

C STORES THEM. THEN WHEN THE LAST PROBLEM IS FINISHED CRT'S ARE MADE

C

SUBROUTINE COMP(NPROB)

DIMENSION T(1000),V(1000),R(1000),TT(9),AR(9),OO(9),TI(1000),AV(9)

1,AT(9),FZ(1000),FZT(1000),FF(9)

2,L0I(100),ROI(100,4),T0I(100,4),V0I(100,4),TI0I(100,4)

3,TS(1000),RS(1000),VS(1000),FZS(1000),FZTS(1000),TS2(100),TS3(100)

4,TS4(100),TS5(100),TS6(100),RS2(100),RS3(100),RS4(100),RS5(100),RS6(100)

5,VS2(100),VS3(100),VS4(100),VS5(100),VS6(100),

6FZS2(100),FZS3(100),FZS4(100),FZS5(100),FZS6(100),

7FZTS2(100),FZTS3(100),FZTS4(100),FZTS5(100),FZTS6(100)

8,TIMS(100)

C

C

COMMON T,V,R,TT,AR,OO,RH0A,RH0P,KX,KY,ND,NS,NC,NF,NG,NX0,NY0,DCX,DJ

1CY,XLI,XUI,YLI,YUI,DTI,RO,V0,TO,NTIME,ZM,TI,I,CP,AV,AT

2,VG,FZ,FZT,FF,ROI,V0I,T0I,L0I,TI0I,L

3,TS,TS2,TS3,TS4,TS5,TS6,RS,RS2,RS3,RS4,RS5,RS6,

4VS,VS2,VS3,VS4,VS5,VS6,FZS,FZS2,FZS3,FZS4,FZS5,FZS6,

5FZTS,FZTS2,FZTS3,FZTS4,FZTS5,FZTS6

6,TIMS,VMAX,RMAX

C

C

NPA= (NPROB*10) + 1

NCK

=

NF

-

NPA

IF (NPROB - 1) 10,10,20

10 RMAX = RO

VMAX = VO

DO 30 I=1,NTIME

TS(I)

=

T(I)

RS(I)

=

R(I)

VS(I)

=

V(I)

FZS(I)

=

FZ(I)

FZTS(I)

=

FZT(I)

30 CONTINUE

WRITE OUTPUT TAPE 6,35,TT

35 FORMAT (1H-,12X,14H THE PROBLEM ,9A6,15H IS REPRESENTED)

WRITE OUTPUT TAPE 6,36

36 FORMAT (1H ,7X14H BY THE CURVE.)

00007550

00007560

00007570

00007580

00008000

00008001

00008002

00008003

00008004

00008010

00008011

00008012

00008013

00008014

00008015

00008016

00008017

00008018

00008020

00008030

00008040

00008041

00008042

00008043

00008044

00008045

00008046

00008050

00008060

00008065

00008070

00008080

00008082

00008085

00008090

00008100

00008105

00008110

00008115

00008120

00008130

00008135

00008136

00008137

00008138

74

C

20 IF (NPA- 60) 38,38,37	00008140
37 CONTINUE	00008150
RMAX = MAX1F(R0,RMAX)	00008160
VMAX = MAX1F(V0,VMAX)	00008162
MP = 1	00008165
JP = 1	00008240
DO 137 I = 1,NTIME	00008250
IF (MP - 10) 237,337,237	00008260
337 TS6(JP) = T(I)	00008270
RS6(JP) = R(I)	00008280
VS6(JP) = V(I)	00008290
FZS6(JP) = FZ(I)	00008300
FZTS6(JP) = FZT(I)	00008310
MP= 0	00008320
JP = JP + 1	00008330
237 CONTINUE	00008340
MP = MP + 1	00008350
137 CONTINUE	00008360
WRITE OUTPUT TAPE 6,56,TT	00008370
56 FORMAT (1H-,12X,14H THE PROBLEM ,9A6,15H IS REPRESENTED)	00008372
WRITE OUTPUT TAPE 6,66	00008375
66 FORMAT (1H ,7X,31H IN THE COMPARISON BY 'CIRCLES')	00008377
GO TO 400	00008379
38 IF (NPROB - 5) 40,39,400	00008380
39 MP = 1	00008390
JP = 1	00008400
RMAX = MAX1F(R0,RMAX)	00008410
DO 139 I = 1,NTIME	00008412
IF (MP - 10) 239,339,239	00008420
339 TS5(JP) = T(I)	00008430
RS5(JP) = R(I)	00008440
	00008450
	00008460
	00008470
	00008480
	00008490
	00008500
	00008510
	00008520
	00008530
	00008540
	00008542
	00008545
	00008547
	00008549

C

VS5(JP) = V(I)	00008540
FZS5(JP) = FZ(I)	00008542
FZTS5(JP) = FZT(I)	00008545
MP = 0	00008547
JP = JP + 1	00008549
239 CONTINUE	
MP = MP +1	
139 CONTINUE	
WRITE OUTPUT TAPE 6,55,TT	
55 FORMAT (1H-,12X,14H THE PROBLEM ,9A6,15H IS REPRESENTED)	
WRITE OUTPUT TAPE 6,65	
65 FORMAT (1H ,7X,31H IN THE COMPARISON BY 'SQUARES')	

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	G0 T0 400	00008550
C		00008560
	40 IF (NPROB - 4) 43,42,400	00008570
	42 MP = 1	00008580
	JP = 1	00008590
	D0 142 I = 1,NTIME	00008600
	IF (MP - 10) 242,342,242	00008610
	342 TS4(JP) = T(I)	00008620
	RS4(JP) = R(I)	00008630
C		00008640
	VS4(JP) = V(I)	00008650
	FZS4(JP) = FZ(I)	00008660
	FZTS4(JP) = FZT(I)	00008670
	MP = 0	00008680
	JP = JP + 1	00008690
	242 CONTINUE	00008700
C		00008710
	MP = MP + 1	00008720
	142 CONTINUE	00008730
	WRITE OUTPUT TAPE 6,55,TT	00008732
	WRITE OUTPUT TAPE 6,64	00008735
	64 FORMAT (1H ,7X,26H IN THE COMPARISON BY '*'.)	00008737
	G0 T0 400	00008740
	43 IF (NPROB - 3) 45,44,400	00008750
	44 MP = 1	00008760
	JP = 1	00008770
	D0 144 I = 1,NTIME	00008780
	IF (MP - 10) 244,344,244	00008790
	344 TS3(JP) = T(I)	00008800
	RS3(JP) = R(I)	00008810
	MP = 0	00008820
	VS3(JP) = V(I)	00008830
	FZTS3(JP) = FZT(I)	00008840
	FZS3(JP) = FZ(I)	00008850
	JP = JP + 1	00008860
	244 CONTINUE	00008870
	MP = MP + 1	00008880
	144 CONTINUE	00008890
	WRITE OUTPUT TAPE 6,55,TT	00008892
	WRITE OUTPUT TAPE 6,63	00008895
	63 FORMAT (1H ,7X,26H IN THE COMPARISON BY 'X'.)	00008897
	G0 T0 400	00008900
C		00008910
	45 IF (NPROB - 2) 47,46,400	00008920
	46 MP = 1	00008930

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      JP = 1
      DO 146 I = 1, NTIME
      IF (MP - 10) 246, 346, 246
346  TMS(JP)      =
      TS2(JP)     =
      RS2(JP)     =
      VS2(JP)     =
      FZS2(JP)    =
      FZTS2(JP)   =
      MP          =
      JP          =
      TI(I)
      T(I)
      R(I)
      V(I)
      FZ(I)
      FZT(I)
      Q
      JP + 1
246  CONTINUE
      MP = MP + 1
146  CONTINUE
      WRITE OUTPUT TAPE 6, 55, TT
      WRITE OUTPUT TAPE 6, 62
62   FORMAT (1H, 7X, 26H IN THE COMPARISON BY '+'. )
      GO TO 400
47   CONTINUE
400  CONTINUE
      RMAX = MAX1F(RQ, RMAX)
      VMAX = MAX1F(VQ, VMAX)
      IF (NCK - 10) 402, 500, 500
402  CALL COMPI(NPROB)
500  CONTINUE
      RETURN
      END
      SUBROUTINE COMPI(NPROB)
      DIMENSION T(1000), V(1000), R(1000), TT(9), AR(9), Q(9), TI(1000), AV(9)
      1, AT(9), FZ(1000), FZT(1000), FF(9)
      2, LQI(100), RQI(100, 4), TQI(100, 4), VQI(100, 4), TIQI(100, 4)
      3, TS(1000), RS(1000), VS(1000), FZS(1000), FZTS(1000), TS2(100), TS3(100)
      4, TS4(100), TS5(100), TS6(100), RS2(100), RS3(100), RS4(100), RS5(100), RS6(100)
      5, VS2(100), VS3(100), VS4(100), VS5(100), VS6(100),
      6, FZS2(100), FZTS3(100), FZTS4(100), FZTS5(100), FZTS6(100), TMS(100),
      7, FZTS2(100), FZS3(100), FZS4(100), FZS5(100), FZS6(100)
      COMMON T, V, R, TT, AR, Q, RHOA, RHOP, KX, KY, ND, NS, NC, NF, NG, NXO, NYC, DCX, D
      1CY, XLI, XUI, YLI, YUI, DTI, RO, VO, TO, NTIME, ZM, TI, I, CP, AV, AT
      2, VG, FZ, FZT, FF, RQI, VQI, TQI, LQI, TIQI, L, TS, TS2, TS3, TS4, TS5, TS6,
      3, RS, RS2, RS3, RS4, RS5, RS6, VS, VS2, VS3, VS4, VS5, VS6,
      4, FZS, FZS2, FZS3, FZS4, FZS5, FZS6, FZTS, FZTS2, FZTS3, FZTS4, FZTS5, FZTS6
      5, TMS, VMAX, RMAX
      READ INPUT TAPE 5, 2, TT

```

```

00008940
00008950
00008960
00008970
00008980
00008990
00009000
00009010
00009020
00009030
00009040
00009050
00009060
00009070
00009072
00009075
00009078
00009080
00009090
00009150
00009152
00009155
00009160
00009161
00009162
00009163
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00009165
00009170
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00009185
00009190
00009200

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2	FORMAT (9A6)	00009210
420	TIN = FLOATF(NTIME)	00009220
	TOTI = NTIME	00009230
	NP = NTIME	00009240
	WRITE OUTPUT TAPE 6,4	00009300
4	FORMAT (1H-,40X,16H CRT INFORMATION)	00009310
C		00009320
	WRITE OUTPUT TAPE 6,6,TT	00009330
6	FORMAT (1H0,4X,6H TITLE,30X,9A6)	00009340
C		00009350
	WRITE OUTPUT TAPE 6,8,TOTI,VMAX,RMAX	00009360
8	FORMAT (1H0,4X,11H TOTAL TIME,F8.3,27H SEC. MAXIMUM VELOCITY,	00009370
	1F8.1,28H FT/SEC. MAXIMUM RADIUS,F10.4,7H MICRON)	00009371
C		00009380
	CALL AICRT3(0,0,TT,TS,NP,ND,2,1,42,TT,00,AT,1,1,DCX,DCY,2,0.0,TOTI	00009420
	1,2,0.0,8000.0)	00009430
	IF (NPROB - 2) 430,422,422	00009440
422	NPX = NP/10	00009450
	CALL AICRT3(0,0,TIMS,TS2,NPX,ND,1,1,16,TT,00,AT,2,1,DCX,DCY,2,0.0,	00009460
	1TOTI,2,0.0,8000.0)	00009470
C		00009480
C		00009490
	IF (NPROB - 3) 430,423,423	00009500
C		00009510
423	CALL AICRT3(0,0,TIMS,TS3,NPX,ND,1,1,55,TT,00,AT,2,1,DCX,DCY,2,0.0,	00009520
	1TOTI,2,0.0,8000.0)	00009530
C		00009540
C		00009550
	IF(NPROB - 4) 430,424,424	00009560
424	CALL AICRT3(0,0,TIMS,TS4,NPX,ND,1,1,44,TT,00,AT,2,1,DCX,DCY,2,0.0,	00009570
	1TOTI,2,0.0,8000.0)	00009580
	IF (NPROB - 5) 430,425,425	00009590
425	CALL AICRT3(0,0,TIMS,TS5,NPX,ND,1,1,63,TT,00,AT,2,1,DCX,DCY,2,0.0,	00009600
	1TOTI,2,0.0,8000.0)	00009610
C		00009620
	IF (NPROB - 6) 430,426,426	00009630
426	CALL AICRT3(0,0,TIMS,TS6,NPX,ND,1,1,38,TT,00,AT,2,1,DCX,DCY,2,0.0,	00009640
	1TOTI,2,0.0,8000.0)	00009650
430	CALL AICRT3(0,0,TT,VS,NP,ND,2,1,42,TT,00,AV,1,1,DCX,DCY,2,0.0,TOTI	00009660
	1,2,0.0,VMAX)	00009670
	IF (NPROB - 2) 440,432,432	00009680
432	CALL AICRT3(0,0,TIMS,VS2,NPX,ND,1,1,16,TT,00,AV,2,1,DCX,DCY,2,0.0,	00009690
	1TOTI,2,0.0,VMAX)	00009700
	IF (NPROB - 3) 440,433,433	00009710
433	CALL AICRT3(0,0,TIMS,VS3,NPX,ND,1,1,55,TT,00,AV,2,1,DCX,DCY,2,0.0,	00009720

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	1T0TI,2,0.0,VMAX)	00009730
C		00009740
	IF (NPROB - 4) 440,434,434	00009750
434	CALL AICRT3(0,0,TIMS,VS4,NPX,ND,1,1,44,TT,00,AV,2,1,DCX,DCY,2,0.0,	00009760
	1T0TI,2,0.0,VMAX)	00009770
C		00009780
	IF(NPROB - 5) 440,435,435	00009790
435	CALL AICRT3(0,0,TIMS,VS5,NPX,ND,1,1,63,TT,00,AV,2,1,DCX,DCY,2,0.0,	00009800
	1T0TI,2,0.0,VMAX)	00009810
C		00009820
	IF (NPROB - 6) 440,436,440	00009830
	1T0TI,2,0.0,VMAX)	00009850
C		00009860
440	CALL AICRT3(0,0,TI,RS,NP,ND,2,1,42,TT,00,AR,1,1,DCX,DCY,2,0.0,T0TI	00009870
	1,2,0.0,RMAX)	00009880
C		00009890
	IF (NPROB - 2) 450,442,442	00009900
442	CALL AICRT3(0,0,TIMS,RS2,NPX,ND,1,1,16,TT,00,AR,2,1,DCX,DCY,2,0.0,	00009910
	1T0TI,2,0.0,RMAX)	00009920
	IF (NPROB - 3) 450,443,443	00009930
443	CALL AICRT3(0,0,TIMS,RS3,NPX,ND,1,1,55,TT,00,AR,2,1,DCX,DCY,2,0.0,	00009940
	1T0TI,2,0.0,RMAX)	00009950
	IF (NPROB - 4) 450,444,444	00009960
444	CALL AICRT3(0,0,TIMS,RS4,NPX,ND,1,1,44,TT,00,AR,2,1,DCX,DCY,2,0.0,	00009970
	1T0TI,2,0.0,RMAX)	00009980
C		00009990
	IF (NPROB - 5) 450,445,445	00010000
445	CALL AICRT3(0,0,TIMS,RS5,NPX,ND,1,1,63,TT,00,AR,2,1,DCX,DCY,2,0.0,	00010010
	1T0TI,2,0.0,RMAX)	00010020
C		00010030
	IF(NPROB -6) 450,446,450	00010040
446	CALL AICRT3(0,0,TIMS,RS6,NPX,ND,1,1,38,TT,00,AR,2,1,DCX,DCY,2,0.0,	00010050
	1T0TI,2,0.0,RMAX)	00010060
C		00010070
450	CALL AICRT3 (0,0,TI,FZS,NP,ND,2,1,42,TT,00,FF,1,1,DCX,DCY,2,0.0,T00010080	
	1TI,2,0.0,1.0)	00010090
	IF(NPROB - 2) 460,452,452	00010100
452	CALL AICRT3(0,0,TIMS,FZS2,NPX,ND,1,1,16,TT,00,FF,2,1,DCX,DCY,2,0.0,	00010110
	1,T0TI,2,0.0,1.0)	00010111
	IF(NPROB - 3) 460,453,453	00010120
453	CALL AICRT3(0,0,TIMS,FZS3,NPX,ND,1,1,55,TT,00,FF,2,1,DCX,DCY,2,0.0,	00010130
	1,T0TI,2,0.0,1.0)	00010140
	IF (NPROB - 4) 460,454,454	00010150
454	CALL AICRT3(0,0,TIMS,FZS4,NPX,ND,1,1,44,TT,00,FF,2,1,DCX,DCY,2,0.0,	00010160
	1,T0TI,2,0.0,1.0)	00010170

IF (NPROB - 5) 460,455,455	00010180
455 CALL AICRT3(0,0,TIMS,FZS5,NPX,ND,1,1,63,TT,00,FF,2,1,DCX,DCY,2,0.000010190	00010191
1,T0TI,2,0.0,1.0)	00010200
IF (NPROB - 6) 460,456,456	00010210
456 CALL AICRT3(0,0,TIMS,FZS6,NPX,ND,1,1,38,TT,00,FF,2,1,DCX,DCY,2,0.000010220	00010221
1,T0TI,2,0.0,1.0)	00010230
460 CALL AICRT3(0,0,TI,FZTS,NP,ND,2,1,42,TT,00,FF,1,1,DCX,DCY,2,0.0,T000010250	00010240
1TI,2,0.C,1.0)	00010251
IF (NPROB - 2) 470,462,462	00010260
462 CALL AICRT3(0,0,TIMS,FZTS2,NPX,ND,1,1,16,TT,00,FF,2,1,DCX,DCY,2,0.00010280	00010270
10,T0TI,2,0.0,1.0)	00010281
IF (NPROB - 3) 470,463,463	00010290
463 CALL AICRT3(0,0,TIMS,FZTS3,NPX,ND,1,1,55,TT,00,FF,2,1,DCX,DCY,2,0.00010310	00010300
10,T0TI,2,0.0,1.0)	00010311
IF (NPROB - 4) 470,464,464	00010320
464 CALL AICRT3(0,0,TIMS,FZTS4,NPX,ND,1,1,44,TT,00,FF,2,1,DCX,DCY,2,0.00010340	00010330
10,T0TI,2,0.0,1.0)	00010341
IF (NPROB - 5) 470,465,465	00010350
465 CALL AICRT3(0,0,TIMS,FZTS5,NPX,ND,1,1,63,TT,00,FF,2,1,DCX,DCY,2,0.00010370	00010360
10,T0TI,2,0.0,1.0)	00010371
IF (NPROB - 6) 470,466,466	00010380
466 CALL AICRT3(0,0,TIMS,FZTS6,NPX,ND,1,1,38,TT,00,FF,2,1,DCX,DCY,2,0.00010400	00010390
10,T0TI,2,0.0,1.0)	00010401
470 NPROB	00010410
500 CONTINUE	00010420
RETURN	00010430
END	00010440
	00010450
	00010460

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

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APPENDIX B

SAMPLE PAM-4 INPUT

This is a sample of the input data required for PAM 4. Some of the data required are for the AICRT-3 subroutine (Reference 12). In earlier versions, all of these data had to be submitted. In PAM-4, some changes have been made and not all are required.

When PAM-4 is used, deck number 3W-715 must be requested. This deck is the AICRT-3 subroutine.

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7350-38

DATA

C. W. SAYLES

xx-yy-65

1

6

DATA

Star Data Card

1

5 0 0 . 0

3 2 0 0 . 0

1 4 0 0 0 . 0

5 . 1 1 2 9 E - 05

14 5 9 . 3

Initial Radius (Microns)

First Case

Initial Temperature

Initial Velocity

Air density at 170,000 feet

Mean air velocity at 170,000 feet

1 0

C A S E 1 7 0 - 5 0

0 - 1 4 0 0 0 S T D

Title card for first case

2 0

T E M P E R A T U R E

D E G R E E F

3 . 0

42

DATA

C. W. SAYLES

xx-yy-65

2

6

7350-38

V E L Ø C I T Y

F T / S E C

Abscissa label 2nd CRT plot

R A D I U S

M I C R Ø N S

40

Abscissa label 3rd CRT plot

F R A C T I Ø N

R E M A I N G

50

Abscissa label 4th CRT plot

T I M E

S E C

60

Ordinate label for CRT plots

70

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FORTRAN FIXED 10 DIGIT DECIMAL DATA

DATA

PROGRAMMER C. W. SAYLES

DATE xx-yy-65

PAGE 3

6

JOB NO. 7350-38

IDENTIFICATION		DESCRIPTION DO NOT KEY PUNCH
0		KX a CRT control number not needed in PAM- 4 version
1		KY metal vaporization control number (KY = -1; no metal vapor.)
1		ND a CRT control number (See reference 12)
1		NS a CRT control number (See Reference 12)
4 2		NC a Crt control number, not needed in PAM - 4 version
75		
5 1		NF number of cases X 10 + 1
1		NG a CRT control number (See Reference 12)
2		NXØ a CRT control number (See Reference 12)
1		NYØ a CRT control number (See Reference 12)
7 0 0		NTIME number of time intervals
8 0		
3 2 . 0		DCX a CRT control number (See Reference 12)
322 . 0		DCY a CRT control number (See Reference 12)
0 . 0		XLI a CRT control number (See Reference 12)
1 0 . 0		XUI a CRT control number (See Reference 12)
0 . 0		YLI a CRT control number not needed in PAM- 4 version
1 0 0 . 0		9 0 YUI a CRT control number not needed in PAM-4 version
3 7 5 . 0		Particle density lb/cu.ft. (RHØP)
0 . 0 7		CP specific heat of particle
0 . 0 1		DTI time interval seconds

FORTRAN FIXED 10 DIGIT DECIMAL DATA

DECK NO. DATA PROGRAMMER C. W. SAYLES

DATE xx-yy-65 PAGE 4 of 6 JOB NO. 7350-38

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1 2 5 0 . 0		Initial radius Second case
13 3 2 0 0 . 0		Initial temperature
25 1 4 0 0 0 . 0		Initial velocity
37 5 . 1 1 2 9 E - 0 5		Air density at 170,000 feet
49 1 4 5 9 . 3	73	Mean velocity of air molecules at 170,000 feet
61	1 1 0	
1 C A S E 3 - V		Title card 2nd case
13 1 7 0 - 25 0 - 1 4 0 0		
25 0		
37		
49	73	
61	1 2 0	
1 1 0 0 0 . 0		Initial Radius 3rd Case
13 3 2 0 0 . 0		Initial Temperature
25 1 4 0 0 0 . 0		Initial Velocity
37 5 . 1 1 2 9 E - 0 5		Air density at 170,000 feet
49 1 4 5 9 . 3	73	Mean velocity of air molecules at 170,000 feet
61	2 1 0	
1 C A S E 1 7 0 - 1 0		Title card 3rd Case
0 0 - 1 4 0 0 0		

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DATA

C. W. SAYLES

xx-yy-65

5

6

7350-38

NUMBER	ELEVATION	DESCRIPTION
5 0 0 . 0		Initial radius 4th Case
3 2 0 0 . 0		Initial temperature
1 8 0 0 0 . 0		Initial velocity
5. 1 1 2 9 E - 0 5		Air density at 170,000 feet
1 4 5 9 . 3		Mean velocity of air molecules at 170,000 feet
	3 1 0	
C A S E 1 7 0 - 5 0		Title Card 4th Case
0 - 1 8 0 0 0		
	3 . 2 0	
5 0 0 . 0		Initial radius 5th Case
3 2 0 0 . 0		Initial Temperature
1 0 0 0 0 . 0		Initial Velocity
5 . 1 1 2 9 E - 0 5		Air density at 170,000 feet
1 4 5 9 . 3		Mean velocity of air molecules at 170,000 feet
	4 1 0	
C A S E 1 7 0 - 5 0		Title Card 5th Case
0 - 1 0 0 0 0		
	4 2 0	

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DATA

C. W. SAYLES

xx-yy-65

6

6

7350-38

VELOCITY -

SIZE 170 K

FT

Title card for CRT plots

570

47

FIGURE 1

Temperature-Time relationship for 500 micron particle released
at 170,000 feet

CASE 31 170-500-14000

VP-1 EPS = ⁷²⁴⁶⁻²²_{001 000}

Unclass
CLASSIFICATION
S. P. Fields 11/3/65
DATE
AUTHORIZED CLASSIFIER

FIGURE 3

Temperature-Time Relationships for Particles Released
at 177,000 feet

SIZE EFFECT 177-630-14200

7350-36
006 00

Unclass
CLASSIFICATION
R. Fields 11/3/61 -

FIGURE 4
Velocity-Time Relationships for Particles Released at
177,000 feet
SIZE EFFECT 177-630-14200

7350-38
997 099

Unclass
CLASSIFIED BY
SP Fields 11/3/65
SIGNATURE
AUTHORIZED CLASSIFIER

FIGURE 5

Radius-Time Relationships for Particles Released at
177,000 feet

SIZE EFFECT 177-630-14200

7559-38
008 000

Unclass
SR Field 11/2/65

FIGURE 6

Fraction Unablated-Time Relationships for Particles
Released at 177,000 feet

Unclass
S. R. L. 12/3/65

FIGURE 7

Temperature-Time Relationships for Particles
VELOCITY - SIZE 170 KFT

7350-38
001 000

Unclass
H. R. Zeld 11/3/65
AUTHORITY OF ACTION

FIGURE 8
Velocity-Time Relationships for Particles

VELOCITY - SIZE 170 KFT

7350-38 L
002 000

17
Unclassified
RD / D1
11/3/64
DATE

FIGURE 9

Radius-Time Relationships for Particles

1/1/65
1/1/65
1/1/65

FIGURE 10
Fraction Unablated-Time Relationships for Particles

Unclassified
SR Field 11/3/65