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RE-ENTRY ABLATION EVALUATION
OF SMALL MOLTEN DROPLETS
OF STRONTIUM-90 SPACE FUEL

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For:

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FOREWORD

This report has been prepared for the Strontium Space Fuel Development Program-Nuclear Safety and Re-entry Evaluation of Sr-90 Space Fuel-Development of the Liquid Droplet Ablation Code. The work was performed for the Martin Nuclear Division under contract No. AT(30-1)-3062.

SUMMARY

This is a study of the effects of physical properties of possible nuclear space fuels on the ablation of small molten droplets of fuel which are entering the earth's atmosphere at hypersonic speeds. The objective is to identify the physical properties which control the rate of "burn-up" of small molten droplets and to specify the approximate values of these physical properties necessary to produce a prescribed total "burn-up." Ablation mechanisms were postulated and programmed for the IBM 7094 Computer. Preliminary results indicate that liquid viscosity, surface tension, heat of vaporization, and boiling point are the dominant physical properties.

NOMENCLATURE

a	$\equiv \frac{\psi A \dot{Q}_c}{\Delta H_v}, \text{ lb}_m/\text{sec.}$
ag	$\equiv 2^{1/4} \sqrt{\frac{\rho_\infty V_\infty R_b}{\mu_\infty}} \frac{3\alpha}{M_\infty}, \text{ ft (ref. 27)}$
A	Altitude, ft.
A _b	Area, ft. ²
b	$\equiv A \epsilon / \beta T_w / \Delta H_v, \text{ lb}_m/\text{sec}$
c	$\equiv \frac{4\pi R_b^3 c_p \rho_s}{3 \Delta H_v} \frac{\Delta T}{\Delta t}$
C _d	Drag coefficient
c _p	Specific heat at constant pressure, BTU/lb _m °R
d	$\equiv \frac{4\pi R_b^3 (KB)}{3 \Delta H_v}, \text{ lb}_m/\text{sec.}$
D	Drag, lb.
f	Fraction of available heat transfer to region 1 (in Phase II Figure 1) transferred through drop-let surface [(1-f) is fraction of available heat transfer to region 1 which results in evaporation in region 1]
f'(0)	$1 + \frac{\alpha \delta}{3} \text{ (ref. 27)}$
g	Fraction of available heat transfer to region 2 (in Phase II Figure 1) transferred through drop-let surface [(1-g) is fraction of available heat transfer to region 2 which results in evaporation in region 2]
h	Specific enthalpy, BTU/lb _m
h _d	Average atomic dissociation energy times atom mass fraction in external flow.

H	Total specific enthalpy, BTU/lb _m
ΔH_v	Heat of vaporization, BTU/lb _m
j	Fraction of available heat transfer to region 3 (in Phase II Figure 1) transferred through droplet surface [(i-j) is fraction of available heat transfer to region 3 which results in evaporation in region 3]
k	Thermal conductivity, Btu/Ft. Sec. °R
KB	Decay heat generated per unit mass, watts/kgm
L	Lewis Number for atom - molecule mixture
m	Droplet mass, lb _m
M	$\frac{29}{M_w}$
M_∞	Free stream Mach Number
M_w	Molecular weight
N_0	Avogadro's number, 6.023×10^{23} molecules/mole
p	Pressure, lb _f /ft ²
$\dot{q}_{BL}$	Rate of stagnation point heat transfer to surface according to boundary layer solution, BTU/ft ² /sec. (ref. 18)
$\dot{q}_c$	Convective aerodynamic heat transfer to body, BTU/ft ² /sec.
$\dot{q}_{cs}$	Convective aerodynamic heat transfer to body at stagnation point BTU/ft ² /sec.
$\dot{q}_{FM}$	Heat transfer rate to body in free molecular flow BTU/ft ² /sec.
$\dot{q}_R$	Radiative heat transfer rate from body, BTU/ft ² /sec.
r_b	Droplet radius above which breakup must occur, ft. (ref. 3).

R_b	Droplet radius, ft.
R	Gas constant, ft. lb_f/lb_m $^{\circ}\text{R}$
Re_b, Re_s	$\equiv \frac{\rho_{\infty} V_{\infty} R_b}{\mu_s} \quad (\text{ref. 13, 15})$
Re_f	$\equiv \frac{\rho_s \sqrt{H_{\infty}} R_b}{\mu_t} \quad (\text{ref. 13})$
S	Surface tension, dynes/cm or $\text{lb}_f/\text{Ft.}$
SL	Slope of vapor pressure curve ($\text{Log}_{10} \text{ V.P. ATM.}$) = $\frac{SL}{T(^{\circ}\text{K})} + W$
t	Time, sec.
T	Temperature, $^{\circ}\text{R}$
ΔT	Incremental change in temperature, $^{\circ}\text{R}$
V	Velocity, ft/sec.
$\bar{V}_e$	Average velocity of molecules emitted from body in first order collision flow, ft/sec
u_e	X- component of external flow velocity, ft/sec (ref 18).
$u(X, 0)$	Liquid flow velocity at droplet surface, ft/sec (ref. 27).
W	y intercept of vapor pressure curve.
X	Curvilinear coordinate measured along droplet surface.
ΔX	Temperature difference between T_{ave} and T , in Phase III.
y	Curvilinear coordinate normal to the droplet surface.
ΔY	Temperature difference between T_{ave} and T_3 in Phase III
Z	Compressibility factor.
α_1	Fraction of heat absorbed in region 1 which is transferred to region 2 (in Phase II Figure 1) and results in evaporation in region 3.
α_2	Fraction of heat absorbed in region 1 which is transferred to region 3 (in Phase II Figure 1) and results in evaporation in region 3.

α	$\equiv \frac{M_\infty}{3} \sqrt{\frac{\mu_\infty}{\mu_m} \sqrt{\frac{\rho_m}{\rho_\infty}}} \quad (\text{ref. 27})$
β	Stefan - Boltzmann constant, watts/M ² °K ⁴
β_1	Fraction of heat absorbed in region 2 which is transferred to region 3 (in Phase II Figure 1) and results in evaporation in region 3.
γ	Fraction of kinetic energy transferred to an air molecule in an unshielded impact (accommodation coefficient).
γ_e	Re-entry angle, degrees
γ_N	Fraction of stagnation pressure (Phase II and Phase III).
γ_s	Ratio of specific heats.
δ	Boundary layer thickness, ft.
δ_s	Shock wave thickness.
ϵ	Density ratio across shock wave.
ϵ_l	Emissivity
ϵ	$\equiv \frac{\gamma_s - 1}{2 \gamma_s} \quad (\text{ref. 13}).$
ζ	Fraction of $\dot{q}_{c_g}$ (Phase II)
Δ	Detachment or stand-off distance of shock wave from stagnation point.
η	Fraction of $\dot{q}_{c_g}$ (Phase I)
θ	Angular coordinate, degrees.
λ	$\equiv \frac{\alpha \delta}{7} \quad (\text{ref. 27}).$
λ_{MF}	Mean free path, ft.
μ	Viscosity, centipoises
ρ	Density, lb _m /ft ³ .
σ	Prandtl Number taken as 0.71 in numerical calculations.
ψ	Blowing factor
γ	$\equiv \sqrt{\frac{\gamma}{2}} M_\infty \quad (\text{ref. 10}).$

SUBSCRIPTS

ave	average
b	body
F	final
i	gas-liquid interface
m	droplet material
o	stagnation
r	recovery
R	rupture
s	conditions behind (down stream of) shock wave
v	vapor
w	wall
∞	free stream conditions

I. Introduction and Programs Developed

The following analysis involves a study of the ablation of molten fuel droplets released into the atmosphere from strontium fueled power generators upon re-entering the earth's atmosphere. The principal objective of this study is to determine the effects of specific fuel physical properties on ablation.

Several analyses¹⁻⁶ are available which postulate mechanisms of "burn-up" of both space fuels and meteors. A survey of these papers led to the conclusion that a more fundamental mechanism of "burn-up" was necessary.

Further study of the problem indicated that an exact solution of the momentum and energy equations for the liquid droplet and a coupling of these solutions with the air layer relationships around the droplet was beyond the scope of the project and, in any case, certainly could not be justified until the problem was better defined.

Thus, it was decided to develop and program on the IBM 7094 computer a general molten droplet model designated "Phase II" (Fig. 1) where the heat can be distributed arbitrarily throughout the model and the surface temperature can be varied according to an arbitrary surface pressure distribution. The droplet surface temperature in this model is determined by the boiling point of the molten droplet material at the local pressure. The basic assumptions made in the use of this model are:

1. The gas temperature (recovery temperature) is equal to or greater than twice the surface temperature (wall temperature).
2. The surface temperature is the local boiling temperature for the molten liquid and is an insensitive function of surface pressure (Fig. 2).

2.

3. The air flow rate over the body is sufficiently high to remove all the vaporized (molten) liquid from the surface of the droplet (that is, wall shear stress is appreciable).

In order to supplement the basic model, two additional models were (Phase III) programmed. The first of the models/is designed to account for the low velocity region of the particle trajectory. The basic assumptions made in this model are:

1. The surface temperature is lower than the boiling point.
2. The general equations for stagnation point region ablation can be used to describe the mechanism of ablation.⁷
(Phase I)

The final model/was developed and programmed in order to estimate the deceleration during the preheating period extending from the time of droplet release to the time when the droplet temperature approaches that surface temperature where an appreciable ablation rate commences.

It should be pointed out that a considerable amount of judgment and auxiliary hand calculation will have to be made in order to use the programs developed in this project. Illustrations of input estimation are given in the section on sample problems.

II. Physical Properties Evaluation

In general, the physical properties of space fuel which have the most important effect on the evaporation and/or "burn-up" of that fuel during re-entry into the earth's atmosphere are:

1. Viscosity.
2. Surface tension.
3. Heat of vaporization.
4. Boiling point temperature (vapor pressure).

The viscosity of molten droplets of space fuel affects the convective heat transfer rate to the droplet surface by affecting blocking. When a

surface is being heated by a higher temperature air stream flowing over it and there exists mass evaporation from the heated surface into the air stream, partial "blocking" of available heat transfer to the surface results. A blocking symbol ψ is commonly used to define the magnitude of this effect and is defined as the ratio of the actual heat transfer rate to the surface to the theoretical heat transfer rate.

When the viscosity of the molten droplet is sufficiently low (estimated 10 cp or less, see Appendix E) calculations indicate that the following conditions exist:

1. A rapid circulation of liquid in and on the surface of the droplet (velocities of the order of 100 ft/sec on a 1 mm radius droplet).
2. A very small rise in temperature in the liquid circulating past the front face of the hemisphere.
3. A very small amount of evaporation on the front face of the hemisphere (because the relatively low front face surface temperature results in a relatively low vapor pressure compared with the local air cap gas pressure).

For liquid viscosities from 10 to 50 cp the analysis of liquid flow in the droplet breaks down, and the estimation of an ablation mechanism becomes more speculative. Furthermore, the result of increasing surface liquid viscosities will be lower surface flow velocities, higher surface temperatures and more vaporization locally in the high convective heating region on the front face of the sphere. Thus, on a relative basis the available convective heat transfer to the front surface of the spherical droplet will be blocked at a rapidly increasing rate as the viscosity increases (Fig. 3). Results of calculations made indicate that if as little as 10% of the available convective heat results in local front face vaporization (in contrast to all available heat being transferred by convection to the side or rear of the

droplet) approximately 50% of the available heat is blocked out. Thus, a minimum blocking effect and a maximum heat transfer rate occurs only for a space fuel which exhibits a very low molten liquid viscosity. Since the objective of this work in the Strontium Space Fuel Program is to study methods for optimizing fuel "burn-up" or evaporation, no effort was put forth to adapt our mechanisms to the higher viscosity cases.

The primary effect of surface tension on "burn-up" of molten droplets of space fuel is on the determination of the original particle size when molten fuel is subjected to air drag forces. Although the mechanism of break-up or atomization of liquids is not understood (Ref. 6 and 8), Opik's (Ref. 3) analysis allows a reasonable approach to the understanding of the role of surface tension in atomization of liquids. The important effect is that the lower the surface tension the smaller the droplet size and obviously the smaller the "burn-up" needed to reach a given minimum molten droplet size.

The effect of heat of vaporization of the space fuel molten liquid on "burn-up" is obvious. Since during re-entry there is only a specific amount of net heating available to the droplet, the amount of heat necessary to evaporate a unit mass of liquid determines the amount of mass lost from the droplet (this statement is general and is meant only to illustrate the point; it should be qualified very carefully and this will be done later).

The vapor pressure of the molten liquid determines the surface temperature, and thus the radiation heat loss from the droplet. In addition, low vapor pressure results in higher convective heat transfer rate and larger available amounts of energy (see cold wall and hot wall graphs).

Taking the previous discussion on physical properties into consideration, the optimum space fuel chosen to maximize the "burn-up" condition would have:

1. A very low viscosity ($\sim 10\text{cp}$) to obtain a maximum aerodynamic heating rate (minimum ψ).
2. A minimum surface tension ($< 100\text{ dynes/cm}$) to attain minimum original droplet size.

(~ 25 kcal/g-mole)

3. A very low heat of vaporization_^ to obtain maximum vaporization of liquid fuel.
4. A low boiling point i.e., high vapor pressure at low temperatures to minimize radiation loss and maximize use of available energy.

Additional physical properties which play a secondary role in the "burn-up" of space fuel during re-entry into the earth's atmosphere are:

1. Emmissivity.
2. Fuel density.
3. Thermal conductivity.
4. Specific heat.
5. Molecular weight.

Emmissivities of molten droplets of fuel are expected to be 0.5 or larger.⁹ Considering that the surface radiation heat loss is directly in proportion to the emmissivity and is proportional to the 4th power of the temperature, it is expected that any appreciable decrease in radiation heat loss from the droplet surface will result from lowering the surface temperature and not from possible changes in emmissivity.

The effect of molten droplet density on "burn-up" has not been investigated so far. A look at the droplet deceleration equation and the radius loss equation indicate that a larger density will result in less deceleration, greater total heat input, and a smaller rate of radius decrease - i.e., one effect should approximately cancel out the second. Parametric studies will have to be performed to determine this effect.

Thermal conductivity does not play an important part in "burn-up" of molten fuel droplets because of the importance of the viscosity effect already discussed.

Specific heat does not influence "burn-up" of small droplets because the volume to area ratio is very small, and thus the rate of change of the heat content of the molten droplet is very small compared to the convective heat transfer to the droplet and the radiation away from the droplet.

The molecular weight affects the blocking term to a minor extent and, therefore, does not influence the "burn-up" of the molten droplets to any appreciable degree.

Some additional factors which are interrelated to physical properties and will be discussed in detail later, are:

Release velocity and altitude.

Droplet shape.

Internal heat generation, both from radioactivity and chemical reaction. (small for strontium)

Re-entry angle.

Internal heat distribution.

Effect of gas phase chemical reaction.

III. Discussion of Results of Strontium Space Fuel "Burn-up" Investigation

The models described in Part A are believed to be adequate to describe the overall ablation process taking place. The general ablation model, Phase II, was used to study a limited group of both hypothetical and realistic cases. The use of Phases I and III to supplement this information was not thought to be needed because the additional information would not materially change the trends of Phase II calculations.

It should be pointed out that the results presented are intended only to indicate trends, and that extensive parametric studies using specific fuel properties will be performed soon.

The hypothetical cases are termed "cold wall" where one fictitious vapor pressure curve and two separate variable heats of vaporization are used as input. Also, the blocking terms are arbitrarily set to zero.

The results are shown in Figs. 4, 5, 6, and 7 for two release velocities and two arbitrary input release radii. These "cold wall" cases represent the limit of "burn-up" capability for the hypothetical fuel studied. Table I gives a list of the hypothetical fuel properties.

The realistic cases have been termed "hot wall". The fuel physical properties investigated are those of possible fuel materials (see Table II). Results of calculations are illustrated in Figs. 9 to 14 inclusive. The "no blocking" case is the one where $f = g = j = 1$ and $\alpha_1 = \alpha_2 = \alpha_3 = 0$; the nomenclature see for definition of these terms. The case where it is intended to illustrate the effect of blocking is identified by $f = .97$, $g = .80$, $j = .40$, $\alpha_1 = \alpha_2 = \alpha_3 = 0$. (See list of symbols).

Figs. 9 to 14 show that a considerable decrease in "burn-up" results for the case where blocking exists. Also, the effect of heat of vaporization on "burn-up" is large.

From the figures presented the trends indicated are that high blocking factors, ψ , λ i.e., about equal to one, low viscosity, relatively small fuel heat of vaporization, low surface tension, and low fuel boiling point are necessary to maximize "burn-up".

The "cold wall" cases were run at three altitudes: 175,000 feet, 200,000 feet, and 225,000 feet, while the "hot wall" cases were run at 200,000 feet, and 225,000 feet. No appreciable effect of altitude on total mass loss was observed. There exists, however, the altitude effect on droplet break-up. According to Öpik³ the maximum droplet size for a given material is determined by a balance between

surface tension and aerodynamic drag. Since for a given velocity the drag is a function of density (and drag coefficient), and since density is a rapidly changing function of altitude, the droplet break-up size will vary appreciably with altitude (Fig. 8).

In addition, when the surface tension is a decreasing function of temperature and the droplet is heated from a low release temperature relative to the boiling temperature toward the boiling temperature, Öpik's analysis predicts the droplet will break-up. The result of such a break-up in Fig. 8 is the dotted line.

The boiling surface model (Phase II) calculations are stopped when the surface liquid temperature is equal to 50% of the gas stagnation temperatures. Ablation study results at the lower velocity end of the trajectory using the "non-boiling surface model", Phase III, as stated before, have not been presented at this time (these studies would extend the curves in Figs. 9 to 14 to lower velocities). The significant results, however, in these studies showed for the realistic vapor pressure curves used that, at about 11 - 12,000 ft/sec velocity, the radiation heat loss became equal to the convective heat input; thus, the mass loss rate approached zero.

The heating effects on chemical reaction in or on the droplet can be added easily to the present models. For the time being, however, these effects have not been included because combustible or decomposing materials have not been considered. Some cursory studies were made of the ablation of iron and strontium metals (not reported), but the added heat of combustion did not increase the droplet heating or mass loss by a significant amount. On the other hand, iron oxide or strontium oxide which was formed would, because of their low vapor pressures, be left as a residue in the droplet.⁶ Since iron oxide and strontium oxide have much higher evaporation temperatures than iron and strontium, the probability of "burn-up" of these droplets is reduced.⁶

Gas phase reactions, oxidation or decomposition of vaporized fuel,

were not considered because (1) if the reactions take place near the front face of the droplet and are significant, the vapor blocking term will be important enough to materially reduce aeroheating to the sphere; so far this low heating case has been excluded; (2) if the gas phase reaction takes place along the center or rear portion of the sphere, its occurrence does not affect the heat balance, and therefore, the mass loss of the droplet.

A better understanding of the potential "burn-up" of molten space fuel droplets is provided by considering the conventional ballistic coefficient, $W/C_D A$ (slugs/ft²). It is known that ICBM ballistic coefficients of 500 or greater are common, while Mercury type re-entry vehicles have ballistic coefficients somewhere between 20 and 50. In addition, isotope power generators, satellites such as the Nimbus, and fuel rods have ballistic coefficients of the order of one.

For these vehicles, generators or fuel rods it is also known that relatively large amounts of total accumulated heat transfer are experienced during re-entry. Thus, when these ideas are projected to considerations of the "burn-up" of very small droplets of space fuel, it seems reasonable to expect a relatively large amount of "burn-up" because the total amount of mass is so small initially.

However, in the case of the re-entry of small droplets of fuel of interest--less than 500 microns radius--calculations indicate the re-entry phenomena which occurs is very much different from that of the ICBM, Mercury, generator, or Nimbus vehicles. Tables IV and V present the important differences between the two cases.

The droplet trajectories are obviously different from those of the larger vehicles; in effect, when a droplet is released into the atmosphere at hypersonic speeds, it is decelerated so rapidly that the unablated

part of the droplet will reach sub-sonic settling velocities in from a few hundred feet to less than say about ten miles depending on release altitude and droplet dimensions. In comparison, for example, the trajectory calculations for the Nimbus vehicle, which trajectory is typical for a $W/C_D A$ of about 2, will travel many times farther during the deceleration period. It can be observed from Tables IV and V that the significant differences between the two cases are:

- 1) deceleration (negative normal acceleration)
- 2) $W/C_D A$
- 3) convective heat transfer rate
- 4) drag coefficient

It turns out that, even though the deceleration rate is extremely high for the small droplet, the increased convective heat transfer rate and the larger ratio of surface area to mass ($C_D A/W$) tends to cancel out the low total heat transfer to the droplet which results from the short duration of flight.

It can be shown that even though the deceleration rate is high, there is sufficient heat transfer available to ablate a large proportion of the original mass if (1) the local boiling point and thus the local surface temperature is very low, (2) the heat of vaporization is low and (3) the heat transfer blocking factor is close to one (negligible blocking of heat).

Example: Figures 4 & 5

Boiling point $< 1000^\circ R$

Heat of vaporization is 243 Btu/lb mole or 17kcal/gm mole

$$\frac{\text{radius final}}{\text{radius initial}} \cong \frac{1}{50} \quad \text{fig. 4} \quad \begin{cases} \text{initial altitude, 200,000 ft} \\ \text{initial velocity, 20,000 ft/sec} \end{cases}$$

On the other hand, when the local boiling point is high, the heat of vaporization is high, and the blocking is negligible (finite by small)

there exists sufficiently high radiation loss and there is required sufficient additional heat for vaporization such that droplets will not burn up to any appreciable extent.

Example: Figures 13 & 14

Boiling range 3200°R to 4000°R

Heat of vaporization $\frac{1000 \text{ Btu}}{\text{lb mass}}$ or $\frac{70 \text{ kcal}}{\text{gm mol}}$

$$\frac{\text{radius final}}{\text{radius initial}} = \frac{1}{2} \quad \text{fig. 13}$$

Thus, it can be concluded that small droplets of fuel released at hypersonic velocities into the atmosphere are capable of being almost completely "burned-up" during the deceleration process only if their physical properties tend to maximize heat transfer to the droplet. In addition, it should be emphasized that the above statement is made without adequate knowledge concerning aerodynamic force "break-up" or dispersion of the droplets. Furthermore, if it can be shown that aerodynamic forces acting at hypersonic velocities on a droplet can shatter the droplet to sub-micron particles, the "burn-up" consideration will become of secondary importance.

TABLE IV

Comparison of Small Droplet and Re-entry Vehicle Parameters
During Re-entry into the Earth's Atmosphere

	Aerodynamic Heating Rate, $\dot{q}_c$ Btu/ft ² sec	Drag Coefficient	Maximum Normal Acceleration $G^{(1)}$	Ballistic Coefficient $W/C_D A^{(2)}$
Small Droplet	Approaches max. $\dot{q}_c$ i.e., free molecular heating rate	Approximately equal to two	Range of -400 to -30,000	$\ll 1.0$ example, 100 micron radius droplet of iron $W/C_D A \approx .003$
ICBM, Mercury, Power Generator, Fuel Rod, & Nimbus Satellite	Reduced well below max. $\dot{q}_c$ by existence of strong shock ahead of R/V - Actual heating rate is order of 1/10 or less of free molecular $\dot{q}_c$	Approximately equal to one	Range of 1 to 100	ICBM $\gg 500$ Mercury ≈ 30 Power Generator $\approx 2-4$ Fuel Rod $\approx 1-2$ Nimbus ≈ 2

NOTES:

(1) $G = \frac{\text{Actual normal acceleration in ft/sec}^2}{g \text{ earth's gravitational constant}}$

(2) $W/C_D A = \text{Slug/ft}^2$; $W = \text{weight in slugs}$; $C_D = \text{drag coeff.}$; $A = \text{Cross-sectional area of body normal to flow}$

Normal acceleration = $dV_{\infty}/dt = - \frac{\rho_{\infty} V_{\infty}^2}{(W/C_D A)}$; $\rho_{\infty} = \text{free stream density}$, $V_{\infty} = \text{free stream velocity}$

Deceleration = -normal acceleration

Observe normal acceleration is inversely proportional to $(W/C_D A)$.

TABLE V

Comparison of Addition Droplet and Re-entry Vehicle Parameters
(1)

Small Droplets

Release Altitude	Release Velocity	Release Radius	Time Elapsed From Droplet Release to End of Ablation	Release Stag. Point Heat Transfer Rate	Distance Travelled by Droplet from Release to End of Ablation	Normal Acceleration	Velocity of Droplet at end of Ablation
Ft	Ft/sec	Microns	Seconds	Btu/ft ² sec	Feet	G	Feet/second
220,000	22,500	150	0.500	1,650	8,400	- 1,040	11,500
189,000	21,000	60	0.050	4,100	900	- 7,600	11,500
150,000	14,000	30	0.005	4,260	65	- 24,000	11,000

Nimbus Vehicle in Orbital Re-entry⁽²⁾

Time Elapsed & Distance Travelled from Point 1 to Point 2

Altitude	Velocity	Stag. Point Heat transfer Rate to a 1 ft. dia. Sphere	Normal Acceleration	Altitude	Velocity	Stag. Point Heat Transfer Rate to a 1 ft. dia. Sphere	Time Elapsed	Distance Travelled
Ft.	Ft/sec	Btu/ft ² sec	G	Ft	ft/sec	Btu/ft ² sec	sec	Feet
250,000	24,730	83	- 0.05	124,000	11,500	93	88	1,883,000
220,000	23,280	131	- 0.17	124,000	11,500	93	50	928,000
188,000	20,970	170	- 0.47	124,000	11,500	93	26	443,000
177,000	19,800	175(max)	- 0.62	---	---	--	--	---
148,000	16,000	154	- 1.10	124,000	11,500	93	8	108,000
111,000	8,800	54	- 1.93(max)	---	---	--	--	----

NOTES: (1) These release altitude-velocity combinations are typical
The other value tabulated are for CPD 3, Table II

(2) Nimbus trajectory (no paddles, no ablation) $W/C_D A = 2$, $\theta = 0$, $\alpha = .1^\circ$
Altitude-velocity combination were chosen at closest points to small droplet release points or for obvious reference points

IV. Conclusions

The present models are sufficiently accurate to justify their use in evaluating the effects of space fuel physical properties on droplet "burn-up".

Verification of the accuracy of the present models to predict the ablation phenomena of molten droplets of space fuel entering the earth's atmosphere should be accomplished by checking the model calculation against experimental results to be done in the future.

However, in the evaluation of a specific fuel, if the question of "burn-up" is resolved into a marginal case where greater accuracy than is now available is required, the present models will have to be revised.

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VI. APPENDICES

Appendix A

Convective Heat Transfer At Hypersonic Speeds In The Rarefied Gas-Flow Regimes

A classification of the "flow regimes" encountered by a blunt body reentering the atmosphere has been proposed by Hayes and Probst¹⁰.

The highest degree of rarefaction is reached in the free molecule flow. Then, in descending order of rarefaction comes the first order collision regime, the transitional regime, the modified boundary layer regimes and finally the boundary layer or continuum regime. Fig. 15 illustrates the boundaries of each gas-flow regime for a blunt body with a nose radius of 1 foot.

A method¹² is also utilized to determine which flow regime a given body is in at a particular speed and altitude. This method compares the body radius R_b with the local mean-free path $\lambda_{0,1}$ (coordinate origin fixed in body) - the smaller R_b is in comparison with $\lambda_{0,1}$, the higher the degree of rarefaction. For example, in free molecule flow,

$$\lambda_{0,1} \gg R_b \quad (A-1)$$

where

$$\lambda_{0,1} = \frac{4}{V_\infty} \sqrt{\frac{RT_b}{\pi}} \lambda_\infty \quad (A-2)$$

and λ_∞ is the conventional mean free path found in tables of atmospheric properties. If it is assumed that much greater means an order of magnitude of about 10, then assume

$$\lambda_{0,1} = 10 R_b \quad (A-3)$$

and the lower bound of the free molecule flow becomes

$$\lambda_\infty = \frac{10 R_b V_\infty}{4} \sqrt{\frac{\pi}{RT_b}} \quad (A-4)$$

When the mean free path $\lambda_{e,i}$ becomes of the same order of magnitude as the characteristic dimension, i.e.,

$$\lambda_{e,i} \sim R_b, \quad (A-5)$$

then reference 12 sets the lower bound of the first-order collision regime at

$$\lambda_{\alpha} = \frac{R_b}{(3)} \frac{V_{\infty}}{(4)} \sqrt{\frac{\pi}{RT_b}} \quad (A-6)$$

In a likewise manner, the lower bounds of the other flow regimes are set.¹²

The manner in which convective stagnation point heat transfer is calculated varies from one flow regime to the next. In the free molecule flow regime, $\dot{q}_{e,s}$ is found using

$$\dot{q}_{e,s} = \frac{\gamma_i \rho_{\infty} V^3}{2J} \left[1 - \frac{1}{2} \left(\frac{\gamma_s + 1}{\gamma_s - 1} \right) \left(\frac{T_b}{T_{\infty}} \right) \frac{1}{\varphi^2} \right] \quad (A-7)$$

where γ_i is the coefficient of accommodation (of the order of 0.9 for practical surfaces) and φ the speed ratio ($= \frac{\gamma_s}{2} M_{\infty}$). The bracketed term in equation (A-7) is added to account for "hot wall" conditions.¹⁰

When the droplet is in the first order collision regime, $\dot{q}_{e,s}$ is calculated according to

$$\dot{q}_{e,s} = \frac{1}{2} \rho_{\infty} V_{\infty}^3 \left[1 - \left(\frac{\bar{V}_e}{V_{\infty}} \right)^2 \right] \left[1 - 0.2 \frac{R_b}{\lambda_{e,i}} \right] \quad (A-8)$$

where $\bar{V}_e$ is the average velocity of molecules emitted from the droplet surface. Reference 12 sets

$$\frac{\bar{V}_e}{U} \sim \left(\frac{3}{\gamma_s} \right)^{1/2} \frac{1}{M_{\infty}} \left(\frac{T_b}{T_{\infty}} \right)^{1/2} \quad (A-9)$$

$$\frac{\lambda_{e,i}}{R_b} \sim 2 \left(\frac{6}{\gamma_s} \right)^{1/2} \frac{\lambda_{\infty}}{M_{\infty} R_b} \left(\frac{T_b}{T_{\infty}} \right)^{1/2} \quad (A-10)$$

In the transistional and modified flow regimes, the approach given by Cheng¹³ was used to determine $\dot{q}_{s,1}$. Another approach considered was that of Chow¹⁴ but his theory did not cover the same extensive range of Cheng's analysis (i.e., first order collision regime to continuum regime). Also, a large amount of experimental data^{15, 16, 17} agreed quite well with Cheng's theory in the region where Chow's results were not applicable (see Fig. 6 of reference 14).

Cheng's heat transfer theory was adapted by curve fitting his results as given in Figure 4.1 of reference 13. This figure is a plot of the ratio of convective stagnation point heat transfer $\dot{q}_{s,1}$ to convective stagnation point heat transfer according to the boundary layer solution¹⁸ versus Reynold's Number $R_{e,1}$. Six values of $\frac{\dot{q}_{s,1}}{\dot{q}_{b,1}}$ were selected to cover the range of $R_{e,1}$ from 20 to 2000. Values of $\dot{q}_{b,1}$ at the selected points were calculated according to the theory of Fay and Riddell.¹⁸ They set $\sigma = 0.71$ then determined $\dot{q}_{b,1}$ using

$$\dot{q}_{b,1} = 0.94(\rho_w \mu_w)^{0.1} (\rho_o \mu_o)^{0.4} \left\{ 1 + (L^{0.52} - 1) \frac{h_d}{h_s} \right\} (h_o - h_w) \sqrt{\left(\frac{du_o}{dx} \right)_s} \quad (A-11)$$

where for a modified Newtonian flow, the stagnation point velocity gradient is

$$\left(\frac{du_o}{dx} \right)_s = \frac{1}{R_b} \sqrt{\frac{2(\rho_o - \rho_\infty)}{\rho_o}} \quad (A-12)$$

Refer to the nomenclature section of this report for a description of the various symbols of equation (A-11). For the sake of simplicity the Lewis Number L was set equal to 1. Equation (A-11) can then be rewritten as

$$\dot{q}_{b,1} = 0.94(\rho_w \mu_w)^{0.1} (\rho_o \mu_o)^{0.4} (h_o - h_w) \sqrt{\left(\frac{du_o}{dx} \right)_s} \quad (A-13)$$

This expression was then the correct relationship to use to evaluate $\dot{q}_{b,1}$ at a given $R_{e,1}$.

Figure 16 is a plot of Cheng's heat transfer theory. The curve was extrapolated beyond the 6 points initially selected in order to match the boundary layer solution at $\frac{\dot{q}_{cs}}{\dot{q}_{b1}} = 1.0$. An analytical expression was necessary to express $\frac{\dot{q}_{cs}}{\dot{q}_{b1}}$ as a function of $R_{o,f}$. In order to accomplish this, the curve was divided into 4 regions. Each segment of the curve could be drawn as a straight line according to the method outlined¹⁹ and the curve fitted with a straight line equation. The results of this study yielded the straight line segments shown in Figure 16 and the following expressions for $\frac{\dot{q}_{cs}}{\dot{q}_{b1}}$:

<u>Region</u>	<u>Equation</u>	<u>Range</u>	
I	$\frac{\dot{q}_{cs}}{\dot{q}_{b1}} = 4.62 (\text{Ref})^{.0628} - 5$	$R_{o,f} \leq 50$	(A-12)
II	$\frac{\dot{q}_{cs}}{\dot{q}_{b1}} = 5.53 (\text{Ref})^{.0189} - 5$	$50 < R_{o,f} \leq 500$	(A-13)
III	$\frac{\dot{q}_{cs}}{\dot{q}_{b1}} = 6.41 (\text{Ref})^{.00817} - 5$	$500 < R_{o,f} < 40,000$	(A-14)

Above $R_{o,f} = 40,000$, the Fay and Riddell equation (A-13) yielded the correct value of $\dot{q}_{b1}$.

Therefore, with the flow regime correctly defined, the convective stagnation heat transfer to a body can be calculated using the relationships given above (equations A-8 through A-14).

Lastly, when thermodynamic properties of air were needed to determine $\dot{q}_{cs}$, references 20, 21, and 22 were used.

APPENDIX B

Summary of Equations Used in Initial Droplet Heating Case - Phase I

Immediately after the fuel element ruptures, the fuel now being in liquid droplet form is subjected to aeroheating as it enters the atmosphere. The initial droplet heating from the rupture temperature T_r to the free surface boiling temperature is termed "Phase I".

Consider the liquid droplet shown below to be entering the atmosphere at velocity V_∞ . The droplet deceleration $\frac{dV_\infty}{dt}$

would be

$$\frac{dV_\infty}{dt} = \frac{-3C_D \rho_\infty V_\infty^2}{8\rho_m R_b} \quad (\text{B-1})$$

while its loss in altitude is

$$\frac{dA}{dt} = -V_\infty \sin \gamma_e \quad (\text{B-2})$$

The local pressure in region 1 is related to the stagnation pressure according to

$$P_1 = \gamma P_0 \quad (\text{B-3})$$

where γ is a fixed fraction and P_0 equals

$$P_0 = \rho_\infty V_\infty^2 \quad (\text{B-4})$$

After the pressure P_1 is found, T_{w_1} is calculated using

$$T_{w_1} (^{\circ}R) = \frac{1.8 SL}{\log_{10} P_1 (2T_m) - W} \quad (B-5)$$

where the slope SL and intercept w are obtained from the vapor pressure curve of the droplet material under consideration. The wall temperature in region 2 is related to T_{w_1} by

$$T_{w_2} = T_{w_1} - X \quad (B-6)$$

x being a fixed temperature.

A heat balance on the droplet yielded an expression for the change in average internal temperature T_{ave} . The expression derived was

$$\frac{dT_{avg}}{dt} = \frac{3\eta \dot{q}_{cs}}{4C_p \rho_m R_b} - \frac{3\epsilon 1 \beta T_{w_1}^4}{4\beta_s C_p R_b} + \frac{KB}{C_p} \quad (B-7)$$

In the above equation, the value of $\dot{q}_{cs}$ is determined according to the procedure given in Appendix A. Since the entire droplet surface is heated, the fraction of $\dot{q}_{cs}$ responsible for this heating is termed η .

Phase I is terminated and Phase II initiated when

$$T_{avg} > Z T_{w_1} \quad (B-8)$$

where Z is a known fraction of T_{w_1} .

Note: In Phase I, it is assumed that (1) the droplet is molten, (2) the droplet viscosity is low, and (3) the liquid circulation rate in the droplet is extremely rapid. Furthermore, the case where high liquid viscosity exists is eliminated (see Part B). Given the assumptions above, and lacking a

closed form solution for temperature distribution inside the droplet, it is necessary to choose arbitrarily the surface temperature distribution in order to estimate the radiation loss levels to the droplet. Actually, the solution, as it exists, would be more accurate if, as in Phase III, the wall temperature were related directly to the droplet average temperature rather than the boiling point temperature. This change, however, it is felt, would not materially affect the accuracy of the solution since in Phase I the gas temperature is considerably higher than the wall temperature and the convective heat transfer to the droplet is considerably larger than the radiation loss. This correction can be added later if the Phase I calculation should, because of decreasing original droplets radius considerations, represent a sizeable part of the high velocity section of the droplet trajectory.

APPENDIX C

Summary of Equations Used in Free Boiling Surface Case - Phase II

Phase II is intended to describe the behavior of a liquid fuel droplet when its surface is boiling freely while traveling at high speeds through the atmosphere. A sketch of the Phase II model droplet is shown in Fig. 1. It has been assumed that the droplet has been heated initially until free boiling occurred on its surface (see Appendix B).

The model droplet of Phase II would decelerate through the atmosphere at a rate again equal to

$$\frac{dV_{\infty}}{dt} = \frac{-3 C_D \rho_{\infty} V_{\infty}^2}{8 \rho_m R_b} \quad (C-1)$$

Its change in altitude would be

$$\frac{dA}{dt} = -V_{\infty} \sin \gamma_e \quad (C-2)$$

as in Phase I. Also, the stagnation pressure would again be calculated using

$$P_o = \rho_{\infty} V_{\infty}^2 \quad (C-3)$$

Since $\dot{q}_{c_s}$ (stagnation point convective heat transfer rate) is known (see Appendix A) then the heat transferred to regions 1, 2 and 3 is

$$\dot{q}_{c_1} = \zeta_1 \dot{q}_{c_s} \quad (C-4)$$

$$\dot{q}_{c_2} = \zeta_2 \dot{q}_{c_s} \quad (C-5)$$

$$\dot{q}_{c_3} = \zeta_3 \dot{q}_{c_s} \quad (C-6)$$

γ_1 , γ_2 and γ_3 being fractions. Also, once the stagnation pressure is determined (Eq. C-3), the local pressures for each region are found using

$$P_1 = \gamma_1 P_0 \quad (C-7)$$

$$P_2 = \gamma_2 P_0, \text{ etc.} \quad (C-8)$$

where γ is a fixed value for each region. As in Phase I, once the local pressure in each region is determined, the corresponding wall temperature can be found from the vapor pressure curve.

The blowing factor ψ which was determined experimentally^{23, 24} can be written as

$$\psi = 1 - 0.68 M^{0.26} (h_r - h_w) \frac{\dot{m}}{\dot{q}_c} \quad (C-9)$$

where $\dot{m}$ is the rate of mass lost from the surface due to evaporation and $\dot{q}_c$ is the unblocked convective heat transferred to the region under consideration. Each region has a different value of ψ since h_w , $\dot{m}$ and $\dot{q}_c$ vary from region to region. The value of $\dot{m}$ in equation C-9 is determined for a specific region using the following equations:

$$\dot{m}_1 = -(a_1 - b_1)(1 - f) \quad (C-10)$$

$$\dot{m}_2 = -(a_2 - b_2)(1 - g) - \alpha_2 f(a_1 - b_1) \quad (C-11)$$

$$\dot{m}_3 = -(a_3 - b_3)(1 - j) - \alpha_2 f(a_1 - b_1) - \beta_2 g(a_2 - b_2) \quad (C-12)$$

where in general

$$a_i = \frac{\psi_i A_i \dot{q}_{ci}}{\Delta H_v}, \quad i = 1, 2, 3 \quad (C-13)$$

and

$$b_i = \frac{A_i \epsilon_i \beta T_{wi}^4}{\Delta H_v}, \quad i = 1, 2, 3, 4 \quad (C-14)$$

with the appropriate subscripts added to indicate the correct region.

The mass loss in region 4 is

$$\dot{m}_4 = \dot{m}_T - \dot{m}_1 - \dot{m}_2 - \dot{m}_3 \quad (C-15)$$

where

$$m_T = -(a_1 + a_2 + a_3) + (b_1 + b_2 + b_3 + b_4) + (c - d) \quad (C-16)$$

$$c = \frac{4\pi R_b^3 C_p \rho_m \Delta T_{wi}}{3\Delta H_v \Delta t} \quad (C-17)$$

$$d = \frac{4\pi R_b^3 (KB)}{3\Delta H_v} \quad (C-18)$$

Refer to the Nomenclature section of this report for the definition of each symbol.

With total mass loss given by Equation (C-16), the change in droplet radius is then calculated from

$$\frac{dR_b}{dt} = \frac{\dot{m}_T}{4\pi R_b^2 \rho_m} \quad (C-19)$$

Phase III is initiated and Phase II terminated when

$$T_r = Z T_o \quad (C-20)$$

where Z is equal to 50% (arbitrary).

Notes: Phase II

In Phase II a closed form solution does not exist because an explicit solution for temperature distribution in the molten droplet is non-existent.

The momentum equation is used to define deceleration and the energy equation is used to define total mass loss. Heat distribution in the droplet is a matter of judgement (see sample problem).

Phase II Unitrac "initialization" step checks input " r_b " and sets radius to correct " r_b ".

Phase II program "delta values" checks r_b at end of each step and splits up molten droplet to $\frac{1.2}{1.9}$ " r_b " = 1.2 " r_s " if radius at end of step is greater than " r_b ".

APPENDIX D

Summary of Equations Used in Non-Free Boiling Surface Case - Phase III

Consider the Phase III model droplet shown in Figure 1 to be entering the atmosphere at velocity V_∞ . Its deceleration rate would therefore be .

$$\frac{dV_\infty}{dt} = \frac{-3C_D \rho_\infty V_\infty^2}{8\rho_m R_p} \quad (D-1)$$

while the corresponding altitude change would be

$$\frac{dA}{dt} = -V_\infty \sin \delta_e \quad (D-2)$$

γ_e again being the re-entry angle. The stagnation pressure p_o at velocity V_∞ and altitude A is calculated as before from

$$p_o = \rho_\infty V_\infty^2. \quad (D-3)$$

The determination of the blowing factor ψ and droplet mass loss rate $\dot{m}$ was accomplished using the relationships given in Appendix C and references 23 & 24. From Appendix C, ψ was calculated using

$$\psi = 1 - 0.68 M^{0.26} (h_r - h_w) \frac{\dot{m}}{\dot{q}_c} \quad (D-4)$$

where h_r is the recovery enthalpy, h_w the wall enthalpy and $\dot{m}$ the mass lost by evaporation. This loss in mass can be related to the gas-liquid interface pressure^{7, 23, 24} by:

$$\dot{m} = \frac{\psi \dot{q}_c - \dot{q}_R}{(h_r - h_w) M \left(\frac{p_o}{p_i} - 1 \right)} \quad (D-5)$$

If equations (D-4 and (D-5) are combined, the resulting expression for ψ is

$$\psi = \frac{M^{0.74} (P - P_{vi}) + 0.68 \left(\frac{\dot{q}_c}{\dot{q}_c} \right) P_{vi}}{M^{0.74} (P - P_{vi}) + 0.68 P_{vi}} \quad (D-6)$$

where $P = \gamma P_o$ or the fraction of P_o at the droplet region under consideration. The values of convective heat transfer and recovery enthalpy to be used in the above equations are

$$\dot{q}_c = \gamma \dot{q}_{cs} A \quad (D-7)$$

$$h_r = 0.9 h_s \quad (D-8)$$

where

$$h_s = 0.24 T_\infty + \frac{V_\infty^2}{2gJ} \quad (D-9)$$

The value of A in equation (D-7) for each region on the droplet surface is given by

$$A = \pi R_b^2 \quad (D-10)$$

$$A = \pi R_b^2 \quad (D-11)$$

$$A = 2\pi R_b^2 \quad (D-12)$$

Equation (D-5) is an expression for the total mass loss from the region under consideration. The total mass loss from the droplet surface would therefore be

$$\dot{m}_T = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 \quad (D-13)$$

where $\dot{m}_3$ equals $\frac{\pi}{8} \left(-\frac{k \Delta T R_1}{\Delta H_v} \right)$ for a boiling back face or $\dot{m}_3 = 0$ if boiling does not occur (see closing paragraphs).

A heat balance performed on the droplet model would yield the following expression for the change in average internal temperature T_{ave}

$$\frac{dT_{ave}}{dt} = \frac{3}{4C_p \pi R_b^3 \rho_m} \left[\Delta H_v \dot{m}_T - \dot{q}_{R_1} - \dot{q}_{R_2} - \dot{q}_{R_3} + \psi_1 \dot{q}_{c_1} + \psi_2 \dot{q}_{c_2} + \frac{1}{3} \rho_m \pi R_b^3 (KB) \right] \quad (D-14)$$

where $\dot{q}_{R_1} = A_1 \epsilon_1 \beta T_{w_1}^4$ (D-15)

$$\dot{q}_{R_2} = A_2 \epsilon_2 \beta T_{w_2}^4 \quad (D-16)$$

$$\dot{q}_{R_3} = A_3 \epsilon_3 \beta T_{w_3}^4 \quad (D-17)$$

The wall temperatures are related to T_{ave} according to the following expressions

$$T_{w_1} = T_{ave} + \Delta X \quad (D-18)$$

$$T_{w_2} = T_{ave} \quad (D-19)$$

$$T_{w_3} = T_{ave} - \Delta Y \quad (D-20)$$

where ΔX is the temperature difference through region 1 and ΔY the temperature difference through region 3.

If boiling is assumed to exist on the back face of the droplet (region 3), then $(T_{ave} - \Delta Y) > T_{w_3}$ and

$$T_{w_3} = \frac{1.856}{\log_{10} \gamma P_{\infty} - W} \quad (D-21)$$

and

$$\dot{m}_3 = \frac{\pi}{8} \left(\frac{k \Delta T R_b}{\Delta H_v} \right) \quad (\text{D-22})$$

where

$$\Delta T = T_{ave} - T_{w3} \quad (\text{D-23})$$

If boiling does not occur on the back side of the droplet then

$$T_{w3} = T_{ave} - \Delta Y \quad (\text{D-24})$$

since $(T_{ave} - \Delta Y) < T_{w3}$ & $\dot{m}_3 = 0$.

The loss in droplet mass due to evaporation results in a radius decrease. This decrease has been found as in Appendix C to equal

$$\frac{dR_b}{dt} = \frac{\dot{m}_r}{4\pi R_b^2 f_m} \quad (\text{D-25})$$

Appendix E

The following solution of the incompressible boundary layer equations for the liquid fuel droplet was contributed by Dr. S. Maslen, Research Department, Martin-Baltimore.

Assumptions

1. Incompressible flow.
2. The liquid surface is acted on by aerodynamic heating and skin friction.
3. μ_m, ρ_m are not functions of (T) ,
 $\therefore$ no energy equation is needed.

4. Pressure distribution is Newtonian

$$p = p_{\infty} u_{\infty}^2 \sin^2 \theta ; \theta = x/A$$

5. Reynolds number based on radius is large -- order of 2,000 or greater.

6. There is no mass transfer from the liquid to the gas.

7. Similarity holds and boundary layer is thin with respect to the radius.

Continuity equation:

$$(r^{\sigma} u)_x + (r^{\sigma} v)_y = 0 \quad (1)$$

$\sigma = 0$, two dimensional; $\sigma = 1$, axisymmetric

Momentum equation:

$$\mu u_{yy} = \rho (u u_x + v u_y) + p_x \quad (2)$$

$$p_y = 0 \quad (3)$$

Stream function ψ is:

$$\psi \equiv F(x) f(\eta) \quad (4)$$

$$\eta \equiv G(x) y \quad (5)$$

$$u r^{\sigma} = \partial \psi / \partial y = \psi_y \quad (6)$$

$$v r^{\sigma} = -(\partial \psi / \partial x) = -\psi_x \quad (7)$$

$$v = \frac{-\psi_x}{r^{\sigma}} = -\left[\frac{F_x}{r^{\sigma}} f + \frac{F G_x}{r^{\sigma} G} \eta f' \right] \quad (8)$$

$$u = \frac{\psi_y}{r^{\sigma}} = \left(\frac{F G}{r^{\sigma}} \right) f' \quad (9)$$

and

$$u u_x + v u_y = \frac{FG}{r^\sigma} f' \left[\left(\frac{FG}{r^\sigma} \right)_x f' + \frac{FG_x}{r^\sigma} \eta f'' \right] - \frac{FG^2}{r^\sigma} \left[\frac{F_x f}{r^\sigma} + \frac{FG_x}{r^\sigma G} \eta f' \right] f''$$

substituting in the momentum eq.

$$\left[\frac{\mu FG^3}{r^\sigma} \right]_I f''' = \left[\frac{\rho_m FG \left(\frac{FG}{r^\sigma} \right)_x}{r^\sigma} \right]_{II} f'^2 - \left[\frac{\rho_m F F_x G^2}{r^{2\sigma}} \right]_{III} f f'' - \left[\frac{2 \rho_m u_\infty^2 \sin \theta \cos \theta}{a} \right]_{IV}$$

where $p_x = 2 \rho_m u_\infty^2 \sin \theta \cos \theta$ let $F_x = \frac{\mu_m r^\sigma G}{\rho_m}$; then $[]_I = []_{III}$ at $y = \delta$; $f'(\delta) = 1$; $f''(\delta) = 0$; $f'''(\delta) = 0$; $[]_{II} = []_{IV}$

and

$$2 \left[\frac{FG}{r^\sigma} \right] \left[\frac{FG}{r^\sigma} \right]_x = \frac{4 \rho_m u_\infty^2 \sin \theta \cos \theta}{a \rho_m} = \left[\frac{2 \rho_m u_\infty^2 \sin^2 \theta}{\rho_m} \right]_x$$

then

$$F^2 G^2 = \frac{2 \rho_m u_\infty^2 r^{2\sigma} \sin^2 \theta}{\rho_m}$$

The above yields

$$2 F F_x = \frac{2 \mu_m r^\sigma}{\rho_m} \sqrt{\frac{2 \rho_m u_\infty^2 r^{2\sigma} \sin^2 \theta}{\rho_m}}$$

$$F^2 = \frac{2 \mu_m a}{\rho_m} \sqrt{\frac{2 \rho_m u_\infty^2}{\mu_m}} \int_0^\theta r^{2\sigma} \sin \theta d\theta$$

since

$$r = a \sin \theta$$

$$F^2 = [u_\infty a^{\sigma+1}]^2 2\sqrt{2} \left(\frac{\mu_m}{\rho_m u_\infty a} \right) \sqrt{\frac{\rho_m}{\rho_m}} \int_0^\theta \sin^{2\sigma+1} \theta d\theta$$

and

$$G^2 = \frac{1}{\sqrt{2} a^2} \left[\frac{\rho_m u_\infty a}{\mu_m} \right] \sqrt{\frac{\rho_m}{\rho_m}} \left[\frac{\sin^{2\sigma+2} \theta}{\int_0^\theta \sin^{2\sigma+2} \theta d\theta} \right]$$

Observe that G is virtually a constant.

$$\beta = \frac{[]_{II}}{[]_{III}} = \frac{(FG/r^\sigma)_X}{(F_X G/r^\sigma)} = \frac{2 \cos \theta \int_0^\theta r^{2\sigma} \sin \theta d\theta}{r^{2\sigma} \sin^2 \theta}$$

$$\beta = \frac{2 \cos \theta \int_0^\theta \sin^{2\sigma+1} \theta d\theta}{\sin^{2\sigma+2} \theta}$$

Then the differential equation is:

$$f''' + f f'' = \beta [f'^2 - 1]$$

with the boundary conditions

$$f(0) = 0$$

$$f'(\infty) = 1$$

$$\mu u_Y)_{Y=0} = -\gamma_0$$

where:

$$\frac{\mu_m F G^2}{r^\sigma} f''(0) = \frac{2}{3} \sqrt{\frac{\rho_e \mu_e}{X}} u_e^{3/2} = \left[\frac{1}{3} \sqrt{\frac{\rho_0 \mu_0}{a}} \frac{u_\infty^{3/2} \sqrt{r} M_\infty}{\sqrt{\theta}} \right] \frac{\sin \theta \cos \theta}{\sqrt{\theta}}$$

$$f''(0) = - \left[\frac{2^{1/4} \sqrt{r}}{3} \right] M_\infty \left[\frac{\rho_m \mu_\infty^2}{\rho_\infty \mu_m^2} \right]^{1/4} \sqrt{\frac{\beta \sin \theta}{\theta}}$$

Observe: $\sigma = 1$

$$\beta = \frac{2 \cos \theta}{3} \left[\frac{2 + \cos \theta}{(1 + \cos \theta)^2} \right] \rightarrow \frac{1}{2}$$

for $\theta = 0^\circ$ to 75°

$\therefore$ solve: $f''' + f f'' = \frac{1}{2} (f'^2 - 1)$

$$f(0) = 0$$

$$f''(0) = -\alpha$$

$$f'(\infty) = 1$$

$$\text{where } \alpha = \frac{M_\infty}{3} \sqrt{\frac{\mu_\infty}{\mu_m}} \sqrt{\frac{\rho_m}{\rho_\infty}}$$

$$u(x,0) = f'(0) \sqrt{\frac{2\rho_0 u_\infty^2 \sin^2 \theta}{\rho_m}} = f'(0) \left[\sqrt{2} u_\infty \sqrt{\frac{\rho_0}{\rho_m}} \right] \sin \theta$$

also $a \gamma \cong 2^{1/4} \sqrt{\frac{\rho_0 u_\infty a}{\mu_\infty}} \frac{3\alpha}{M_\infty}$

The boundary layer thickness is, approximately

$$\frac{\delta}{a} = \frac{3}{a \gamma}$$

Using a polynomial profile

$$f = \eta + K \left[\left(\frac{\eta}{\delta} - 1 \right)^4 - 1 \right] \quad f(0) = 0$$

$$f' = 1 + \frac{4K}{\delta} \left(\frac{\eta}{\delta} - 1 \right)^3 \quad f'(\delta) = 1$$

$$f'(0) = 1 - \frac{4K}{\delta} \quad f''(\delta) = 0$$

$$f''(0) = \frac{12K}{\delta^2} = -\alpha \quad f'''(\delta) = 0$$

$$K = \frac{-\alpha \delta^2}{12}$$

integrate the differential equation

$$\int_0^\delta (f''' + ff'' + \frac{1}{2} - \frac{f'^2}{2}) d\eta = 0$$

$$f'' + ff' + \frac{11}{2} \Big]_0^\delta = \frac{3}{2} \int_0^\delta f'^2 d\eta$$

LET $\eta/\delta = x$

$$(0+\alpha) + (\delta-K) + \frac{\delta}{2} = \frac{3}{2} \delta \int_0^1 \left[1 + \frac{4K}{\delta} (x-1)^3 \right]^2 dx$$

$$\alpha + \frac{3\delta}{2} - \frac{\alpha \delta^2}{12} = \frac{3\delta}{2} \left[1 - \frac{\alpha \delta}{6} + \frac{\alpha \delta^2}{63} \right]$$

$$\left(\frac{\alpha \delta}{7} \right)^3 - 2 \left(\frac{\alpha \delta}{7} \right)^2 = \frac{6\alpha^2}{49}$$

Solve for δ

then $\frac{\text{b. l. thickness}}{a G} = \frac{3}{a G}$

and $f'(0) = 1 + \frac{\alpha \delta}{3}$

Example.

Given the following values,

$$M_{\infty} = 20$$

$$\text{altitude} = 200,000 \text{ ft.}$$

$$R_b \text{ (initial)} = 100 \text{ microns}$$

$$\mu_m \text{ (droplet)} = 10 \text{ centipoises} = 6.72 \times 10^{-3} \text{ lb /ft sec}$$

$$\mu \text{ (air)} = 0.1076 \times 10^{-4} \text{ lb /ft sec}$$

$$\rho_m = 6.77 \text{ lb}_f \text{ sec}^2 / \text{ft}^4$$

$$\rho_{\infty} = 0.6118 \times 10^{-6} \text{ lb}_f \text{ sec}^2 / \text{ft}^4$$

$$f = 0.8$$

$$a = 4.59 \times 10^{-7} \text{ lb /sec}$$

$$\Delta H_v = 243 \text{ B/lb}_m$$

$$\theta = 37^\circ \text{ (when } M_{\infty} = 1 \text{ on droplet surface)}$$

the value of $u(x, 0)$ and $T_{\delta_1} - T_{\text{ave}}$ or ΔT_1 are found in the following manner:

$$\text{if } \alpha = \frac{M_{\infty}}{3} \sqrt{\frac{\mu_{\infty}}{\mu_m}} \sqrt{\frac{f_m}{f_{\infty}}} = 14.9$$

$$6\alpha^2/49 = 27$$

then

$$\lambda^3 - 2\lambda^2 = 27.$$

Solving the above equation for λ yields

$$\lambda = 3.37$$

and the thickness of the moving liquid boundary layer δ is then

$$\delta = \frac{7\lambda}{\alpha} = 1.58$$

Since
$$\frac{\delta}{R_b} = \frac{3}{aq}$$

and with
$$aq = 2^{1/4} \sqrt{\frac{f_{\infty} V_{\infty} R_b}{\mu_{\infty}}} \quad \frac{3\alpha}{M_{\infty}} = 9.55$$

then
$$\frac{\delta}{R_b} \approx \frac{1}{3}$$

or the liquid boundary layer is small in comparison to R_b . Therefore, the value of $\mu_m = 10$ centipoises is acceptable and the results of the study will be valid. However, if $\mu_m > 10$ centipoises, then δ becomes of the same order of magnitude as R_b and the theory breaks down. The variation of δ with μ_m is shown in Fig. 17 with the maximum value of μ_m set at 10 and maximum $\frac{\delta}{R_b}$ set at approximately 0.34.

The liquid flow velocity $u(x,0)$ at the droplet surface is calculated using

$$\frac{u(x,0)}{\sin \theta} = f'(0) \left[\sqrt{2} V_{\infty} \sqrt{\rho_{\infty}/\rho_m} \right]$$

where

$$f'(0) = 1 + \frac{\alpha \delta}{3}$$

and θ (see figure below) is the distance measured from the stagnation point to the end of region 1 (where $M_{\infty} = 1$).

For this example,

$$f'(0) = 8.83$$

and

$$\frac{u(x,0)}{\sin \theta} = 75.3 \text{ ft/sec}$$

The average velocity of the liquid boundary layer is assumed to equal

$$v_{ave} = \frac{75.3 \text{ ft/sec}}{4} = 18.8 \text{ ft/sec}$$

With v_{ave} known, the mass flow through the liquid boundary layer,

$\dot{m}_{\delta_1}$, can be found using

$$\dot{m}_{\delta_1} = \rho_m A v_{ave}$$

where

$$A = \pi (\sin \theta) \delta (2R_b - \delta)$$

(see derivation of above expression at end of appendix).

At $\theta = 37^\circ$ ($M_\infty = 1$), this cross-sectional area equals

$$A = 1.91 \times 10^{-5} \text{ ft}^2$$

$$\dot{m}_{\delta_1} = 7.83 \times 10^{-5} \text{ lb}_m/\text{sec.}$$

The temperature rise ΔT_1 can now be calculated from

$$\Delta T_1 = \frac{\psi, A, \dot{q}_c, f}{\dot{m}_{\delta_1} c_p}$$

since

$$\psi, A, \dot{q}_c, f = a, \Delta H_v f = 0.8 \times 10^{-4} \text{ BTU/sec}$$

and it is found that $T_1 = 7.6^\circ \text{R.}$

Thus, the temperature rise from T_{ave} to T_{δ_1} is very small.

This implies that if boiling is not occurring at the stagnation point, it can be assumed that it will not occur at all in region 1.

The boiling will most likely occur in regions 3 and/or 4.

The variation of δ with M_∞ at constant R_b is shown in Fig. 18 when $\mu_m = 5$ centipoises and the droplet altitude is 200,000 ft.

Table III presents a summary of the entire study.

Derivation of Equation to Calculate Liquid
Droplet Boundary Layer Cross-Sectional Area

$$\begin{aligned}\text{Let } r_2 &= R_b \sin \theta \\ h_2 &= R_b \cos \theta\end{aligned}$$

$$\begin{aligned}r_1 &= (R_b - \delta) \sin \theta \\ h_1 &= (R_b - \delta) \cos \theta\end{aligned}$$

Since the surface area of a cone is $\pi r \sqrt{r^2 + h^2}$, then the area of cone 2 is

$$A_{\text{cone } 2} = \pi R_b^2 \sin \theta \sqrt{R_b^2 \sin^2 \theta + R_b^2 \cos^2 \theta} = \pi R_b^2 \sin \theta$$

and for cone 1

$$\begin{aligned}A_{\text{cone } 1} &= \pi (R_b - \delta)^2 \sin \theta \sqrt{(R_b - \delta)^2 \sin^2 \theta + (R_b - \delta)^2 \cos^2 \theta} \\ &= \pi (R_b - \delta)^2 \sin \theta.\end{aligned}$$

The droplet boundary layer cross-sectional area is the difference between $A_{\text{cone } 2}$ and $A_{\text{cone } 1}$, or

$$A = \pi \sin \theta [R_b^2 - (R_b - \delta)^2].$$

Simplifying the right hand side of the above equation yields the equation

$$A = \pi (\sin \theta) \delta (2 R_b - \delta).$$

Appendix F

Probability of Fuel Droplet Combustion

A study was performed to determine the probability of fuel droplet combustion in air. The fuel droplet material was not specified, but it was assumed that the radius was 100 microns. The droplet velocity considered was 20,000 ft/sec while at an altitude of 200,000 ft.

It was necessary initially to determine the region/area on the droplet surface. In the figure below, the surface area included within the solid angle 2Θ is termed "region 1."

At $\Theta = 37^\circ$, this area projected was found to equal

$$A_1 = 1.138 R_b^2$$

Since $R_b = 100$ microns, then $A_1 = 1.224 \times 10^{-7} \text{ ft}^2$ and the mass flow of air reaching region 1 was

$$\dot{m}(\text{air}) = \rho_\infty V_\infty A_1 = 4.82 \times 10^{-8} \text{ lbm/sec.}$$

Since 23.2% of the weight of air is attributed to the presence of oxygen, then,

$$\dot{m}_1(\text{O}_2) = .232 \dot{m}_1(\text{air}) = 11.9 \times 10^{-9} \text{ lbm/sec.}$$

The collision rate of O_2 molecules with region 1 of the fuel droplet in the free molecule or first order collision flow is $\dot{m}_1(\text{O}_2) N_0 / M_w(\text{O}_2)$ or,

$$11.9 \times 10^{-9} \text{ lbm/sec} \times \frac{6.023 \times 10^{23} \text{ molecules}}{\text{mole}} \times \frac{1 \text{ mole}}{32 \text{ lb O}_2} = 2.24 \times 10^{14} \frac{\text{molecules}}{\text{sec}}$$

Since this figure is very large, it was concluded that if the fuel is combustible (such as Pu or Sr or Fe), then there are sufficient O_2 collisions for rapid combustion.

Furthermore, it is assumed that in the free molecular and first collision regimes, oxygen combusts at the surface with the resulting high vapor pressure oxides (high with respect to the metal vapor pressure) remaining at the droplet.

VII. SAMPLE PROBLEM

The following information must be assembled initially:

surface tension vs. temperature

ρ_m at correct temperature

c_p at correct temperature

ϵ at correct temperature

M_w

k_t

internal heat generation

ΔH_v

vapor pressure vs. temperature

molten liquid viscosity vs. temperature

chemical reaction information (if applicable)

and

release temperature

velocity

altitude

γ_e (entry angle)

then the procedure given below should be followed.

Step 1 Initial Radius Determination

a. S decreases with temperature increase.

If S decreases appreciably with temperature (say > 10%) and the droplet is released at a temperature near the melting point (well below ablation temperature), it is to be expected that the droplet will break up as aeroheating progresses (Phase I program is used to measure the

temperature change). This break-up takes place because " r_b " is decreasing as the droplet is heated and, since no ablation has occurred, the actual droplet radius is greater than " r_b " (see Figure 8). An appreciable ablation rate commences when the vapor pressure of the molten liquid approaches or equals the local gas pressure on the droplet surface. The actual droplet break-up (given an original droplet size at release) should be estimated from a plot of " r_b " vs. droplet temperature.

b. Surface tension S does not change with temperature.

If S is not affected by temperature, then,

$$r_b \text{ release} = \frac{7.6 S}{\rho v^2} .$$

Step 2 Pressure Distribution

Pressure is arbitrarily distributed according to the areas designated in Phases I, II, and III by varying in:

Phase I ; COEY

" II ; $\gamma_1, \gamma_2, \gamma_3, \gamma_4$

" III ; $\gamma_1, \gamma_2, \gamma_3$

The recommended pressure distribution for a sphere is Newtonian (see

Example, Step 5). For shapes other than a sphere, the correct pressure distribution can be simulated by varying COEY or γ 's.

Step 3 Heat Transfer Distribution (Front of Hemisphere Only)

Heat transfer is arbitrarily distributed according to the areas designated in Phases I, II, and III by varying in:

Phase I ; COEZ

" II ; $\gamma_1, \gamma_2, \gamma_3$

" III ; γ_1, γ_2

Heat transfer distribution recommended is that of Kemp, Rose and Detra* - Figure 3 for laminar distribution.

Step 4 Use of Phase I

The purpose of Phase I is to estimate the deceleration of the droplet before appreciable ablation commences (a necessary step). The use of Phase I assumes viscosity to be low (order of 10 cp or less) and that temperature distribution in the droplet is not the controlling factor (see Appendix E). Thus, in the program set

T_{ave}	=	release temperature
KB	=	internal heat generation
COENU	=	1
COEX		see Phase II
COEY		about .25
COEZ		.70 to .80

Step 5 Use of Phase II

An estimate of the temperature rise of the liquid resulting from circulation over the front face of the droplet should be made (see Appendix E). From the resulting temperature distribution an estimate of the vapor pressure distribution over the front face of the droplet should follow. Then the distribution of the partial pressure of the vapor can be estimated. With a knowledge of partial pressure and the flight conditions, the amount of liquid vaporizing can be computed.

Combining the above results with estimates of heat transfer to a particular region provides a knowledge of heat distribution in the droplet. With this overall knowledge, appropriate $f, g, j, \alpha_1, \alpha_2, \beta$ factors can be estimated.

* Kemp, N., Rose, P., Detra, R., "Laminar Heat Transfer Around Blunt Bodies in Dissociated Air," Journal of Aero/Space Sciences, July 1959.

Example

Assume:

$$\begin{aligned}
 P_o &= .116 \text{ atm} \\
 A &= 200,000 \text{ ft.} \\
 V &= 200,000 \text{ ft/sec} \\
 \mu_m &= 10 \text{ centipoises}
 \end{aligned}$$

Initial point on trajectory

Before estimating the average droplet temperature refer to the figure below which depicts the nomenclature used and circulation pattern.

The temperature rise from T_{ave} to T_{surf} along the front face is approximately 10°R (see Appendix E). Also, notice the boiling point variation for an arbitrary pressure distribution as given below:

			Vapor pressure determined boiling points
$\gamma_1 = .8$;	$P_1 = .093$	atm	$T_{w1} = 4130^{\circ}\text{R}$
$\gamma_2 = .24$;	$P_2 = .028$	atm	$T_{w2} = 3860^{\circ}\text{R}$
$\gamma_3 = .08$;	$P_3 = .009$	atm	$T_{w3} = 3640^{\circ}\text{R}$
$\gamma_4 = 1$;	$P_4 = .00022$	atm	$T_{w4} = 3100^{\circ}\text{R}$

Note: Values shown are used to calculate radiation from droplet -- these numbers will be checked later.

where:

$$\log_{10} p(\text{atm}) = \frac{-17,250}{T(\text{K})} + 6.49$$

The estimation of the average droplet temperature can now be undertaken.

The front surface temperatures are obviously high as estimated from the vapor pressure curve and surface pressures (i.e., based on a 10°R temperature rise); the result is high front surface radiation. However, the back face is probably about $100\text{--}200^{\circ}\text{R}$ lower (as assumed in calculations). It should be also noted that if the mass loss could be estimated independently of the energy equation, then the droplet temperature could be determined explicitly from this equation (as in Phase III).

The back face temperature is estimated by arbitrarily setting the back face pressure at $\gamma_1 p_{\infty}$. It can be seen that the back face temperature is considerably lower than the region 3 temperature. Thus, the pressure on the back of the sphere is perhaps somewhere between p_{∞} and $5 p_{\infty}$ (in free molecular and first collision flow regimes).

If $p_4 = 5 p_{\infty}$ for example, then $T_{w4} = 3300^{\circ}\text{R}$. It appears safe to assume that T_{w4} lies somewhere between 3300°R and 3100°R .

For a sphere one can estimate that the majority of the vaporization will take place at approximately $\theta = 60^{\circ}$ to 120° . Also, the pressure will be in the range of 0.5 to 10% of p_0 in free molecular flow, first collision and the low density transition region.

In order to investigate the cases where it is assumed that the boiling pressure is both 2% and 5% of p_0 , set

$$T_{\text{ave}} (\text{boiling point} = 6\% \text{ } \phi) = 3600^{\circ}\text{R}$$

$$T_{\text{ave}} (\text{boiling point} = 2\% \text{ } \phi) = 3400^{\circ}\text{R}.$$

Now, the following type of calculation should be made by hand:

$$\begin{aligned}
 P_o = P_{\text{stag}} &= 0.116 \text{ atm} \\
 T_{\text{ave}} &= 3600^\circ\text{R} \\
 \text{Vapor Pressure} &= 0.007 \text{ atm}
 \end{aligned}$$

$$\begin{aligned}
 \bar{P}_A &= \text{Partial Press. CPDA} \\
 \Delta H_v &= 1015 \text{ BTU/lb}_m
 \end{aligned}$$

$$P_{\text{LOCAL}} = .06 P_{\text{stag}}$$

θ	$\cos^2 \theta$	P_{LOCAL} atm	$\bar{P}_A$	$\sin \theta$	$R_o \sin \theta$ Ft.	R_o^2 Ft. ²	Projected Area Ft. ²	① #Mols Air Sec.	② $\frac{P_A}{P_{\text{air}}}$	①*② #Mol A Sec.	⑥ lb _m A(evaporated) Sec.
REGION 1 0°	1	.116	.0603								
30	.75	.087	.0805	.500	1.38 ⁻⁴ *	1.9 ⁻⁸	6 ⁻⁸	8.05 ⁻¹⁰	.087	7.0 ⁻¹¹	8.83 ⁻⁹
37	.64	.074	.0950	.600	1.66 ⁻⁴	2.76 ⁻⁸	8.7 ⁻⁸	1.16 ⁻⁹	.105	1.2 ⁻¹⁰	1.50 ⁻⁸
REGION 2 45	.50	.058	.1210	.707	1.95 ⁻⁴	3.8 ⁻⁸	1.2 ⁻⁸	1.60 ⁻⁹	.136	2.2 ⁻¹⁰	2.74 ⁻⁸
60	.25	.029	.2410	.866	2.39 ⁻⁴	5.7 ⁻⁸	5.7 ⁻⁸	2.40 ⁻⁹	.315	7.5 ⁻¹⁰	9.50 ⁻⁸
REGION 3 90	---	.007	1.00	1.000	2.76 ⁻⁴	7.6 ⁻⁸	7.6 ⁻⁸	3.20 ⁻⁹	---	---	---

θ	③ f_1	④ Surface Area Ft ²	⑤ ges BTU/Ft ² Sec	③*④*⑤ q_1 BTU/Sec	⑧ #Mass/Sec Vaporized in Region	⑧*⑦ BTU/Sec	⑧*⑦ ③*④*⑤
REGION 1 0			2411				
30	.9	1.12 ⁻⁷		2.43 ⁻⁴	1.50 ⁻⁸	1.52 ⁻⁵	.063
37							
REGION 2 45	.6	1.28 ⁻⁷		1.85 ⁻⁴	8.0 ⁻⁸	9.63 ⁻⁵	.52
60							
REGION 3 90	.3	2.4 ⁻⁷	↓	1.23 ⁻⁴			

$$\therefore f = .94$$

$$\therefore g = .48$$

$$\text{est. } j = .2$$

estimated

$$\begin{aligned}
 \alpha_1 &= 0 \\
 \alpha_2 &= .5 \\
 \beta_1 &= .5
 \end{aligned}$$

*10⁻⁴

$$\begin{aligned}
 P_o &= P_{\text{stag}} = 0.116 \text{ atm} \\
 T_{\text{ave}} &= 3400^\circ\text{R} \\
 \text{Vapor Pressure} &= 0.00232 \text{ atm @ } 3400^\circ\text{R}
 \end{aligned}$$

$$\begin{aligned}
 \bar{P}_a &= \text{Partial pressure cpd A} \\
 \Delta H_v &= 1015 \text{ BTU/lb}_m
 \end{aligned}$$

$$P_{\text{LOCAL}} = 0.02 P_{\text{stag}}$$

	①	②	①*②						
θ	$\cos^2 \theta$	P_{LOCAL} (atm)	$\bar{P}_A$ cpd A	Projected Area πR^2	# Mol Air sec	$\bar{P}_{\text{air}}$	cpd A Pair	# Mol cpd A sec	lbm cpd A sec
0	1	.1160	.020	-----	-----	-----	-----	-----	-----
REGION 1 30	.75	.0870	.0267	6 ⁻⁸	8.05x10 ⁻¹⁰	.980	.0273	2.2x10 ⁻¹¹	2.77x10 ⁻⁹
37	.64	.0740	.0314	8.63 ⁻⁸	1.16 ⁻⁹	.973	.0323	3.75 ⁻¹¹	4.72 ⁻⁹
REGION 2 45	.50	.0580	.040	1.2 ⁻⁷	1.59 ⁻⁹	.960	.0417	6.63 ⁻¹¹	8.35 ⁻⁹
60	.25	.0290	.080	1.8 ⁻⁷	2.41 ⁻⁹	.920	.087	2.1 ⁻¹⁰	2.64 ⁻⁸
REGION 3 75	.067	.00778	.300	2.23 ⁻⁷	3.0 ⁻⁹	.430	.700	2.1 ⁻⁹	2.65 ⁻⁷
90	----	.00232	1.00	2.39 ⁻⁷	3.2 ⁻⁹	-----	-----	-----	-----

	③	④		③*④* $\mathcal{J}_1$ = ⑤			⑥/⑤
θ	Surface Area (ft ²)	q_{c_s} (BTU/ft ² sec)	$\mathcal{J}$	$\dot{q}_1$ (BTU/sec)	lb _m cpd A sec Vaporized in Region	($\dot{m}_A$) * (ΔH_v) = ⑥ (BTU/sec)	$\frac{\dot{m}_A * \Delta H_v}{\dot{q}_1}$
REGION 1 0°							
30	1.12x10 ⁻⁷	2.411x10 ³	.9	2.43x10 ⁻⁴	4.72x10 ⁻⁹	4.80x10 ⁻⁶	.02(1-f) ∴ f = .98
37							
REGION 2 45	1.28x10 ⁻⁷		.6	1.85 ⁻⁴	2.17 ⁻⁸	2.2 ⁻⁵	.12(1-g) ∴ g = .86
60							
REGION 3 75	2.4x10 ⁻⁷		.3	1.73 ⁻⁴	-----	-----	----- est. j = 4
90							

estimated

$$\begin{aligned}
 \alpha_1 &= 0 \\
 \alpha_2 &= .4 \\
 \beta_1 &= .4
 \end{aligned}$$

A comparison of radiation losses for the two average temperatures considered and for the 200,000 ft. alt., 20,000 ft/sec velocity point (see page 43 for T_{w1} to T_{w4}) would be as follows:

	<u>T</u>	$\left(\frac{T}{1000}\right)^4$	<u>Area/R²</u>	<u>$(T/1000)^4 * \text{Area}$</u>	
T_{ave}	3400	135	4π	1700	
T_{ave}	3600	169	4π	2100	
T_{w1}	4130	293	1.47	430	} Estimated - Based on Boiling Temps.
T_{w2}	3860	222	1.65	366	
T_{w3}	3750	198	π	620	
T_{w4}	3100	88	2π	554	
				<u>1970</u>	

The range of the radiation heat loss is shown above in the last column. Under this heading, it can be seen that the sum 1970 is the approximate mean value of 1700 and 2100.

Note: The purpose of the above calculations is to show that good estimates of of radiation heat loss can be made by using boiling points (in lieu of an explicit relationship for droplet temperature distribution).

Observe that if $T_{ave} = 3400^{\circ}\text{R}$ or 3600°R then,

<u>T_{ave}</u>	<u>f</u>	<u>g</u>	<u>j</u>	<u>α_1</u>	<u>α_2</u>	<u>β_1</u>	<u>Relative Radiation</u>
3400	.98	.86	.4	0	.4	.4	1700
3600	.94	.48	.2	0	.5	.5	2100

Calculations using the Phase II IBM program should be performed at both ends of the above temperature span. Radiation terms should be adjusted accordingly.

The crucial guess in this study involves pressure distribution. It certainly is possible to visualize Newtonian pressure distribution in the free molecular regions and it seems

plausible to expect near Newtonian flow in the first collision regime. For a hot wall in free molecular flow, Hayes and Probst submit that the following equation is valid (see reference 10, page 405, equation 10.4.8).

$$P = P_{\infty} V_{\infty}^2 \sin^2 \theta \left[(2 - f_n) + \frac{f_n}{2} \sqrt{\pi} \sqrt{\frac{T_b}{T_{\infty}}} \frac{1}{f \sin \theta} \right]$$

Note: Redefine θ as the angle generated by the radius moving away from the stagnation point, -hence, change $\sin \theta$ in the above equation to $\cos \theta$.

For the case under consideration, the pressure at $\theta = 75^\circ$ is:

$$\text{if } \gamma = \sqrt{\frac{\gamma}{2}} M_{\infty} = (.82) (19.3) = 15.8$$

$$\text{and } \sqrt{\frac{T_b}{T_{\infty}}} = 3.5 \quad ; \quad \cos^2 \theta = .067$$

$$\theta = 75^\circ$$

$$\text{hence } \frac{\sqrt{\pi}}{2} \sqrt{\frac{T_b}{T_{\infty}}} \frac{1}{\gamma \cos \theta} \Big|_{\text{at } \theta = 75^\circ} = \frac{.384}{2 \times 26} = .74$$

$$P_{75^\circ} = P_{\infty} V_{\infty}^2 (.067) [(2 - f_n) + .74 f_n]$$

then for various values of f_n ,

f_n	$\overleftarrow{P_{\text{LOCAL}}}$		$\overrightarrow{P_{\text{LOCAL}} @ 75^\circ}$		$\overleftarrow{P_{\text{STAG.}}}$	
	$(2 - f_n)$	$(.74 f_n)$			$.192 f_n$	$P_{\text{stag}} @ 0^\circ$
1.0	1	.74	.117	$* P_{\infty} V_{\infty}^2$	.192	$1.19 * P_{\infty} V_{\infty}^2$
.9	1.1	.665	.118	" "	.172	1.27 " "
.8	1.2	.59	.120	" "	.153	1.35 " "
.6	1.4	.445	.124	" "	.115	1.52 " "
.4	1.6	.300	.1275	" "	.077	1.68 " "

At $\theta = 90^\circ$, the predicted pressure would be zero. One would expect, however, considering the relatively large amount of vaporization taking place to find that the pressure does not

drop appreciably below the 75° pressure. In the free molecular flow range, the pressure is essentially a measure of the collision frequency. For example, a sphere of about 85 microns at 200000 feet altitude and 20000 feet/sec velocity, has a collision frequency assuming free molecular flow (actually 1st collision but very near free molecular flow) of:

$$\frac{N_0}{M_w} \rho_\infty V_\infty \underbrace{A_\infty}_{\pi R^2} = \frac{1.9 \times 10^{-5} \times 2 \times 10^4 \times 14 \times 10^{-8}}{29} (6 \times 10^3) = 1.1 \times 10^{15} \frac{\text{COLLISIONS}}{\text{SEC}}$$

If the sphere was not losing mass, the pressure at 90° would be free stream; but since the mass loss is large especially in region 3 (see Figure 1), it is estimated that the pressure will not drop below $\frac{P_{\text{stag}}}{200}$. The approximate mass loss for the case discussed is about:

Mass loss Cpd A

$$\frac{2 \times 10^{-7} \text{ \# mass}}{\text{sec}}$$

or

$$\frac{1.6 \times 10^{-9} \text{ \# mols A}}{\text{sec}}$$

Air Flow for πR^2 cross-section

$$\frac{5.3 \times 10^{-8} \text{ \# mass}}{\text{sec}}$$

or

$$\frac{1.83 \times 10^{-9} \text{ \# mol air}}{\text{sec}}$$

NOTE:

If ΔH_v were $1/4$ as large, the mass loss would theoretically be 4 times as large. This in turn would mean that it would be necessary to estimate what the new pressure distribution would be with such a huge mass loss. Of course, if one postulated for the purpose of comparison of mass flow, that the cross-sectional area for a sphere emitting mass was, in near free molecular flow, say

$$\pi (R + .25R)^2,$$

then the air flow for this particular case would be $8.27 \times 10^{-8} \text{ lb}_m/\text{sec air}$ (or $2.75 \times 10^{-9} \text{ \# mole/sec air}$).

In making the above calculations and in interpreting the results, the important point is that there should be sufficient drag on the evaporated fuel vapor so that at a very high

evaporation rate the surface pressure will not be built up locally ($\theta = 60^\circ$ to 135°) to the point where evaporation would be suppressed.

Therefore, it is evident that great care must be exercised when using the Phase II program. Also, due to the complexity of the situation, the development of a more sophisticated program does not seem justifiable at this time since greater accuracy will not be insured.

VIII. TABLES AND ILLUSTRATIONS

NOMENCLATURE FOR TABLES I & II (ONLY)

A	Altitude
R_b	Radius at Start of Ablation
R_F	Final Limiting Radius
σ	Surface Tension
M_w	Molecular Weight
ΔH_v	Heat of Vaporization
f	Fraction of available heat transfer to region 1 (in Phase II Figure 1) transferred through droplet surface [(1-f) is fraction of available heat transfer to region 1 which results in evaporation in region 1]
g	Fraction of available heat transfer to region 2 (in Phase II Figure 1) transferred through droplet surface [(1-g) is fraction of available heat transfer to region 2 which results in evaporation in region 2]
j	Fraction of available heat transfer to region 3 (in Phase II Figure 1) transferred through droplet surface [(i-j) is fraction of available heat transfer to region 3 which results in evaporation in region 3]
K_B	Internal Heat Generation
ρ_m	Droplet Density
SL	Slope of Vapor Pressure Curve
W	Intercept of Vapor Pressure Curve
ϵ	Emissivity
c_p	Specific Heat
f_i	Fraction of q_{cs} (Phase II) in region i; i=1, 2, 3. See Fig. 1
α_1	Fraction of heat absorbed in region 1 which is transferred to region 2 (in Phase II Figure 1) and results in evaporation in region 3.
α_2	Fraction of heat absorbed in region 1 which is transferred to region 3 (in Phase II Figure 1) and results in evaporation in region 3.
β_1	Fraction of heat absorbed in region 2 which is transferred to region 2 (in Phase II Figure 1) and results in evaporation in region 3.
γ_{Ni}	Fraction of stagnation pressure (Phase II and Phase II) in region i; i = 1, 2, 3, 4. See Fig. 1

TABLE I

PHYSICAL PROPERTIES USED FOR COLD WALL ABLATION STUDY PHASE II

<u>Velocity</u> <u>ft/sec.</u>	<u>A</u> <u>ft.</u>	<u>R_p</u> <u>ft.</u>	<u>R_F</u> <u>ft.</u>	<u>STENI</u> <u>Dynes/cm</u>	
20,000	175,000	3.28×10^{-4} (100 microns)	3.3×10^{-6} (1 micron)	150	
23,000	200,000	1.65×10^{-4} (50 microns)			
	225,000				
<u>M_w</u>	<u>H_v</u> <u>Btu/lb. mass</u>	<u>f</u>	<u>g</u>	<u>j</u>	<u>KB</u>
130	243 (Cpd 1)	1	1	1	4.0
	720 (Cpd 2)	.97	0.8	0.4	
<u>ρ_m</u> <u>lbs mass/ft.³</u>	<u>SL</u>	<u>W</u>	<u>E</u>	<u>C_p</u> <u>Btu/lb. mass °R</u>	
220	-5600	9.0	.80	.15	
<u>γ_1</u>	<u>γ_2</u>	<u>γ_3</u>	<u>α_1</u>	<u>α_2</u>	<u>β_1</u>
.9	.6	.3	0	0	0
<u>γ_{N1}</u>	<u>γ_{N2}</u>	<u>γ_{N3}</u>	<u>γ_{N4}</u>		
.8	.24	.14	1.0		

- Note:**
1. Organization of this page is identical to input card for Phase II of IBM 7094 computer program
 2. Multiple values are shown under one heading to indicate the variation of parameters used in the studies to determine Figures 4, 5, 6, 7.
 3. See accompanying nomenclature sheet

TABLE II

PHYSICAL PROPERTIES USED FOR HOT WALL ABLATION STUDY PHASE

<u>Velocity</u> <u>ft./sec.</u>	<u>A</u> <u>ft.</u>	<u>R_d</u> <u>ft.</u>	<u>R_F</u> <u>ft.</u>	<u>STENI</u> <u>Dynes/cm</u>	
20,000	200,000	2. x 10 ⁻⁴ (60 microns)	3.3 x 10 ⁻⁶	150	
23,000	225,000	5 x 10 ⁻⁴ (150 microns)			
<u>M_w</u>	<u>ΔH</u> <u>Btu/lb. mass</u>	<u>f</u>	<u>g</u>	<u>l</u>	<u>KB</u>
130	243 (Cpd 1)	1	1	1	4.0
	1000 (Cpd 3)	.97	.80	.40	
<u>ρ_m</u> <u>lbs. mass/ft.³</u>	<u>SL</u>	<u>W</u>	<u>ε</u>	<u>C_p</u> <u>Btu/lb. Mass °R</u>	
220 (3.5 g/cc)	-17250	6.49	.88 .50	.15	
<u>γ₁</u>	<u>γ₂</u>	<u>γ₃</u>	<u>α₁</u>	<u>α₂</u>	<u>β₁</u>
.9	.6	.3	0	0	0
<u>γ_{N1}</u>	<u>γ_{N2}</u>	<u>γ_{N3}</u>	<u>γ_{N4}</u>		
.8	.24	.14	1.0		

- Note: 1. Organization of this page is identical to input card for Phase II of IBM 7094 computer program.
2. Multiple values are shown under one heading to indicate the variation of parameters used in the studies to determine Figures 9 through 14.
3. See accompanying nomenclature sheet.

TABLE III

Results of Study Performed to Determine the Temperature
Rise Between Average Internal Temperature and Surface
Temperature in Phase II

M_∞	A (ft)	R_b (microns)	μ_m (centipoises)	$\frac{\delta}{R_b}$	$\frac{u(x,0)}{\sin\theta}$ (ft/sec)	f	ΔT_1 (°R)
20	200,000	200	5	3/19.3	-	-	-
20	↓	100	↓	3/13.7	-	-	-
20	↓	50	↓	3/9.7	-	-	-
15	↓	200	↓	3/16.7	-	-	-
15	↓	100	↓	3/11.9	-	-	-
15	↓	50	↓	3/8.4	-	-	-
12	↓	200	↓	3/15	-	-	-
12	↓	100	↓	3/10.5	-	-	-
12	↓	50	↓	3/7.5	-	-	-
20	200,000	100	1	1/10	144.0	0.8	6.10
20	↓	↓	10	1/3	75.0	↓	7.60
20	↓	↓	100	1	45.0	↓	7.56
20	↓	↓	500	2.23	35.0	↓	6.20
			1000	3	32.0	↓	5.33
20	225,000	100	5	3/10	61.2	-	-
20	225,000	200	↓	3/14.7	61.2	-	-
23	200,000	50	↓	3/10	119.5	-	-
23	200,000	100	↓	3/14	119.5	-	-
20	225,000	100	10	3/7.4	51.0	-	-
20	225,000	200	↓	3/10	51.0	-	-
23	200,000	50	↓	3/7.4	99.0	-	-
23	200,000	100	↓	3/10	99.0	-	-

MODEL DROPLETS

FIGURE 1

FIG. 2

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STRONTIUM SPACE FUEL PROGRAM

VARIATION OF VAPOR PRESSURE P_v
WITH TEMPERATURE

COMPOUND 1

EUGENE DIETZGEN CO.
MADE IN U.S.A.
VAPOR PRESSURE P_v (ATM)

NO. 340R-LS10 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

FIG. 3

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF BLOWING FACTOR ψ WITH FRACTION f

REGION I
 $L=0.30$

KEY:

- 23,000 FT/SEC
- + 20,000 "
- 19,500 "
- ⊗ 18,100 "
- ▽ 17,000 "
- △ 16,100 "
- 1 3.3×10^{-4} FT
- 2 1.65×10^{-3} "
- 3 1.12×10^{-3} "
- 4 1.79×10^{-2} "
- 5 3.35×10^{-4} "
- 6 5.06×10^{-4} "
- 7 1.15×10^{-3} "
- 8 6.19×10^{-4} "
- 9 3.3×10^{-4} "
- 10 5×10^{-5} "
- 11 1×10^{-4} "
- 12 3.3×10^{-5} "

BLOWING FACTOR ψ

1.0

0.8

0.6

0.4

0.2

0

FRACTION f

0.2

0.4

0.6

0.8

1.0

$V_{\infty} = 23,000$ FT/SEC

FIG. 4

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STRONTIUM SPACE FUEL PROGRAM
 VARIATION OF DROPLET RADIUS R
 WITH FLIGHT VELOCITY V_{∞}
 (COLDWALL)

V_{∞} (INITIAL) = 20,000 FT/SEC

$\Delta H_v = 293$ BTU/LB_m (COMPOUND 1)

$\xi = \eta = \gamma = 1.0$

$\epsilon = 0.80$

ALTITUDES : 175,000'

200,000'

225,000'

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF DROPLET RADIUS r WITH FLIGHT VELOCITY V_∞ (COLDWALL)

$$V_0 \text{ (INITIAL)} = 23,000 \text{ FT/SEC}$$

$$\Delta H_v = 243 \text{ BTU/LB. (COMPOUND 1)}$$

$$\gamma = \rho = \beta = 1.0$$

$$L = 0.80$$

ALTITUDES: 175,000'
200,000'
225,000'

DROPLET RADIUS - MICRONS

FIG. 6

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF DROPLET RADIUS R WITH FLIGHT VELOCITY V_∞ (COLDWALL)

V_∞ (INITIAL) = 20,000 FT/SEC
 $\Delta H_v = 720$ BTU/LB_m (COMPOUND 2)
 $f = g = j = 1.0$
 $z = 0.80$

PROPLET RADIUS ~ MICRONS

EUGENE DIETZGEN CO.
MADE IN U. S. A.

NO. 340R-L210 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
2 CYCLES X 10 DIVISIONS PER INCH

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF DROPLET RADIUS R WITH FLIGHT VELOCITY V_∞ (COLDWALL)

V_∞ (INITIAL) = 23,000 FT/SEC
 $\Delta H_v = 720$ BTU/LB_m (COMPOUND 2)
 $f = g = j = 1.0$
 $\epsilon = 0.80$
 ALTITUDES: 175,000 FT
 200,000
 225,000

DROPLET RADIUS - MICRONS

EUGENE DIETZGEN CO.
MADE IN U. S. A.

NO. 340R-L310 DIETZGEN GRAPH PAPER
 SEMI-LOGARITHMIC
 3 CYCLES X 10 DIVISIONS PER INCH

FIG. 8

STRONTIUM SPACE FUEL PROGRAM

DROPLET RADIUS ABOVE WHICH
BREAKUP MUST OCCUR VERSUS
ALTITUDE

COMPOUND 1
 $C_D = 2.0$

STRONTIUM SPACE FUEL PROGRAM VARIATION OF DROPLET RADIUS r WITH FLIGHT VELOCITY V_∞

(HOT WALL)

 V_∞ (UNITILE) = 20,000 FT/SEC

ALT. = 200,000 FT

 $\Delta H_f = 2.43 \text{ BTU/LB}_m$ (COMPOUND 1)DROPLET RADIUS r - MICRONS

70

60

50

40

30

20

10

0

20,000

18,000

16,000

14,000

12,000

10,000

8,000

FLIGHT VELOCITY V_∞ - FT/SEC $f = 0.91, g = 0.8, j = 0.9$ 0.88 = ϵ

0.85

0.50

 $f = g = j = 1$

FIG. 9

8

STRONTIUM SPACE FUEL PROGRAM VARIATION OF DROPLET RADIUS R WITH FLIGHT VELOCITY V_∞

(HOT WALL)

 V_∞ (INITIAL) = 20,000 FT/SEC

ALT = 225,000 FT

 $\Delta H_v = 2.93$ BTU/LB_m (COMPOUND 1)

FIG. 10

STRONTIUM SPACE FUEL PROGRAM VARIATION OF DROPLET RADIUS R WITH FLIGHT VELOCITY V_{∞}

(HOTWALL)

 $V_{\infty} \text{ (INITIAL)} = 23,000 \text{ FT/SEC}$ $ALT = 200,000 \text{ FT}$ $\Delta H_f = 2.43 \text{ BTU/LB}_m \text{ (COMPOUND 1)}$

STRONTIUM SPACE FUEL PROGRAM VARIATION OF PROPELLANT RADIUS R WITH FLIGHT VELOCITY V_{∞}

(NOT WALL)

V_{∞} (INITIAL) = 23,000 FT/SEC

ALT = 225,000 FT

$CH_4 = 243 \text{ BTU/LB}_m$ (COMPOUND 1)

STRONTIUM SPACE FLIET PROGRAM

VARIATION OF DROPLET RADIUS R
WITH FLIGHT VELOCITY V_0
(HOT WALL)

V_0 (INITIAL) = 20,000 FT/SEC

ALT = 200,000 FT

$\Delta H_f = 1000$ BTU/LB., (COMPOUND 3)

$\epsilon = 0.88$

DROPLET RADIUS R - MICRONS

100

90

80

70

60

50

40

30

20

10

0

20,000

18,000

16,000

14,000

12,000

10,000

8,000

FLIGHT VELOCITY V_0 - FT/SEC

$\epsilon = 0.97, g = 0.8, j = 0.4$

$\epsilon = 0.9, g = 1.0$

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF DROPLET RADIUS R
WITH FLIGHT VELOCITY V_∞

(HOT WALL)

V_∞ (INITIAL) = 23,000 FT/SEC

ALT. = 200,000 FT

$\Delta H_v = 1000$ BTU/LB_m (COMPOUND 3)

$\epsilon = 0.88$

DROPLET RADIUS $R \sim$ MICRONS

60
50
40
30
20
10
0

23000

21000

19000

17000

15000

13000

11000

FLIGHT VELOCITY $V_\infty \sim$ FT/SEC

$\xi = .97, \eta = .8, \zeta = .7$

$\xi = \eta = \zeta = 1.0$

FIG. 14

74

RAREFIED GAS-FLOW REGIMES OF A
HIGHLY COOLED BLUNT BODY AT HYPER-
SONIC SPEED (BOUNDARIES BASED ON
DATA OF PROBSTEN) (REF. - FIG 1.1
OF CHEN 6)¹³

FIGURE 15

STRONTIUM SPACE FUEL PROGRAM

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VARIATION OF RATIO OF CONVECTIVE STAGNATION
HEAT TRANSFER $\dot{q}_c$ TO BOUNDARY LAYER HEAT
TRANSFER $\dot{q}_{BL}$ AS A FUNCTION OF REYNOLD'S NO. Re_F

FIGURE 16

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF LIQUID BOUNDARY LAYER THICKNESS WITH VISCOSITY μ_m

$$M_0 = 20$$

$$h = 200,000'$$

$$R_b = 100 \text{ MICRONS}$$

$$f = 0.8$$

STRONTIUM SPACE FUEL PROGRAM

VARIATION OF LIQUID BOUNDARY
LAYER THICKNESS WITH F.S. MACH
NUMBER AT CONSTANT R_p

$\mu_m = 5$ CENTIPOISES

ALT. = 200,000'

①

1. DECK NUMBER

FB080

2. TITLE

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE I

3. PROGRAMMER

B. CLEMENZ

DATE

5-15-64

4. GENERAL DESCRIPTION

THE PROGRAM IS ONE PHASE OF A THREE-PART PROGRAM TO COMPUTE THE ABLATION OF SMALL MOLTEN DROPLETS WHICH ARE RE-ENTERING THE ATMOSPHERE OF THE EARTH AT HYPERSONIC SPEEDS. PHASE I (DECK NUMBER FB-080) IS USED TO ESTIMATE THE DECELERATION DURING THE PREHEATING PERIOD EXTENDING FROM THE TIME OF DROPLET RELEASE TO THE TIME WHEN THE PARTICLE TEMPERATURE APPROACHES THAT SURFACE TEMPERATURE WHERE AN APPRECIABLE ABLATION RATE COMMENCES. PHASE II (DECK NUMBER FB-096) IS A GENERAL MOLTEN DROPLET MODEL WHERE THE HEAT CAN BE DISTRIBUTED ARBITRARILY THROUGHOUT THE MODEL AND THE TEMPERATURE CAN BE VARIED ACCORDING TO AN ARBITRARY SURFACE PRESSURE DISTRIBUTION. COMPUTATION OF THE TRAJECTORY, RADIUS, AND MASS LOSS OF THE PARTICLE IS CONTINUED UNTIL THE SURFACE TEMPERATURE IS GREATER THAN AN INPUT PERCENTAGE OF THE GAS TEMPERATURE OR UNTIL THE DROPLET IS SMALLER THAN AN INPUT RADIUS. PHASE III (DECK NUMBER FB-097) IS USED TO ACCOUNT FOR THE LOW VELOCITY REGION OF THE PARTICLE TRAJECTORY. THIS PHASE IS CONCLUDED BY THE RADIUS OF THE DROPLET BEING LESS THAN AN INPUT FINAL RADIUS, BY A RATE OF CHANGE OF THE RADIUS (DR/DT) LESS THAN AN INPUT FINAL DR/DT , OR BY A POSITIVE DR/DT .

5. REFERENCES

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- B. IDC OF JANUARY 7, 1964, **ENGINEERING SUPPORT EFFORT, STRONTIUM SPACE FUEL DEVELOPMENT**, LEO SULLIVAN, DEPT. 2550, SPACE SYSTEMS DIV., MARTIN-MARIETTA CORP.
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JULY 1963

E. UNITRAC PROGRAMMING COURSE NOTES
S. JAMES, W. OUTTEN, S. DORWEIS

6. DEFINITIONS

VARIABLE	DEFINITION	DIMENSION
ALT	ALTITUDE OF PARTICLE	FT
CD	DRAG COEFFICIENT	-----
COENU	ACCOMODATION COEFFICIENT OF HEAT TRANSFER	-----
COEX	DIFFERENCE IN WALL TEMPERATURE BETWEEN SECTION 1 AND SECTION 2 ($TW1R - TW2R =$ COEX)	DEG R
COEY	FRACTION OF STAGNATION PRESSURE IN SECTION 1	-----
COEZ	STOP FOR PHASE 1. PROGRAM STOPS WHEN TAVE IS GREATER THAN COEZ * TW1R.	-----
CP	SPECIFIC HEAT	BTU/(LBM-DEG R)
DALT	RATE OF CHANGE OF THE ALTITUDE	FT/SEC
DELTI	MAXIMUM COMPUTING INTERVAL OR CHANGE IN TIME BETWEEN POINTS OF CONVERGENCE DURING INTEGRATION	SEC
DVFS	ACCELERATION OF PARTICLE	FT/(SEC**2)
EPS1	EMISSIVITY OF SPHERE SURFACE	-----
GAME	ANGLE OF DROPLET RE-ENTRY	DEG
KA1	RADIATION HEAT TRANSFER RATE FROM BODY SECTION	DEG R/SEC

DEFINITIONS (CONT)

VARIABLE	DEFINITION	DIMENSION
KA2	RADIATION HEAT TRANSFER RATE FROM BODY SECTION	DEG R/SEC
KB	INTERNAL HEAT GENERATION RATE	BTU/(LBM-SEC)
LAM1	MEAN FREE PATH BETWEEN AIR MOLECULES	FT
QDOCS	STAGNATION HEAT TRANSFER RATE TO BODY	BTU/(FT**2-SEC)
R	RADIUS OF PARTICLE	FT
RHOIS	DENSITY OF ABLATING SPHERE MATERIAL	LBM/CU FT
SL	SLOPE OF LOG(VAPOR PRESSURE IN ATMOSPHERES) VERSUS 1 / TEMPERATURE IN DEG K CURVE	DEG K
TAVE	AVERAGE TEMPERATURE OF PARTICLE	DEG R
TCOE3	SENSIBLE HEAT CHANGE IN PARTICLE DUE TO INTERNAL HEAT GENERATION.	DEG R/SEC
TIME	TIME. THE INDEPENDENT VARIABLE IN THE DIFFERENTIAL EQUATIONS.	SEC
TOLER	SIGNIFICANCE CONTROL FOR CONVERGENCE OF INTEGRATION. WHEN SUCCESSIVE VALUES (D1 AND D2) OF ALL DEPENDENT VARIABLES FULLFILL THE FOLLOWING CONDITION: $(D1 + D2) / D1$ CONVERGENCE IS ASSUMED. $(D1 + D2) / D1$ MUST BE LESS THAN $100 * TOLER$ FOR CONVERGENCE. IF THE CONDITION IS NOT MET, THE COMPUTING INTERVAL MAY BE HALVED AND ANOTHER ATTEMPT IS MADE. ON THE OTHER HAND, IF $(D1 + D2) / D1$ IS LESS THAN TOLER, THEN THE COMPUTING INTERVAL IS DOUBLED UNLESS IT IS ALREADY AT ITS MAXIMUM VALUE, DELTJ.	----
TW1R	WALL TEMPERATURE OF PARTICLE SECTION 1	DEG R
TW2R	WALL TEMPERATURE OF PARTICLE SECTION 2	DEG R
VFS	FREE STREAM VELOCITY OF PARTICLE	FT/SEC

DEFINITIONS (CONT)

VARIABLE	DEFINITION	DIMENSION
W	INTERCEPT OF VAPOR PRESSURE AXIS OF THE LOG(VAPOR PRESSURE IN ATMOSPHERES) VERSUS 1 / TEMPERATURE IN DEG K CURVE.	

7. INPUT FORMAT

PARAMETER INPUT

VALUES MUST APPEAR IN THE SEQUENCE INDICATED BELOW ON EACH CARD
WITH AT LEAST ONE BLANK OR A COMMA SEPARATING THEM. THESE CARDS MUST
BE FOLLOWED BY A CARD CONTAINING THE WORDS- PROBLEM DIVIDER

CARD	DATA
1.	VFS ALT R TAVE
2.	KB GAME RHOIS CP SL W
3.	COENU COEX COEY COEZ EPSI
4.	TIME DELTI TOLER
5.	PROBLEM DIVIDER

8. PRINT FORMAT

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RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 1

VFS	=X.XXXXX	ALT	=X.XXXXX	R	=X.XXXXX	TAVE	=X.XXXXX		
KB	=X.XXXXX	GAME	=X.XXXXX	RHOIS	=X.XXXXX	CP	=X.XXXXX	SL	=X.XXXXX
W	=X.XXXXX								
COENU	=X.XXXXX	COEX	=X.XXXXX	COEY	=X.XXXXX	COEZ	=X.XXXXX	EPSI	=X.XXXXX
TIME	=X.XXXXX	DELT	=X.XXXXX	TOLER	=X.XXXXX				

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE I

[illegible]

9. TIMING

THIS PROGRAM TAKES APPROXIMATELY ONE MINUTE TO COMPUTE ONE PROBLEM.

10. PROGRAM DESCRIPTION

ALL PHASES WERE COMPILED UTILIZING UNITRAC (REF. E) TO SET UP THE SOLUTION OF THE DIFFERENTIAL EQUATIONS INVOLVED, THE INPUT-OUTPUT TO THE PROGRAM, AND THE GENERAL FLOW OF THE PROGRAM. THE UNITRAC PROCESSOR TRANSLATED GENERAL ENGINEERING STATEMENTS TO A FORTRAN PROGRAM WHICH WAS MODIFIED AS WILL BE DISCUSSED LATER. THE METHODS OF INTEGRATION THAT ARE PRESENTLY AVAILABLE IN UNITRAC ARE A FOURTH-ORDER RUNGE-KUTTA AND THE BOWIE METHOD, A SPECIAL APPROACH DERIVED AT THE MARTIN COMPANY BY CLAGGETT BOWIE. THE BOWIE METHOD WAS UTILIZED IN PHASES I AND II BECAUSE OF ITS APPARENT SPEED AND GOOD ACCURACY. IN SEVERAL PROBLEMS FOR PHASE III THE BOWIE METHOD WAS FOUND TO CONVERGE ON INCORRECT RESULTS AND SO THE SLOWER BUT MORE ACCURATE RUNGE-KUTTA TECHNIQUE WAS APPLIED. IN THE INTEGRATIONS ALL THE PROGRAMS USE VARIABLE INTERVAL IN THE INDEPENDENT VARIABLE, TIME.

THE GENERAL FLOW DIAGRAM FOR THE MAIN PROGRAM FOR ALL THREE PHASES IS SHOWN IN FIGURE 1. FOR EACH PROBLEM THE PROPERTIES OF THE DROPLET ARE INPUT PARAMETERS ALONG WITH THE INITIAL CONDITIONS, VARIOUS COEFFICIENTS, AND THE INTEGRATION INFORMATION. INITIALIZATION OF THE INPUT DATA AND SETUP OF THE INTEGRATION IS COMPLETED AND IS FOLLOWED BY PRINTOUT OF THE INPUT PARAMETERS. THE AUXILIARY EQUATIONS AND DIFFERENTIAL EQUATIONS ARE THEN SOLVED CONTINUOUSLY UNTIL SUCCESSIVE VALUES OF EACH DEPENDENT VARIABLE ARE CONVERGED. AFTER CONVERGENCE THE FINAL CONDITIONS ARE CHECKED SO AS TO KEY THE TERMINATION OF THE PROBLEM. IF NECESSARY, SINCE PRINTOUT IS DESIRED AT ALL CONVERGENCE POINTS IN THESE PROGRAMS, THE DATA IS PREPARED FOR PRINTING IN THE OUTPUT CONVERSION SECTION AND THEN IS WRITTEN OUT. IF THE PROBLEM HAS REACHED FINAL CONDITIONS, A NEW PROBLEM IS READ INTO THE COMPUTER. ON THE OTHER HAND, IF THE TERMINATION KEY IS OFF, THE DELTA VALUES SECTION IS ENTERED AND COMPUTATION OF ANOTHER INTEGRATION STEP IS BEGUN IN THE AUXILIARY EQUATIONS.

AMONG THE SUBROUTINES USED BY EACH PHASE IS ATMDAT, WHICH IS PROVIDED BY UNITRAC. IN THESE PROGRAMS ATMDAT IS A 1959 STANDARD ATMOSPHERE WHICH USES THE ALTITUDE AS AN INPUT TO COMPUTE THE PROPERTIES OF AIR. SINCE FOR THE COMPUTATION OF HEAT TRANSFER RATE AND DRAG COEFFICIENT IT IS NECESSARY TO COMPUTE THE THERMODYNAMIC PROPERTIES OF AIR, A SUBROUTINE, CQDOT(-1,-2,-3, DEPENDING ON THE PHASE), IS USED IN ALL PROGRAMS. ARGUMENTS ARE TRANSMITTED TO THIS SUBROUTINE BY MEANS OF THE COMMON AND DIMENSION PACKAGE OF THE MAIN PROGRAM. CQDOT CONTAINS ANOTHER SUBROUTINE, WRKMAT (REF. D), WHICH COMPUTES THE THERMODYNAMIC PROPERTIES OF EQUILIBRIUM DISSOCIATING AND IONIZING AIR VIA EMPIRICAL EQUATIONS WITH PRESSURE AND ENTROPY AS INPUT ARGUMENTS. SINCE ENTROPY IS NOT AVAILABLE BY EXPLICIT RELATIONSHIPS, ITERATIVE SCHEMES HAVE BEEN SET UP IN CQDOT TO ALLOW THE COMPUTATION OF

PROGRAM DESCRIPTION (CONT)

WALL AND GAS CONDITIONS UTILIZING THE KNOWN VALUES OF WALL TEMPERATURE AND STAGNATION ENTHALPY. IF THE ITERATIVE SCHEMES DO NOT CONVERGE OR IF THE WALL ENTHALPY IS FOUND TO BE GREATER THAN .8 OF THE STAGNATION ENTHALPY, ERROR STATEMENTS ARE PRINTED OUT AND THE CONTROL, ERROR, IS SET TO 1 OR 2 ON THE RETURN TO THE MAIN PROGRAM. THIS CONTROL IS CHECKED IN THE MAIN PROGRAM AND IF AN ERROR WAS MADE IN CODOT, THE MAIN PROGRAM PRINTS THE STATE OF EACH VARIABLE AND PROCEEDS TO READ IN A NEW PROBLEM. IN ALL THREE PHASES THE FORTRAN DECK PRODUCED BY UNITRAC WAS MODIFIED TO INCLUDE THE CODOT SUBROUTINE IN THE AUXILIARY EQUATION SECTION.

THE PHASE I FORTRAN PROGRAM IS AS TRANSLATED BY UNITRAC EXCEPT THAT THE CODOT1 SUBROUTINE HAS BEEN INSERTED IN THE AUXILIARY SECTION TO COMPUTE THE HEAT TRANSFER RATE, DRAG COEFFICIENT, AND MEAN FREE PATH BETWEEN AIR MOLECULES. IN THIS PROGRAM DELTA VALUES ARE USED ONLY TO UPDATE A COUNT OF THE NUMBER OF CONVERGENCES, WHICH IS CHECKED IN THE FINAL CONDITION SECTION. THE DIFFERENTIAL EQUATIONS SOLVED IN PHASE I ARE THE RATES OF CHANGE OF VELOCITY, ALTITUDE, AND TEMPERATURE OF THE PARTICLE.

THE PHASE II UNITRAC PRODUCED FORTRAN DECK HAS BEEN ALTERED QUITE DRASTICALLY. IT WAS DECIDED THAT TO MORE EASILY FACILITATE THE WRITING OF THIS PROGRAM IT WOULD BE WISE TO USE SUBSCRIPTED VARIABLES, WHICH ARE NOT ALLOWED BY UNITRAC AT THIS TIME. THE CODOT2 SUBROUTINE IS CALLED SEVERAL TIMES IN THE AUXILIARY EQUATION SECTION TO GET NOT ONLY THE HEAT TRANSFER RATE, DRAG COEFFICIENT, AND STAGNATION WALL TEMPERATURE, BUT ALSO THE GAS STAGNATION ENTHALPY, GAS STAGNATION TEMPERATURE, AND THE WALL TEMPERATURE AND ENTHALPY OF EACH SEGMENT OF THE DROPLET. INSERTED IN THE PARAMETER PRINT SECTION OF THE PROGRAM ARE EQUATIONS TO ASSURE THAT THE INITIAL RADIUS OF THE PARTICLE IS NOT GREATER THAN THE RADIUS OF THE DROPLET WHICH IS DETERMINED BY EQUATING THE SURFACE TENSION FORCES AND THE DRAG FORCES ($R\delta_0$). IN THE DELTA VALUES SECTION IF THE RADIUS OF THE PARTICLE IS GREATER THAN $R\delta_0$, DROPLET BREAKUP IS FORCED BY ALTERING THE RADIUS TO ABOUT .6 OF ITS PREVIOUS SIZE. BECAUSE OF THIS DISCONTINUITY IN THE COMPUTATION OF THE RADIUS, THE INTEGRATION TECHNIQUE IS REINITIALIZED AND RESTARTED AT THE TIME OF THE DROPLET BREAKUP. THE DIFFERENTIAL EQUATIONS SOLVED BY PHASE II ARE THE RATES OF CHANGE OF VELOCITY, ALTITUDE, AND RADIUS. THE RATE OF CHANGE OF THE TOTAL MASS LOSS IS COMPUTED IN THE AUXILIARY EQUATION SECTION AND, THUS, IS NOT FORCED TO CONVERGE IN THE INTEGRATION.

THE PHASE III FORTRAN DECK INCLUDES THE CODOT3 SUBROUTINE IN THE AUXILIARY EQUATION SECTION TO ALLOW COMPUTATION OF THE HEAT TRANSFER RATE, DRAG COEFFICIENT, GAS STAGNATION ENTHALPY, GAS STAGNATION TEMPERATURE, AND WALL ENTHALPY FOR EACH DROPLET SECTION. ALSO IN THE AUXILIARY EQUATIONS LOGIC HAS BEEN INSTALLED TO AIDE IN THE COMPUTATION OF THE WALL TEMPERATURE AND THE MASS RATE OF CHANGE OF SECTION 3 OF THE PARTICLE. THE BLOCKING TERMS ARE NOT ALLOWED TO BECOME NEGATIVE AND THE MASS RATES OF CHANGE CANNOT BECOME POSITIVE DUE TO OTHER LOGIC. DIFFERENTIAL EQUATIONS SOLVED ARE THE RATES OF CHANGE OF VELOCITY, ALTITUDE, TEMPERATURE, AND RADIUS. THE MASS RATE OF CHANGE IS COMPUTED

PROGRAM DESCRIPTION (CONT)

IN THE AUXILIARY EQUATIONS SECTION AND IS NOT FORCED TO CONVERGE ON EACH INTEGRATION STEP.

11. SPECIAL CONSIDERATIONS

IF ERRORS ARE FOUND BY THE PROGRAM IN EXECUTING A PROBLEM, APPROPRIATE STATEMENTS ARE PRINTED OUT AND A PANIC DUMP OF MOST OF THE VARIABLES IN THE PROGRAM IS MADE.

IT HAS BEEN OBSERVED THAT MOST ERRORS ARE DUE TO THE INCREMENT OF THE INDEPENDENT VARIABLE, DELTI, BEING TOO LARGE. THUS DURING THE INTEGRATION IMPOSSIBLE VALUES OF THE DEPENDENT VARIABLES ARE COMPUTED. IF ERRORS OCCUR EARLY IN THE COMPUTATION OF THE TRAJECTORY, CORRECT THEM BY DIVIDING DELTI BY A FACTOR OF 5.

7094 CUSTOMER UTILIZATION REPORT

1. DECK NUMBER

FB096

2. TITLE

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 2

3. PROGRAMMER

DATE

B. CLEMENZ

5-15-64

4. DESCRIPTION

THE PROGRAM IS ONE PHASE OF A THREE-PART PROGRAM TO COMPUTE THE ABLATION OF SMALL MOLTEN DROPLETS WHICH ARE RE-ENTERING THE ATMOSPHERE OF THE EARTH AT HYPERSONIC SPEEDS. PHASE I (DECK NUMBER FB-080) IS USED TO ESTIMATE THE DECELERATION DURING THE PREHEATING PERIOD EXTENDING FROM THE TIME OF DROPLET RELEASE TO THE TIME WHEN THE PARTICLE TEMPERATURE APPROACHES THAT SURFACE TEMPERATURE WHERE AN APPRECIABLE ABLATION RATE COMMENCES. PHASE II (DECK NUMBER FB-096) IS A GENERAL MOLTEN DROPLET MODEL WHERE THE HEAT CAN BE DISTRIBUTED ARBITRARILY THROUGHOUT THE MODEL AND THE TEMPERATURE CAN BE VARIED ACCORDING TO AN ARBITRARY SURFACE PRESSURE DISTRIBUTION. COMPUTATION OF THE TRAJECTORY, RADIUS, AND MASS LOSS OF THE PARTICLE IS CONTINUED UNTIL THE SURFACE TEMPERATURE IS GREATER THAN AN INPUT PERCENTAGE OF THE GAS TEMPERATURE OR UNTIL THE DROPLET IS SMALLER THAN AN INPUT RADIUS. PHASE III (DECK NUMBER FB-097) IS USED TO ACCOUNT FOR THE LOW VELOCITY REGION OF THE PARTICLE TRAJECTORY. THIS PHASE IS CONCLUDED BY THE RADIUS OF THE DROPLET BEING LESS THAN AN INPUT FINAL RADIUS, BY A RATE OF CHANGE OF THE RADIUS (DR/DT) LESS THAN AN INPUT FINAL DR/DT , OR BY A POSITIVE DR/DT .

5. REFERENCES

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E. UNITRAC PROGRAMMING COURSE NOTES
S. JAMES, W. OUTTEN, S. DORWEIS

6. DEFINITIONS

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SYMBOLS	UNITS	DEFINITION
ALP1	(-----)	FRACTION OF SF HEAT TRANSFERED FROM SECTION 1 TO 2 WHICH RESULTS IN VAPORIZATION IN SECTION 2
ALP2	(-----)	FRACTION OF SF HEAT TRANSFERED FROM SECTION 1 TO 3 WHICH RESULTS IN VAPORIZATION IN SECTION 3
ALT	(FT)	ALTITUDE OF PARTICLE
BET1	(-----)	FRACTION OF SG HEAT TRANSFERED FROM SECTION 2 TO 3 WHICH RESULTS IN VAPORIZATION IN SECTION 3
CD	(-----)	DRAW COEFFICIENT
CP	(BTU/(LBM-DEG R))	SPECIFIC HEAT
DELHV	(BTU/LBM)	HEAT OF VAPORIZATION
DELT1	(SEC)	MAXIMUM COMPUTING INTERVAL OR CHANGE IN TIME BETWEEN POINTS OF CONVERGENCE DURING INTEGRATION
DMT	(LBM/SEC)	TOTAL MASS RATE OF CHANGE
DM1	(LBM/SEC)	MASS RATE OF CHANGE SECTION 1
DM2	(LBM/SEC)	MASS RATE OF CHANGE SECTION 2
DM3	(LBM/SEC)	MASS RATE OF CHANGE SECTION 3
DM4	(LBM/SEC)	MASS RATE OF CHANGE SECTION 4
DR	(FT/SEC)	RATE OF CHANGE OF THE RADIUS
DVFS	(FT/(SEC**2))	ACCELERATION OF PARTICLE
EPS1	(-----)	EMISSIVITY OF SPHERE SURFACE
EX	(-----)	STOP FOR PHASE 2. PROGRAM STOPS WHEN TW1 EXCEED EX * TST
GAME	(DEG)	ANGLE OF DROPLET RE-ENTRY
GAM1	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 1
GAM2	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 2
GAM3	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 3
GAM4	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 4
HS1	(BTU/LBM)	STAGNATION ENTHALPY (PHASE 2)

0	OKB	(BTU/(LBM-SEC))	INTERNAL HEAT GENERATION RATE	
0	OLAMI	(FT)	MEAN FREE PATH FOR FREE STREAM AIR MOLECULES	// //
0	OMOLW	(-----)	MOLECULAR WEIGHT OF THE PARTICLE	
0	PSI	(LBF/SQ FT)	STAGNATION PRESSURE (PHASE 2)	
0	PSIG(1)	(-----)	RATIO OF ACTUAL CONVECTIVE HEAT TRANSFER TO MAX- IMUM HEAT TRANSFER IN SECTION 1 (BLOCKING TERM)	
0	PSIG(2)	(-----)	RATIO OF ACTUAL CONVECTIVE HEAT TRANSFER TO MAX- IMUM HEAT TRANSFER IN SECTION 2 (BLOCKING TERM)	
0	PSIG(3)	(-----)	RATIO OF ACTUAL CONVECTIVE HEAT TRANSFER TO MAX- IMUM HEAT TRANSFER IN SECTION 3 (BLOCKING TERM)	
0	QDOCS	(BTU/(FYW2-SEC))	STAGNATION HEAT TRANSFER RATE TO BODY BY CONVECTION	
0	R	(FT)	RADIUS OF PARTICLE	
0	RFIN	(FT)	FINAL RADIUS. WHEN R IS LESS THAN RFIN COMPU- TATION IS HALTED.	
0	RHOIS	(LBM/CU FT)	DENSITY OF ABLATING SPHERE MATERIAL	
0	SAT(1)	(LBM/SEC)	MASS LOSS RESULTING FROM ACTUAL HEAT TRANSFER TO SECTION 1.	
0	SA(2)	(LBM/SEC)	MASS LOSS RESULTING FROM ACTUAL HEAT TRANSFER TO SECTION 2	
0	SA(3)	(LBM/SEC)	MASS LOSS RESULTING FROM ACTUAL HEAT TRANSFER TO SECTION 3	
0	SB(1)	(LBM/SEC)	THEORETICAL MASS GAIN TO SECTION 1 RESULTING FROM HEAT RADIATED AWAY FROM SURFACE	
0	SB(2)	(LBM/SEC)	THEORETICAL MASS GAIN TO SECTION 2 RESULTING FROM HEAT RADIATED AWAY FROM SURFACE	
0	SB(3)	(LBM/SEC)	THEORETICAL MASS GAIN TO SECTION 3 RESULTING FROM HEAT RADIATED AWAY FROM SURFACE	
0	SB(4)	(LBM/SEC)	THEORETICAL MASS GAIN TO SECTION 4 RESULTING FROM HEAT RADIATED AWAY FROM SURFACE	
0	SC	(LBM/SEC)	MASS RATE OF CHANGE DUE TO ACCUMULATION OF SENSIBLE HEAT IN PARTICLE	
0	SD	(LBM/SEC)	MASS RATE OF CHANGE RESULTING FROM RADIOACTIVE HEAT GENERATION IN PARTICLE	
0	SF	(-----)	FRACTION OF ACTUAL CONVECTIVE HEAT TRANSFER ABSORBED BY SURFACE OF SECTION 1 AND CONDUCTED AND CONVECTED AWAY FROM THE SURFACE. (1.0 = SF) RESULTS IN VAPORIZATION AT SURFACE.	
0	SG	(-----)	FRACTION OF ACTUAL CONVECTIVE HEAT TRANSFER	

ABSORBED BY SURFACE OF SECTION 2 AND CONDUCTED
AND CONVECTED AWAY FROM THE SURFACE. (1.0 - SG)
RESULTS IN VAPORIZATION AT SURFACE.

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SJ (-----) FRACTION OF ACTUAL CONVECTIVE HEAT TRANSFER
ABSORBED BY SURFACE OF SECTION 3 AND CONDUCTED
AND CONVECTED AWAY FROM THE SURFACE. (1.0 - SJ)
RESULTS IN VAPORIZATION AT SURFACE.

SL (DEG K) SLOPE OF LOG(VAPOR PRESSURE IN ATMOSPHERES)
VERSUS 1 / TEMPERATURE IN DEG K CURVE

STEN1 (DYNES/CM) SURFACE TENSION

TIME (SEC) TIME. THE INDEPENDENT VARIABLE IN THE DIFFEREN-
TIAL EQUATIONS.

TOLER (-----) SIGNIFICANCE CONTROL FOR CONVERGENCE OF INTEGRA-
TION. WHEN SUCCESSIVE VALUES (D1 AND D2) OF ALL
DEPENDENT VARIABLES FULLFILL THE FOLLOWING CON-
DITION, CONVERGENCE IS ASSUMED. $(D1 + D2) / D1$
MUST BE LESS THAN $100 * TOLER$ FOR CONVERGENCE.
IF THE CONDITION IS NOT MET, THE COMPUTING
INTERVAL MAY BE HALVED AND ANOTHER ATTEMPT IS
MADE. ON THE OTHER HAND, IF $(D1 + D2) / D1$ IS
LESS THAN TOLER, THEN THE COMPUTING INTERVAL IS
DOUBLED UNLESS IT IS ALREADY AT ITS MAXIMUM
VALUE, DELT1.

TS1 (DEG R) STAGNATION TEMPERATURE (PHASE 2)

TWA(1) (DEG R) WALL TEMPERATURE SECTION 1

TWA(2) (DEG R) WALL TEMPERATURE SECTION 2

TWA(3) (DEG R) WALL TEMPERATURE SECTION 3

TWA(4) (DEG R) WALL TEMPERATURE SECTION 4

VFS (FT/SEC) FREE STREAM VELOCITY OF PARTICLE

V (-----) INTERCEPT OF VAPOR PRESSURE AXIS OF THE LOG(
VAPOR PRESSURE IN ATMOSPHERES) VERSUS 1 / TEMP-
ERATURE IN DEG K CURVE.

ZET1 (-----) FRACTION OF STAGNATION HEAT TRANSFER IN SECTION1

ZET2 (-----) FRACTION OF STAGNATION HEAT TRANSFER IN SECTION2

ZET3 (-----) FRACTION OF STAGNATION HEAT TRANSFER IN SECTION3

7. INPUT FORMAT

VALUES MUST APPEAR IN THE SEQUENCE INDICATED BELOW ON EACH CARD
IN EITHER THE I, E, OR F MODE WITH AT LEAST ONE BLANK OR A COMMA
SEPARATING THEM. THESE CARDS MUST BE FOLLOWED BY A CARD CONTAIN-
ING THE INFORMATION **PROBLEM DIVIDER** IN ANY COLUMNS.

CARD

DATA

1. VFS ALT R RFIN STEN1
 2. TIME DELT1 TOLER GAME
 3. OMOLW DELHV SF SG SJ EX
 4. RHOTS SL W OKB EPS1 CP
 5. ZET1 ZET2 ZET3 ALP1 ALP2 BET1
 6. GAM1 GAM2 GAM3 GAMA
 7. PROBLEM DIVIDER

8. OUTPUT FORMAT

THE INPUT PARAMETERS ARE PRINTED ON THE FIRST PAGE OF OUTPUT FOR EACH PROBLEM WITH THE FOLLOWING FORMAT

MAY 12, 1964-1 PAGE 1

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 2

VFS =X.XX ALT =X.XX R =X.XX RFIN =X.XX STEN1 =X.XX
 TIME =X.XX DELT1 =X.XX TOLER =X.XX GAME =X.XX
 OMOLW =X.XX DELHV =X.XX SF =X.XX SG =X.XX SJ =X.XX
 EX =X.XX
 RHOTS =X.XX SL =X.XX W =X.XX OKB =X.XX EPS1 =X.XX
 CP =X.XX
 ZET1 =X.XX ZET2 =X.XX ZET3 =X.XX ALP1 =X.XX ALP2 =X.XX
 BET1 =X.XX
 GAM1 =X.XX GAM2 =X.XX GAM3 =X.XX GAMA =X.XX

PAGES OF OUTPUT WITH THE FORMAT BELOW WILL BE PRINTED UNTIL THE PROBLEM IS COMPLETED. EACH SET OF DATA IS A POINT OF CONVERGENCE IN THE INTEGRATION. THE TITLE IS FOLLOWED BY 8 SETS OF DATA.

MAY 12, 1964-1 PAGE 2

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 2

TIME	VFS	ALT	R	DVFS	DR	PSI	HS1	TS1	QDOCS	CD	OLAM1	DMT	DM1	DM2	DM3	DM4	SC	SD
SA(1)	SA(2)	SA(3)	SB(1)	SB(2)	SB(3)	SB(4)	PSIG(1)	PSIG(2)	PSIG(3)	TWA(1)	TWA(2)	TWA(3)	TWA(4)					
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX

ETC.

9. TIMING

1 min. per prob.

7094 CUSTOMER UTILIZATION REPORT

1. DECK NUMBER

FB-097

2. TITLE

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 3

3. PROGRAMMER

DATE

B. CLEMENZ

5-15-64

4. DESCRIPTION

THE PROGRAM IS ONE PHASE OF A THREE-PART PROGRAM TO COMPUTE THE ABLATION OF SMALL MOLTEN DROPLETS WHICH ARE RE-ENTERING THE ATMOSPHERE OF THE EARTH AT HYPERSONIC SPEEDS. PHASE I (DECK NUMBER FB-080) IS USED TO ESTIMATE THE DECELERATION DURING THE PREHEATING PERIOD EXTENDING FROM THE TIME OF DROPLET RELEASE TO THE TIME WHEN THE PARTICLE TEMPERATURE APPROACHES THAT SURFACE TEMPERATURE WHERE AN APPRECIABLE ABLATION RATE COMMENCES. PHASE II (DECK NUMBER FB-096) IS A GENERAL MOLTEN DROPLET MODEL WHERE THE HEAT CAN BE DISTRIBUTED ARBITRARILY THROUGHOUT THE MODEL AND THE TEMPERATURE CAN BE VARIED ACCORDING TO AN ARBITRARY SURFACE PRESSURE DISTRIBUTION. COMPUTATION OF THE TRAJECTORY, RADIUS, AND MASS LOSS OF THE PARTICLE IS CONTINUED UNTIL THE SURFACE TEMPERATURE IS GREATER THAN AN INPUT PERCENTAGE OF THE GAS TEMPERATURE OR UNTIL THE DROPLET IS SMALLER THAN AN INPUT RADIUS. PHASE III (DECK NUMBER FB-097) IS USED TO ACCOUNT FOR THE LOW VELOCITY REGION OF THE PARTICLE TRAJECTORY. THIS PHASE IS CONCLUDED BY THE RADIUS OF THE DROPLET BEING LESS THAN AN INPUT FINAL RADIUS, BY A RATE OF CHANGE OF THE RADIUS (DR/DT) LESS THAN AN INPUT FINAL DR/DT , OR BY A POSITIVE DR/DT .

5. REFERENCES

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E. UNITRAC PROGRAMMING COURSE NOTES
S. JAMES, W. OUTTEN, S. DORWEIS

6. DEFINITIONS

SYMBOLS	UNITS	DEFINITION
ALT	(FT)	ALTITUDE OF PARTICLE
CD	(-----)	DRAW COEFFICIENT
CP	(BTU/(LBM-DEG R))	SPECIFIC HEAT
DALT	(FT/SEC)	RATE OF CHANGE OF THE ALTITUDE
DELHV	(BTU/LBM)	HEAT OF VAPORIZATION
DELTI	(SEC)	MAXIMUM COMPUTING INTERVAL OR CHANGE IN TIME BETWEEN POINTS OF CONVERGENCE DURING INTEGRATION
DMT	(LBM/SEC)	TOTAL MASS RATE OF CHANGE
DMT1	(LBM/SEC)	MASS RATE OF CHANGE OF SECTION 1
DMT2	(LBM/SEC)	MASS RATE OF CHANGE OF SECTION 2
DMT3	(LBM/SEC)	MASS RATE OF CHANGE OF SECTION 3
DR	(FT/SEC)	RATE OF CHANGE OF THE RADIUS
DRFIN	(FT/SEC)	FINAL RATE OF CHANGE OF THE RADIUS WITH RESPECT TO TIME (DR/DT). WHEN DR/DT IS LESS THAN DRFIN OR GREATER THAN ZERO, COMPUTATION IS HALTED.
DTAVE	(DEG R/SEC)	RATE OF CHANGE OF THE AVERAGE TEMPERATURE
DTEM1	(DEG R)	DIFFERENCE BETWEEN TAVE AND TEMPERATURE OF WALL FOR SECTION 1 (TW1 = TAVE + DTEM1)
DTEM3	(DEG R)	DIFFERENCE BETWEEN TAVE AND TEMPERATURE OF WALL FOR SECTION 3 (TW3 = TAVE - DTEM3)
DVFS	(FT/(SEC**2))	ACCELERATION OF PARTICLE
EPS1	(-----)	EMISSIVITY OF SPHERE SURFACE
GAME	(DEG)	ANGLE OF DROPLET RE-ENTRY
GAM1	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 1
GAM2	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 2
GAM3	(-----)	FRACTION OF STAGNATION PRESSURE IN SECTION 3
HST	(BTU/LBM)	STAGNATION ENTHALPY
HW1	(BTU/LBM)	WALL ENTHALPY OF SECTION 1

HW2 (BTU/LBM) WALL ENTHALPY OF SECTION 2

OKB (BTU/(LBM-SEC)) INTERNAL HEAT GENERATION RATE

OMOLW (-----) MOLECULAR WEIGHT OF THE PARTICLE

PS11 (-----) RATIO OF ACTUAL CONVECTIVE HEAT TRANSFER TO MAXIMUM HEAT TRANSFER IN SECTION 1 (BLOCKING TERM)

PS12 (-----) RATIO OF ACTUAL CONVECTIVE HEAT TRANSFER TO MAXIMUM HEAT TRANSFER IN SECTION 2 (BLOCKING TERM)

PS101 (BTU/SEC) ACTUAL CONVECTIVE HEAT TRANSFER TO SECTION 1

PS102 (BTU/SEC) ACTUAL CONVECTIVE HEAT TRANSFER TO SECTION 2

PST (LBF/SQ FT) STAGNATION PRESSURE

PV1 (LBF/SQ FT) VAPORIZATION PRESSURE OF SECTION 1

PV2 (LBF/SQ FT) VAPORIZATION PRESSURE OF SECTION 2

QDOC5 (BTU/(FT**2-SEC)) STAGNATION HEAT TRANSFER RATE TO BODY BY CONVECTION

QDOR1 (BTU/SEC) RADIATION HEAT TRANSFER RATE FROM BODY SECTION 1

QDOR2 (BTU/SEC) RADIATION HEAT TRANSFER RATE FROM BODY SECTION 2

QDOR3 (BTU/SEC) RADIATION HEAT TRANSFER RATE FROM BODY SECTION 3

R (FT) RADIUS OF PARTICLE

RFIN (FT) FINAL RADIUS. WHEN R IS LESS THAN RFIN COMPUTATION IS HALTED.

RHO15 (LBM/CU FT) DENSITY OF ABLATING SPHERE MATERIAL

SL (DEG K) SLOPE OF LOG(VAPOR PRESSURE IN ATMOSPHERES) VERSUS 1 / TEMPERATURE IN DEG K CURVE

TAVE (DEG R) AVERAGE TEMPERATURE OF PARTICLE

THK (BTU/(FT-SEC-DEG R)) THERMAL CONDUCTIVITY OF THE PARTICLE

TIME (SEC) TIME. THE INDEPENDENT VARIABLE IN THE DIFFERENTIAL EQUATIONS.

TOLER (-----) SIGNIFICANCE CONTROL FOR CONVERGENCE OF INTEGRATION. WHEN SUCCESSIVE VALUES (D1 AND D2) OF ALL DEPENDENT VARIABLES FULLFILL THE FOLLOWING CONDITION, CONVERGENCE IS ASSUMED. $(D1 + D2) / D1$ MUST BE LESS THAN $100 * TOLER$ FOR CONVERGENCE. IF THE CONDITION IS NOT MET, THE COMPUTING INTERVAL MAY BE HALVED AND ANOTHER ATTEMPT IS MADE. ON THE OTHER HAND, IF $(D1 + D2) / D1$ IS LESS THAN TOLER, THEN THE COMPUTING INTERVAL IS DOUBLED UNLESS IT IS ALREADY AT ITS MAXIMUM VALUE, DELT1.

TST (DEG R) STAGNATION TEMPERATURE

TW1 (DEG R) WALL TEMPERATURE OF SECTION 1

TW2 (DEG R) WALL TEMPERATURE OF SECTION 2

TW3 (DEG R) WALL TEMPERATURE OF SECTION 3

VFS (FT/SEC) FREE STREAM VELOCITY OF PARTICLE

W (-----) INTERCEPT OF VAPOR PRESSURE AXIS OF THE LOG:
VAPOR PRESSURE IN ATMOSPHERES VERSUS 1 / TEMPERATURE
IN DEG K CURVE.

ZET1 (-----) FRACTION OF STAGNATION HEAT TRANSFER IN SECTION1

ZET2 (-----) FRACTION OF STAGNATION HEAT TRANSFER IN SECTION2

7. INPUT FORMAT

VALUES MUST APPEAR IN THE SEQUENCE INDICATED BELOW ON EACH CARD
IN EITHER THE I, E, OR F MODE WITH AT LEAST ONE BLANK OR A COMMA
SEPARATING THEM. THESE CARDS MUST BE FOLLOWED BY A CARD CONTAINING
THE INFORMATION **PROBLEM DIVIDER** IN ANY COLUMNS.

CARD

DATA

1.	VFS	ALT	R	TAVE	RFIN	DRFIN
2.	TIME	DELT1	TOLER	GAME	OMOLV	DELHV
3.	RHOIS	SL	W	KB	EPS1	CP
4.	GAM1	GAM2	ZET1	ZET2	DTEM1	DTEM3
5.	THK	GAM3				
6.	PROBLEM DIVIDER					

8. OUTPUT FORMAT

THE FIRST PAGE OF OUTPUT FOR EACH PROBLEM IS THE PARAMETER PRINT
WHICH HAS THE FOLLOWING FORMAT.

DATE -- PAGE --

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 3

VFS	--	ALT	--	R	--	TAVE	--	RFIN	--
DRFIN	--								
TIME	--	DELT1	--	TOLER	--	GAME	--	OMOLV	--
DELHV	--								
RHOIS	--	SL	--	W	--	KB	--	EPS1	--
CP	--								
GAM1	--	GAM2	--	ZET1	--	ZET2	--		
DTEM1	--	DTEM3	--						
THK	--	GAM3	--						

PAGES OF OUTPUT WITH THE FORMAT BELOW WILL BE PRINTED UNTIL THE
PROBLEM IS COMPLETED. EACH SET OF DATA IS A POINT OF CONVERGENCE
IN THE INTEGRATION. THE TITLE IS FOLLOWED BY 8 SETS OF DATA.

DATE -- PAGE --

RE-ENTRY BURNUP OF SMALL DROPLETS--PHASE 3

TIME	VFS	ALT	R	YAVE	DVFS	DR	
DALT	DTAVE	PSY	HST	TST	CD	QDOCS	
QDOR1	QDOR2	QDOR3	PSI1	PSI2	PVI	PV2	18
DMT3	PSI01	PSI02	HW1	HW2	TW3		
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	

ETC.

9. TIMING

THIS PROGRAM TAKES APPROXIMATELY ONE MINUTE TO COMPUTE ONE PROBLEM.

10. PROGRAM DESCRIPTION

ALL PHASES WERE COMPILED UTILIZING UNITRAC (REF. E) TO SET UP THE SOLUTION OF THE DIFFERENTIAL EQUATIONS INVOLVED, THE INPUT-OUTPUT TO THE PROGRAM, AND THE GENERAL FLOW OF THE PROGRAM. THE UNITRAC PROCESSOR TRANSLATED GENERAL ENGINEERING STATEMENTS TO A FORTRAN PROGRAM WHICH WAS MODIFIED AS WILL BE DISCUSSED LATER. THE METHODS OF INTEGRATION THAT ARE PRESENTLY AVAILABLE IN UNITRAC ARE A FOURTH-ORDER RUNGE-KUTTA AND THE BOWIE METHOD, A SPECIAL APPROACH DERIVED AT THE MARTIN COMPANY BY CLAGGETT BOWIE. THE BOWIE METHOD WAS UTILIZED IN PHASES I AND II BECAUSE OF ITS APPARENT SPEED AND GOOD ACCURACY. IN SEVERAL PROBLEMS FOR PHASE III THE BOWIE METHOD WAS FOUND TO CONVERGE ON INCORRECT RESULTS AND SO THE SLOWER BUT MORE ACCURATE RUNGE-KUTTA TECHNIQUE WAS APPLIED. IN THE INTEGRATIONS ALL THE PROGRAMS USE VARIABLE INTERVAL IN THE INDEPENDENT VARIABLE, TIME.

THE GENERAL FLOW DIAGRAM FOR THE MAIN PROGRAM FOR ALL THREE PHASES IS SHOWN IN FIGURE 1. FOR EACH PROBLEM THE PROPERTIES OF THE DROPLET ARE INPUT PARAMETERS ALONG WITH THE INITIAL CONDITIONS, VARIOUS COEFFICIENTS, AND THE INTEGRATION INFORMATION. INITIALIZATION OF THE INPUT DATA AND SETUP OF THE INTEGRATION IS COMPLETED AND IS FOLLOWED BY PRINTOUT OF THE INPUT PARAMETERS. THE AUXILIARY EQUATIONS AND DIFFERENTIAL EQUATIONS ARE THEN SOLVED CONTINUOUSLY UNTIL SUCCESSIVE VALUES OF EACH DEPENDENT VARIABLE ARE CONVERGED. AFTER CONVERGENCE THE FINAL CONDITIONS ARE CHECKED SO AS TO KEY THE TERMINATION OF THE PROBLEM, IF NECESSARY. SINCE PRINTOUT IS DESIRED AT ALL CONVERGENCE POINTS IN THESE PROGRAMS, THE DATA IS PREPARED FOR PRINTING IN THE OUTPUT CONVERSION SECTION AND THEN IS WRITTEN OUT. IF THE PROBLEM HAS REACHED FINAL CONDITIONS, A NEW PROBLEM IS READ INTO THE COMPUTER. ON THE OTHER HAND, IF THE TERMINATION KEY IS OFF, THE DELTA VALUES SECTION IS ENTERED AND COMPUTATION OF ANOTHER INTEGRATION STEP IS BEGUN IN THE AUXILIARY EQUATIONS.

AMONG THE SUBROUTINES, EACH PHASE IS ATMDAT, WHICH IS

FIG. 1- MAIN PROGRAM

1. SUBROUTINE TITLE

WRKHAT

2. PROGRAMMER

B. CLEMENZ

3. REFERENCE

LEWIS, C.H. AND BURGESS, TIT, E.G. **EMPIRICAL EQUATIONS FOR THE THERMODYNAMIC PROPERTIES OF AIR AND NITROGEN TO 15000 DEG. K.**
ARNOLD ENGINEERING DEVELOPMENT CENTER AFSC-USAF, TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-63-138, JULY 1963

4. PURPOSE

THIS SUBROUTINE COMPUTES THE THERMODYNAMIC PROPERTIES OF AIR FOR EQUILIBRIUM DISSOCIATING AND IONIZING AIR FOR TEMPERATURES FROM 90 TO 15000 DEG. K. AND FOR ENTROPY RANGE 1%2 LESS THAN LOG TO THE BASE 10 OF S/R LESS THAN 2.06.

5. METHOD

GIVEN THE PRESSURE AND ENTROPY, THIS SUBROUTINE UTILIZES EMPIRICAL EQUATIONS TO COMPUTE THE THERMODYNAMIC PROPERTIES AT THAT PRESSURE AND ENTROPY.

6. CALLING SEQUENCE

CALL WRKHAT (PIN,SRIN,ZOUT,HOUT,RHOUT,TOUT,AOUT)

A. INPUT ARGUMENTS

SYMBOL	UNITS	DEFINITION
PIN	LBF/50 FT	PRESSURE
SRIN	-----	ENTROPY (S/R)

B. OUTPUT ARGUMENTS

SYMBOL	UNITS	DEFINITION
ZOUT	-----	COMPRESSIBILITY
HOUT	BTU/LBM	ENTHALPY
RHOUT	LBM/CU FT	DENSITY

TOUT DEG R TEMPERATURE
AOUT FT/SEC SPEED OF SOUND

21

12

7. RESTRICTION

THE PROGRAM HAS BEEN FOUND TO HAVE A DISCONTINUITY IN ENTHALPY
FOR CONSTANT PRESSURE AT THE ENTROPIES OF APPROXIMATELY 39.89,
57.54, AND 63.17.

CWRKMAT EMPIRICAL EQUATIONS FOR THERMODYNAMIC PROPERTIES OF AIR

SUBROUTINE WRKMAT (PIN,SRIN,ZOUT,HOUT,RHOUT,TOUT,AOUT)

C PIN IN LB. / SQ. FT. SRIN DIMENSIONLESS ZOUT DIMENSIONLESS

C HOUT IN BTU / LB. RHOUT IN LB. / CU. FT. TOUT IN DEG. R

C AOUT IN FT. / SEC.

C PROPERTIES FROM 90 DEG K TO 15000 DEG K

C AIR

C PLOG= LOG(P/PA)

C SRLOG=LOG(S/R)

C LOGARITHMS TO BASE 10

R = 3089.67

AREF = 1086.98

PREF = 2116.224

RHOREF = 2.507542E-3

PLOG = LOG10(PIN / PREF)

SRLOG = LOG10(SRIN)

X15=-39.1442+83.0558*SRLOG-38.2842*SRLOG*SRLOG

X151=-10.*(PLOG-X15)

IF (X151-40.) 306,305,305

305 T15=0.0

GO TO 309

306 IF (X151+40.) 307,308,308

307 T15=1.0

GO TO 309

308 T15=1./(1.+EXP F(X151))

309 A=PLOG*PLOG

B=SRLOG*SRLOG

C=A*PLOG

D=B*SRLOG

C Z=F(LOGP,LOG(S/R))

303 XZ12=62.91-41.5*SRLOG

XZ23=72.945-45.75*SRLOG

XZ34=65.75-37.5*SRLOG

XZ45=62.92-32.0*SRLOG

XZ121=-10.*(PLOG-XZ12)

XZ231=-10.*(PLOG-XZ23)

XZ341=-10.*(PLOG-XZ34)

XZ451=-10.*(PLOG-XZ45)

ZCAL2=519.80374-23.753514*PLOG-983.90729*SRLOG+.37296957*A

1+30.084379*PLOG*SRLOG+620.04168*B-.0021648826*C+.23710079*A*SRLOG

2-9.496903*PLOG*B-129.78921*D

ZCAL3=366.40674-15.517444*PLOG-647.42436*SRLOG+.18701758*A

1+18.040383*PLOG*SRLOG+379.59834*B-.00087958438*C-.10580129*A*SRLOG

2-5.1888254*PLOG*B-73.504269*D

ZCAL4=516.07331-16.59277*PLOG-808.49823*SRLOG+.071256235*A

1+16.526813*PLOG*SRLOG+418.45341*B+.00094183347*C-.019727817*A*

2SRLOG-3.9948906*PLOG*B-71.038921*D

IF (XZ121-40.) 7,10,10

7 IF (XZ121+40.) 8, 9, 9

8 TZ12=1.

GO TO 11

9 TZ12=1./(1.+EXP F(XZ121))

GO TO 11

10 TZ12=0.0

11 IF (XZ231-40.) 12,15,15

12 IF (XZ231+40.) 13,14,14

13 TZ23=1.

GO TO 16

14 TZ23=1./(1.+EXP F(XZ231))

GO TO 16

```

XR341=-10.*(PLOG-XR34)
XR451=-10.*(PLOG-XR45)
IF (XR121-40.)34.37.37
34 IF (XR121+40.)35.36.36
35 TR12=1.0
GO TO 38
36 TR12=1./(1.+EXP F(XR121))
GO TO 38

```

```

15 TZ23=0.0
16 IF (XZ341-40.)17.20.20
17 IF (XZ341+40.)18.19.19
18 TZ34=1.0
GO TO 21
19 TZ34=1./(1.+EXP F(XZ341))
GO TO 21
20 TZ34=0.0
21 IF (XZ451-40.)22.25.25
22 IF (XZ451+40.)23.24.24
23 TZ45=1.0
GO TO 26
24 TZ45=1./(1.+EXP F(XZ451))
GO TO 26
25 TZ45=0.0
26 ZCAL=1.0+ (ZCAL2-1.)*TZ12+(ZCAL3-ZCAL2)*TZ23+(ZCAL4-ZCAL3)*TZ34
1+(4.0-ZCAL4)*TZ45
ZCAL=1.+(ZCAL-1.)*T15
C LOG(H/R)=F(LOGP,LOG(S/R))
304 IF (SRLOG-1.6)27.27.28
27 HRCAL=12.693869+5.3975312*PLOG-48.729217*SRLOG-.14961521*A
1-5.8788774*PLOG*SRLOG+48.19278*B+.0009014*132*C+.091151*73*A*SRLOG
2+1.6282829*PLOG*B-13.065267*D
GO TO 33
28 IF (SRLOG-1.76)29.29.30
29 HR22 =-156.37194+6.6959228*PLOG+269.93097*SRLOG-.097179965*A
1-7.5379714*PLOG*SRLOG-152.13866*B+.00057029937*C+.058364795*A*
2SRLOG+2.1592755*PLOG*B+28.940926*D
HR21=-84.008522+2.5761318*PLOG+107.06198*SRLOG-.014352904*A
1-1.5313194*PLOG*SRLOG-32.316439*B
XH=-61.2053+114.103*SRLOG-47.5532*B
XH1=-10.*(PLOG-XH)
IF (XH1-40.)291.294.294
291 IF (XH1+40.)292.293.293
292 TH=1.0
GO TO 295
293 TH=1./(1.+EXP F(XH1))
GO TO 295
294 TH=0.0
295 HRCAL= HR21+ (HR22-HR21)*TH
GO TO 33
30 IF (SRLOG-1.92)31.31.32
31 HRCAL=-35.160671+.5366924*PLOG+56.99585*SRLOG-.022661358*A
1-.48470305*SRLOG*PLOG-27.641087*B+.00058568839*C+.016299962*A*
2SRLOG+.14073606*B*PLOG+4.712261*D
GO TO 33
32 HRCAL=-114.94796+4.004583*PLOG+180.08427*SRLOG-.041327787*A
1-4.0366535*PLOG*SRLOG-90.76006*B+.00040320694*C+.024360248*A*SRLOG
2+1.0462299*PLOG*B+15.467804*D
33 HR15=28.160664-2.2339873*PLOG-59.053694*SRLOG+.054973544*A
1+3.7183257*PLOG*SRLOG+40.986503*B-.0004292698*C-.040726332*A*SRLOG
2-1.3704505*PLOG*B-8.253645*D
HRCAL=HR15+ (HRCAL-HR15)*T15
C LOG(RHO/RHOA)=F(LOGP,LOG(S/R))
310 XR12=-16.5527+57.45*SRLOG-30.8036*B
XR23=499.544-938.91*SRLOG+609.028*B-135.995*D
XR34=360.507-634.538*SRLOG+389.174*B-82.4653*D
XR45=489.628-458.5*SRLOG+106.25*B
XR121=-10.*(PLOG-XR12)
XR231=-10.*(PLOG-XR23)

```

XA34=1703.78-2602.97*SRLOG+1337.93*B-231.422*D
 XA22=1043.37-1820.34*SRLOG+1076.36*B-215.445*D
 XA121=-10.*(PLOG-XA12)
 XA231=-10.*(PLOG-XA23)
 XA341=-10.*(PLOG-XA34)
 XA221=-10.*(PLOG-XA22)
 A1=-4409.6241+196.82259*PLOG+8746.4634*SRLOG-3.1650299*A
 1-262.32947*PLOG*SRLOG-5786.449*B+.020004186*C+2.1429825*A*SRLOG
 2+87.589029*PLOG*B+1277.6718*D
 A21=-1814.5117+86.096078*PLOG+3315.6099*SRLOG-1.7593034*A
 1-107.2534*PLOG*SRLOG-2023.201*B+.016287679*C+1.1398134*A*SRLOG
 2+33.659607*PLOG*B+413.41945*D
 A22=2651.2944-81.405596*PLOG-3099.0064*SRLOG+.69752668*A
 1+48.062596*PLOG*SRLOG+907.70889*B
 IF (XA221-40.)402.401.401
 401 TA22=0.0
 GO TO 405
 402 IF (XA221+40.)403.403.404
 403 TA22=1.0
 GO TO 405
 404 TA22=1./(1.+EXP(XA221))
 405 A2=A21+(A22-A21)*TA22
 A3=-3217.8037+195.34964*PLOG+5348.2143*SRLOG-4.6268475*A
 1-221.12705*PLOG*SRLOG-2970.8649*B+.044614358*C+2.7079177*A*SRLOG
 2+63.042803*PLOG*B+553.12007*D
 A4=16976.939-476.10242*PLOG-17445.315*SRLOG+3.6534057*A
 1+246.41125*PLOG*SRLOG+4486.3118*B
 IF (XA121-40.)407.406.406
 406 TA12=0.0
 GO TO 410
 407 IF (XA121+40.)408.408.409
 408 TA12=1.0
 GO TO 410
 409 TA12=1./(1.+EXP(XA121))
 410 IF (XA231-40.)412.411.411
 411 TA23=0.0
 GO TO 415
 412 IF (XA231+40.)413.413.414
 413 TA23=1.0
 GO TO 415
 414 TA23=1./(1.+EXP(XA231))
 415 IF (XA341-40.)417.416.416
 416 TA34=0.0
 GO TO 420
 417 IF (XA341+40.)418.418.419
 418 TA34=1.0
 GO TO 420
 419 TA34=1./(1.+EXP(XA341))
 420 AOAO=A1+(A2-A1)*TA12+(A3-A2)*TA23+(A4-A3)*TA34
 600 ZOUT=ZCAL
 HOUT=(R*EXP(HRCAL*2.3025851))/25051.6
 RHOUT=RHOREF*EXP(RHCAL*2.3025851)*32.2
 TOUT=T*1.8
 AOUT=AOAO*AREF
 RETURN
 END

1. SUBROUTINE TITLE

CODOT

2. PROGRAMMER

B. CLEMENZ

3. PURPOSE

THIS SUBROUTINE IS DESIGNED TO COMPUTE THE HEAT TRANSFER RATE AND DRAG COEFFICIENT OF A SPHERE IN AN EQUILIBRIUM FLOW FIELD IN FREE MOLECULAR, FIRST COLLISION, TRANSITION, OR CONTINUUM FLOW. THE SUBROUTINE CAN ALSO BE UTILIZED TO CALCULATE THE THERMODYNAMIC PROPERTIES OF A POINT IN AN EQUILIBRIUM FLOW FIELD WITH EITHER PRESSURE AND ENTHALPY OR PRESSURE AND TEMPERATURE AS INPUTS.

4. METHOD

WHEN IT IS DESIRED TO COMPUTE HEAT TRANSFER RATE AND DRAG COEFFICIENT, A DECISION IS MADE EARLY IN THE SUBROUTINE AS TO THE TYPE OF FLOW. THIS DECISION IS BASED UPON THE MEAN FREE PATH BETWEEN AIR MOLECULES. IF FREE MOLECULAR OR FIRST COLLISION FLOW EXISTS, THE HEAT TRANSFER RATE IS COMPUTED BY EXPLICIT RELATIONSHIPS USING INPUT PROPERTIES AND THE DRAG COEFFICIENT IS SET TO A CONSTANT. ON THE OTHER HAND, IF TRANSITION OR CONTINUUM FLOW EXISTS, IT IS NECESSARY TO COMPUTE THE STAGNATION CONDITIONS OF THE GAS AND THE WALL CONDITIONS BY ITERATIVE METHODS. THE SUBROUTINE, WRKHAT, IS USED IN THE ITERATION TO COMPUTE THE THERMODYNAMIC PROPERTIES AND WEGSTEIN ITERATION METHODS ARE APPLIED NOT ONLY TO SPEED CONVERGENCE, BUT ALSO TO FORCE CONVERGENCE. THE REYNOLDS NUMBER, DRAG COEFFICIENT, AND CONTINUUM FLOW HEAT TRANSFER RATE ARE THEN DETERMINED. THE HEAT TRANSFER RATE IS SMOOTHED FOR TRANSITION FLOW JUST BEFORE RETURNING TO THE MAIN PROGRAM.

THE ITERATION METHODS CAN BE ENTERED DIRECTLY BY SETTING THE CONTROL, ERROR, TO PARTICULAR VALUES WHEN CALLING THE SUBROUTINE. WHEN THIS IS DONE, THE THERMODYNAMIC PROPERTIES CAN BE COMPUTED USING ONLY PRESSURE AND ENTHALPY OR PRESSURE AND TEMPERATURE AS INPUT PROPERTIES.

5. CALLING SEQUENCE

CALL CODOT

ALL ARGUMENTS ARE TRANSFERRED TO THIS SUBROUTINE BY MEANS OF COMMON STATEMENTS.

A. INPUT ARGUMENTS

SYMBOL	UNITS	DEFINITION
--------	-------	------------

ERROR

INPUT CONTROL (ALSO USED AS OUTPUT
CONTROL AS DESCRIBED BELOW)

- 1.0--COMPUTE TEMSR, HS, HW, RHOW,
AND TWR USING PS, SL, W, TRFS,
AND VFS AS INPUTS.
- 0.0--COMPUTE ODOCS, CD, TEMSR, AND
HS WITH PS, SL, W, TRFS, VFS,
RHOF, R, AND VSFS AS INPUTS.
- 1.0--COMPUTE TEMSR, RHOS, AND TSR
WITH PS, SL, W, AND HS AS
INPUTS.
- 9.0--SAME AS ERROR = -1.0 EXCEPT
THAT TEMSR IS AN INPUT
- 10.0--SAME AS ERROR = 0.0 EXCEPT
THAT TEMSR IS AN INPUT
- 11.0--SAME AS ERROR = 1.0 EXCEPT
THAT TEMSR IS AN INPUT

HS

BTU/LBM

STAGNATION ENTHALPY

PS

LBF/SQ FT

PRESSURE OF POINT AT WHICH HEAT
TRANSFER RATE IS DESIRED

R

FT

RADIUS OF SPHERE OR DROPLET

RHOF

SLGS/CU FT

FREE STREAM DENSITY

SL

DEG K

SLOPE OF THE LOG TO THE BASE 10 OF
VAPOR PRESSURE IN ATMOSPHERES VERSUS
1 / TEMPERATURE IN DEG K CURVE

TEMSR

DEG R

WALL TEMPERATURE

TRFS

DEG R

FREE STREAM TEMPERATURE

VFS

FT/SEC

FREE STREAM VELOCITY

VSFS

FT/SEC

FREE STREAM VELOCITY OF SOUND

W

INTERCEPT OF VAPOR PRESSURE AXIS OF
THE LOG TO THE BASE 10 OF THE VAPOR
PRESSURE IN ATMOSPHERES VERSUS
1 / TEMPERATURE IN DEG K CURVE

B. OUTPUT ARGUMENTS

SYMBOL

UNITS

DEFINITION

CD

DRAG COEFFICIENT

ERROR

ERROR RETURN FROM SUBROUTINE

0.0--NO ERROR

1.0--ITERATION OF GAS CONDITIONS OR
OF WALL CONDITIONS FAILED DUE
TO MORE THAN 50.0 ITERATIONS

2.0--ERROR IN COMPUTING CONTINUUM
FLOW CONDITIONS. THE WALL
ENTHALPY COMPUTED IS GREATER

THAN .8 OF THE STAGNATION
ENTHALPY.

HS BTU/LBM STAGNATION ENTHALPY
HW BTU/LBM WALL ENTHALPY
QDOCS BTU/(FT**2-SEC) HEAT TRANSFER RATE
RHOS LBM/CU FT GAS STAGNATION DENSITY
RHOW LBM/CU FT WALL DENSITY
YMSR DEG R WALL TEMPERATURE
YSR DEG R GAS STAGNATION TEMPERATURE
YWR DEG R WALL TEMPERATURE AFTER ITERATION

6. SPECIAL PRINTOUT

IF ERRORS OCCUR IN THIS SUBROUTINE THE FOLLOWING STATEMENTS ARE
WRITTEN ON THE NORMAL OUTPUT TAPE.

A. **ITERATION FAILURE IN LOOP 1 AT P = XXXXX**

THIS IS DUE TO 50.0 ITERATIONS IN GAS STAGNATION COMPUTATION

B. **ITERATION FAILURE IN LOOP 2 AT P = XXXXX**

THIS IS DUE TO 50.0 ITERATIONS IN WALL CONDITION COMPUTATION

C. **POOR WALL ENTHALPY IN QDOT**

THIS IS DUE TO THE WALL ENTHALPY BEING GREATER THAN .8 OF THE
STAGNATION ENTHALPY IN CONTINUUM FLOW.

२१

CCODOT1

SUBROUTINE CODOT1

DIMENSION

1 KOM (1), OCOM (1), OEQ (50), ODEQ (50), MICE0100 MICE0101

2 TITLES (200), SUBTLE (200), OUTPUT (300), BUFCRD (14) MICE0102

EQUIVALENCE MICE0103

1 (KOM(1), OCOM(1), XINDVR), (OXXXX1, OEQ(1)), (OXXXX2, ODEQ(1)) MICE0104

COMMON MICE0105

1 XINDVR, OEQ, ODEQ, BOTTOM, COMPT1, DELVAR, DIRECT, MICE0106

2 DLVFLG, ERROR1, ERROR2, FINCK1, FINCK2, FLAGON, ICHECK, MICE0107

3 IEXIT, IHDFLG, INIT, INPRNT, INTAPE, IOUTPE, IPAGE, MICE0108

4 IPARAM, IPROB, ITEST, IUPFLG, KBRCH, LICE, LINESO, MICE0109

5 LINST, LINPGE, LINTB, LOCOUT, LOCTLE, LOCT, LOWCON, MICE0110

9 LINECT, LINESS, LOCSUB, COM A13

6 LOWFLG, NCOPMX, NICE, NOPROB, NPHASE, NPHMAX, NVRGCT, MICE0112

7 PHSTOP, PROBLE, PRTIME, SAVEIT, TYPICE, TESTWD, UPPERL, MICE0113

COMMON BUFCRD, TITLES, SUBTLE, OUTPUT, LOCAMT, NSIZE, PSTOP.

9 XMXMIN, FINCK3, FINCK4 MICE0115

COMMON MONTH, NDAY, NYEAR

DIMENSION DUMMY(126)

COMMON DUMMY MICE0117

EQUIVALENCE(DTAVE, ODEQ(00001)), (TAVE, OEQ(00001))

EQUIVALENCE(DVFS, ODEQ(00002)), (VFS, OEQ(00002))

EQUIVALENCE(DALT, ODEQ(00003)), (ALT, OEQ(00003))

EQUIVALENCE(TIME, XINDVR)

COMMON PFS, RHOF, TRFS, VSFS, OKOUNT, R, OKB, GAME, RHOTS, CP, SL, W, COENU, CO

1EX, COEY, COEZ, EPS1, DELT1, TOLER, EPS1B, TDENO, TCOE1, TCOE2, TCOE3, TCOE4,

1VCOE, SGAME, ODOCS, OKA1, OKA2, CD, PSNOY, PS, ERROR, OLAMI, TEMSR, TW1R, TW2R

1, TAVFI

DIMENSION SRIT(2), HIT(2)

C ERROR CELL CONTROLS CALCULATION TO BE MADE

C ERROR = +1.0---COMPUTE TSR(STAG. TEMP. OF GAS) USING INPUT HS AND PS

C ERROR = -1.0---COMPUTE TEMSR AND HW (WALL COND). USING INPUT PS

C ERROR = 0.0---COMPUTE ODOCS, CD, AND TEMSR USING OLAMI, OLANI, PS,

C1 FREE STREAM PROPS., AND R

C ERROR CAN BE 10.0 GREATER THAN PROPER VALUE IN WHICH CASE TEMSR IS

C1 AN INPUT ARGUMENT

C ALL INPUTS NEED SL AND W

SWITCH = 0.0

COUNT = 0.0

PSA = PS / 2116.

PSALOG = LOG10F(PSA)

IF (ERROR - 3.0) 96,96.95

C TEMSR IS INPUT ARGUMENT

95 ERROR = ERROR - 10.0

GO TO 97

C TEMSR TO BE COMPUTED

96 TEMSR = 1.8 * SL / (PSALOG - W)

97 IF (ERROR) 98,98.100

98 HS = .24 * TRFS + VFS ** 2 / 50103.2

IF (ERROR) 100,99.99

99 OLAMI = .5158696E-9 / RHOF

C 1.8302909E-3 = 3.1415927 / 3089.6 / 1.8

C OLASI-LIMIT BETWEEN FREE MOLECULAR AND FIRST COLLISION

500 OLASI = 10.0 * R * (VFS / 4.0) * (1.8302909E-3 / TEMSR) ** .5

IF (OLAMI - OLASI) 504,504.502

C FREE MOLECULAR FLOW (RANGE 1.0)

502 ZETSOD = .65 * (VFS / VSFS) ** 2

ODOCS = (.9 * RHOF * VFS ** 3 / 1556.0) * (1.0 - 3.8333333 *

1 (TEMSR / TRFS) / ZETSOD)

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CD = 2.0
GO TO 998
504 OLATI = OLASI / 30.0
IF (OLAMI - OLATI) 100,100,510
C FIRST COLLISION (RANGE 2.0)
C GAM = 1.3 (3.0/GAM)**.5 = 1.5191091 2.*(6.0/GAM)**.5 = 4.2966892
510 OMFS = VSFS / VFS
TA = (TEMSR / TRFS) **.5
BERA = TA * OMFS * 1.5191091
BASA = 4.2966892 * TA * OLAMI * OMFS / R
CD = 2.01
QDOTF = .9 * RHOF * VFS ** 3 / 1556.0
QDOCS = QDOTF * (1.0 - BERA ** 2) * (1.0 - .2 / BASA)
GO TO 998
C TRANSITION AND CONTINUUM FLOW (RANGE = 3.0)
C GET FIRST GUESS AT STAGNATION SR
100 IF (HS - 1200.0) 101,101,102
101 SRIS = 32.0 - 2.0 * PSALOG
GO TO 104
102 SRIS = 42.0 - 3.0 * PSALOG
C COMPUTE STAGNATION CONDITIONS OF GAS
104 IF (ERROR) 1120,1104,1104
1104 SRDEL = .01 * SRIS
SRIT(1) = SRIS - SRDEL
SRIT(2) = SRIS
DO 105 I=1,2
CALL WRKHAT (PS,SRIT(I),ZDUM,HIT(I),RHOS,TSR,VDUM)
105 CONTINUE
DSROH = SRDEL / (HIT(2) - HIT(1))
SRISI = DSROH * (HS - HIT(2)) + SRIS
IF (ABS(SRISI - SRIS) - .05) 120,120,106
120 IF (ERROR) 1120,1120,998
106 COUNT = COUNT + 1.0
IF (COUNT - 50.0) 108,110,110
108 IF (COUNT - 1.0) 8108,8108,8109
C WEGSTEIN ITERATION
C FIRST ITERATION
8108 SRISMI = SRIS
SRIS = SRISI
GO TO 8110
C AFTER FIRST ITERATION
8109 SRSWEG = (SRISI * SRISMI - SRISO * SRIS) / (SRISI + SRISMI - SRISO)
1 - SRIS)
SRISMI = SRIS
SRIS = SRSWEG
8110 SRISO = SRISI
GO TO 1104
110 LOOP = 1
112 WRITE OUTPUT TAPE 6,113,LOOP,PS
113 FORMAT (//5X29H ITERATION FAILURE IN LOOP NO.12,8H AT P = E15.8//)
ERROR = 2.0
GO TO 999
C SET UP INITIAL GUESS AT WALL SR
1120 SRIW = SRIS
COUNT = 0.0
SRMIN = 23.0 - 2.5 * PSALOG
SRMAX = 64.0 - 5.0 * PSALOG
SBASE = SRMIN
IF (HS - 1200.0) 122,122,1121
1121 CALL WRKHAT (PS,SBASE,ZDUM,HW,RHOW,TBASE,VDUM)

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      SRIT(1) = SRIW
      NUP = 1
      GO TO 1122
C FIND WALL CONDITIONS FOR STAGNATION TEMP. (TEMSR)
      122 SRDEL = .01 * SRIW
      SRIT(1) = SRIW - SRDEL
      SRIT(2) = SRIW
      NUP = 2
      1122 DO 123 I=1,NUP
      CALL WRKHAT (PS,SRIT(I),ZOOM,HWR,RHOW,HIT(I),VDUM)
      123 CONTINUE
      IF (NUP - I) 1123,1123,1124
      1123 TGI = HIT(1)
      HIT(2) = HIT(1)
      SRIW1 = (TEMSR - TBASE) / (TGI - TBASE) * (SRIW - SBASE) + SBASE
      GO TO 1125
      1124 DSROT = SRDEL / (HIT(2) - HIT(1))
      SRIW1 = DSROT * (TEMSR - HIT(2)) + SRIW
      1125 IF (ABS(SRIW1 - SRIW) - .01) 130,130,124
      130 TWR = HIT(2)
      IF (ERROR) 998,1130,1130
      124 COUNT = COUNT + 1.0
      IF (COUNT - 50.0) 126,125,125
      125 LOOP = 2
      GO TO 112
C WEGSTEIN ITERATION METHOD
      126 IF (SRIW1 - SRMIN) 1126,1129,1127
      1126 SRIW1 = SRMIN
      GO TO 1129
      1127 IF (SRIW1 - SRMAX) 1129,1129,1128
      1128 SRIW1 = SRMAX
      1129 IF (COUNT - 1.0) 127,127,128
C FIRST ITERATION
      127 SRIWM1 = SRIW
      SRIW = SRIW1
      GO TO 129
C AFTER FIRST ITERATION
      128 SRWEG = (SRIW1 + SRIWM1 - SRINO * SRIW) / (SRIW1 + SRIWM1 - SRINO
      1 - SRIW)
      SRIWM1 = SRIW
      SRIW = SRWEG
      129 SRINO = SRIW1
      GO TO 122
C COMPUTE REYNOLDS NO. AND CD
      1130 RHOW = RHOW / 32.2
      RHOS = RHOS / 32.2
      IF (.8 * HS - HW) 132,134,134
      132 WRITE OUTPUT TAPE 6,8132
      8132 FORMAT (//5X27HPOOR WALL ENTHALPY IN CDDOT//)
      ERROR = 2.0
      GO TO 999
      134 AMUS = (2.27E-08 * (TSR ** 1.5)) / (TSR + 198.0)
      REYN = 2.0 * RHOS * VFS * R / AMUS
      CD = .92 + 2.1 / (REYN ** .5) - .8 / REYN
C GET QDOCS
      136 AMUW = (2.27E-08 * (TWR ** 1.5)) / (TWR + 198.0)
      ARA = ((RHOS * AMUS) ** .4) * ((RHOW * AMUW) ** .1)
      ARB = (HS - HW) / (R ** .5)
      ARC = (2.0 * PS / RHOS) ** .25
C 30.268 = 32.2 * .94

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      QDOCS = ARA * ARB * ARC * 30.268
140 OMACH = VFS / VSFS
      IF (OMACH - 20.0) 142,141,141
141 EPS2 = .065
      GO TO 150
142 IF (OMACH - 14.0) 144,143,143
143 EPS2 = .080
      GO TO 150
144 IF (OMACH - 10.0) 146,146,145
145 EPS2 = .095
      GO TO 150
146 EPS2 = .1667
150 REF = REYN / (1.414214 * EPS2) * 2.
      IF (REF - 50.0) 151,151,152
151 QDOCS = QDOCS * (4.62 * (REF) ** .0628 - 5.0)
      GO TO 160
152 IF (REF - 500.0) 153,153,154
153 QDOCS = QDOCS * (5.53 * (REF) ** .0169 - 5.0)
      GO TO 160
154 IF (REF - 40000.0) 155,155,160
155 QDOCS = QDOCS * (6.41 / (REF) ** .00617 - 5.0)
160 GO TO 998
998 ERROR = 0.0
999 RETURN
      END

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CPHASE1	UNITRAC 1	
C....	DIMENSION	MICE0005
1	KOM (1) , OCOM (1) , OEO (50) , ODEO (50) ,	MICE0100
2	TITLES (200) , SUBTLE (200) , OUTPUT (300) , BUFCRD (14)	MICE0101
	EQUIVALENCE	MICE0102
1	(KOM(1),OCOM(1), XINDVR) , (OXXXX1, OEO(1)) , (OXXXX2,ODEO(1))	MICE0103
	COMMON	MICE0104
1	XINDVR , OEO , ODEO , BOTTOM , COMPT1 , DELVAR , DIRECT	MICE0105
2	DLVFLG , ERROR1 , ERROR2 , FINCK1 , FINCK2 , FLAGON , ICHECK	MICE0106
3	LEXIT , IHDFLG , INIT , INPRNT , INTAPE , IOUTPE , IPAGE	MICE0107
4	IPARAM , IPROB , ITEST , IUPFLG , KBRCH , LICE , LINESO	MICE0108
5	LINEST , LINPGE , LINTB , LOCOUT , LOCTLE , LOCT , LOWCON	MICE0109
9	LINECT , LINESS , LOCSUB ,	MICE0110
6	LOWFLG , NCOPMX , NICE , NOPROB , NPHASE , NPHMAX , NVRGCT	COM A13
7	PHSTOP , PROBLE , PRTIME , SAVEIT , TYPICE , TESTWD , UPPERL	MICE0112
	COMMON BUFCRD,TITLES,SUBTLE,OUTPUT,LOCAMT,NSIZE,PSTOP,	MICE0113
9	XXMIN , FINCK3 , FINCK4	MICE0115
	COMMON MONTH,NDAY,NYEAR	
	DIMENSION DUMMY(126)	
	COMMON DUMMY	MICE0117
1	CALL PANSET(MONTH,NDAY,NYEAR,INTAPE,IOUTPE)	
	IPAGE = 0	MICE0122
	LINPGE = 60	MICE0123
	NCOPMX = 5000	MICE0124
	NOPROB = 0	MICE0125
	PROBLE = 6HPROBLE	MICE0126
8	DUMPWD = 606024644447	MICEA126
8	BLANKS = 606060606060	MICEB126
	CALL RESTAR	
	INIT = 0	MICE0128
	IPROB = 0	MICE0129
	LEXIT = 0	MICE0130
	NPHMAX = 1	MICE0132
	LINESO = 0	MICE0135
	LOCOUT = 0	MICE0137
	670 IF (SENSE SWITCH 5) 671,2	
	671 PRINT 672	
	672 FORMAT(23H PUT SENSE SWITCH 5 UP)	
	GO TO 670	
	2 NPHASE = 0	MICE0133
	GO TO 1000	MICE0150
	1004 NOPROB = NOPROB + 1	MICE0154
	PRINT 1005 , NOPROB	MICE0155
	1005 FORMAT(13H)PROBLEM NO. 13,19H NOW BEING EXECUTED)	MICE0156
C....	DETERMINE IF A DUMP REQUEST IS INCLUDED AS INPUT	MICEA161
600	DUMPFL = 0.0	MICEB161
601	READ INPUT TAPE INTAPE , 9999, DUMPST, DUMPND, DUMPSP	MICEC161
602	ISKIP = 1	MICED161
603	WORD = BLANKS	MICEE161
604	DO 607 J= 1,4	MICEF161
605	CALL TABID (ISKIP, ICHAR, NENDCD)	MICEG161
606	CALL ADD CHR (ICHAR, WORD)	MICEH161
607	CONTINUE	MICEI161
608	IF (WORD = DUMPWD) 614,616,614	
616	IF (DUMPST = 1.E36) 619,617,619	
617	DUMPF0 = 1.0	
618	GO TO 615	
619	DUMPF0 = 0.0	
609	IF (DUMPSP = 1.E36) 611,610,611	MICEK161

610	DUMPSP = 1.0		MICEL161
611	DUMPFL = 1.0		MICEM161
	DUMPMX = 10.0		
612	DUMPMX = 0.0		MICEN161
613	GO TO 615		MICE0161
614	BACKSPACE INTAPE		MICEP161
	DUMPF0 = 0.0		
615	CONTINUE		MICE0161
	LOCT = 0		MICE0161
3	GO TO 1100		MICE0165
1101	IF (LOCT)	199,4,4	MICE0169
4	GO TO 2000		MICE0173
2999	IF (NPHMAX = 1)	5,6,5	MICE0178
5	IF (NPHASE = NPHMAX)	10,6,10	MICE0179
6	READ INPUT TAPE INTAPE , 7 , (BUFCRD(J),J=1,14)		MICE0189
7	FORMAT(13A6,A2)		MICE0190
	CALL WORDGT (BUFCRD(1), TESTWD)		MICE0194
	IF (TESTWD = PROBLE)	8,10,8	MICE0198
8	CALL UJECT		
	WRITE OUTPUT TAPE IOUTPE,9		
	PRINT 9		MICE0203
9	FORMAT(54H0EXCESSIVE INPUT DATA CARDS OR MISSING PROBLEM DIVIDER)		MICE0204
	GO TO 200		MICE0208
10	GO TO 1200		MICE0212
1201	GO TO 1202		MICE0217
1203	GO TO 1300		MICE0218
1301	ERROR1 = TYPICE		MICE0223
	ERROR2 = ERROR1 * 100.		MICE0224
	GO TO 1400		MICE0228
1401	DIRECT = COMPTI / ABSF(COMPTI)		MICE0231
	IPARAM = 1		MICE0233
	GO TO 3000		MICE0237
3999	IPARAM = 0		MICE0240
99	LICE = 4		MICE0242
	NPHASE = NPHASE + 1		MICE0244
	NVRGCT = 0		MICE0246
	FINCK2 = 0.0		MICE0248
100	IF (NICE) 17, 11, 17		
11	IF (LICE-4) 13, 12, 19		
19	IF (DLVFLG) 20, 15, 20		
20	LICE=3		
	GO TO 1700		
12	IHDPLG=1		
	KBRCH = 1		
	IUPFLG= 0		
	INPRNT= 0		
	GO TO 16		
13	LICE=LICE+1		
14	IF (LICE - 4) 101, 15, 15		
15	XINDVR=XINDVR+COMPTI		
16	LICE = 1		
	GO TO 101		
17	GO TO 18		MICE0262
101	IF (LICE - 2)	104,106,102	MICE0263
102	IF (LICE - 4)	151,205,103	MICE0264
103	IF (LICE - 6)	205,104,105	MICE0265
104	GO TO 1500		MICE0269
1501	GO TO 1600		MICE0271
1601	IF (LICE - 6)	100,105,100	MICE0275
105	GO TO 1700		MICE0279

1701	IF (IEXIT)	184,100,184	MICE0283
106	NVRGCT = NVRGCT +1		MICE0288
C....	REQUESTED PANIC CHECK AREA		MICEA288
650	CONTINUE		MICEB288
651	IF (DUMPFL) 652,661,652		MICEC288
652	IF ((XINDVR = DUMPST) * DIRECT) 661,655,653		MICEE288
653	IF ((XINDVR = DUMPND) * DIRECT) 654,659,659		MICEF288
654	IF (DUMPCK) 657,655,657		MICEG288
655	DUMPCK = DUMPSP		MICEH288
	DUMPMX = DUMPMX - 1.0		
	IF(DUMPMX) 656,659,656		
656	CALL PANIC (IOUTPE)		
	WRITE OUTPUT TAPE IOUTPE , 667		
667	FORMAT(1H0//)		
657	DUMPCK = DUMPCK - 1.0		MICEJ288
658	GO TO 661		MICEK288
659	DUMPFL = 0.0		MICEL288
660	GO TO 656		MICEM288
661	IF(SENSE SWITCH 5) 675,666		
675	PRINT 676		
676	FORMAT(48H SENSE SWITCH 5 DOWN - OPERATOR INTERRUPT OF RUN /		
1	29H VALID INTERRUPT - HIT START /		
2	52H UNINTENTIONAL - RAISE SENSE SWITCH 5 - HIT START)		
	PAUSE 12345		
	IF (SENSE SWITCH 5) 662,666		
662	WRITE OUTPUT TAPE IOUTPE,663		
663	FORMAT(50HOMACHINE OPERATOR INTERRUPT - RESTART INFORMATION)		
664	CALL PANIC (IOUTPE)		
665	CALL EXIT		
666	CONTINUE		
	IF(NVRGCT - NCOPMX) 109,107,189		MICE0290
107	WRITE OUTPUT TAPE IOUTPE , 108, NCOPMX		MICE0292
	PRINT 108 , NCOPMX		MICE0293
108	FORMAT(1H0,16,48H COMPUTING INTERVALS FAILED TO TERMINATE PROBLEM)		MICE0294
	GO TO 199		MICE0295
109	FINCK1 = 0.0		MICE0298
	GO TO 4000		MICE0300
4999	IF (FINCK1)	111,110,110	MICE0305
110	IF (FINCK2)	112,115,112	MICE0306
111	XINDVR = PHSTOP		MICE0309
	IEXIT = -1		MICE0311
	GO TO 113		MICE0313
112	IEXIT = 1		MICE0315
113	IF (KBRCH = 3)	114,114,166	MICE0319
114	PRTIME = XINDVR		MICE0322
	GO TO 100		MICE0324
115	IF (INIT)	117,116,117	MICE0327
116	INIT = 1		MICE0330
	INPRNT = 1		MICE0332
	LOWCON = 1		MICE0333
	LOWFLG = 1		MICE0335
	IUPFLG = 0		MICE0337
	IHDFLG = 1		MICE0339
	LOPRT1=0		
	LOPRT2=0		
	IF (NICE) 5998, 5999, 5000		
117	IF (KBRCH = 2)	122,118,122	MICE0346
118	IF (DIRECT * (XINDVR = UPPERL)) 119,169,120		MICE0354
119	IF (ABSF (UPPERL - XINDVR) = .0001) 169,169,151		MICE0363
120	PRTIME = UPPERL		MICE0367

121	IUPFLG = 1		MICE0369
	GO TO 126		MICE0371
122	IF (KBRCH = 5)	128,123,100	MICE0376
123	IF (DIRECT * (XINDVR - UPPERL))	124,169,125	MICE0384
124	IF (ABSF(UPPERL - XINDVR) - .0001)	169,169,100	MICE0392
125	ITEST = 1		MICE0396
126	IPROB = 0		MICE0398
127	LOWFLG = 0		MICE0400
	GO TO 100		MICE0402
128	IF (IPROB)	5998,5000,129	MICE0410
129	IF (KBRCH = 4)	140,100,140	MICE0415
5998	LOWFLG = 1		MICE0418
130	LOWCON = 0		MICE0419
132	LICE = 5		MICE0421
133	KBRCH = 0		MICE0424
134	IF (INPRNT)	151,100,151	MICE0427
5999	IPROB = 1		MICE0430
137	INPRNT = 0		MICE0432
138	IF (KBRCH = 4)	140,139,140	MICE0434
139	PRTIME = XINDVR		MICE0439
	GO TO 100		MICE0442
140	IF (KBRCH = 1)	141,151,141	MICE0445
141	IF (LOWFLG)	142,143,142	MICE0449
142	LOWFLG = 0		MICE0451
143	IF (LOWCON)	144,146,144	MICE0454
144	LOWCON = 0		MICE0456
145	PRTIME = XINDVR		MICE0458
	IF (KBRCH-3)	150,150,100	
146	PRTIME = BOTTOM		MICE0462
147	IF (KBRCH-3)	520,520,100	
520	LOPRT1=1		
	GO TO 100		
148	IF (KBRCH-3)	521,521,149	
521	IF (IUPRNT)	522,150,522	
522	IUPRNT=0		
523	PRTIME=XINDVR		
	LOPRT2=1		
	GO TO 100		
149	IF (KBRCH = 5)	168,176,168	MICE0472
150	LICE = 5		MICE0475
151	SAVEIT = XINDVR		MICE0479
152	IF (KBRCH-3)	153,156,155	
153	IF (IUPFLG)	154,156,154	MICE0487
156	IF (FINCK1)	155,530,530	
530	IF (LOPRT1)	155,1800,155	
154	IUPFLG = 0		MICE0489
	IUPRNT=1		
155	XINDVR = PRTIME		MICE0492
	GO TO 1800		MICE0494
1801	CALL SPACE (0)		
157	IF (IHDFLG)	158,6001,158	MICE0501
158	IHDFLG = 0		MICE0504
	GO TO 6000		MICE0506
6999	XINDVR = SAVEIT		MICE0509
160	IF (INPRNT)	161,162,161	MICE0518
161	INPRNT = 0		MICE0520
	GO TO 100		MICE0522
162	IF (LICE-3)	169,524,100	
524	IF (LOPRT1)	525,526,525	
525	LOPRT1=0		

	IF (XINDVR-PRTIME)	523,169,523	
526	IF (LOPRT2)	527,163,527	
527	LOPRT2=0		
	GO TO 169		
163	IF (IEXIT)	164,170,209	MICE0532
164	XINDVR = PHSTOP		
209	IF (XINDVR - PRTIME)	165,180,165	MICE0537
165	PRTIME = PRTIME + DELVAR		MICE0540
166	IF (DIRECT * (XINDVR - PRTIME))	167,100,100	MICE0544
167	PRTIME = XINDVR		MICE0546
	GO TO 100		MICE0548
168	PRTIME = PRTIME + DELVAR		MICE0552
	GO TO 100		MICE0555
169	LICE = 5		MICE0558
	GO TO 100		MICE0560
170	IF (KBRCH = 2)	171,128,171	MICE0564
171	IF (KBRCH = 5)	168,172,168	
172	IF (DIRECT * (PRTIME - UPPERL))	173,174,179	MICE0571
173	IF (ABSF(UPPERL - PRTIME) - .0001)	174,174,176	MICE0573
174	IF (ITEST)	175,100,175	MICE0577
175	ITEST = 0		MICE0579
	GO TO 128		MICE0581
176	PRTIME = PRTIME + DELVAR		MICE0584
177	IF (DIRECT * (PRTIME - UPPERL))	178,100,179	MICE0586
178	IF (ABSF(UPPERL - PRTIME))	179,179,100	MICE0589
179	PRTIME = UPPERL		MICE0592
	GO TO 100		MICE0593
180	IF (IEXIT)	181,186,186	MICE0596
181	NPHASE = NPHASE + 1		MICE0599
182	IF (NPHASE - NPHMAX)	183,183,185	MICE0601
183	IF (DLVFLG)	1700,184,1700	MICE0603
184	FLAGON = 1.0		MICE0607
	GO TO 500		MICE0608
185	FLAGON = 0.0		MICE0610
	GO TO 500		MICE0611
186	IF (NPHASE- NPHMAX)	187,185,187	MICE0616
187	WRITE OUTPUT TAPE IOUTPE , 188 , NPHASE , NPHMAX		MICE0618
188	FORMAT(29HOPROBLEM TERMINATED IN PHASE 13,4H OF 13)		MICE0619
	PRINT 188 , NPHASE, NPHMAX		MICE0620
	GO TO 199		MICE0621
189	CALL UJECT		
	IF(NPHMAX-1) 191,191,190		
190	IF (NPHASE- NPHMAX)	195,191,191	MICE0625
191	BACKSPACE INTAPE		MICE0628
192	READ INPUT TAPE INTAPE , 7 , (BUFCRD(J),J=1,14)		MICE0629
193	CALL WORDGT (BUFCRD(1), TESTWD)		MICE0631
194	IF (TESTWD = PROBLE)	195,197,195	MICE0633
195	WRITE OUTPUT TAPE IOUTPE , 196 , (NPHASE,(BUFCRD(J),J=1,14))		MICE0636
	PRINT 196 , (NPHASE,(BUFCRD(J),J=1,14))		MICE0637
196	FORMAT(33HOF THE FOLLOWING DATA CARD IN PASS 13,28H CONTAINED INSUFFICIENT DATA//10X,13A6,A2//)		MICE0638
	GO TO 200		MICE0639
197	WRITE OUTPUT TAPE IOUTPE , 198 , NPHASE		MICE0640
	PRINT 198 , NPHASE		MICE0642
198	FORMAT(28HOMISSING DATA CARD IN PHASE 13)		MICE0643
	GO TO 201		MICE0644
199	BACKSPACE INTAPE		MICE0645
200	READ INPUT TAPE INTAPE , 7 , (BUFCRD(J),J=1,14)		MICE0648
	CALL WORDGT (BUFCRD(1) , TESTWD)		MICE0649
	IF (TESTWD = PROBLE)	200,201,200	MICE0650
			MICE0651

```

201 FLAGON = 0.0 MICE0654
202 WRITE OUTPUT TAPE (OUTPE, 203, NOPROB MICE0656
      PRINT 203, NOPROB MICE0657
203 FORMAT(13H)PROBLEM NO. 13,26H FAILED FOR ABOVE REASON. ) MICE0658
204 GO TO 500 MICE0659
205 PRINT 206, NPHASE,NOPROB MICE0662
      WRITE OUTPUT TAPE (OUTPE,206,NPHASE,NOPROB
206 FORMAT(30H)INTEGRATION TOLERANCE NOT MET/30H PANIC PRINT PROVIDED
      1= PHASE 13,12H OF PROBLEM 13)
207 CALL PANIC (OUTPE) MICE0664
208 GO TO 199 MICE0665
500 IEXIT = 0 MICE0667
501 IPROB = 0 MICE0668
502 INIT = 0 MICE0669
503 INDFLG= 1 MICE0670
504 IF ( FLAGON ) 99,505,99 MICE0671
505 IPAGE = 0 MICE0672
506 NPHASE= 1 MICE0673
507 IF (DUMPPD) 508, 2, 508
508 CALL PANIC (OUTPE)
      GO TO 2
9999 FORMAT(6G) MICE0695
C.... UNITRAC GENERATED PROGRAM MICE0696
      EQUIVALENCE(DTAVE,ODEQ(00001)),(TAVE,DEQ(00001))
      EQUIVALENCE(DVFS,ODEQ(00002)),(VFS,DEQ(00002))
      EQUIVALENCE(DALT,ODEQ(00003)),(ALT,DEQ(00003))
      EQUIVALENCE( TIME, XINOV)
1202 CALL ARDC59(LOCMT,NSIZE)
      GOTO1203
      COMMONPFS,RHOF,TRFS,VFS,OKOUNT,R,OKB,GAME,RHOTS,CP,SL,W,COEN,CO
      IEX,COEY,COEZ,EP,DELTI,TOLER,EP,TDENO,TCOE1,TCOE2,TCOE3,TCOE4,
      IVCOE,SGAME,ODOCS,OKA1,OKA2,CD,PSNOY,PS,ERROR,OLAMT,YEMSR,YWIN,YWZR
      1,TAVFI
01000 CONTINUE
      B TITLES(00001)=606060606060
      B TITLES(00002)=606060606060
      B TITLES(00003)=606060606060
      B TITLES(00004)=606060606060
      B TITLES(00005)=606060606060
      B TITLES(00006)=606060606060
      B TITLES(00007)=606060512540
      B TITLES(00008)=254563517060
      B TITLES(00009)=226451456447
      B TITLES(00010)=604626606244
      B TITLES(00011)=214343602451
      B TITLES(00012)=464743256362
      B TITLES(00013)=404047382162
      B TITLES(00014)=256001606060
      B TITLES(00015)=606060606060
      B TITLES(00016)=606060606060
      B TITLES(00017)=606060606060
      B TITLES(00018)=606060606060
      B TITLES(00019)=606060606060
      B TITLES(00020)=606060606060
01001 NICE= 00003
      LINTB=00002
      DLVFLG=1.0
01002 LINEST = 00001
      LOCTLE = 00020
01003 GO TO 01004

```

39

6

MICROFILMED BY
 100-100000-100
 100-100000-100

```

18 CALL MICE
GO TO 101
01100 GO TO 01101
02000 READINPUTTAPEINTAPE,9999,
1,VFS,ALT,R,TAVE
IF(TAVE-1.E36)02001,189,02001
02001 READINPUTTAPEINTAPE,9999,
1,OKB,GAME,RHOIS,CP,SL,W
IF(W-1.E36)02002,189,02002
02002 READINPUTTAPEINTAPE,9999,
1,COENU,COEX,COEY,COEZ,EPS1
IF(EPS1-1.E36)02003,189,02003
02003 READINPUTTAPEINTAPE,9999,
1,TIME,DELTI,TOLER
IF(TOLER-1.E36)02004,189,02004
02004 GO TO 02999
01200 CONTINUE
UKOUNT=0.
EPS1B=EPS1*4.75986E-13
TDENO=4.0*CP*RHOIS*R
TCOE1=3.0*COENU/TDENO
TCOE2=3.0*EPS1B/TDENO
TCOE3=OKB/CP
TCOE4=9.0*EPS1B/TDENO
VCOE=-96.6/(8.0*HMOIS*R)
SGAME=-SINF(GAME/57.29578)
GO TO 01201
01300 TYPICE = TOLER
GO TO 01301
01400 COMPTI = DELTI
GO TO 01401
03000 CALL UJECT
03001 FORMAT(1X,1P, 8H VFS =E15.7, 9H ALT =E15.7, 9H R =E15.7
1, 9H TAVE =E15.7 )
03002 WRITEOUTPUTTAPEIOUTPE,03001
1,VFS,ALT,R,TAVE
03003 FORMAT(1X,1P, 8H KB =E15.7, 9H GAME =E15.7, 9H RHOIS =E15.7
1, 9H CP =E15.7, 9H SL =E15.7 )
03004 WRITEOUTPUTTAPEIOUTPE,03003
1,OKB,GAME,RHOIS,CP,SL
03005 FORMAT(1X,1P, 8H W =E15.7 )
03006 WRITEOUTPUTTAPEIOUTPE,03005
1,W
03007 FORMAT(1X,1P, 8H COENU =E15.7, 9H COEX =E15.7, 9H COEY =E15.7
1, 9H COEZ =E15.7, 9H EPS1 =E15.7 )
03008 WRITEOUTPUTTAPEIOUTPE,03007
1,COENU,COEX,COEY,COEZ,EPS1
03009 FORMAT(1X,1P, 8H TIME =E15.7, 9H DELTI =E15.7, 9H TOLER =E15.7
1 )
03010 WRITEOUTPUTTAPEIOUTPE,03009
1,TIME,DELTI,TOLER
03011 GO TO 03999
01500 CONTINUE
CALLATMDAT(ALT,PFS,RHOF,VSFS,TRFS)
PSNOY=RHOF*VFS**2
C GET QDOCS, CD, TEMSR, AND OLAMI
PS=COEY*PSNOY
ERROR=0.0
CALL QDOOT1
IF(ERROR)1530,1530,207

```

1530 CONTINUE

TW1R=TEMSR

TW2R=TW1R-COEX

TAVF1=COEZ*TW1R

OKA1=TCOE2*(TW1R**4)

OKA2=TCOE4*(TW2R**4)

GO TO 01501

01600 CONTINUE

DTAVE=TCOE1*ODOCS-OKA1+TCOE3-OKA2

DVFS=VCOE*(VFS**2)*RHOF5*CD

DALT=SGAME*VFS

GO TO 01601

04000 IF(OKOUNT-(50.0))04007,04007,04001

04001 FINCK2=1.0

04007 IF(TAVE-(TAVF1))04014,04014,04008

04008 FINCK2=1.0

04014 GO TO 04999

05000 KBRCH= 1

05001 GO TO 05999

01800 CONTINUE

GO TO 01801

06000 CONTINUE

B OUTPUT(00001)=606060606331

B OUTPUT(00002)=442574622523

B OUTPUT(00003)=346060606060

B OUTPUT(00004)=606060652662

B OUTPUT(00005)=742663616225

B OUTPUT(00006)=233460606060

B OUTPUT(00007)=606060606021

B OUTPUT(00008)=436374266334

B OUTPUT(00009)=606060606060

B OUTPUT(00010)=606060632165

B OUTPUT(00011)=257424252760

B OUTPUT(00012)=513460606060

B OUTPUT(00013)=502446236274

B OUTPUT(00014)=226364616226

B OUTPUT(00015)=636225346060

B OUTPUT(00016)=606060606060

B OUTPUT(00017)=232474346060

B OUTPUT(00018)=606060606060

B OUTPUT(00019)=602465266274

B OUTPUT(00020)=266361622523

B OUTPUT(00021)=545402346060

B OUTPUT(00022)=606060636601

B OUTPUT(00023)=517424252760

B OUTPUT(00024)=513460606060

B OUTPUT(00025)=606060636602

B OUTPUT(00026)=517424252760

B OUTPUT(00027)=513460606060

B OUTPUT(00028)=604642210174

B OUTPUT(00029)=242527605161

B OUTPUT(00030)=622523346060

B OUTPUT(00031)=604642210274

B OUTPUT(00032)=242527605161

B OUTPUT(00033)=622523346060

B OUTPUT(00034)=422261234774

B OUTPUT(00035)=242527605161

B OUTPUT(00036)=622523346060

B OUTPUT(00037)=606060604643

B OUTPUT(00038)=214431742663

B OUTPUT(00039)=346060606060
B OUTPUT(00040)=602421436374
B OUTPUT(00041)=266361622523
B OUTPUT(00042)=545402346060

42

LINEO = 00002
LOCOUT = 00042
CALL UJECT
CALL SPACE (000000)

06001 CONTINUE
06002 FORMAT(1X,1P,7(E15.7,2X))
06003 WRITEOUTPUTTAPE1OUTPE,06002
1,TIME,VFS,ALT,TAVE,QDOCS,CD,DVFS
06004 FORMAT(1X,1P,7(E15.7,2X))
06005 WRITEOUTPUTTAPE1OUTPE,06004
1,TW1R,TW2R,OKA1,OKA2,TCOE3,OLAM1,DALT
06006 GO TO 06999
01700 CONTINUE
OKOUNT=OKOUNT+1.
GO TO 01701
END

C PHASE 2 (MAIN BODY OF PROGRAM)

9999 FORMAT(6G)

MICE0695

C...

UNITRAC GENERATED PROGRAM

MICE0696

EQUIVALENCE(DVFS,ODEQ(00001)),(VFS,OEQ(00001))

EQUIVALENCE(DALT,ODEQ(00002)),(ALT,OEQ(00002))

EQUIVALENCE(DR,ODEQ(00003)),(R,OEQ(00003))

EQUIVALENCE(TIME ,XINDVR)

1202 CALL ARDC59(LOCAMT,NSIZE)

GOTO 1203

COMMON PFS,RHOFS,TRFS,VFS,RFIN,DELTI,TOLER,GAME,EPS,OMOLW,DELHV,SF

,SG,SJ,EX,RHOIS,SL,W,OKB,EPS1,CP,ZET1,ZET2,ZET3,ALP1,ALP2,BET1,GAM

1,GAM2,GAM3,GAM4,DUM1,RECOD,DTSDT,VCOET,SGAME,CDCOE,SCCOE,SDCOE,SB

1COE,OLANCO,SCOE,RCOE,SL18,ALP1F,ALP2F,BET1G,DEL10,PS,ERROR,QDOCS,C

1D,Hw,TSR,TEMSR,TWALT,HS,HR,OLANT,OLAMI,PS1,VCOE2,RSQD,SC,SD,DMT,HS

11,DHS1,DPS1,TS1,HSIN,PSIN,TSIN,DMI,DM2,DM3,DM4,TSFIN

COMMON TWR

DIMENSION GAM(4),ZET(3),ACO(4),BCO(3),A(4),P(4),TWA(4),

QDOC(3),HWA(3),SB(4),B(3),ST(3),CT(3),PSIG(3),SA(3)

DIMENSION PATCH (50)

01000 CONTINUE

B TITLES(00001)=606060606060

B TITLES(00002)=606060606060

B TITLES(00003)=606060606060

B TITLES(00004)=606060606060

B TITLES(00005)=606060606060

B TITLES(00006)=606060606060

B TITLES(00007)=606060512540

B TITLES(00008)=254563517060

B TITLES(00009)=226451456447

B TITLES(00010)=604626606244

B TITLES(00011)=214343602451

B TITLES(00012)=464743256362

B TITLES(00013)=404047302162

B TITLES(00014)=256002606060

B TITLES(00015)=606060606060

B TITLES(00016)=606060606060

B TITLES(00017)=606060606060

B TITLES(00018)=606060606060

B TITLES(00019)=606060606060

B TITLES(00020)=606060606060

01001 NICE= 00003

LINTB=00005

DLVFLG=1.0

01002 LINEST = 00001

LOCTLE = 00020

01003 GO TO 01004

18 CALL MICE

GO TO 101

01100 GO TO 01101

2000 READ INPUT TAPE INTAPE,9999,VFS,ALT,R,RFIN,STEN1

IF (STEN1 - 1.E36) 2001,189,2001

02001 READ INPUT TAPE INTAPE,9999,

1,TIME,DELTI,TOLER,GAME

IF (GAME - 1.E36) 2002,189,2002

02002 READ INPUT TAPE INTAPE,9999,

1,OMOLW,DELHV,SF,SG,SJ,EX

IF (EX-1.E36) 02003,189,02003

02003 READ INPUT TAPE INTAPE,9999,

1,RHOIS,SL,W,OKB,EPS1,CP

IF (CP-1.E36) 02004,189,02004


```

02004 READINPUTTAPEINTAPE.9999.
      1,ZET1,ZET2,ZET3,ALP1,ALP2,BET1
      IF(BET1-1.E36)02005,189,02005
02005 READINPUTTAPEINTAPE.9999.
      1,GAM1,GAM2,GAM3,GAM4
      IF(GAM4-1.E36)02006,189,02006
02006 GO TO 2999
01200 CONTINUE
      GAM(1) = GAM1
      GAM(2) = GAM2
      GAM(3) = GAM3
      GAM(4) = GAM4
      ZET(1) = ZET1
      ZET(2) = ZET2
      ZET(3) = ZET3
      ACO(1) = 1.465
      ACO(2) = 1.680
      ACO(3) = 3.140
      ACO(4) = 6.280
      BCO(1) = 1.0 - SF
      BCO(2) = 1.0 - SG
      BCO(3) = 1.0 - SJ
      STEN = STEN1 / (454.6 * 32.2)
      VCOE1=.375/RHOIS *32.2
      SGAME=SINF(GAME/57.29578)
      SCCOE = .2412 * 32.2 * 3.1415927 * CP / (DELHV * SL)
      SDCOE = 4.0 * 3.1415927 * OKB / (3.0 * DELHV)
      SBCOE=4.75986E-13*EPS1/DELHV
      SCOE=.68*(29.0/OMOLW)**.26
      RCOE=1.0/(4.0*3.1415927*RHOIS)
      SL18=SL*.18
      ALP1F=ALP1*SF
      ALP2F=ALP2*SF
      BET1G=BET1*SG
      GO TO 01201
01300 TYPE = TOLER
      GO TO 01301
01400 COMPT = DELT1
      GO TO 01401
03000 CALL UJECT
      CALL ATMDAT (ALT,PFS,RHOF,VSFS,TRFS)
      RBO = 7.6 * STEN / (RHOF * VFS **.2)
      IF (R - RBO) 1420,1420,1421
1421 R = RBO
1420 CONTINUE
03001 FORMAT(1X,1P, 8H VFS =E15.7, 9H ALT =E15.7, 9H R =E15.7
      1, 9H RFIN =E15.7, 9H STEN1 =E15.7)
03002 WRITE OUTPUT TAPE 1OUTPE,3001, VFS,ALT,RTRFIN,STEN1
03003 FORMAT(1X,1P, 8H TIME =E15.7, 9H DELT1 =E15.7, 9H TOLER =E15.7
      1, 9H GAME =E15.7)
03004 WRITEOUTPUTTAPE1OUTPE,03003
      1, TIME,DELT1,TOLER,GAME
03005 FORMAT(1X,1P, 8H MOLW =E15.7, 9H DELHV =E15.7, 9H SF =E15.7
      1, 9H SG =E15.7, 9H SJ =E15.7)
03006 WRITEOUTPUTTAPE1OUTPE,03005
      1,OMOLW,DELHV,SF,SG,SJ
03007 FORMAT(1X,1P, 8H EX =E15.7)
03008 WRITEOUTPUTTAPE1OUTPE,03007
      1,EX
03009 FORMAT(1X,1P, 8H RHOIS =E15.7, 9H SL =E15.7, 9H W =E15.7

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1, 9H KB =E15.7, 9H EPS1 =E15.7 )
03010 WRITEOUTPUTTAPE(OUTPE,03009
1,RHO15,SL,W,OKB,EP51
03011 FORMAT(1X,1P, 8H CP =E15.7 )
03012 WRITEOUTPUTTAPE(OUTPE,03011
1,CP
03013 FORMAT(1X,1P, 8H ZET1 =E15.7, 9H ZET2 =E15.7, 9H ZET3 =E15.7
1, 9H ALP1 =E15.7, 9H ALP2 =E15.7 )
03014 WRITEOUTPUTTAPE(OUTPE,03013
1,ZET1,ZET2,ZET3,ALP1,ALP2
03015 FORMAT(1X,1P, 8H BET1 =E15.7 )
03016 WRITEOUTPUTTAPE(OUTPE,03015
1,BET1
03017 FORMAT(1X,1P, 6 GAM1 =E15.7, 9H GAM2 =E15.7, 9H GAM3 =E15.7
1, 9H GAM4 =E15.7 )
03018 WRITEOUTPUTTAPE(OUTPE,03017
1,GAM1,GAM2,GAM3,GAM4
03019 GO TO 03999
01500 CONTINUE
CALL ATMDAT(ALT,PFS,RHOF5,V5FS,TRFS)
PS1=RHOF5*V5FS**2
RSOD=R**2
DO 1535 I=1,3
A(I) = ACO(I) * RSOD
P(I) = GAM(I) * PS1
1535 CONTINUE
A(4) = ACO(4) * RSOD
P(4) = GAM(4) * PFS
C GET ODOCS, CD, TEMSR, AND HS
PS = PS1
ERROR = 0.0
CALL CODOT2
IF (ERROR) 1536,1536,207
1536 TWALL = TEMSR
HR = .9 * HS
C GET GAS STAG. TEMP. (TS1)
HS1 = HS
PS = PS1
ERROR = 1.0
CALL CODOT2
IF (ERROR) 1520,1520,207
1520 TS1 = TSR
TSFIN = TS1 * EX
TWA(4) = SL18/(LOG10(P(4)/2116.0) - W)
SB(4) = A(4) * SBCOE * TWA(4) ** 4
DO 1548 I=1,3
ODOC(I) = ZET(I) * ODOCS
PS = P(I)
ERROR = -1.0
CALL CODOT2
IF (ERROR) 1539,1539,207
1539 TWA(I) = TWR
HWA(I) = HW
SB(I) = A(I) * SBCOE * TWA(I) ** 4
AQDOC = A(I) * ODOC(I)
B(I) = AQDOC * BCO(I) / DELHV
S(I) = SCOE * (HR - HWA(I)) / AQDOC
IF (I - 2) 1541,1542,1543
1541 C(I) = SB(I) * BCO(I)
GO TO 1544

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1542 C(2) = SB(2) * BCO(2) - ALP1F * (SA(1) - SB(1))
      GO TO 1544
1543 C(3) = SB(3) * BCO(3) - ALP2F * (SA(1) - SB(1)) - BET1G * (SA(2) -
      SB(2))
1544 PSIG(1) = (1.0 + S(1) * C(1)) / (1.0 + S(1) * B(1))
      IF (PSIG(1)) 1545,1546,1546
1545 PSIG(1) = 0.0
1546 SA(1) = PSIG(1) * AQDOC / DELHV
1548 CONTINUE
      SC = SCCOE * RSOD * (TWA(1) ** 2) * CD * RHOF5 * VFS
      SD = SDCOE * RSOD * R
      DMT = - SA(1) - SA(2) - SA(3) + SB(1) + SB(2) + SB(3) + SB(4) +
      SC - SD
      GO TO 01501
01600 CONTINUE
      DVFS = - VCOE1 * CD * RHOF5 * VFS ** 2 / R
      DALT = - SGAME * VFS
      DR = RCOE * DMT / (R ** 2)
      GO TO 01601
04000 IF (TSFIN - (TWALL)) 04001,04007,04007
04001 FINCK2 = 1.0
04007 IF (R - (RFIN)) 04008,04014,04014
04008 FINCK2 = 1.0
04014 GO TO 04999
05000 KBRCH = 1
05001 GO TO 05999
C DELTA VALUES IF R .GT. RBO, CHANGE AND RESTART INTEGRATION IN
C1 UNITRAC SKELETON.
1700 IF (R - RBO) 1701,1701,1705
1705 R = .63157895 * R
      GO TO 3999
01800 CONTINUE
      RBO = 7.6 * STEN / (RHOF5 * VFS ** 2)
      DM1 = (SB(1) - SA(1)) * BCO(1)
      DM2 = (SB(2) - SA(2)) * BCO(2) - ALP1F * (SA(1) - SB(1))
      DM3 = (SB(3) - SA(3)) * BCO(3) - ALP2F * (SA(1) - SB(1)) - BET1G
      * (SA(2) - SB(2))
      DM4 = DMT - DM1 - DM2 - DM3
      GO TO 01801
06000 CONTINUE
B OUTPUT(00001)=606060606060
B OUTPUT(00002)=633144256060
B OUTPUT(00003)=606060606060
B OUTPUT(00004)=606065254346
B OUTPUT(00005)=233163707465
B OUTPUT(00006)=256234606060
B OUTPUT(00007)=606021436331
B OUTPUT(00008)=636424257421
B OUTPUT(00009)=436334606060
B OUTPUT(00010)=606060605121
B OUTPUT(00011)=243164627451
B OUTPUT(00012)=346060606060
B OUTPUT(00013)=606060606024
B OUTPUT(00014)=652662246360
B OUTPUT(00015)=606060606060
B OUTPUT(00016)=606060606060
B OUTPUT(00017)=245124636060
B OUTPUT(00018)=606060606060
B OUTPUT(00019)=606060606060
B OUTPUT(00020)=246352246360

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B OUTPUT(00081)=606060606060
 B OUTPUT(00082)=606060606244
 B OUTPUT(00083)=214343602204
 B OUTPUT(00084)=606060606060
 B OUTPUT(00085)=606060606060
 B OUTPUT(00086)=476231600160
 B OUTPUT(00087)=606060606060
 B OUTPUT(00088)=606060606060
 B OUTPUT(00089)=476231600260
 B OUTPUT(00090)=606060606060
 B OUTPUT(00091)=606060606060
 B OUTPUT(00092)=476231600360
 B OUTPUT(00093)=606060606060
 B OUTPUT(00094)=606060606063
 B OUTPUT(00095)=662143436001
 B OUTPUT(00096)=606060606060
 B OUTPUT(00097)=606060606063
 B OUTPUT(00098)=662143436002
 B OUTPUT(00099)=606060606060
 B OUTPUT(00100)=606060606063
 B OUTPUT(00101)=662143436003
 B OUTPUT(00102)=606060606060
 B OUTPUT(00103)=606060606063
 B OUTPUT(00104)=662143436004
 B OUTPUT(00105)=606060606060
 LINESO = 00005
 LOCOUT = 00105
 CALL UJECT
 CALL SPACE (000000)
 06001 CONTINUE
 6002 FORMAT (1X,1P,6(E15.7,2X))
 06003 WRITEOUTPUTTAPE(OUTPE,06002
 1,TIME,VFS,ALT,R,DVFS,DR
 6004 FORMAT (1X,1P,6(E15.7,2X))
 06005 WRITEOUTPUTTAPE(OUTPE,06004
 1,PSI,HSI,TSI,ODOCS,CD,OLAM)
 06006 FORMAT(1X,1P,7(E15.7,2X))
 06007 WRITEOUTPUTTAPE(OUTPE,06006
 1,DMT,DM1,DM2,DM3,DM4,SC,SD
 06008 FORMAT(1X,1P,7(E15.7,2X))
 06009 WRITEOUTPUTTAPE(OUTPE,06008
 1,SA(1),SA(2),SA(3),SB(1),SB(2),SB(3),SB(4)
 06010 FORMAT(1X,1P,7(E15.7,2X))
 06011 WRITEOUTPUTTAPE(OUTPE,06010
 1,PSIG(1),PSIG(2),PSIG(3),TWA(1),TWA(2),TWA(3),TWA(4)
 06012 GO TO 06999
 END

C PHASE 3 (MAIN BODY OF PROGRAM)

9999 FORMAT(6G)

MICE0695

C....

UNITRAC GENERATED PROGRAM

MICE0696

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8/2

EQUIVALENCE(DVFS,ODEQ(00001)),(VFS,OEQ(00001))
EQUIVALENCE(DALT,ODEQ(00002)),(ALT,OEQ(00002))
EQUIVALENCE(OTAVE,ODEQ(00003)),(TAVE,OEQ(00003))
EQUIVALENCE(DR,ODEQ(00004)),(R,OEQ(00004))
EQUIVALENCE(TIME ,XINDVR)

1202 CALL ARDC59(LOCAMT,NSIZE)

GOTO 1203

COMMON PFS,RHOF,TRFS,VFS,RFIN,DRFIN,DELT,TOLER,GAME,OMOLW,DELHV,
1,RHOIS,SL,W,OKB,EP1,CP,GAM1,GAM2,ZET1,ZET2,DELTE,OMWT,OMW174,P1,VC
1OE,SGAME,TACOE,RCOE,EP1B,OKBCOE,SL1B,CD,DMT,QDOR1,QDOR2,QDOR3,PS1
1Q1,PS1Q2,PST,P1,P2,A1,A2,A3,PS,HS,ERROR,QDOCS,TSR,HW,HST,TST,TWR,T
1EMSR,TW1,TW2,TW3,PV1,PV2,HW1,HW2,PS11C,PS11,PS12C,PS12,QDOT1,QDOT2
1,HR,DMT1,DMT2

DIMENSION PATCH(50)

01000 CONTINUE

B TITLES(00001)=606060606060
B TITLES(00002)=606060606060
B TITLES(00003)=606060606060
B TITLES(00004)=606060606060
B TITLES(00005)=606060606060
B TITLES(00006)=606060606060
B TITLES(00007)=606060516540
B TITLES(00008)=254563517060
B TITLES(00009)=226451456447
B TITLES(00010)=604626606244
B TITLES(00011)=214343602451
B TITLES(00012)=464743256362
B TITLES(00013)=404047302162
B TITLES(00014)=256003606060
B TITLES(00015)=606060606060
B TITLES(00016)=606060606060
B TITLES(00017)=606060606060
B TITLES(00018)=606060606060
B TITLES(00019)=606060606060
B TITLES(00020)=606060606060

01001 NICE= 00004

LINTB = 5

DLVFLG=0.0

01002 LINEST = 00001

LOCTLE = 00020

01003 GO TO 01004

18 CALL UNICE

GO TO 101

01100 GO TO 01101

02000 READ INPUT TAPE INTAPE,9999,

1,VFS,ALT,R,TAVE,RFIN,DRFIN

IF(DRFIN-1.E36) 02001,189,02001

02001 READ INPUT TAPE INTAPE,9999,

T,TIME,DELT,TOLER,GAME,OMOLW,DELHV

IF(DELHV-1.E36) 02002,189,02002

02002 READ INPUT TAPE INTAPE,9999,

1,RHOIS,SL,W,OKB,EP1,CP

IF(CP-1.E36) 02003,189,02003

02003 READ INPUT TAPE INTAPE,9999,

1,GAM1,GAM2,ZET1,ZET2,DTEM1,DTEM3

IF(DTEM3-1.E36) 2004,189,2004

2004 READ INPUT TAPE INTAPE,9999,TRK,GAM3

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IF (GAM3 - 1.E36) 2005,189,2005
2005 GO TO 2999
01200 CONTINUE
PI=3.1415927
OMT3C = PI / 8.0 * THK / DELHV
OMW1=29.0/OMOLW
OMW174=(OMW1)**.74
SL18=1.8*SL
EPS1B=4.75986E-13*EPS1
VCOE=.375*32.2/RHOIS
SGAME=SINF(GAME/37.29578)
TACOE=.75/(CP*RHOIS*PI)
RCOE=1.0/(4.0*PI*RHOIS)
OKBCOE=4.0*PI*RHOIS*OKB/3.0
GO TO 01201
01300 TYPICE = TOLER
GO TO 01301
01400 COMPTI = DELTI
GO TO 01401
03000 CALL UJECT
03001 FORMAT(1X,1P, 8H VFS =E15.7, 9H ALT =E15.7, 9H R =E15.7
1, 9H TAVE =E15.7, 9H RFIN =E15.7 )
03002 WRITEOUTPUTTAPE(OUTPE,03001
1,VFS,ALT,R,TAVE,RFIN
03003 FORMAT(1X,1P, 8H DRFIN =E15.7 )
03004 WRITEOUTPUTTAPE(OUTPE,03003
1,DRFIN
03005 FORMAT(1X,1P, 8H TIME =E15.7, 9H DELTI =E15.7, 9H TOLER =E15.7
1, 9H GAME =E15.7, 9H MOLW =E15.7 )
03006 WRITEOUTPUTTAPE(OUTPE,03005
1,TIME,DELT1,TOLER,GAME,OMOLW
03007 FORMAT(1X,1P, 8H DELHV =E15.7 )
03008 WRITEOUTPUTTAPE(OUTPE,03007
1,DELHV
03009 FORMAT(1X,1P, 8H RHOIS =E15.7, 9H SL =E15.7, 9H W =E15.7
1, 9H KB =E15.7, 9H EPS1 =E15.7 )
03010 WRITEOUTPUTTAPE(OUTPE,03009
1,RHOIS,SL,W,OKB,EPS1
03011 FORMAT(1X,1P, 8H CP =E15.7 )
03012 WRITEOUTPUTTAPE(OUTPE,03011
1,CP
03013 FORMAT(1X,1P, 8H GAM1 =E15.7, 9H GAM2 =E15.7, 9H ZET1 =E15.7
1, 9H ZET2 =E15.7)
03014 WRITEOUTPUTTAPE(OUTPE,03013
1,GAM1,GAM2,ZET1,ZET2
WRITE OUTPUT TAPE (OUTPE,3016,DTEM1,DTEM3
3016 FORMAT (1X,1P,8H DTEM1 =E15.7,9H DTEM3 =E15.7)
3015 WRITE OUTPUT TAPE (OUTPE,3017,THK,GAM3
3017 FORMAT (1X,1P,8H THK =E15.7,9H GAM3 =E15.7)
GO TO 3999
01500 CONTINUE
CALLATMOAT(ALT,PFS,RHOFS,VFS,TRFS)
PST=RHOFS*VFS**2
TW1 = TAVE + DTEM1
TW2=TAVE
P3 = GAM3 * PFS
TW3 = SL18 / (LOG10(P3 / 2116.) - W)
TW3OP = TAVE - DTEM3
IF (TW3OP - TW3) 1540,1540,1541
1540 TW3 = TW3OP

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50

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DMT3 = 0.0
GO TO 1542
1541 DMT3 = - DMT3C * R * (TAVE - TW3)
1542 CONTINUE
C GET QDOCS, CD, AND HS
PS = PST
TEMSR = TW1
ERROR = 10.0
CALL CQDOT3
IF (ERROR) 1531,1531,207
1531 HST = HS
HR=.9*HST
C GET GAS STAG. TEMP. (TSR)
ERROR = 11.0
CALL CQDOT3
IF (ERROR) 1532,1532,207
1532 TST = TSR
QDOT1=ZET1*QDOCS
QDOT2=ZET2*QDOCS
P1=GAM1*PST
P2=GAM2*PST
A1=P1*HR**2
A2=A1
A3=2.0*A1
PV1=2116.*10.0**((SL18/TW1+W)
PV2=2116.*10.0**((SL18/TW2+W)
C GET HW
PS = P1
TEMSR = TW1
ERROR = 9.0
CALL CQDOT3
IF (ERROR) 1534,1534,207
1534 HW1 = HW
PS = P2
TEMSR = TW2
ERROR = 9.0
CALL CQDOT3
IF (ERROR) 1535,1535,207
1535 HW2 = HW
QDOR1=A1*EPS1B*TW1**4
QDOR2=A2*EPS1B*TW2**4
QDOR3=A3*EPS1B*TW3**4
PSI1C=OMW174*(P1-PV1)
PSI1=PSI1C/(PSI1C+.68*PV1)
PSI2C=OMW174*(P2-PV2)
PSI2=PSI2C/(PSI2C+.68*PV2)
IF (PSI1) 1544,1544,1545
1544 PSI1 = 0.0
PSI01 = 0.0
1550 DMT1 = 0.0
GO TO 1546
1545 PSI01 = PSI1 * QDOT1 * AT
DMT1 = (QDOR1 - PSI01) / ((HR - HW1) * OMW1 * (P1 / PV1 - 1.0))
IF (DMT1) 1546,1546,1550
1546 IF (PSI2) 1547,1547,1548
1547 PSI2 = 0.0
PSI02 = 0.0
1551 DMT2 = 0.0
GO TO 1549
1548 PSI02 = PSI2 * QDOT2 * A2

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DMT2 = (QDOR2 - PS1Q2) / ((HR - HW2) * OMW1 * (P2 / PV2 - 1.0))
IF (DMT2) 1549,1549,1551
1549 DMT = DMT1 + DMT2 + DMT3
GO TO 01501
01600 CONTINUE
DVFS=-VCOE*CD*RHOF5*VFS**2/R
DALT=-SGAME*VFS
DTAVE = TACOE * ( DELHV * DMT - QDOR1 - QDOR2 - QDOR3 + PS1Q1 +
1 PS1Q2 + OKBCOE * R ** 3) / R ** 3
DR=RCOE*DMT/R**2
GO TO 01601
04000 IF (R-(RFIN)) 04001,04007,04007
04001 FINCK2=1.0
4007 IF (DR - DRFIN) 4014,4014,4008
04008 FINCK2=1.0
04014 GO TO 04999
05000 KBRCH= 1
05001 GO TO 05999
01700 CONTINUE
GO TO 01701
01800 CONTINUE
GO TO 01801
06000 CONTINUE
B OUTPUT(00001)=606060606060
B OUTPUT(00002)=633144256060
B OUTPUT(00003)=606060606060
B OUTPUT(00004)=606060606060
B OUTPUT(00005)=606526626060
B OUTPUT(00006)=606060606060
B OUTPUT(00007)=606060606060
B OUTPUT(00008)=602143636060
B OUTPUT(00009)=606060606060
B OUTPUT(00010)=606060606060
B OUTPUT(00011)=606051606060
B OUTPUT(00012)=606060606060
B OUTPUT(00013)=606060606060
B OUTPUT(00014)=632165256060
B OUTPUT(00015)=606060606060
B OUTPUT(00016)=606060606024
B OUTPUT(00017)=652662246360
B OUTPUT(00018)=606060606060
B OUTPUT(00019)=606060606060
B OUTPUT(00020)=245124636060
B OUTPUT(00021)=606060606060
B OUTPUT(00022)=606060606024
B OUTPUT(00023)=214363246360
B OUTPUT(00024)=606060606060
B OUTPUT(00025)=606060606024
B OUTPUT(00026)=632165252463
B OUTPUT(00027)=606060606060
B OUTPUT(00028)=606060606060
B OUTPUT(00029)=476263212760
B OUTPUT(00030)=606060606060
B OUTPUT(00031)=606060606060
B OUTPUT(00032)=306263212760
B OUTPUT(00033)=606060606060
B OUTPUT(00034)=606060606060
B OUTPUT(00035)=636263212760
B OUTPUT(00036)=606060606060
B OUTPUT(00037)=606060606060

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B	OUTPUT(00038)=602324606060
B	OUTPUT(00039)=606060606060
B	OUTPUT(00040)=606060606050
B	OUTPUT(00041)=244663236260
B	OUTPUT(00042)=606060606060
B	OUTPUT(00043)=606060606060
B	OUTPUT(00044)=602444636060
B	OUTPUT(00045)=606060606060
B	OUTPUT(00046)=606060606060
B	OUTPUT(00047)=244463016060
B	OUTPUT(00048)=606060606060
B	OUTPUT(00049)=606060606060
B	OUTPUT(00050)=244463026060
B	OUTPUT(00051)=606060606060
B	OUTPUT(00052)=606060606060
B	OUTPUT(00053)=476231600160
B	OUTPUT(00054)=606060606060
B	OUTPUT(00055)=606060606060
B	OUTPUT(00056)=476231600260
B	OUTPUT(00057)=606060606060
B	OUTPUT(00058)=606060606060
B	OUTPUT(00059)=476560016060
B	OUTPUT(00060)=606060606060
B	OUTPUT(00061)=606060606060
B	OUTPUT(00062)=476560026060
B	OUTPUT(00063)=606060606060
B	OUTPUT(00064)=606060606050
B	OUTPUT(00065)=244663510160
B	OUTPUT(00066)=606060606060
B	OUTPUT(00067)=606060606050
B	OUTPUT(00068)=244663510260
B	OUTPUT(00069)=606060606060
B	OUTPUT(00070)=606060606050
B	OUTPUT(00071)=244663510360
B	OUTPUT(00072)=606060606060
B	OUTPUT(00073)=606060606060
B	OUTPUT(00074)=636660016060
B	OUTPUT(00075)=606060606060
B	OUTPUT(00076)=606060606060
B	OUTPUT(00077)=636660026060
B	OUTPUT(00078)=606060606060
B	OUTPUT(00079)=606060606060
B	OUTPUT(00080)=636660036060
B	OUTPUT(00081)=606060606060
B	OUTPUT(00082)=606060606060
B	OUTPUT(00083)=606060606060
B	OUTPUT(00084)=606060606060
B	OUTPUT(85)=606060606060
B	OUTPUT(86)=244463036060
B	OUTPUT(87)=606060606060
B	OUTPUT(88)=606060606047
B	OUTPUT(89)=623150016060
B	OUTPUT(90)=606060606060
B	OUTPUT(91)=606060606047
B	OUTPUT(92)=623150026060
B	OUTPUT(93)=606060606060
B	OUTPUT(94)=606060606060
B	OUTPUT(95)=306601606060
B	OUTPUT(96)=606060606060
B	OUTPUT(97)=606060606060