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NON-EQUILIBRIUM SHOCK-LAYER COMPUTATION FOR SATURN PROBES

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DR. KUO: This study actually is a joint effort by Dr. Lewis Leibowitz and myself.

Figure 5-12 gives the objective and the approach of the shock layer analysis. The objective is to develop physically sound methods for computing the flow field, energy fluxes and heat shield requirements. The justification of the approach is, as we just heard Walt comment this morning about the technical challenges, that total simulation is not feasible; at least as of now.

So it calls for an analytical approach, first carefully examining the governing mechanisms and then seeing how far we could go by uncoupling them, if possible. Then we would study those governing mechanisms separately. Finally, by putting them together and, by synthesizing experimental and theoretical inputs we would provide necessary information for the heat shield computation.

Figure 5-13 gives the approach for the shock layer analysis. First we are going to make a statement that radiation can be uncoupled in the shock layer, an effect which will be ascertained in the subsequent slide; which means then, that the aerothermochemistry of the inviscid shock layer can be uncoupled from radiation as if it is radiatively adiabatic or inert. So, by solving the aerothermochemistry of the inviscid shock layer, we will obtain the constituent densities, N_J, the heavy particle temperature, T_I, and the electron temperature, T_E. With this, it provides sufficient information for the computation of the radiation of the shock layer as if it is a static layer of radiating medium. That is what is meant by the uncoupling.

So, eventually, from both of these then, we will obtain the boundary conditions at the boundary layer. I want to point out here, that the uncoupling, first of all, greatly simplifies the analysis of the problem, and secondly, it allows the shock layer radiation characteristics to be studied in full spectral detail.

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- OBJECTIVE

  TO DEVELOP PHYSICALLY SOUND METHOD(S) FOR COMPUTING THE FLOW FIELD, ENERGY FLUXES AND HEAT SHIELD REQUIREMENT.

- JUSTIFICATION

  TOTAL SIMULATION NOT FEASIBLE. CALLS FOR AN ANALYTICAL APPROACH BY PUTTING TOGETHER IMPORTANT MECHANISMS, AND BY SYNTHESIZING EXPERIMENTAL (E.G. REACTION RATES) AND THEORETICAL INPUTS.

Figure 5-12

FLOW CHART OF SHOCK LAYER ANALYSIS

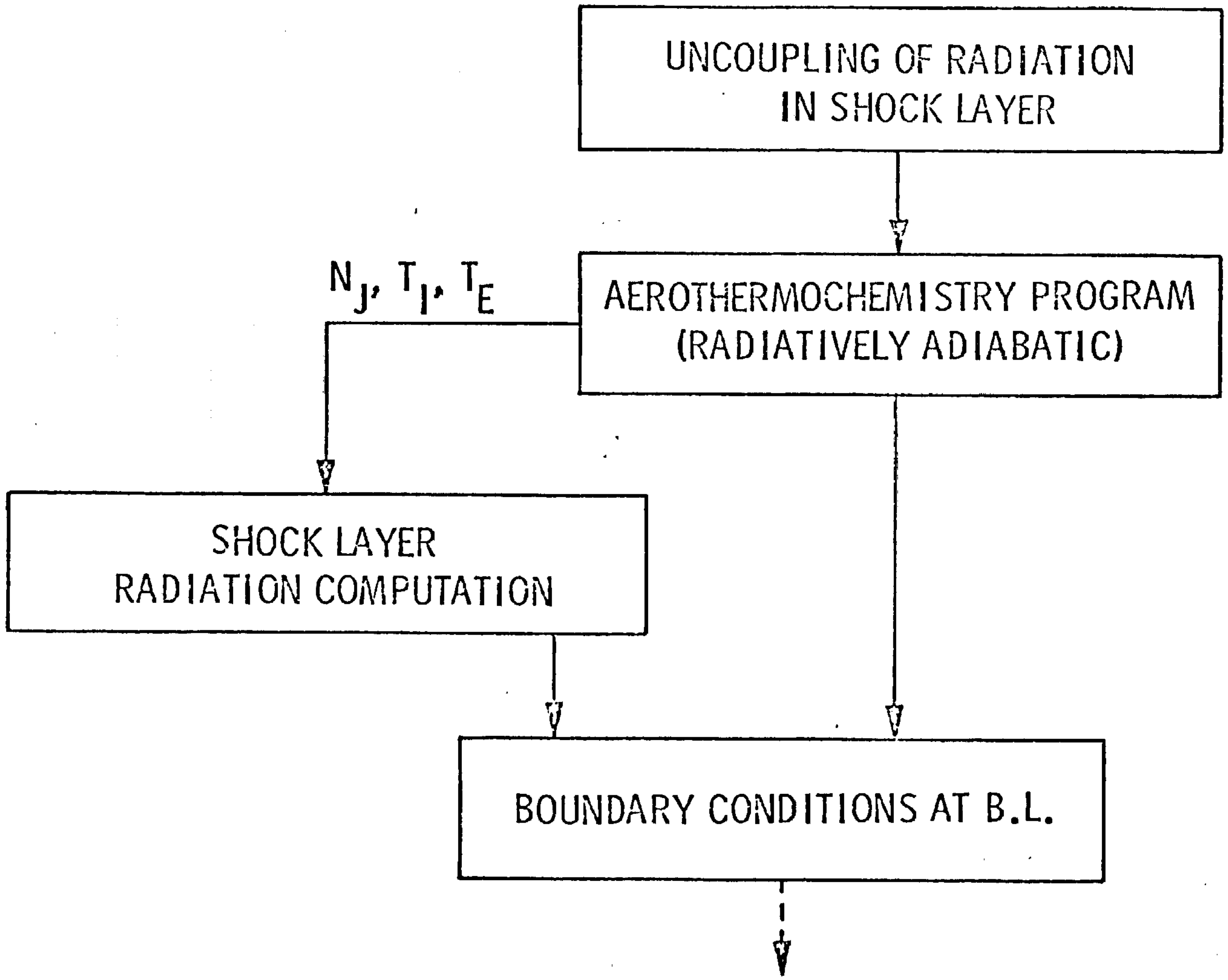

Figure 5-13

The graph of Figure 5-14 is taken from Angus McRonald's trajectory computations which shows that radiation can be uncoupled from the aerothermochemistry, at least for the Saturn probes. The ordinate here represents the ratio of two fluxes. F_{eq}^{SL} is the radiative flux from the inviscid shock layer evaluated under equilibrium conditions towards the edge of the boundary layer. The denominator, $\frac{\rho U^3}{2}$, represents the enthalpy flux as convected by the mass flow.

Now this dimensionless quantity appears as a multiplier in the non-dimensionalized shock layer energy equation. So that, physically, what it shows is the relative importance of the radiative flux term versus the convection term on the left hand side of the energy equation. If this non-dimensional quantity is small, the radiative flux can be ignored in the first order of consideration, which is the case of practical importance.

The abscissa of this represents the time of flight in seconds so the curves actually show the time history of this non-dimensional parameter. We know that for cases of Saturn probes, the cases of interest, the entry angle would be bounded above by forty degrees or fifty degrees. This peaks around two percent, actually slightly less than two percent in the case of a forty-degree entry angle with a probe of 0.7 meters. We can say for sure prior to actual computation, that for the fifty degree angle case, this would be somewhere around 2.5%.

So this number, actually, is small and radiation can be uncoupled from the aerothermochemistry in the first consideration, at least for the Saturn probes. Furthermore, because this is based on the evaluation of tangent slab equilibrium conditions, and we know that under non-equilibrium conditions the radiative flux would be still less, this actually gives an overestimate of what the parameter actually should be.

THE UNCOUPLING OF RADIATION FROM AEROTHERMOCHEMISTRY FOR SATURN PROBES

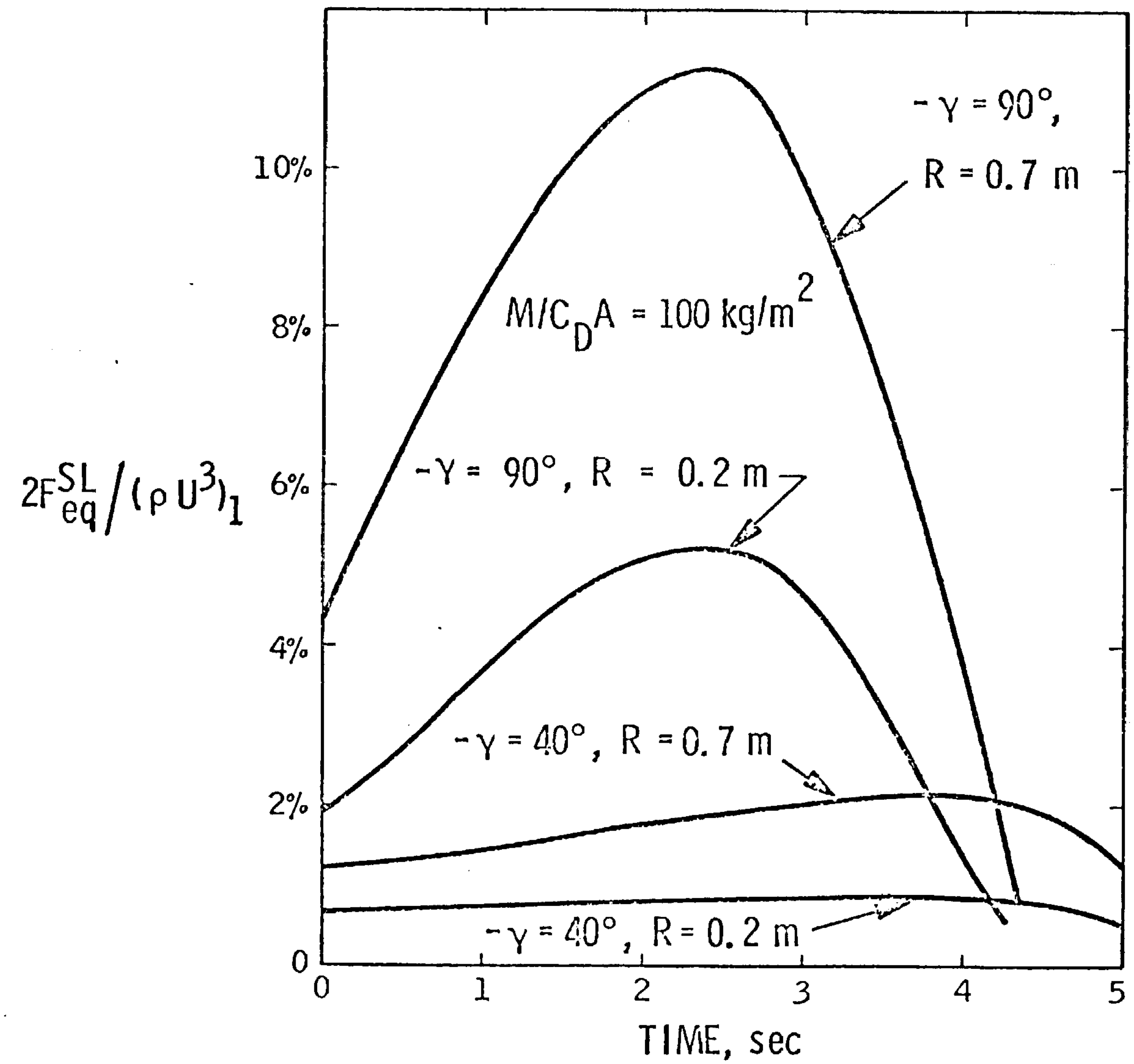

Figure 5-14

As shown in Figure 5-15, with the radiation uncoupled from the aerothermochemistry, we can tackle the inviscid shock layer separately without consideration of radiation. On the right, which gives the geometry for the shock layer analysis, a simple analysis actually, R_b is the body radius, Δ_0 the stand-off distance, δ the displacement of the shock center from that of the body center, and R_{os} the radius of the shock front at the axis.

On the right are the formulas actually used in the computation to get the stand-off distance, its relation versus the density-compression ratio. The quantity ε is the compression ratio which is the ratio of the free stream density to the mean density in the shock layer. These formulas are good over a wide range of ε.

The approach to tackle this problem is, first of all to define a quantity, Ω, which is in essence, the characteristic fluid mechanical time over the characteristic ionization relaxation time which Lewis just talked about a moment ago. This is used to obtain the stand-off distance and to give the shock shape in a manner which Hornring described in his paper which was published in JFM in 1972.

The second point is that the pressure along the boundaries is prescribed because along the body surface we can assume that it follows the modified Newtonian model and along the shock front obeys the oblique shock relation. In between we use a certain interpolation formula so that the pressure field of the entire flow field is obtained.

Thirdly, we use a constant density model to obtain streamlines so that the streamline configuration is thus determined. Finally, we use the reaction rates as taken from Lewis Leibowitz'

AEROTHERMOCHEMISTRY PROGRAM

- APPROACH
  - $\Omega = \dfrac{R_b}{U_1 \tau_{ion}}$ USED TO OBTAIN Δ_0 AND SHOCK SHAPE
  - PRESSURE ALONG THE BOUNDARIES PRESCRIBED
  - CONSTANT DENSITY MODEL USED TO OBTAIN STREAMLINES AND VELOCITY
  - CHEMICAL KINETICS MARCHING FROM SHOCK FRONT

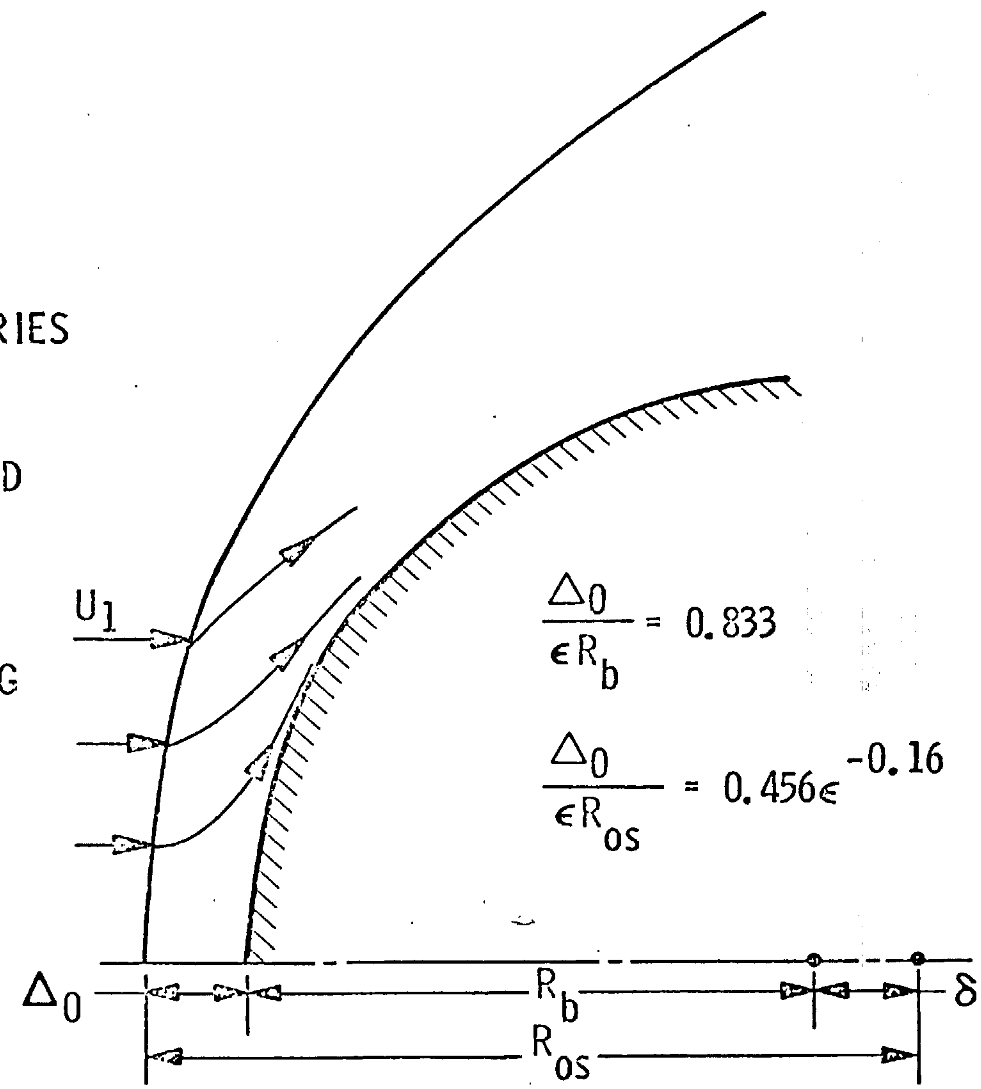

Figure 5-15

shock tube data to compute the chemical kinetics. First of all we march ahead from the shock front and then, step by step, march downstream until the solution is carried far enough. Then we shift to another streamline and, again, march ahead. So, first of all, it is station by station along a streamline and then streamline by streamline until the entire flow field is covered.

By this, then we obtain the chemistry as well as the aero-thermodynamics of the entire flow field.

Figure 5-16 presents the actual computation which we obtained some time ago for the parameters as shown for a Saturn probe, forty-degree entry angle case. The ballistic coefficient is 100 kg/m^2, the reaction rate parameter is given here - about seven - and the probe diameter is 0.7 meters. The probe is at the critical altitude where the heat flux is about at its peak.

Now, we note very briefly that there is a demarcation line between the non-equilibrium zone and the equilibrium zone that Lewis just talked about a moment ago. On the left of this line is the relaxation zone, and on the right of the line is the equilibrium zone. We can see that particularly in the stagnation region the majority of the shock layer gas is actually relaxing, so if we use the equilibrium approach, then, it would be far from the truth, at least in the stagnation region. Please note that for certain cases that the shock layer is not optically thick so this would result in a considerable reduction of radiative flux to the body, at least in this stagnation region.

The next figure, Figure 5-17, shows some later results that we just completed which give the shock layer electron concen-

EFFECT OF IONIZATION RELAXATION

RECENT COMPUTER RESULT SHOWS AT LEAST 60% OF THE STAGNATION REGION SHOCK LAYER IS RELAXING. HEAT SHIELD WEIGHT SIGNIFICANTLY REDUCED

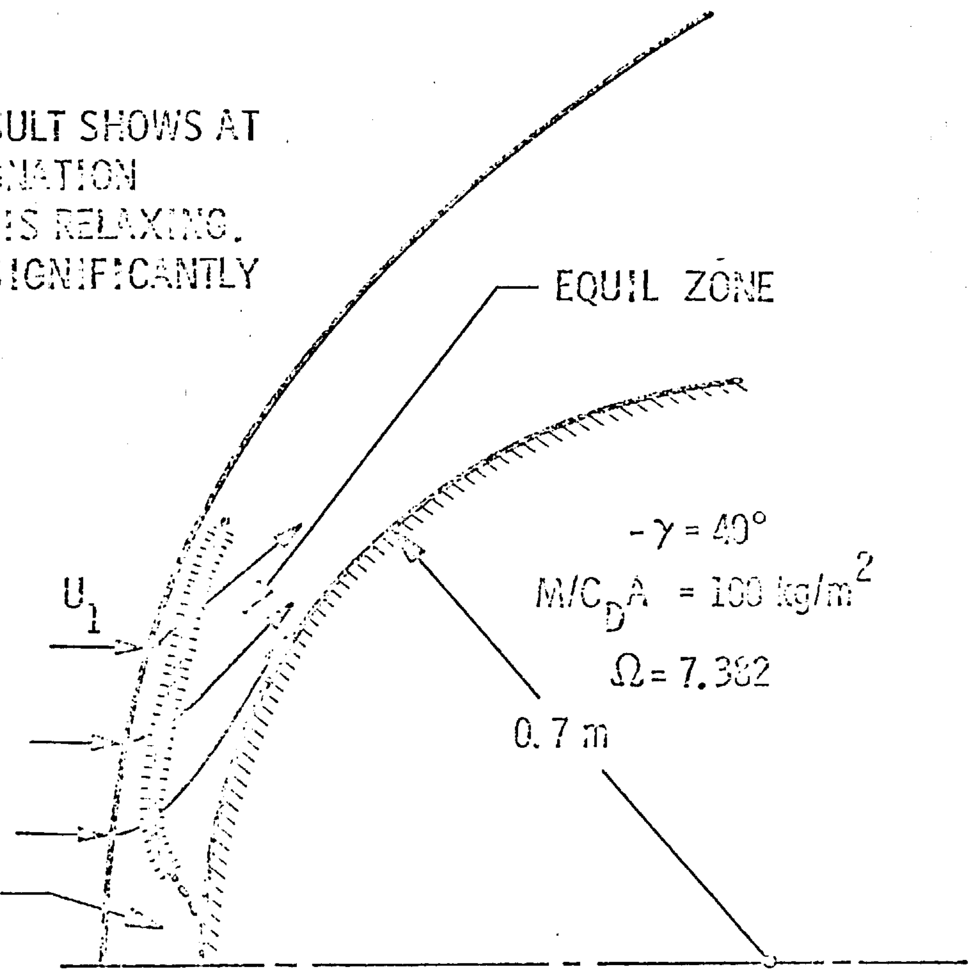

Figure 5-16

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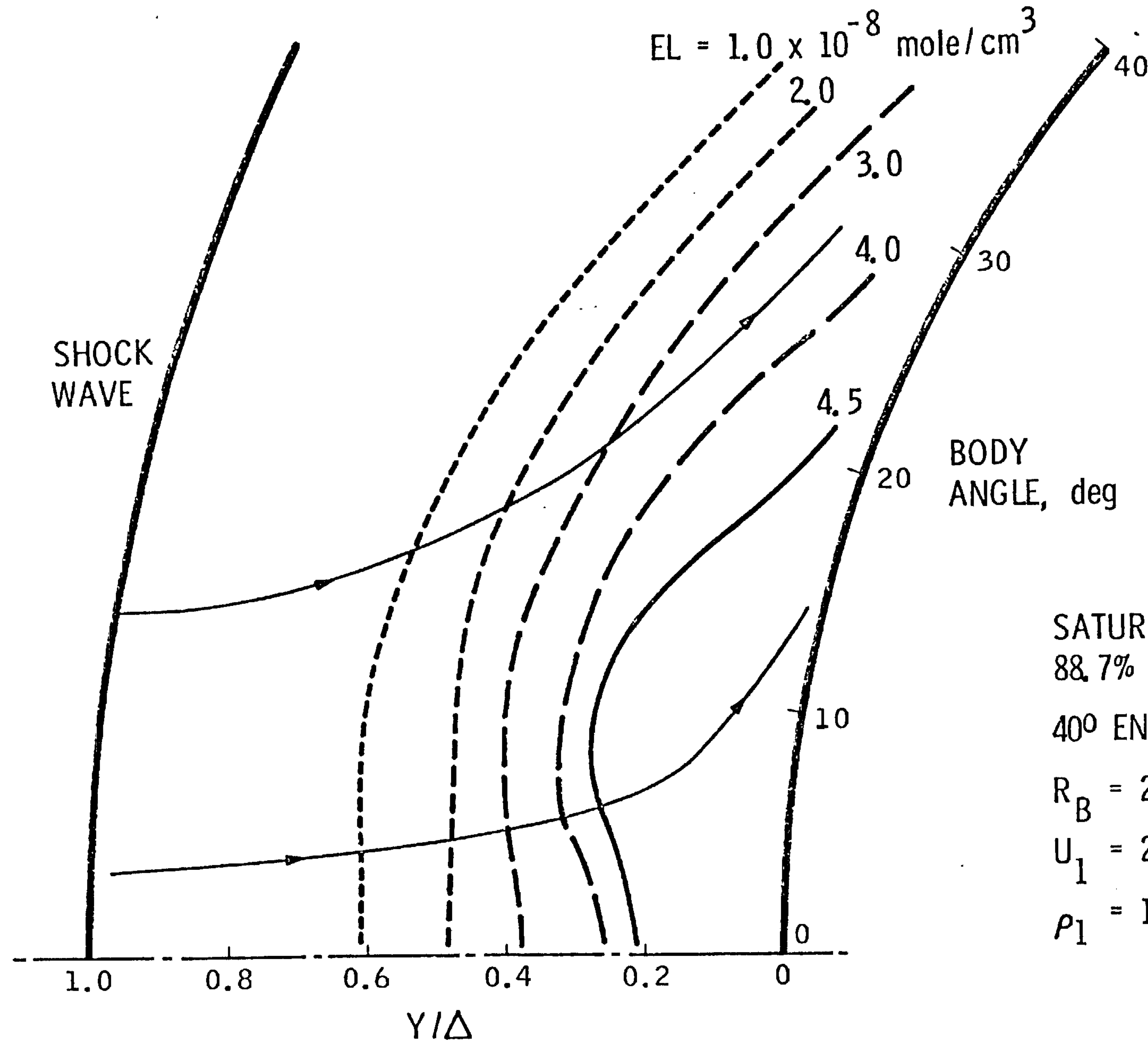
SHOCK LAYER ELECTRON CONCENTRATION



SATURN ENTRY
88.7% H_2 - 11.3% He
40° ENTRY ANGLE

R_B = 20 cm
U_1 = 29.9 km/sec
$\rho_1 = 1.06 \times 10^{-7}$ gm/cm^3

Figure 5-17

tration profile. The conditions are given on the right of the figure. We can see that electron densitites are plotted so that the first line is 10^{-8} grammoles per cm^3. In increasing order, the next line is 2×10^{-8} grammoles per cm^3; the next ones are three, four, and 4.5. Here the shock layer is enlarged out of proportion so that it will give more details of the profiles. Also, the shock layer thickness should increase as we go further down the streamline. Please note that the profiles are essentially parallel to the body. In other words, the gradient is, basically, normal to the body surface instead of along the streamlines.

Next, in Figure 5-18, we are going to bend the shock layer, pull this over so that the body line will be a straight line and then turn it 90°. That is a different representation. This one is a computation under identical conditions which gives the electron temperature within the shock layer. Again, the parameters are given on the right. The other parameters were already given in the previous figure. The body line is transformed into a straight line, and we see that because the shock layer thickness increases, the shock wave bends upwards as we go downstream. Now, regarding the electron temperature profile on which the radiative properties are dependent, we see 13,00°K, 12,000°K, 11,500°K and 11,000°K lines. Again, essentially, they are parallel to the body so the gradient is, basically, pointing towards the normal direction.

With these preliminary computations completed, we are going to talk about our longer-range studies (Figure 5-19). First of all we are going to compute in great detail the radiative flux to the boundary layer when radiative transport is important. This is being studied by Dr. Peter Poon. First of all, it is a non-gray gas and, secondly, he is going to use a tangent slab model. This is valid because the shock layer thickness is very small and, as we have just seen, the gradients of the profile are, basically, along the normal direction.

SHOCK LAYER ELECTRON TEMPERATURE

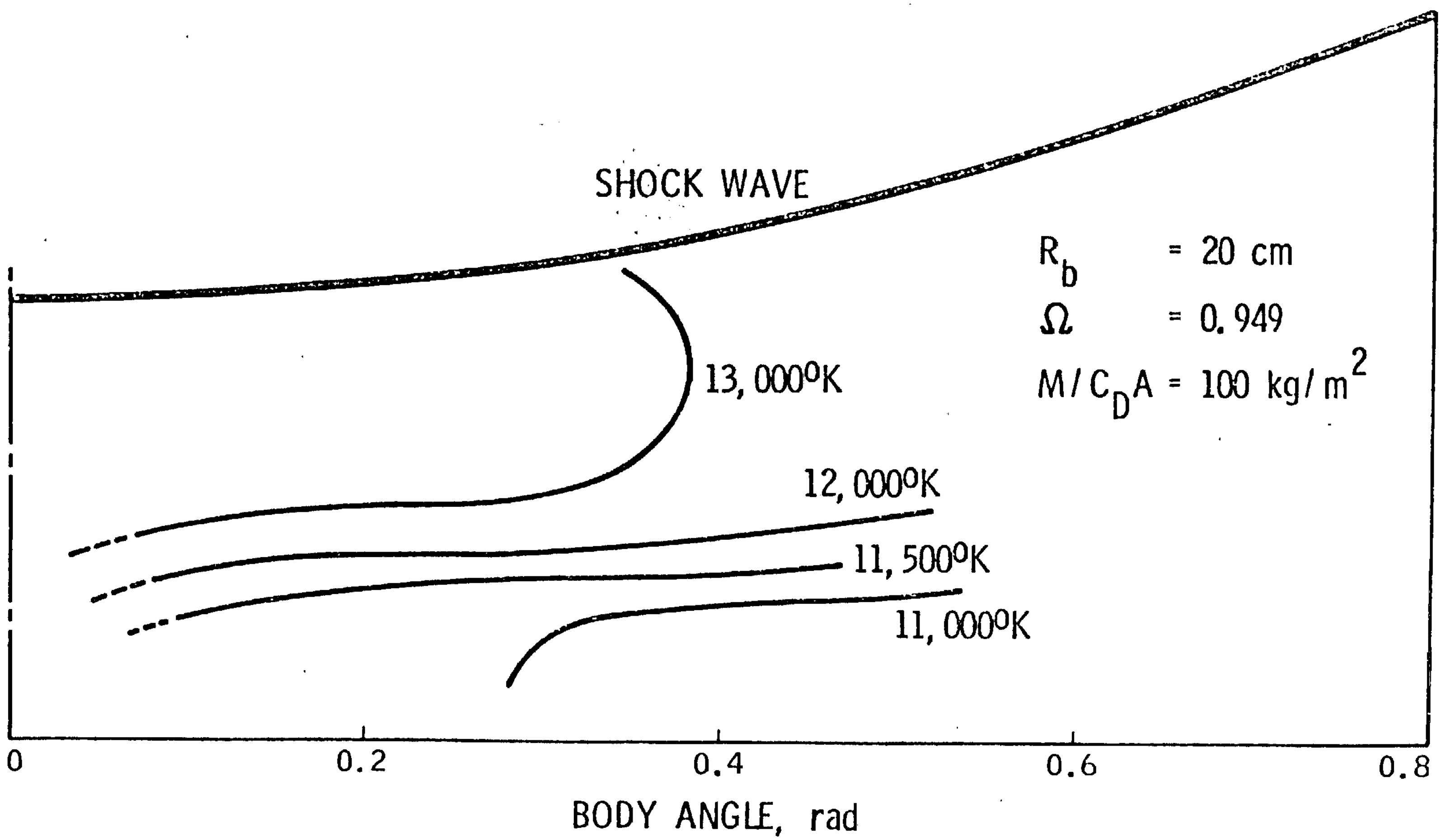


Figure 5-18

LONGER RANGE STUDIES

- DETAILED COMPUTATION FOR RADIATIVE FLUX TO THE BOUNDARY LAYER WHEN RADIATIVE TRANSPORT IS IMPORTANT (WITH Dr. Peter T. Y. Poon)

- INCORPORATE BOUNDARY LAYER STUDIES, SHOCK LAYER ANALYSIS AND MATERIAL RESPONSE INTO A UNIFIED COMPUTATION SCHEME

Figure 5-19

Secondly, we are going to incorporate, eventually, the boundary layer, the shock layer analysis and material response into a unified computation scheme. Gil Yanow of our group is now studying the boundary layer transition problem in actual experiments.

MR. SEIFF: Do you have a figure for the actual level of the radiative heating in this case where the probe energy is weaker than two percent? The reason for my question is that ordinarily when that number is small the radiative heating is not likely to be an overpowering thing and so I think that the conditions that you are relying on to perform your analysis automatically puts you into the range where the problem is not important.

DR. KUO: Yes. First of all, I don't have the figure with me, but it has been computed. Angus McRonald took the computation from George Stickford's previous isothermal slab computation. At peak heating, radiative transfer is of the same order as convective transfer.

MR. SEIFF: My point is that when the assumption is valid, the problem may be unimportant.

MR. OLSTAD: I think that is not the case here, because when you do compute one half ρU^3, you come out with a very large number. When you calculate the adiabatic heating rate, you come out with a substantial heating rate. You will see some numbers later when Bill Nicolet gives his paper. Dr. Kuo was just saying that under those conditions the cooling parameter is not a particularly large number.

MR. SEIFF: If I may, I would like to make one other comment, again harking back to the work of Bill Page, he discovered that even when the fraction is small, as for example, for Apollo, that the effect on the radiative heating can still be an interestingly large one; that is like, twenty or thirty percent reduction in the radiation even when the full energy fraction is as small as one or two percent.

MR. OLSTAD: Right. You have a significant amount of radiation from the ultraviolet where the optical pathlengths are short. A small radiation cooling parameter means that the cooling just has to take place close to the body. That is where the ultraviolet radiation comes from, and that is important.

Now, we are going to hear about Viking entry aerodynamics and heating. The problems of entry heating for Viking are not particularly severe but they do have to be predicted and there are some interesting aerodynamics that must be predicted. Bob Polutchko from the Martin Marietta Corporation will speak on Viking Entry Aerodynamics and Heating.