CALCULATION OF DOWNSTREAM RADIATIVE FLOW FIELDS WITH MASSIVE ABLATION

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MR. WALBERG: I would like to give you a rather broad-brush picture of the state of the art in radiative flow field calculations for downstream flows with massive ablation as viewed from the Langley Research Center. Why downstream flow fields? Well, that is where most of the heat shield weight is and that is also where our theoretical descriptions are the shakiest.

Let me quickly contrast the situation, as I see it, between the stagnation region analyses and the downstream analyses. Now, over the past several years a lot of people have done a lot of work on stagnation region radiative flow fields. A number of researchers now have developed analyses which appear to incorporate all the important phenomena. I don't mean to say that these stagnation point analyses have been verified as being correct; they have not. We don't have the experimental data to accomplish such a verification, but the analyses are self-consistent and do appear to account for the important phenomena as we understand them.

The downstream situation is a bit more complicated. In the first place, the gas dynamics of the problem are basically two-dimensional rather than one-dimensional. This means that the computer storage requirements and computing times are much greater than those required for the stagnation region. Most important of all, we have to consider the possibility, as we go from the stagnation point downstream, of transition to turbulent flow, which is probably the biggest single unknown in downstream radiative flow fields.

The first figure (5-34) shows some typical downstream radiative flow fields. I just want to point out the major characteristics. There are two bodies shown here: a 60° cone and a 45° cone. I have done this because the nature of the flow field and the problems that you encounter in the solution are very much dependent on the cone angle; in particular, the location of the sonic line in the inviscid flow. I will come back to that in a moment.

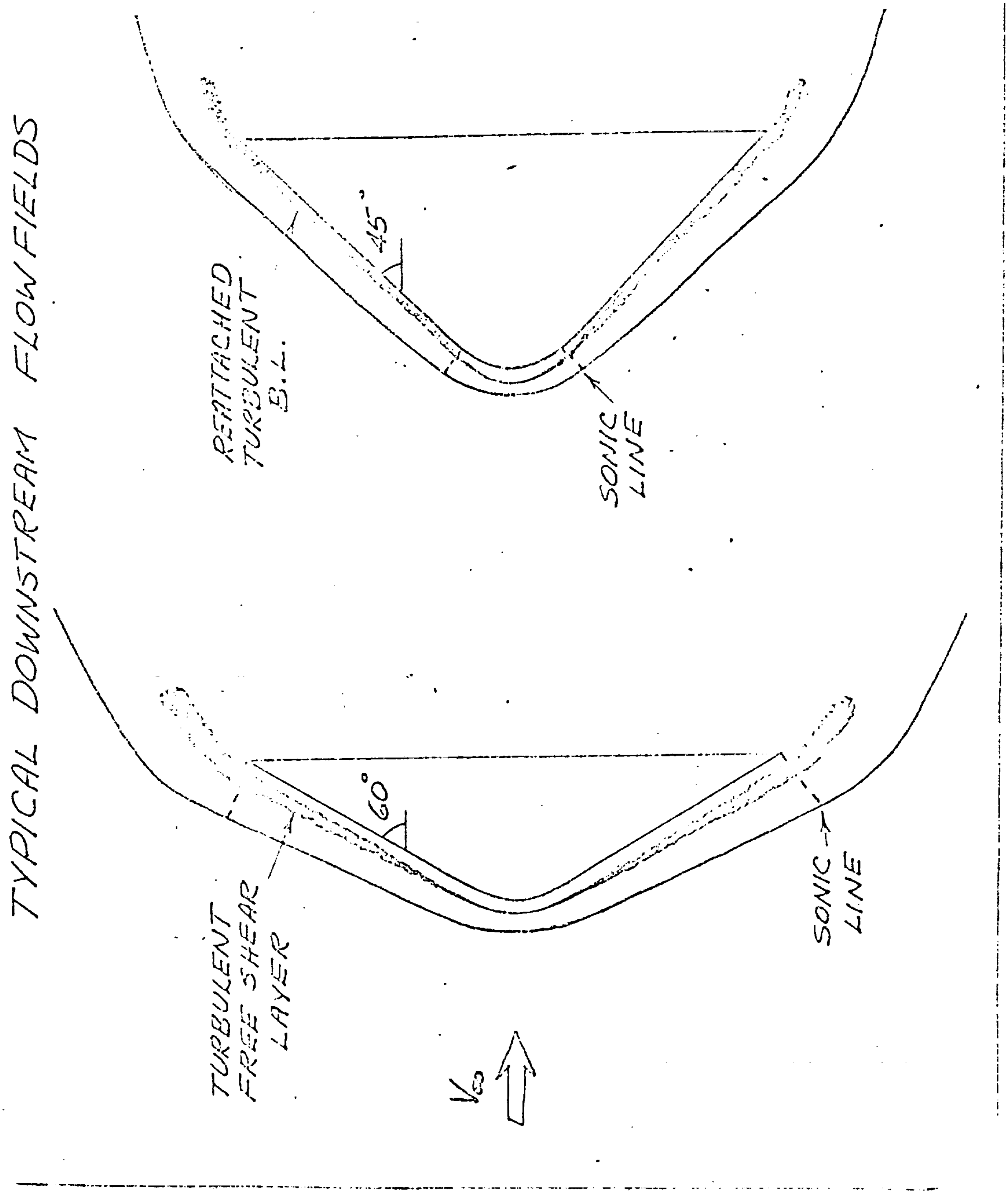

TYPICAL DOWNSTREAM FLOW FIELDS
REATTACHED TURBULENT B.L.
45°
SONIC LINE
TURBULENT FREE SHEAR LAYER
60°
SONIC LINE
V_∞

Figure 5-34

In the first place, we are talking about entry into the giant planets so the radiative heating rates are high. At the stagnation point we are dealing with massive ablation; so, rather than having an attached boundary layer in the normal sense, the ablation rates are sufficient to blow the boundary layer off the surface and we have, instead, a free shear layer.

As we progress from the stagnation point downstream, the question is: Will that initially laminar layer undergo transition to turbulence? Nobody really knows, of course. We don't have dependable transition criteria for this type of a mixing layer. Most people think the answer is "yes". So let's assume that it does undergo transition. Now, how fast will that layer grow in extent? Will it reattach to the surface of the vehicle? Or will it stay off the surface and just be dumped into the wake? This is important because there is a good likelihood, particularly for the Jovian entries, that this mixing layer will absorb a lot of the radiant energy coming from the inviscid shock layer and, so it will be carrying a lot of energy and it will be a turbulent layer. If it attaches to the surface of the vehicle the local heating rates could be very high.

What I've shown here is sort of a scenario of my guess at what will happen. If it's a 60° cone, our calculations of inviscid radiative heating rates say that the radiative heating will still be relatively high on the flanks. The ablation rates will be high and so, perhaps, the mixing layer will not reattach to the surface. For the 45° body on the other hand, the radiative heating rates - at least the inviscid rates - are predicted to drop off. So, the ablation rates on the flanks will not be so high and, in this case, perhaps there will be a reattachment of the free shear layer.

Finally, the question of sonic line location must be answered. For the 45° body the sonic line, at least in the inviscid part of the flow, will almost certainly be near the sphere-cone juncture. Most of the analyses that have been developed for downstream flows, so far, really handle this situation better than the one where the sonic line is near the aft edge of the cone. The worst situation you can be in, from an analytical standpoint is a cone angle where the sonic line is just on the verge of moving from the sphere-cone juncture to the base; and you can actually encounter the situation where, during an entry, the sonic line moves along the flank of the cone.

So, these are the important aspects of the downstream flow problem, as I see it. Now, let me describe two analyses that are presently under way at Langley. They are differing approaches, with different problems and promises.

On Figure 5-35 I have labeled these approaches as rigorous analyses. The intent is rigor; the result is far from being rigorous. We still can't account for everything that we know is important here. They are ambitious analyses. I have listed the characteristics of these analyses and, as you can see, they allow arbitrary, multi-component gas; a detailed radiation model is used; the intent is to include laminar or turbulent mixing layers; they do assume equilibrium, and this harks back to Lou Lebowitz' point. For these really detailed flow field calculations, nobody that I know of has been brave enough to include non-equilibrium chemistry in addition to all the other complicated phenomena.

The first approach is that by Ken Sutton. Here, the inviscid outer flow field is calculated using a time asymptotic solution and that's matched to a first-order boundary layer solution calculated along the vehicle surface.

The second approach, by Jim Moss, is a viscous shock layer analysis where the viscous shock layer equations are solved throughout the entire flow. Sutton's analysis, is to my knowledge, the only analysis that has been carried out to date where the radiatively coupled flow field all along the surface of a conical entry

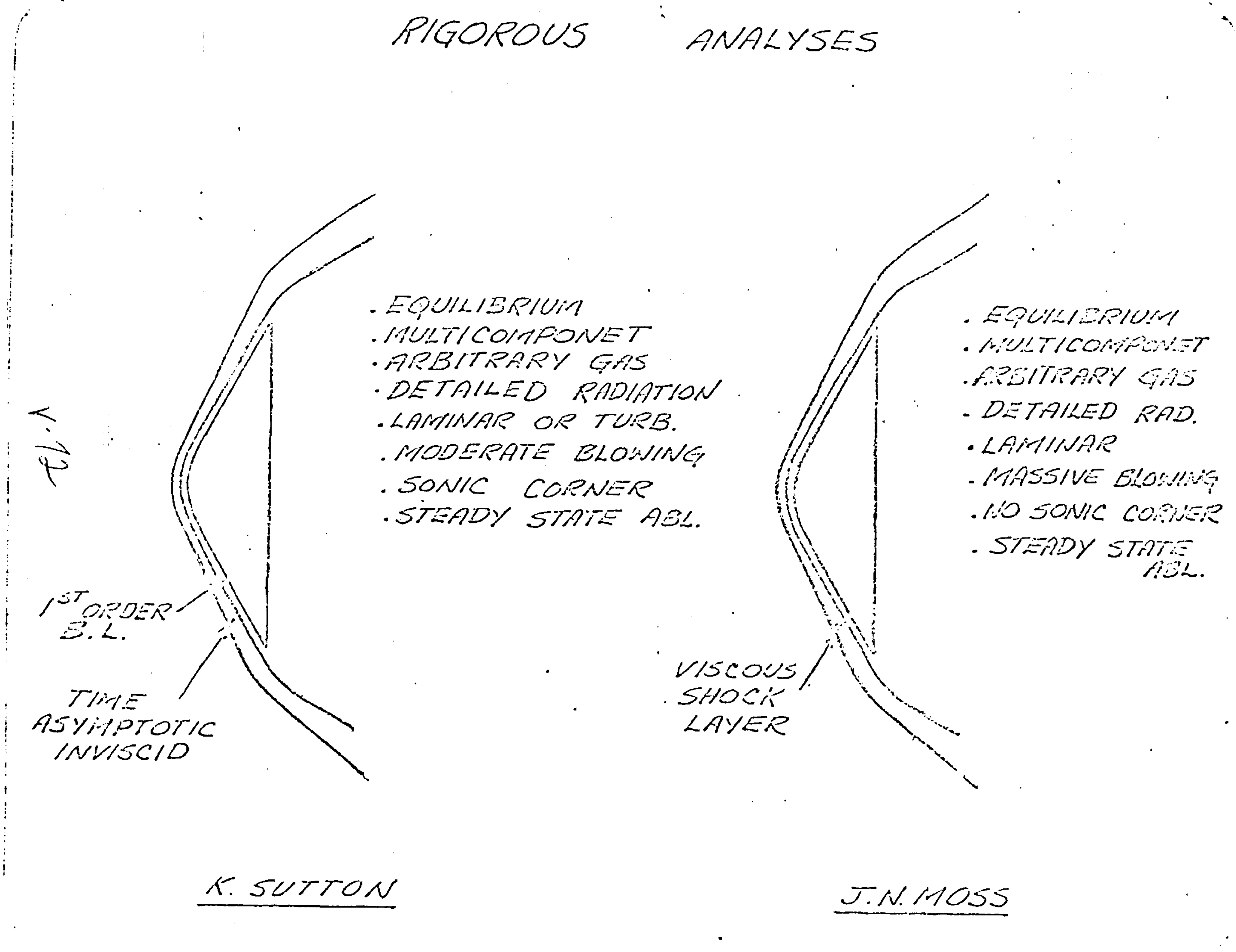

RIGOROUS ANALYSES
. EQUILIBRIUM
. MULTICOMPONET
. ARBITRARY GAS
. DETAILED RADIATION
. LAMINAR OR TURB.
. MODERATE BLOWING
. SONIC CORNER
. STEADY STATE ABL.
1ST ORDER B.L.
TIME ASYMPTOTIC INVISCID
K. SUTTON
. EQUILIBRIUM
. MULTICOMPONET
. ARBITRARY GAS
. DETAILED RAD.
. LAMINAR
. MASSIVE BLOWING
. NO SONIC CORNER
. STEADY STATE ABL.
VISCOUS SHOCK LAYER
J.N. MOSS
V.12

Figure 5-35

probe has been calculated with a turbulent boundary layer. Unfortunately, the boundary layer solution that is used in this analysis becomes unstable at massive blowing rates and, so, the analysis presently is limited to moderate blowing rates.

The viscous shock layer solution, on the other hand, has been demonstrated to be stable at very high ablation rates but, at the present time, it is only formulated for a laminar flow. Dr. Clay Anderson at Old Dominion University is in the process of incorporating various turbulence models into this viscous shock layer analysis but, at the present time, no results are available.

Let me show you some results from these two analyses to demonstrate their capabilities. I would point out that the results you will see will not be for the giant planets. You will see some results for Venus; you will see some results for Earth entry. The fact is there are no downstream rigorous analyses for the giant planets, yet. We are still working on them.

Figure 5-36 presents some of the results that Ken Sutton obtained for the large Pioneer Venus probe when it was assumed to be a 60° cone. This analysis is as far as I know the only one that's been presented with a detailed coupled radiative solution and a turbulent boundary layer. The solution is obtained for the entire surface of the conical vehicle. The solid line denotes convective heating; the dashed line denotes radiative heating. Transition was assumed at a momentum thickness Reynolds number of approximately two hundred.

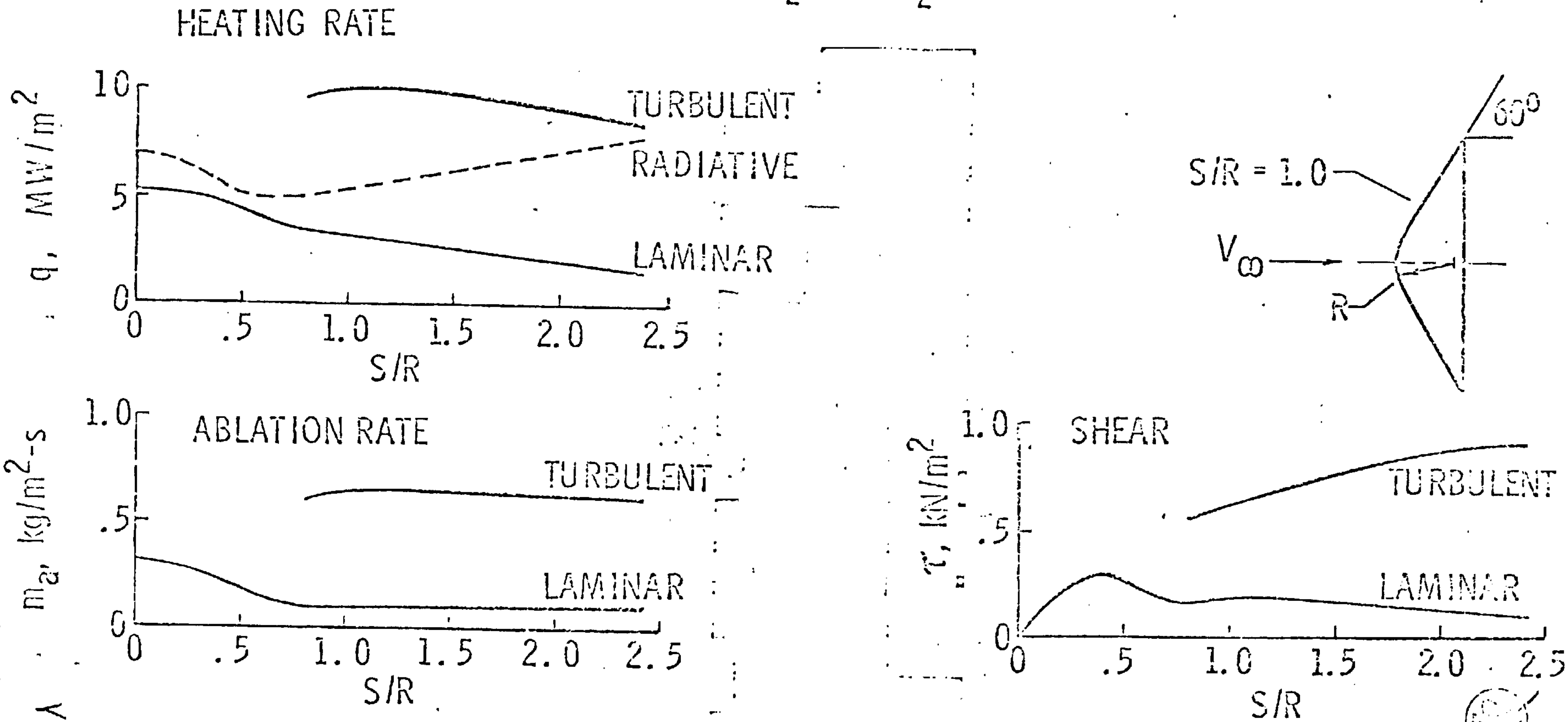
Notice that there is only one curve for radiative heating. The reason for this is that the same answers were obtained for both laminar and turbulent boundary layers. This is sort of surprising but the next figure will clarify the situation.

What happened is illustrated in the plot of radiative flux to the wall presented in Figure 5-37. This is a spectral distribution of

SOLUTION FOR LARGE PIONEER VENUS PROBE

STEADY-STATE ABLATION OF CARBON – PHENOLIC HEATSHIELD

$V_\infty = 8.80$ km/s
$\rho_\infty = .0058$ kg/m^3
$R = .34$ m
$.97\ CO_2 - .03\ N_2$



V.74

Figure 5-36

SPECTRAL DISTRIBUTION

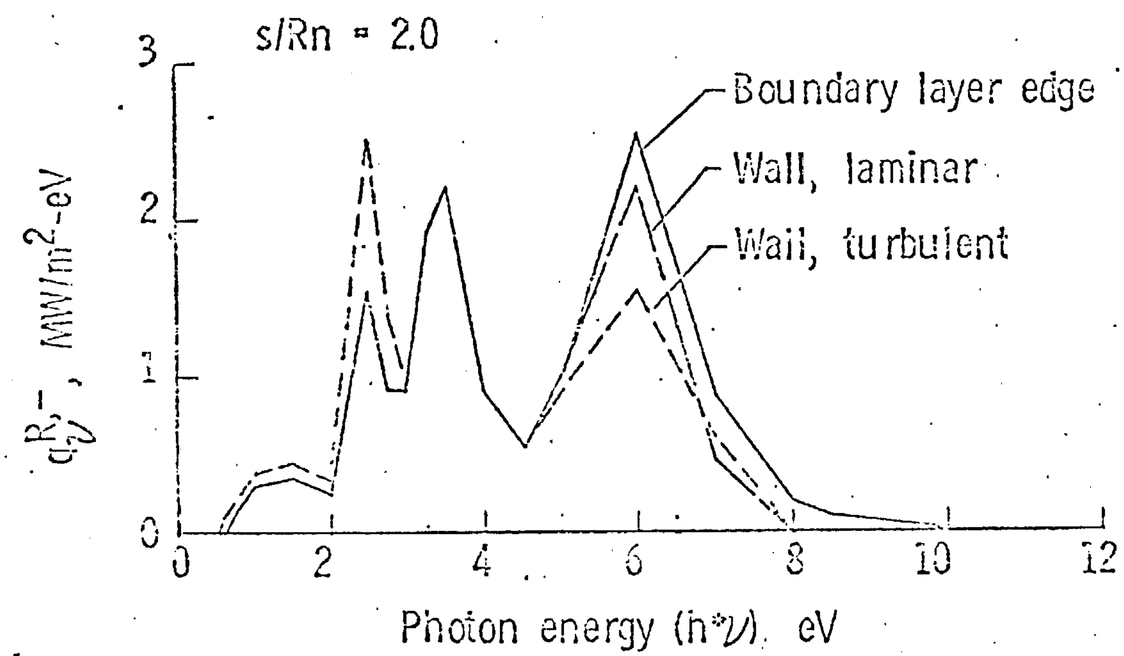


Figure 5-37

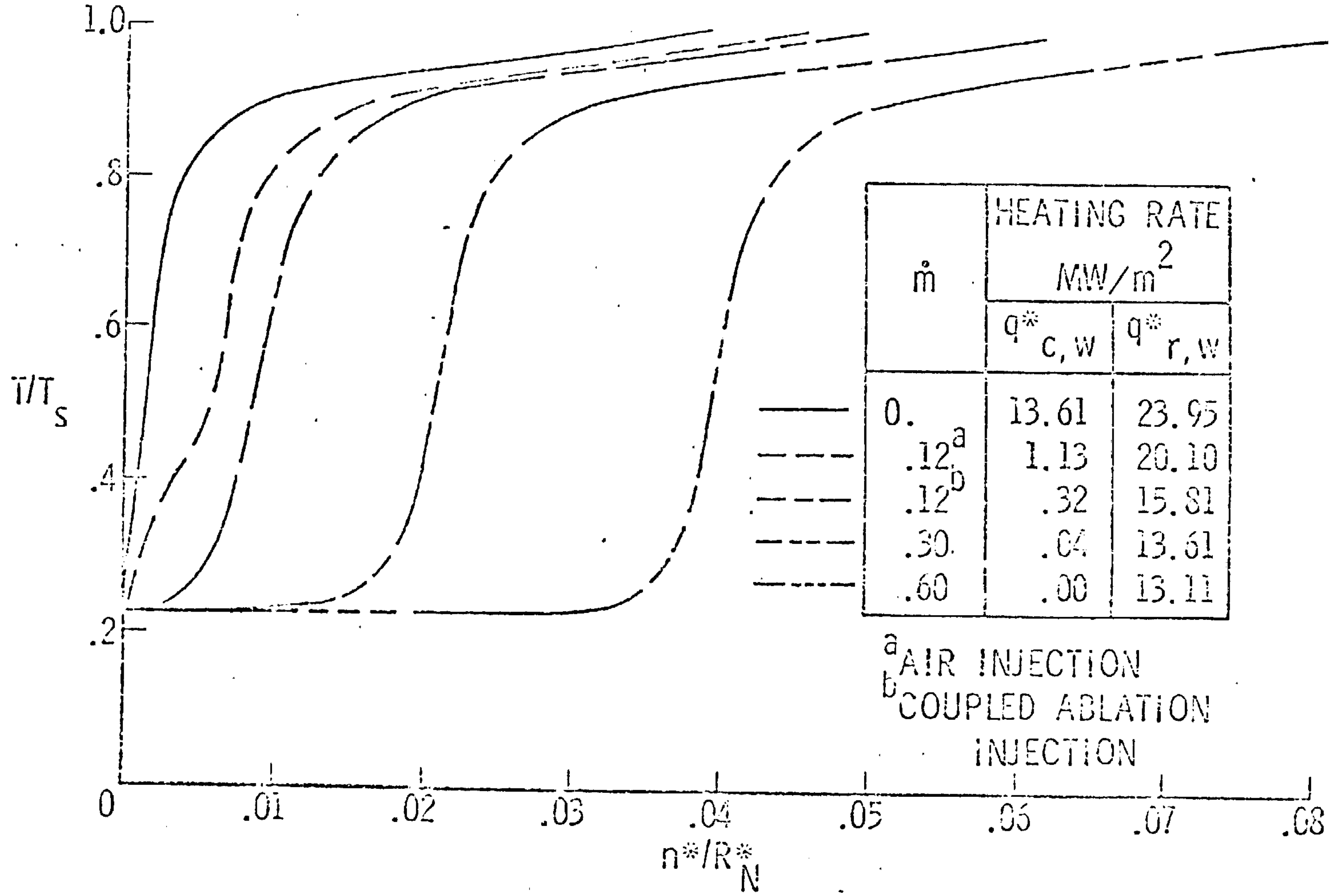
radiative flux as a function of photon energy. The solid line indicates the flux to the outer edge of the boundary layer. The long-dash line is the flux to the wall when the boundary layer was laminar and the short-dash line is the flux to the wall for the turbulent boundary layer. For the laminar boundary layer there was some absorption at uv wavelengths from five to eight eV. When the boundary layer was turbulent there was more significant absorption in this range but, in addition, there was emission in the visible and IR end of the spectrum. It is just a coincidence that the two cancel each other in this case, yielding virtually the same answers for laminar and turbulent boundary layers. These results show significant differences in the spectral distribution of radiative heating depending on whether the boundary layer is laminar or turbulent, and I feel that, in general, you should expect differences in the magnitude of the frequency-integrated heating as well.

Now, a couple of viewgraphs to demonstrate the capabilities of the viscous shock layer solution of Jim Moss. As I said, Sutton's solution is presently limited to moderate blowing rates, so we can't really tackle the giant planet entries with it. Figure 5-38 presents some stagnation point results that Jim Moss obtained for earth entry. These are temperature distributions through the complete layer - both what amounts to a boundary layer and the inviscid layer - for various dimensionless ablation rates. The highest value of this dimensionless ablation rate that Sutton has managed to get a solution for is approximately 0.2. Here you see answers for 0.6 which really is massive ablation; and yet the viscous shock layer solution did remain stable and give answers for this case. It promises that if we can incorporate all the other phenomena that we would like to account for, perhaps this approach will handle the massive blowing.

Figure 5-39 shows some downstream solutions that Jim Moss obtained for an Earth entry case with the viscous shock layer solution. Basically, what this shows is that the thing does, indeed, calculate

STAGNATION TEMPERATURE PROFILES FOR VARIOUS INJECTION RATES

ALT = 62.2 km; U^*_∞ = 15.24 km/s; T^*_s = 14,700 K, P^*_s = 0.5 atm; R^*_N = 0.305 m



$\dot{m}$	HEATING RATE MW/m²	
	$q^*_{c,w}$	$q^*_{r,w}$
0.	13.61	23.95
.12[a]	1.13	20.10
.12[b]	.32	15.81
.30	.04	13.61
.60	.00	13.11

[a]AIR INJECTION
[b]COUPLED ABLATION INJECTION

Figure 5-38

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RADIATIVE VISCOUS SHOCK-LAYER RESULTS WITH COUPLED ABLATION INJECTION

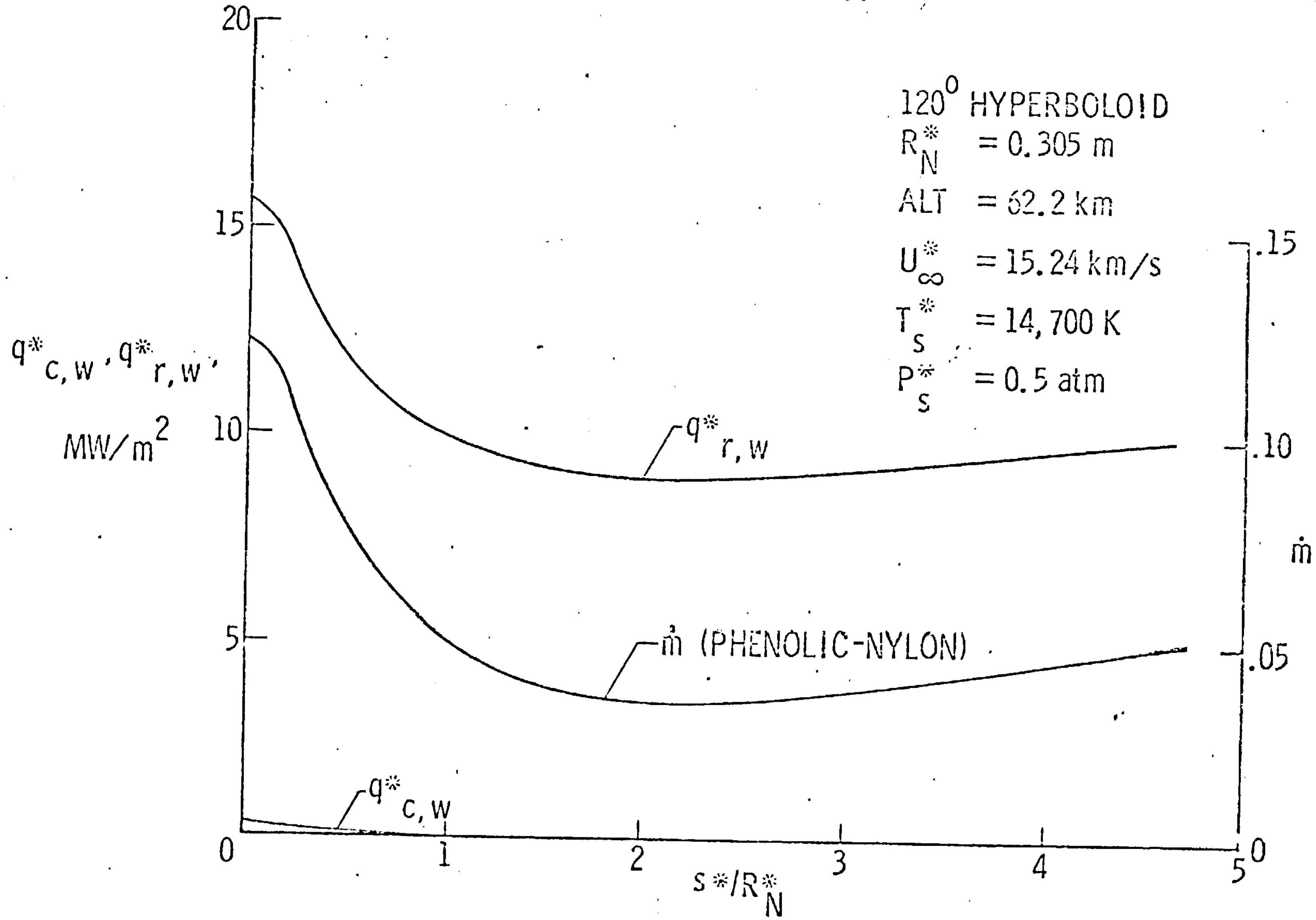

Figure 5-39

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all the way around the body and this is a radiatively coupled downstream solution; albeit for Earth entry, and a laminar boundary layer.

The biggest shortcoming for both of these analyses really is the description of the turbulent mixing layer. While Sutton has obtained answers for the turbulent mixing layer, it really amounted to an attached turbulent boundary layer and, in this case, we have turbulence models that we can use with some confidence. For the massively blown free mixing layer I'm not sure anybody knows what the proper turbulence model is. This is really the big thing that we need to know. We need a turbulence model that we can include in these flow field analyses with some confidence.

Even if we have the turbulence model, and if we include all the other good things that we have to in these detailed rigorous solutions, the computing times required are still going to be so large that I doubt we will ever use them for parametric studies or mission analysis studies. So, there is a need for an approximate solution and there is a real possibility that you can develop an approximate solution if you have a detailed solution to sort of calibrate the approximate solution with.

Figure 5-40 shows a couple of approaches that have been taken at Langley toward producing these approximate solutions. The first is due to Walt Olstad. It's a two inviscid layer model, really most applicable to the massively blown situation where a Maslen-type inviscid flow field is assumed in both layers. The second is an approach due to Louis Smith where a one strip method of integral relations approach is used in the outer inviscid layer and a simplified integral boundary layer solution for the inner layer.

Here, again, the location of the sonic line starts to be important because at its present state of development, anyway,

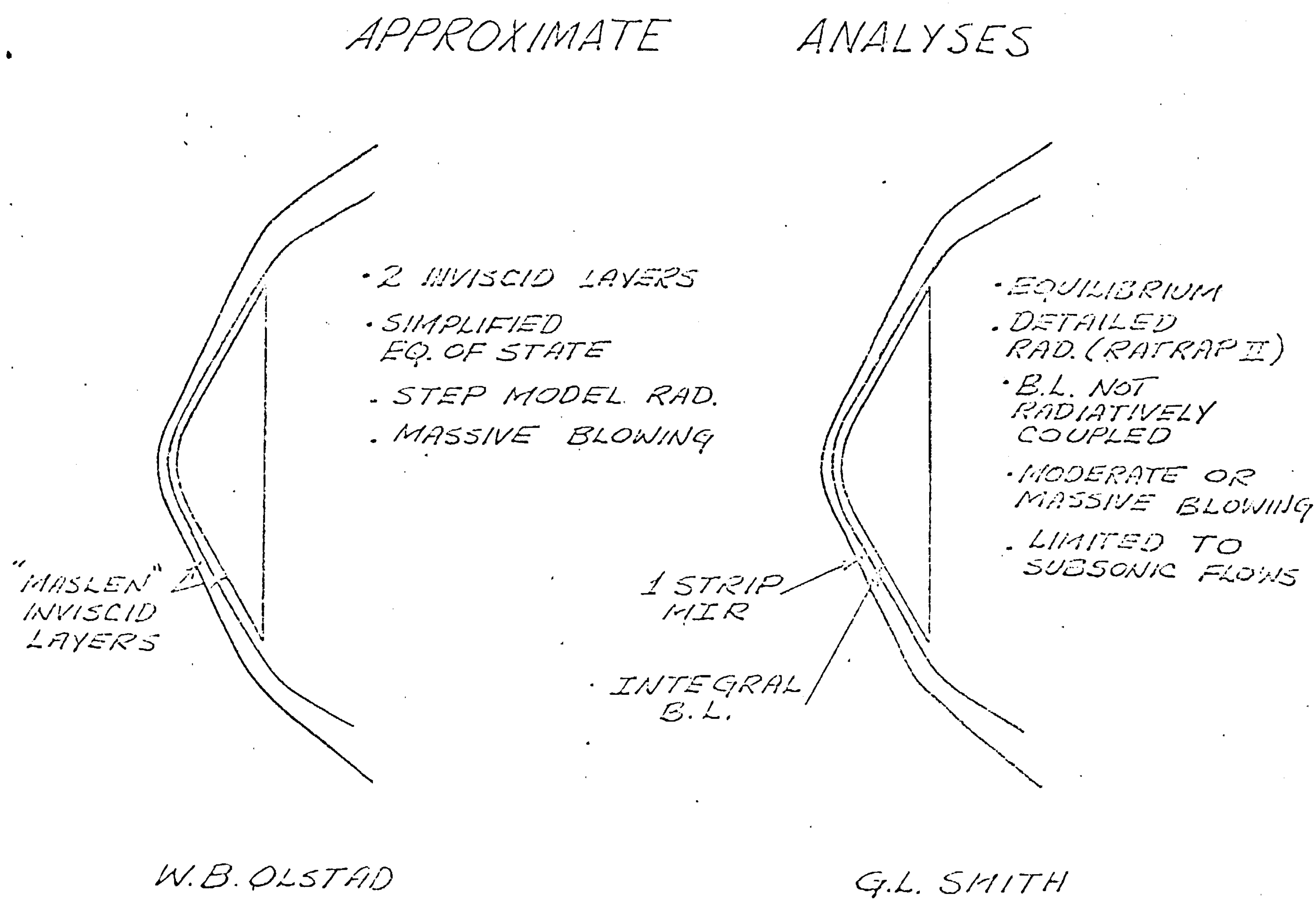

Figure 5-40

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Olstads' analysis can't handle the sonic line at the aft corner; and in the Smith method's present state of development, it can't handle it anywhere else. It only works for a subsonic flow field. So, the sonic line location determines which of these approximate analyses you want to use.

Just to show you what you can do with an approximate solution, if you have a good rigorous analysis with which to calibrate, Figure 5-41 and 5-42 show some inviscid radiative heating rates computed for two proposed Pioneer Venus probes. Radiative heating rates are plotted as a function of dimensionless wetted length from the stagnation point. The solid curve is Ken Sutton's very detailed solution; the dashed curve is an Olstad-Maslen type solution worked out by Ralph Falanga at Langley. The agreement is very good but before you can get this type of agreement you really need a benchmark to compare with the approximate solution when you are working up the radiation step model and the thermodynamic approximations in the solution.

In summary, then, our present situation is that while we are attempting to develop rigorous flow field models for downstream radiative flows of massive ablation and we are making progress, there are significant unknowns. The biggest of these is the turbulence model for the mixing layer. For engineering calculations for trade-off studies, there really is a need for approximate solutions. It appears that there are several promising avenues to follow in developing these, but you do need the rigorous solution, or experimental data, to calibrate the approximate approaches.

RADIATIVE HEATING DISTRIBITION

V_∞ = 11.18 km/s

ρ_∞ = 0.00285 kg/m^3

0.90 CO_2 - 0.10 N_2

Rn = 0.305 m

θ_c = 60^0

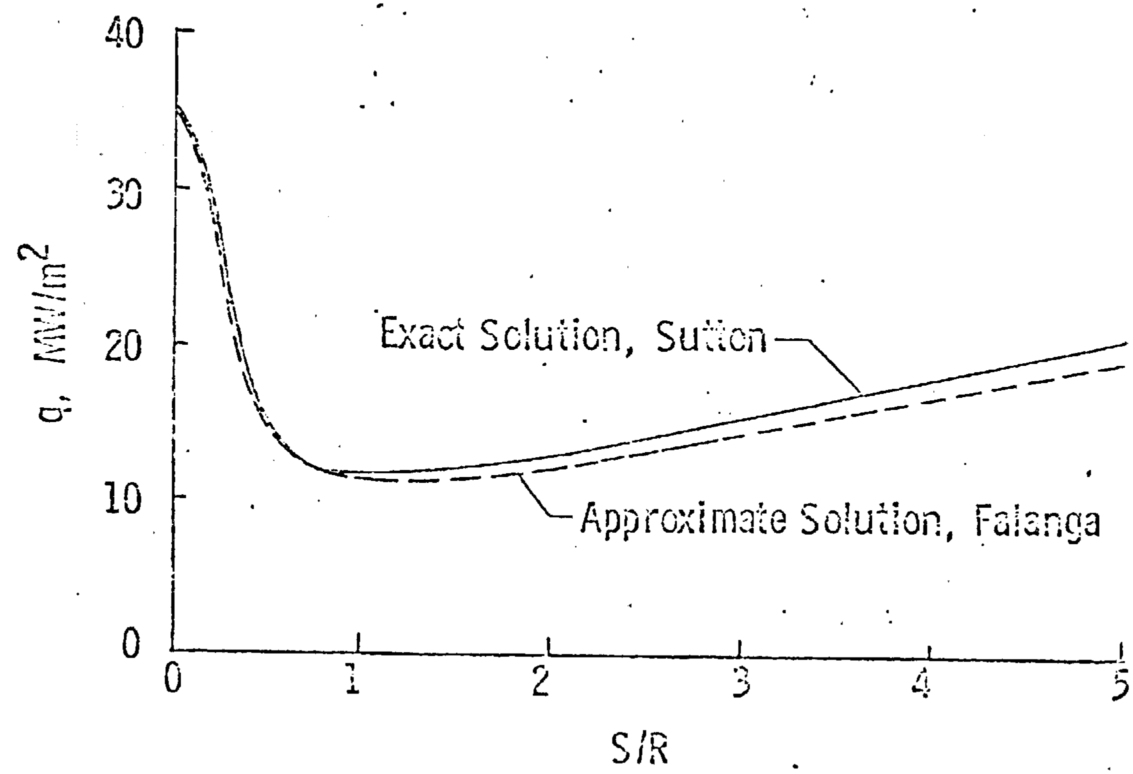

Figure 5-41

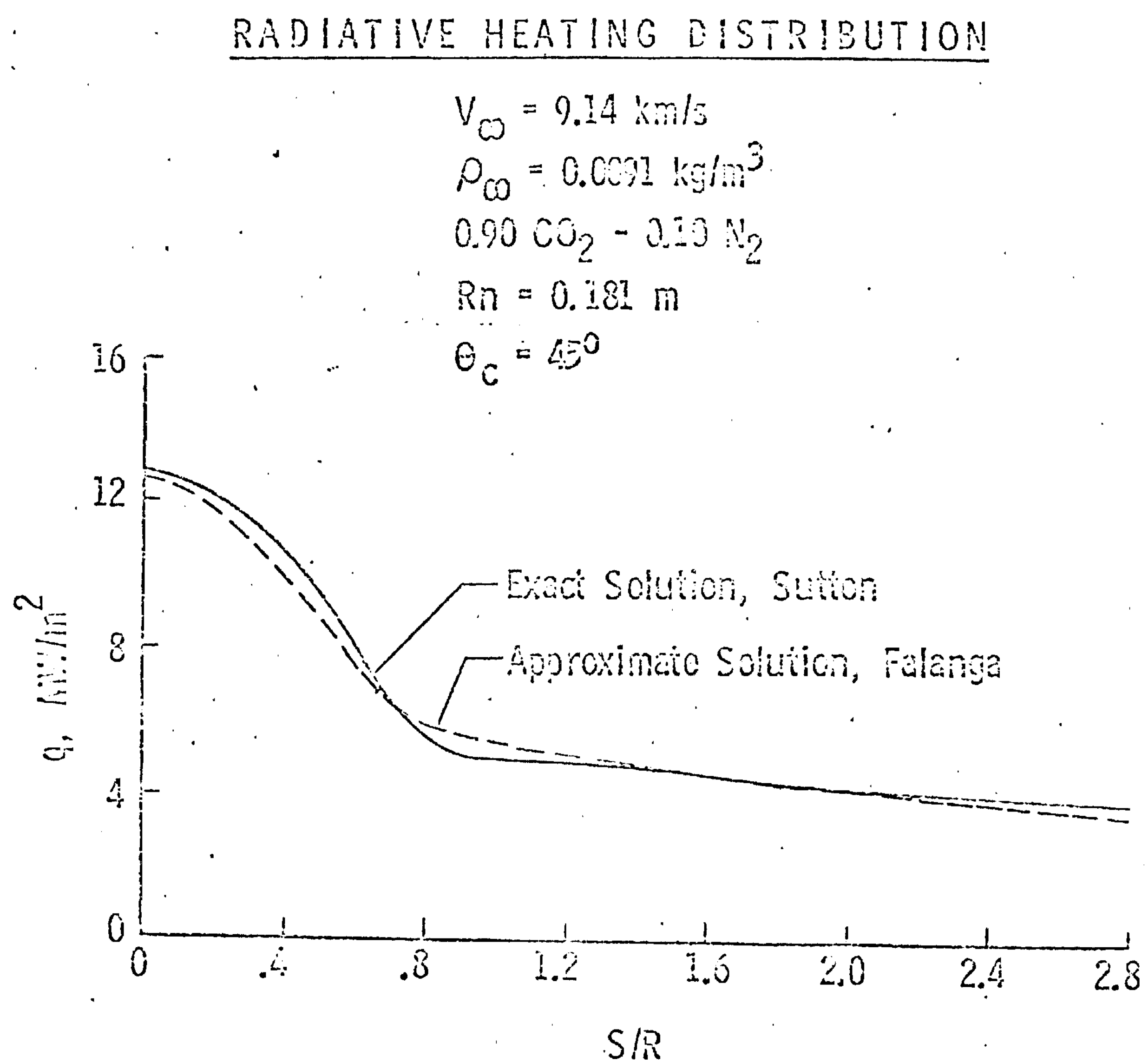

Figure 5-42

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UNIDENTIFIED SPEAKER: In the rigorous analysis by Jim Moss you have this shock layer analysis which is split into two parts: one is inviscid. I believe the energy transport is important but not the momentum transport. Is that the case?

MR. WALBERG: I think I don't understand your question, you should ask it again.

UNIDENTIFIED SPEAKER: There is a viscous shock layer so - this is a generalized term. It implies that energy transport is important. You said viscous, and then you said something about an inviscid shock layer. Did you say that?

MR. WALBERG: First of all, in Jim Moss' analysis of the viscous shock layer you have one set of governing equations that apply uniformly throughout the entire flow field. I may have referred to the outer flow as effectively inviscid or inviscid. If I did, I meant what you are saying that the energy transport is more important.

UNIDENTIFIED SPEAKER: My questions actually are, is the Reynolds number or the Péclet number that important, to justify this complicated approach as versus the other approach; that is the viscous shock layer, because it is much hotter?

MR. WALBERG: The question is, in view of the Reynolds number that we encounter, do we have to go to a complicated viscous shock layer solution, or could we use a simpler analysis.

The answer is in many cases we could use a simpler analysis, but the objective here is to develop a rigorous solution that can be applied to many different entry situations and it should have wide applicability rather than one that's limited to a particular planetary encounter.

MR. OLSTAD: Our next speaker is Bill Nicolet, from Aerotherm Acurex Corporation. I think maybe, finally, you will se some numbers on heating rates for the outer planet entry. Bill's topic is Aerothermal Environment and Material Response, A Review.