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NOTE: This paper is as it was presented during the workshop. The Author's review and editorial comments were not received. His slides and figures appear at the end of this session.

THE AEROTHERMAL ENVIRONMENT AND MATERIAL RESPONSE, A REVIEW

William E. Nicolet
Aerotherm Acurex Corporation

MR. WILLIAM NICOLET: Thank you. In response to the letter of invitation, as I recall, the wording was that we were invited to review and assess current states of technology and make recommendations, and so I addressed myself to that, rather than giving a lot of numbers. It seems like I've been promised, repeatedly, to give numbers. I did give a few just to orient the audience, but this will not be a presentation oriented to that end.

In addition, in the initial response to the letter, I promised to review both aerothermal environments and material response. After looking at the time allocation, I decided I'd better delete material response and leave that to this afternoon's sessions and to other people. So, the focus of this particular talk will be a review of the aerothermal environment.

Figure 5-43 - I'm going to end up duplicating some of the material that Jerry presented, clearly, but let's start off by looking at the flow and the material response as Aerotherm sees it as opposed to how Langley sees it. There are, pretty clearly, a lot of overlaps here.

To begin with, you have a normal shock wave with some relaxation zone behind it, usually of some maximum thickness, at the stagnation point. Typically, there is the hot shock layer of gases behind it emitting radiation to the body. There is some type of a mixing region, hopefully out in the middle of the shock layer, bounded by ablation gases flowing inviscidly out from

FLOW PHENOMENOLOGY

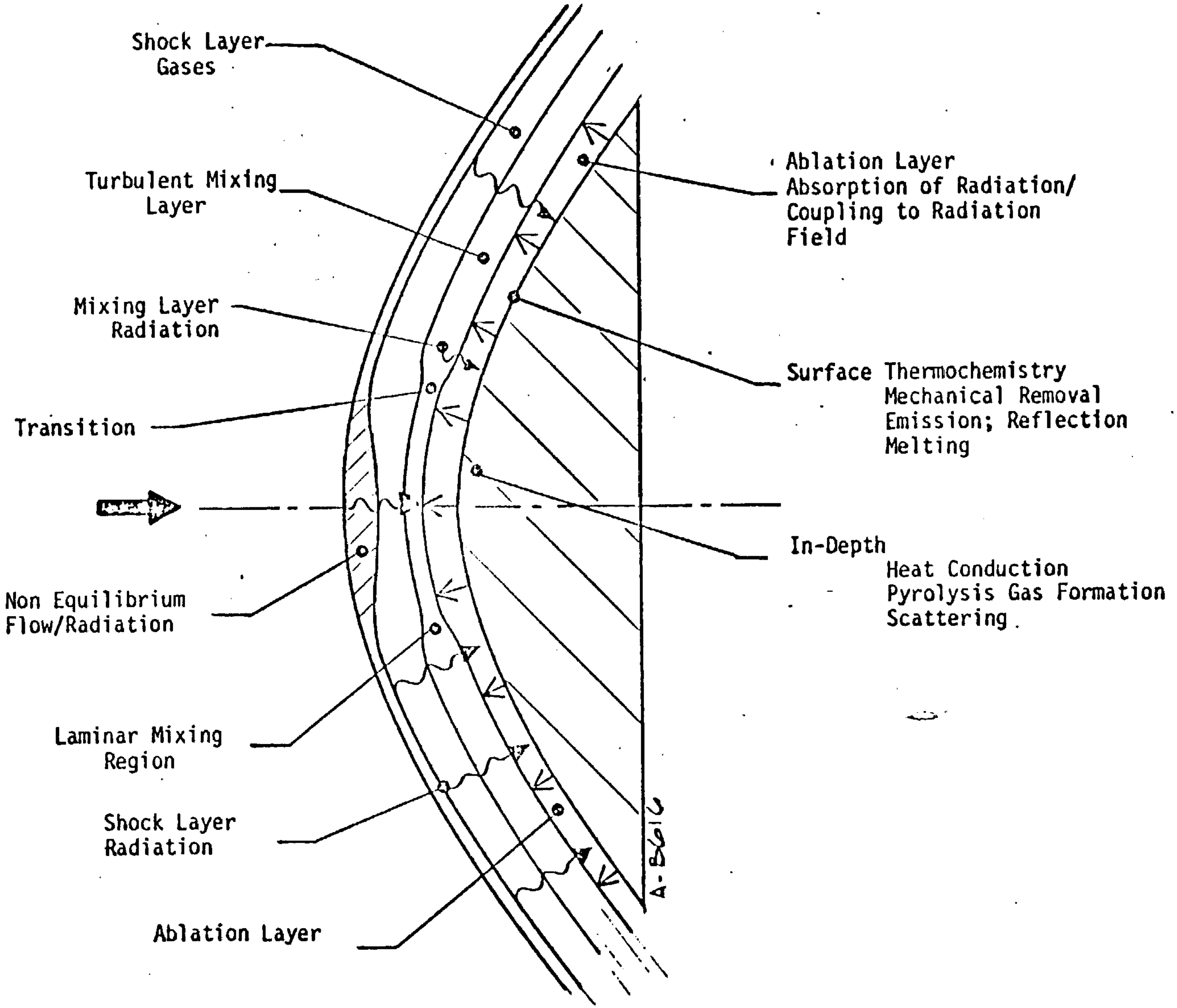


FIGURE 5-43

the body on the inside, and by environmental gases flowing more or less tangentially on the outside. One might expect this to be laminar in the region near the stagnation point with transition of turbulence back further. There will be absorption of radiation in the mixing layer and in the ablation layer. In addition, there appears to be important radiation components emitted by the mixing layer itself. If one goes over and looks at the other end - and I am just going to touch on this - as I said, important absorption in the ablation layer; important events going on at the surface: thermochemical events, mechanical removal, radiation emission, reflection, melting, depending on the type of ablator selected; important events going on in depth: heat conduction, pyrolysis gas formation, scattering; again, depending on the material selected.

Figures 5-44, 45, and 46 are three slides that I will put up here really just to allow us to focus down to some numbers. To begin with, note that the solid lines are for Saturn, and the dashed lines are for Uranus. This is the stagnation-point radiative heating flux as a function of time.

To begin with, two different atmospheres are considered here; the cold dense and warm atmospheres for both planets. Also two different body shapes were considered. Most of the data is for a 60° aft angle cone, but the very high radiative flux (above 60 kW/cm^2) was computed for an Apollo-type configuration. The convective fluxes show slight quantitative differences but, qualitatively, are very similar. In contrast, the radiative fluxes are vastly different, with the Uranus cold-dense fluxes being nearly an order of magnitude greater than those for the Saturn cold-dense entries. Moreover, entries into cold-dense atmospheres have radiative flux levels which are at least an order-of-magnitude greater than the corresponding entries into the nominal or warm entries for the same planet. This point will be made over and over again, but has to do with the composition of the atmospheres and almost nothing else.

COMPARISON OF SELECTED SATURN AND URANUS STAGNATION POINT HEAT PULSES WITH NO ABLATION

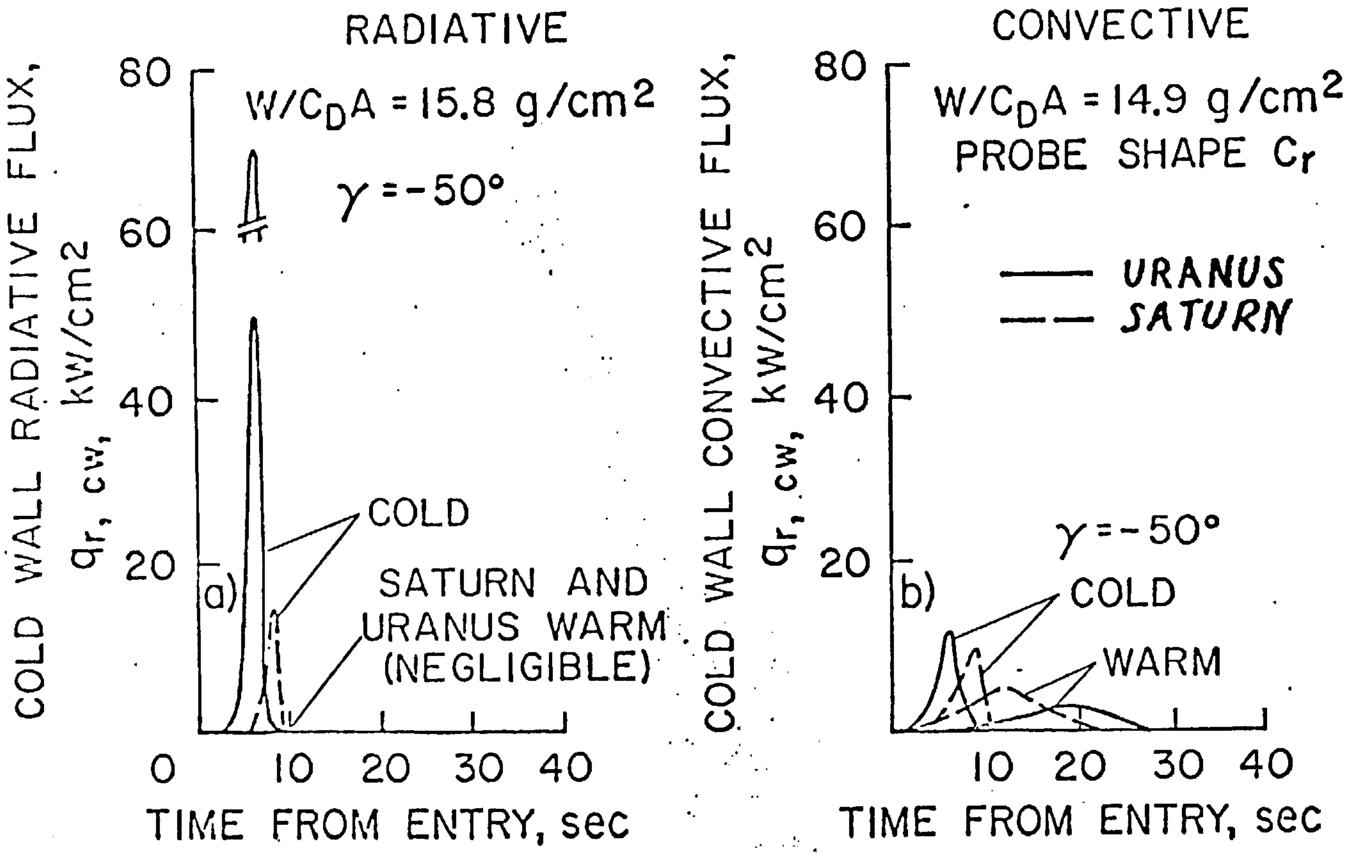
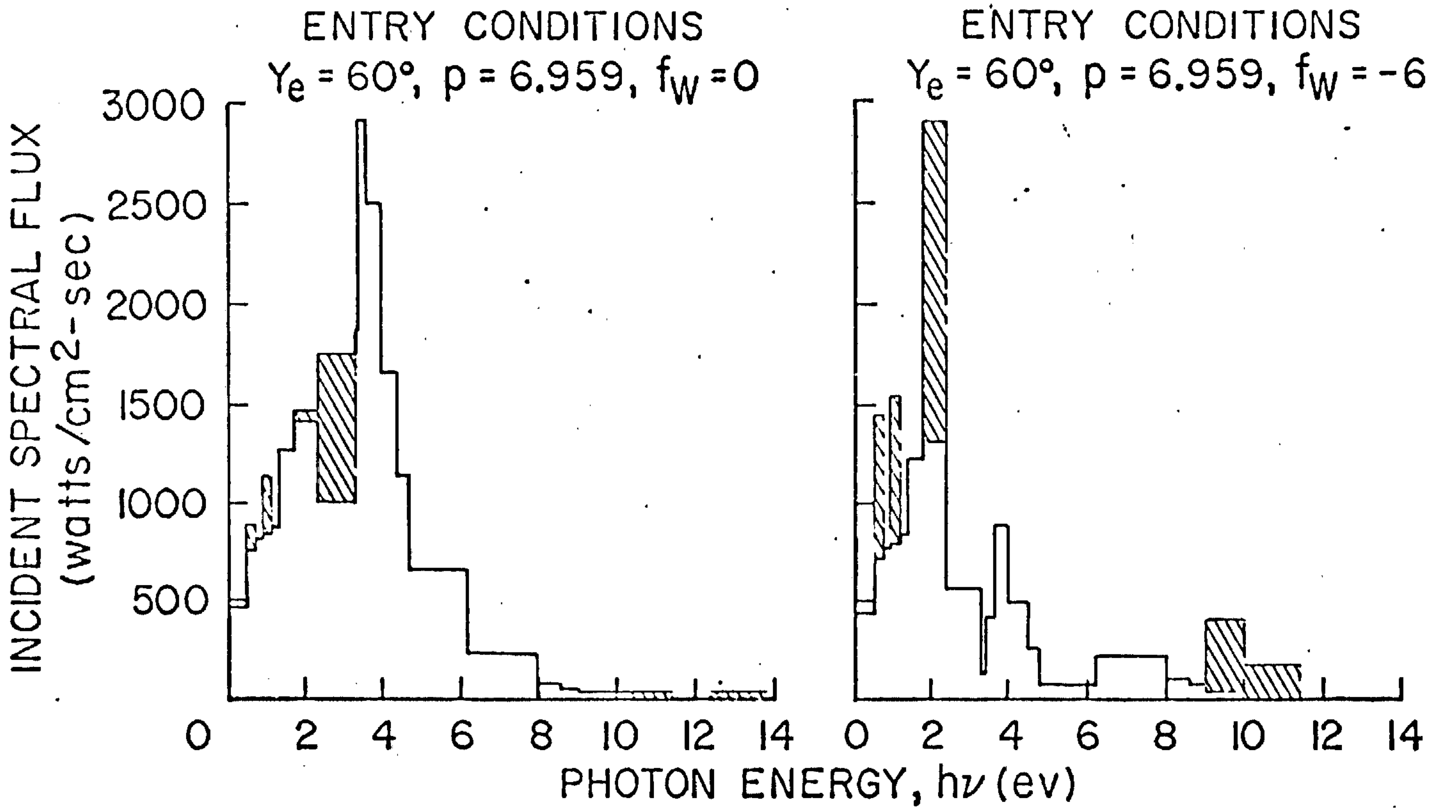


FIGURE 5-44

IMPACT OF CARBON ABLATION ON STAGNATION REGION RADIATIVE HEAT FLUX TO PROBE SURFACE - SATURN ENTRY



ENTRY CONDITIONS
$Y_e = 60°, p = 6.959, f_W = 0$

ENTRY CONDITIONS
$Y_e = 60°, p = 6.959, f_W = -6$

(a) NO ABLATION

(b) WITH ABLATION

FIGURE 5-45

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RADIATIVE HEAT BLOCKAGE CORRELATIONS FOR CARBON AND SiO_2 ABLATION

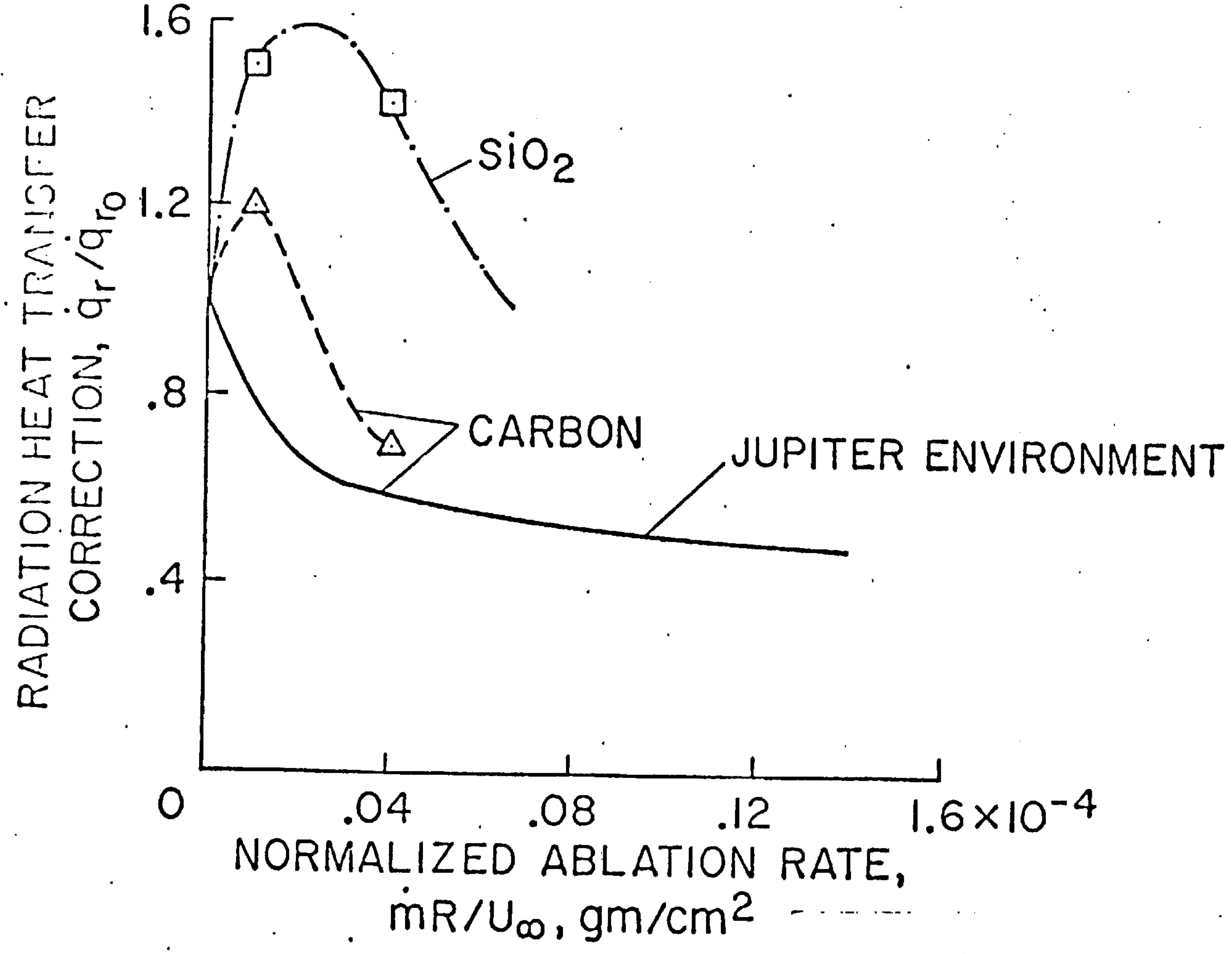

FIGURE 5-46

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OF POOR QUALITY

Figure 5-45 presents the spectral distributions of the incident radiation flux. Typically, these are calculated from our computer program. These would be for the Saturn nominal entry, a relatively steep entry into the Saturn nominal atmosphere. The plot on the left shows the radiation coming from the shock layer alone.

On the right we see the radiation with ablation products. Note that we have cut out a good part of the radiation in the U.V. Simultaneously, we added radiation in the visible portion of the spectrum. This is the radiation coming directly from the mixing layer. In both of these figures, the clear parts refer to continuum radiation; the slashed parts refer to line radiation.

One might hope to get from a detailed calculation of the radiation heat transfer correction and blockage correlation of the nature shown in Figure 5-46. The solid line represents work that was done in support of a Jupiter entry study. It was done three or four years ago by Ken Wilson, and subsequently correlated by Bill Page. The focus there was for large blowing rates. The Jupiter entry case was very severe. Typically, we would see it reduce the radiation flux by about a factor of two. My point in doing additional calculations for smaller blowing rates which is important in the Saturn-Uranus nominal type entries was to investigate the effects due to the mixing layer radiation that I discussed in the previous slide. As you see, typically, we have important additive effects.

These types of correlations developed from stagnation-point solutions, are generally used for the whole body. The objection Mr. Walberg was making a few minutes ago was that, in fact, these might change shape as you go around the body. John Howell and C. H. Liu, here at Ames, are greatly expanding the matrix of calculations on this particular subject. Again, it is focused primarily on the stagnation point, but it, supposedly, would do a lot to firm confidence in this type of calculation and the correlations of it.

Hopefully, I have set the stage for the type of numbers, the type of effects, the type of events we are dealing with, I would like to now review calculational and experimental approaches to solve the problem, focusing on areas where there are uncertainties and suggesting, as a last item, ways to reduce the uncertainties.

The most uncertain item - and notice on Figure 5-47 I have listed input conditions now - the most uncertain item in the whole analysis is the atmospheric composition and, particular, elemental mass fractions of helium. My calculations jump up and down and go all over the place, depending on what we assume there. In particular for the Uranus case we can find fantastic radiation fluxes for a high-helium-content mixture; and almost none for a low-helium-content mixture.

The elemental mass fraction of the primary radiating species in the environment is important, as are the atmospheric scale heights. But they certainly take a distant second place in importance to the elemental mass fraction of helium.

I am going to briefly run down some of the calculational methods. To begin with, all of my focus will be on the 2-D flow capabilities. There is a figure in the handout dealing with 3-D capabilities but, for those of you who are interested in the angle of attack, I suggest you look at that and perhaps, talk to me. I will not discuss it as part of the oral presentation.

Let's start with the inviscid type of calculations (Figure 5-48) applicable right behind the shock front. There are a number of finite - difference, time dependent or integral relation methods - Jerry Walberg alluded to some - focusing primarily on situations where there is no radiation coupling. These would be used for basic studies or pressure or boundary layer edge velocities, and the like. They would be applicable in the cases where the radiation is not important. If we add radiation coupling on the second line (indicating), we find that there are a couple of calculations that can be done. There are a couple of codes available

REVIEW OF INPUT CONDITIONS

ATMOSPHERIC COMPOSITION:

- ELEMENTAL MASS FRACTION OF HELIUM
- ELEMENTAL MASS FRACTION OF IMPORTANT RADIATING SPECIES, E.G., H_2, C, O

ATMOSPHERIC SCALE HEIGHT

FIGURE 5-47

REVIEW OF 2-D FLOW CAPABILITIES

TYPE	APPROACH	USE	STATUS
INVISCID	FINITE - DIFFERENCE, TIME DEPENDENT OR INTEGRAL RELATIONS (REAL GAS - NO RADIATION COUPLING)	BASIC STUDIES OF PRESSURE, B.L. EDGE VELOCITIES	OPERATIONAL AT MANY ORGANIZATIONS
	SAME AS ABOVE (RADIATION COUPLING)	BASIC STUDIES OF SHOCK SHAPES, RADIATION COOLING FACTORS	OPERATIONAL AT ONE OR TWO ORGANIZATIONS
	CORRELATIONS OF SHOCK SHAPE, PRESSURE DISTRIBUTIONS, ETC. (NO RADIATION COUPLING)	SUPPORT OF HEAT SHIELD SIZING STUDIES	OPERATIONAL AT MANY ORGANIZATIONS
	CORRELATIONS OF SHOCK SHAPE, PRESSURE DISTRIBUTIONS, ETC. (WITH RADIATION COUPLING)	SUPPORT OF HEAT SHIELD SIZING STUDIES	NOT AVAILABLE

FIGURE 5-48

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with selected organizations. If we go on down to talk about what would be required to support heat shield sizing studies, correlations of shock shape, pressure distributions, and the like are certainly vital inputs. They are generally available for the shapes of interest for the non-radiation coupling situation.

Let's go on to boundary or merged layers, Figure 5-49. Here my terminology for merged layer is the same that Jerry was using for viscous shock layer, that is, a boundary-layer-type calculation extending from the shock wave all the way to the body. I tend to use them interchangeably since the mathematics tends to be quite similar.

If we talk about a finite difference method coupled to ablation chemistry, with the laminar or turbulent flow, but without radiation, we have such codes as the BLIMP that has been discussed previously. It is operational without radiation coupling. There are other codes like it, provided that the blowing rates remain modest. If we add radiation coupling; same types of codes, same types of restrictions. If we reduce, or subtract off, the turbulent flow requirement we have codes that are applicable for all blowing conditions, and this is certainly the situation for the typical outer planetary entry of interest.

If we go on down and ask about a finite difference approach considering finite rate chemistry, even without radiation coupling and without turbulence, we find that this type of approach has generally not been used in the planetary entry situation, although the RV community has developed that type of code and some capability does exist. I point out that this type of discussion was made before I was aware of the most recent presentation of the people from JPL.

Figure 5-50 continues and gets more into intermediate or tool-type things that would support heat shield sizing, there are various stream tube methods. I would consider Olstad's method a

REVIEW OF 2-D FLOW CAPABILITIES

TYPE	APPROACH	USE	STATUS
BOUNDARY OR MERGED LAYER	FINITE DIFFERENCE, ABLATION COUPLED, EQUILIBRIUM, REAL GAS CHEMISTRY, LAMINAR OR TURBULENT, WITHOUT RADIATION	BASIC STUDIES, SURFACE HEATING, BLOWING CORRECTIONS, ETC.	OPERATIONAL FOR MODEST BLOWING
	SAME AS ABOVE BUT WITH RADIATION COUPLING	SAME	OPERATIONAL FOR MODEST BLOWING
	SAME AS ABOVE BUT WITHOUT TURBULENT FLOW	SAME	OPERATIONAL FOR ALL BLOWING CONDITIONS OF INTEREST
	FINITE DIFFERENCE. FINITE RATE CHEMISTRY NO RADIATION, LAMINAR	SAME	NOT GENERALLY IN USE IN THE PLANETARY ENTRY COMMUNITY ALTHOUGH SOME CAPABILITY EXISTS

FIGURE 5-49

REVIEW OF 2-D FLOW CAPABILITIES

TYPE	APPROACH	USE	STATUS
BOUNDARY OR MERGED LAYER	STREAM TUBE, WITH RADIATION, WITHOUT ABLATION	INTERMEDIATE METHOD, RADIATION COOLING FACTORS, COLD WALL HEAT FLUX DISTRIBUTIONS	OPERATIONAL
	SAME AS ABOVE BUT WITH ABLATION	BLOWN WALL FLUX DISTRIBUTIONS	OPERATIONAL
	INTEGRAL METHOD, REAL GAS EFFECTS, RADIATION COOLING. FACTORS, BLOWING CORRECTIONS, LAMINAR OR TURBULENT	SUPPORT OF HEAT SHIELD SIZING STUDIES	OPERATIONAL
	CORRELATIONS, BLOWING CORRECTIONS FOR CONVECTION, RADIATION	SUPPORT OF HEAT SHIELD SIZING STUDIES	OPERATIONAL FOR CARBON SiO_2

FIGURE 5-50

stream tube method. Typically, they can't handle radiation. They will do things like radiation cooling factors or cold wall heating distributions. If you add ablation they also have some capability, but it is more limited.

If we go into straight integral methods, we can handle most of the items of interest, provided we restrain ourselves to cold wall events - no blowing or whatever - and we have to resort to other types of approximate methods to get the radiation fluxes. These are the methods that I have typically used in support of heat shield sizing.

Finally, we have correlations which, again, will be required for the heat shield sizing. That would include blowing corrections for the convection and the radiation and would refer back to the figure I showed before. Some are available for such ablation species as carbon and SiO_2 and there are efforts underway right now to expand the correlation base.

I would like to go now to Figure 5-51, review of transport properties. This is with application to input to the flowfield calculations. To begin, there is a total properties approach, and this is a classic approach that has been used for years. It was originated by Butler and Brokaw. The entry calculations that have been done with it are almost without number. It is very simple, however, it is restricted to non-varying elemental composition across the layer. And that, in effect, restricts the calculations to no ablation or to ablation of a gas which has the same elemental composition as the environmental gas. So, with that restriction, that approach is losing favor.

There is a series here of three successively more complicated approaches, namely: correlations for such properties as viscosity, diffusivity, thermoconductivity plus equal diffusion; coefficient approximation, bifurcation approximation, actual solution to the first order Chapman; Enskog solutions. These successively

REVIEW OF TRANSPORT PROPERTIES

APPROACH	COMMENT
TOTAL PROPERTIES (BUTLER AND BROKAW)	REQUIRES FIXED ELEMENTAL COMPOSITION (NO ABLATION) RESTRICTED APPLICATION TO PLANETARY PROBLEMS
CORRELATIONS FOR PROPERTIES PLUS EQUAL DIFFUSION COEFFICIENT APPROXIMATION OF LEE'S	ADEQUATE UNTIL SUBSTANTIAL IONIZATION OCCURS
CORRELATIONS FOR PROPERTIES PLUS BIFURCATION APPROXIMATION WITH MULTICOMPONENT DIFFUSION	BETTER THAN EQUAL DIFFUSION APPROXIMATION AT LOW LEVELS OF IONIZATION, BUT ALSO FAILS WHEN SUBTANTIAL IONIZATION OCCURS
CORRELATIONS FOR PROPERTIES PLUS FIRST ORDER CHAPMAN - ENSKOG SOLUTION TO MULTICOMPONENT DIFFUSION	SAME AS ABOVE
HIGHER ORDER SOLUTIONS OR IMPROVED CORRELATIONS	REQUIRED IF TRANSPORT PROPERTIES ARE TO BE SIGNIFICANTLY IMPROVED AT HIGH LEVELS OF IONIZATION

FIGURE 5-51

increase the accuracy of the solutions to the diffusion equations. They all run into trouble when ionization begins to be important. This would, typically, be in the 8,000° to 10,000° Kelvin range. It is my feeling that higher order solutions or improved correlations are required to go above that substantially.

Figure 5-52 reviews the radiation transport codes or properties that are available, detailed codes have been generated and are available from several organizations. They are used in support of basic studies, reduction of experimental data. There is at least one that is available that will support flow coupling calculations. Typically, they are also used to define multi-group radiation models.

Concerning the properties, these have been the subject of a recent review at Langley. It is my feeling - although I haven't read the report yet - that the environmental gases are in good shape; the ablation type gases are somewhat uncertain.

On Figure 5-53 I am going to touch briefly on the status of the experiments. Basically, in terms of laboratory experiments - now this is only in terms of the aerothermal environment simulation and not the material response - certain aspects can be simulated with shock tubes, arcs, lamps, and combined arc-lamp facilities. There is no known facility that will do a full job of just covering the important parameters that exist. Flight experiment feasibility studies indicate promise but a lot of expense. It has been suggested that we consider shuttle as the launch vehicle which may help with the cost problems.

On the final figure, 5-54, I have selected some priorities as to what I think should be done; pretty much in the order that I think they should be done, although, for example, the first one is certainly just a wish, namely, obtain better input on atmospheric composition. I am somewhat in agreement with Jerry; I think we ought to do some fundamental work in upgrading the turbulent model. I think we ought to make an effort to continue

REVIEW OF GAS PHASE RADIATION TRANSPORT

CODES

TYPE	USE	STATUS
DETAILED	BASIC STUDIES REDUCTION OF EXP. DATA	SEVERAL OPERATIONAL
DETAILED	COUPLING TO FLOW FIELD CODE	ONE OPERATIONAL
MULTI-GROUP	COUPLING TO FLOW FIELD CODE	MANY PROPOSED

PROPERTIES

SYSTEM	STATUS
AIR CO_2 - N_2 H_2 - He	GOOD SHAPE
C SiO_2 TFE	UNCERTAIN

FIGURE 5-52

EXPERIMENTAL VERIFICATION

LABORATORY FACILITIES

SPECIFIC ASPECTS OF THE AEROTHERMAL ENVIRONMENT CAN BE SIMULATED IN SHOCK-TUBE, ARC, LAMP, AND COMBINED ARC-CAMP FACILITIES

NO FACILITY EXISTS WHICH WILL PERFORM A FULL SIMULATION OF ALL THE PARAMETERS VIEWED AS BEING IMPORTANT

FLIGHT EXPERIMENT

FEASIBILITY STUDIES INDICATE PROMISE BUT COST IS VERY HIGH FOR RV LAUNCHED EXPERIMENTS

PROSPECTIVE USE OF SHUTTLE AS LAUNCH VEHICLE MAY REDUCE COST PROBLEMS

FIGURE 5-53

SUGGESTED PRIORITIES

1. OBTAIN BETTER INPUT ON ATMOSPHERIC COMPOSITION
2. UPGRADE TURBULENT MIXING LAYER MODELS
3. UPGRADE RADIATION TRANSPORT MODELS TO BE CONSISTENT INDUSTRY - WIDE AND CONSISTENT WITH RECENT LANGLEY REVIEW
4. OBTAIN BETTER RADIATION PROPERTIES FOR ABLATION PRODUCTS
5. CONTINUE GENERATION OF BLOWING REDUCTION CORRELATIONS
6. DEVELOP CORRELATIONS OF INVISCID PARAMETERS INCLUDE EFFECT OF RADIATION
7. PERFORM VERIFICATION TESTS
8. UPGRADE TRANSPORT PROPERTY CORRELATIONS
9. UPGRADE CODES TO CONSIDER NONEQUILIBRIUM EFFECTS

FIGURE 5-54

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making the radiation models that are used throughout the industry consistent so that we can talk about apples and apples instead of apples and oranges. I would like to see something done better with the radiation properties for ablation products. I think we ought to continue worrying about blowing reduction correlations. That is certainly important in terms of planetary entries. I would like to see some development of correlations of the inviscid parameters which include the effect of radiation. That capability exists; it seems a shame it is not being exploited. I think we have to worry the verification tests business further. I would like to see some upgrading of the transport property correlations, and I think that there ought to be some attention given to the non-equilibrium effects.

SESSION VI - HEAT PROTECTION

Chairman: Dr. Phil Nachtsheim
NASA Ames Research Center

MR. VOJVODICH: This is kind of like one of the old western movies where you can tell the antagonists and the protagonists as the guys who wear the black hats and the guys who wear the white hats. We have two different view points here: the traditional approach to the black, carbon phenolic type of heat shield and the white, reflecting heat shield.

DR. NACHTSHEIM: In this session we are going to talk about the evaluation of heat shield materials, development of new heat shield materials, and then the question of simulation. The evaluation will be concerned with the heat shield materials that are very well characterized: the carbon phenolic and graphite heat shields. Those evaluations will be discussed in terms of what was done at the HIP facility in St. Louis and the high-powered laser which is here at Ames. In other words, existing materials with existing facilities. We will talk about the developmental effort on the reflecting heat shield. This concept was introduced several years ago, and most people agree that it's a good idea. The question remains: how do you do this? So, we will be addressing the development of the reflecting heat shield, the silica heat shields; and we will have two papers discussing that. Then, finally, we will discuss the question of simulation. Whether the heat shield be a black heat shield or a white heat shield, we do feel that in order to flight qualify it, it should be evaluated as closely as possible in the environment that we would expect for a planetary entry.

With that, I would like to introduce Sam Mezines from McDonnell-Douglas who will talk about the work he's done on sizing the heat shields for Saturn and Jupiter, and some tests he performed in the HIP facility.