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# PERFORMANCE OF REFLECTING SILICA HEAT SHIELDS DURING ENTRY INTO SATURN AND URANUS

John Howe
NASA Ames Research Center

MR. HOWE: I just want to take a moment to orient some in the audience who may not be familiar with the reflective heat shield concept.

The idea is that you take a material that doesn't absorb radiation, like a window (Figure 6-30) - the radiation will go through it - and you pulverize it and you then use that as your heat shield; that is, you put it back together somehow. But now it's in finely divided particles, and voids, as Bill Congdon just talked about. It still is not absorbing radiation significantly, but it is also not transmitting it. It's back scattering it, reflecting it. This is the whole idea.

We've tried to analyze the performance of silica heat shields in the outer planet environments. Very briefly, I want to show you what's in this analysis (Figure 6-31). This is a picture of the front end of an entry probe, and one has incident radiative flux and convective flux and the surface is ablating. One can divide the radiation into an inward intensity and an outward, backscattered intensity, and one can have a mirrored surface on the back if he wants. For boundary conditions, we insulate the back to see that no heat gets through. This system is described in a set of differential equations: an energy equation, that is the usual heat conduction equation - unsteady - with terms having to do with absorption - where K is the absorption coefficient - the absorption of the outward intensity and the inward intensity; and the emission of radiation because the material gets hot.

These intensities are obtained for each spectral band, "m" for a pair of equations: one having to do with the outward intensity and the other having to do with the inward intensity. All of the properties are temperature dependent; that is thermal conductivity, density, specific heat, absorption coefficient, scat-

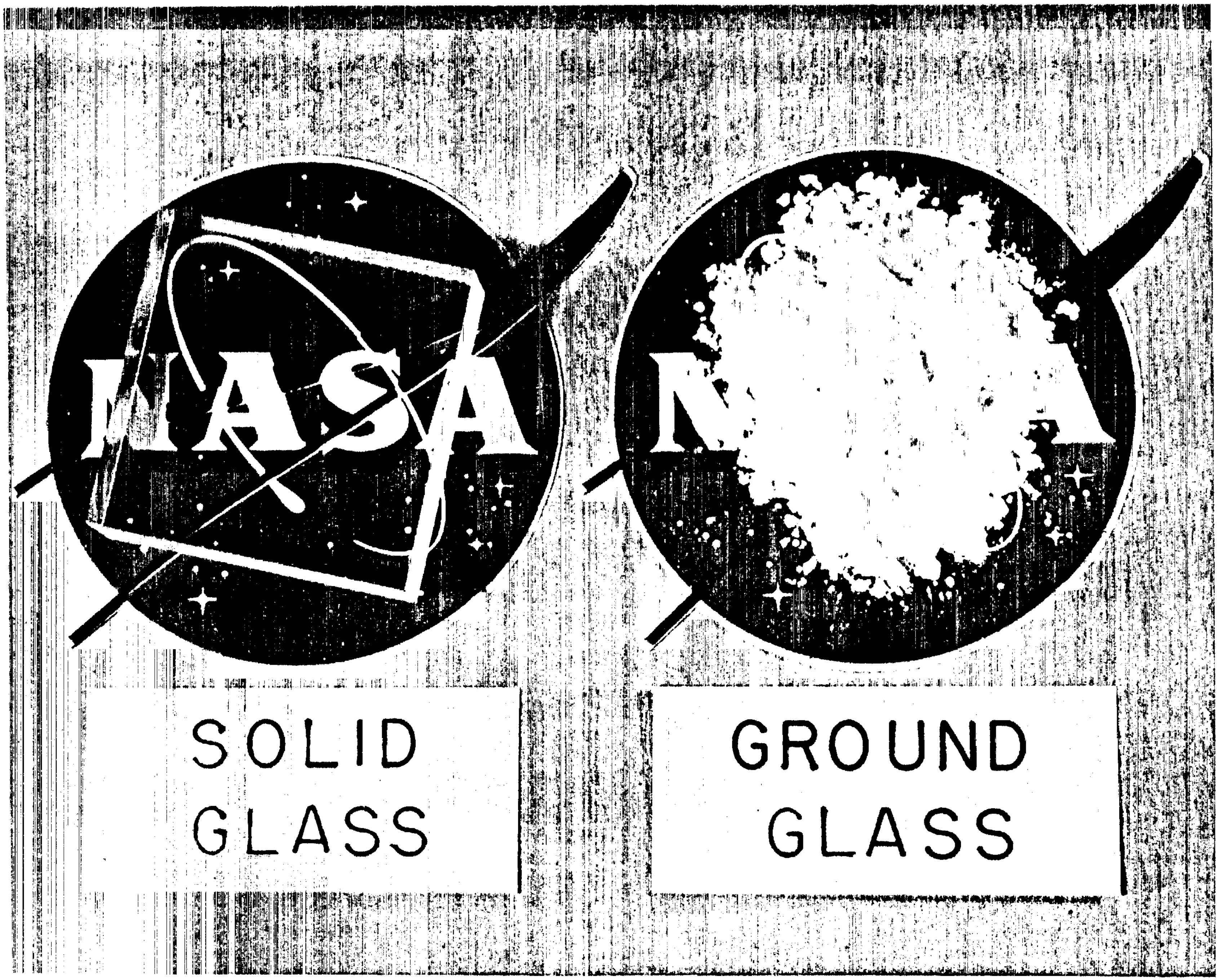
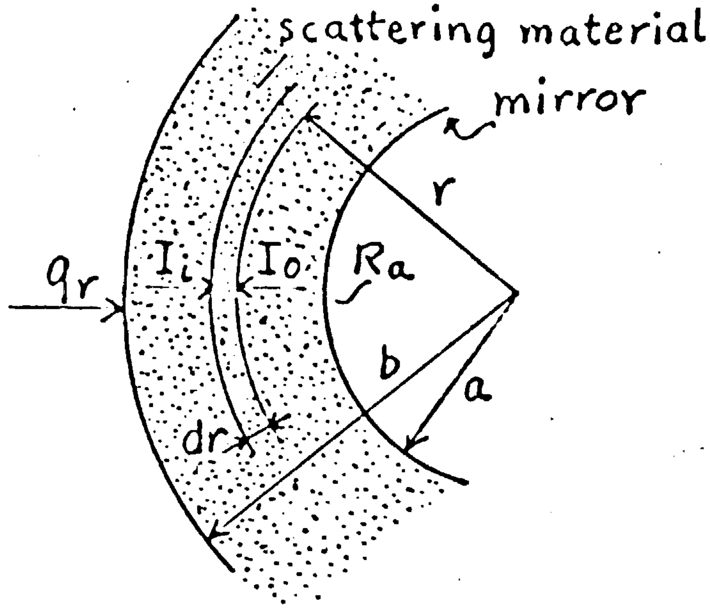



Figure 6-30




I = bidirectional intensity

K = bidirectional absorbtion coefficient ($cm^{-1}$)

S = bidirectional scattering coefficient ($cm^{-1}$)

differential equations:

$$\left.\begin{aligned}\frac{1}{r^2}\frac{d}{dr}(r^2 I_o) &= -(S+K)I_o + SI_i + n^2 K I_B \\ \frac{1}{r^2}\frac{d}{dr}(r^2 I_i) &= (S+K)I_i + SI_o + n^2 K I_B\end{aligned}\right\}$$ 2 equations for each frequency band "m"

$$\rho c_p \frac{\partial T}{\partial t} = -\frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(-r^2 k \frac{\partial T}{\partial r}\right) - r^2 \sum_{m=1}^{M} K_m \pi \left(I_{o_m} + I_{i_m}\right) + 2r^2 \pi \sum_{1}^{M} r_m^2 K_m I_{B_m}\right]$$

FIGURE 6-31

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tering coefficient. The optical properties are not only temperature dependent but they are wavelength dependent. So one has to solve this mess. It's non-linear, and it's coupled, and it's transient; and we've got a scheme for solving that.

I want to show you the results for that. First of all, let me just tell you what some of the properties are that have to go into this. The absorption coefficient is very important, and we want to know what it is as a function of wavelength and temperature. Figure 6-32 shows what we have been able to get out of the literature for a material called Ultrasil. There is data in the catalogs at room temperature. There is some data in a narrow temperature band region near 1600°K by a man named Rupp for certain wavelengths; and then Spivak, in the infrared end of the spectrum, has some data that goes out fairly uniformly over a broad temperature range. But, clearly, we need more data in the intermediate range, and we need some higher temperature data on absorption coefficient. You can see that the absorption varies wildly with temperature - orders of magnitude - and this is built into our code.

The scattering coefficient shown in Figure 6-33 tells you how much radiation is reflected. With high scattering, there is high reflection. The bottom curve is the scattering coefficient for a fibrous astroquartz laminate - fibre size of five or six microns - and it's really not a very high scattering coefficient - something like 40 reciprocal centimeters - at the most. The upper curve is a slipcast silica, Glasrock. It's a commercially available fused silica and it's not particularly good, either, but we are going to use both of these and show the effects.

Theoretically, I think that one can come up with a scattering coefficient that's about twice as good as this Glasrock, depending on the void size, and so forth, as Bill Congdon just talked about. You can see that the Glasrock is far better than the fibrous material.

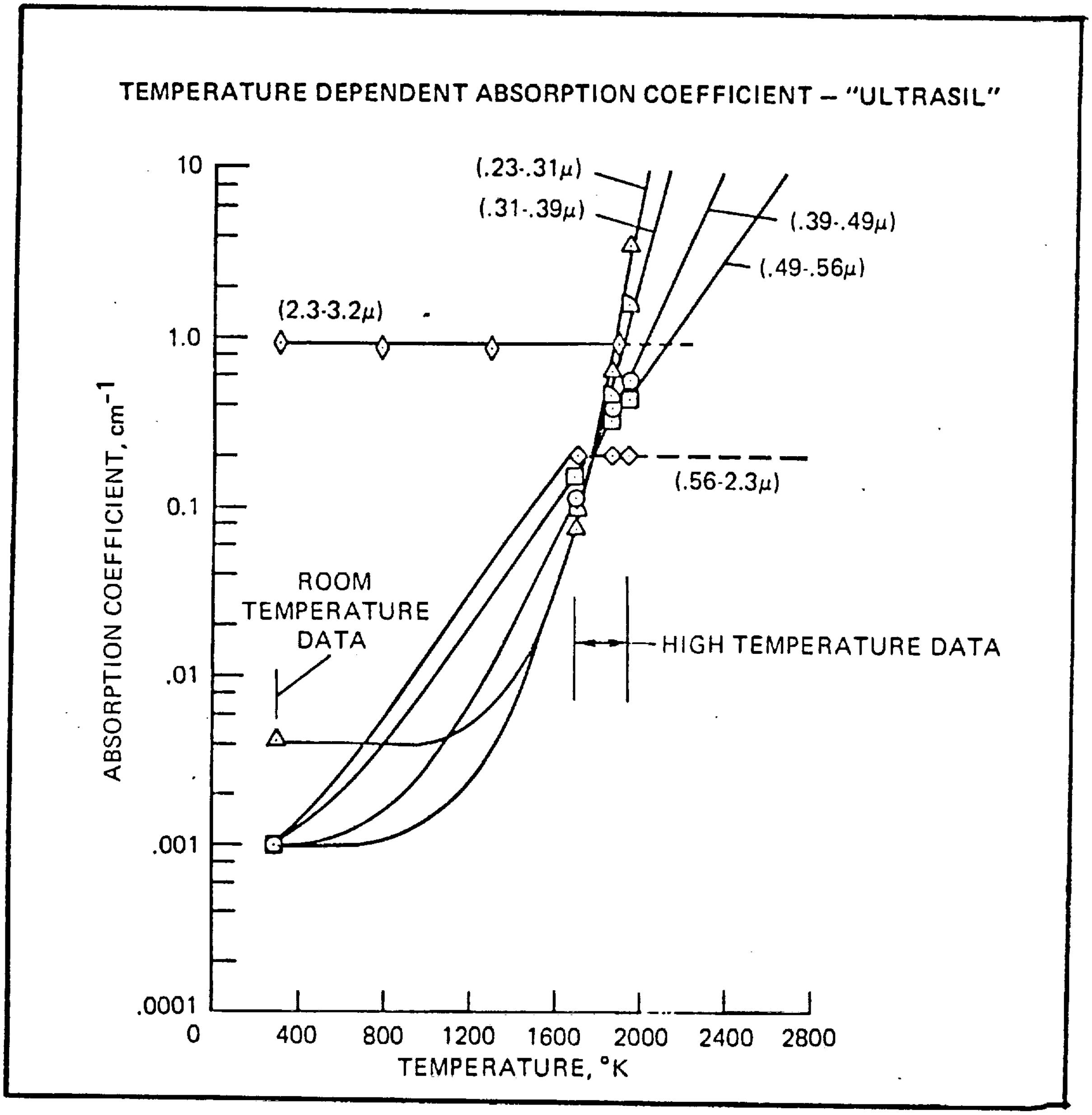


FIGURE 6-32



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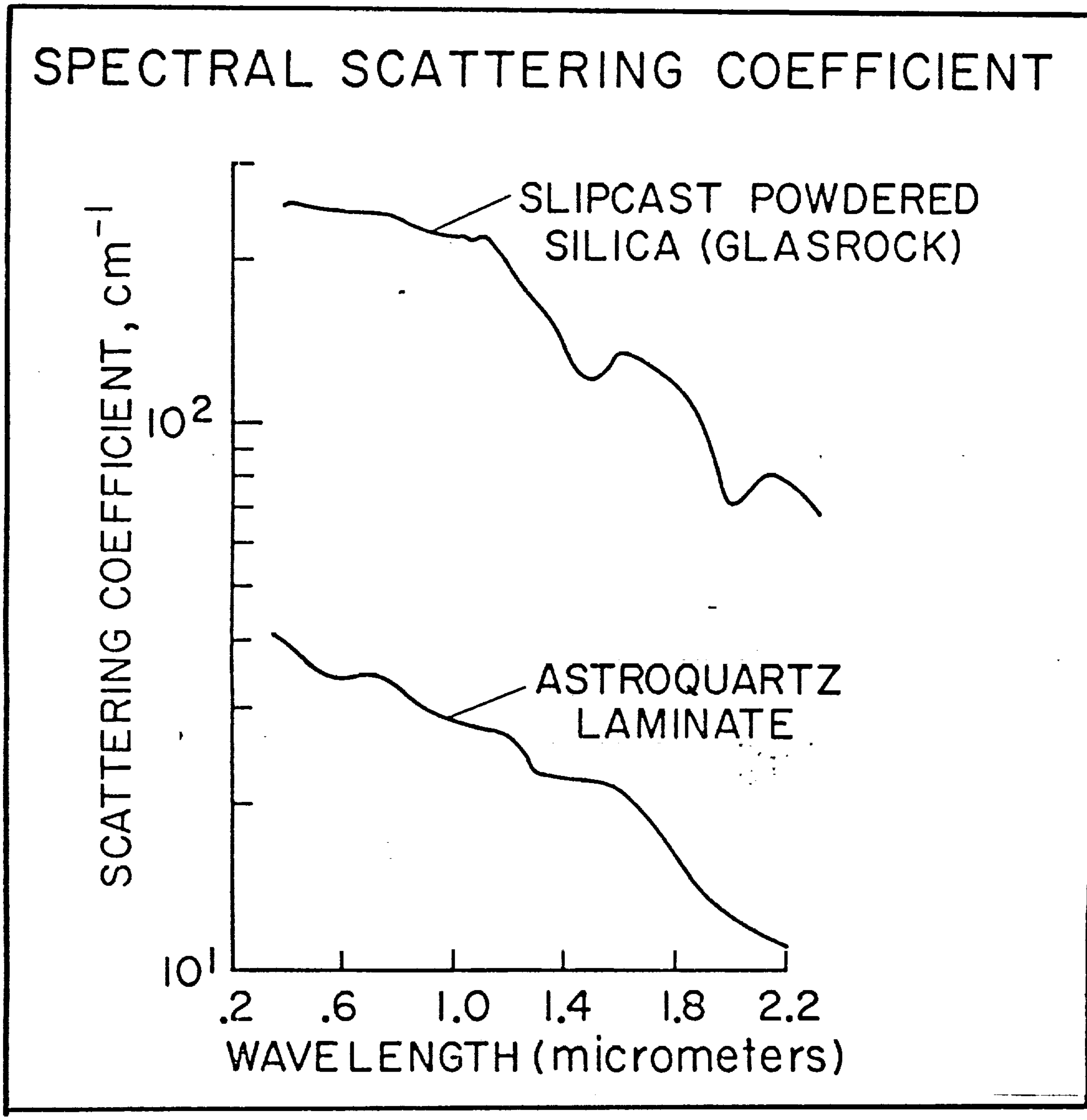

SPECTRAL SCATTERING COEFFICIENT
SLIPCAST POWDERED SILICA (GLASROCK)
ASTROQUARTZ LAMINATE
SCATTERING COEFFICIENT, cm$^{-1}$
10$^2$
10$^1$
.2
.6
1.0
1.4
1.8
2.2
WAVELENGTH (micrometers)

FIGURE 6-33

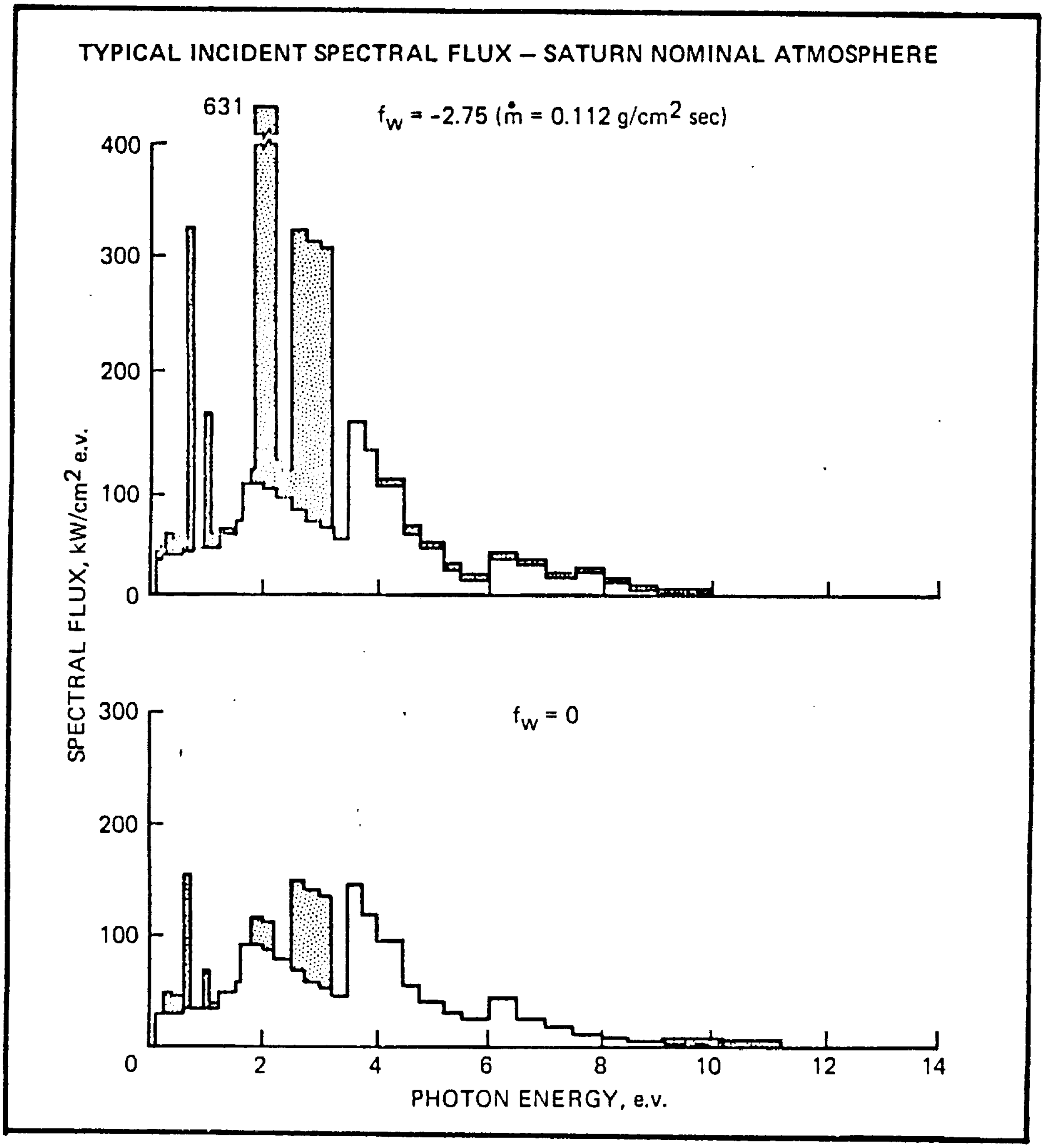
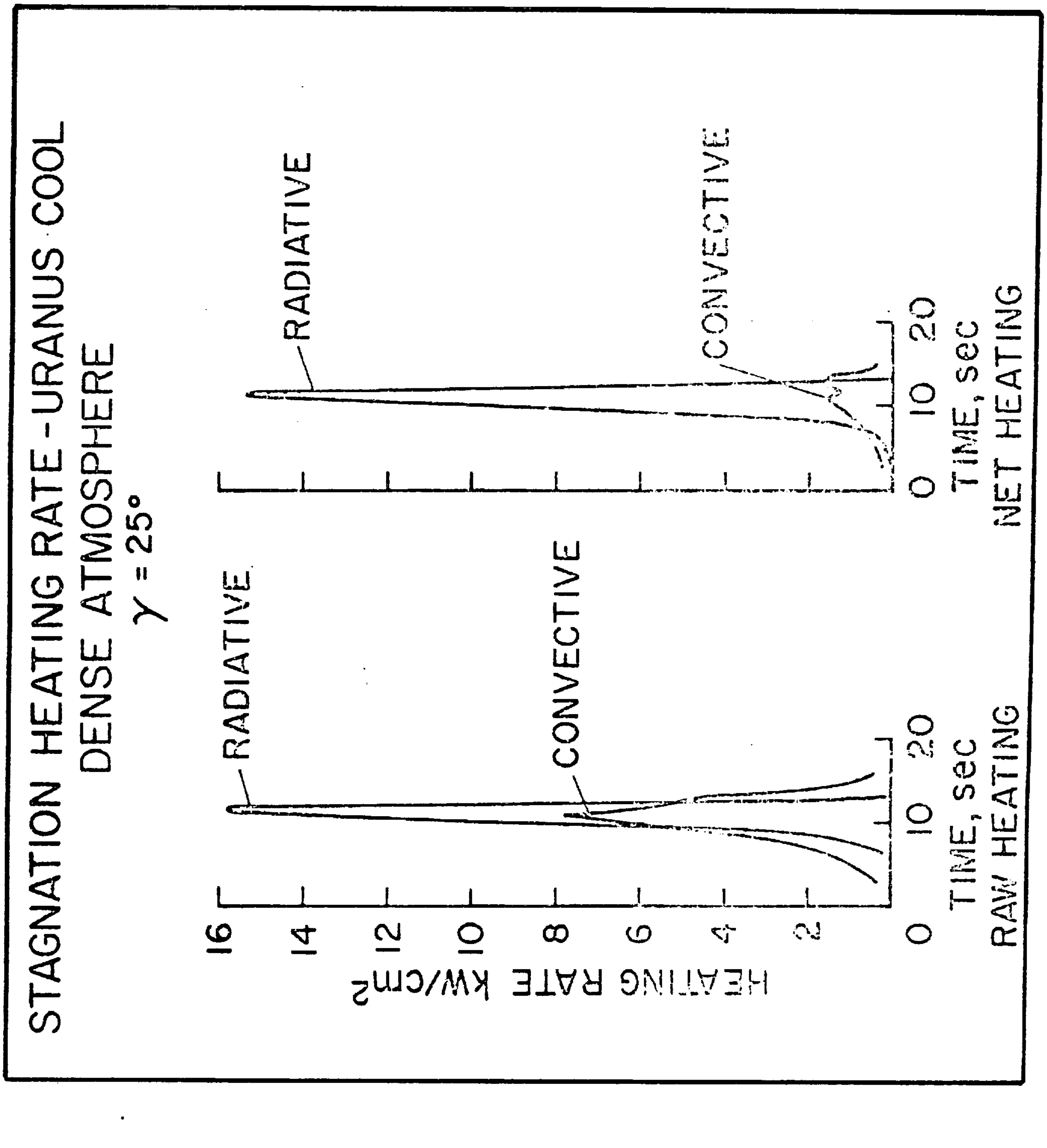

TYPICAL INCIDENT SPECTRAL FLUX – SATURN NOMINAL ATMOSPHERE
631
fw = -2.75 (ṁ = 0.112 g/cm2 sec)
400
300
200
100
0
SPECTRAL FLUX, kW/cm2 e.v.
fw = 0
300
200
100
0
2
4
6
8
10
12
14
PHOTON ENERGY, e.v.

FIGURE 6-34



STAGNATION HEATING RATE - URANUS COOL
DENSE ATMOSPHERE
γ = 25°
HEATING RATE KW/cm2
16
14
12
10
8
6
4
2
0
RADIATIVE
CONVECTIVE
10
20
TIME, sec
RAW HEATING
RADIATIVE
CONVECTIVE
0
10
20
TIME, sec
NET HEATING


FIGURE 6-35

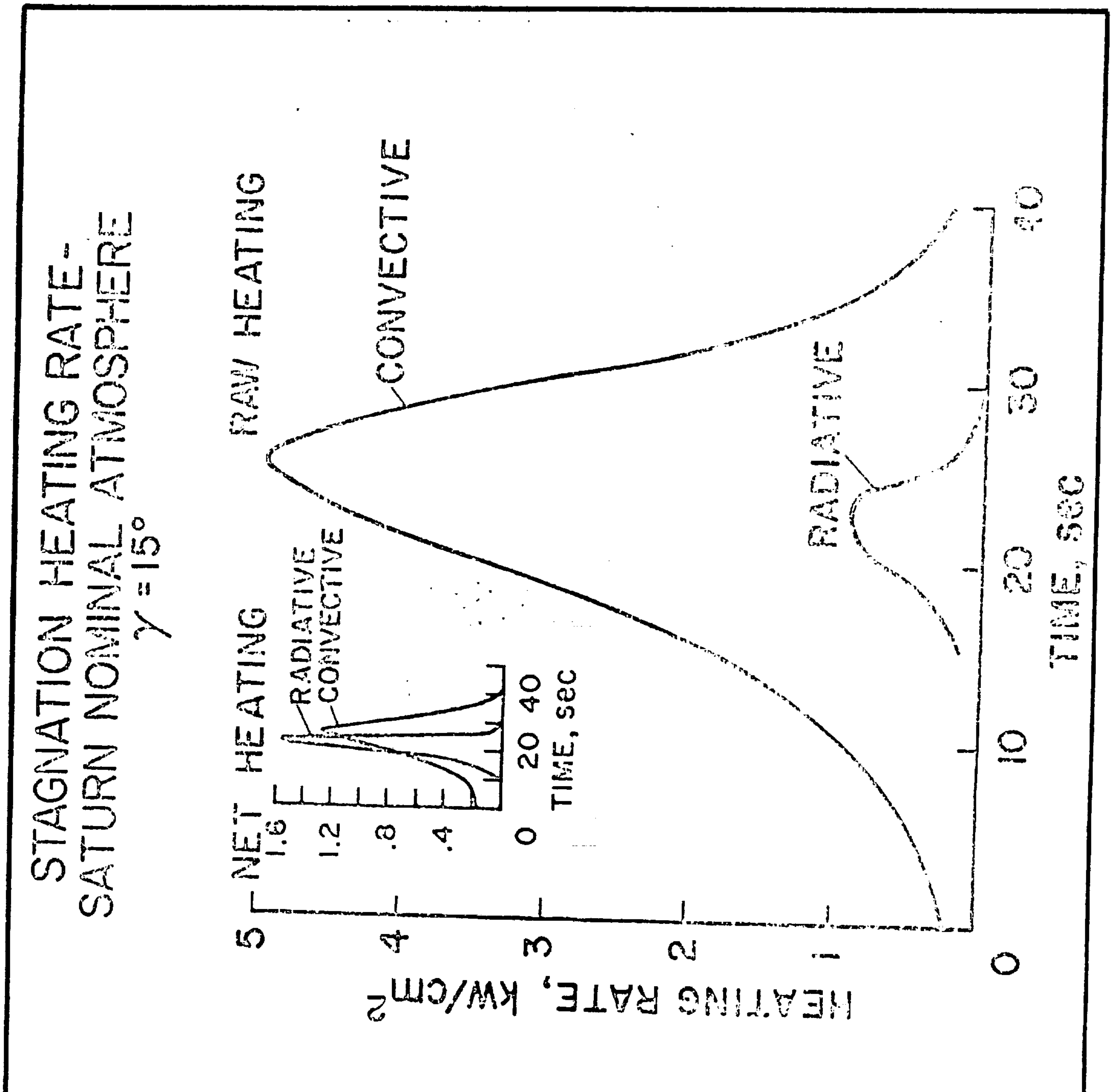



FIGURE 6-36

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# MATERIAL RESPONSE FOR 25° ENTRY INTO URANUS
## COOL DENSE ATMOSPHERE
$\delta_0 = 2$ cm

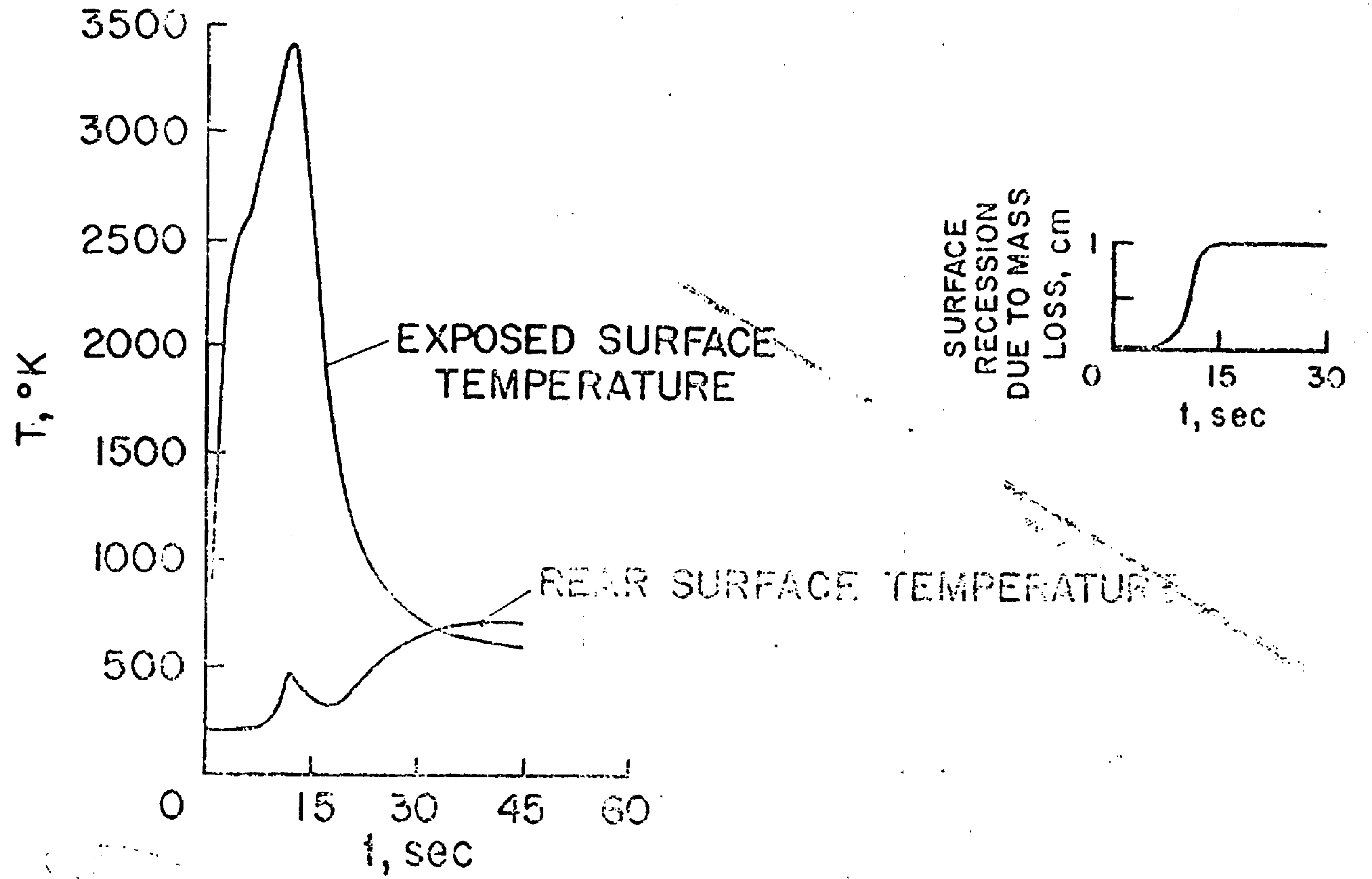


FIGURE 6-37

the front surface temperature rises rather sharply because some of the radiation bands are absorbed right on the surface. So the front surface temperature passes through a peak corresponding to both the radiation and the convection pulse and then begins to cool down so that when a subsonic mach number (of 0.7 here) is reached, the front surface is really quite cool. It's being cooled by the atmosphere flowing over it.

The interesting thing is that the rear surface temperature doesn't really see any heat at time zero; but, when that radiation pulse comes on, some of that gets through instantaneously to the back surface. This is a finite thick slab. Not all of the radiation is reflected, some of it is deposited there. So, this shoots the rear surface temperature up to a little peak and, as the light goes out, or the radiation diminishes, that begins to drop down. But, then conduction from the hot front surface finds its way through the material and the back surface temperature begins to rise again. For this particular case we lost about a centimeter of material due to ablation for this 2 centimeter thick shell.

Figure 6-38 shows the corresponding temperature profiles at various points in time. The peak temperature was at about twelve seconds, and it's dropping at sixteen seconds; at twenty-three seconds there is some heat flowing toward the front as well as heat flowing toward the rear; and at forty-six seconds it's a fairly uniform temperature - everything is over.

Figure 6-39 shows a thicker slab going into the same atmosphere, but I want to show you something. The previous two figures use the Glasrock scattering coefficient, and I noted that there was just a small temperature rise at the back surface when the radiation came on. But if we use the Astroquartz scattering coefficient, which is nowhere near as good, the rear surface temperature really shoots up. So, you see how important this is. The rear surface temperature, essentially, designs the heat shield. If you are going to have a low rear surface temperature,

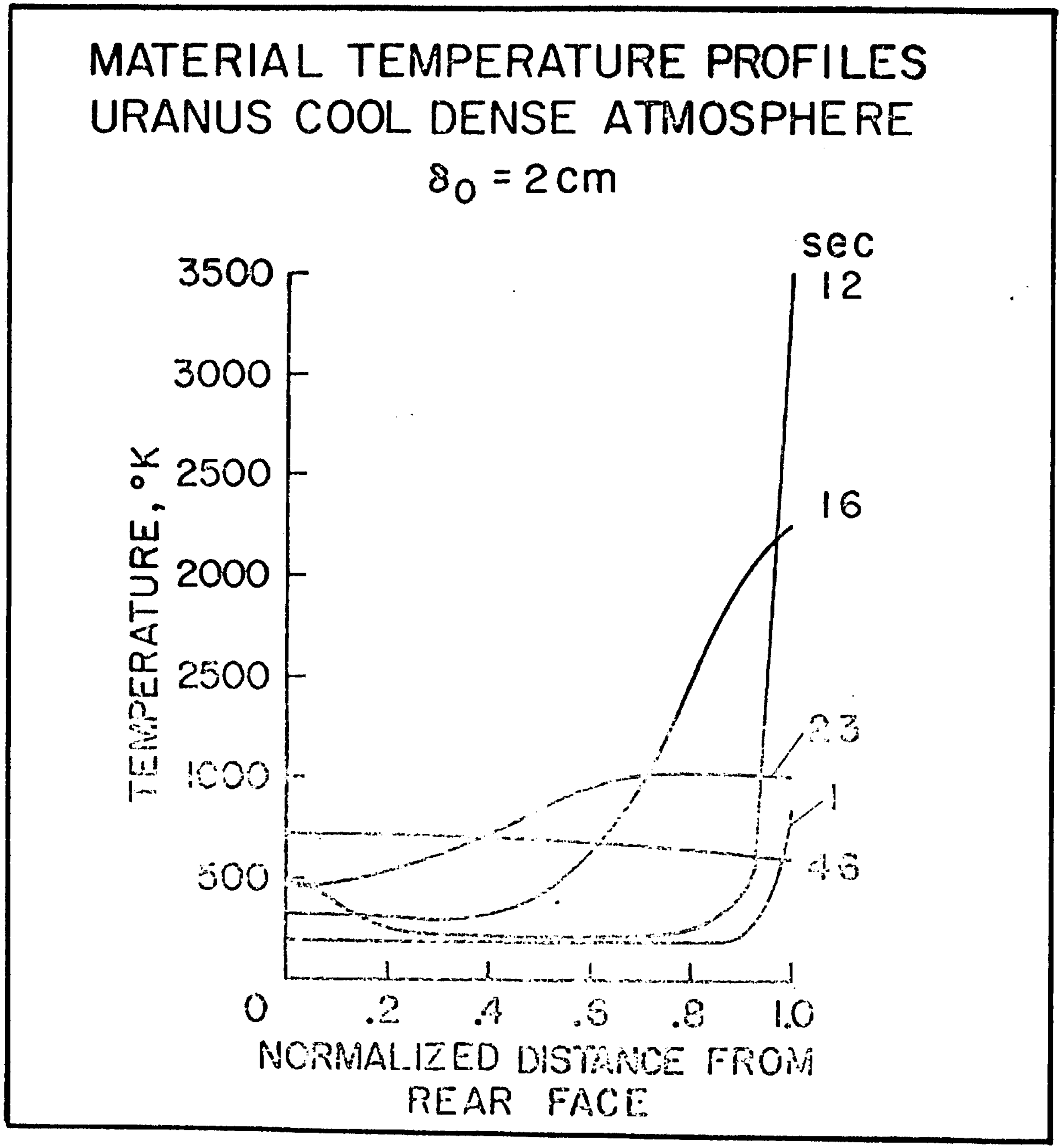
MATERIAL TEMPERATURE PROFILES
URANUS COOL DENSE ATMOSPHERE
$\delta_o = 2\,cm$
sec
12
16
2.3
1
4.6
3500
3000
2500
2000
2500
1000
500
0
.2
.4
.6
.8
1.0
TEMPERATURE, °K
NORMALIZED DISTANCE FROM REAR FACE

FIGURE 6-38

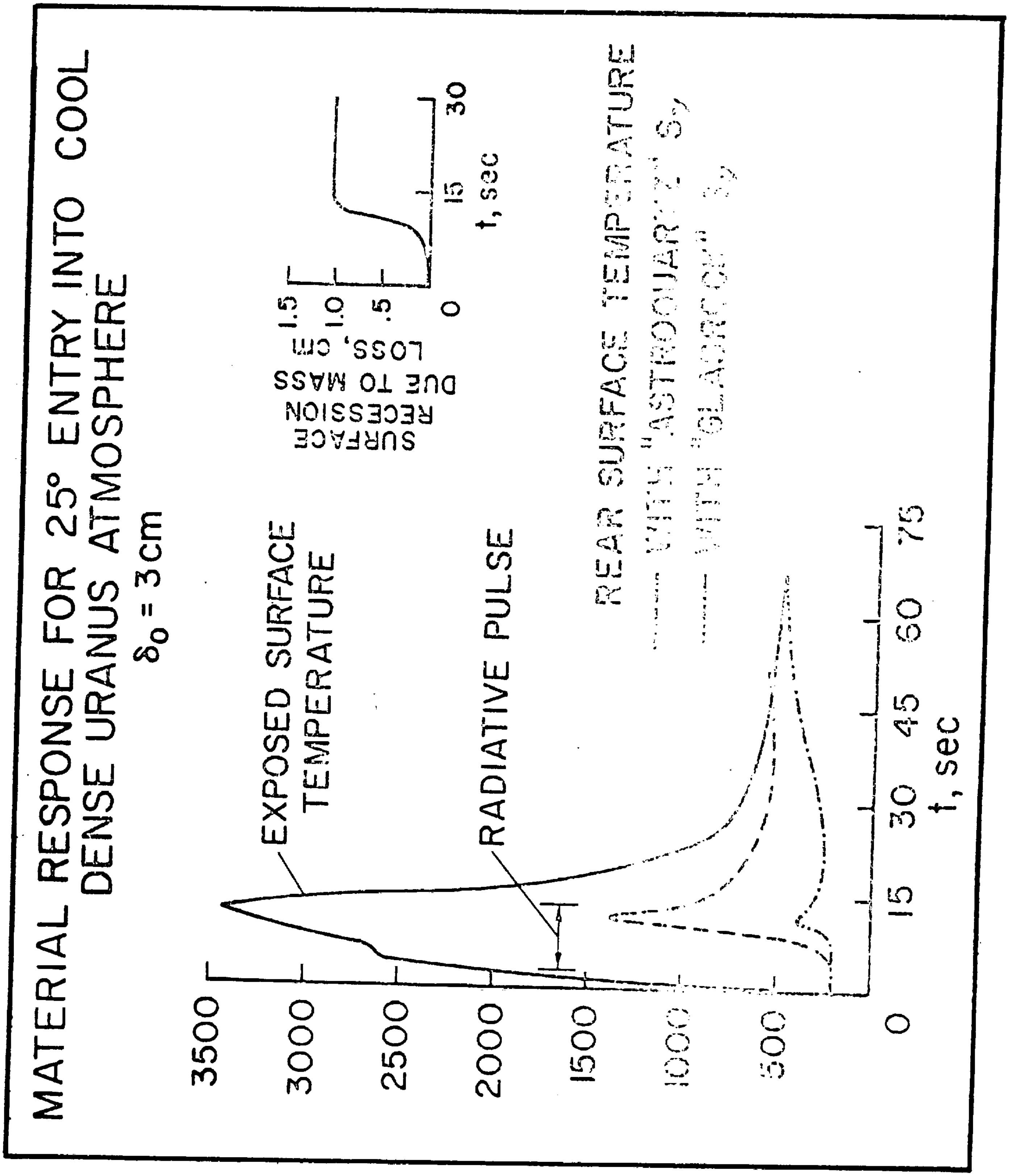
MATERIAL RESPONSE FOR 25° ENTRY INTO COOL DENSE URANUS ATMOSPHERE
δo = 3 cm
EXPOSED SURFACE TEMPERATURE
RADIATIVE PULSE
REAR SURFACE TEMPERATURE
WITH "ASTROQUARTZ"
SURFACE RECESSION DUE TO MASS LOSS, cm
1.5
1.0
.5
0
15
30
t, sec
3500
3000
2500
2000
1500
1000
500
0
15
30
45
60
75
t, sec

FIGURE 6-39

you have to have a high scattering coefficient. Going from Astroquartz to Glasrock, effectively knocks that rear surface temperature by a thousand degrees, Kelvin. So, this is really great; you can get by with thinner heat shields with the higher scattering coefficient. If we can, indeed, double the scattering coefficient above Glasrock, we can go thinner yet.

Figure 6-40 shows a result for the nominal Saturn atmosphere at a 15° entry; we saw the environment in Figure 6-36. This is just a one and a half centimeter thick shell; not thick enough it turns out, because the rear surface temperature goes up to almost 1700° or 1800° Kelvin. This is essentially due to the conduction from the front face through. On this one we lost about three quarters or eight tenths of a centimeter of thickness due to ablation.

A Jupiter case is shown in Figure 6-41. It is five centimeters (original thickness) shell, and you can see the case wasn't quite finished. It's been finished since this slide was drawn. The surface temperature goes up quite high - around 3500°K. This is a 20" entry into Jupiter, which is very severe. The radiative heating is something like a hundred kilowatts per square centimeter - up in the extreme range that John Lundell talked about - so this is really a very hard entry. We lose about two and a half centimeters of material. The rear surface temperature doesn't go very high, something around 400 or 500 degrees Kelvin. So this is thicker than we need.

We have made quite a number of runs for these three planets, one entry angle for each planet. We haven't really run any extensive parametric studies as yet, but we have summarized the results of these studies on Figure 6-42.

As I mentioned, the backface temperature essentially designs the heat shield. This Figure is for a heat shield density of 1.49 grams per centimeter cubed which is about the same as the carbon phenolic density that Sam Mezines discussed. The figure is for the Glasrock scattering coefficient.

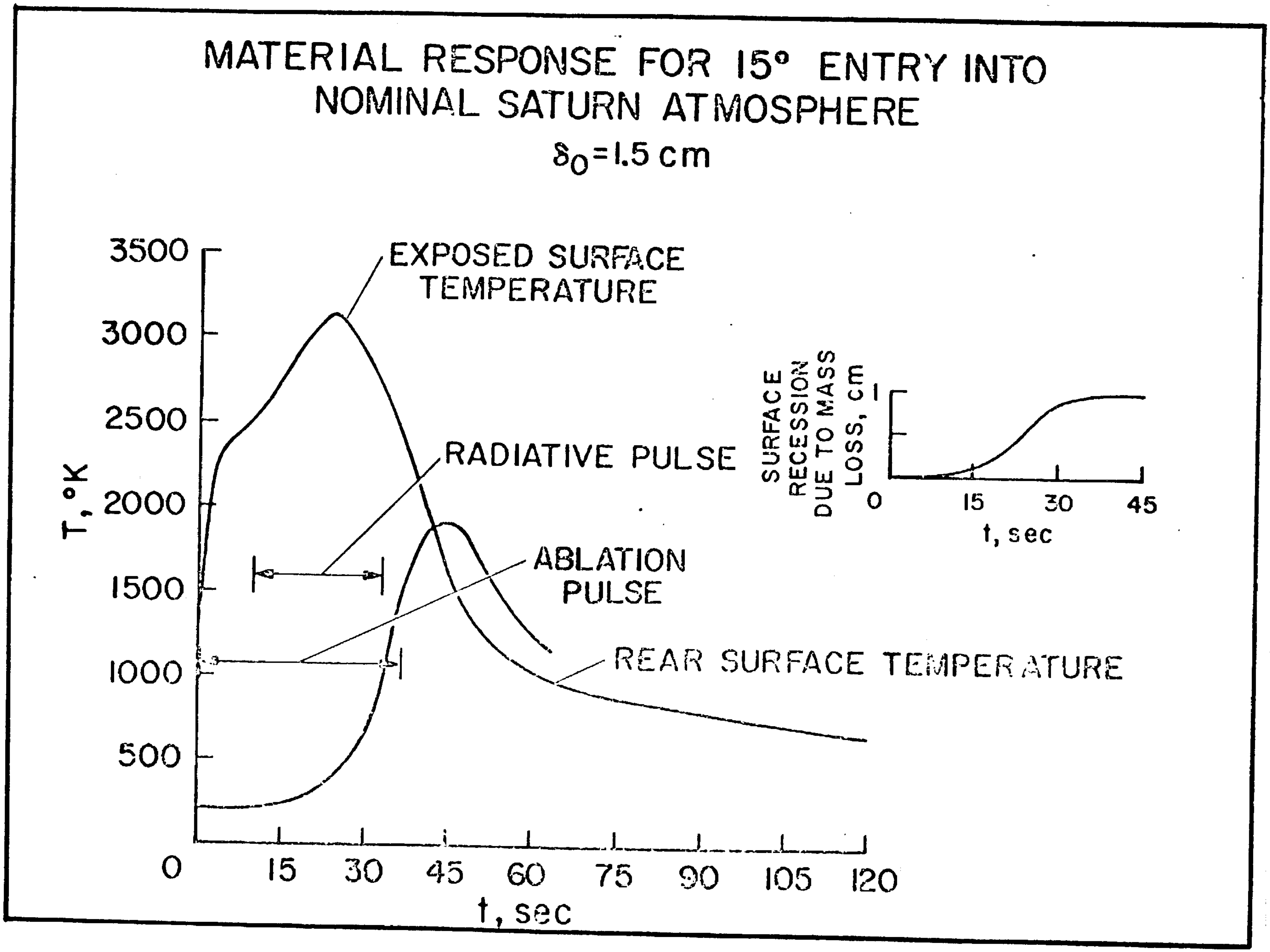
MATERIAL RESPONSE FOR 15° ENTRY INTO
NOMINAL SATURN ATMOSPHERE
δ0=1.5 cm
EXPOSED SURFACE TEMPERATURE
RADIATIVE PULSE
ABLATION PULSE
REAR SURFACE TEMPERATURE
SURFACE RECESSION DUE TO MASS LOSS, cm
T, °K
t, sec
3500
3000
2500
2000
1500
1000
500
0
15
30
45
60
75
90
105
120

FIGURE 6-40

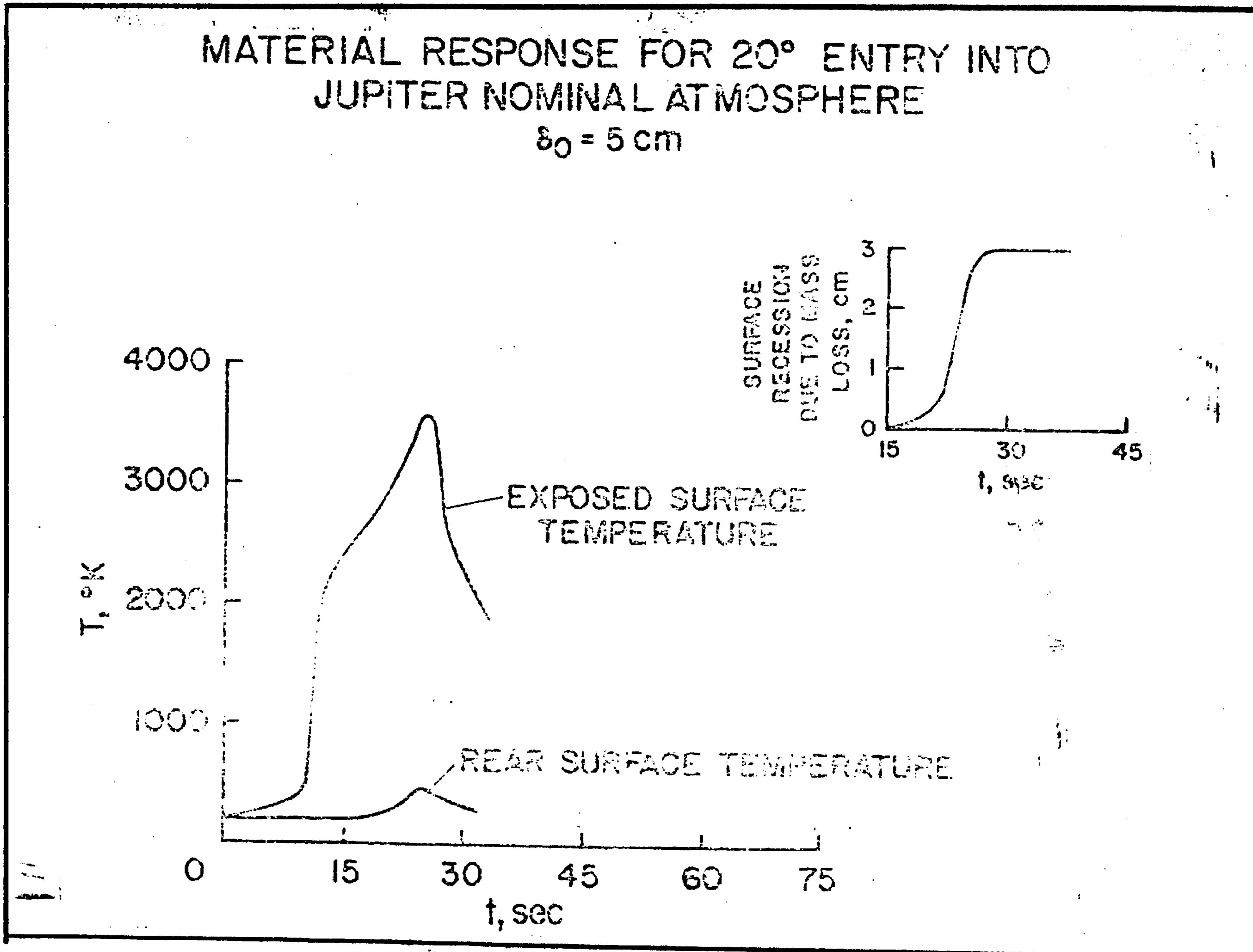


FIGURE 6-41

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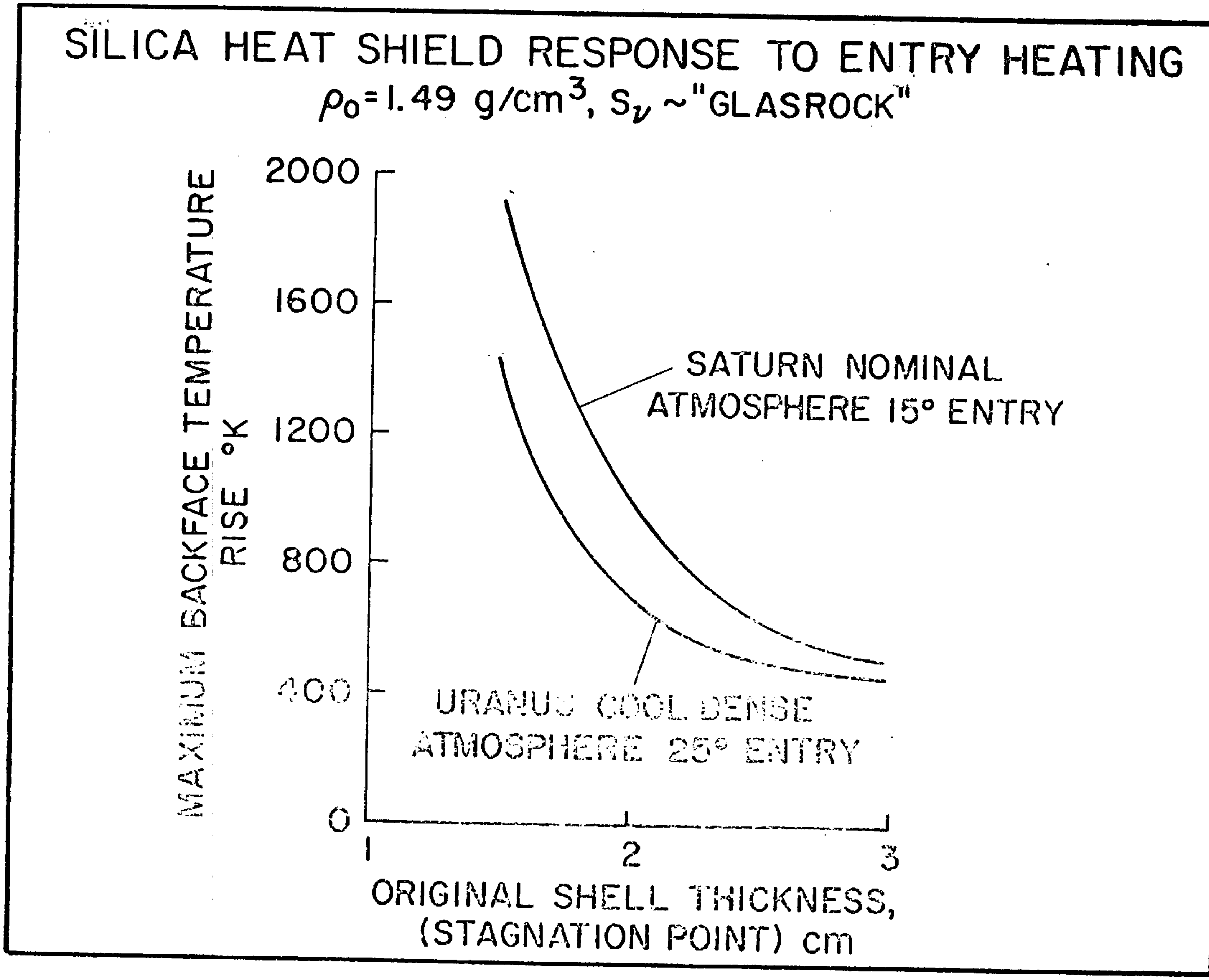
SILICA HEAT SHIELD RESPONSE TO ENTRY HEATING
$\rho_0$=1.49 g/cm$^3$, $S_\nu$ ~"GLASROCK"
MAXIMUM BACKFACE TEMPERATURE RISE °K
2000
1600
1200
800
400
0
1
2
3
SATURN NOMINAL ATMOSPHERE 15° ENTRY
ATMOSPHERE 25° ENTRY
ORIGINAL SHELL THICKNESS, (STAGNATION POINT) cm

FIGURE 6-42

The figure shows rather surprisingly, perhaps, that it is easier to go into the Uranus cool dense atmosphere than it is into the Saturn nominal atmosphere; the reason being, this is essentially a radiative environment and this heat shield just doesn't accept the radiation. It back-scatters it. So it is pretty easy in terms of backface temperature rise. What it tells us is that if we are limited to, say, 700 degrees Kelvin backface temperature, (that corresponds to Sam Mezines' 800 degree Fahrenheit interface temperature), you can get into the Uranus cool dense atmosphere with a less than two centimeters thick shell, into the Saturn atmosphere with a little over a two centimeter shell, and into Jupiter with four centimeters. That comes out to about 1.56 inches of heat shield for the 20-degree Jupiter entry. And that is really a severe environment. So silica really looks very attractive for severe radiative environments.

I think one thing that this silica heat shield could do is broaden the entry envelope into these planets, if that is of any interest for other mission considerations.

So these are the results so far, and we are busy trying to extend these results to other entry angles, other atmospheres.

UNIDENTIFIED SPEAKER: The vitrification process, is that as simple as surface melting that then propagates back through the silica material?

MR. HOWE: We don't have that modeled in great detail. What we have is a density change; that is, when we reach a certain temperature we say the material from then on is transparent; it no longer scatters. So, we have that built in, but we don't have it modeled in any great detail.

UNIDENTIFIED SPEAKER: Isn't the temperature like 3200° or something like that? I thought maybe your peak temperature would have melted the surface.

MR. HOWE: Oh, yes; there's a region at the front of it that's melted and is no longer back scattering. The scattering is being done in the depths.

UNIDENTIFIED SPEAKER: A question of clarification: Were you limited to 800°F temperature, or temperature rise, because you have plotted there a temperature rise?

MR. HOWE: That 800°F was a design temperature that McDonnell Douglas used for the interface temperature between insulation and the heat shield. The ordinate on Figure 6-42 is really absolute temperature, I shouldn't have said temperature rise.

MR. LEIBOWITZ: Does the performance of this heat shield change dramatically for a very intense Jupiter entry where the peak radiation falls below two thousand angstroms?

MR. HOWE: That is about 6 e.v. at the peak. It will reflect effectively in wavelengths between about 0.5 and 6.0 e.v. Those are the constraints for this. So, if it falls into the vacuum ultraviolet - I guess that's what you are thinking?

MR. LEIBOWITZ: Yes.

MR. HOWE: Well, then, it's not going to reflect. Actually, my own opinion is if you have radiation in the vacuum ultraviolet the material won't see it anyway; it will be absorbed by all the molecular species in the gas phase - in the boundary layer.

GEORGE DEUTSCH: I notice that you dealt with an appreciable thickness above the liqueous temperatures of the silica; what's to keep that from simply flowing away?

MR. HOWE: I think that a melt layer that flows along the body would be very thin, George. Bill Nicolet took a look at that in an earlier stage of the Saturn-Uranus studies and concluded that it was really a thin melt layer. These temperature profiles are quite sharp, and the material is eroding at a great rate; so that the primary mass loss is due to the thermochemical erosion normal to the surface.

UNIDENTIFIED SPEAKER: It looks like the equations you first showed were spherical coordinates. Are all of these spherical coordinates?

MR. HOWE: Oh, there's a little exponent in there. If you set it to one it's a spherical geometry, and if you set it to zero it's a slab.

UNIDENTIFIED SPEAKER: But it's either a slab or a sphere?

MR. HOWE: Yes, if we want to do a cone, those are essentially slabs. That is, these are very thin shells, with large internal radii. So, I think a slab would do us well anywhere except at the stagnation point. And even there it is pretty accurate.

SAM MEZINES: Based on the fact that you got most of the heat shield requirements from the shock layer radiation contributions, would a shallow Jupiter entry with higher convective heating require more heat shield than you have shown here?

MR. HOWE: I don't really know, Sam; it's a possibility. We would like to try that seven and a half degree angle Jupiter case to find out. These are not trivial things to run, I might mention. In order to get one case, somebody has to stay up all night - me. We are trying to improve that situation.