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TESTS OF HEAT SHIELD MATERIALS IN INTENSE LASER RADIATION

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MR. LUNDELL: As shown above, I have changed the title of the talk from what's listed in the program for several reasons. First of all, I don't think in fifteen minutes we can review the work that's been done on the behavior of graphitic materials in intense heating environments. Secondly, I thought you might be more interested in some very recent results we got testing heat shield materials under intense radiation in our gas dynamic laser.

Figure 6-9 schematically presents our gas dynamic laser. The facility was funded by Paul Tarver, at Headquarters, several years ago when it became apparent that the only way we would get radiative rates of interest for planetary entry - particularly Jovian entry - was to have a laser. It is a gas dynamic laser in which we burn CO to CO_2. It lases at 10.6 microns and produces a continuous output at powers up to about 45 kilowatts. For the test I'll describe today we focused the beam with a one and a half meter focal length mirror and simply re-imaged its focal point on the target, which is sitting out in a room environment. We did have a nitrogen jet blowing in front of the target. It was spaced away from the target such that it was not impinging on the target to cool it. The motive here was to try to blow the plume away.

In some early work we did on graphite in the laser, we found that at low intensities the plume could effectively block about two thirds of the incident radiation, so we wanted to blow it away and let as much radiation get to the target as possible. Thus, the beam impinges on the target, and what we do is measure the time from the moment it impinges until it first burns thru. That is, we are measuring burn-thru time. We do that with either TV or movie cameras, and we also measure the surface temperature

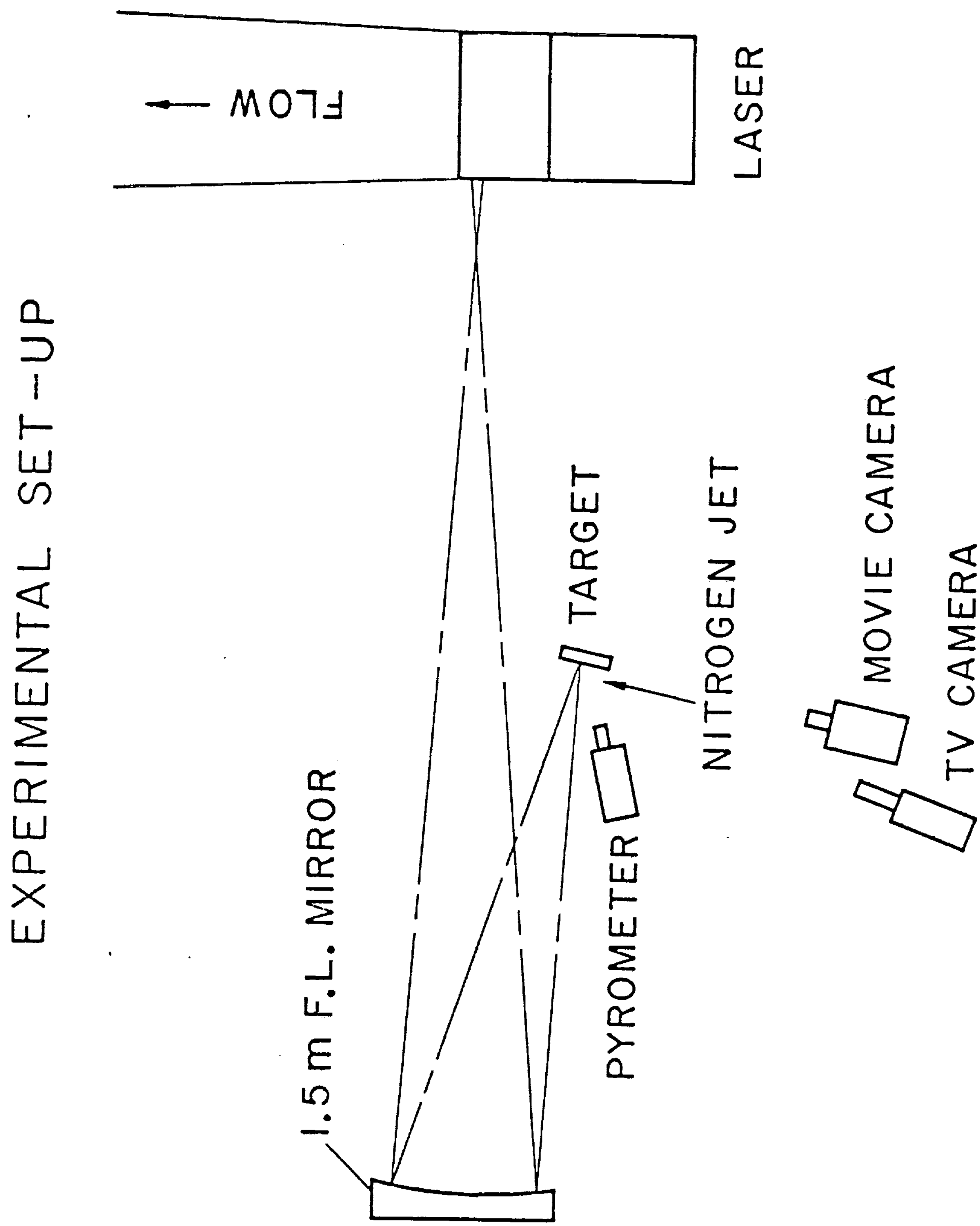
EXPERIMENTAL SET-UP
FLOW
LASER
TARGET
NITROGEN JET
MOVIE CAMERA
TV CAMERA
PYROMETER
1.5 m F.L. MIRROR

Figure 6-9

by focusing an automatic optical pyrometer on the irradiated spot on the target.

Figure 6-10 shows the test conditions. We looked at three different materials: ATJ graphite, which is a representative, fine-grain graphite typical of what's being used for ballistic missile nose tips today; Carbitex 100 is a carbon-carbon composite which is made by Carborundum Corporation. We found in our preliminary survey of a lot of different materials, in the laser, that Carbitex was the best carbon-carbon composite that we tested. The third material is a phenolic carbon. This is representative of what's being used as a heat shield material on ballistic missiles today. These models were furnished by McDonnell Douglas, St. Louis. Carbon phenolic is simply made by stacking up layers of carbon cloth and then, essentially, gluing them together with a phenolic resin.

We placed the models in the laser beam at a point where we had about a third of a square centimeter irradiated spot. We had to go to that small a spot in order to get intensities of interest. So, what we did, then, was to leave the models at the same point in the beam and vary the output power of the laser from essentially four to 35 kilowatts. If we divide these power numbers by the area of the irradiated spot, we come up with the indicated average intensities: from ten to 92 kilowatts per square centimeter; in English units, from 9,000 to 81,000 BTU's per square foot per second. Now I want to emphasize that these numbers are the average intensity. The laser does not have a spatially uniform output beam; it's more Gaussian. So, the peak intensity may be a factor of two or more above the average intensity; at this time, I don't know the ratio of the peak to average intensity. You should note that the burn-through time is probably more closely related to the peak intensity than the average intensity.

Incidentally, we selected these conditions so that the lowest intensity would represent entry into Jupiter using the warm at-

TEST CONDITIONS

MATERIALS: ATJ GRAPHITE

CARBITEX 100

MDAC PHENOLIC CARBON

EXPOSED AREA: 0.377 cm^2

POWER	AVERAGE INTENSITY	
3.86 kw	10.2 kw/cm^2 ;	9,000 Btu/ft^2-sec
19.2	51.0	44,900
34.7	92.1	81,200

Figure 6-10

mosphere, at about a six-degree angle. The intermediate intensity represents a nominal atmosphere, going in at about seven degrees; and the highest intensity represents the cold atmosphere, going in at about nine degrees.

Figure 6-11 shows the results we obtained at the lowest intensity, namely, an average intensity of 9,000 BTU/FT^2-sec. What I am plotting here then is, essentially, the target thickness against the burn-through time. For each of these materials we ran three or four different thicknesses from about an eighth of an inch up to in excess of a half inch. As you can see, the curves, then, to obtain a burn-through velocity or the velocity at which the beam penetrates into the material.

We find that for this condition ATJ graphite has the lowest penetration velocity, about an eighth of an inch per second; and the carbon phenolic was in excess of a half inch per second; and the carbitex fell in between.

Figure 6-12 shows the results we obtained at the intermediate intensity. Here I am plotting the same coordinates. The relative ranking in the materials is the same: ATJ has the lowest velocity, then the Carbitex, and then the Phenolic carbon. Note that we are up to penetration velocities in the order of one to almost two inches per second.

Figure 6-13 shows the results for the highest intensity; up around 81,000 BTU/FT^2-sec. The relative ranking in the materials is still the same: ATJ is the lowest and phenolic carbon the highest. However, you will note now that the materials are all kind of coalescing together as far as performance goes. We have penetration velocities from 2.2 up to about two and three quarter inches per second. For the carbon phenolic point, for example, the thickest model was 1.08 inches and the beam penetrated that in about .39 seconds.

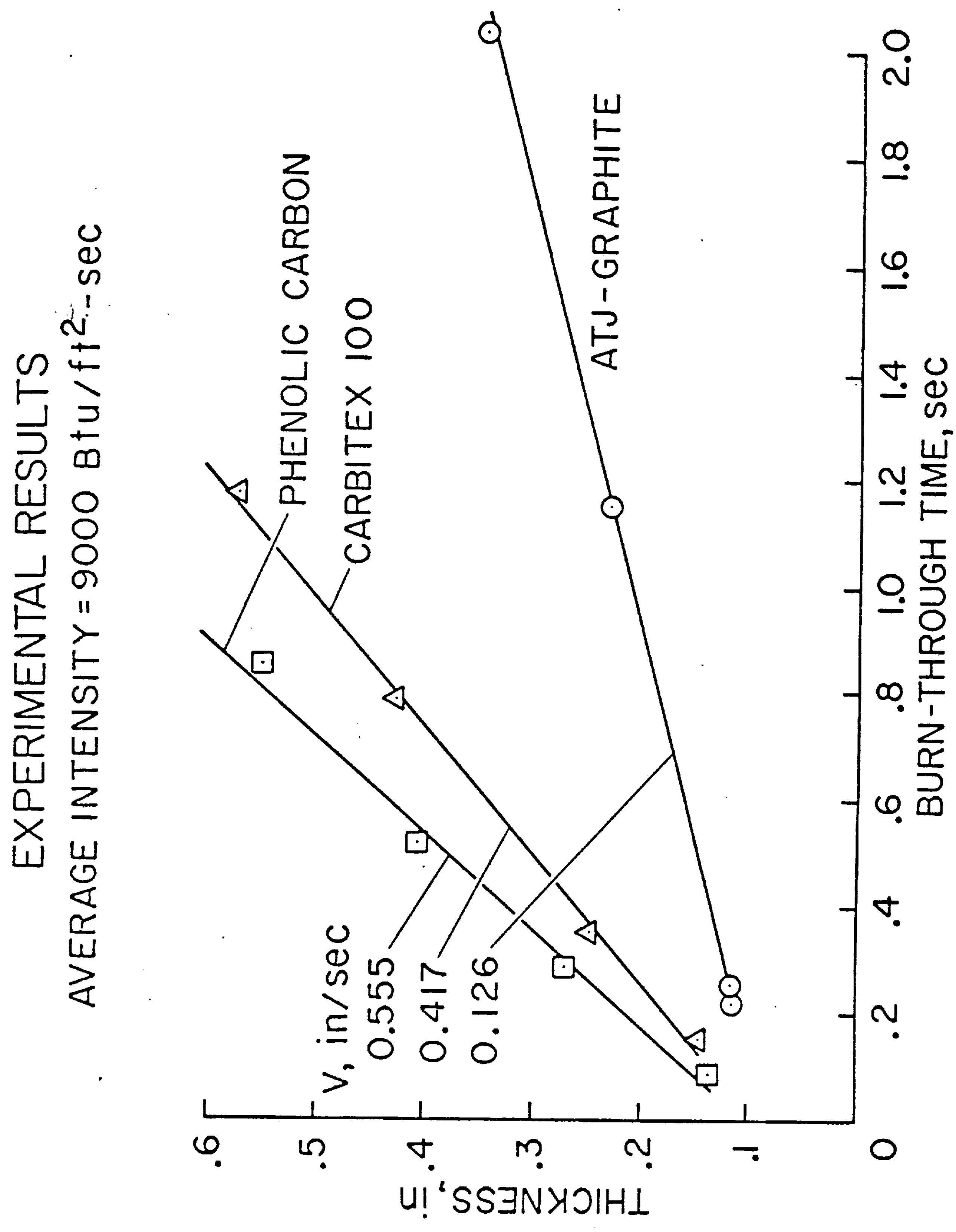
EXPERIMENTAL RESULTS
AVERAGE INTENSITY = 9000 Btu/ft^2-sec
PHENOLIC CARBON
CARBITEX 100
ATJ-GRAPHITE
V, in/sec
0.555
0.417
0.126
THICKNESS, in
0
.1
.2
.3
.4
.5
.6
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
BURN-THROUGH TIME, sec

Figure 6-11

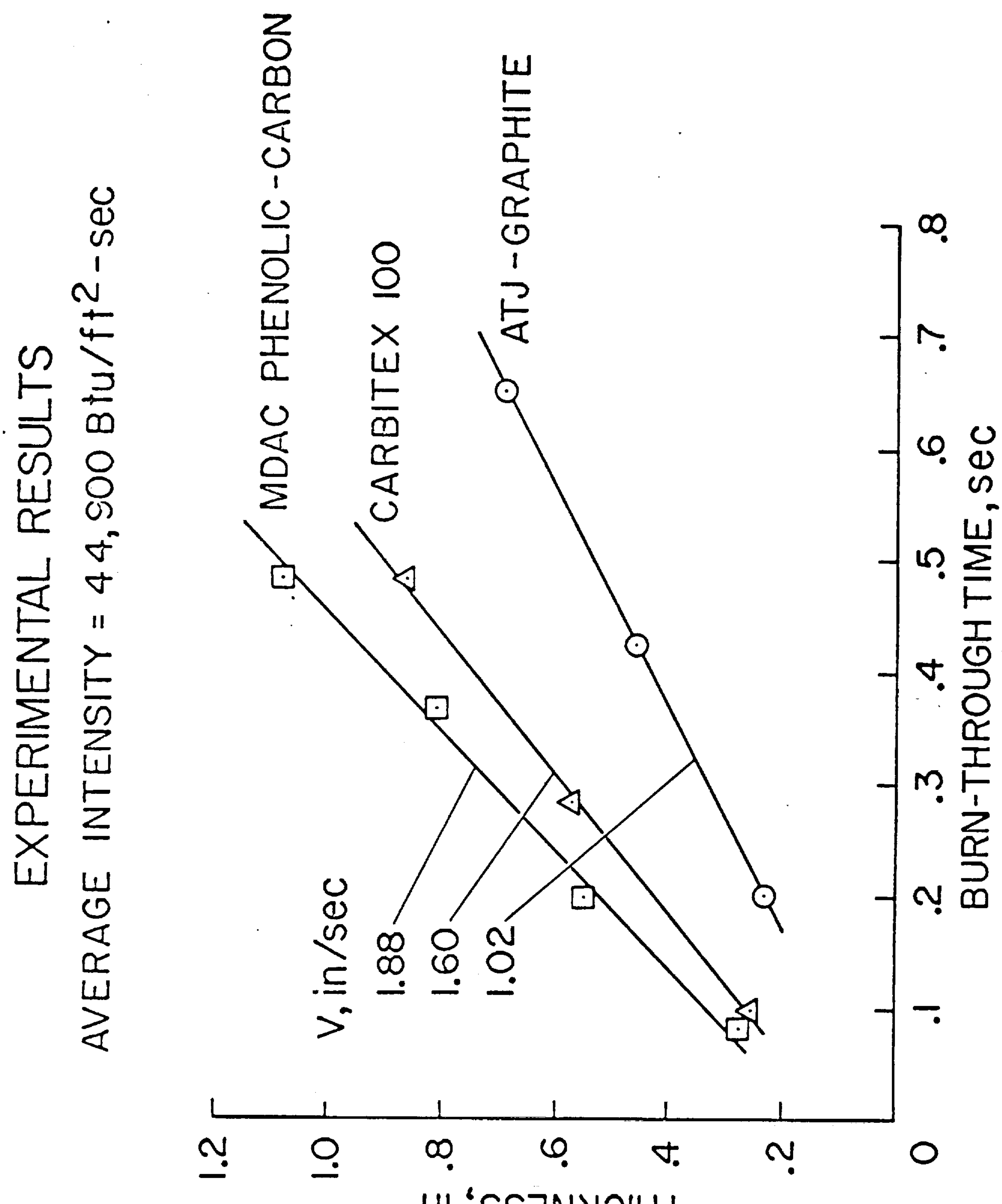
EXPERIMENTAL RESULTS
AVERAGE INTENSITY = 44,900 Btu/ft2-sec
MDAC PHENOLIC-CARBON
CARBITEX 100
ATJ-GRAPHITE
V, in/sec
1.88
1.60
1.02
THICKNESS, in
1.2
1.0
.8
.6
.4
.2
0
.1
.2
.3
.4
.5
.6
.7
.8
BURN-THROUGH TIME, sec

Figure 6-12

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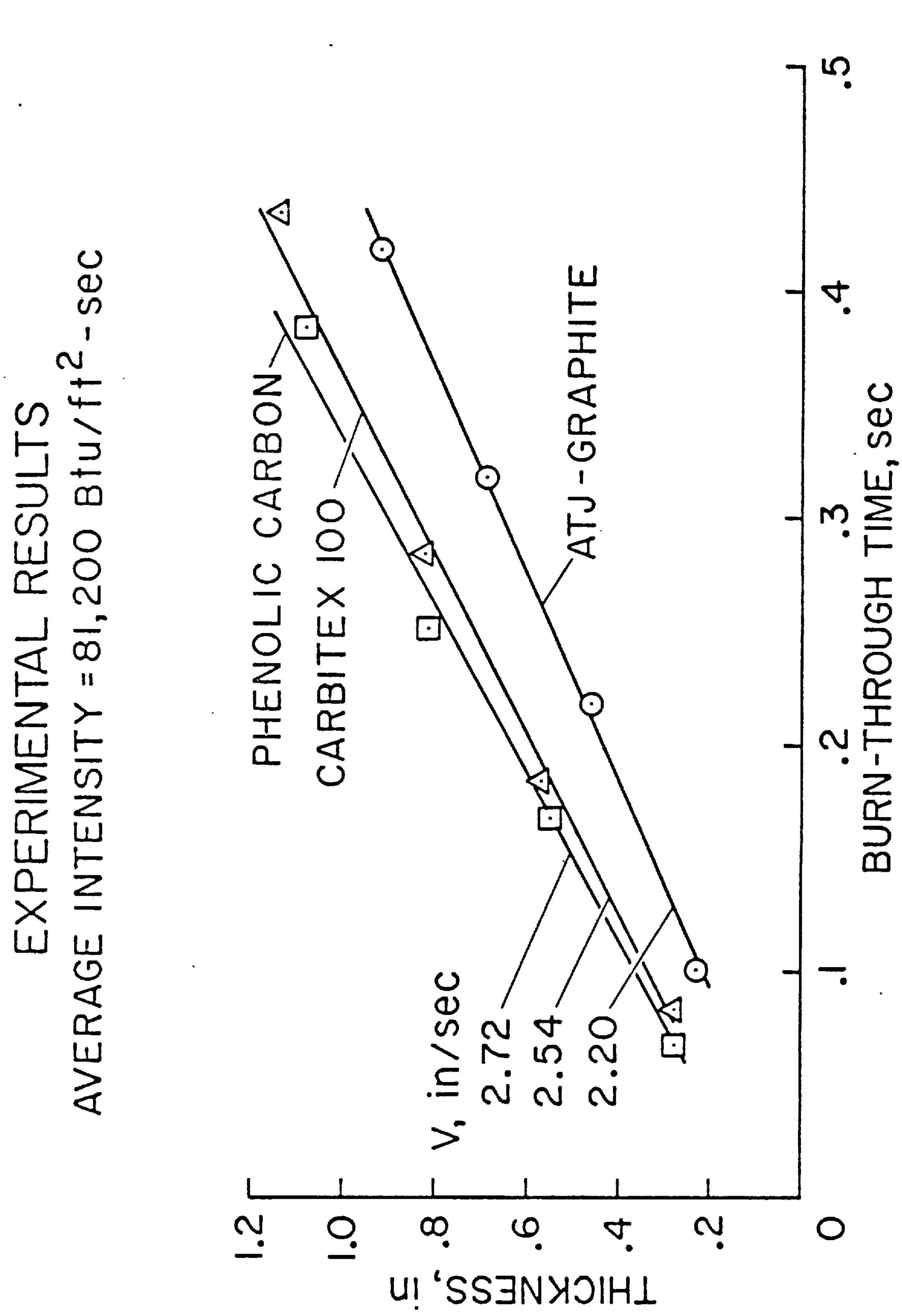
EXPERIMENTAL RESULTS
AVERAGE INTENSITY = 81,200 Btu/ft^2-sec
PHENOLIC CARBON
CARBITEX 100
ATJ-GRAPHITE
V, in/sec
2.72
2.54
2.20
THICKNESS, in
1.2
1.0
.8
.6
.4
.2
0
.1
.2
.3
.4
.5
BURN-THROUGH TIME, sec

Figure 6-13

I thought it might be of interest to show you very briefly a film clip of the test of that particular model to give you an idea of what these things look like when they get hit with very intense radiation. (Film clip shown)

MR. LUNDELL: We shot these pictures at 600 frames per second and they are being projected at 24, so we are slowing it down by a factor of twenty five.

The film indicates that the carbon phenolic puts on quite a fireworks display at this intensity level. The other materials give you about the same amount of plume, but you don't see as much evidence of particulate mass loss as you see with carbon phenolic.

Figure 6-14 summarizes the results in terms of mass loss rates. The quantity we were determining from the previous slides was the recession velocity. If you multiply that by the density of the material, you can get a mass loss rate. So, that is what we have here for the various average intensities and the three different materials: ATJ, Carbitex and carbon phenolic. As you can see, at the lowest intensity we've got almost a factor of four to one difference in the mass loss rate between the graphite and the carbon phenolic. When we get to the intermediate intensity, this ratio drops to about 1.5. They got about 50 percent more mass loss rate for the carbon phenolic. And when we get to the highest intensity, they are all pretty comparable: from about 18 to 21 lbs/ft^2-sec, which was a pretty good mass loss rate. To give you an idea of what that compares to in our convective tests, I think the highest ablation rate I ever obtained in a convective test on graphitic materials was about a half pound per square foot per second.

These results are shown graphically on Figure 6-15, where I'm plotting the mass loss rate against intensity. As you can see, and as I noted before, down at the lowest intensity we have

SUMMARY OF EXPERIMENTAL RESULTS

AVG INTENSITY Btu/ft^2-sec	MASS-LOSS RATE, lb/ft^2-sec ATJ GRAPHITE	CARBITE × 100	PHENOLIC CARBON
9000	1.13	3.02	4.21
44,900	9.18	11.6	14.3
81,200	19.8	18.4	20.7

Figure 6-14

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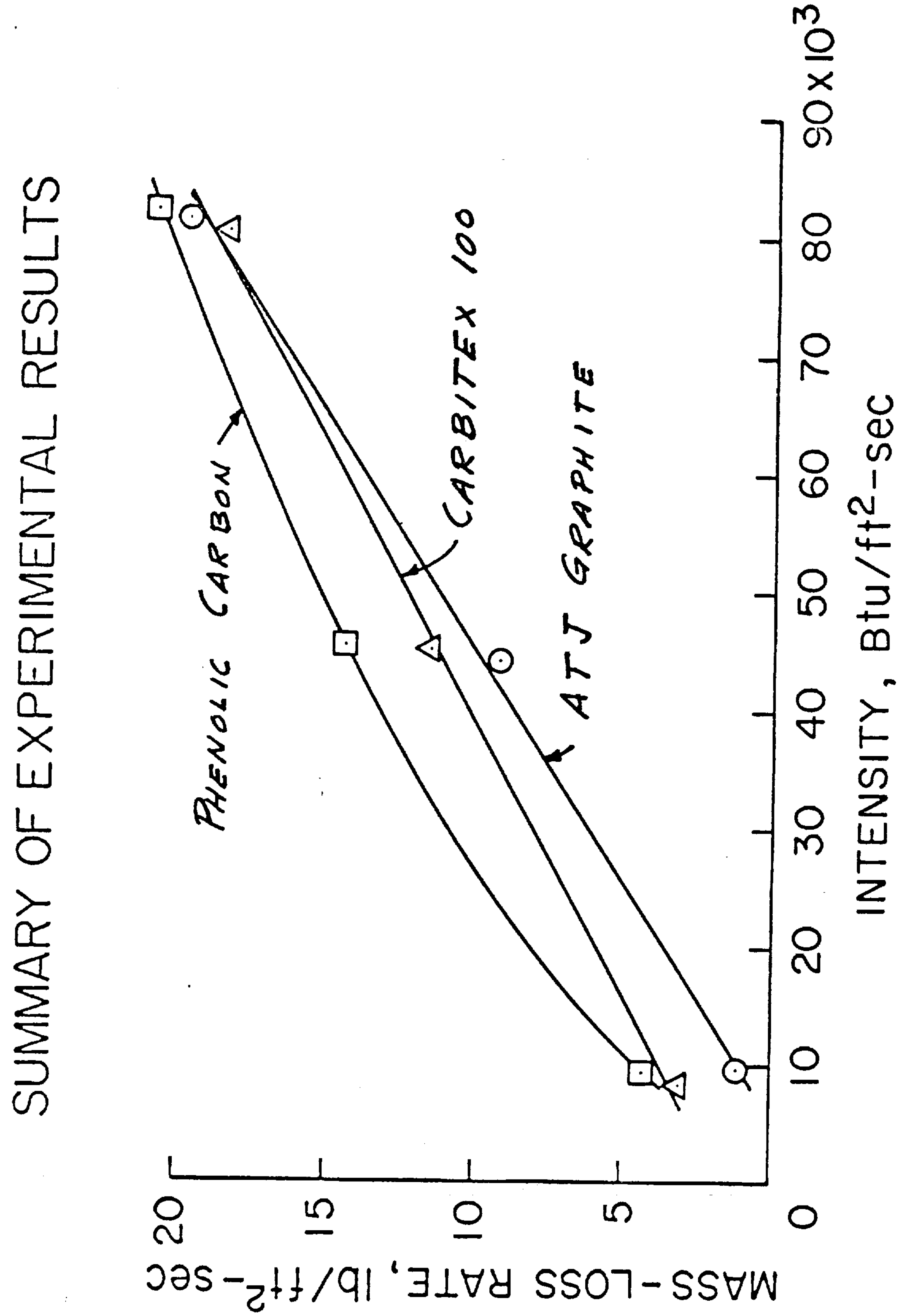
SUMMARY OF EXPERIMENTAL RESULTS
PHENOLIC CARBON
CARBITEX 100
ATJ GRAPHITE
MASS-LOSS RATE, lb/ft2-sec
INTENSITY, Btu/ft2-sec
0
5
10
15
20
10
20
30
40
50
60
70
80
90x10³

Figure 6-15

the largest difference on a relative basis between the materials; and when we get up to the highest intensity, they are all running about the same.

The thing to note here, however, is that the two all-carbon materials are performing better than the phenolic carbon; and this isn't too surprising. A predominant heat accommodation mechanism under these severe heating conditions is sublimation and, in that case, you want as much carbon up front as you can get. These curves do turn out to be linear and if you take the slope of this curve for ATJ you will come up with an effective heat of ablation of about 4,000 BTU's per pound, which is about half the heat of sublimation if one assumes that the specie being sublimed is C_3.

The curvature in the phenolic carbon curve, I think, is probably due to the fact that we've got the phenolic there complicating things when it pyrolyzes.

In conclusion I'd like to say that it does appear as though the heat shield problem is going to be rather severe for entry into the outer planets but, with the laser and the up-coming arc-jet facilities which are going to be developed here at Ames and which Howard Stine will describe shortly, I think we will be able to do a pretty good job of simulating entry into the outer planets and we will be able to determine why these materials perform the way they do under these intense heating environments. Then, we will be able to design the flight heat shield with a great degree of confidence.

UNIDENTIFIED SPEAKER: Because of the linear relationship in your last chart there it seems fair for an actual entry case where the heating intensity reaches a peak and then comes down to just integrate the area under it and make the thickness proportional to that?

MR. LUNDELL: Yes, I think that would be a pretty reasonable thing to do, for a first approximation, based on what we know now. In other words, I think even though the heating rate is varying very rapidly with time, you are going to stay pretty close to thermal equilibrium.

UNIDENTIFIED SPEAKER: Did you get any surface temperature measurements?

MR. LUNDELL: Yes, we did. They are running about 7400° Rankine; that's about 4100°K.

UNIDENTIFIED SPEAKER: Do you consider your monochromatic results reasonably applicable to the real case?

MR. LUNDELL: That's the real question in using the laser as a simulation facility for planetary entry. In a planetary entry case we expect radiation in the visible and the UV and, of course with the laser we are way out in the infrared. In answer to your question, I think it's okay for graphitic materials, or black materials. It certainly would not be for the reflective materials.

UNIDENTIFIED SPEAKER: Is that 2.2 inches per second some sort of a world's record?

MR. LUNDELL: It is for me.

DR. NACHTSHEIM: The next speaker will be Bill Congdon from Martin Marietta and there is a slight discrepancy in the program: he will be describing Dave Carlson's work, which is the applicability of the Pioneer Venus hardware to Saturn probes, and he will also be discussing Martin's efforts on the development of silica heat shields. So, in his talk he will essentially make two talks, and make the transition from the evaluation of heat shield materials to the development of heat shield materials.