Impact of Science Objectives and Requirements on Probe Mission and System Design

MR. KENNETH W. LEDBETTER: You have heard from previous speakers the basic objectives and rationale for outer-planets probe missions. I would like to build on these basics by discussing some of the problem areas in probe science technology that require a solution before the probe systems can actually be designed.

There are three areas I would like to briefly discuss. First, the effects of the model atmospheres on the probe design; secondly, the effects of implementing the requirements to locate and measure the clouds; and, third, trade-offs between descent sampling and measurement criteria as they affect the probe system design.

Composition is one of the basic objectives and although the probe will measure the actual composition, engineers must have a model with which to design subsystems. The model atmospheres that have been used by both NASA and industry for various studies that have been done are those in the NASA SP series of monographs assembled under the cognizance of Goddard Space Flight Center. The authors for the atmospheric sections were primarily Neil Divine and Frank Palluconi of JPL.

Figure 2-24 lists some of the variant properties of the monograph model atmospheres for Saturn and Uranus. The document numbers are given in the footnotes on the figure. The corresponding number for the Jupiter monograph is NASA SP-8069. Some of the major differences are apparent. Since helium cannot be identified directly from the spectrum, the models are necessarily quite variable in Helium content. It varies extensively at both planets, ranging at Uranus from about 4 percent in the warm to 60 percent in the cool. Adding to this, the variability of methane from a negligible amount at Saturn to 9 percent in the Uranus cool, the resulting molecular weight is between 2.1 and

MAJOR DIFFERENCES IN MODEL ATMOSPHERES

		SATURN[1]			URANUS[2]		
		WARM	NOMINAL	COOL	WARM	NOMINAL	COOL
PERCENT COMPOSITION BY NUMBER	H_2	94.7	88.6	73.0	95.3	85.9	30.6
	He	5.3	11.2	26.3	3.7	11.0	60.0
	CH_4	Trace	0.1	0.2	1.0	3.0	9.0
TEMPERATURE AT 10 BARS (^{0}K)		424	310	191	300	185	114
PRESSURE AT TOP OF MODELED CLOUDS (BARS)		0.3	0.7	3.0	0.1	0.5	1.0
ALTITUDE DIFFERENTIAL 100 mb to 10 bars	(km)	446	257	132	363	177	75

1. NASA SP 8091

2. NASA SP 8103

Figure 2-24

4.6. Trying to design a probe to this range of atmospheres is extremely difficult and unrealistically restrictive.

The second-most important item on Figure 2-24 is the temperature differential between models at ten bars. It extends from about 114° (Kelvin) in the Uranus cool to over 400° at Saturn; and the Jupiter monograph models show a maximum of about 470°. If you recall Arv Kliore's graph shown earlier, his Pioneer 10 data, extrapolated down to ten bars at the bottom of his graph, would give a temperature on the order of 900° to 1000°. Therefore, there could be as much as an order of magnitude of difference in the final temperature to which a truly common probe must be designed. This, of course, is very significant to both thermal control and to the life of various components of an entry probe.

Figure 2-25 shows the effect of these variations upon entry probe design for Saturn and Uranus with the same set of model atmospheres. Note that the entry ballistic coefficient and the descent ballistic coefficient were essentially constant for all six models. The values are typical for non-parachute probe descents. The slight difference in the descent value is due to the different amounts ablated from the entry heatshield. The peak decelerations vary from a little over a hundred to about six hundred with the entry angles shown. Note that there is a five-degree difference in the entry angle. This allows the design peak G's. specifically about 585, to be about the same for each planet. This flexibility in entry angle permits the designer to account for some of the differences between planets. A Saturn entry at 35° would have greater than 650 peak G's.

Instrument deployment parameters are also shown in Figure 2-25. This particular design was for a non-parachute probe where the instruments were deployed slightly above a hundred millibars in pressure. At three G's descending plus twenty seconds the temperature gauge is deployed, the mass spectrometer opening pyros

ENTRY AND DESCENT SCIENCE MISSION PARAMETER VARIATION

	SATURN			URANUS		
	WARM	NOMINAL	COOL	WARM	NOMINAL	COOL
ENTRY ANGLE (deg.)	→	-30	←	→	-35	←
ENTRY BALLISTIC COEF. (kg/m^2)	→	142.6	←	→	142.6	←
DESCENT BALLISTIC COEF. (kg/m^2)	→	161.3	←	→	160.0	←
PEAK DECELERATION (g)	232	385	585	148	240	570
INSTRUMENT DEPLOYMENT:						
TIME FROM ENTRY TO 3g+20s	96	71	54	121	78	49
MACH NUMBER	.71	.58	.49	.86	.76	.60
ALTITUDE ABOVE 1 BAR (km)	156	86	46	152	84	37
PRESSURE (mb)	63	85	114	39	46	59
TIME TO 10 BARS (min.)	63	43	27	74	47	29

Figure 2-25

are fired, and the nephelometer cover is removed. Again, there are variations in the time from entry, the mach number at deployment, and the altitude above one bar.

The bottom line on Figure 2-25 lists the time to reach ten bars which is also very important for a probe design. It varies from about 27 minutes to 74 minutes; a very large factor when considering thermal control and especially when considering the communications link. The data must be relayed to the spacecraft before it passes out of range of the probe. Also, descent time is important for sizing some of the subsystems, particularly, the power subsystem. In fact, since some components must be designed to the minimum time (e.g. memory dump data rate) while related components are designed to the maximum time (e.g. total battery power) resulting conflicts yield an inefficient design.

It is interesting to note from both Figure 2-24 and 2-25 that the differences between models for a given planet are greater than the differences between planets for a given model, pointing out our overall ignorance as to the real atmosphere.

Of course, we all know we need better models. What can be done to obtain them? Pioneer 10, has changed the essence of these models for Jupiter. In fact, it might be better to discard the old models and start over again. In addition, when progressing from Jupiter to Saturn and Uranus the majority of models that have appeared in the literature have utilized extrapolations from Jupiter. Therefore, when the Pioneer 10 data are fully applied to Jupiter, the results should be extrapolated to Saturn and Uranus.

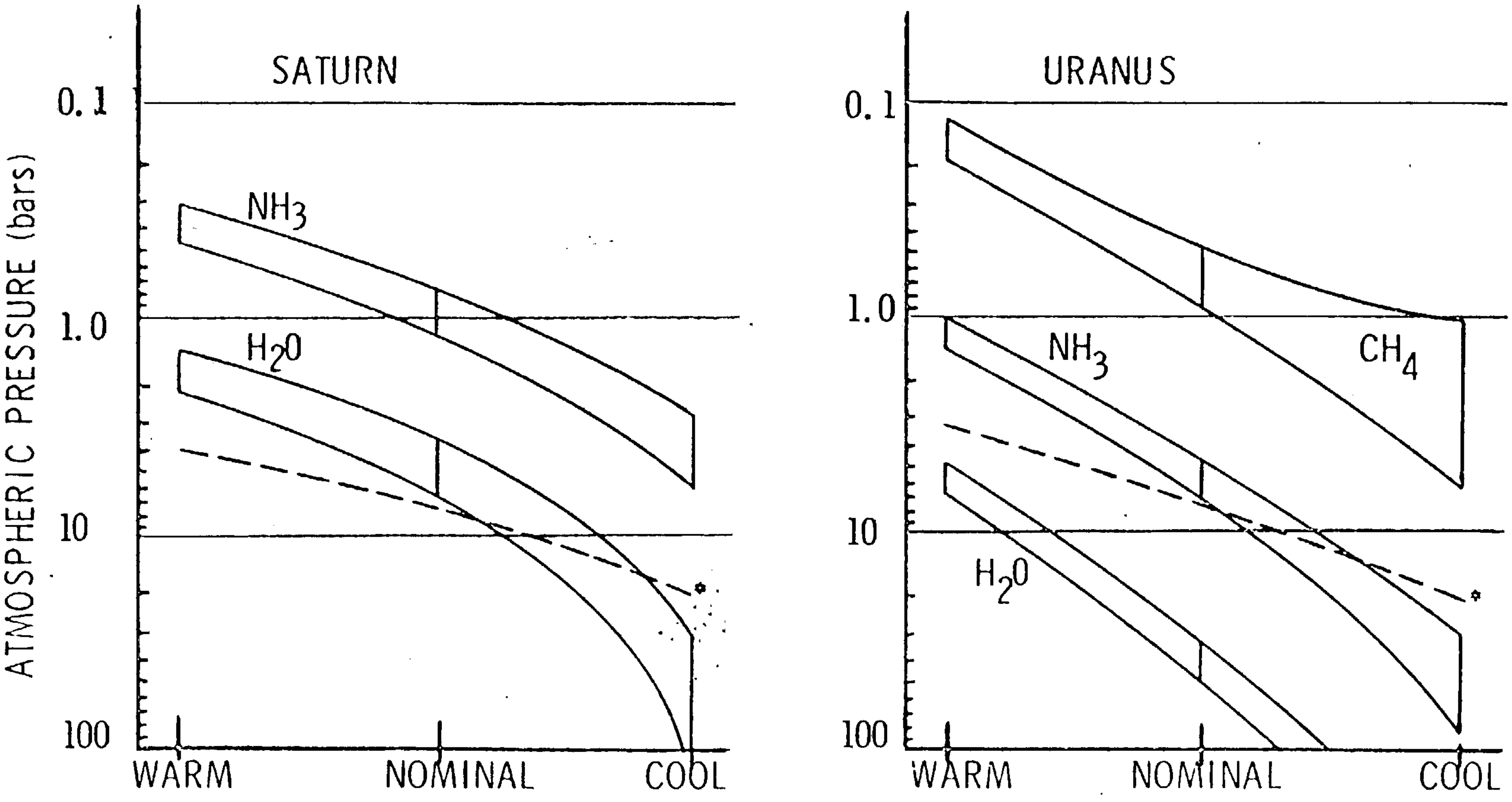
Secondly, statistical means can be used to reduce some of the uncertainty. Starting with a given nominal model and the various 3-Sigma possibilities for each of the individual parameters that comprise the model atmosphere, Gaussian-type distributions can be constructed around that nominal and the extremes decreased. This has been done for Jupiter by W. S. Cook at Martin Marietta. He has a paper appearing in the July, 1974 issue of the *Journal of Spacecraft and Rockets* which uses the nominal atmosphere from the Jupiter monograph and performs Monte Carlo probabilistic statistics to establish warm and cool limiting models. The results show that Cook's limiting models are less extreme than those in the monograph. This is largely because the monograph models were established with the intent of being worst-case models, therefore, the effects of all worst-case parameters were added together. This means that if a probability distribution were superimposed upon the monograph models, the actual probability of the cool or warm model existing would be near zero since the probability of *all* parameters being the maximum worst-case value in the same direction at the same time is near zero.

The second topic of discussion is the impact of the basic objective to locate and measure clouds. Figure 2-26 shows the pressure location of the clouds as given in the NASA monograph model atmospheres. The three models are represented by vertical lines as indicated by the abscissa, where for each modeled cloud,the cloud top and the cloud base are shown. The solid lines are smooth fits through the three points, representing the cloud top and the cloud base. The reason for this method of presentation is to emphasize the point that there is only one cloud and that its location is very uncertain, even in these models which the Pioneer 10 data may replace. For example, the water cloud base at Saturn is located between two bars of pressure in the warm and well beyond a hundred bars in the cool.

The dashed line on Figure 2-26 represents the end of a 38-minute mission with a ballistic coefficient of 160 kg/m^2. Note that the probe will just penetrate the cloud base of the second cloud in the nominal atmosphere at about 7 bars. Since the clouds tend to appear higher in the warm models and lower in the cool, the

C-2

CLOUD LOCATIONS AND CONSTANT MISSION TIME



* 38 Minute Mission at B = 160 kg/m^2

Figure 2-26

probe penetrates well past the cloud base in the warm but does not reach the cloud tops in the cool. To penetrate the entire cloud in the cool model is prohibitive.

Therefore, this implies a philosophy of designing to a constant time rather than a constant pressure. This eliminates the problem mentioned earlier of designing to different times for communications, thermal control, and power subsystems. It is also more compatible with the atmospheres themselves since the probe penetrates deeper into the atmosphere in a cool model as do the clouds. The time to reach a given pressure, is a function of ballistic coefficient. The end-of-mission line on Figure 2-26 would basically just move up and down for different ballistic coefficients at different times. (Although for large changes in B, the line would tilt.)

Another important consideration is the difficulty in measuring the high clouds. In the Uranus warm model, the methane cloud is up near a tenth of a bar. The probe has a high velocity at this altitude and low density, and as the atmospheric density increases, it slows down. Figure 2-27 shows that with the indicated ballistic coefficient, the probe spends about seventy-four seconds inside that Uranus cloud. A mass spectrometer with a 1 to 40 amu scan might be lucky to get one measurement inside. For a temperature gauge, to make one measurement per kilometer, the sampling interval would be on the order of about five seconds. Figure 2-27 also shows similar information for the other Uranus modeled clouds.

Thus, a re-evaluation needs to be made of the requirements for measuring the high clouds in any of the outer-planet atmospheres to determine if it is realistic to impose stringent requirements upon the instruments to sample those clouds when the basic objective is to look at the total atmosphere.

PROBE VELOCITIES THRU URANUS CLOUDS (B=160 kg/m^2)

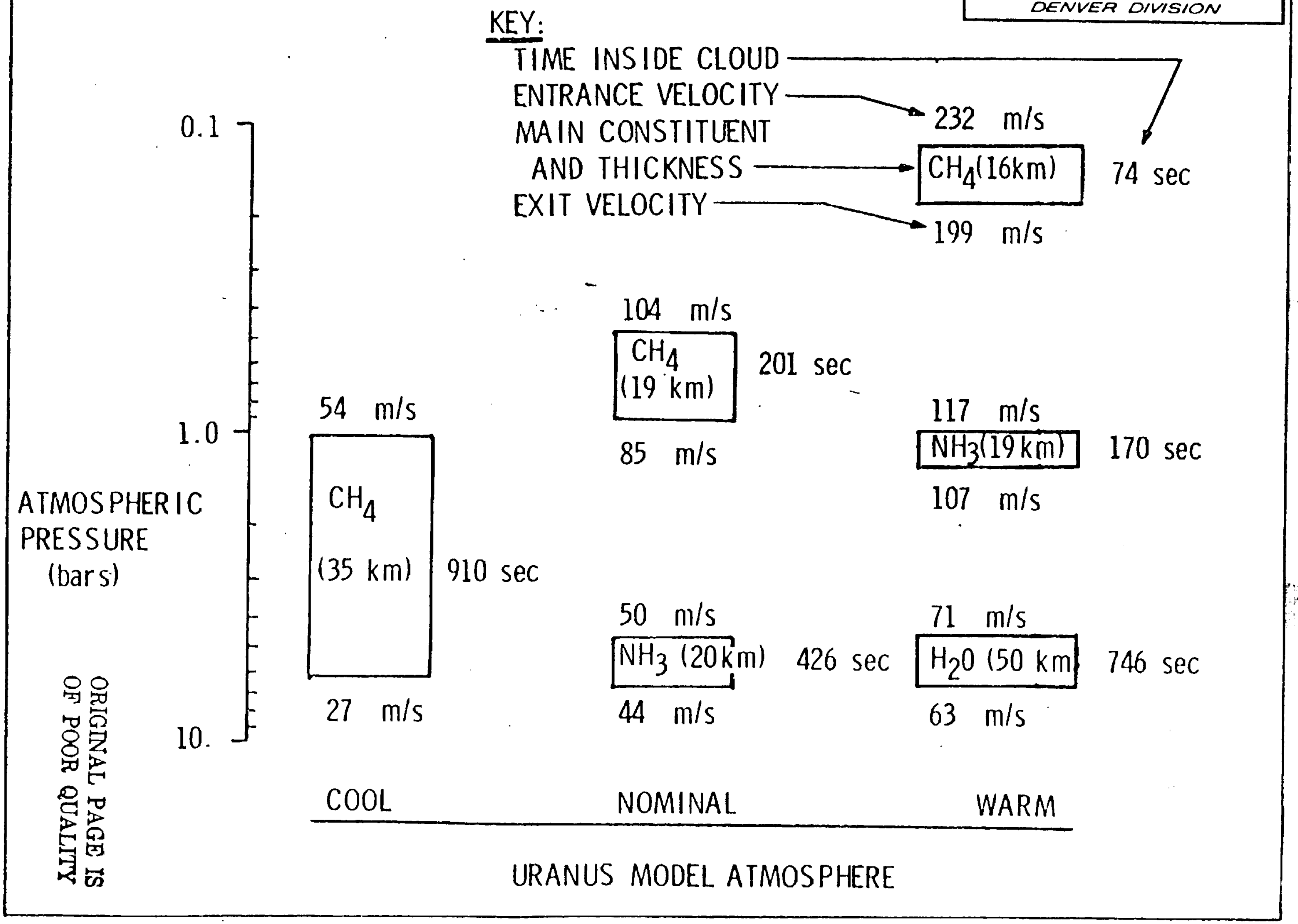


Figure 2-27

Figure 2-28 shows the overall trade-offs and related parameters involved in descent sampling. The descent profile, indicated in the left box, is essentially the ballistic coefficient or the rate with which the probe falls into the atmosphere. The sampling criteria or performance in the bottom right-hand box has two meanings: it is criteria before the mission and it is measurement performance after a simulated mission and, hopefully, the performance is equal to or greater than the criteria. The top box is the instrument sampling time or more correctly, the interval between measurements during a descent. It is constrained primarily by the data rate, since there is a maximum amount of data rate available from the power system onboard the probe. If the criteria is fixed and states that the probe must make a given number of measurements in a given altitude differential, the probe can descend fast and have a short sampling time or descend slower and have a longer time. These factors all interplay.

One point to be made from this is brought out by Figure 2-29 and it is that good criteria are needed with which to design. The design criteria directly reflects upon the ballistic coefficient, data rate, and power subsystem. This figure shows three that Martin Marietta has used during contract performance. The first line is one that was used with contract NAS2-7488 with Ames Research Center in 1973 entitled, "Study of Adaptability of Existing Hardware Designs to a Pioneer Saturn/Uranus Probe." The second line is a set of criteria that was obtained from a panel of science consultants that Martin regularly convenes. The third is a set of criteria that was used for Contract JPL 953311 entitled, "Outer Planet Entry Probe System Study" performed for the Jet Propulsion Laboratory in 1972.

For the temperature and pressure gauges, the requirement from set 1 is five kilometers per measurement, that is, one measurement every five kilometers. From the 3rd set, the pressure requirement is one measurement every half a kilometer. There is an order of magnitude of difference between these two requirements. It

FACTORS INFLUENCING DESCENT SAMPLING

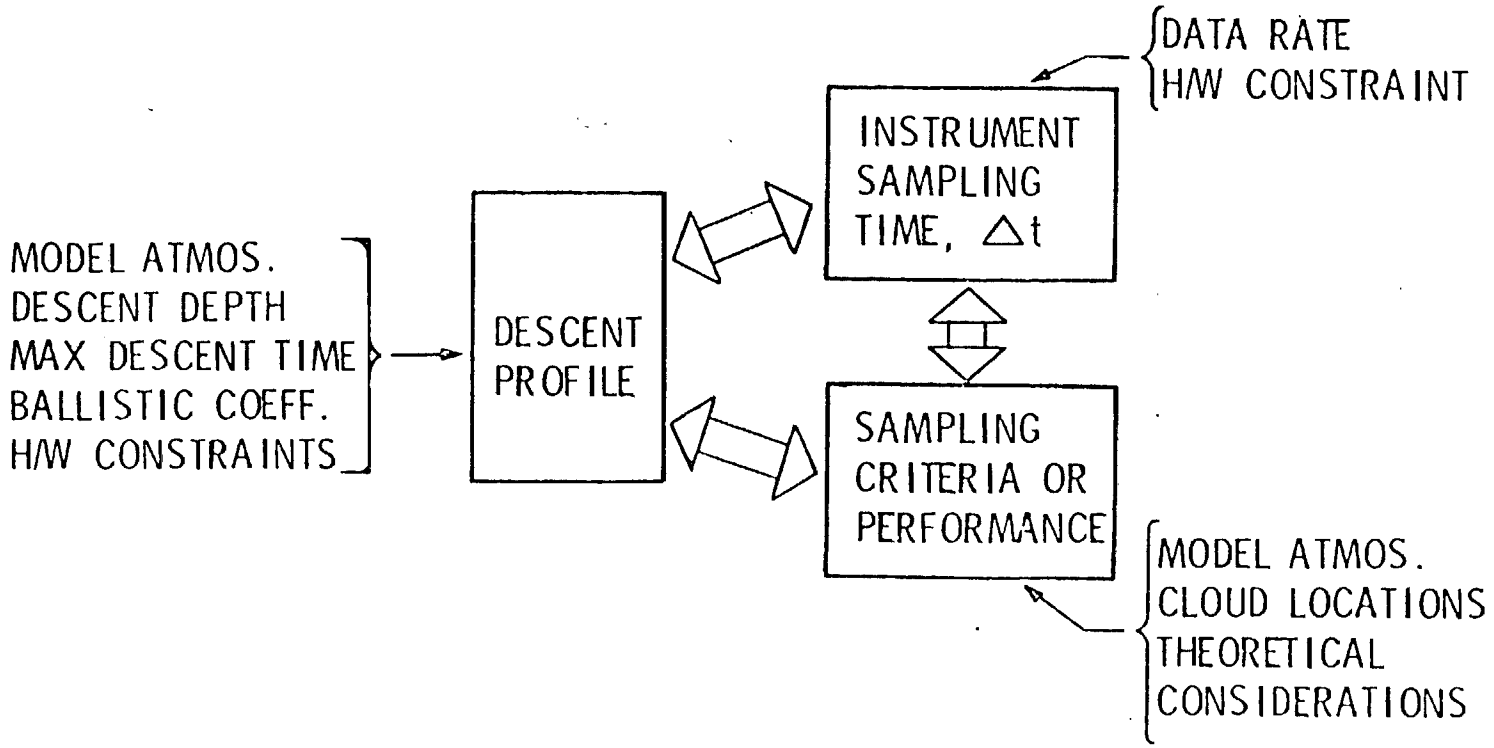


Figure 2-28

VARIOUS SETS OF PROBE MEASUREMENT CRITERIA

	TEMPERATURE PRESSURE	NEUTRAL MASS SPECTROMETER	NEPHELOMETER
1.	5 km/meas.	6 meas. to 10 bars	1 km/meas.
2.	5-10 meas/scale ht.	4 meas. (2 below 1 bar)	10 meas/scale ht.
3.	P: 2 meas/km T: 1 meas/^{0}K (Below Cloudtops)	2 meas/scale ht. (Below Cloudtops)	1 meas/km (Below Cloudtops)

Figure 2-29

is about a factor of six for the mass spectrometer and, surprisingly, for the nephelometer the requirements are almost identical, when translating a typical scale height.

An improved set of criteria desperately needs to be developed. Perhaps it would be money well spent to employ those principal investigators that will actually receive the data, to determine, perhaps statistically, how close together in the atmosphere the points really have to be measured in order to make a realistic interpretation of the data returned.

The next two figures show additional details of the descent parametrics. Figure 2-30 graphically shows that the measurement performance for a fixed ballistic coefficient and instrument sampling time increases with depth into the atmosphere. This increase is more pronounced with either smaller ballistic coefficients or lower instrument sampling times.

The effects of ballistic coefficient and sampling time variations on performance at a given point in the atmosphere are better shown in Figure 2-31. It displays measurements per kilometer at cloud tops in each of the Saturn model atmospheres versus ballistic coefficient. This is the range of ballistic coefficients for a non-parachute probe. The parachute regime is off the graph to the left and these curves become very much steeper. The third parameter is the instrument sampling time or, again, the interval between samples. Note that with a given ballistic coefficient, changes in sampling time make a significant effect on performance. The solid lines are for the nominal atmospheres; the dashed and dotted lines represent the extremes. The lines indicating four second sampling times illustrate the effect of the three NASA monograph model atmospheres on performance.

The last Figure (2-32) then summarizes the items I feel are important to emphasize. For the model atmospheres: whenever possible extrapolate the Pioneer 10 data to Saturn and Uranus to

TYPICAL MEASUREMENT PERFORMANCE PROFILES

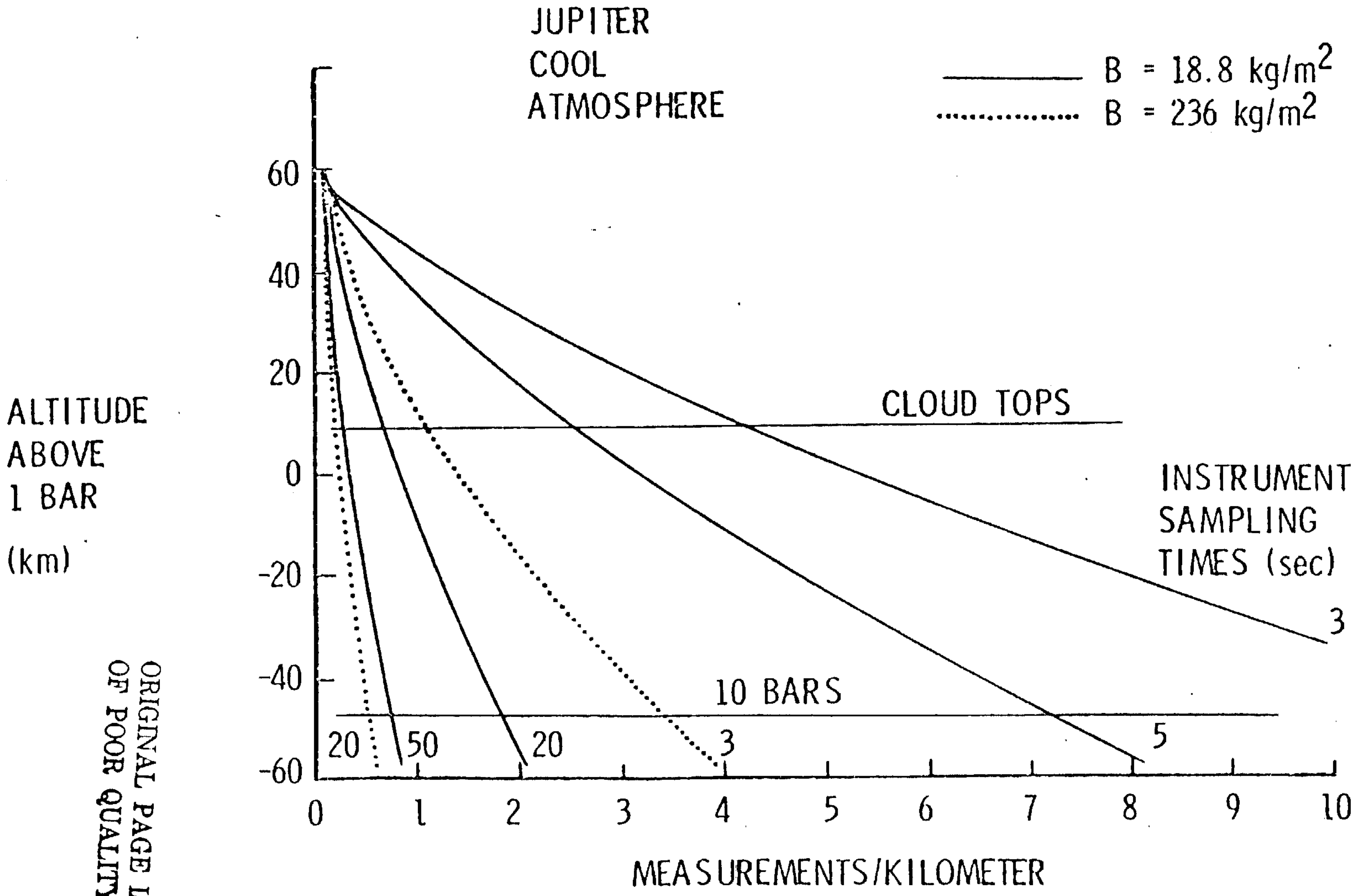


Figure 2-30

DESCENT SAMPLING PARAMETRICS

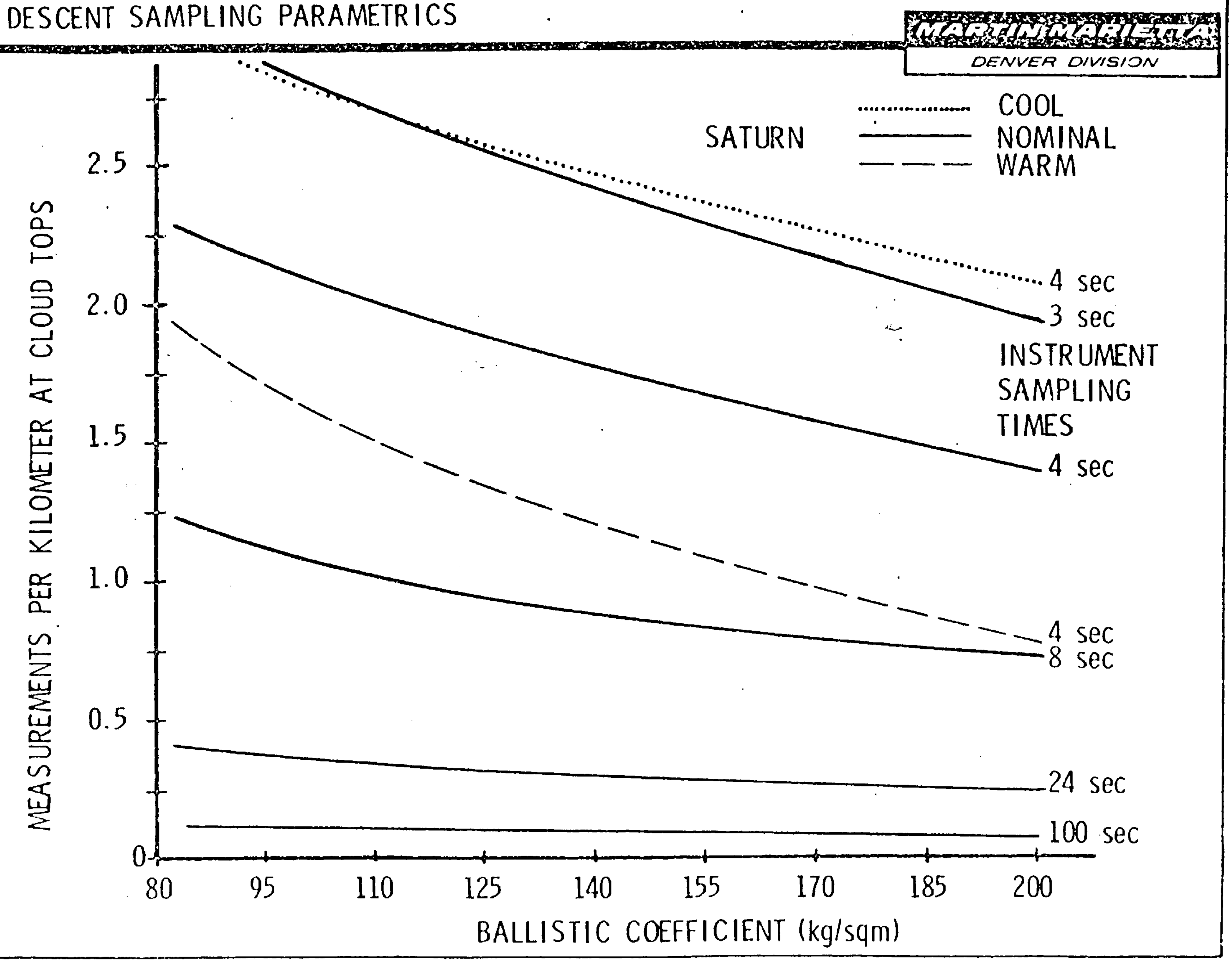


Figure 2-31

SUMMARY AND CONCLUSIONS

MODEL ATMOSPHERES (IMPROVE TO REDUCE PROBE DESIGN MARGINS)

- EXTRAPOLATE PIONEER 10 DATA TO SATURN/URANUS
- USE STATISTICAL ANALYSIS TO REDUCE MODEL UNCERTAINTY

CLOUD LOCATION/MEASUREMENT

- INSTRUMENTS MUST SEARCH DURING ENTIRE DESCENT
- MEASUREMENT OF HIGH CLOUDS COSTLY IN DESIGN

DESCENT MEASUREMENT PERFORMANCE CRITERIA

- NEED STUDY TO ACCURATELY DETERMINE MEASUREMENT REQUIREMENTS

DESCENT DESIGN PHILOSOPHY

- DESIGN FOR MAXIMUM TIME FOR ALL MODELS
- BASE REQUIREMENTS ON NOMINAL MODEL WITH EXTREMES AS 3σ LIMITS

Figure 2-32

MARTIN MARIETTA

see what effect this would have on the atmospheres that are currently being used. Secondly, use statistical analysis to reduce some of the model uncertainties to arrive at the best nominal atmosphere possible. Then use statistical analysis and physical relationships in a manner such that the various parameters do not contradict each other when warm and cool atmospheres are derived.

Concerning cloud location measurements, the instruments must search during the entire descent because, for a given cloud, its location is uncertain even in the models currently being used. Also, the measurement of high clouds is costly in design. For descent measurement performance, a set of criteria need to be accurately determined. This, of course, is related to model atmosphere improvement and requires at least a good nominal model atmosphere before this can be satisfactorily done.

Lastly, in descent design philosophy, we recommend designing for a maximum time in the nominal atmosphere, which may be the time to ten bars, but that the overall probe design shouldn't be penalized by going to identical pressures in all models. The requirements should be based on the nominal model and then consider extreme model atmospheres as 3-Sigma limits.

DR. RASOOL: I think Ken made a very important point that we need, much more than ever, communications between the scientists and the people who are designing the mission and, even more so, with the third person involved in between, the model maker. It is not necessarily the scientists who make the models. Usually, there is a time lag of a year and that's very bad because, these days, as you saw, the measurements are being made at a very fast rate. Toby Owen showed some slides which are very interesting, but by the time they get reflected in the model, it's a year or two years. So, we need interaction between the scientists making measurements, the model maker, and the design maker.

MR. HERMAN: Just one comment. At the MJU meeting, Al Cameron stated that it was vital that we reduce the various uncertainties of these models. He felt that these models are unnecessarily unconstrained, which present unrealistic and very complex requirements for the probe design. The models are unnecessarily and unrealistically restrictive and the variables can be reduced.

DR. RASOOL: Ken made another important point; that we have three models of Jupiter and now we have entirely different measurements; and that we should reflect this into Uranus and Saturn.