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## OUTER PLANET PROBE COST ESTIMATES - FIRST IMPRESSIONS

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MR. NIEHOFF: The purpose of this paper is to examine early estimates of outer planet atmospheric probe cost, evaluating these estimates by comparison with past planetary projects. Of particular interest is identification of project elements which are likely cost drivers for future probe missions. Discussion is divided into two parts: first, the description of a cost model developed by SAI for the Planetary Programs Office of NASA, and second, use of this model and its data base to evaluate estimates of probe costs. Several observations are offered in conclusion regarding the credibility of current estimates and specific areas of the outer planet probe concept most vulnerable to cost escalation.

Cost Model

A cost model has been developed by SAI for the Planetary Programs Offices as an estimating tool for long-range mission planning. The model is based on cost data from seven lunar and planetary unmanned spacecraft projects completed (or in progress) between the ten-year period 1964-1974. The model input requirements are matched to the level of mission definition available from pre-Phase A studies. The basic estimation parameter is direct labor hours. The labor estimating relationships (LER's) are primarily a function of subsystem weights due to the limited detail of pre-Phase A data.

At the present time the cost model can be applied to flyby, orbiter, atmospheric probe and soft lander mission concepts. Features include non-recurring and recurring division of cost, specified fiscal year dollars, project inheritance, and cost spreads of estimates. The model will reproduce the costs of the data base projects with a mean absolute error of 10%. The error

goal for future program estimates is 20%. Initial test results, shown below, indicate that this accuracy is achievable. A detailed description of the cost model is given in Reference 1.

For the purpose of this paper it is instructive to take a closer look at the cost model data base, the method for translating labor hours into cost, and overall estimation accuracy. The roots of any cost estimation procedure are buried in its data base. The seven projects comprising the SAI cost model data base are listed in Table 10-1. The list includes almost all the lunar and planetary unmanned spacecraft flown between 1964 and 1974, as well as Viking which will be launched next year. With these data, it has been possible to construct a model capable of estimating flyby orbiter and soft lander mission costs. Atmospheric probes are also modeled using Viking entry system cost data, although this single project data point is considered tenuous and mismatched to smaller entry probe concepts for Venus and the outer planets.

TABLE 10-1  
SAI COST MODEL DATA BASE

- o Programs in Current Model
  - o Mariner Mars '64
  - o Surveyor
  - o Lunar Orbiter
  - o Mariner Mars '69
  - o Mariner Mars '71 (FY '72 status)
  - o Pioneer F/G (FY '72 status)
  - o Viking '75 (FY '72 status)
- o Programs Under Evaluation
  - o Mariner Mars '71 (complete)
  - o Viking '75 (FY '74 status)
  - o Mariner Venus/Mercury (complete)
  - o Mariner Jupiter/Saturn (FY '74 status)
- o New Programs to be Added
  - o Pioneer Venus '78

Also shown in Table 10-1 are programs currently under evaluation for updating and expanding the data base. The first two programs, Mariner Mars '71 and Viking '75, involve updates to estimated run-out costs for these programs in the original data base. The Mariner Venus/Mercury program is a new addition which not only will expand the data base, but is also proving useful for modeling inheritance savings. Mariner Jupiter/Saturn, a program just getting under way, will further expand the data base and permit refinement of model inheritance factors.

An important future addition to the cost model data base is the Pioneer Venus '78 project. Cost data from this program are of interest for the following reasons: (1) it is the first planetary program involving atmospheric probes, (2) it will be only the second program in the data base for spin-stabilized spacecraft, and (3) it is the first planetary program evolved under low cost (expanded weight) guidelines. The Pioneer Venus '78 data represent a significant improvement in the data base for estimating probe costs. The evaluation of current probe estimates (presented below) is only preliminary in nature as indicated by the title of this paper. Low cost (expanded weight) program philosophy, and its impact on cost modeling, will not be discussed further here. Although a potentially significant alteration to traditional estimating procedures, it is not immediately relevant to the subject of this paper and must be treated in detail to be properly understood.

Within, then, the cost model data base, manpower and dollar costs are broken down into elements of two basic categories: support categories and subsystem categories. The various elements within each category are itemized in Table 10-2. Elements within the support categories relate to project functions and non-flight hardware. Elements within the subsystem categories are flight hardware. Table 10-2 illustrates how data base project resources (dollars and manhours) are allocated across these elements. The data are averages of all seven projects in the data base.

TABLE 10-2

SAI COST MODEL ELEMENTS(Comparison of Dollar\* and Labor Hour Distributions\*\*)

● <u>Support Categories</u>	<u>Cost</u>	<u>Man Hours</u>
○ Program Management	5.3%	5.4%
○ Systems Analysis/Sys. Eng.	4.0	4.3
○ Test	7.0	7.2
○ Quality Assurance & Reliability	4.7	5.3
○ Assembly & Integration	2.8	2.8
○ Ground Equipment	9.0	8.1
○ Launch/Flight Ops.	<u>10.0</u>	<u>10.0</u>
Subtotal	42.8%	43.1%
● <u>Subsystem Categories</u>		
○ Structure	8.9	9.0
○ Propulsion	5.2	4.5
○ Guidance & Control	9.2	9.1
○ Communication	13.9	14.7
○ Power	4.1	4.7
○ Science	15.2	14.0
○ Miscellaneous	<u>0.7</u>	<u>0.9</u>
Subtotal	57.2%	56.9%
Total	100.0%	100.0%

\*w/o fee

\*\*all-project average percentages of totals

Several important observations should be noted from Table 10-2 relevant to NASA's planetary flight projects in general, and the cost modeling procedure in particular. Some subsystem category elements contain more subsystems than their names imply. Structure, for example, is actually a conglomeration of structure, mechanisms, landing gear (when applicable), thermal control, pyrotechnics and cabling. The reasons for combining subsystem hardware are two-fold. First, certain component costs are difficult to separate from available project financial records. Second, some hardware element costs can be modeled (with pre-Phase A definition) better in combination than separately. Note in Table 10-2 that less than 1% of the total project man hours and cost are unaccounted for (miscellaneous subsystem category element) using the described element breakdown.

Direct labor hours, while an intrinsic understandable unit of cost, is only part of a project's total cost. Material, burden, ancillary support, and fee make up the remainder of required project costs. Fortunately, due in part to NASA's rigid contracting requirements, direct labor hours consistently accounted for 30% of total costs within the seven-project data base. This result has a maximum deviation of less than 3%. The close comparisons between labor hour and dollar percentages, evident in Table 10-2 further illustrate that this is true at the project category level as well as on totals.

Finally, note that the subsystem categories, science and communications, are comparable in cost, and are the largest single cost elements in automated lunar and planetary projects. This point will be readdressed in the discussion of atmospheric probe cost estimates below.

A schematic diagram of the SAI Cost Model, illustrated in Figure 10-1 summarizes the cost estimation process. Subsystem direct labor hours are estimated, using the cost model LER's from mission definition input parameters. These estimates can be re-

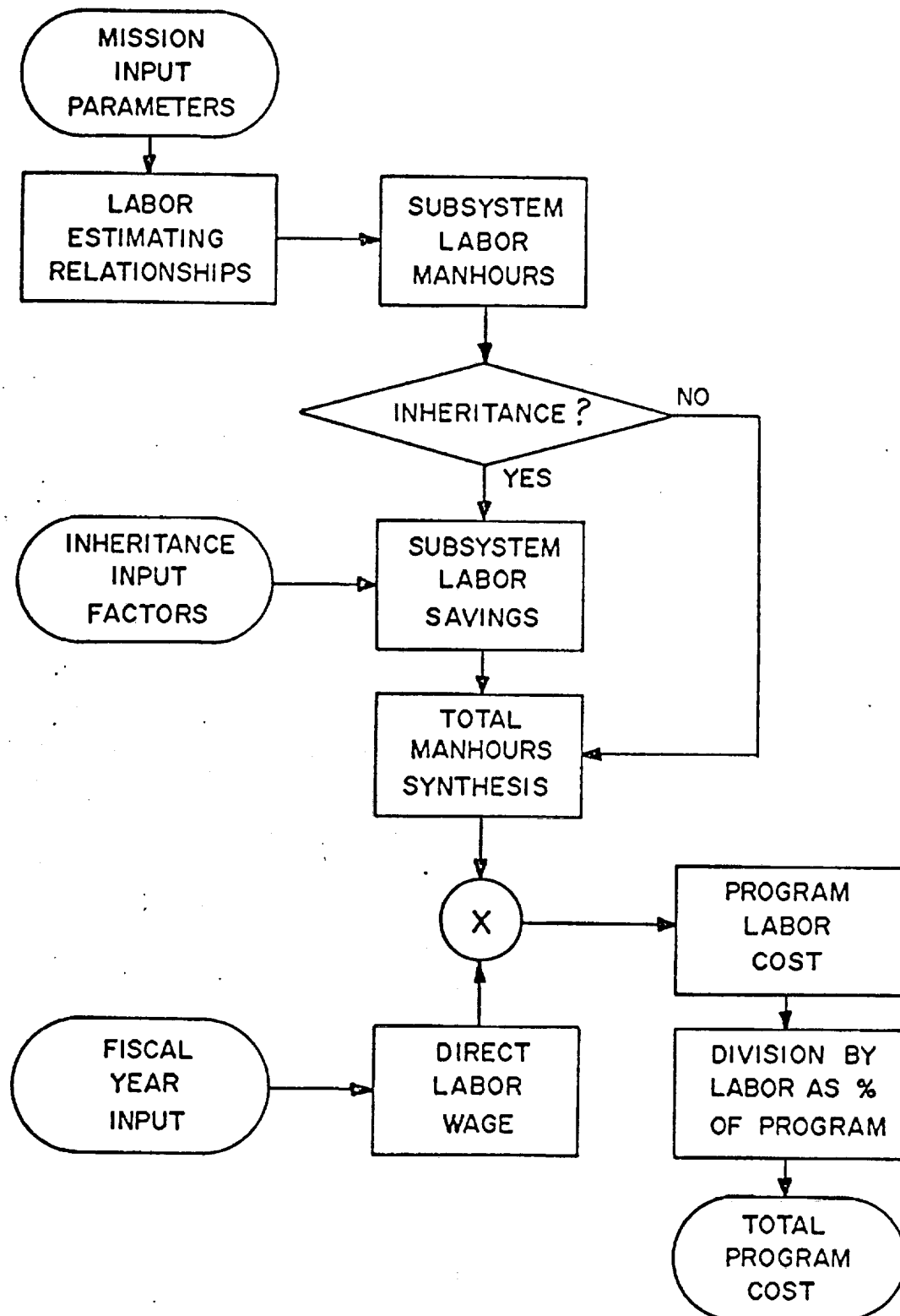


FIGURE 10-1 COST MODEL SCHEMATIC

duced if subsystem hardware inheritance from a previous project is applicable. Total direct labor man hours are synthesized from the subsystem labor estimate using additional LER's for the project support category elements. The total direct labor hours are converted to dollars by applying estimated labor wage rates for the fiscal year cost output of interest. It is only at this point the inflation factors are added to the estimate. The total program cost (less fee, NASA management, and contingencies) is computed by assuming that direct labor accounts for 30% of the total cost.

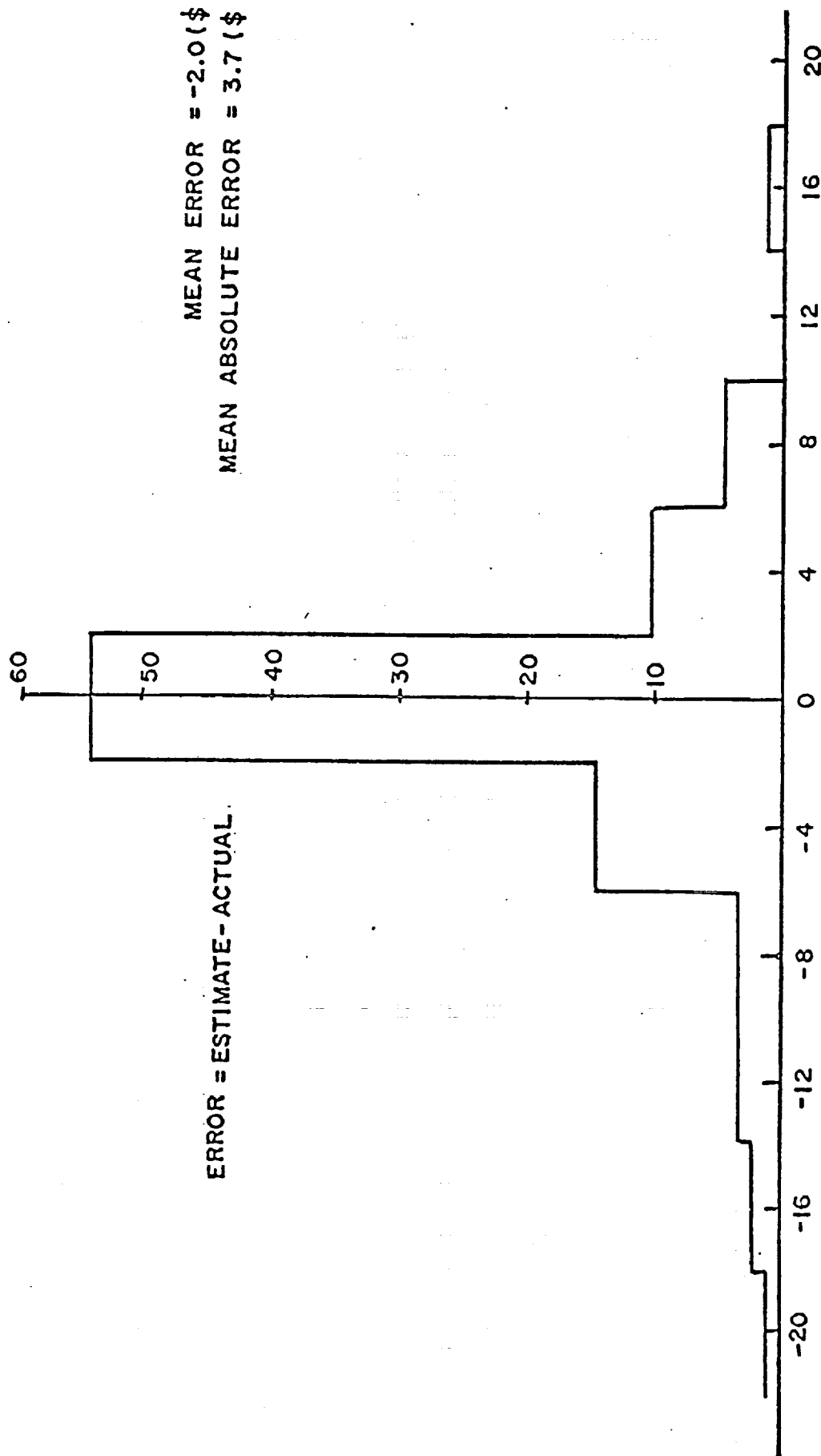
An accuracy of  $\leq 10\%$  error has been demonstrated<sup>1</sup> by the cost model in reproducing the project costs of the data base. This result involved the estimation of 88 individual cost elements. A statistical histogram of the 88 element errors is presented in Figure 10-2. Ideally one would like the density function to have a sharp spike entered around zero error and a relatively rapid tail-off such that the probability of exceeding 2 or 3 mean absolute errors is essentially zero. The actual distribution has a sharper peak (greater density) within one mean absolute error of zero than a Gaussian function, but the tail-off is slower than desired. Estimation errors associated with the Surveyor Project in the data base are mainly responsible for the negative bias in the distribution. The mean error and mean absolute error taken over the remaining six projects in the data base are only  $-\$0.4\text{M}$  and  $\$2.3\text{M}$ , respectively. The mean absolute error of all seven projects is just 10% of total cost.

An error goal of  $\leq 20\%$  on cost model estimates of projects not in the data base has been realized from limited applications to date. Some test comparisons with completed projects and independently estimated future projects are presented in Table 10-3. On this sample of six cases the maximum error estimate is under 12%. Note that the six projects vary considerably in mission concept, total dollar level, number of spacecraft, and period of performance. The results are indeed encouraging. The negative

NUMBER OF ELEMENTS (%)

ERROR = ESTIMATE - ACTUAL

MEAN ERROR = -2.0 (\$ MIL)  
MEAN ABSOLUTE ERROR = 3.7 (\$ MIL)



COST ELEMENT ERROR (\$ MIL)

FIGURE 10-2. DISTRIBUTION OF ESTIMATION ERRORS FOR 88 COST ELEMENTS



TABLE 10-3  
SOME COST MODEL TEST COMPARISONS

Missions	FY \$	SAI Cost Estimate* (\$M)	Comparison		% Difference
			Cost (\$M)*	Basis	
Pioneer (A-E)	1965	55.8	58.7	Actual	-4.9
ATS (A-E)	1966	133.1	137.3	Actual	-3.1
Planetary Explorer Bus	1970	63.2	65.2	GSFC 3/71 Est.	-3.1
MJS-77	1972	187.4	210.0	JPL/SAG 2/72 Est.	-10.8
MVM-73	1973	93.2	94.1	Actual	-1.0
Mini-MSSR	1973	455.3	515.0	JPL 5/73 Est.	-11.6

\*Excludes contractor fee, NASA mgmt., and contingencies

bias in all the estimates, however, indicates some necessary refinement required in the estimating procedure.

### Probe Cost Estimates

A certain degree of ambivalence exists with respect to planetary entry probe cost data. On the one hand, considerable data exists from earth reentry programs including test programs, military applications, and NASA manned projects. On the other hand, atmospheric entry is only one function of planetary entry probes; many of its systems and operations differ markedly from past reentry programs. To date the only planetary entry probe missions flown have been the Venera and Zond series launched by the U.S.S.R. Hence, despite the undeniable feasibility of planetary entry probes, there is little or no historical data directly applicable to the cost estimation of such probes. The situation is not altogether hopeless, however, and a start must eventually be made somewhere. The preliminary cost evaluation of outer planet entry probes which follows, is presented with these thoughts in mind.

Considerable Phase A level analysis has been performed in the last several years on the definition of a first-generation outer planet entry probe concept. This effort includes several contractor studies as well as NASA in-house work at both JPL and ARC. For practical as well as programmatic reasons, the options have been narrowed to a Saturn-Uranus common probe design capable of atmospheric penetration to at least 10 bars. The cost of three flight articles and one spare is currently estimated at \$40M (FY'74 dollars). This estimate is sufficiently detailed to be compared with the cost model described above. Such a comparison should highlight similarities and differences in cost between future planetary probe missions and past automated lunar and planetary spacecraft experience. It should also contribute to the process of firming up the cost estimate of this outer planet probe concept.

A category element comparison of cost between the Probe Study Estimate, PSE, and the SAI Cost Model data base (presented in

Table 10-2) is illustrated in Table 10-4. The clear bars are PSE cost percentages and the hatched bars are data base cost percentages. It is apparent from a comparison of the individual bar sets that the probe support category costs are less (by %), and the probe subsystem category costs are more, than the averages from the cost model data base. The ratio of subsystem/support cost for the PSE is 2.6, whereas the data base indicates a more equal distribution of 1.3. This difference is probably due more to the fact that the PSE is only part of the cost of a complete probe mission than to any intrinsic difference between the construction of entry probes and spacecraft. Adding the probe carrier bus estimate, and non-probe launch and flight operations costs should bring the subsystem/support ratio for the complete project in line with the data base.

There are, however, some real differences in cost distribution within the subsystem category elements. Since the outer planet probe concept is a passively stabilized device guided by the carrier bus no costs appear for guidance and control. However, significant instrument and electronics packaging constraints must be imposed to insure stability during entry and descent. Packaging costs, precipitated by stability control, show up in the structure element and, indeed, increase the structure cost percentage above the average data base value.

Two other subsystem elements are also considerably above the data base averages - science and communications. The differences are reconcilable if one accepts the notion that these subsystem elements are more dependent in definition and cost on mission objectives than on the specific mission mode (flyby, orbiter, probe or lander). In particular, there is no reason to believe the cost of science and communications for probes should be any less than non-imaging science and communications of a flyby spacecraft. Since the total PSE is less than the cost of, say, a Pioneer flyby mission to Jupiter, the science and communication cost percentages for the probe will, therefore, be higher even considering the

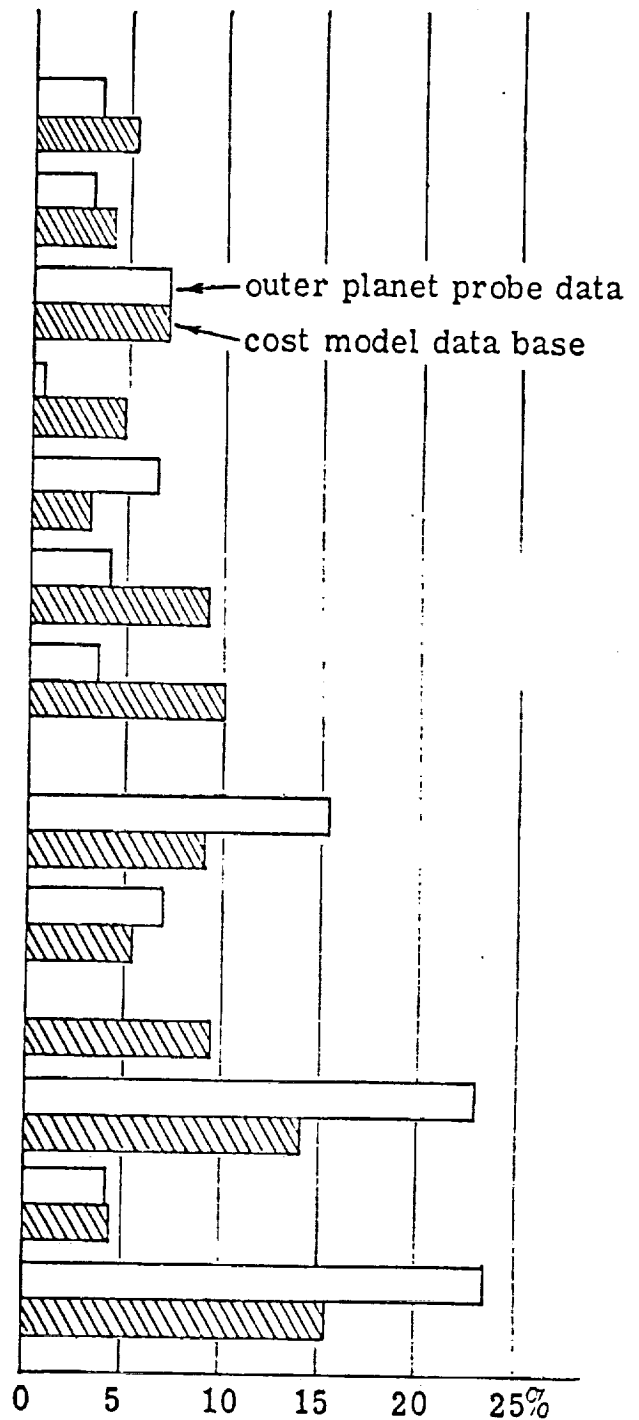
TABLE 10-4

COST DISTRIBUTION COMPARISON● Support Categories

- Program Management
- Systems Analysis and Engineering
- Test
- Quality Assurance and Reliability
- Assembly and Integration
- Ground Support Equipment
- Launch and Flight Operations

● Subsystem Categories

- Structure
- Propulsion and Aerodeceleration
- Guidance and Control
- Communication
- Power
- Science

● Subsystem/Support Ratio

- Outer Planet 10-Bar Probe \_\_\_\_\_ 2.6
- SAI Cost Model Data Base \_\_\_\_\_ 1.3

additional cost of imaging on the Pioneer spacecraft. Hence, where these two subsystems were seen to be the largest cost elements in the cost model data base, they become even stronger cost drivers of atmospheric entry probe costs.

As a second point of this assessment, the cost of the 10-bar outer planet entry probe was reestimated using the SAI Cost Model. The same assumptions of three flight articles and one spare, and FY '74 dollars were used in making the estimate. Applying the cost model without modification yielded a first estimate of \$64.9M compared to the PSE of \$40M. After examining the estimates of the individual subsystem elements, it was found that the costs for the aero deceleration and power subsystems were too high for the probe concept. The aero deceleration system LER was based on only one data point, that being the much larger Viking lander aeroshell. The power system LER was developed from data which always included solar arrays or RTG's. The probe, of course, only has a battery power source. Adjustments to these two LER's yielded a lower second estimate of \$58.8M.

One more necessary change was found in a further review of this second estimate. The cost model assumes that what it's estimating is a complete program, which, of course, is not true for the probes. As a result of the costs for ground equipment and launch and flight operations charged to the probes was unrealistically high. Modifying the ground support equipment and operations cost to match the requirements of the probes part of a total flight project, yielded a third and final estimate of \$48.0M. A comparison of this estimate with the PSE is presented in Table 10-5. The agreement between the two estimates on a percentage basis is quite good. The SAI cost model estimate, however, is 20% higher than the PSE on a total dollar basis. In view of the paucity of actual probe cost data available, it seemed prudent to conclude the comparison and estimation exercise at this point.

TABLE 10-5

PROBE DATA/COST MODEL COMPARISON

	<u>Probe Data</u>	<u>Cost Model</u>
● <u>Total Cost for Three Probes</u>	\$40M	\$48M
● <u>Distribution of Cost*</u>		
○ Management/Design	6.3%	7.5%
○ Science Instruments	23.4	23.3
○ Probe	63.0	62.9
○ GSE and Operations	7.3	6.3
Total	<u>100.0%</u>	<u>100.0%</u>

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\*Percent of Total

## Summary

The most important point to be stressed, is the lack of any directly applicable data base with which to compare present cost estimates of the 10-bar outer planet common probe design. There are similarities with past projects on a subsystem level, and the Pioneer Venus Probe mission, just getting started, should provide relevant cost data in the near future. But for the present, the estimation and validation process of outer planet probe costs is in an embryonic stage.

Still, the similarity between two estimates presented here is encouraging. Based on the available definition of the probe design with the SAG recommended baseline payload, a reasonable preliminary estimate of the probe cost for three closely spaced missions is \$50M  $\pm$  10M (FY '74 dollars).

This investigation of outer planet probe costs has also brought out several interesting points relevant to the continued development of the present 10-bar common design concept. Using the carrier bus for targeting the probe to the correct entry conditions largely eliminates the cost of guidance and control, traditionally 9% of a total project. The savings, however, is largely offset by the difficult packaging of instruments, batteries and electronics in the probe for atmospheric stability. The two most costly subsystems of the probe are science and communications. This has been true in past lunar and planetary automated missions, and appears to be even more apparent in the probe cost estimates. There has already been discussion in this Workshop about expanding the capability of the probe's science and communications. In pursuing those suggestions, one should recognize that these may well be the cost drivers of probe missions. Finally, the cost of the aero deceleration system seems quite reasonable, provided, of course, that entry conditions remain within the bounds of current and near-future laboratory simulation test facilities.

In conclusion, the concern over the lack of an adequate data base from which to evaluate probe cost estimates is restated. The necessary alternative is to closely monitor the developing definition of outer planet probes, so that significant excursions in cost from present estimates are immediately identified.

#### References

1. Pekar, P.P., Friedlander, A. L., and Roberts, D. L., "Manpower/ Cost Estimation Model for Automated Planetary Projects," Science Applications, Inc., August 1973.



MR. HERMAN: One comment with regard to why the cost model is useful to you and why we need this kind of study.

The Space Science Board is holding is a summer study to assess what can be done in the next five or ten years and to recommend to NASA the optimum series of programs which yield the greatest degree of science value per dollar. In order to provide meaningful data to the summer study we have to have estimates of the programs that are in a relatively nebulous state. Some of the studies conducted were only Phase A, and some were not even Phase A studies.

In order to define the important costs per fiscal year, the nature of the summer study, by the way, is such that the Space Science Board is going to look at several funding levels for the Office of Space Sciences and on the basis of the various funding levels, determine towards what series of programs we should provide assistance in our planning. On that basis, the closer our estimates come to the actual cost of the program, the less problems we will have when we have to fight for the new program with the Office of Management and Budget and the Congress. So it is a rough job that we have and the data are being used for that purpose. It is not just an endeavor to see how close we can come to making a profit.

The other point I wanted to make, the thing that bothered me about John's model is the fact that the Pioneer-Venus philosophy is not factored to date. That is, you must rigorously constrain your payload and yet allow yourself plenty of weight and volume, but use the weight and volume margins to bail yourself out of trouble rather than a million dollars, as is the case with Viking. That experience does not seem to be factored into your particular model.

MR. VOJVODICH: Do you want to comment on that, John?

MR. NIEHOFF: Yes. Dan and I have talked about modeling "low-cost" projects at some length. This is one reason why we are very anxious to see the Pioneer-Venus project cost data. We feel that by comparing PV '78 data against our existing data base, we can determine to what extent low-cost expanded-weight concepts really work. We do, indeed, expect to see differences in the Pioneer-Venus data if money is being saved by removing weight constraints.

MR. CANNING: Do you plan also to add as available on missions the planning for the space shuttle, which, presumably, is on the same basis of unlimited weight?

MR. NIEHOFF: Yes. As Dan Herman implied, one of the criticisms of the current model is that it is embedded in history and does not reflect many new cost-saving ideas, particularly those motivated by the space shuttle. We are very anxious to incorporate data that is designed for shuttle launches. I am also anxious to see how significant proposed cost savings will be with the Space Transportation System.

MR. GEORGIEV: John, on the cost data that comes from the ten-bar studies and in comparison to your cost model, are there any particular elements of the cost that are significantly farther out of bed than the twenty-percent differential that you show? Are there any particular elements of the costing system that are much different?

MR. NIEHOFF: Yes. The cost model estimate almost exactly replicated the subsystem costs, but more than doubled the estimate of support category costs. The largest dollar difference was in the estimate of assembly, integration, test and quality assurance - \$6.2M. We were unable, however, to determine whether this was a real difference or largely due to differences in book-keeping cost allocations. You will recall that the percentage comparison between the two estimates presented in Table 10-5

showed much better agreement than this using a coarser distribution of costs.

MR. SWENSON: Is the data handling system lumped into science or communications?

MR. NIEHOFF: Communications. It includes transmitter/receiver assembly, data handling, storage, and antenna assemblies.

MR. HERMAN: I was going to say that the SAI results suggest that in programs where we are going to use these payload effects maybe a better variable than weight would be science weight since no data is derived from communications inherently. Actually, that was a suggestion made by SAI.

MR. NIEHOFF: That is right. At the present time, the communication system is based only on communication weight parameters and evidence exists that science weight has an impact on the cost of the communications system.

MR. HYDE: John, would you care to speculate, with regard to forty-eight-million-dollar figure that you have shown up there, if we had to incorporate the capability of the capsule deflection maneuver and also sterilization?

MR. NIEHOFF: We saw some numbers earlier, by Bob DeFrees of McDonnell-Douglas, on sterilization which I think were on the order of eight million dollars, and we do not have sterilization in this estimate. We have looked at sterilization costs in other programs and the \$8M figure compares favorably with those results.

As far as the probe deflection goes, the cost model does have an estimating relationship for guidance and control. There is

no money in that category in our estimate, since the ten-bar probe is a passive device. I really have no idea what the additional cost would be since I haven't seen any proposed hardware for intrinsic probe guidance. A rough guess would be about the same percentage of the total cost as reflected in the cost model data base for this subsystem element. From Table 10-2 that percentage is 9.1% which would raise the cost by \$4.8M to \$52.8M.

We are talking about putting deltas on an estimate that I have said is very preliminary. I think we have a forty-million-dollar estimate and a forty-eight-million-dollar estimate at the present time, but the data base is so small that I don't believe these kinds of extrapolation are realistic.

MR. VOJVODICH: I would like to reflect on what Dan Herman said, too. Although we are talking about pre-project or phase zero type cost estimates, as you know, the planning cycle is one in which we frequently get locked into a number that we have to live with based on these types of numbers. So it is important that the data reflect as much reality as possible.