RELATIONSHIP OF PLANETARY QUARANTINE TO BIOLOGICAL SEARCH STRATEGY

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ABSTRACT OF COSPAR PAPER

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Previous quantitative studies(1) which form the basis of the COSPAR standard of planetary quarantine were based on two predicates. First, that the scientific issue of detection and characterization of life was the overriding value to be considered, and, secondly, that as many as 60 missions might be ultimately needed to settle this issue. The Mariner IV encounter and other recent observations have narrowed the range of uncertainty of a number of parameters. These findings have led to debate on the standards of planetary quarantine for subsequent missions(2,3,4,5). The relationship between planetary strategy and quarantine standards is a dynamic one. Both are affected by completed explorations, future technology, and changes in the goals of the exploration.

The future utility of the planet Mars, other than for scientific investigation, has not been carefully analyzed but it has an important bearing on both these issues. We might, at some time in the future, want to attempt to revise the atmosphere of Mars to make it more habitable. A likely component of such an engineering scheme would be specially contrived plant forms which might be at a great disadvantage in competition with accidental terrestrial contaminants. For such a scheme, contaminants could be a hazard even if they merely persisted on Mars without extensive proliferation prior to attempts to reengineer the planet. However, we would not wish to incur the great increases in costs that might be involved in protecting this potential value without a better estimate of the possible gains. This suggests a mission strategy which initially emphasizes remote reconnaissance. Mariner IV demonstrates that such missions can be undertaken with understood and controllable levels of risk of contamination.

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(1) C. Sagan and S. Coleman, Astronaut. Aeron., 3, 22 (1965).
(2) N. H. Horowitz, R. P. Sharp, and R. W. Davies, Science, 155, 1501 (1967).
(3) R. G. Bond, J. H. Brewer, et al., Science, 156, 1436 (1967).
(4) N. H. Horowitz, Science, 155, 1436 (1967).
(5) C. Sagan, E. Levinthal, and J. Lederberg (to be published).

Remote reconnaissance in the visible and infrared would also serve to engage the attention of a much broader community than now finds the present sparse information about Mars to be of great interest, and which is necessary to properly evaluate its future utility. Our policy of preserving a planetary resource should not be based merely on a test of our ingenuity at blind prediction when more information can be easily acquired.

Search strategies which include return samples raise new questions about back-contamination of the earth. The answers to these questions depend crucially on the extent of the biological exploration that has been carried out prior to the return of samples. Regardless of the formal protocol invoked, how will one really behave in the event of certain failure modes which might involve certain and serious risk to a small group, i.e., astronauts or sample-handlers, if the risks to the whole species are possibly grave but known only with great uncertainty? Whose gains and whose risks can be used in making decisions? Do manned return sample missions become fail-safe with regard to back-contamination?

Errors in judgment about the appropriate standards of planetary quarantine and the risks associated with techniques of sterilization can lead to irremediable losses. Thus, even though a return sample might give more information than a sophisticated mobile laboratory and such a laboratory will have a higher information yield than an orbiter, a search strategy which progresses from orbiter to lander to return sample allows a better evaluation of the risks being undertaken at each step. Such a progression should also reduce costs by averting needless concerns.

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Introduction

"When we wish to decide whether to adopt a particular course of action, our decision clearly depends on the values to us of the possible alternative consequences. A rational decision depends also on our degree of belief that each of the alternatives will occur. Probability. . . is the logic (rather than the psychology) of degrees of belief and their possible modification in the light of experience." This quotation(1) is a general statement of our concerns in this paper. Previous efforts have been chiefly concerned with statistical calculations(2,3) of required standards to accomplish certain mission goals and the methods for achieving these standards. Little has been explicitly stated about the values necessary to make judgments about strategy, the beliefs that determine the initial probabilities of the relevant hypothesis and the costs associated with different policies.

Our present decision is a choice among possible configurations of missions to Mars that will take place over a period that takes into account the lead time for implementation and acquisition of new data. Planetary quarantine procedures are an important element in mission configurations. What we seek is the application of decision theory to arrive at a rational choice. The initial decisions we are seeking include the cost that will be allocated to sterilization. Unless the relationship of level of sterilization to be achieved to these costs is known, this represents a second decision. Finally the configurations for missions through 1975 must be decided. Nineteen seventy five is chosen to allow lead times necessary for commitment of resources and delays in acquisition of new data. Comparisons are required between flyby, orbiter, lander missions of various kinds, returned samples both manned and unmanned, etc. The results to be sought from these missions involve tradeoffs between science and engineering, between present and future benefits. Future benefits include the use of the

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(1) I. J. Good, Probability and the Weighing of Evidence, (Preface), Charles Griffin & Co., Ltd., London (1950).

(2) C. Sagan and S. Coleman, Astronaut. Aeron., 3, 22 (1965).

(3) C. Sagan and S. Coleman, Biology and the Exploration of Mars, Chap. 27, Publication 1296, National Academy of Sciences, National Research Council, Washington (1966).

results to further optimize policy decisions with respect to succeeding missions. A decision is essentially a wager. Since in the ventures we are talking about the stakes are indeed very high, we are very much concerned about calculating the odds associated with different policies. This is done by enlarging our body of beliefs by drawing deductions from a set of comparisons between beliefs. A belief depends very roughly on three variables. The proposition believed, the proposition assumed, and the general state of mind of the person who is doing the believing. A probability or decision theory, being a fixed procedure, lends a certain amount of objectivity to subjective beliefs. It requires an explicit quantification of the comparisons involved. It provides greatly improved communication with new individuals or groups who must continually enter the decision-making processes during their development. It is also likely to be of value in focusing on specific areas of disagreement between decision makers.

Initial efforts to use these methods have already been made by Matheson & Roths(4). After using material from these studies to explain the general methods we wish to discuss some important elements that still have to be introduced into the calculations to take quarantine into account.

Method of Analysis

Matheson and Roths start by considering as a pilot problem a simplified version of the decision required for the selection of the Voyager-Mars mission configuration of the 1970's. Figures 1-4* illustrate the application of the method to the pilot problem although no attempt is made here to explain it in detail.

Four possible lander configurations have been postulated that represent steps in sophistication from the simplest useful capsule to the most complex one which is capable of obtaining all the data ultimately desired. These four configurations are illustrated in fig. 1 along with the level of achievement they can produce if they are successful.

The question is, what configuration should be selected for the first opportunity, and what sequence of configurations should be planned to follow the first choice?

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(4) J. E. Matheson, W. J. Roths (to be published), Proceedings National Symposium, Saturn/Apollo and Beyond, American Astronautical Society, June 11, 1967.

* Figures 1-4 and Tables 1 and 2 have been kindly provided by James E. Matheson.

The heart of the decision model is a decision tree that represents the structure of all possible sequences of decisions and outcomes, and contains slots into which costs, value, and probability inputs must be fed. The tree contains two types of nodes (decision nodes and chance nodes) and two types of branches (alternative branches and outcome branches). Emanating from each decision node is a set of alternative branches, each branch representing one of the configurations available for selection at that point of decision in the project. Each chance node is followed by a set of outcome branches, one branch for each outcome that may be achieved from the point in the project represented by that chance node. Probabilities of occurrence and values are assigned to each of these outcomes. Costs are assigned to each decision alternative. Figure 2 is an example of such a decision tree using only two configurations and outcome levels from fig. 1. The full pilot decision tree is shown in fig. 3.

To derive a value function we construct a value tree by considering first the major components of value, both direct and indirect, and then the subcategories of each type identified in more and more detail until no further distinction is necessary. Then each tip of the tree constructed as above is subdivided into four categories, each corresponding to the contribution of one of the four levels of achievement to the value subcategory represented by that tip. To compare these values to costs a subjective judgment must be made of the total worth of the program if it reaches the highest level of outcome possible. Specifically, the value tree which serves as the value function in the pilot analysis is pictured in fig. 4. A more complete model has been developed using the configurations shown in table 1. This increase in number of configurations leads to an increase in the number of possible outcomes and hence the number of decision tree nodes and policies. Table 2 is a summary comparing the complexity of the pilot model with the more complete model.

Additional Considerations

What are the beliefs bearing on the relationship of planetary quarantine to biological search strategy that must be introduced into the decision analysis? The most crucial belief that needs to be evaluated is the total utility of the planet Mars. Scientific investigation is merely one of these uses, the most visible at the present time. A high value for this utility implies the most stringent sterilization policy; for example, we might wish to revise the atmosphere at Mars to make it more habitable. Such an engineering scheme would probably include specifically contrived plant forms that might be at a great disadvantage in competition with accidental terrestrial contaminants. Thus spores could be a hazard by persisting on Mars until reengineering the planet is attempted. To evaluate this utility a complex probability analysis is needed. We would not wish to incur the great increases in cost that might be involved in protecting this potential value without a better estimate of the possible gains.

Many observational facts bear on the measurement of two other important beliefs, namely, the probability of survival and propagation of terrestrial organisms in a Martian environment. Recent findings have led to controversy(5,6,7,8) concerning the relaxation of standards of planetary quarantine for subsequent missions.

Voyager missions can launch landers from orbit. The size of the possible landed payloads allows consideration of mobility for the landed laboratory. It is in the unusual, not the average environment of Mars that we will want to search for life. Our sterilization standards must take account of the fact that the successful mission will seek out the most desirable habitat. On the other hand, for the consequences of an unsuccessful mission with accidental landing, the relevant environment is the average one.

A decision on quarantine procedures requires an explicit statement concerning our belief on the probability of life on the target planet. This needs to be further subdivided into the question of whether or not the life resembles earth biota. This distinction is important because it relates to contamination as a source of confusion. Does it frustrate or permit some scientific objectives to be achieved? It has been stated that "the identification of an extensible exobiont as a member of an earth taxon would prove not only that it was adventitious, but that the introduction was relatively recent in the time scale of planetary evolution."(9) However, this requires an estimate of the expected state of biological knowledge at the time of the mission.

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(5) N. H. Horowitz, R. P. Sharp, and R. W. Davies, Science, 155, 1501 (1967).
(6) R. G. Bond, J. H. Brewer, et al., Science, 156, 1436 (1967).
(7) N. H. Horowitz, Science, 155, 1436 (1967).
(8) C. Sagan, E. Levinthal, and J. Lederberg (to be published).
(9) K. C. Atwood, Ref. (3), Chap. 25, p. 455.

That level of knowledge is especially important for the problems of back-contamination which are raised by return sample missions whether manned or not. It has been asserted that if an astronaut survives the long return flight, the potential damage of back-contamination would be amenable to repair. The survival of the returning astronaut proves that at least some humans will not be immediately and rapidly obliterated by the extraterrestrial infection. On the other hand, many viruses need living vectors!

Evaluations of return sample missions will be very sensitive to the state of mind of those making the judgments. Whose gains and whose risks will be assessed? The appropriate constituencies need to be informed and engaged so as to influence the assessment of gains and risks. Possible failure modes for return sample missions, either manned or unmanned, create very difficult problems for rational decision. How does one choose between certain mortal risk to some few individuals and uncertain risk, possibly also mortal, to the rest of the world? It may be impossible to rationalize a decision that compares alternatives differing widely in the precision with which their initial probabilities can be estimated. This difficulty can only be removed by experiments which reduce the discrepancy. For example, the President's Science Advisory Committee, in considering post-Apollo programs, contemplated a decision to proceed towards eventual manned planetary exploration(10). This plan did not envisage the need for more advanced and sophisticated unmanned spacecraft for planetary exploration. But precisely such sophistication may be required to rationalize policy for manned or unmanned return sample missions.

Falsely positive results of any experiments designed to reveal life on the planet would have an important effect on future decisions, in spite of low initial probabilities for life on the planet and for the survival or propagation of terrestrial organisms. The probability of such false positive results is obviously determined by the level of sterilization achieved.

Conclusion

The introduction of these concepts into the analysis is a formidable task. Could such an analysis be completed in time to generate a rational decision for a 1973

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(10) The Space Program in the Post-Apollo Period, A Report of the President's Science Advisory Committee, February 1967.

mission? What alternatives are then possible? Should missions be postponed until the analysis is complete? This would imply an international agreement among space-faring nations and that the analysis will be successful without requiring additional empirical data from space missions. This latter difficulty can be stated generally as follows: "In order to build up your beliefs it is theoretically sufficient to use reasoning only without collecting empirical information. But in practice this would take too much time."(11)

We conclude that mission policy should be conservative, involving only initial probabilities with narrow intervals. The Mariner IV mission showed that a probability limit for accidental planetary impact by an unsterilized flyby of 3×10^{-5} or less does not preclude carrying out useful missions. The initial probability that orbiter missions with the same constraint can be carried out and gather new information is likely to be of narrow interval and calculable. The hypothesis that terminal dry heat sterilization achieves a probability of a single valuable organism aboard a spacecraft intended for a Martian landing of less than 1×10^{-4} has a calculable initial probability of small interval. This method of sterilization, being terminal, minimizes the effect of errors of procedure or execution prior to launch. It involves a decision tree with relatively few nodes. Policy based on this hypothesis would lead to possible and useful missions. Initial policy should then be limited to configurations involving flybys, orbiters and terminally-heat sterilized landers and combinations of these which meet at least as stringent sterilization standards as presently recommended by COSPAR. In addition, a structure for rational decisions in the future in light of expected data needs to be formulated. The problems of contamination are insensitive to the national origin of the inoculum. Hence, such a formulation needs international methodologies for evaluation and decision independent of the parochial interests of the space-faring nations. Furthermore, this planetary exploration strategy requires an international agreement that there will be no manned landings and no return samples from the planets until enough new information can be obtained to permit explicit decision analysis and a rational consideration of such missions with a level of uncertainty many orders of magnitude less than now obtains.

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(11) Ref. (1), p. 4.

TABLE 1

FULL SCALE MODEL POTENTIAL MISSION CONFIGURATIONS

		Year of Launch					
	CONFIGURATION	'71	'73	'75	'77	'79	'81
1	CANCEL PROJECT	X	X	X	X	X	X
2	SKIP OPPORTUNITY	X	X	X	X	X	X
3	MARINER '71	X					
4	VOYAGER JR.		X				
5	TWO VOYAGER JR.'s		X				
6	ORBITER ONLY		X				
7	ORBITER WITH ATMOSPHERIC PROBE		X	X			
8	ORBITER WITH DESCENT TV PROBE		X	X			
9	ORBITER WITH MEDIUM SOFT LANDER		X	X	X	X	X
10	ORBITER WITH SURFACE LABORATORY		X	X	X	X	X
11	ORBITER WITH BIOLOGICAL LABORATORY			X	X	X	X
12	ORBITER WITH TWO ATMOSPHERIC PROBES		X	X			
13	ORBITER WITH ATMOSPHERIC PROBE & DESCENT TV PROBE		X	X			
14	ORBITER WITH ATMOSPHERIC PROBE & MEDIUM SOFT LANDER			X	X		

TABLE 2

DECISION TREE COMPARISON

Pilot	Parameter	Full Scale
4	Mission Configurations	14
13	Mission Outcomes	56
5	Project Outcomes	56
5	Capsule Outcomes	14
None	Orbiter Outcomes	4
Open	Last Possible Flight	1981
60	Decision Tree Nodes	$\approx$ 3000
1000	Decision Policies	$\rightarrow \infty$

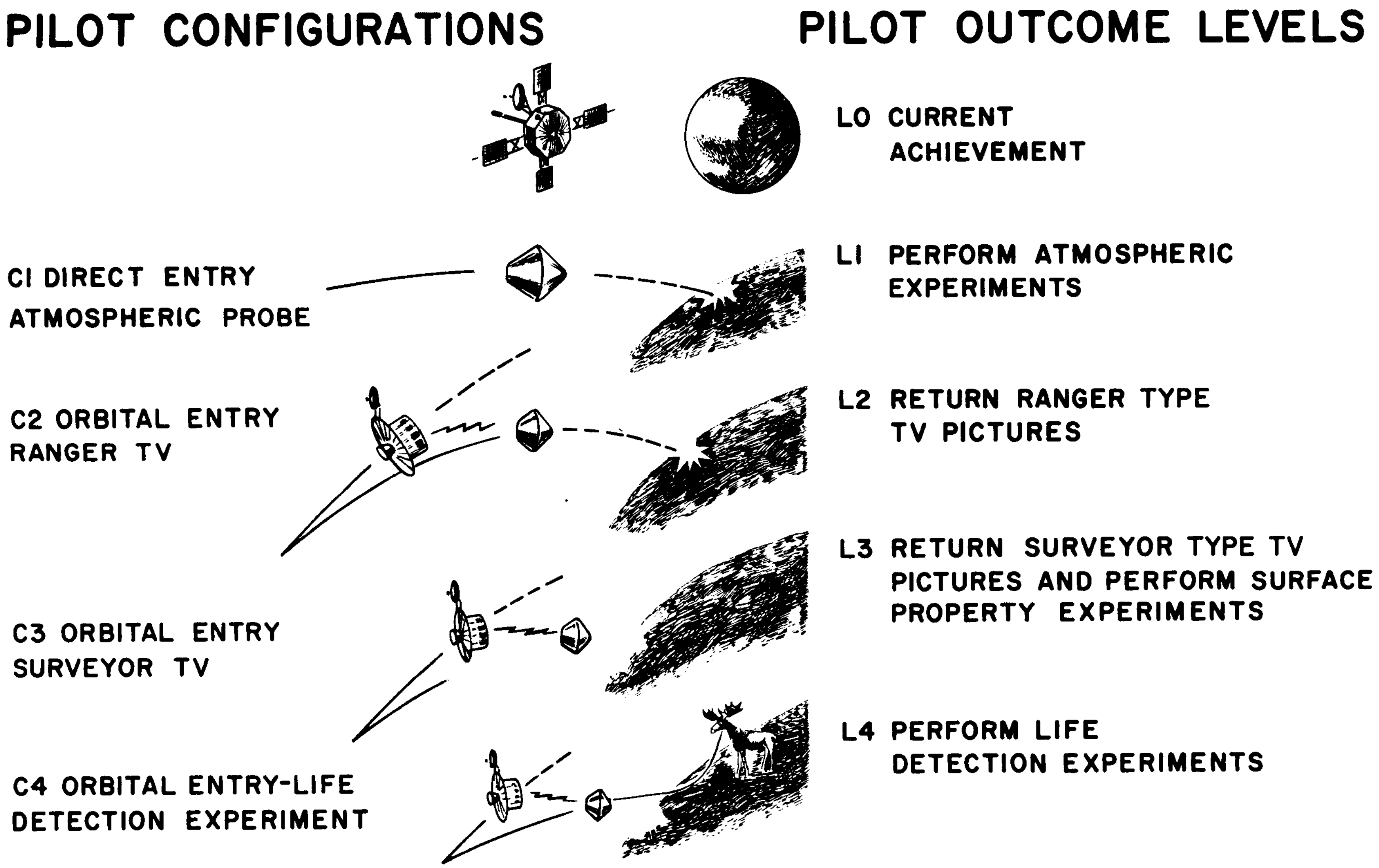


Figure 1. Configurations and Outcomes Distinguished in Pilot Analysis

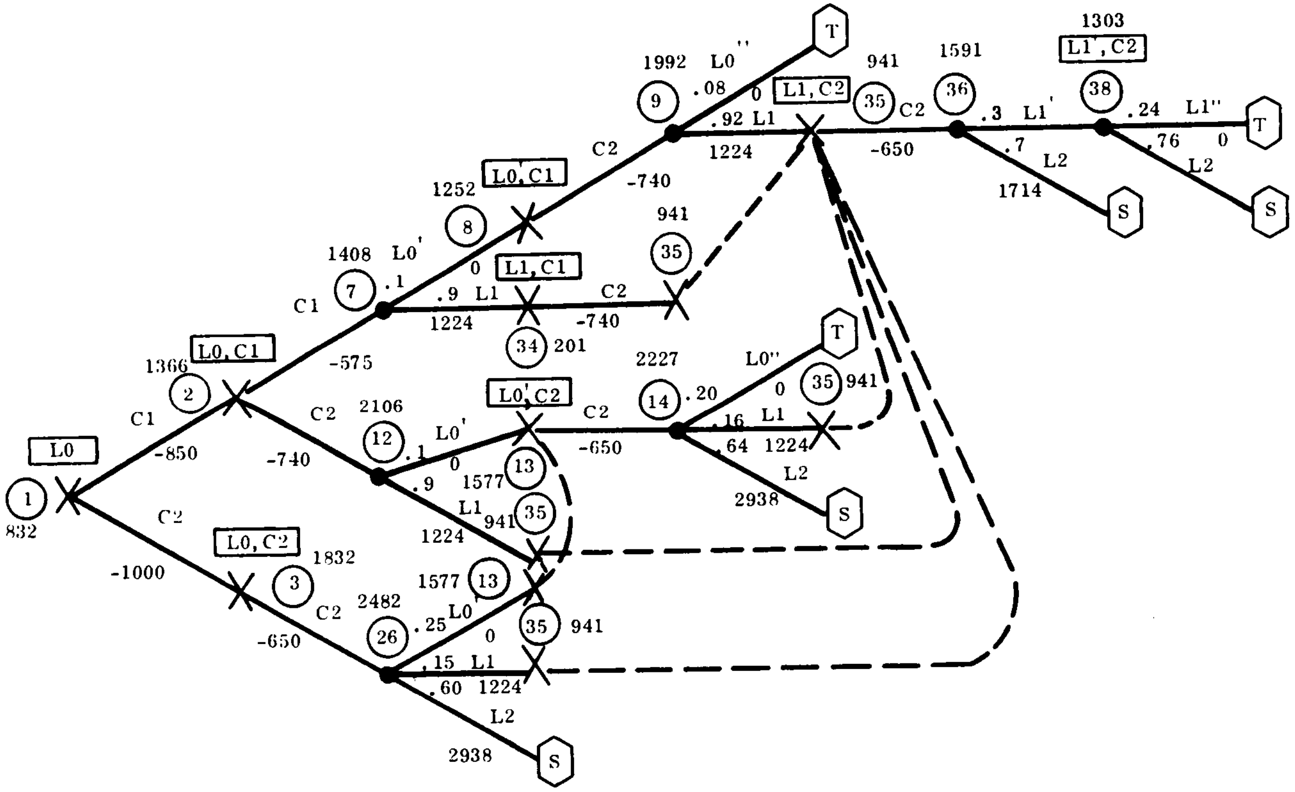
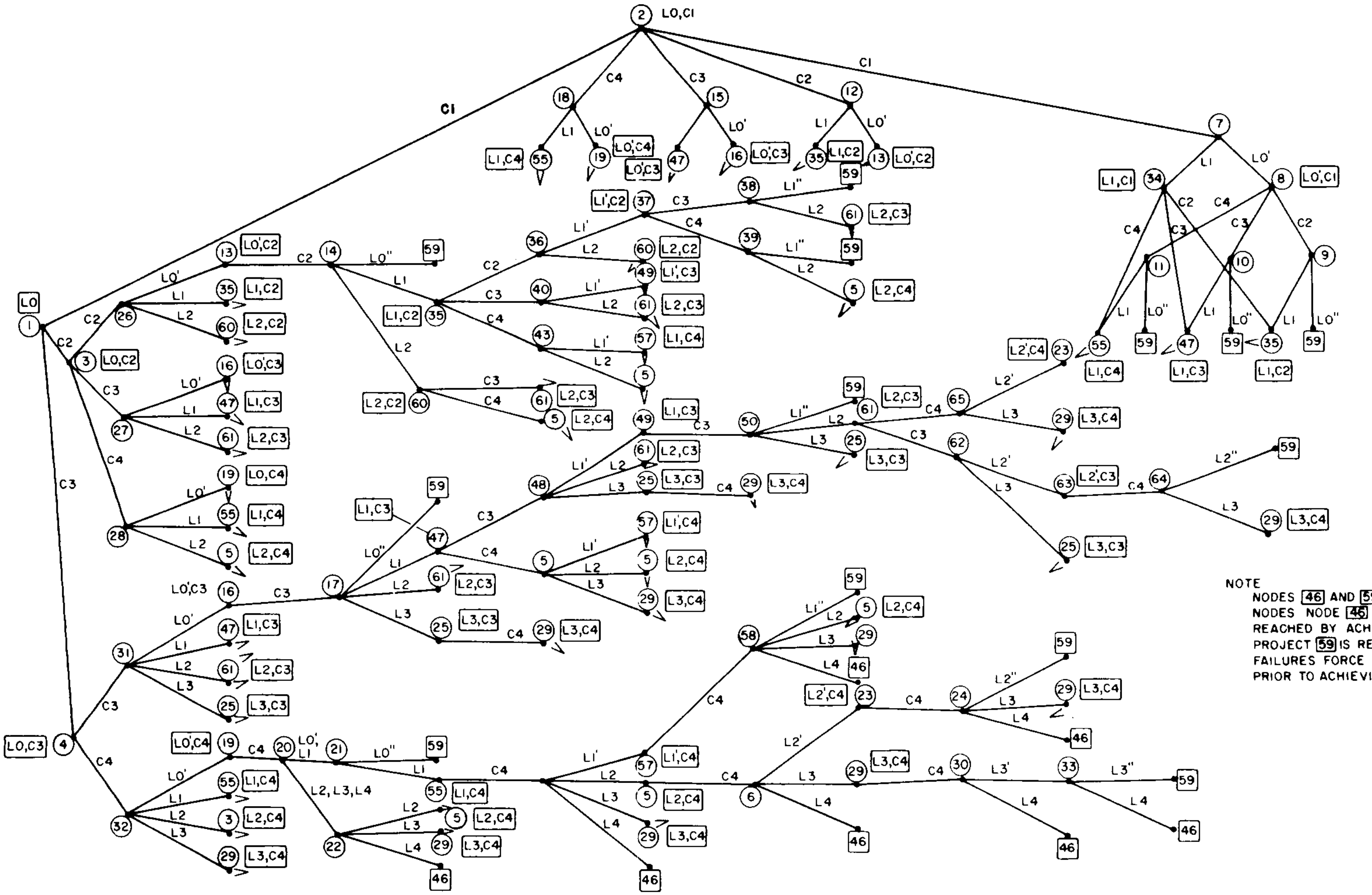
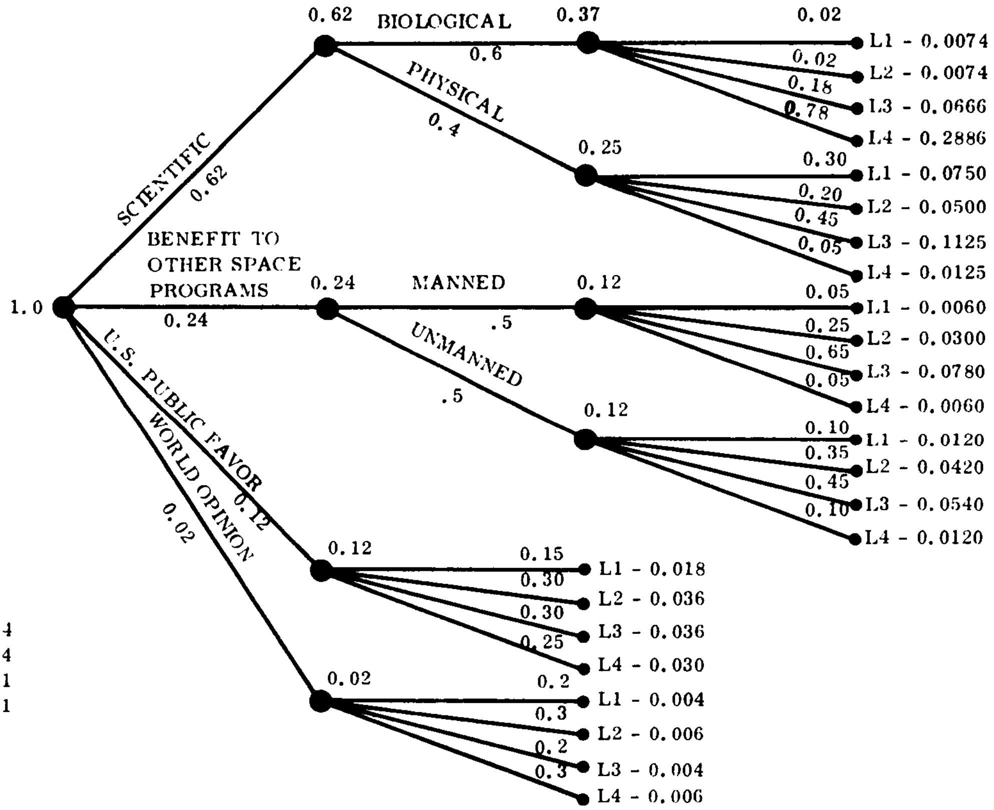


Figure 2. Example Decision Tree



NOTE
NODES 46 AND 59 ARE THE TERMINAL NODES NODE 46 CORRESPONDS TO L4 AND IS REACHED BY ACHIEVING A TOTALLY SUCCESSFUL PROJECT 59 IS REACHED WHEN TWO SUCCESSIVE FAILURES FORCE TERMINATION OF THE PROJECT PRIOR TO ACHIEVING L4

Figure 3. Decision Tree for Pilot Voyager Project



RESULTS

L1	.1224
L2	.1714
L3	.3511
L4	.3551

Figure 4. The Value Tree