IN-SITU RESOURCE UTILIZATION FOR THE HUMAN EXPLORATION OF MARS: A BAYESIAN APPROACH TO VALUATION OF PRECURSOR MISSIONS

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ABSTRACT

The need for sufficient quantities of oxygen, water, and fuel resources to support a crew on the surface of Mars presents a critical logistical issue of whether to transport such resources from Earth or manufacture them on Mars. An approach based on the classical Wildcat Drilling Problem of Bayesian decision theory was applied to the problem of finding water in order to compute the expected value of precursor mission sample information. An implicit (required) probability of finding water on Mars was derived from the value of sample information using the expected mass savings of alternative precursor missions.

INTRODUCTION

In-Situ Resource Utilization (ISRU) technologies have the potential to significantly reduce launch mass delivered from Earth by producing propellants and consumables for life support from indigenous Mars resources [1][2]. The question of identifying preferred ISRU concepts was heavily dependent on the availability of In-Situ water (ice). Preliminary science measurements from orbit and the surface have indicated the presence of such water, but the question of whether sufficient quantities are available for ISRU processing remains an open question [3]. Precursor missions to identify the location of sufficient water deposits prior to a commitment to an ISRU strategy were viewed as an important part of the ISRU selection decision. The purpose of this paper was to further structure the ISRU selection decision by including an approach for evaluating the value of alternative precursor missions for finding and identifying water deposits.

APPROACH

Because the ISRU decision is dependent on finding In-Situ water which would depend on the outcome of a search for water, the ISRU selection problem has parallels to a classic decision analysis problem known as the Wildcat Oil Drilling Problem [4]. The analogous ISRU problem involves a search for In-Situ water (ice instead of oil) in areas of interest around the equator. The decision was to identify whether to send any of a number of precursor missions to determine the likelihood that water would be present in landing areas of interest.

This problem contained a variety of decision making concepts useful to the ISRU question. As a Bayesian decision problem, the decision maker has a number of choices: (1) Select the ISRU system independent of the water issue, absorb the costs of transporting resources, and select the option with lowest cost and risk that meets the resource requirements; or (2) Obtain additional (sample) information about the presence and location of water by launching precursor missions to establish whether In-Situ water is available. Then, after the outcome (water or no water) of the precursor mission, select the appropriate ISRU system for development.

For the purposes of this paper, the masses of current or planned missions were used to estimate the information costs of each alternative. The orbiter option assumed a system comparable to the Mars Reconnaisance Orbiter [5]; the Mars Exploration Rover (MER) system mass was used as an analog for the rover option [6]; and a preliminary drilling concept was found for the lander-drilling alternative [7]. The estimated likelihood for each of the precursor mission approaches were based on the relative capabilities of each precursor. For example, the orbiter, while capable of detecting signs of subsurface water, cannot, with the same level of confidence, confirm the presence of water that a rover would by direct measurement. Similarly, a rover with minimal drilling capacity (~one meter), would be less likely to detect water at a shallow depth than a drilling mission which could sample to greater depths (~tens of meters).

RESULTS

The expected mass savings were computed for each of the decision sets in the decision tree—the choice of ISRU process, the selection of precursor mission, and the decision whether to invest in a precursor mission or proceed without a precursor using an ISRU process absent In-Situ water. The calculations are summarized in Figure 1 showing the expected mass savings values for a parametric range of prior probabilities of water presence. The horizontal line represents the floor of expected mass savings for no precursor information and simply proceeding with one of the ISRU options. For each precursor, the probability of water to be found must be at least as high as the no-sample information line. Thus, the lowest acceptable probability of water is 30% for the drilling system (due in part to its high detection rate) and the highest required probability of water is just over 70% (due in part to its potentially high error rate).

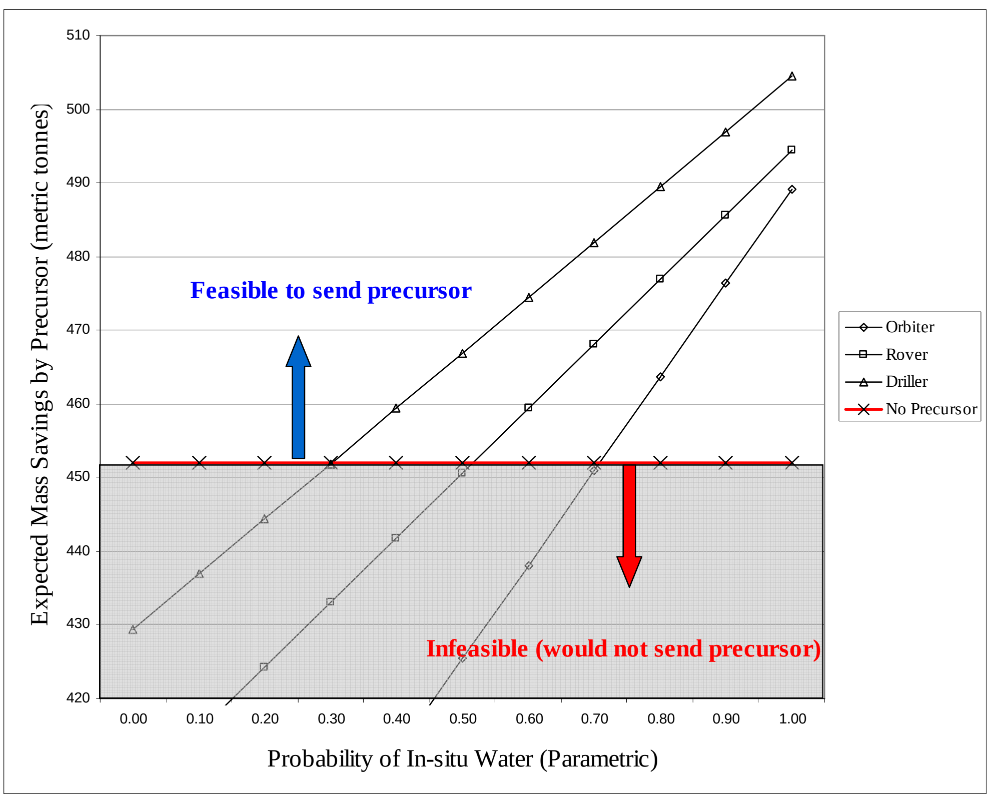

Figure 1. ISRU expected mass savings versus (parametric) probability of In-Situ water

DISCUSSION AND CONCLUSIONS

Because the Mars reference mission is only a concept at present and subject to many changes over the period of its design, the results described herein were intended primarily to illustrate the Bayesian nature of the Mars exploration process.

During the course of this study the following conclusions were drawn. For the precursor problem outlined here, the decision strategy for mass savings was dependent on the probability of finding water. If the probability of finding water was greater than 30%, the terminal decision was to launch a precursor to obtain more information about the likelihood of water and the choice with the highest expected mass savings was the drilling system due to the high probability of detecting actual water coupled with a low error rate for detecting water none was present. However, if the probability of In-Situ water was less than 30%, the terminal decision was to launch one of the ISRU process systems without a precursor and use an ISRU process that does not require In-Situ water (i.e., bring the water from Earth).

The application of a systematic Bayesian decision analysis described in this paper to Mars ISRU technology and mission planning provided a quantifiable and traceable approach for examining key elements of mission, ISRU, and exploration interdependencies.

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