In-Situ Resource Utilization for Economical Space Missions

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Abstract

This paper presents some recent developments in the technologies of ISRU with the specific intention of *cost reductions in space missions*. Recognizing that a certain level of technology maturation is necessary before the mission designers will seriously consider any technology, the hypothesis is made that the overall cost-index is inversely proportional to the TRL. Also recognizing that the cost is directly proportional to the mass at launch, the cost-index is identified as the ratio of the launch mass to the TRL. Whether this cost-index is the true measure of the overall mission cost is arguable; however, the *relative* costs of comparable technologies can be readily assessed by applying identical rules of such an evaluation. As one example of this approach, Mars Sample Return (MSR) is studied, and nine competing technologies are evaluated for the key Mars Ascent Vehicle (MAV). It is found that the technology of oxygen production through the dissociation of atmospheric carbon dioxide can be a key technology. In addition to reporting upon this technology briefly, one *innovative application* that significantly enhances the science capabilities of a rover is discussed.

INTRODUCTION

Cost, perceived or real, continues to be a major deterrent in the timely execution of space missions. Despite rosy promises by managers, and valiant efforts by engineers, the cost of the first step itself (space access) continues to be around $10,000/kg to LEO, and much higher for planetary targets. Smaller, cheaper, faster, better approaches to spacecraft (the payload) have introduced significant economy, compared to previous missions; however, when more ambitious missions are considered, the state-of-the-art costs continue to be high.

Three facets of this cost issue are important. First, improvements are necessary in the launch system. The trend towards RLV's from the ELV's is encouraging. A program on hybrids[33] has been making advances in lower costs through simpler propellants. Second, the advances in micro-technologies[34] will help us achieve greater science returns for a given mass. Third, an entirely new approach to space missions, specifically ***utilizing local resources*** instead of relying upon earth-transported resources, has been studied for a number of years[1-17], but not executed in any space missions so far. In addition to the understandable reluctance to try something "untested and new", in the place of "tried and proven" components, on high-profile missions which are constantly under media scrutiny, it is only fair to acknowledge that these ISRU technologies have not yet advanced to acceptable TRL's, at least in the judgment of the mission planners; the burden of the proof-of concept of ISRU is on the engineers. Additionally, there is need for a rational, quantitative methodology for evaluating the overall economics of ISRU, just as it is the case for any component of a spacecraft. What had been an "innate feel" and "experience driven evaluations" were given a formal structure through the Figure-of-Merit concept, first proposed[9] in 1989. The overall mission was divided into five major components: (1) the trajectory/orbital mechanics, (2) transportation/propulsion, (3) c^3I, (4) power/support components, and (5) ISRU. These five components were studied in detail for any mission; however, the heart of the new concept is the recognition that the *effective combination* of these components is far more important than achieving the best available components by themselves. This FoM can be, in fact should be, different for different missions. For example, in a simple earth-observation mission, the number of bits of data received per kg of launch mass could be one definition; on the other hand, in a sample return mission, the mass of sample returned to earth divided by the mass of the initial craft leaving the earth, may be a better definition. While these are only the initial steps towards an acceptable FoM, the overall costs and risk must be introduced for a fuller reflection of the true picture. The numerical values of the component performance are constantly changing, especially in ISRU, and the best estimates (1997) are used in this paper.

The specific example of Mars Sample Return (MSR) is studied in the context of a simple (direct) ascent which is taken to require 6km/s (incremental velocity, or, delta v). While other maneuvers are possible such as throttling, multistaging, or, combinations thereof, for the purposes of this comparative study, the simple approach illustrates the point.

THE BACKGROUND

There is need for a quantitative and rational methodology for estimating the overall (mission) effect of choosing various subsystems that comprise the spacecraft.[9] (Ideally, one would like to extend the choices beyond the spacecraft subsystems, and include the other details such as the orbital mechanics and the communication network). With a description of the components, it is desirable to predict the outcome, of which life-cycle costs and the reliability (probability of success) appear to be very important currently (1996-97). The Technology Readiness Levels (TRL) of various components play a role in the mission outcome; generally, lower TRL's lead to greater costs that must be invested to bring the component to a sufficiently high TRL to be flightworthy. On the other hand, it is possible to use a lower TRL component, and accept the penalty. This penalty is usually in the form of heavier mass, or superfluous sub-components. The heavier mass (at launch) can be translated into cost. However, it is not clear that the lower TRL components are any less *reliable* than the higher TRL ones. A simple example may help illustrate the point. In the field of ISRU for low-cost Mars missions, the production of oxygen and a fuel has been pursued for a long time. The technology of solid oxide electrolysis of atmospheric carbon dioxide is almost 100 years old (Walther Nernst, U.S. Patent #623,811, dated April 25, 1899). For a long time, the preferred *geometrical* configuration has been the tube, which has the advantage of cooler ends for easy seals, and the preferred *material* has been "ceramic" polycrystalline zirconia doped with vacancy promoters. This system has been studied by a number of companies, notably, Westinghouse, Ceramatec, and United Technologies. While continuing to pursue other higher-tech options, the University of Arizona, NASA Space Engineering Research Center (SERC) built and delivered a four-cell, lower TRL system to NASA LeRC for demonstration purposes[5]. First used at LeRC in the summer of 1992, with a few simple modifications, the unit has worked reliably since. In fact, LeRC has operated this unit at several locations in the USA during the AIAA annual propulsion meetings. At the end of a typical 30 minute presentation, it has operated a CO-O_2 rocket to confirm that the fuel-oxidizer produced can indeed develop thrust in a rocket motor. The higher-tech options that the UA SERC has pursued since that time have been most promising, shown higher efficiency and a much higher specific production rate, but have simply ***not*** been as reliable; they have failed at various levels. The main point is that the lower TRL "kluge" unit, although heavy and power-hungry, has operated more reliably than the higher TRL units.

The complexity of the system can be expected to lead to lower reliability. Again using the above example, the lower TRL ceramic tube unit is very simple, while the higher TRL units are more complex.

THE BASIC HYPOTHESES

The basic hypotheses used in this paper are:

the overall mission *cost* is inversely proportional to the TRL, and
the probability of mission *failure* is directly proportional to the complexity.

It is understood that the TRL and complexity are independent of each other. This highly simplified approach has the advantage that the usual cost index, namely the *mass at launch* can be divided by the TRL to arrive at a relative cost index for competing technologies; similarly, the complexity number is divided by the TRL to arrive at a relative (probability of) failure index for missions using competing technologies.

Relevant work by others in the field are available in references 18-24. It is important to clearly understand a fundamental point of difference: "risk", as used by many of the authors, seems to be the *program* risk. That is, an evaluation of whether the program (leading to the launch) will, or will not, meet its cost goals. In the current interpretation, the risk is clearly the probability that the *mission* will fail to meet its goal(s). In addition, some of the authors have restricted their methodology to the launch vehicles, and some to small satellites only. Thus, the current work, although a simple first step, *is* different from the available studies.

The TRL and complexity numbers (indices) are arrived at using the NASA ITP document (1991), where the TRL definitions leave very little room for interpretation. In the area of previous missions, the Voyager (MJS77) was chosen for comparisons. Here, the TRL of components that were selected (1977) were discerned through a detailed telephone conversation with Bud Schurmeier. The objective of this exercise was to show that the current approach can be verified for its intrinsic merit through its "predictions" of a past successful mission.

The approach uses a simple spreadsheet to interlink the various calculations.

The example is Mars Sample Return. Recent studies have shown that the Mars Ascent Vehicle (MAV) is the most critical component of the overall mission. For this reason, this initial study considers variations in the

MAV propulsion options. The incremental velocity for the Mars ascent (returning towards earth) is calculated to be 6 km/s. If different trajectory plans are used, the number could change, but will not alter the main message of this report. A consistent structural factor is used from the literature. (In the case of hydrogen storage, extensive literature search, and contacts with experts in the field, led us to the number used, namely, two kg of inert mass for every kg of hydrogen stored; in fact, there appears to be no known case of successful storage of liquid hydrogen in space for longer than a few months.) The nine options encompass the usual technology options for propulsion. These vary from the tried-and-tested LOX-Hydrogen system at a TRL of 9,..to...the interesting possibility of a simple hybrid rocket at a much lower TRL. Also included are the traditional storage mono and bipropellant systems. One recent contender has been the glow discharge system pioneered at ODU for the production of a fuel (CO) and the oxygen from atmospheric carbon dioxide.

Admittedly, some interpretation and technical judgment are involved in the complexity numbers. However, it is emphasized that changes in these numbers will not affect the mainstream theme of this report which is showing a methodology for rational comparisons of competing technologies. In other words, what is presented is a "living" spreadsheet where different input data can be incorporated.

THE RESULTS

The results are presented in tabular and graphical form. It is interesting to note that the hybrid rocket emerges as the clear winner in terms of lower cost and overall merit. The relative ranking, or the merits of one system over the other, are secondary to the main conclusion: the current approach provides the first step in a rational evaluation of competing technologies in space missions. The probability of failure, as used here, is merely a relative index of the competing systems. Thus, a number equal to or greater than 1 (one) should not be (mis)interpreted to mean certainty of failure. It merely states the fact that a high number means a higher probability of failure, or inherent risk compared to a lower number system.

Future work should pursue the further refinement of the approach and should specifically examine the immediate and future missions of importance. These could include all of the Mars Surveyor missions, and the aerobot missions.

The inherent simplicity and flexibility of the current approach have much to offer in comparison with more sophisticated cost/risk models.

SUMMARY

This preliminary work, aimed at relating the emerging ISRU approach to the *overall economics* of space missions, has shown promise in identifying a Figure-of-Merit that can be an index of the overall effectiveness. The aim, at this stage, is only to indicate the technique of assessing the cost/benefit of using any new family of technologies; here we have chosen to illustrate the point with ISRU. The specific technological advances in ISRU are not the subject of this paper. The recent advances are available from our website, and one specific advance in the area of greatly enhanced science return through an intelligent, locally refueled robot (Locally Refueled Planetary Explorer, or, LORPEX) was the subject of a recent paper[35]. Several other related technologies have also been pursued, and vary from water use on Mars[25] to thermal control[26] to testbeds[27] to some lunar applications[28] as well. More detailed accounts of ISRU and asteroidal impacts, with the possible interest in mining them, are available in references 29-31. It is hoped that these technological advances, combined with a rational, quantitative methodology for evaluating the overall economics, will provide the incentive for embarking upon an entirely new class of reliable, low-cost, high-return science missions of the near-term future explorations.

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Mission estimation overview

	Program cost	Mission cost	Program risk	Mission risk
Bearden & Law	Yes	Yes	*	No
Young	Yes	No	*	No
Burgess & Gobreial [1]	Yes	Yes	Yes	No
Harding & Pichi [2]	Yes	Yes	No	No
Moore et Alt.	Yes	Yes	No	No
Oxnevad	Yes	Yes	No	No
Ramohalli	Yes	Yes	Yes	Yes

* Only partial economic evaluation

1 Small satellite only

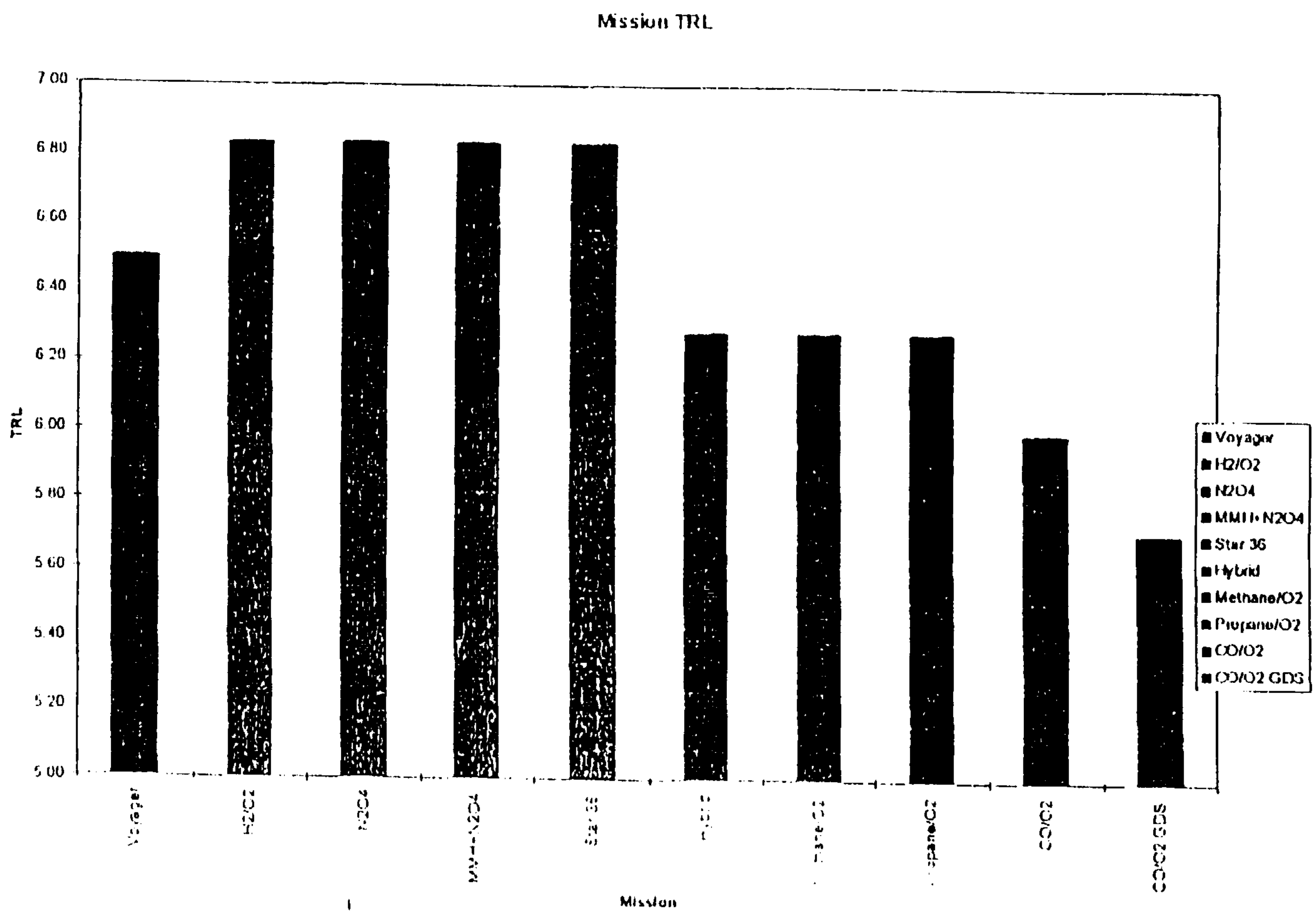
2

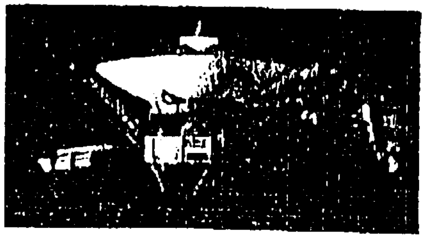
Composite TRL for the missions

Mars Sample Return mission

Components	Voyager	H2/O2	N2O4	MMH+N2O4	Star 36	Hybrid	Methane/O2	Propane/O2	CO/O2	CO/O2 GDS
ISRU				6.00		6.00	6.00	6.00	6.00	4.00
Power	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Propulsion	9.00	9.00	9.00	9.00	9.00	6.00	6.00	6.00	4.00	4.00
Mission Dynamics	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Communication	6.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Scientific Instruments	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Thermal control	8.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Average	6.50	6.83	6.83	6.71	6.83	6.29	6.29	6.29	6.00	5.71

Composite TRL for the missions

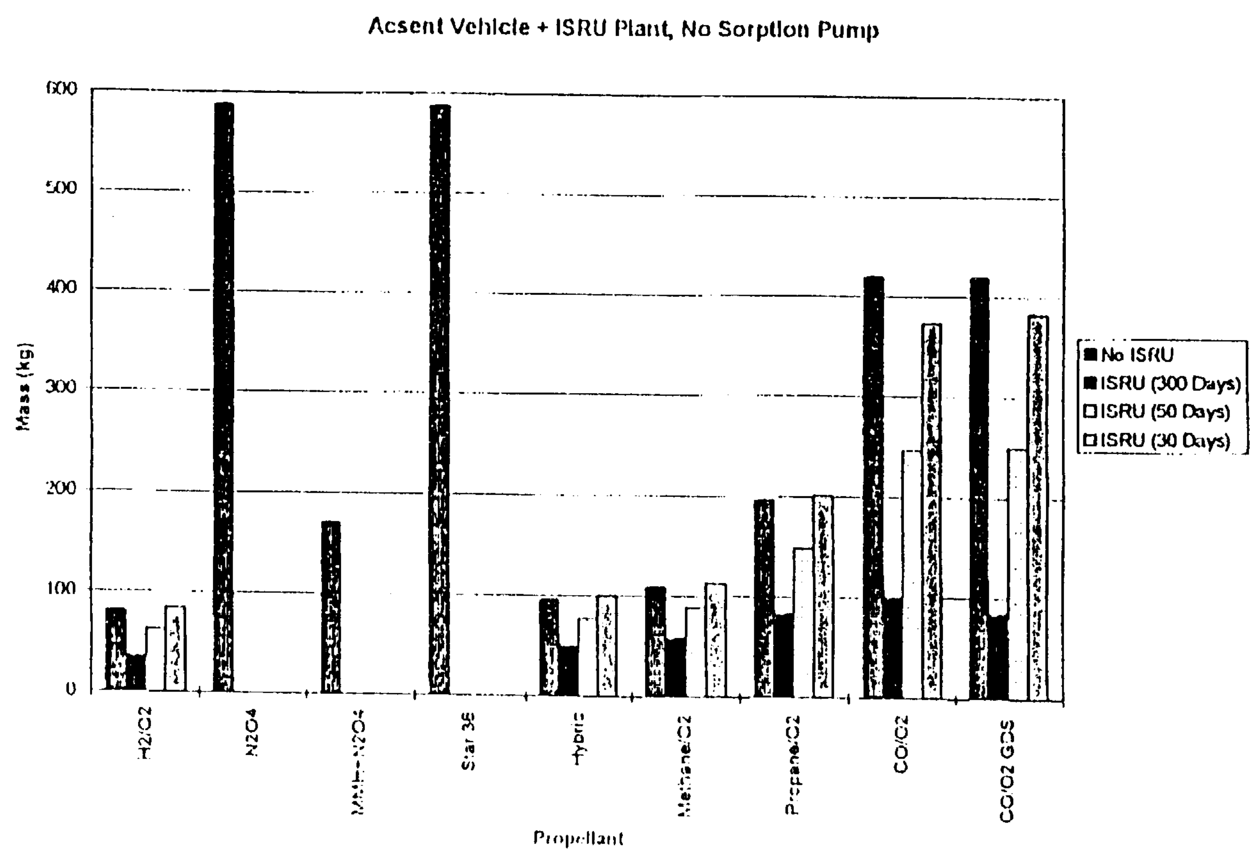




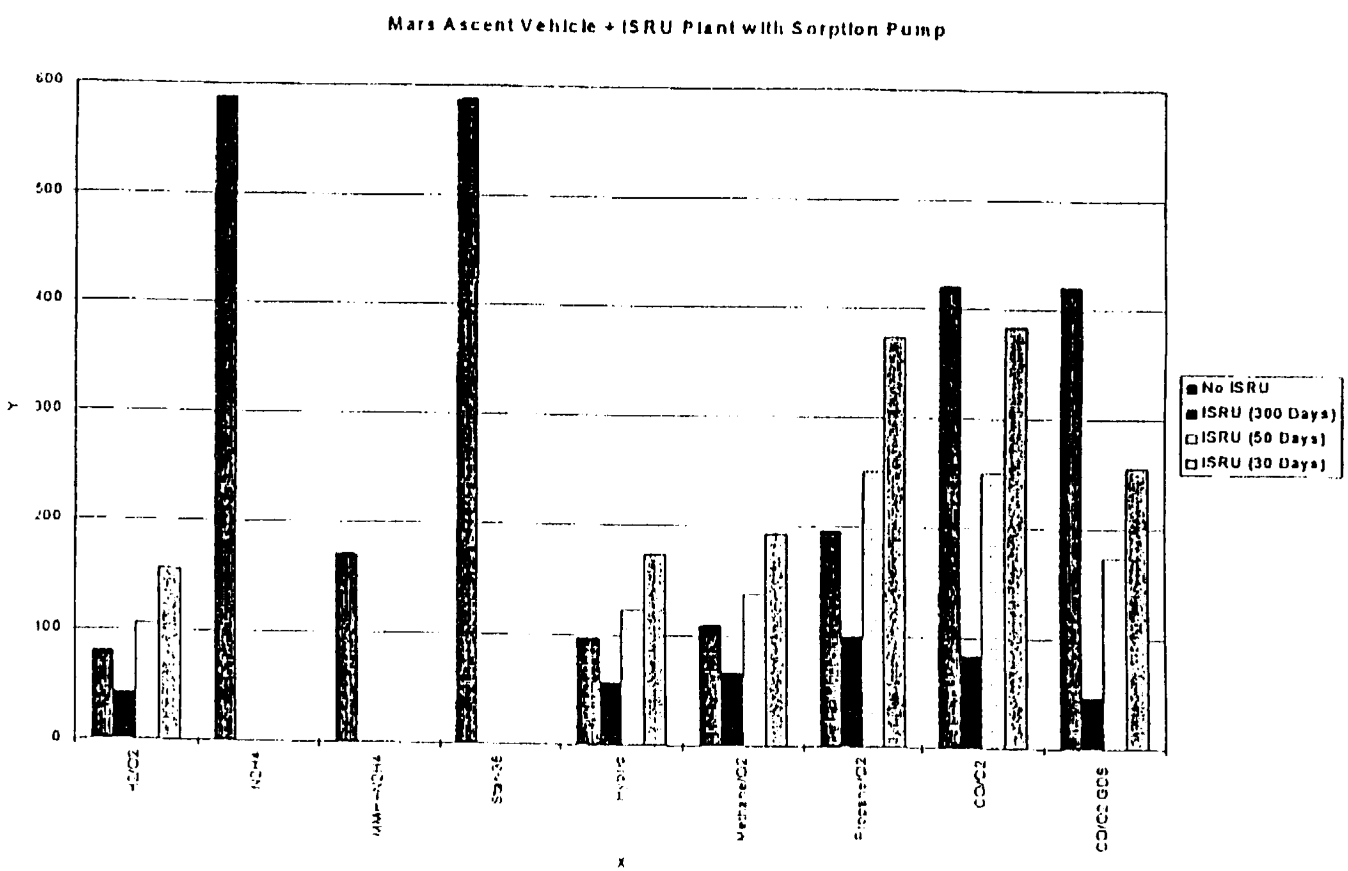
Voyager mission

Components	TRL
ISRU	
Power	9.00
Propulsion	9.00
Mission Dynamics	4.00
Communication	6.00
Scientific Instruments	3.00
Thermal control	8.00
Average	6.50

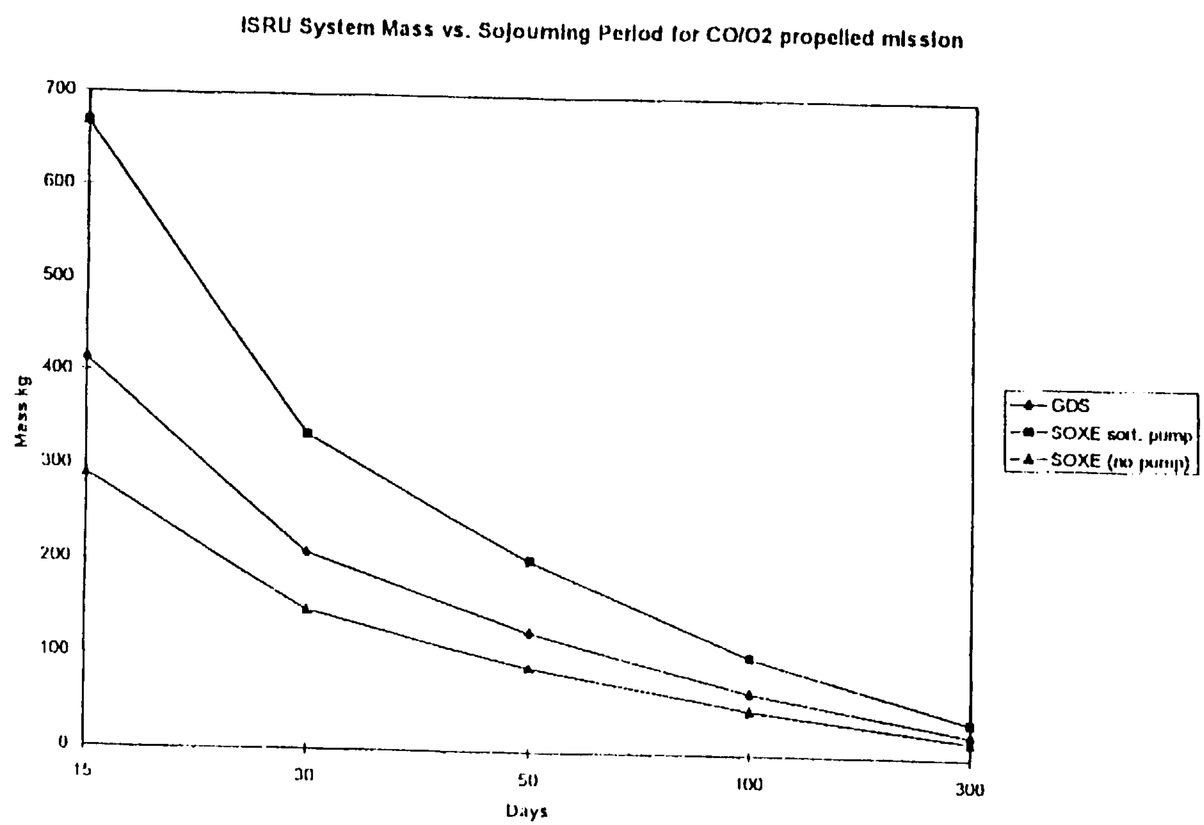
Comparison of different duration of stay for different propellants (No sorption pump utilized)



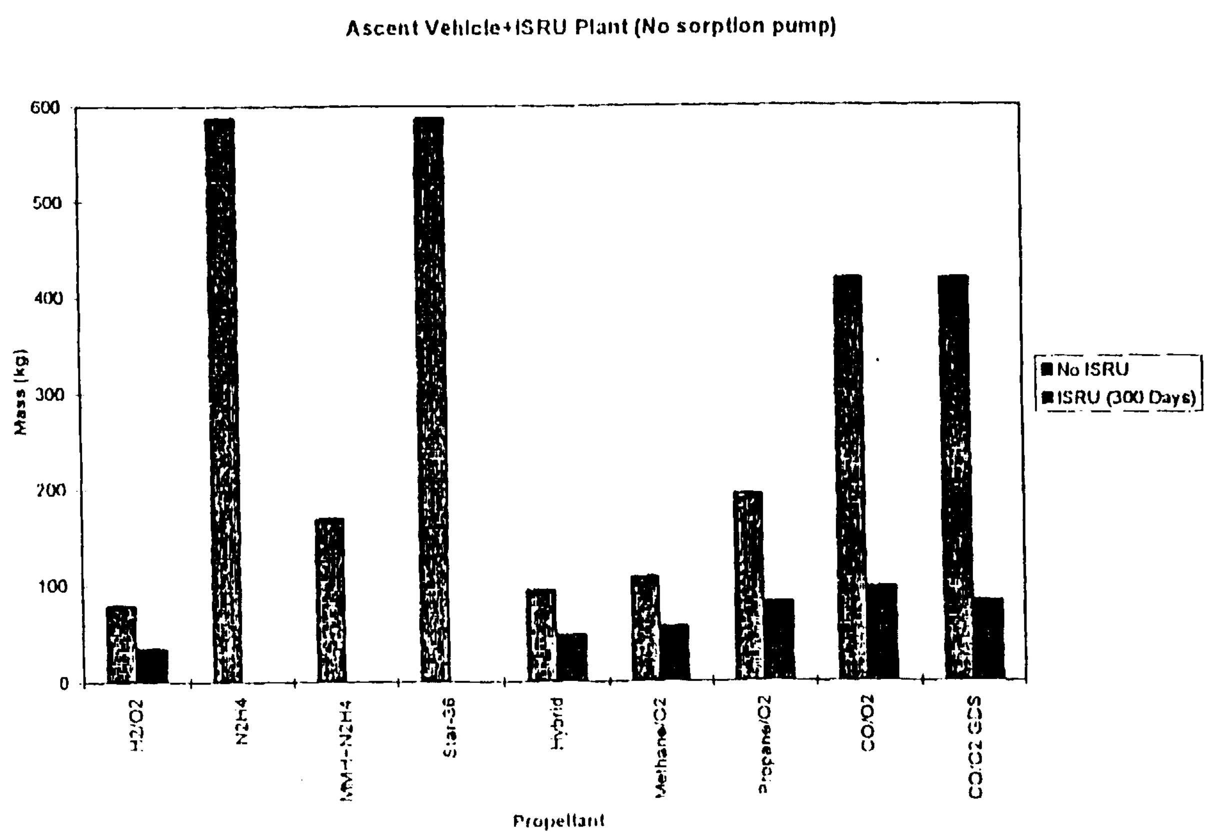
Comparison of different duration of stay for different propellants (sorption pump utilized)



ISRU Plant Mass for different sojourning periods (CO/O2 case)

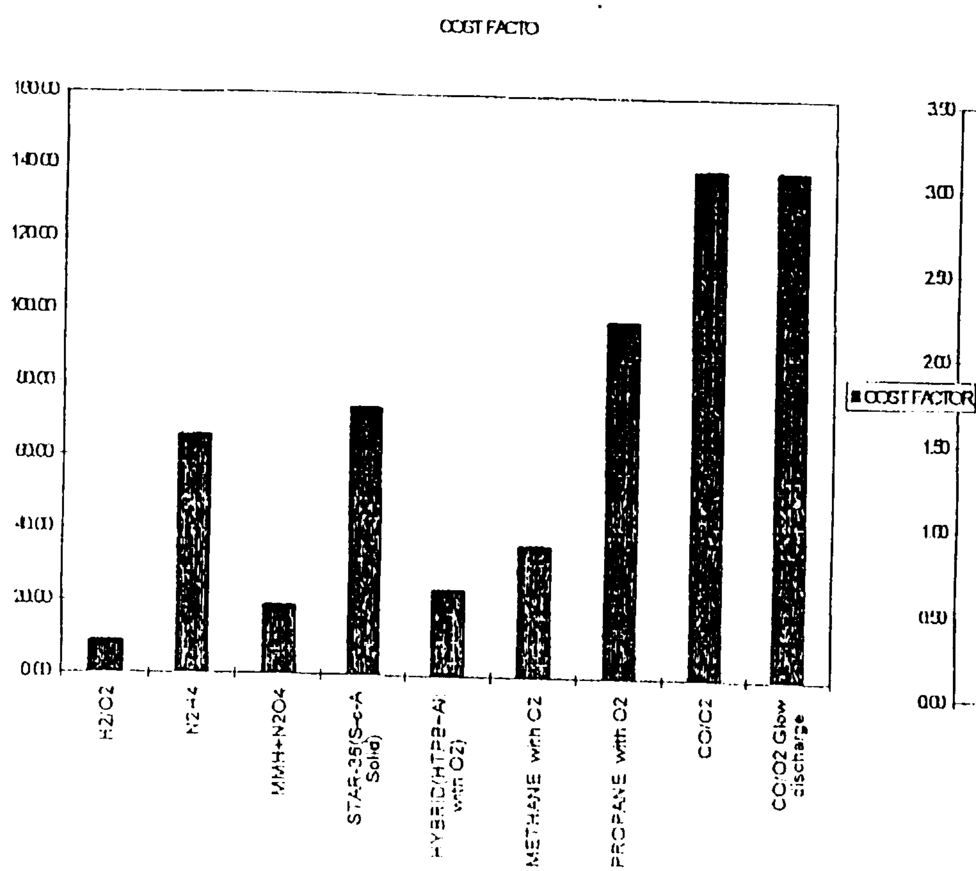


Mass comparison for 300 days sojourning missions (no pump)



Mission comparison for Cost and Risk

Developement Cost=Wet Mass/TRL



Probability of failiure
(Risk)=Complexity/TRL