Mars Biosignature-Detection Capabilities: A Method for Objective Comparison of In Situ Measurements and Sample Return

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A Mars sample-return mission has been proposed within NASA's Mars Exploration Program. Studying Martian samples in laboratories on Earth could address many important issues in planetary science, but arguably none is as scientifically compelling as the question of whether biosignatures indicative of past or present life exist on that planet. It is reasonable to ask before embarking on a sample-return mission whether equivalent investigation of Martian biosignatures could be conducted in situ. This study presents an approach to (1) identifying an optimal instrument suite for in situ detection of biosignatures on Mars, and (2) comparing the projected confidence level of in situ detection in a 2026 timeframe to that of Earth-based analysis. We identify a set of candidate instruments, the development of which is projected to be achievable by 2026 well within a $200 million cost cap. Assuming that any biosignatures near the surface of Mars are similar to those of terrestrial life, we find that this instrument suite, if successfully developed and deployed, would enable in situ biosignature detection at essentially the same level of confidence as that of Earth-based analysis of the same samples. At a cost cap of half that amount, the confidence level of in situ biosignature detection analysis could reach about 90% that of Earth-based investigations.

I. Introduction

Possibly the most compelling driver of Mars exploration is the question of whether life has ever existed there. Many scientists have long desired a sample-return mission to that planet, which would collect specimens from one or more locations thought to have been both habitable and conducive to preservation of biosignatures, and bring them to Earth for examination by instruments sensitive enough to detect whatever signs of life may be present.

In support of the National Environmental Policy Act (NEPA), NASA has developed policies and regulations which state in part that "a space flight project/program that would return extraterrestrial samples to Earth from solar system bodies" requires an environmental assessment, and that "NASA will take no action which would … limit the

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choice of reasonable alternatives prior to completion of its NEPA review." (NASA Document 14 CFR 1216.3)

In an effort to support the consideration of alternative methods to accomplish the astrobiological objectives of a proposed sample-return mission to Mars, we pose the question: How effectively, relative to Earth-based analysis, could one determine whether the highest priority biosignatures exist on Mars without bringing samples to Earth? This study presents an approach to developing an optimal instrument suite for in situ detection of biosignatures on Mars, and to calculating the confidence level that could be reached by in situ detection relative to that of Earth-based analysis. It is important to note that the approach presented here is valid independent of the example scenarios that were used in this particular study. Alternate inputs for instruments, biomarkers and their abundances, value weightings, etc. can easily be accommodated.

II. Approach

A. Select scenario.

1. Identify biosignatures to be observed along with metrics, anticipated availability ranges, and relative values for demonstrating the existence of life. Note that certain combinations of biosignatures have greater value than the sum of their individual values. Alternate scenarios which accommodate different opinions regarding biosignatures and different cost caps for instrument development can be developed as needed.

B. Assemble candidate instrument suites.

1. Specify constraints on instrument payload mass, cost, and power.
2. Identify each potential instrument, its measurement threshold for each biosignature addressed, and its fractional coverage (the percentage of the biosignature's assumed distribution which the instrument can detect).

C. Identify optimal instrument suite for the selected scenario.

1. Set initial objective value of in situ candidate instrument suite to zero.
2. Select candidate instrument suite. Determine whether it is consistent with constraints and, if so, estimate its life-detection value.
    a. If a given instrument detects a biosignature at multiple steps, compute cumulative probability over all steps
    b. We have chosen the following steps, which follow typical conservative sequences of sample analyses on Earth:
        1) extraction of gas from head space of sample container
        2) extraction of any liquid from headspace of container (heat to boil off liquids)
        3) non-destructive techniques to characterize exterior and interior of sample
        4) direct (destructive) analysis of solid sample
    c. Insert probabilities from previous step into a matrix of instrument vs. biosignature-detection probability.
    d. For the candidate suite of instruments under examination, select the instrument with the highest detection probability for each

biosignature. This results in a matrix of biosignature type vs. instrument with maximum detection potential.

3. Repeat step 2. If objective value of new instrument suite is greater than that of those previously analyzed, reset the best value found so far. Repeat until candidate instrument suites have all been evaluated and the suite with the highest value has been identified.

D. Compute analytical value of selected in situ instrument suite relative to Earth-based analysis. For both in situ and Earth-based detection of the same hypothetical samples:

1. Compute probability of detection for each instrument and biosignature combination by calculating the fractional coverage of the instrument (based on threshold) relative to the total potential availability.
2. Estimate the expected life-detection value of the instrument set under consideration by multiplying probabilities of detection by the value associated with the biomarkers detectable by that instrument set.
3. Search the tree of biosignature combinations (e.g., Figure 1) for expected value from the instrument suite under consideration (avoiding duplication of value when the same biosignature appears in multiple distinct combinations).

III. Initial example

A. Identifying the biosignatures to be sought

We begin by identifying a set of biomarkers to be sought, along with their metrics and the anticipated range of their availability in the samples, and assigning each biomarker an assumed value in demonstrating the presence of extinct or extant life (Table 1). The list of biomarkers was based on that of Summons et al. (2011) with a few modifications (see III.D.1.c.). The lower limits of availability ranges were derived from what instruments on Earth are perceived to be capable of detecting today. Value weighting was determined by the judgment of our team members who work in the astrobiology field, based on the vigorous discussions going on in the astrobiology community about what constitutes evidence of life as applied, for example, to the ALH84001 meteorite from Mars.

For the set of importance value weights chosen for this analysis, Biomarker 1 is clearly dominant, responsible for 60 percent of a potentially positive identification. Biomarkers 2 and 6 are the next most dominant.

Note that the biomarkers which we assume have the highest probability of being detected (e.g., minerals, structures) have the lowest certainty of biological origin and thus were assigned the lowest estimated value. Conversely, the biomarkers with the highest certainty of biological origin (e.g., organic molecules with chirality), and thus the highest assigned value, are those we assume are least likely to be detected.

Table 1. Biomarkers with assumed distribution ranges and assigned importance values

	Biomarker	Metrics	Availability range		Value
			Low	High	
1	Biogenic organic molecules in solid sample	Presence of specific biomarkers (e.g., hopane, cholestane, amino acid with chirality)	10^{-12} ppm	0.75 ppm	0.60
2	Biogenic gases in head space (of container) (e.g., presence of methane in oxidizing atmosphere)	Concentration of specific molecules (partial pressure – fraction of Mars pressure)	10^{-12}	10^{-6}	0.08
3	Body fossils (physical structures)	Imaged shapes, body fossils	1 μM	1000 μM	0.03
4	Biofabrics (large-scale physical structures)	Imaged shapes, large scale – e.g., stromatolites	10 cm	100 cm	0.02
5	(same as #4)	Repeat pattern of #4	1 mm	2 mm	0.01
6	Isotopic ratios (stable isotope compositions for C, N, O, SO_2, CO_2, H, Cl)	Isotope ratio difference between two different samples	2 per mill	200 per mill	0.08
7	Biomineralization / alteration (solid sample)	Specific minerals and assemblage	0.1 micron	100 microns	0.03
8	Biomineralization / alteration (solid sample)	Characterization and concentration of rock	0.01 percent	1 percent	0.02
9	Spatial chemical patterns (binary range of availability)	Correlations between shapes (greater than 1 μM) and distribution of concentrations (Y/N)	0.01 ppm	1 ppm	0.03

The systems engineering model of value from the detection of combinations of biosignatures is represented by a tree (Figure 1). As noted above, certain combinations of biosignatures have greater value than the sum of their individual values. This model also captures the phenomenon that when more definitive biosignatures are detected, the marginal value of other less definitive biosignatures is reduced due to saturation of evidence and overlap. For example, the second row in Figure 1 has values 0.68, 0.31, and 0.12, so that if Set 2 and Set 3 are fully detected, the value of Set 4 is effectively 0.01 due to saturation and overlap of biosignatures.

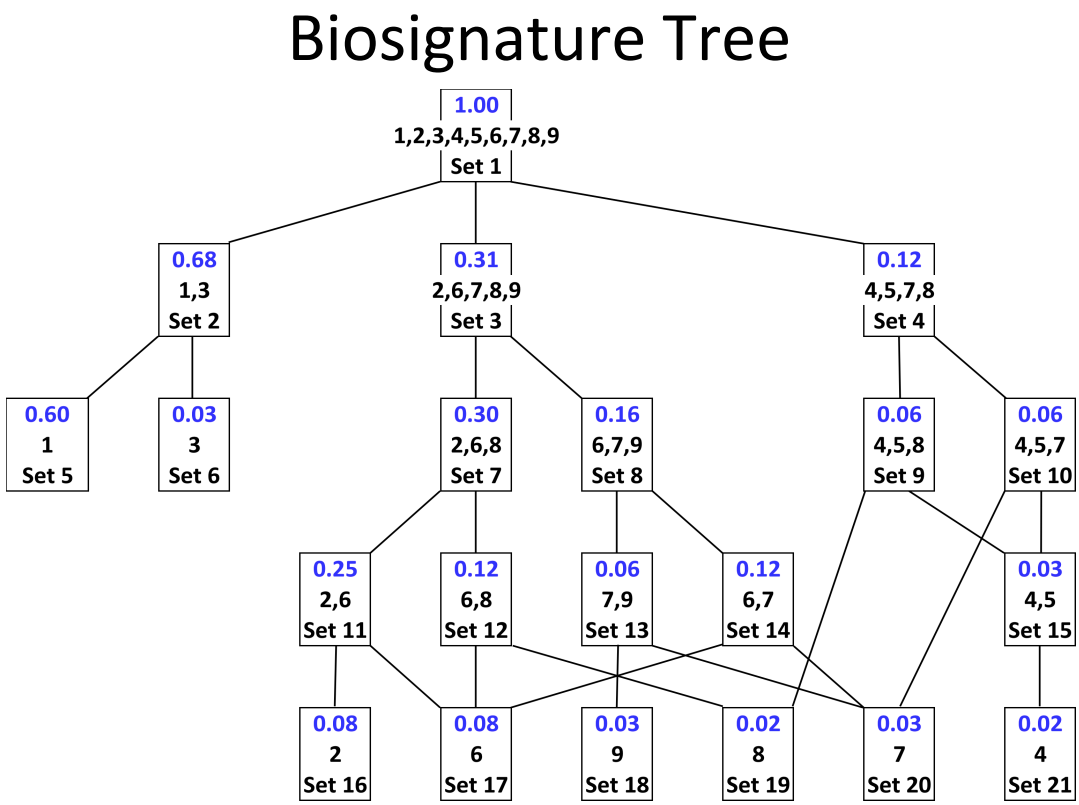

Figure 1. Values of combinations of biomarkers. For each set, we identify the biosignatures involved and the net value of the importance (in blue) of the detected biosignatures.

B. Assembling candidate instruments

We consider instruments currently in use or in development. We then estimate likely improvements in performance in the near future, based on experience from other instrument-development activities. The list of instruments considered is given in Table 2. Descriptions regarding the existing and projected future capabilities assumed for this analysis are given in References 3-10.

C. Analysis of Instrument capabilities

We conduct analyses under two alternate cost caps for instrument development: $200 million and $100 million. (The total mission cost is likely to be on the order of $1.5 billion.)

Under each cost cap, we conduct analyses within four alternate sets of conditions:

1. All nine of the biomarkers are present and detectable, and we select instruments based on that assumption.

2. Biomarker 1 is not detectable but the other eight are, and we select instruments based on that assumption.

3. Biomarker 1 is not detectable, but the other eight are. However in this case, instrument selection is based on the erroneous assumption that all nine biomarkers are detectable.

4. All nine biomarkers are detectable, but instrument selection is based on the erroneous assumption that Biomarker 1 is not detectable.

Table 2. Instruments considered with coverage.

Biosignature—>		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Instrument	Cost ($M FY13)	Portion of total biosignature availability covered by instrument (1 = 100%)								
NGen GC-MS	25	0	7.1E-61	0	0	0	0	0	0	0
NGen isotope mass spec	25	0	0	0	0	0	1	0	0	0
NGen QMS	25	0	7.1E-61	0	0	0	1	0	0	0
NGen MOMA	30	0	0	0	0	0	0	0	0	0
NGen TLS	25	0	1	0	0	0	1	0	0	0
NGen SAM	100	0	0	0	0	0	1	0	0	0
MAHLI	0	0	0	0.154	1	1	0	1.1E-6	0	1
MastCam	0	0	0	0	1	0	0		0	0
NGen CheMin	35	0	0	0	0	0	0		0.072	0
Green 532 nm laser Raman	20	0	0	0	0	0	0	0.574	0	0
NGen APXS	5	0	0	0	0	0	0	0	0	0
NGen deep UV Raman laser	20	0	0	1	0	0	0	0.574	1	0
NGen ChemCam	55	0	0	0	0	0	0.036	1.1E-6	0	0
MARCEAU PIDDP	75	0	0	0	0	0	0	0	0	0
NGen Urey	75	1	0	0	0	0	0	0	0	0
Maximum performance	n/a	**1**	**1**	**1**	**1**	**1**	**1**	**0.574**	**1**	**1**

Note: "NGen" stands for "Next-Generation."

D. Uncertainties, assumptions and caveats

1. Biosignatures and their abundances
    a. As a first example, we assume for purposes of these analyses that life existed on Mars 4 billion years ago, that it left traces (biosignatures, aka biomarkers) that have been preserved and that samples are recoverable by drilling. We further assume that any living organisms that happen to be present in the samples are detectable by a subset of the same biosignatures.
    b. We assume that the availability distribution of each biomarker is highest at the lowest limit of the assumed distribution, and decreases exponentially for more abundant biosignature presence. Below the lower limit of

availability (see Table 1), biomarkers cannot be detected even with Earth-based instruments, so whether they are there and not detectable or not there at all has little consequence.

c. We derive our list of nine biomarkers mainly from Summons et al. (2011), which reports the results of a working group convened by the co-chairs of NASA's Mars Science Laboratory (MSL) Project Science Group in part to identify biosignatures detectable by the instruments aboard the mission's "Curiosity" rover which is currently operating on Mars. Since MSL's instrument package was not designed explicitly to detect biosignatures, we have modified the biosignature list to better suit an instrument package dedicated to the detection of signs of extinct or extant life.

d. The values we assigned to the various biomarkers and to the relationships between biomarkers are in accord with the judgment of the scientists participating in our study. We recognize that other scientists may have different opinions about which biomarkers to look for and the relative values of various biomarkers. As previously noted, our methodology can easily accommodate alternate inputs resulting from differing opinions.

2. Instruments

a. We assume that the instruments we have designated for in situ analysis will be developed in time to deploy in a 2026 mission and that we have assigned the correct threshold level for each. This assumption is based on technology development currently being conducted. We further assume that if an instrument can detect a biomarker, it will do so perfectly anywhere above its threshold level. See Section IV, B "Robustness to instrument selection" for additional discussion about the specifics of the selected instrument suites.

b. Scientists in our study have made projections regarding performance of future in situ instruments based upon experience, literature, etc., but it is recognized that these projections are inherently uncertain and other scientists may have different viewpoints. Once again, we note that our analysis process easily accommodates differing inputs regarding instrument performance and other aspects of the study. Where there were differences in opinion about estimations of development costs among the experts who were consulted for this study, we always selected the highest estimate in order to be conservative.

c. The selected instruments focus only on biosignature detection. For other purposes, e.g., geological context, other instruments may be desirable.

d. This example study does not take into consideration any potential development of Earth-based instrument capabilities over the next 10 years.

e. MastCam and MAHLI are included in all instrument suites because they are essential for sample context and selection for analysis. However, we assume no further development of these instruments beyond what is already included in MSL, and thus we assume no development cost for them.

3. Constraints

a. We derive the constraints on payload mass, cost, and power from previous missions.
b. The cost caps sited here are only for development of analytical instruments and do not include the cost of equipment needed for sample preparation. We assume that sample preparation for the analyses described in this paper would be comparable to that required for the MSL rover currently operating on Mars, and that the cost (about $106 million for MSL) is accounted for separately.

E. Results

1. Instrument selection
   As noted above, MAHLI and MastCam are automatically included in each instrument suite and are assumed to add nothing to the development cost.

   a. At an instrument-development cost cap of $200 million, using the instrument characteristics assumed in Table 2, we are able to assemble a suite of six instruments capable of in situ detection of all of the biomarkers, including Biomarker 1, which is by far the most dominant for determining the existence of life. The selection of instruments remains unchanged if we assume that this biomarker is not detectable. The selected instruments are the following:
      i. MAHLI
      ii. MastCam
      iii. Next-generation isotope ratio mass spectrometer
      iv. Next-generation TLS
      v. Next-generation deep-UV Raman laser
      vi. Next-generation Urey instrument

      The estimated development cost of these six instruments is $145 million. Although that leaves $55 million available to be spent at this cost cap, little additional value (for astrobiological purposes) would be achieved by including additional instruments.

   b. At $100 million, the choice of conditions is significant because, while Biomarker 1 is the most important (with a value of 0.60), the instrument needed to detect it, the Next-Generation Urey, is estimated to cost $75 million. If Biomarker 1 is correctly assumed to exist and to be detectable, and if our estimate for the cost of the Urey is correct, then including the Urey provides good value. But if, as some scientists think, there is virtually no chance of detecting that biomarker, then better value can be achieved by substituting other instruments.

      Optimal in situ instrument suite if Biomarker 1 is assumed to be detectable:
      i. MAHLI
      ii. MastCam

iii. Next-generation TLS
iv. Next-generation Urey instrument

Optimal in situ instrument suite if Biomarker 1 is assumed not to be detectable (by either in situ or Earth-based instruments):

i. MAHLI
ii. MastCam
iii. Next-generation deep-UV Raman laser
iv. Next-generation isotope ratio mass spectrometer

Our analysis finds that if the probability is 15 percent or greater that Biosignature 1 is detectable, the highest value is obtained by including the Urey instrument. Otherwise, the suite that does not include the Urey provides the highest value.

2. Confidence level

a. At a cost cap of $200 million (with an actual estimated cost of $145 million), in situ detection results are equivalent to Earth-based analysis of the same samples (confidence level of 1.0). As mentioned above, with this instrument suite, it is not necessary to decide in advance whether to search for Biomarker 1. The budget is sufficient to include instruments capable of detecting all of the potential biomarkers we have identified. If Biomarker 1 is detectable, both the in situ and Earth-based analyses achieve a value of 1.0. If Biomarker 1 is not detectable, both the in situ and Earth-based analyses achieve a value of 0.45 (i.e., evidence of life with a confidence level of 45 percent). Thus in both scenarios, in situ analysis is equivalent to Earth-based analysis.

b. At a cost cap of $100 million, we find the following results for the various sets of conditions that were analyzed:

i. Condition Set 1: Biomarker 1 is correctly assumed to be detectable and the Next-Generation Urey is included in the instrument suite. In situ analysis achieves a value of 0.91, compared to 1.0 for Earth-based analysis of the same samples. Thus, in situ analysis has a value of 91 percent that of Earth-based analysis under these circumstances.

ii. Condition Set 2: Biomarker 1 is correctly assumed *not* to be detectable and the Next-Generation Urey is not included in the instrument suite. Earth-based analysis achieves a value of 0.45. Without spending money on the Urey, the in situ package is able to include instruments capable of detecting more of the remaining biomarkers, and in situ analysis achieves 0.40, for a value of 89 percent that of Earth-based analysis of the same samples.

iii. Condition Set 3: Biosignature 1 is assumed to be detectable and the Next-Generation Urey is included in the instrument suite, but Biosignature 1 is not detected (either in situ or with Earth-based instruments). In situ analysis achieves a value of 0.31 and Earth-based analysis achieves a value of 0.45. Thus, in this situation, in situ analysis has a value of 69 percent that of Earth-based instruments.

iv. Condition Set 4: Biosignature 1 is *incorrectly* assumed *not* to be detectable and the Next-Generation Urey is not included in the instrument suite. Earth-based analysis detects Biosignature 1 for a value of 1.0, but the in situ mission without the Urey is incapable of doing so and thus achieves only a value of 0.4. In situ's confidence ratio in this case is 40 percent that of Earth-based analysis of the same samples.

Table 3. Results for 4 sets of conditions at $100 million cost cap

Condition Set	Truth	Assumption on which instrument selection is based	In situ confidence level (% of Earth-based conf. level)
i	All 9 biosigs detectable	All 9 biosigs detectable	91
ii	Biosig 1 not detectable	Biosig 1 not detectable	89
iii	Biosig 1 not detectable	All 9 biosigs detectable	69
iv	All 9 biosigs detectable	Biosig 1 not detectable	40

IV. Sensitivity analysis

A. Robustness to availability curves.

As noted above, each biosignature is assigned an estimated range of availability, which decreases exponentially from the upper limit to the lower limit, and each instrument is determined to be capable of detecting some portion of that range. Our sensitivity analysis reveals that our results are robust with respect to possible changes in the shape of the distribution curve or its upper limit. The results are significantly sensitive only to the threshold (the lower limit) at which a given instrument is capable of detecting

a given biosignature, since the estimated thresholds for next-generation instruments provide for full-range coverage in most cases.

B. Robustness to instrument selection.

In order to determine how closely the high values we obtained for in situ life-detection are dependent on the highest-rated suites of instruments, we computed not only the optimal instrument selections for each case, but the top 40 alternate suites in decreasing order of performance value. Such knowledge could be useful if, for example, the mission designers want to do other kinds of scientific analysis in addition to biosignature-detection, which might make it desirable to use somewhat different suites of instruments.

At a cost cap of $200 million, for the case in which Biosignature 1 is detectable, all 40 suites have a value above 0.99, i.e., virtually equivalent to the value of Earth-based instruments analyzing the same samples (defined as 1.0). Five instruments are selected for all 40 suites: MAHLI, MastCam, Next-Generation TLS, Next-Generation deep-UV Raman laser, and Next-Generation Urey. The only differences among the suites are the choices of sixth (or in some cases, sixth and seventh) instruments, which add little to the value of the five repeaters for life detection, but could be more important for some other kinds of investigation. For example, if the mission designers specifically want to include the Next-Generation ChemCam instrument, they will find it in the ninth-ranked suite, which still has a very high value for life detection. The development costs range from $120 million for the core suite of five instruments to $200 million for some slightly lower-ranked suites.

At a cost cap of $100 million, there is considerably more variation in value among the 40 alternate instrument suites ranked for each set of circumstances. In the case in which Biosignature 1 is correctly assumed to be detectable, values range from 0.91 for the first-place suite to 0.38 for the bottom 14 suites. The top five suites each have a value of 0.74 or higher. In addition to MAHLI and MastCam, which are automatically included in every suite, the top 10 suites each include the Next-Generation Urey instrument. They differ in the remaining instruments selected for each suite. The suites ranked 11 through 40 each include both Next-Generation TLS and Next-Generation deep-UV Raman laser instead of the Urey.

V. Discussion

An in situ life-detection mission might serve as a valuable precursor to a sample-return mission. In contrast to a sample-return mission that would select and cache samples based entirely on their location in environments thought to have been conducive to habitability and preservation of biomarkers, a rover with strong life-detection capabilities would be able to analyze samples at multiple locations in situ and “home in” on regions with the strongest biomarker signals. If it detects biosignatures in certain samples, a follow-on mission could bring those or similar samples to Earth for confirmation, with a potentially dramatic increase in the likelihood of finding strong biosignatures in Earth-based labs.

When comparing the two types of missions, we note that in situ and sample-return each have advantages:

- An in situ mission for life detection as described in this paper is estimated to cost about $1.5 billion total. A sample-return suite of missions (e.g., selecting and caching the samples, lifting them to orbit and transporting them to Earth) is expected to cost several multiples of that amount even before taking into account the cost of Earth-based analytical instruments, and it would lack the in situ mission's capability of using results in various locations to "home in" on samples with strong biosignatures. Further, a long-lived in situ mission has the potential of analyzing many more samples over a much wider range of locations than a sample-return mission.
- However, samples returned to Earth could be studied with ever-improving instruments over the course of decades. For example, lunar samples retrieved in the 1970s are studied today with instruments greatly superior to those available at the time of sample return. Also, samples returned to Earth could be studied with additional instruments as the need arises – e.g., explicitly to detect evidence of living organisms in the samples if their biomarkers are determined to differ from those of extinct organisms, or for purposes other than astrobiology.

VI. Conclusions

We have demonstrated an approach to identifying an optimal suite of instruments for in situ biosignature-detection on Mars at two alternate cost caps and under several sets of conditions, and to quantifying the confidence level for results of analyses employing in situ instruments compared to investigations of the same samples using Earth-based instruments.

Given the assumptions stated above, at an instrument-development cost cap of $200 million (actually for less than $150 million), an in situ mission can be developed for Mars which would be capable of detecting biosignatures with essentially the same confidence level as examination by Earth-based instruments of the same hypothetical samples.

At a cost cap of $100 million, an in situ mission would be capable of a confidence level of about 90 percent that of Earth-based investigation of the same specimens, unless either (a) the in situ instrument suite includes the Urey but neither in situ nor Earth-based investigations detect Biosignature 1, in which case in situ has a confidence level about 70 percent that of Earth-based analysis, or (b) the in situ instrument suite is assembled with the assumption that Biosignature 1 is not detectable (Urey is not included), but the Earth-based instruments find that it is detectable. In that case, the in situ value is 40 percent that of Earth-based analysis of the same samples.

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