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SUBJECT: Sabatier Trade Study Report

Attached is the revised report, "Trade Study - An ARS With and Without A Sabatier CO2 Reduction Subsystem". This report is to replace the previous one of Feb. 28. Please call the author at (281-333-7178) or e-mail at frank.jeng@lmco.com with any questions.

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# TRADE STUDY – AN ARS WITH AND WITHOUT
A SABATIER C02 REDUCTION SUBSYSTEM

Subtask HECECAYS

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**National Aeronautics and Space Administration**
Lyndon B. Johnson Space Center
Houston, Texas

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# TRADE STUDY – AN ARS WITH AND WITHOUT A SABATIER CO2 REDUCTION SUBSYSTEM

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April 2000

## Summary

For advanced missions, because of resupply constraint, closed Air Revitalization Systems (ARS) and Water Recovery Systems (WRS) are desirable. A CO2 Reduction Subsystem (CRS) may play an important role in both ARS and WRS, since in a CRS CO2 recovered from human metabolism will react with H2 (a co-product from an oxygen generation subsystem) and water is generated. Water can be electrolyzed into oxygen and hydrogen. The goal of a closed ARS system is thus achieved with a CO2 removal subsystem, an O2 generation subsystem and a CO2 reduction subsystem combined. Since O2 demands can be supplied by electrolysis of water and a certain amount of water is available from food supplies, these ARS, WRS and food systems are interrelated. Depending on missions, O2 and water requirements differ significantly. The decision of integrating a CO2 reduction subsystem into an ARS necessitates a thorough study of O2 usage, water balance, CO2 and H2 availability, water generation capability of the CO2 reduction subsystem, etc.

A brief review of CO2 reduction technologies was conducted and the Sabatier CO2 reduction technology is suggested as the CO2 reduction technology for an advanced ARS.

O2 and water mass balances of all possible demands and supplies of advanced human missions were conducted for both Mars transit and surface exploration missions. The impacts of not using water in EVA spacesuit cooling device, of using in situ water and using in situ O2 from Mars were investigated. Equivalent System Masses (ESM) were compared between an ARS with Sabatier CRS subsystem and an ARS without Sabatier CRS for both Mars transit and surface exploration missions.

The study results indicated that, for Mars surface missions in general, integration of a Sabatier CRS into an ARS is justified. If Mars in situ O2 is available (probably from processing of Martian CO2), then a Sabatier CRS is not needed. If Mars in situ water is available, the integration of a Sabatier CRS into an advanced ARS is not needed either.

For Mars transit missions, the situation is more complicated. A parametric analysis of the impacts of percent water recovery from a WRS and percent food water recovery on the pay-off time of including a Sabatier CRS was conducted. Basically if water recovery from a WRS is less than 99.5%, then a Sabatier CRS is needed for whatever percent food water recovery. If the water recovery efficiency of the WRS reaches 99.9% (i.e., total net water loss less than 0.19 kg/day), inclusion of a Sabatier CRS in an ARS is not needed.

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# *1.0 INTRODUCTION*

Because of resupply constraint in long duration missions, minimizing mass, volume and power is essential in an advanced mission. A closed Advanced Life Support System (ALS), including Air Revitalization Subsystem, Water Revitalization Subsystem, etc., is desirable. In a typical Advanced Air Revitalization System, water is electrolyzed into oxygen (O2) and hydrogen (H2) in an oxygen generation subsystem. Water is also consumed in various hygiene needs, physiological loads and other life support functions. A typical Water Recovery System (WRS) will regenerate water from various wastewater streams. One of the subsystems that can generate water from byproducts of life support subsystems is a CO2 reduction subsystem. It is desirable to conduct a trade study of including a CO2 reduction subsystem in an advanced ARS for various advanced mission scenarios.

One option of an advanced Air Revitalization System (ARS) is shown in Figure 1. Major components of the ARS include, as shown in Figure 1, a CO2 removal subsystem, an O2 Generation Subsystem (OGS), trace contaminant control subsystem (not shown) and a regenerative water recovery system (WRS). CO2, which is removed from the cabin by a CO2 removal subsystem, is vented overboard. H2, which is generated with O2 by the OGS, is also vented overboard. There will be other air and water losses, such air leaks through spacecraft seals, EVA air loss in airlock operation, and possible water loss from EVA cooling device, such as a sublimator. These O2 losses can be made up from electrolysis of water carried with the spacecrafts. Water lost in life support functions can be supplied from the stored water. The penalty of this simple system is the mass and volume of the water launched with the spacecraft.

Figure 1. An ARS Without A CO2 Reduction Subsystem

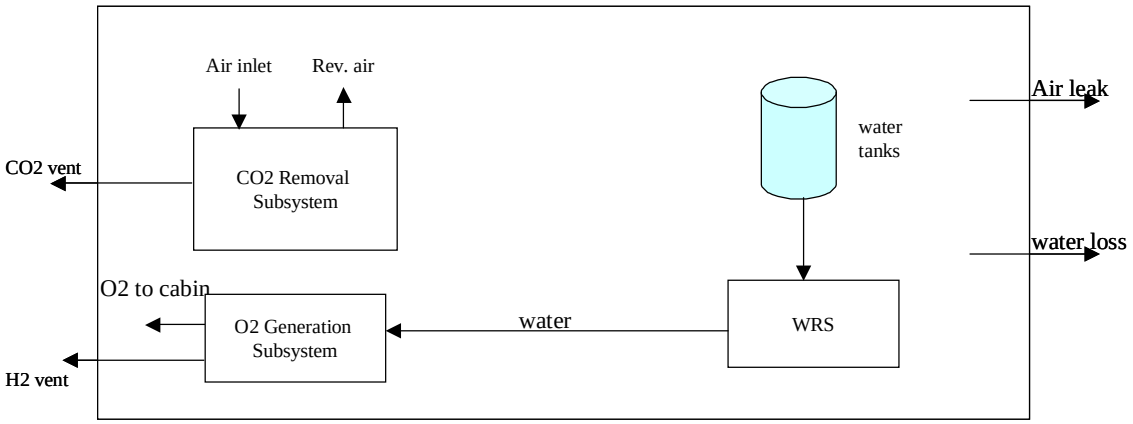
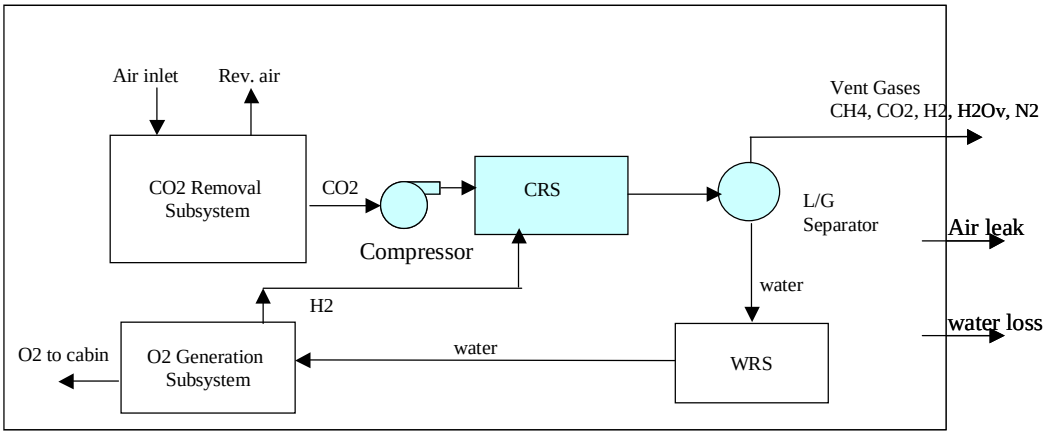



Figure 2. An ARS With A CO2 Reduction Subsystem



Another option of an advanced ARS is shown in Figure 2. A CO2 Reduction Subsystem (CRS) is added to the ARS. In the CRS, CO2, which is recovered from the CO2 removal subsystem, catalytically reacts with H2, which is generated with O2 from the OGS, and water is a product of the reaction. Water then flows to the water recovery system and eventually is fed to the OGS for O2 generation. Methane, another product of the CRS, is vented overboard along with unreacted CO2, H2 and other gases. By adding the CRS subsystem, some of the O2 in CO2 can be recovered as water. With this option, the penalty of reducing water resupply is the mass, volume and power of the added CRS subsystem.

To justify the integration of a CO2 reduction subsystem into an advanced life support system, a trade study of these two options has been conducted. Two different mission scenarios, Mars transit and Mars surface exploration, were analyzed. Mass balance analyses of oxygen and water for these two mission scenarios were also conducted. A detailed analysis of water generation and loss in a Sabatier CRS was conducted. Based on the mass balance results and estimated mass, volume and power of the components shown in Figure 1 and 2, values of Equivalent System Masses (ESM) of the above two options were compared for the transit and surface missions. To better understand the impacts of percent water recovery from a water recovery system on the payoff time for including a Sabatier CRS, a parametric analysis was conducted for transit missions. Conclusion of the trade study was drawn based on these analysis results.

# *2.0 CO2 REDUCTION SUBSYSTEM*

The goal of a CO2 Reduction Subsystem (CRS) is to recover O2 from CO2 generated from human metabolic output. Available technologies for CO2 reduction include Sabatier CRS, Bosch CRS, advanced CRS, etc. Sabatier CO2 reduction technology is assessed with the highest Technology Readiness Level (TRL), TRL=5, among competing CO2 reduction technologies (4). Sabatier CRS technology has been successfully integrated in the air revitalization system in LMLSTP phase III test at JSC. Therefore the Sabatier CRS technology was selected as the CO2 reduction technology in this trade study.

## 2.1. Sabatier CO2 Reduction Subsystem

CO2 reacts with H2 and generates water and methane according to the following Sabatier reaction:

$$CO_2 + 4H_2 \longrightarrow 2H_2O + CH_4$$

The catalytic methanation reaction between CO2 and H2 is exothermic and self-sustainable. Water vapor generated from Sabatier reactor can be recovered by passing the product gases through a condensing heat exchanger. Methane and unreacted reactants will be vented overboard. Although further recovery of H2 from methane is possible through methane pyrolysis or other processes, further recovery of H2 is not analyzed in this study since the TRL of most of these technologies are lower than Sabatier CRS technology and further technology development is necessary (1,4). The following analyses on Sabatier reaction are concentrated on the impacts of Sabatier operation parameters on water generation and recovery in advanced mission environments.

### 2.1.1. H2/CO2 Molar Ratio

Based on human metabolic quotient (CO2/O2 molar ratio) of 0.87 and the mass balance of an Oxygen Generation Subsystem (OGS), the following simple molar relationship exists (basis: 1 mole O2):

| Gas | Mole |
|---|---|
| O2 | 1.0 |
| CO2 | 0.87 |
| H2 | 2.0 |
| H2/CO2 | 2.3 (molar ratio) |

With 10% excess O2 generation to compensate for O2 losses through non-metabolic causes such as air loss through seals, airlock operations (see Sections 3.1.1 and 3.3.1), the available H2/CO2 molar ratio for the Sabatier CRS is approximately 2.6.

## 2.2. Sabatier Reaction Efficiency

Typical conversion efficiencies of the Sabatier reaction have been reported by Murdoch (1). With H2/CO2 molar ratio at 2.6, the conversion efficiencies of the Sabatier reactants are as follows (1):

| | |
|---|---|
| H2 | 99.5% |
| CO2 | 64.7% |

These conversion efficiencies were used in mass balance calculations of the Sabatier CO2 reduction subsystem in this study.

## 2.3. Water Vapor Loss with Dry Vent Gases

A comprehensive analysis on the performance of the liquid/gas (L/G) separator as functions of its operation parameters has been reported (1). In this study typical L/G separator parameters were assumed as follows: 1% liquid carryover, 3 °F water reheat from the rotary L/G separator, and effective liquid outlet at 73 °F.

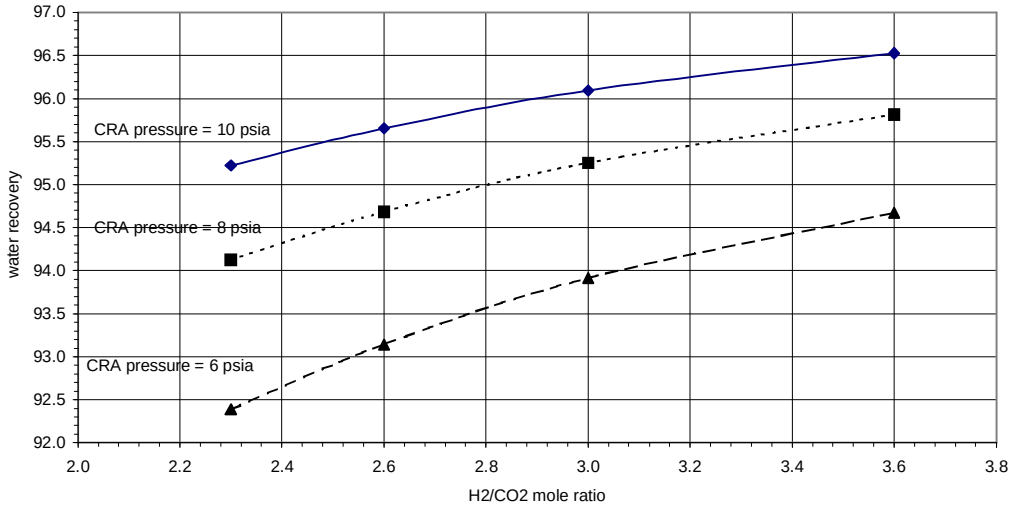
As dry gases ($CH_4$, $CO_2$, $H_2$, $N_2$) vented from the liquid/gas separator, some water vapor will leave with these gases. It was assumed that water vapor pressure will be in equilibrium at the liquid temperature (73 °F), the rate of water vapor lost with the vent gases can be calculated, given the vent rate of dry gas. The vent rate of dry gas from the water separator is a function of following parameters: the Sabatier reactant $H_2/CO_2$ molar ratio, Sabatier conversion efficiency, liquid/gas separator pressure, and outlet gas temperature. A brief discussion of these parameters and their impacts follows:

### 2.3.1. Liquid/Gas Separator Pressure

Recent studies for NASA (1) recommended that the Sabatier subsystem be operated at lower than ambient pressure to prevent leakage of combustible gas into the International Space Station. For the same concern the advanced Sabatier subsystem operating pressure should be operated at pressure lower than 10 psia (current arbitrary set pressure for advanced ARS). Water vapor losses with CRS operating at 10, 8 and 6 psia were estimated and the results are shown in Figure 3.

Figure 3. % Water Recovery of Sabatier System vs H2/CO2 Ratio and Sabatier System Operation Pressure

Basis: cabin 10 psia, separator gas outlet temperature 73 F, liquid carryover 1%

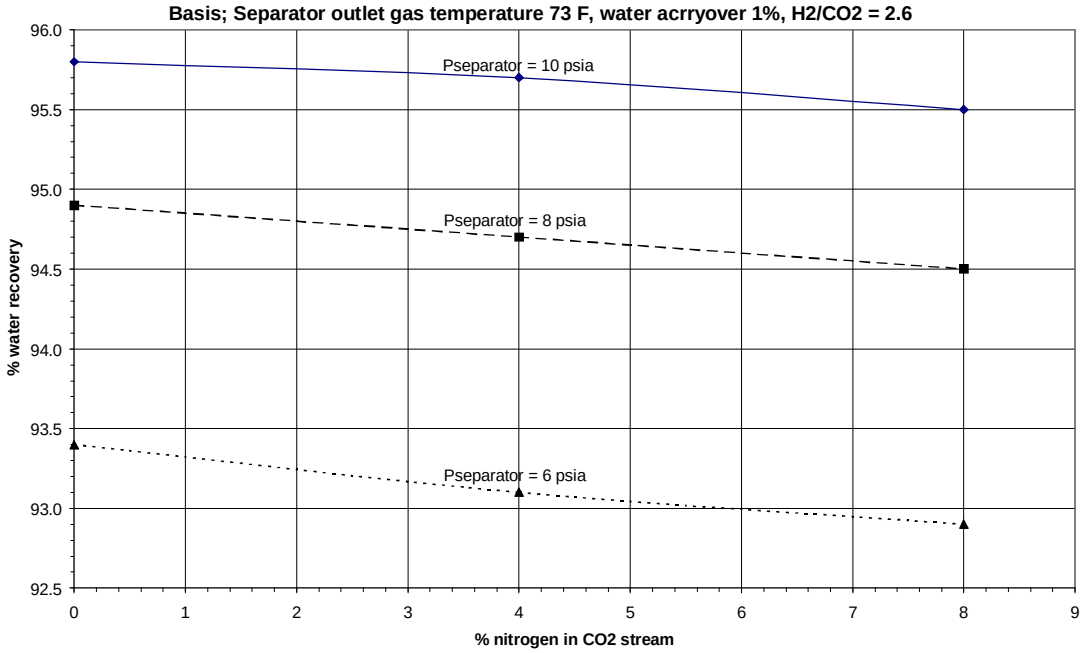



In mass balance calculations for the Sabatier CRS in this trade study, the pressures of Sabatier reactor and L/G separator are arbitrarily set at 8 psia. Based on this plot, with cabin at 10 psia, Sabatier CRS at 8 psia, $H_2/CO_2$ molar ratio at 2.6, separator outlet gas at 73 °F and 1% liquid carryover, approximately 94.7% of all the water generated from the Sabatier reactor will be recovered as liquid water.

## 2.3.2. Impurity in Inlet CO2 Stream

Depending on the CO2 removal technology used in the proposed advanced ARS system, impurity of the CO2 stream varies. For the four-bed molecular sieve CO2 removal technology, air leak-in to the CDRA (Carbon Dioxide Removal Assembly) is practical. Co-adsorption of N2 and O2 with CO2 in adsorption bed was also reported (1). Test data during LMLSTP Phase III test indicated that CO2 purity ranged between 87% and 95%. O2 in CO2 product stream will react with H2 in the Sabatier reactor and produces water, which will be recovered from the separator eventually. N2 in the CO2 product stream is an inert gas and will be vented with methane from the liquid/gas separator. As the flow rate of the vent gas increases, so does the vent rate of water vapor. Figure 4 shows the impacts of % N2 in the CO2 stream on water recovery of the separator. The plot shows that with 8% N2 in CO2, water recovery could be reduced by about 0.4% for a separator operated at 8 psia, comparing with a CO2 stream with 0% N2 (assumed the spacecraft cabin pressure is at 10 psia).

**Figure 4 CRA Water Recovery vs N2 % in the CO2 Stream and the CRA Separator Pressure Basis; Separator outlet gas temperature 73 F, water acrryover 1%, H2/CO2 = 2.6**




## 2.3.3 Separator Outlet Gas Temperature and Liquid Carryover from the Liquid/Gas Separator

In this study the following L/G separator parameters are assumed: 1% liquid carryover, 3 °F water reheat from the rotary separator operation, and effective liquid outlet at 73 °F.

In mass balance calculations for the Sabatier CRS, the Sabatier is arbitrarily set at 8 psia. Based on Figure 4, with cabin at 10 psia, Sabatier CRS at 8 psia, H2/CO2 molar ratio at 2.6, separator outlet gas at 73 °F and 1% liquid carryover, approximately 94.7% of all the water generated from the Sabatier reactor can be recovered as water.

## 2.3.4. Moisture in CO2 and H2 Streams

Basically, moisture content in reactants of the Sabatier CRS will not have impacts on water recovery percentage if an effective condensing heat exchanger is designed into the CRS assembly. Moisture in reactants eventually will be collected in the condensing heat exchanger and processed by the WRS.

## 2.4 Water Mass Balance of Sabatier CO2 Reduction Subsystem

Table 1 shows spreadsheet mass balance calculations for the Sabatier CRS reaction and the related liquid/gas separation performance with H2/CO2 molar ratio at 2.3, 2.6, 3.0 and 3.6 and separator pressure at 6, 8 and 10 psia.

Table 1 Mass Balance Calculations of Sabatier CO2 Reduction subsystem

| | | |
|---|---|---|
| **Basis** | 1 mole O2 generated | |
| | Sabatier pressure = | 6, 8, 10 psia |
| | L/G Separator Outlet Gas Outlet = | 70 F |
| | water reheat from G/L sep. = | 3 F |
| | water carryover from sep. = | 1% |
| | CO2 product: | CO2 95%, N2 4%, O2 1% |

| **H2/CO2 molar ratio** | 2.3 | 2.6 | 3 | 3.6 |
|---|---|---|---|---|
| CO2 available, mole | 0.87 | 0.87 | 0.87 | 0.87 |
| N2, mole | 0.0366 | 0.0366 | 0.0366 | 0.0366 |
| H2 req'd based on H2/CO2, mole | 2.001 | 2.262 | 2.61 | 3.132 |
| H2 conversion efficiencies | 99.5 | 99.5 | 99.5 | 99.1 |
| CO2 reacted | 0.4977 | 0.5627 | 0.6492 | 0.7760 |
| % CO2 conversion | 57.2125 | 64.6750 | 74.6250 | 89.1900 |
| | | | | |
| **Product** | | | | |
| H2 vent, mole | 0.0100 | 0.0113 | 0.0131 | 0.0282 |
| CO2 vent, mole | 0.3723 | 0.3073 | 0.2208 | 0.0940 |
| CH4 vent, mole | 0.4977 | 0.5627 | 0.6492 | 0.7760 |
| N2 vent, mole | 0.0366 | 0.0366 | 0.0366 | 0.0366 |
| Total dry vent gases, mole | 0.9166 | 0.9179 | 0.9197 | 0.9348 |
| H2Ov generated, mole | 0.9955 | 1.1253 | 1.2985 | 1.5519 |
| H2Ov in vent gas-10 psia, mole [1] | 0.0376 | 0.0377 | 0.0377 | 0.0384 |
| H2Ov in vent gas-8 psia, mole[1] | 0.0485 | 0.0486 | 0.0487 | 0.0495 |
| H2Ov in vent gas-6 psia, mole [1] | 0.0658 | 0.0659 | 0.0661 | 0.0671 |
| H2Ov + inert vent gas-10 psia, mole | 0.9543 | 0.9556 | 0.9574 | 0.9732 |
| H2Ov + inert vent gas-8 psia, mole | 0.9651 | 0.9665 | 0.9684 | 0.9843 |
| H2Ov + inert vent gas- 6 psia, mole | 0.9825 | 0.9839 | 0.9857 | 1.0020 |
| Liquid water carry over, 1% | 0.0100 | 0.0113 | 0.0130 | 0.0155 |
| Net water recovery 10 psia, mole H2O/mole O2 | 0.9479 | 1.0764 | 1.2477 | 1.4980 |
| Net water recovery 8 psia, mole H2O/mole O2 | 0.9370 | 1.0655 | 1.2368 | 1.4869 |
| Net water recovery 6 psia, mole H2O/mole O2 | 0.9197 | 1.0482 | 1.2194 | 1.4692 |
| % water recovery-10 psia | 95.2212 | 95.6524 | 96.0933 | 96.5279 |
| % water recovery-8 psia | 94.1270 | 94.6831 | 95.2516 | 95.8121 |
| % water recovery-6 psia | 92.3860 | 93.1408 | 93.9124 | 94.6732 |

Notes:

1) Assume vent gas temperature at a water-cooled condenser outlet at 70 F. Also assume reheat temperature of the condensate from the liquid/gas separator is 3 deg. F. The final vent gas temperature is 73 deg. F.

Based on this table, at $H_2/CO_2=2.6$ and L/G separator at 8 psia, as 1 mole of $O_2$ is generated from the OGS, 1.066 mole liquid water will be recovered from the Sabatier CRS. For a 6-person crew, with $H_2/CO_2 = 2.6$, a Sabatier CRS will generate 1050 kg/yr water (2.88 kg/day).

## *3.0 WATER MASS BALANCE FOR ADVANCED MISSIONS*

Since the product of a Sabatier CRS is water, an essential part of the trade study to justify the integration of a Sabatier CRS into an advanced ARS is to conduct a comprehensive water mass balance analysis of all possible demands and supplies for Mars transit and surface missions. A major potential water sources among all possible supply lists is the water in food. Depending on the practice of waste food processing, up to 100% of food water can be recovered. In water consumption side a major consumption is water consumed in EVA. The bases for estimating these major water mass balance items are covered in sections 3.1 and 3.2. Water mass balance calculations for various mission scenarios are treated in sections 3.3 – 3.9.

It was assumed that, for both surface and transit missions, oxygen supply for crew metabolic consumption will be provided by electrolysis of water using an Oxygen Generation Subsystem (OGS). It was also assumed that the use of an OGS has been justified previously. A Biological Water Recovery System (BWRS) was assumed in the Advanced Life support System (ALS) and 99.9% water recovery was assumed for this BWRS (5).

### 3.1 Water in Food

It was assumed that 0.674 kg/cd dry weight of food is needed, as shown in ISS plans [8]. It was also assumed that 1.955 kg/cd (average moisture content 66%) fresh weigh is needed [8], corresponding to the requirement of dry weight of food. For Mars missions it was assumed that 50% of daily food will be shipped as fully hydrated, the other 50% will be shipped as dehydrated (water content: 20% by weight). Daily food requirements and water available in food are listed as follows:

| | Daily amount Kg/cd | water available kg/cd | water available kg/6-person-day |
|---|---|---|---|
| Fresh food | 0.978 | 0.645 | 3.871 |
| Dehydrated food | 0.421 | 0.084 | 0.505 |
| Total | | | 4.376 |

Depending on percentages of food water recovery, the water recoverable from food (6-person crew) is as follows:

| | 0% food water recovery, kg/cd | 50% food water recovery, kg/cd | 100% food water recovery, kg/cd |
|---|---|---|---|
| Water recovery from food | 0 | 2.188 | 4.376 |

### 3.2 Water Usage and Wastewater Production in EVA

It was assumed that there will be daily 2-person EVA for surface missions. O2 and water consumption rates associated with EVA operations are listed in the following:

| EVA loads | 8-hr EVA total/person, [6,14] |
|---|---|
| Oxygen consumption[1] | 0.608 kg |
| Drinking water | 1.92 kg |
| Water for LCG and sublimation | 1.1 kg |
| Air loss from airlock with final pressure = 1 psia | 0.145 kg (airlock volume = 188 ft3) |
| Urine, respiration and perspiration (in addition to Average daily urine, respiration and perspiration) | 0.884 kg |

$CO_2$ generated during EVA was assumed to be collected for recovery of $O_2$. Wastewater (urine, respiration and perspiration) was also assumed to be collected for recovery of water.
.

## 3.3 Water Mass Balance for Mars Surface Missions without Sabatier CRS

The following mission parameters were assumed for Mars surface missions:

| | |
|---|---|
| Crew: | 6 person |
| EVA: | daily 2-person EVA |
| Habitat Volume: | 97.69 m3 |
| Cabin air: | 10 psia, $O_2$ 30.9%, $N_2$ 69.1% |

An overall water mass balance for Mars surface mission without a Sabatier CRS subsystem is shown in Table 2.

Table 2 Overall Water Mass Balance for Mars Surface Mission Without a Sabatier CRS Subsystem

| Demand items | Demand rates (kg/day) water (equiv) | O2 | Supply items | Supply rates (kg/day) water |
|---|---|---|---|---|
| Physiological loads | | | | |
| Metabolic oxygen (6) | 5.64 | 5.01 | | 0. |
| Drinking water, food (6) rehydration water, and water in food | 21.14 | | Respiration and perspi-ration water | 13.66 |
| | | | Urine water | 9.01 |
| | | | Fecal water[1] | 0. |
| Physiological subtotal | 26.79 | | Physiological subtotal[2] | 22.65 |
| Hygiene loads | | | | |
| Oral hygiene water | 2.16 | | hygiene waste water | 2.16 |
| Dish wash water | 32.64 | | Dish wash water, liquid | 32.43 |
| | | | Dish wash water, latent | 0.18 |
| Hand/face wash water | 24.48 | | Wash wastewater, liquid | 38.96 |
| Shower water | 16.32 | | Wash wastewater, latent | 1.80 |
| Clothes wash water | 74.82 | | Clothes wash water, liquid | 71.15 |
| | | | Clothes wash water, latent | 3.60 |
| Urine flush water | 2.94 | | Urine flush water | 2.94 |
| Hygiene subtotal | 153.36 | | Hygiene subtotal[2] | 153.21 |
| Air leaks[3] | 0.087 | 0.077 | | 0. |
| $O_2$ co-adsorbed with $CO_2$ /CDRA[4] | 0.05 | 0.044 | | 0.047. |
| EVA loads | | | | |
| $O_2$ loss in airlock operations | 0.163 | 0.145 | | 0 |
| Additional $O_2$ with respect to nominal requirement [6] | 0.753 | 0.669 | | 0 |
| Additional drinking water | 1.651 | | urine, respiration and perspiration water | 1.768[5] |
| Water used in sublimator | 2.2 | | | 0 |

Table 2 Overall Water Mass Balance for Mars Surface Mission Without a Sabatier CRS Subsystem (continued)

| | | | |
|---|---|---|---|
| O2 consumption in biological WRS (7) | 0.304 | 0.27 | 0.068 |
| Water in food | | | |
| 0% food water recovery | | | 0 |
| 50% food water recovery | | | 2.188 |
| 100% food water recovery | | | 4.376 |
| Total | | | |
| Total O2 required | | 6.21 | |
| 0% food water recovery | 185.35 | | 177.74 |
| 50% food water recovery | 185.35 | | 179.92 |
| 100% food water recovery | 185.35 | | 182.11 |

Notes
1. Total fecal water available is estimated at 0.55 kg/day [6]. Assume no water recovery from feces.
2. Assume 99.9% water recovery for the biological waste recovery system.
3. The air leak rate was estimated as 0.1% of total air mass of the habitat. This leak rate percentage is approximately two times the specified leak rate of the ISS Habitat.
4. Assume CO2 purity at 95%, with 4% N2 and 1% O2.
5. Assume that urine generated in EVA will be collected and recovered.
6. The additional O2 requirements was based on the assumption of 1000 BTU/hr metabolic rate for EVA and 450 BTU/hr for nominal crew activity in spacecraft.

### 3.3.1 Per Cent Excess O2 of Metabolic O2 Requirements

Based on Table 2, percent excess O2 than metabolic requirements to be generated for the surface missions is calculated as follows:

| | | |
|---|---|---|
| Total O2 generated O2 : | 6.21 | kg/day |
| Total O2 needed for metabolic consumption: | 5.68 | kg/day (including EVA O2 consumption) |
| Percent excess O2: | 9.3% | |

## 3.4 Water Mass Balance for Mars Surface Missions with A Sabatier CRS

The following basic parameter values were assumed for the Sabatier CRS subsystem:

| | |
|---|---|
| H2/CO2 molar ratio: | 2.6 |
| Sabatier Reactor pressure: | 8 psia |
| Liquid/Gas separator liquid carryover: | 1.0 % of all the water generated |
| Separator liquid reheat: | 3 ºF |

A water mass balance for Mars surface mission and for an ARS with a Sabatier CRS is shown in Table 3.

Table 3 Overall Water Mass Balance for Mars Surface Mission with Sabatier CRS Subsystem

| | Demand Rate (kg/day) | Supply rate (kg/day) | Net Supply Rate (kg/day) |
|---|---|---|---|
| Without Sabatier CRS | | | |
| 0% food water recovery | 185.35 | 177.74 | -7.62 |
| 50% food water recovery | 185.35 | 179.92 | -5.43 |
| 100% food water recovery | 185.35 | 182.11 | -3.24 |

Table 3 Overall Water Mass Balance for Mars Surface Mission with Sabatier CRS Subsystem (continued)

| | | | |
|---|---|---|---|
| Sabatier CRS water generation (see Table 1) | 0. | 3.728 | |
| with Sabatier CRS | | | |
| 0% food water recovery | 185.35 | 181.46 | -3.89 |
| 50% food water recovery | 185.35 | 183.65 | -1.70 |
| 100% food water recovery | 185.35 | 185.84 | 0.49 |

## 3.5 Water Mass Balance for Mars Transit Missions without A Sabatier CRS

The following parameters are assumed for Mars transit missions:

| | |
|---|---|
| Crew: | 6 person |
| EVA: | No EVA |
| Habitat Volume: | 97.69 m3 |
| Cabin air: | 10 psia, O2 30.9%, N2 69.1% |

An overall water mass balance for Mars transit mission is shown in Table 4.

Table 4 Overall Water Mass Balance for Mars Transit Mission Without A Sabatier CRS Subsystem

| Demand items | Demand rate (kg/day) water(equiv) | O2 | Supply items | Supply rate (kg/day) water |
|---|---|---|---|---|
| Physiological loads | | | | |
| Metabolic oxygen (6) | 5.64 | 5.01 | | 0. |
| Drinking water, food (6) rehydration water, and water in food | 21.14 | | Respiration and perspiration water | 13.66 |
| | | | Urine water | 9.01 |
| | | | Fecal water[1] | 0. |
| Physiological subtotal | 26.79 | | Physiological subtotal[2] | 22.65 |
| Hygiene loads | | | | |
| Oral hygiene water | 2.16 | | hygiene waste water | 2.16 |
| Dish wash water | 32.64 | | Dish wash water, liquid | 32.43 |
| | | | Dish wash water, latent | 0.18 |
| Hand/face wash water | 24.48 | | Wash wastewater, liquid | 38.96 |
| Shower water | 16.32 | | Wash wastewater, latent | 1.80 |
| Clothes wash water | 74.82 | | Clothes wash water, liquid | 71.15 |
| | | | Clothes wash water, latent | 3.60 |
| Urine flush water | 2.94 | | Urine flush water | 2.94 |
| Hygiene subtotal | 153.36 | | Hygiene subtotal[2] | 153.21 |
| Air leaks[3] | 0.087 | 0.077 | | 0. |
| O2 co-adsorbed with CO2 /CDRA[4] | 0.05 | 0.044 | | 0. |
| EVA loads | | | | |
| O2 loss in airlock operations | 0. | 0. | | 0 |

Table 4 Overall Water Mass Balance for Mars Transit Mission Without A Sabatier CRS Subsystem (continued)

| | | | | |
|---|---|---|---|---|
| Additional O2 with respect to nominal requirement | 0. | 0. | | 0 |
| Additional drinking water | 0. | | urine, respiration and perspiration water | 0. |
| Water used in sublimator | 0. | | | 0 |
| O2 consumption in biological WRS (7) | 0.304 | 0.27 | | 0.068 |
| Water in food | | | | |
| 0% food water recovery | | | | 0 |
| 50% food water recovery | | | | 2.188 |
| 100% food water recovery | | | | 4.376 |
| Total | | | | |
| 0% food water recovery | 180.59 | | | 175.97 |
| 50% food water recovery | 180.59 | | | 178.16 |
| 100% food water recovery | 180.59 | | | 180.34 |
| Total O2 required | | 5.40 | | |

Notes
1. Assume no water recovery from feces.
2. Assume 99.9% water recovery for the biological waste recovery system.
3. The air leak rate was estimated as 0.1% of total air mass of the habitat. This leak rate percentage is approximately two times the specified leak rate of the ISS Habitat.
4. Assume CO2 purity at 95%, with 4% N2 and 1% O2.

### 3.5.1 Per Cent Excess O2 Generation of Metabolic O2 Requirements

Based on Table 4, percent excess O2 than metabolic requirements to be generated for transit missions is calculated as follows:

| | | |
|---|---|---|
| Total O2 generated O2 : | 5.40 | kg/day |
| Total O2 needed for metabolic consumption: | 5.01 | kg/day |
| Percent excess O2: | 7.8% | |

## 3.6 Water Mass Balance for Mars Transit Missions with Sabatier CRS

A water mass balance for Mars transit mission and for the case with Sabatier CRS integrated in the ARS is shown in Table 5.

Table 5. Overall Water mass Balance for Mars Surface Mission with Sabatier CRS Subsystem

| | Demand Rate (kg/day) | Supply rate (kg/day) | Net Supply Rate (kg/day) |
|---|---|---|---|
| without Sabatier CRS | | | |
| 0% food water recovery | 180.59 | 175.97 | -4.62 |
| 50% food water recovery | 180.59 | 178.16 | -2.43 |
| 100% food water recovery | 180.59 | 180.34 | -0.24 |
| Sabatier CRS water generation (see section 2.100) | 0. | 3.240 | |

Table 5. Overall Water mass Balance for Mars Surface Mission with Sabatier CRS Subsystem (continued)

| | | | |
|---|---|---|---|
| with Sabatier CRS | | | |
| 0% food water recovery | 180.59 | 179.21 | -1.38 |
| 50% food water recovery | 180.59 | 181.40 | 0.81 |
| 100% food water recovery | 180.59 | 183.58 | 3.00 |

## 3.7 Water Mass Balance for Mars Surface Missions with No Water Consumption in a EVA Spacesuit Cooler (Surface Missions)

Water mass balances for Mars surface missions with no water consumption for a spacesuit-cooling device and for cases with and without a Sabatier CRS are shown in Table 6.

Table 6 Overall Water Mass Balance for Mars Surface Mission With No Water Consumption in EVA Suit Cooling

| | Demand Rate (kg/day) | Supply rate (kg/day) | Net Supply Rate (kg/day) |
|---|---|---|---|
| without Sabatier CRS | | | |
| 0% food water recovery | 183.15 | 177.74 | -5.42 |
| 50% food water recovery | 183.15 | 179.92 | -3.23 |
| 100% food water recovery | 183.15 | 182.11 | -1.04 |
| Sabatier CRS water generation (see Table 1) | 0. | 3.728 | |
| With Sabatier CRS | | | |
| 0% food water recovery | 183.15 | 181.46 | -1.69 |
| 50% food water recovery | 183.15 | 183.65 | -0.50 |
| 100% food water recovery | 183.15 | 185.84 | 2.89 |

## 3.8 Water Mass Balance for Mars Missions with In Situ O2/Water Supply (Surface Missions)

It was assumed that the ESM of Mars in situ water is lower than the ESM of water launched with the spacecraft from Earth. Water mass balances for Mars surface mission and for cases (assuming EVA sublimator draws 2.2 kg/day water) with and without a Sabatier CRS are shown in Table 7.

Table 7 Overall Water Mass Balance for Mars Surface Mission with In Situ O2 Supply

| | Demand Rate (kg/day) | Supply rate (kg/day) | Net Supply Rate (kg/day) |
|---|---|---|---|
| without Sabatier CRS | | | |
| 0% food water recovery | 178.35 | 177.74 | -0.62 |
| 50% food water recovery | 178.35 | 179.92 | 1.57 |
| 100% food water recovery | 178.35 | 182.11 | 3.76 |
| with Sabatier CRS | | | |
| 0% food water recovery | 178.35 | 181.46 | 3.11 |

Table 7 Overall Water Mass Balance for Mars Surface Mission with In Situ O2 Supply (continued)

| | | | |
|---|---|---|---|
| 50% food water recovery | 178.35 | 183.65 | 5.30 |
| 100% food water recovery | 178.35 | 185.84 | 7.49 |

The table indicates that with in situ O2 available and without a Sabatier CRS subsystem, there will be daily water shortage of 0.62 kg/day if no food water is recovered. Without a Sabatier CRS and with food water recovery at 50% and more, there will be water surplus. Since percentages of food water recoverable are expected to be above 90%, the water mass balance will be a surplus for the scenarios that in situ water is available. A Sabatier CRS will not be needed for these scenarios.

If in situ water is available, the daily net water generation is not an issue. A Sabatier CRS is not needed to generate extra water.

## 3.9 Summary of Water Mass Balance for Various Scenarios

A summary of water mass balance of the above cases is shown in Table 8:

**Table 8 Summary of Water Mass Balance Calculations for Mars Surface and Transit Missions**

Basis :

| | |
|---|---|
| Crew | 6 person |
| Mars Surface mission: | daily 2-person EVA |
| Mars Transit mission: | no EVA |

| Mission | Food Supply | Sabatier CRA | Sublimator Water Use | O2 supplied from insitu O2 generation | water/wastewater demand | water/wastewater supply | net water supply |
|---|---|---|---|---|---|---|---|
| | | | kg/day | kg/day | kg/day | kg/day | kg/day |
| surface | 0% water recovery from food, 0 kg/day food water | no | 2.2 | 0 | 185.35 | 177.74 | -7.61 |
| surface | 50% water recovery from food, 2.19 kg/day food water | no | 2.2 | 0 | 185.35 | 179.92 | -5.43 |
| surface | 100% water recovery from food, 4.38 kg/day food water | no | 2.2 | 0 | 185.35 | 182.11 | -3.24 |
| surface | 0% water recovery from food, 0 kg/day food water | yes | 2.2 | 0 | 185.35 | 181.46 | -3.89 |
| surface | 50% water recovery from food, 2.19 kg/day food water | yes | 2.2 | 0 | 185.35 | 183.65 | -1.70 |
| surface | 100% water recovery from food, 4.38 kg/day food water | yes | 2.2 | 0 | 185.35 | 185.84 | 0.49 |
| | | | | | | | |
| surface | 0% water recovery from food, 0 kg/day food water | no | 0 | 0 | 183.15 | 177.74 | -5.41 |
| surface | 50% water recovery from food, 2.19 kg/day food water | no | 0 | 0 | 183.15 | 179.92 | -3.23 |
| surface | 100% water recovery from food, 4.38 kg/day food water | no | 0 | 0 | 183.15 | 182.11 | -1.04 |
| surface | 0% water recovery from food, 0 kg/day food water | yes | 0 | 0 | 183.15 | 181.46 | -1.69 |
| surface | 50% water recovery from food, 2.19 kg/day food water | yes | 0 | 0 | 183.15 | 183.65 | 0.50 |
| surface | 100% water recovery from food, 4.38 kg/day food water | yes | 0 | 0 | 183.15 | 185.84 | 2.69 |
| | | | | | | | |
| surface | 0% water recovery from food, 0 kg/day food water | no | 2.2 | 6.21 | 178.35 | 177.74 | -0.61 |
| surface | 50% water recovery from food, 2.19 kg/day food water | no | 2.2 | 6.21 | 178.35 | 179.92 | 1.57 |
| surface | 100% water recovery from food, 4.38 kg/day food water | no | 2.2 | 6.21 | 178.35 | 182.11 | 3.76 |
| surface | 0% water recovery from food, 0 kg/day food water | yes | 2.2 | 6.21 | 178.35 | 181.46 | 3.11 |
| surface | 50% water recovery from food, 2.19 kg/day food water | yes | 2.2 | 6.21 | 178.35 | 183.65 | 5.30 |
| surface | 100% water recovery from food, 4.38 kg/day food water | yes | 2.2 | 6.21 | 178.35 | 185.84 | 7.49 |

**Table 8 Summary of Water Mass Balance Calculations for Mars Surface and Transit Missions**
(continued)

| Mission | Food Supply | Sabatier CRA | Sublimator Water Use | O2 supplied from insitu O2 generation | water/wastewater demand | water/wastewater supply | net water supply |
|---|---|---|---|---|---|---|---|
| | | | kg/day | kg/day | kg/day | kg/day | kg/day |
| transit | 0% water recovery from food, 0 kg/day food water | no | N/A | 0 | 180.59 | 175.97 | -4.62 |
| transit | 50% water recovery from food, 2.19 kg/day food water | no | N/A | 0 | 180.59 | 178.16 | -2.43 |
| transit | 100% water recovery from food, 4.38 kg/day food water | no | N/A | 0 | 180.59 | 180.34 | -0.25 |
| transit | 0% water recovery from food, 0 kg/day food water | yes | N/A | 0 | 180.59 | 179.21 | -1.38 |
| transit | 50% water recovery from food, 2.19 kg/day food water | yes | N/A | 0 | 180.59 | 181.40 | 0.81 |
| transit | 100% water recovery from food, 4.38 kg/day food water | yes | N/A | 0 | 180.59 | 183.58 | 2.99 |

# 4.0 Trade Study Results and Discussions

Equivalent System Mass (ESM) values for the systems with and without a Sabatier CRS in an ARS were compared to estimate trade-off time for including a Sabatier CRS in air revitalization systems. Trade-off time for the following systems have been estimated: surface missions with 2.2 kg water used for the EVA sublimator cooler, surface missions with no water consumption for the EVA cooler, and transit missions. For the cases with in situ O2 or water available, mass balance analyses conducted in Chapter 3 indicate that water mass balance is in surplus in general, therefore no trade-off analyses were needed. A parametric analysis of the impacts of percent water recovery from a water recovery system and percent food water recovery from food on the trade-off of integrating a Sabatier CRS into an ARS was also included.

## 4.1 Basis for Trade Studies

Mass, volume and power data of the Sabatier CO2 Reduction Subsystem (2) estimated for Node 3 project were used as one of the baselines of this study. Mass, volume and power data for CO2 accumulator and CO2 compressor were based on the CO2 compressor requirements developed for the same Node 3 project (9). Mass, volume and power requirements for water tanks were estimated based on the data from fuel cell water tank of Space Station ISS (10). These baseline data are listed below:

| | Mass (kg) | Volume ($m^3$) | Power (w) | Cooling (w) | Labor (hr) | Total (kg) |
|---|---|---|---|---|---|---|
| Sabatier CRS[1] | 120 | 0.208 | 106 | 173 | 0 | |
| CO2 Accumulator[2] | 2.6 | | | | | |
| CO2 Compressor[2] | 27 | | 500 | | | |
| Controller[1] | 3 | | | | | |
| Total | 153 | 0.208 | 606 | 173 | 0 | |
| ESM (kg) | 153 | 0.43 | 52.7 | 11.5 | 0 | 217.7 |
| | | | | | | |
| OGS[8] | 1541 | 0.699 | 3250 | | | |
| ESM (kg) | 1541 | 1.46 | 216.7 | | | 1759.1 |
| | | | | | | |
| Water Tank (75 kg)[3] | 96.2 | 0.103 | 5 | | | |
| ESM (kg) | 96.2 | 0.22 | 0.44 | | | 96.9 |

Mass, volume and power requirements for capacities other than the baseline values were estimated using ESDM method (11). Conversion into Equivalent System Mass (ESM) from mass, volume, and power data of Sabatier CRS, CO2 accumulation tank, CO2 compressor and water tank were based on the infrastructure equivalencies proposed in Advanced Life Support Research and Technology Development Metric (12).

## 4.2 Trade Study Results for Systems with and without a Sabatier CRS for Surface Missions

### 4.2.1 EVA Using a Sublimator Consuming 2.2 kg/day Water

Figure 5 shows ESM values of systems with and without a Sabatier CRS for the case of no food water recovery, based on water mass balance calculations in Sections 3.3 and 3.4 and their respective ESM values. Figure 6 shows Equivalent System Mass (ESM) of systems with and without a Sabatier CRS for the case of partial food water recovery at 2.2 kg/day. Figure 7 shows Equivalent System Mass (ESM) of systems with and without a Sabatier CRS for the case of full food water recovery at 4.4 kg/day. By comparing the ESM numbers for systems with and without a Sabatier CRS, the pay off time for including a Sabatier CRS in the advanced ARS were obtained. The estimated pay-off time for including a Sabatier CRS in an ARS are listed in the following:

| Mission | Food water recovery (water recovery, kg/day) | Water used in EVA Cooler (kg/day) | Pay-off time (days) |
|---|---|---|---|
| Surface | No (0. kg/day ) | 2.2 | 52 |
| Surface | Partial (2.2 kg/day) | 2.2 | 48 |
| Surface | Full (4.4 kg/day) | 2.2 | 45 |

Therefore, for a surface mission, which could last at lest 500 days, inclusion of a Sabatier CRS is suggested.

**Figure 5 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars surface missions, 0% food water recovery, 2.2 kg/day EVA sublimator water**

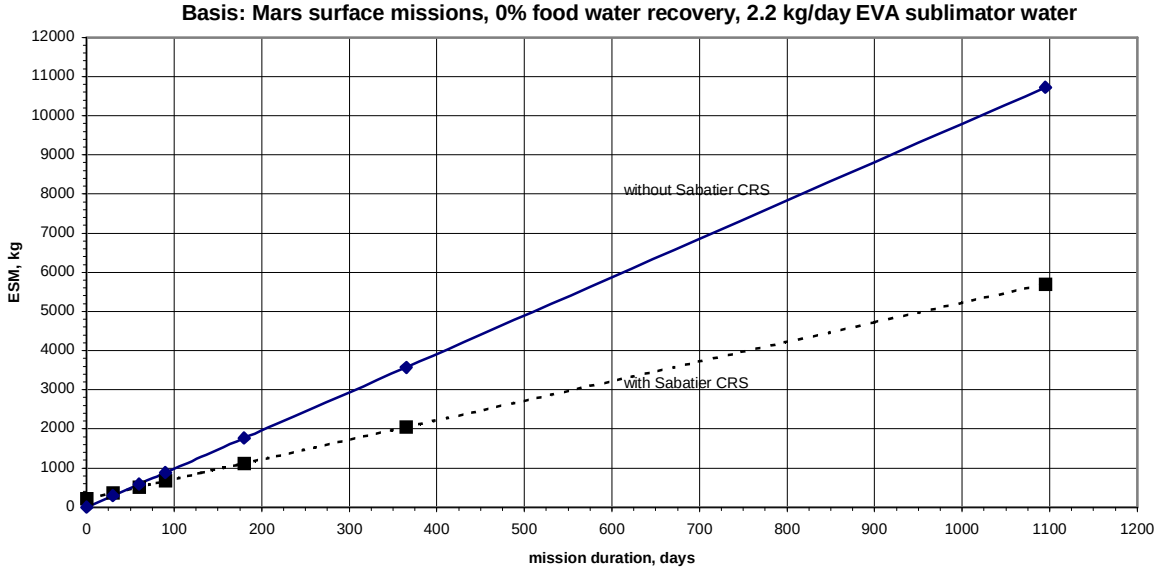



**Figure 6 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars surface missions, 50% food water recovery, 2.2 kg/day EVA sublimator water**

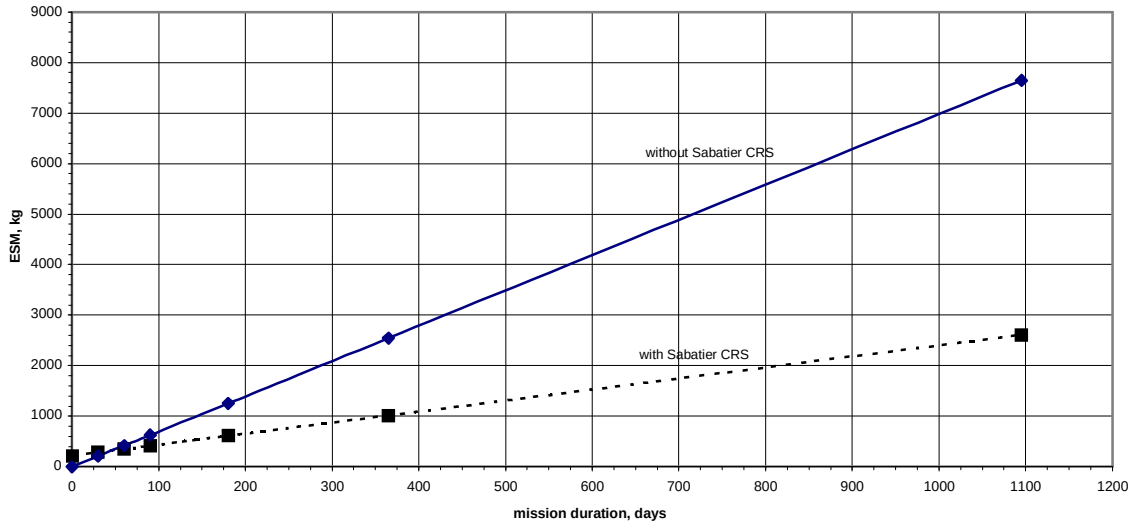
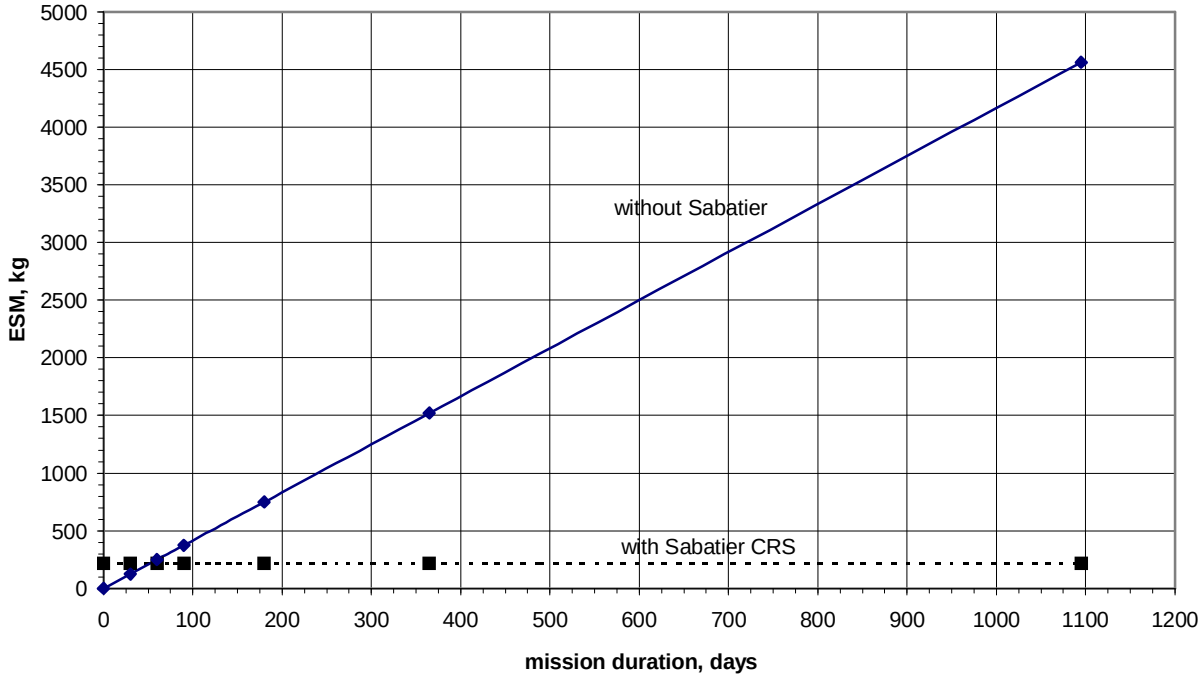


**Figure 7 Equivalent System Mass of Systems with and without Sabatier CRS**
**Basis: Mars surface missions, 100% food water recovery, 2.2 kg/day EVA sublimator water**




## 4.2.2 EVA Using A Cooling Device (radiator) Without Consuming Water

Water consumption for spacesuit cooling, estimated at 2.2 kg/EVA for a two-person EVA using a sublimator, is a major net water consumption item among all the water usages shown in Table 2. By using an alternate design, for example a radiator cooler, this water lost to space may be eliminated. Figure 8 compares Equivalent System Mass (ESM) of systems with and without a Sabatier CRS for the case with no food water recovery, based on water mass balance calculations in Sections 3.7 and their associated ESM. For the cases with 50% and 100% food water recovery, the trade-off analysis results are shown in Figures 9 and 10.

The pay off time for including a Sabatier CRS are listed in the following:

| Mission | Food water recovery (water recovery, kg/day) | Water used in EVA Cooler (kg/day) | Pay-off time (days) |
|---|---|---|---|
| Surface | No (0 kg/day) | 0. | 43 |
| Surface | Partial (2.19 kg/day) | 0. | 51 |
| Surface | Full (4.38 kg/day) | 0. | 163 |

These plots indicate that integration of a Sabatier CRS in an advanced ARS system is justified if water consumption in EVA spacesuit cooling for Mars surface missions is eliminated.

**Figure 8 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars surface missions, 0% food water recovery, no water consumption in EVA spacesuit cooling**

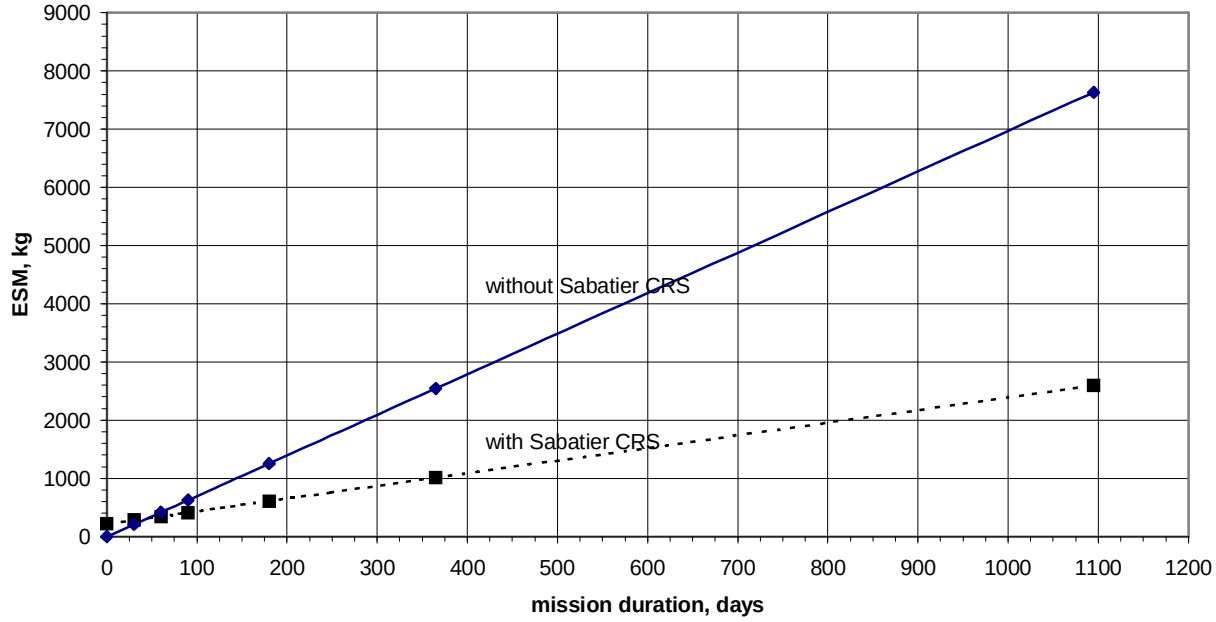



**Figure 9 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars surface missions, 50% food water recovery, no water consumption in EVA spacesuit cooling**

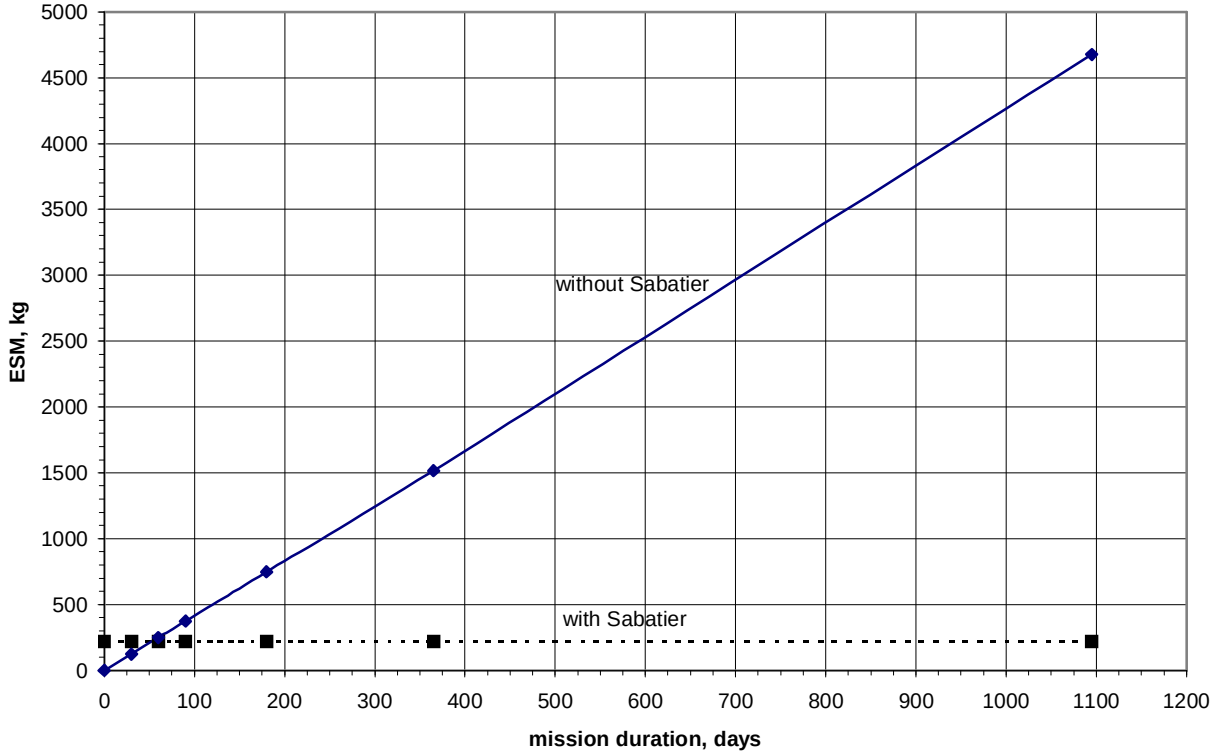
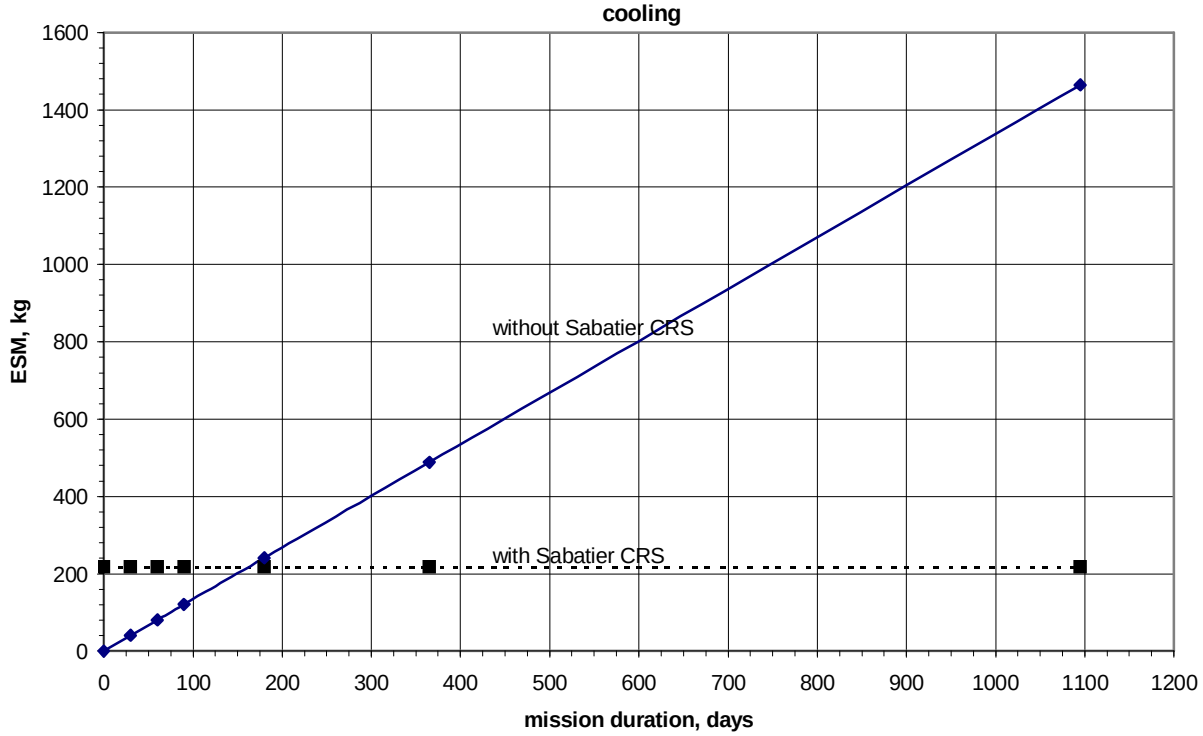


**Figure 10 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars surface missions, 100% food water recovery, no water consumption in EVA spacesuit cooling**




### 4.2.3 Mars In Situ O2/Water Supply Available

Water mass balance calculations shown in Section 3.8 indicate that, with in situ O2 available and even with 2.2 kg/day water consumption from an EVA sublimator, there will be water supply surplus except for the case of no food water recovery. Since significant food water recovery will be a normal case, it was concluded that if in situ O2 is available (probably from processing of Martian CO2), the inclusion of Sabatier is not needed.

If in situ water is available (assuming the ESM of in situ water is less than the ESM of water generated from a Sabatier CRS), then water supply is not an issue. A Sabatier CRS is not needed for this case.

## 4.3 Trade Study Results for Systems with and without Sabatier CRS for Mars Transit Missions

Figure 11 shows Equivalent System Mass (ESM) of systems with and without a Sabatier CRS, based on water mass balance calculations in Sections 3.5 and 3.6 and their associated ESM. Figure 11 indicates that it takes 52 days to pay off the inclusion of a Sabatier CRS in an ARS, assuming no food water recovery. Figure 12 compares ESM of systems with and without a Sabatier CRS assuming partial food water recovery (2.2 kg/day water from food). It takes 69 days to pay off the inclusion of a Sabatier CRS for this case. Figure 13 shows that for full food water recovery case (4.4 kg/day), the inclusion of a Sabatier CRS is not needed (trade-off time = 676 days).

For Mars transit missions, which take 180 days one way, the above trade analyses indicate that inclusion of a Sabatier CRS depends upon the extent of food water can be achieved. With 99.9% water recovery from a water recovery system, this analysis indicated that a Sabatier CRS is needed if less than 50% food water is

recovered; a Sabatier CRS is not needed if food water recovery is 100%.

**Figure 11 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars transit missions, 0% food water recovery, 99.9% water recovery in WRS**

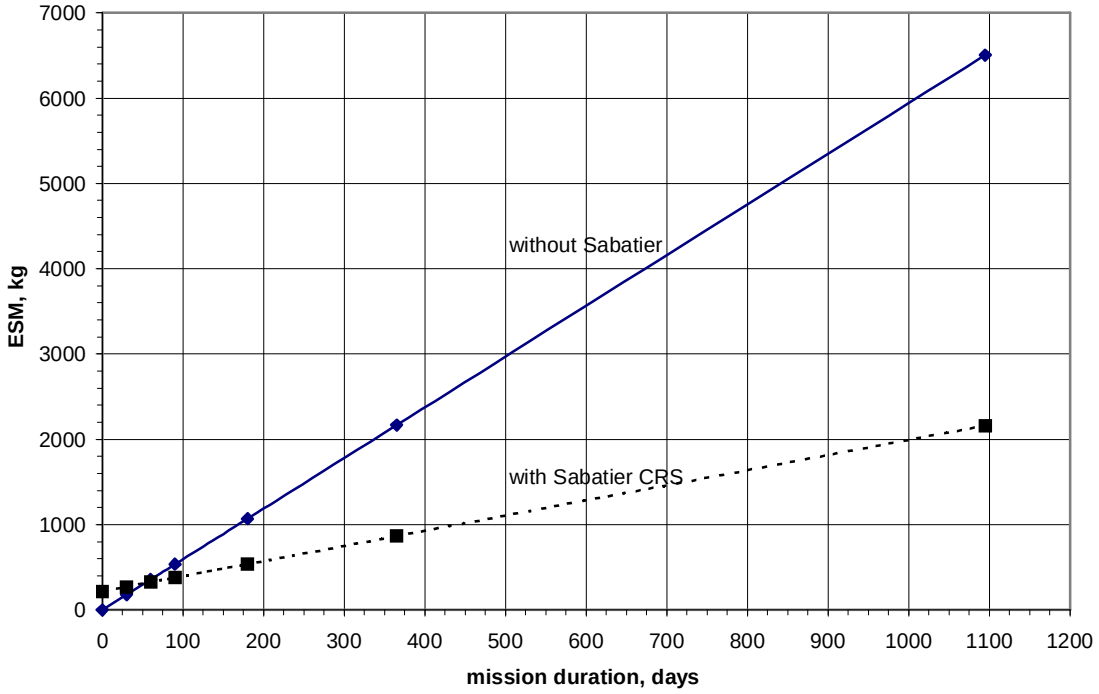



**Figure 12 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars transit missions, 50% food water recovery**

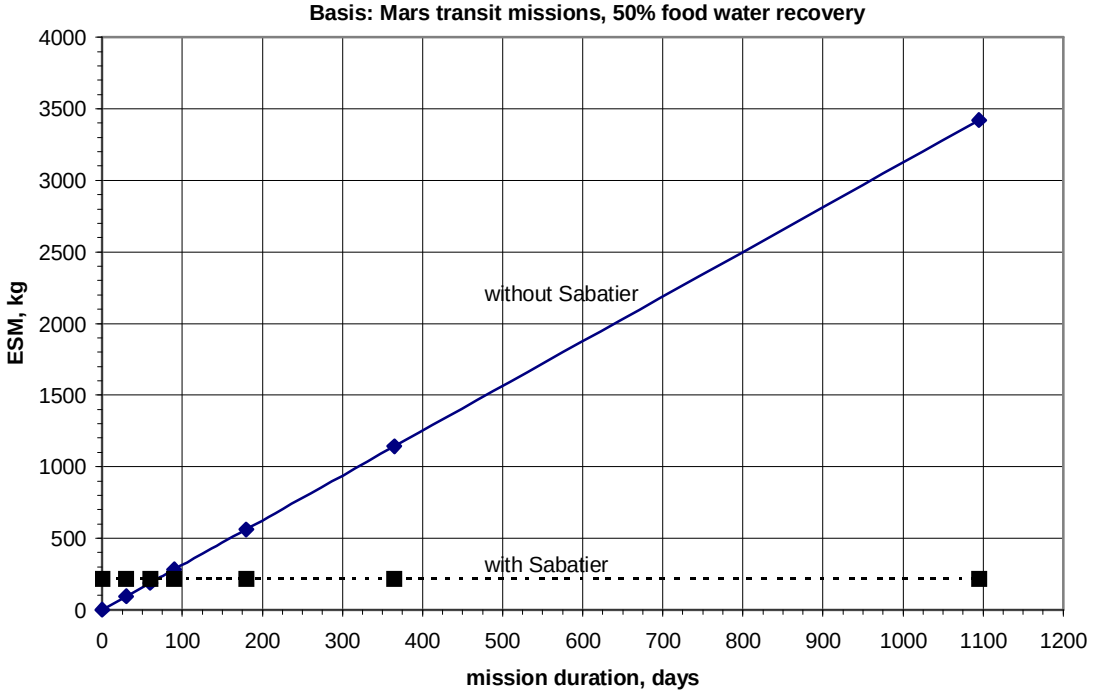
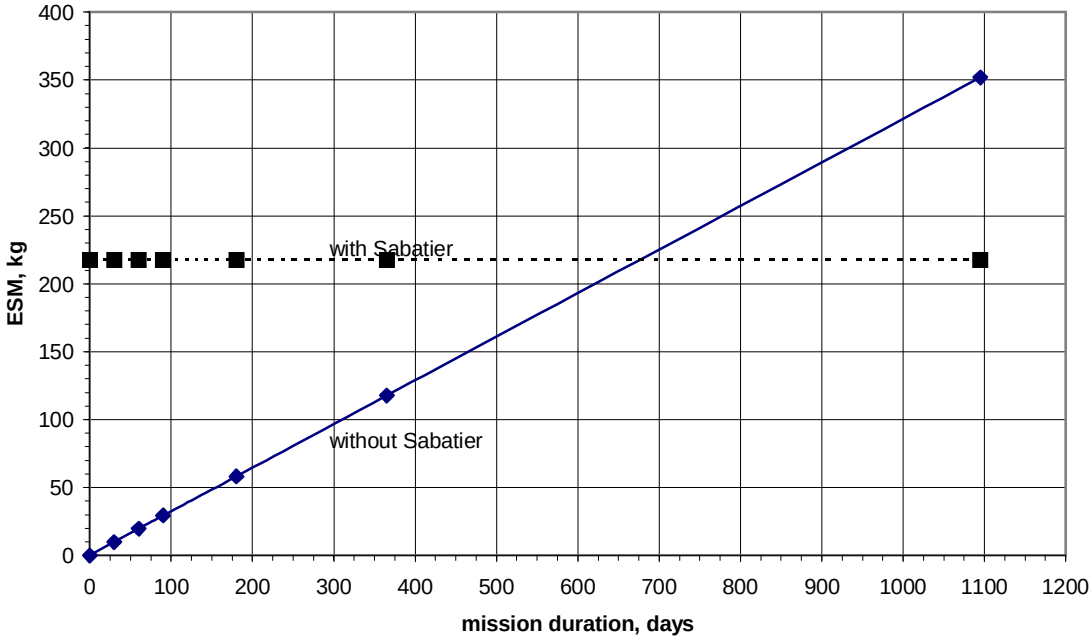


**Figure 13 Equivalent System Mass of Systems with and without CRS**
**Basis: Mars transit missions, 100% food water recovery**




## 4.4 Parametric Analysis of Pay-off Time for Inclusion a Sabatier CRS in Mars Transit Missions

A parametric analysis of pay-off time as functions of % water recovery from a water recovery system and % food water recovery for inclusion of a Sabatier CRS in transit missions is shown in Figure 14.

For 180-day transit missions (i.e., in situ water available case), Figure 14 indicates that, if water recovery of a water recovery system is less than 99.5%, a Sabatier CRS is needed for whatever percentage of food water recovery. If water recovery of a WRS is 99.9%, food water recovery needs to be greater than 63% to be able to have an ARS without a Sabatier CRS.

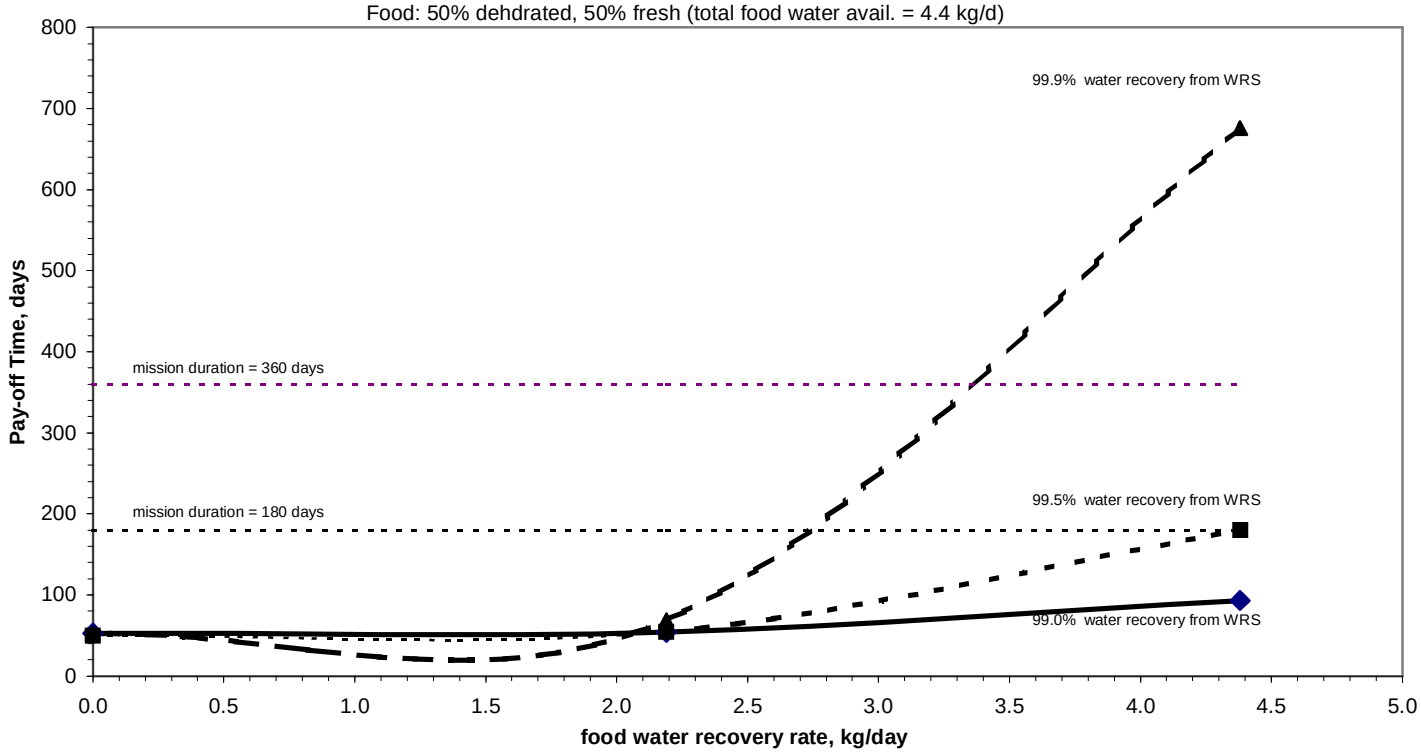
For 360-day transit missions (i.e., in situ water not available case), Figure 14 indicates that, if water recovery of a water recovery system is less than 99.5%, a Sabatier CRS is needed for whatever percentage of food water recovery. If water recovery of a WRS is 99.9%, food water recovery needs to be greater than 78% to be able to have an ARS without a Sabatier CRS.

Since nominal food water recovery is expected to be higher than 90%, it can be concluded that if water recovery efficiency of the WRS is 99.9% (i.e., daily total water losses less than 0.19 kg), a Sabatier CRS is not needed. All the water lost (including oxygen losses) to space will be compensated from food water recovery in this 99.9% efficiency WRS case.

Figure 14 Parametric Analyisis of Pay-off Time for Inclusion of a Sabatier CRS as Functions of % Water Recovery in WRS and % Food Water Recovery

Basis: Mars transit mission, 6-person crew, no EVA, no fecal water recovery

Food: 50% dehdrated, 50% fresh (total food water avail. = 4.4 kg/d)



## *5.0 CONCLUSION*

The payoff time for including a Sabatier CO2 reduction subsystem in an advanced ARS were estimated as follows:

| Mission | Food Water Recovery (%) | EVA Sublimator water usage (kg/day) | Payoff Time (days) |
|---|---|---|---|
| Mars surface | 0 - 100 | 2.2 | <52 |
| Mars surface | 0 - 100 | 0 | <163 |
| Mars surface (in situ O2 available) | 0 | 2.2 | 279 |
| Mars surface (in situ O2 available) | 50 – 100 | 2.2 | infinite |
| Mars surface (in situ water available) | 0 - 100 | 0 | infinite |
| Mars transit | 0 | no EVA | 52 |
| Mars transit | 50 | no EVA | 69 |
| Mars transit | 100 | no EVA | 676 |

The above pay-off time were estimated based upon an assumption that the Biological Water Recovery System (BWRS) is used and 99.9% water recovery is achieved by this BWRS.

For Mars surface missions which could last more than 500 days, integration of a Sabatier CRS into an ARS is suggested, if in situ O2 or in situ water is not available. If in situ O2 is available, a Sabatier CRS is not needed since food water recovery at greater than 90% is expected. If in situ water is available, a Sabatier CRS is not needed either.

For 180-day transit missions (in situ water available case), results from a parametric analysis indicated that, if the water recovery efficiency of the water recovery system is less than 99.5%, inclusion of a Sabatier CRS in an ARS is justified for whatever percentage of food water recovery. If water recovery of a WRS reaches 99.9%, food water recovery needs to be greater than 63% to have an ARS without a Sabatier CRS.

For 360-day transit missions (in situ water not available case), the same parametric analysis indicated that, if the water recovery efficiency of the water recovery system is less than 99.5%, inclusion of a Sabatier CRS in an ARS is also justified for whatever percentage of food water recovery. If water recovery of a WRS reach 99.9%, food water recovery needs to be greater than 78% to have an ARS without a Sabatier CRS.

For transit missions in general, if the water recovery efficiency of the WRS is less than 99.5%, inclusion of a Sabatier CRS in an ARS is justified. If the water recovery efficiency of the WRS reaches 99.9% (i.e., total net water loss to be less than 0.19 kg/day), inclusion of a Sabatier CRS in an ARS is not needed. All the water lost (including oxygen losses) to space will be compensated from food water recovered in this 99.9% efficiency WRS case.

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