Title : **ALCHEMIST - Lunar ISRU Demonstration Mission Definition Study - Segment 1 ISRU Payload**

Executive Summary Report

Abstract : This document concisely summarises ALCHEMIST- Lunar ISRU Demonstration Mission Definition Study - Segment 1 ISRU Payload.

Contract N° : 4000123271

Technical officer : Mr. Bernhard Hufenbach

DOCUMENT APPROVAL SHEET

	Name	Company	Signature and Date
Prepared by:	Diego Urbina	Space Applications Services	
PA Checked by:	Lahcen Tazi	Space Applications Services	
Approved by:	Diego Urbina	Space Applications Services	
Accepted by:	Bernhard Hufenbach	ESA	

Space Applications Services SA/NV
Leuvensesteenweg 325
B-1932 Zaventem, Belgium

Tel: +32-(0)2-721.54.84
Fax: +32-(0)2-721.54.44
Web: www.spaceapplications.com

DOCUMENT CHANGE RECORD				
Version	**Date**	**Author**	**Changed Sections / Pages**	**Reason for Change / RID No**
1.0.0	13/11/2018	Diego Urbina	All	Release
1.0.1	24/11/2018	Diego Urbina	All	Small edits for completeness

Table of Contents

List of Figures

1 Introduction

1.1 Purpose and Scope

ALCHEMIST ESR concisely summarises work performed during this study.

1.2 Document Structure

This document is divided into the following chapters:

Section 1: (this section) introduces the present deliverable and reference documents and acronyms

Section 2: indicates the background and objectives of the payload

Section 3: provides an overview of the activities performed

Section 4: provides the basics of the chemical process at the core of ALCHEMIST

Section 5: gives an overview of the payload

Section 6: indicates the assumed landing site based on which the analyses have been made

Section 7: shows high level system budgets and interfaces towards the lander

Section 8: summarizes considerations for future work and payload development

1.3 Applicable Documents

AD1 Design Rationale and High-Level Requirements for the Lunar ISRU Demonstration Mission (DRM) - ESA-HSO-K-TN-0010 – issue 1, Revision 1 – 26-02-2018

AD2 Margin Philosophy Document CDF-TN-057

AD3 Guidelines for the use of TRLs in ESA programmes ESSB-HB-E-002, iss. 1

AD4 ISRU Demonstration Mission, Mission and Systems – Presentation. ESTEC 27 February 2018, ESA-HSO-K-HO-026

1.4 Reference Documents

RD1 ALCHEMIST-SA-TN1 - ALCHEMIST- Payload Description Document

RD2 ALCHEMIST-SA-TN2 - ALCHEMIST- Payload Interface Definition Document (PL-IDD)

RD3 ALCHEMIST-SA-TN3 - ALCHEMIST- Payload Development Plan (PL-DP)

1.5 Acronyms

Acronym	Definition
AD	Applicable Documents
AIV	Assembly Integration and Verification
ALCHEMIST	A Lunar Chemical In-Situ Resource Utilisation Test Plant
C&DH	Command and Data Handling
ESA	The European Space Agency
ESR	Executive Summary Report
RD	Reference Documents
RD	Reference Documents
TBD	To Be Determined
TBW	To Be Worked/Written

2 Background and objectives

ALCHEMIST is a payload design created in order to produce water from Lunar regolith so as to demonstrate the end-to-end process of hydrogen reduction of FeO on the Lunar surface.

The overall objectives of the payload as identified by the team based on ESA information are:

- To produce at least the minimum amount of water – 100 grams (and/or equivalent amount of oxygen) on the Moon before 2025
- To obtain better information of feedstock properties in order to inform design of a large plant
- To constitute a payload that is part of a mission enabled through commercialization and partnerships, with an ESA industrial procurement budget of 250 M Euro

Hydrogen is widely used as reducing reagent in earth-based process in order to obtain particular metals from their respective oxides. ALCHEMIST uses oxide FeO to meet the mission objectives, which occurs mainly in the form of ilmenite ($FeTiO_3$), but also is present in other minerals. Reducing Iron oxide (II) leads to obtaining water vapour. This water is typically considered a by-product in Earth mining, however, on the Moon, this water can be leveraged for myriad uses, notably the production of Oxygen. Reaction temperatures between 900 and 1000 degrees Celsius are typically reported in order to achieve adequate rates for this reaction.

The project team is Space Applications Services (BE, prime contractor), CIEMAT Plataforma Solar de Almeria (ES), Ariane Group (ES), Aavid Thermacore (UK) and Colorado School of Mines (US).

3 Overview of the performed activities

An initial trade-space exploration has taken place to explicitly analyse the mission design trade-space provided by the customer and the baseline mission design to validate or replace it; and indicate how the associated challenges it contains and identifies are addressed and reflected in the ALCHEMIST design. As a result, the team obtained a first iteration of a Payload Description Document, and a Payload Interface Definition.

The industrial team continued the Payload Design of ALCHEMIST, elaborating on the payload description and interfaces between subsystems. This was done in coordination with Delivery Segment and the Communications Segment (parallel contracts).

Dedicated work was performed on the Electromechanics, Payload Support and Fluid Management subsystem groups, as well as on the detailed definition of the chemical products, their properties. Through a combination of plenary and off-line sessions the maturity of the design was expedited.

The team has come up with a concept of operations congruent with the system characteristics, and the preliminary lander/communications service, power and data profiles will be initiated and iterated as the concept evolves.

A partnership identification was done, not restricted to, but focusing on Earth and space-related stakeholders of the key technologies being explored. Select contacts have been established.

The consortium has participated at the Mission Integration with the other segments and led together with ESA the integration of the payload segment into the overall architecture, aligning interface requirements and definition, leading to an update in the Payload Interface Definition. Discrepancies and other potential issues were identified and addressed to the possible extent.

4 The Hydrogen Reduction Process

Over twenty different methods have been proposed to extract Oxygen from resources on the Moon. The reduction processes, and particularly those in which hydrogen is the reducing agent are considered the technologically most mature (Allen et al.)

Oxygen that is chemically bound to iron in lunar minerals and glasses can be extracted by heating the regolith to high temperatures while exposing it to hydrogen gas, releasing oxygen as water vapour.

$$FeO + H2 \rightarrow Fe + H2O$$

Hydrogen is widely used as a reducing reagent in earth-based processes in order to obtain particular metals from their respective oxides. ALCHEMIST uses Iron Oxide FeO (II), which occurs mainly in the form of ilmenite ($FeTiO_3$), but also is present in other minerals. Multiple experiments with lunar Ilmenite, basalt, soil and volcanic glass have demonstrated the process on Earth. Reducing Iron Oxide (II) leads to the production of water vapour. Reaction temperatures between 900 and 1000 degrees Celsius are typically reported in order to achieve adequate rates for this reaction.

The advantages of the Hydrogen Reduction Process are the following:

- Relative simplicity and proven chemical feasibility
- Possibility to recover reductant in one single step (water electrolysis)
- Reduced mass for resupplies of makeup gas (hydrogen) given its low molecular mass
- Availability of terrestrial counterparts for all important process equipment (fluidized beds, kilns…)
- Low process temperatures
- Technical possibility of obtaining iron (with eventual subsequent steps)

The disadvantage of the process is the need to separate the utmost FeO-bearing regolith from the regolith in order to obtain larger yields and relatively slow reaction kinetics.

5 ALCHEMIST Overview

ALCHEMIST is a payload using the Hydrogen Reduction process to demonstrate the production of water from the regolith of the Moon. It is composed by an Excavator System, a Regolith Acquisition and Beneficiation System (processing solid regolith); a Hydrogen Reduction System comprising a reactor and a fluid management system; Power, C&DH, thermal control, structures and mechanisms, and a software subsystem.

Figure 1 and Figure 2 depict the payload configuration on the lander, where the payload is distributed on two side panels.

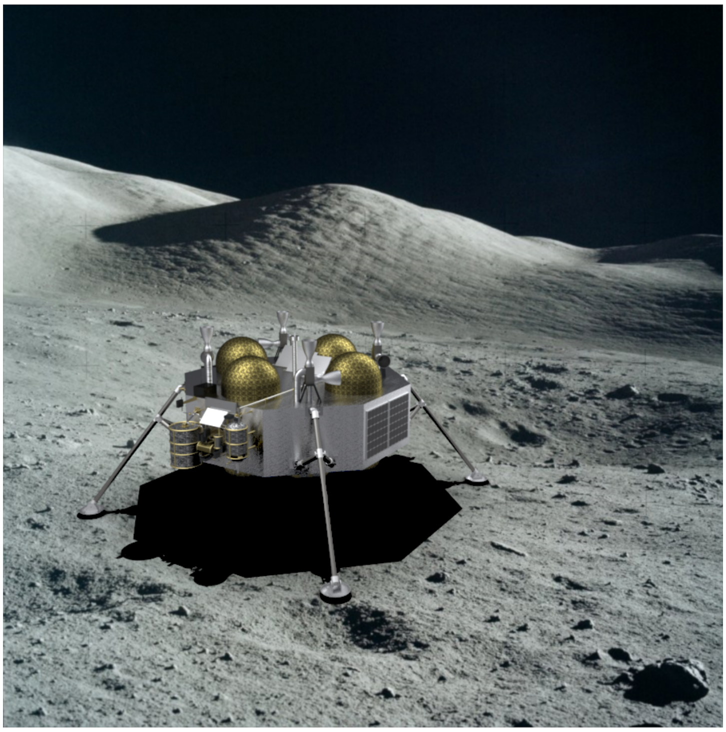

Figure 1 - ALCHEMIST Payload on the side of a Lunar lander – Image credit: Space Applications Services. Lander based on concept by Thales Alenia Space.

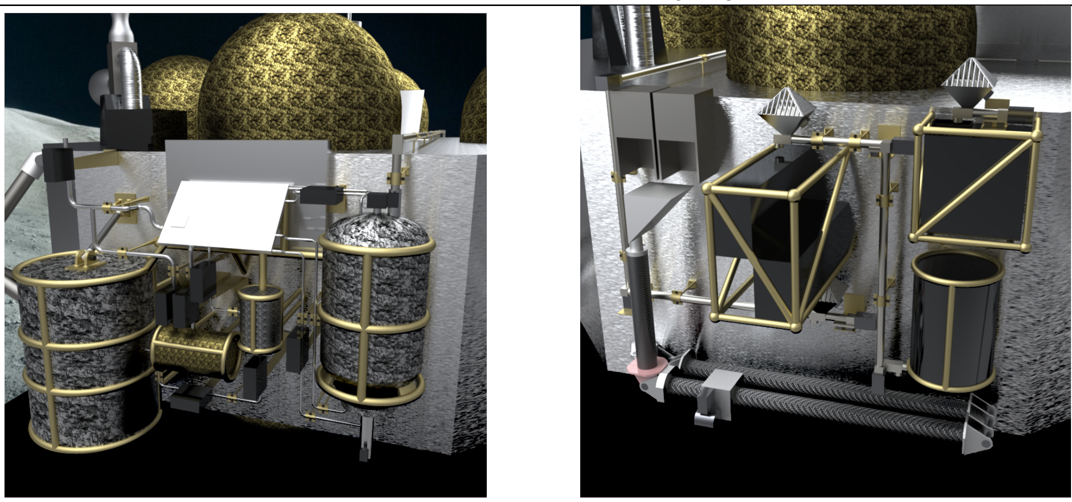

Figure 2 – Left: ALCHEMIST Fluid Management System. Right: Regolith Acquisition and Beneficiation System – Image credit: Space Applications Services

6 A potential landing site

Various landing sites have been analysed, selecting Schrodinger Pyroclastic Flow on the far side, mainly to look into the influence of a far side site on the concept. A range of interest is selected for areas at the Schrodinger Pyroclastic Flow having a minimum of 10.5% of FeO content. Figure 3 shows the existence of a continuous area of at least 3x3 kms, candidate for landing (only with mineral content considerations).

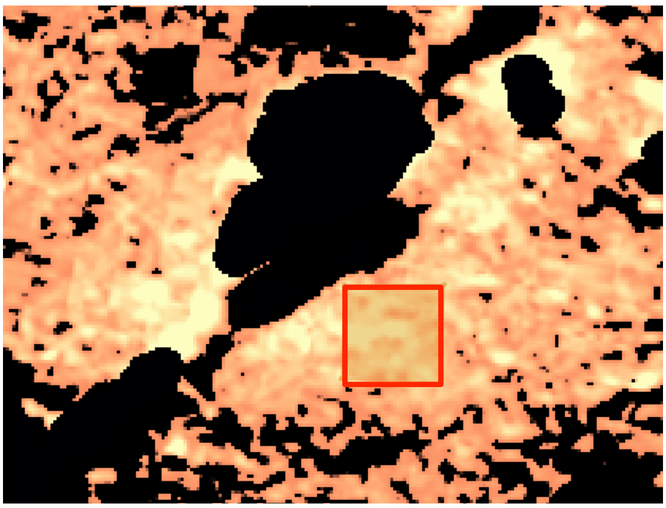

Figure 3 – Detail of a zone with FeO content larger or equal to 10.5% (all colored). The area in the square box corresponds to ~3 x 3 kms and could serve as first iteration of a landing area (topography and other considerations aside). Data courtesy of G. Kramer, generated using algorithms by Lucey et al.

7 System budgets and high-level lander interfaces

Various operation cases have been investigated, which depend on the landing site (in particular high FeO areas or low FeO areas), and the scope of the demonstration (in particular partial beneficiation or full beneficiation). The reference scenario is a far side operation with relay satellites providing specific windows of communication. For the following system budgets and interfaces, one of the cases, so-called PM1-C (partial beneficiation, high FeO location such as Schroedinger Pyroclastic). However, mass and volume budgets include components that could perform full beneficiation.

Figure 4 depicts the timeline for one batch of the PM1-C case.

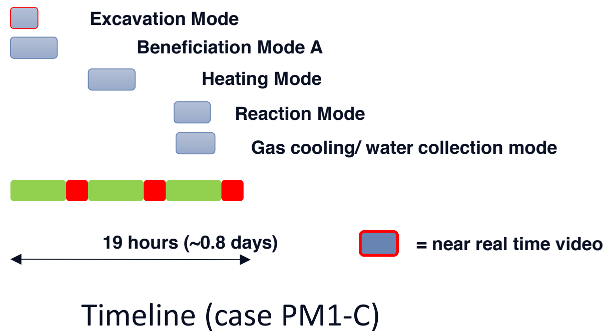

Figure 4 - Timeline of operation per batch for a given communication window (4.8 h availability and 2.1 h of gap) – Case PM1-C. Green: comms available; Red: comms unavailable.

The total mass of the system is 122.79 kg with system margin. Volume envelopes of 1000x860x410 for the Regolith Acquisition and Beneficiation, and 1000x850x370 are considered.

The peak operational power of the design is about 600 Watts and the total energy consumption is about 4300 W-h per batch (case PM1-C).

The data budget is about 9 Gb per batch (for a short batch duration requiring partial beneficiation such as case PM1-C). After each batch of the process, the hot spent regolith is disposed on the lunar surface. The net radiation heat transfer from hot pile to lander's lower deck is about 0.832 kW. As the pile cools down the radiative heat drops with time. Radiation and conduction from the H2 reduction system are purposely kept low to enable the reaction and therefore the conductive and radiative heat are low, however the lander will require a level of protection from heat radiated from cooling stages.

8 Future Work and Payload Development

Various technologies require maturation for space, including

- Regolith handling (electro-)mechanisms
- Beneficiation systems
- Regolith mixing techniques
- Gas cleaning

- Fluid management elements (e.g. gas and solid valves, reactor, recirculation)
- Excavation elements

Ground truth experiments (on the Moon) would be beneficial to the characterization of the feedstock.

Based on the study findings (using a combination of parametric analysis and analogies) a system implementation before 2025 is considered ambitious, requiring appropriate scope/cost/schedule balance as the design progresses, to meet programmatic requirements.