Construction and Resource Utilization eXplorer (CRUX): Implementing Instrument Suite Data Fusion to Characterize Regolith Hydrogen Resources

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Abstract—CRUX is a modular suite of geophysical and borehole instruments combined with display and decision support system (Mapper/DSS) tools to characterize regolith resources, surface conditions, and geotechnical properties. CRUX is a NASA-funded Technology Maturation Program effort to provide enabling technology for Lunar and Planetary Surface Operations (LPSO). The Mapper/DSS uses data fusion methods with CRUX instruments, and other available data and models, to provide regolith properties information needed for LPSO that cannot be determined otherwise. We demonstrate the data fusion method by showing how it might be applied to characterize the distribution and form of hydrogen using a selection of CRUX instruments: Borehole Neutron Probe and Thermal Evolved Gas Analyzer data as a function of depth help interpret Surface Neutron Probe data to generate 3D information. Secondary information from other instruments along with physical models improves the hydrogen distribution characterization, enabling information products for operational decision-making[1,2].

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1. INTRODUCTION: WHAT IS CRUX?

The success of future lunar and planetary missions will depend critically on the ability to identify optimal sites to conduct LPSO related to in situ resource utilization (ISRU), construction, environmental management, and surface mobility. Successful LPSO will require a good knowledge of local surface relief and roughness, geotechnical properties (e.g., grain size, mineralogy, bulk density, thermal and mechanical properties) and the concentration and distribution of resources (with a particular interest in the presence of water, most likely present in the form of ice). We are developing a Construction and Resource Utilization eXplorer (CRUX) that consists of an integrated modular suite of instruments (Prospector-Surveyor) combined with display (Mapper) and decision support system (DSS) analysis tools to characterize regolith resources, surface conditions, and geotechnical properties (Figure 1). The CRUX project is a NASA technology maturation project for the Exploration Systems Research and Technology Program, Exploration Systems Mission Directorate designed to provide critical technology for a return to the Moon and later planetary exploration. The current project focus is to operate under lunar conditions in keeping with current NASA priorities, but with the recognition that our development path should also take into account the

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[2] IEEEAC paper #1279, Version 1, Updated Oct, 19 2005

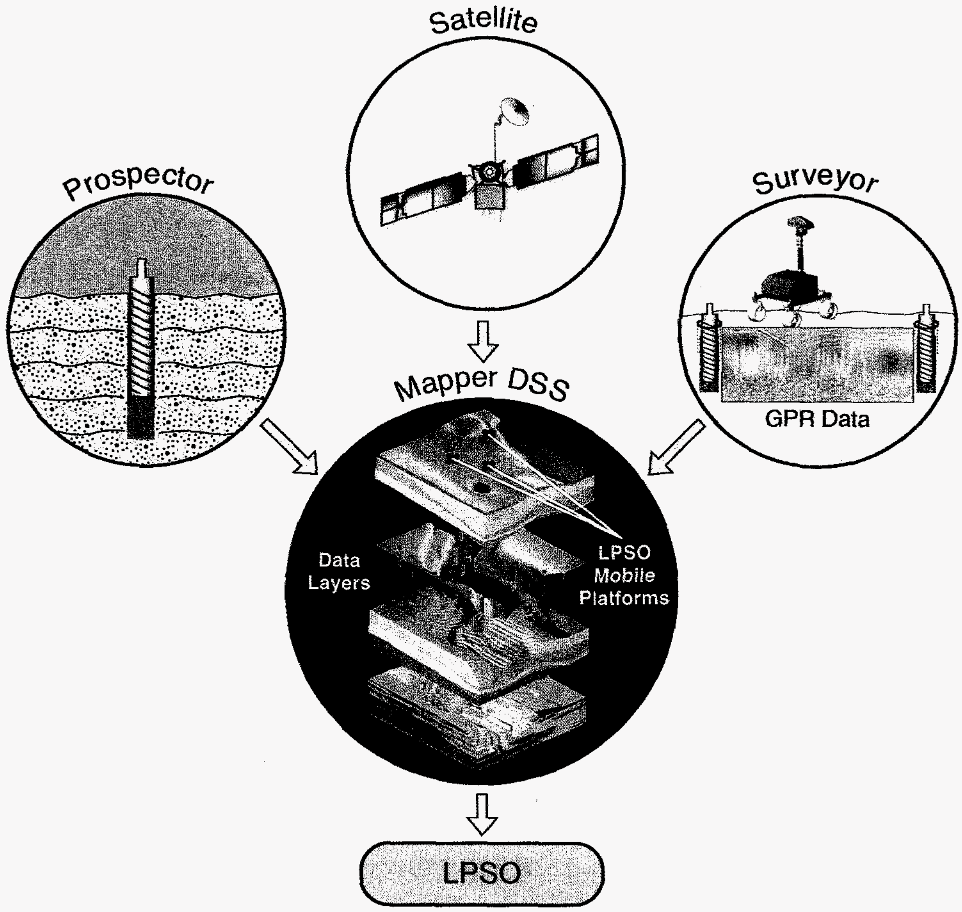

Figure 1. The Construction and Resource Utilization explorer (CRUX) Architecture consists of an integrated modular suite of instruments (Prospector and Surveyor) combined with display (Mapper) and decision support system (DSS) analysis tools to characterize regolith resources, surface conditions, and geotechnical properties.

possibility of surface operations on Mars at some future date.

Integrated modularity allows instruments to be added or removed from the instrument suite and to operate seamlessly with existing installed instruments and associated control and analysis software. The instrument suite and associated software will be designed to allow additions, deletions, or modifications to the instrument suite as needed to accommodate future mission architectures that may include robotic or human controlled landers or mobile platforms.

The selection and deployment of the CRUX instrument suite will be determined based on existing lunar and planetary satellite data, and exploration priorities. Once deployed, the Surveyor will have geophysical instruments to survey the upper portion of the local regolith to help locate optimal drilling sites. The Prospector will use an instrumented drill to measure down-hole, site-specific, geotechnical properties of the regolith, and detect water, to a depth of 2 m. Surveyor data, when linked to Prospector borehole data, will provide an accurate, reliable way to regionally map regolith geotechnical properties and ISRU potential. Surface relief and roughness will be derived from a Surveyor mounted stereo camera system.

Ten instruments have been selected for the Prospector/Surveyor package to provide a rich dataset of regolith geotechnical, surface, resource, and water information. Prospector components include a drill subsurface access system (SAS) that can acquire samples, a borehole neutron probe (BNeuP) to detect hydrogen, a thermal conductivity and diffusivity probe (TCDP) to determine thermal properties, a mechanical properties probe (MPT) to determine shear and compaction, an electrical properties probe (EPP) for dielectric constant and density measurements, and a down-hole camera (DCAM) to observe particle size and mineral composition. Sample analysis to determine mineral and elemental concentration is done using a Thermal Evolved Gas Analyzer (TEGA). The Surveyor geophysical instruments include a seismic profiler (SEIP), ground-penetrating radar (GPR), and surface neutron probe (SNeuP), for hydrogen detection, to profile the upper 1—2 m of regolith. A stereo-pair regolith camera (RCAM) is used for terrain reconnaissance and determining surface topography. This suite of instruments delivers data for analysis to the Mapper/DSS.

While the CRUX instruments are useful individually, their true value is reached when they are integrated to provide interrelated information that can be fused to derive regolith property information that cannot be determined from a single data source. To fully optimize the use of these data for decision-making, we will focus strongly on instrument integration, data fusion and display, and DSS tools. The Mapper/DSS uses data fusion methods with CRUX instruments, and other available data and models, to provide regolith properties information needed for Lunar and Planetary Surface Operations (LPSO) that cannot be determined otherwise.

In the rest of this paper we will examine some of the details of one example of this integrated value-added capability for ISRU, specifically to assess the hydrogen resource potential of lunar regolith. Hydrogen, depending whether it is in the form of water or solar wind deposits is a potential source of fuel, water, and oxygen for space operations. Lunar Prospector orbital neutron probe data imply that regions of enhanced hydrogen exist in the lunar polar regions, possibly associated with permanently shadowed craters. The form of that hydrogen is unknown. Data fusion methods can both resolve interpretation uncertainties of the neutron data and produce 3D characterization of the hydrogen. We will first introduce the approach to data fusion with a description of the significance of lunar hydrogen deposits and then outline the scenario for its characterization with CRUX. This will be followed by brief descriptions of the different primary elements contributing to the data fusion, and then brought together with a discussion of the anticipated value of the 'fused' information.

2. Lunar Hydrogen Resource

ISRU of oxygen, hydrogen, and water enables substantial mission architecture efficiency and cost reductions [1][2].

While Lunar soils contain abundant oxygen in the form of oxide minerals, no significant source of hydrogen had been identified until the recent data from the Lunar Prospector mission. The data from Prospector's neutron spectrometer have been interpreted as showing significant quantities of hydrogen (in an uncertain chemical form) in the permanently shadowed craters of the lunar poles [3]. Even though the resolution of these data is only 10s of kilometers, the mapping shows significant deposits in large (> 40 km in diameter) craters in the lunar polar regions (longitude >75°), where temperatures can range from 40 to 100K, depending on the amount of radiation received from nearby crater walls and other features [4,5]. These temperatures are sufficient to preserve water layers for billions of years if they are covered by a thin layer of regolith [4-6]. Radiation from extra-solar sources (such as cosmic rays and UV radiation) can drive reactions involving hydrogen, water and the regolith. The analysis of the Lunar Prospector data places the hydrogen concentration at 1700 ± 900 ppm, which would translate to 1.5 ± 0.8% as water in the crater floor bottom regolith near the south pole. Given the coarse resolution of the data, local concentration of up to 10% water may be present near the north pole, a clearly significant deposit for ISRU production. If these deposits resulted from comet impacts, the layers may be even more concentrated and contain a variety of other valuable compounds, such as CO, methanol, carbon dioxide, ammonia and methane [7]. Modeling of such cometary impacts suggest that a 10 cm thick layer would survive for a billion years [8,9]. Since random drilling and excavation to locate such deposits would be both costly and ineffective, our approach is to use the Prospecter-Surveyor/Mapper-DSS to optimize the surveying and prospecting efforts that support LPSO – making it an enabling technology for ISRU.

3. CRUX Hydrogen Prospecting Scenario

A regolith characterization system includes the capability to use existing data, collect new data in an integrated fashion (this means existing data is analyzed to plan future measurement needs), use display and analysis tools to evaluate the data, and apply data and models to create decision support tools.

The use of the CRUX regolith characterization system for determining the concentration and distribution of hydrogen as water or solar wind products might proceed by first using satellite neutron data on hydrogen enhancement to select a region to send CRUX. The objective would be to use the CRUX data to infer the 3D distribution of the resource, and provide information to aid resource recovery. Such information might include the amount of resource recovered per unit volume of regolith, the energy required per unit of resource recovered, abrasion rates on recovery machines, mobility routes for ore transport and tailings disposal, tailings management design, and others.

Once in the region of interest, CRUX would deploy the SNeuP, GPR, RCAM, and SEIP to determine regional bulk hydrogen, surface and subsurface objects to guide surface mobility, and estimate regolith physical and mechanical properties. This information would then be used to determine where to deploy the SAS for borehole measurements. The SAS could deploy the BNeuP to determine the depth distribution of hydrogen and to determine where to deploy the SHS to take a regolith sample for analysis by a TEGA to directly determine resource products and their relative concentrations. Additional borehole characterizations might be done to define regolith layering, texture, grain properties, ice form and distribution, mechanical properties, and thermal properties using the DCAM, and EPP, MPT, and TCDP. The EPP measurements of borehole regolith dielectric properties can be used to help interpret GPR data to extend borehole layering and ice information over the region. MPT and TCDP are tied to regolith physical properties and bonding that can be extrapolated over the region using SEIP data. TCDP, TEGA, BNeuP data can be combined with a drilling energetics/volatiles loss model to define drilling protocols to maximize drilling efficiency, minimize volatile loss, and estimate the fate and transport of volatiles during drilling.

4. DATA FUSION

In the preceding operational scenario, primary data fusion is between the TEGA, SNeuP, and BNeuP. The drill system provides access to the subsurface and sample collection. The BNeuP provides information about hydrogen as a function of depth and time and the TEGA can detect water and solar wind hydrogen (and other elements or molecules, e.g., mercury to help interpret neutron data) as a function of depth. Data fusion consists of using the hydrogen concentration as a function of depth information from BneuP and TEGA to help interpret SNeuP data to generate 3D information.

Secondary information from the GPR, the DCAM and the EPP along with models of known and expected physical properties of granular materials to correlate different data sets can be used to improve the characterization of the hydrogen distribution. By combining individual data displays with the results derived from data fusion and models, products for operational decision-making can be produced. Some of these products may be maps of hydrogen distribution, regolith layering, individual borehole plots, and other important information for LPSO.

The process of data fusion is by necessity a driver of the system design of the various elements of the CRUX regolith characterization system. The primary tool for data fusion within CRUX is the Mapper/DSS. Other primary tools for the hydrogen prospecting scenario are the SNeuP, BNeuP, and TEGA and their data.

5. CRUX MAPPER/DSS

The Mapper/DSS is the tool that will allow both engineers and astronauts to utilize CRUX measurements in conjunction with existing lunar and planetary data to plan and conduct LPSO. It is a service-oriented approach to the acquisition, management, analysis and dissemination of real-time geospatial data collected during CRUX missions (Figure 2). Using the Mapper/DSS, CRUX data and mission telemetry will be acquired and managed as eXtensible Markup Language (XML) documents over a scalable web service bus. Web Services will be used to acquire, process and disseminate data at all levels of processing from raw telemetry to reduced data streams to model output.

Principal technical components of the Mapper/DSS include the Oracle database, Interactive Data Language (IDL), and

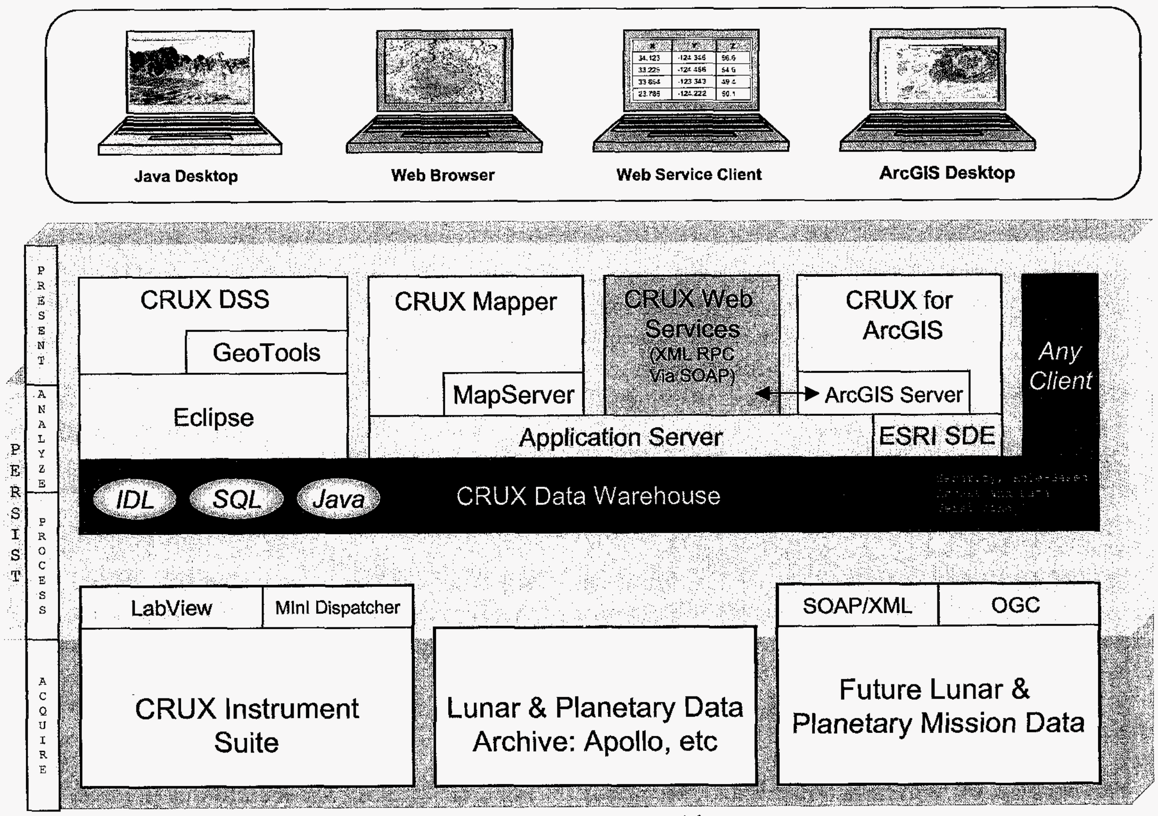

Figure 2. Mapper/DSS Architecture

Eclipse. The Oracle database is linked with spatial and temporal data elements for data persistence, management, and replication. The IDL enables server side data reduction and analysis. Eclipse (an open source development platform for software alignment and integration) is coupled with the ongoing development of NASA's Science Activity Planer (SAP/Maestro), commercial and open source geospatial components including GIS from Earth Sciences Research Institute (ESRI), geotools (an open source Web applications development application) and mapserver (an open source Web map delivery application). The use of open source and standard software platforms ensures compatibility and interoperability with existing NASA software development efforts.

Principal data flow into the Mapper/DSS comes from the CRUX instrument suite measurements, along with archival lunar and planetary data, and future mission data. CRUX instrument data passes through the CEC Mini Dispatcher and is made available via object request broker (ORB) publish and subscribe mechanism. Archival data is converted from legacy formats and loaded directly to a Mapper/DSS database when necessary or may be accessed from cooperating programs via web service interface. Future mission data are anticipated to be accessed by a combination of standards based web services including XML/RPC via SOAP, and Open Geospatial Consortium (OGC) web services. The CRUX data warehouse is responsible for persistence and dissemination of all relevant program data. The data warehouse will be responsible for data archive, replication to distributed sites, data security and role-based review, validation and release. Multi-versioned data will also be supported in the data warehouse. It is anticipated that any data reduction or analysis that can be done at the data warehouse/persistence tier will be done at this tier. This could include server side IDL, Java applications and stored database procedures. Above the data warehouse tier of our architecture a series of application development and deployment frameworks will allow a diverse suite of users to use any standards-based application to display and analyze CRUX program data. Anticipated clients include a Java desktop application built upon the Eclipse framework. This application and its modules should allow for integration of unique CRUX analysis capabilities with the NASA Maestro/Science Activity Planner. A web-based Mapper/DSS interface will provide the broadest possible audience access to data visualization and analysis tools. The web-based system which is currently under development supports geographic display and analysis of program data, and the display and query of models processed through the decision support system. Commercial off the shelf software such as ESRI ArcGIS, ENVI IDL, and MATLAB along with a suite of open source and proprietary data reduction and analysis tools will be used to analyze and reduce CRUX data. These tools will interact with the warehouse via common protocols such as ODBC, ESRI SDE, and through a series of data discovery and delivery web services provided at this tier.

6. HYDROGEN PROSPECTING INSTRUMENTS

Three CRUX instruments provide primary data to characterize hydrogen in the lunar regolith scenario.

SNeuP

The SNeuP neutron spectrometer is a remote sensing tool for locating hydrogenous materials by detecting a large decrease (up to nearly two orders of magnitude) of the epithermal neutron leakage flux. This flux develops as high-energy neutrons, created from galactic comic ray impingement on lunar or planet surfaces with a thin or nonexistent atmosphere, lose energy either by elastically or inelastically scattering in the planetary material or are absorbed by neutron capture reactions.

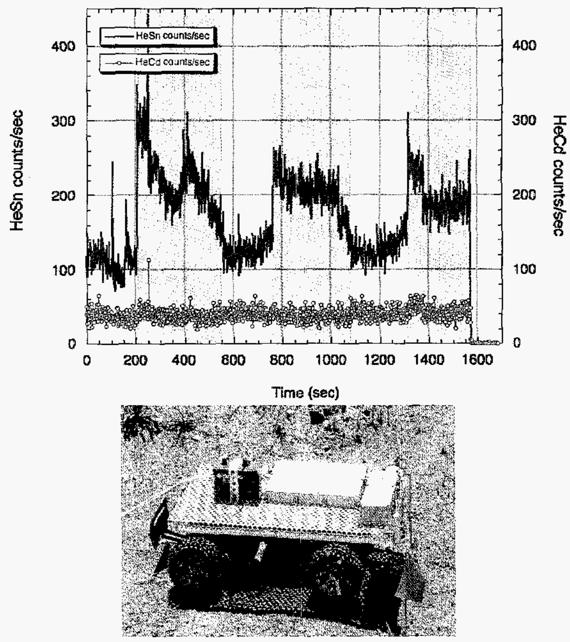

Figure 3. HYDRA field test data taken during a traverse over three buried polyethylene slabs (green bars) The mini-rover carrying HYDRA modules is shown below the data graph.

For terrestrial field testing, a neutron source is used to provide a signal for the HYDRA detectors because galactic cosmic rays do not reach the Earth's surface. Figure 3 shows data from a mini-rover traverse over three buried polyethylene sheets (a proxy for water ice) using an RTG-like neutron source; enhancements in thermal counting rate (blue) are very pronounced over the buried polyethylene "ice" slabs (light green). Other count rate variations are due to variable soil water content and variable soil cover thickness. We have performed a number of field tests that demonstrated HYDRA's functionality and sensitivity to buried hydrogenous materials. HYDRA has also been temperature tested from -40° to +40° C with no degradation of performance.

The instrument is currently under development through a NASA Mars Instrument Development Program (MIDP) grant as the HYDRA Neutron Spectrometer, with one system fabricated and tested, and a second in development. SNeuP is sensitive to hydrogenous material abundances of less than 1 wt% within about 70 cm of the surface over a target surface footprint size of ~1 m diameter, if cosmic rays are the primary neutron-generating source. SNeuP's heritage includes the Lunar Prospector neutron spectrometer, programmatic neutron detectors for treaty monitoring, and the Mars Odyssey neutron spectrometer.

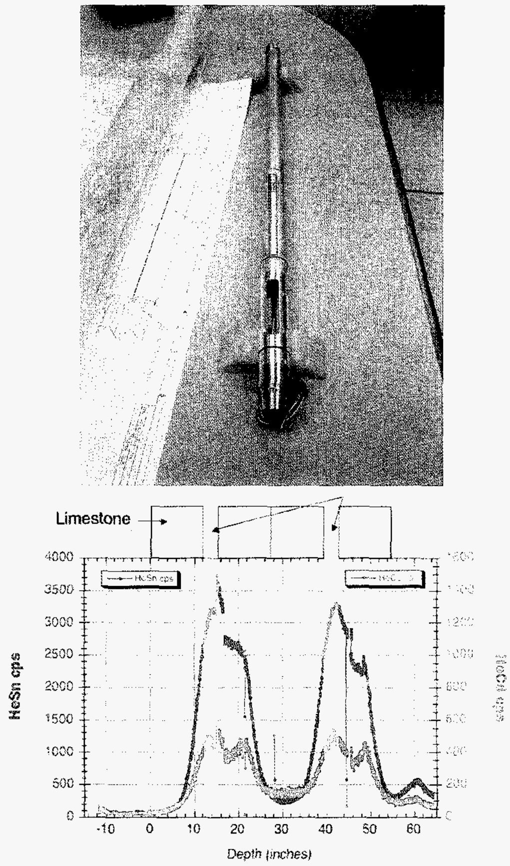

Figure 4. BNeuP/D-HYDRA drill-integrated neutron spectrometer (top) and test data for traverse of a two-meter borehole in limestone (bottom). A drawing of the test configuration is shown above the test data–dry limestone blocks separated by polyethylene 'water ice' proxy.

BNeuP

The BNeuP is currently the only Prospector instrument integrated into the drill system, as shown in Figure 4. The BNeuP is a mature drill-integrated neutron spectrometer borehole/well-logging tool for locating hydrogenous materials. It is sensitive to such materials within about 10 m of the surface, if cosmic rays are the primary neutron-generating source. The BNeuP (also referred to as D-HYDRA), is currently under development in partnership with Honeybee Robotics under a NASA MIDP with one system fabricated and under test. Its heritage includes the heritage of the SNeuP/ HYDRA.

TEGA

The primary direct measure of regolith volatile properties is the combination of the SAS sample acquisition and delivery system and the TA The TA receives the sample from the SAS and applies a controlled sample heating volatilize minerals and elements for analysis by the evolved gas analyzer (EGA). The combined TA and EGA is referred to as the TEGA. The TEGA instrument is a thermal and evolved-gas analyzer. It was originally flown on the 1998 Mars Polar Lander Mission [10], which failed to land successfully. It is being rebuilt, with substantial changes, for the Phoenix lander mission, which is scheduled to launch in August, 2005 and to land near the north pole of Mars in 2008.

The TA for the TEGA was designed to receive crushed samples from a scoop, but for CRUX it will be redesigned to receive samples from a drill. Depending on the nature of the drill, the interface might be very different from the Phoenix lander design. The TEGA ovens are very small with inside dimensions of about 2.4 mm diameter and 8 mm long (Figure 5). The male half, which contains the sample, is inserted into the female half, which contains the heater and temperature sensor. This design will be changed as ongoing design discussions and trade studies dictate.

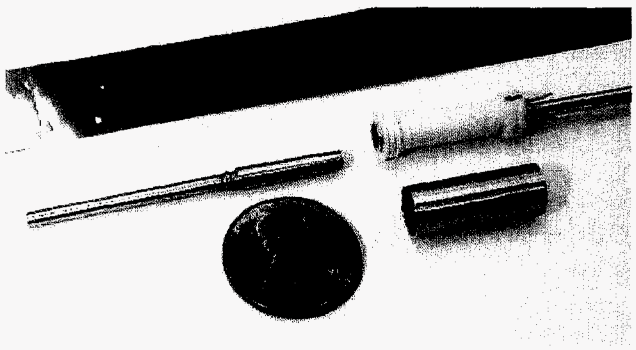

Figure 5. TEGA TA oven, which is delivered to the planetary surface in two halves. The small tapered male half receives the sample and is then inserted into the female half making a seal with the tapered joint. The female half contains the heater and temperature sensor.

As the sample is heated, various gases are evolved depending on the nature of the sample. These gases are passed on to an evolved-gas analyzer (EGA), which determines the nature of the gases that are evolved. The evolved gas is carried to the EGA with a stream of high-purity nitrogen. In the case of the Mars TEGA, the EGA is a magnetic-sector mass spectrometer, which can determine both the quantity of the evolved gas and its isotopic composition. The previously constructed Mars Polar Lander TEGA used tunable diode lasers to identify the quantity and composition of evolved gases (Boynton et al., 2001).

Evolved gas analysis can be conducted using either mass spectrometry or tunable diode laser technology. Mass spectrometry has the advantage of being able to detect lower concentrations and requiring fewer gas molecules to conduct analyses.

For an application to measure the lunar regolith, especially in the cold permanently shaded polar regions, TEGA is useful for its ability to determine the amount of ice, volatile hydrocarbons, and other minerals that may be present. It can detect ice, either calorimetrically as shown in Figure 6, or by seeing a release of H2O detected in the EGA at a temperature near 0 deg C. It can detect the presence of organic compounds based on the mass spectrum of the evolved gases in the EGA.

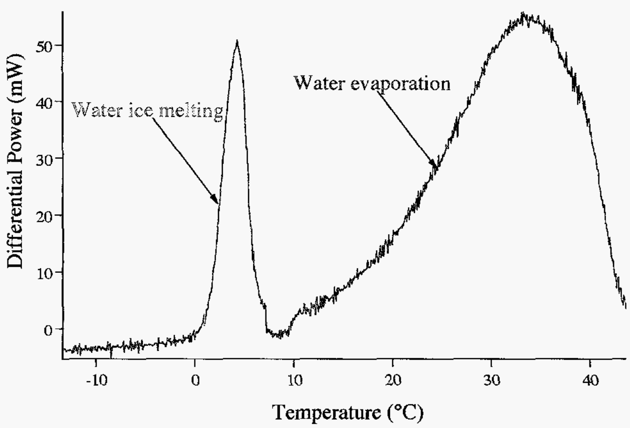

Figure 6. Calorimeter output for ice upon heating. The first peak represents the melting of the ice and the second represents the vaporization of the resulting water. The area of the peak is equal to the heat of the phase change. For ice this heat is well known, and can be used to determine the amount of ice present.

Specific design for the SAS sample acquisition system and the TA sample receiving system will be formulated through trade studies to determine the influence of drilling and regolith handling on retained volatiles in the regolith. If too much energy is imparted into the regolith, water ice or adsorbed solar wind hydrogen may be volatilized reducing the accuracy of the measurement and/or producing explosive release of the volatilized substance. Theoretical and experimental studies are being conducted to determine and predict the fate of retained volatiles in the regolith to allow development of designs for sample acquisition and to set drilling protocols. Preliminary results indicate that keeping volatile temperatures below 150K should prevent significant loss of volatiles during drilling and sample transfer.

7. Decision Support Products and Process

The delivered products from Mapper/DSS will be a series of science-based engineering guidelines and data interpretation protocols implemented in software. These guidelines will be driven by engineering scenarios developed as needed by astronauts and engineers. The present example to accurately evaluate if hydrogen detected by neutron spectrometers is solar wind hydrogen or water ice requires direct measurement by a TEGA-like device. Measurments from the TEGA can then be used through data fusion processes to more accurately interpret the spectrometer data. Some of the derived and 'fused' pieces of information are:

- Water/hydrogen regolith volume concentration
- Water/hydrogen distribution as a function of depth
- Water/hydrogen spatial location (3D distribution)
- Water/hydrogen stratigraphy
- Quantity of water/hydrogen volatilized by regolith disturbance through drilling and/or engineering recovery operations
- Ratio of water to hydrogen in the regolith

These types of information are developed from the comprehensive set of data acquired by the CRUX instrument suite, and listed in Table 1.

Table 1. CRUX Measurements for Hydrogen Characterization (partial secondary instrument list)

Instrument	Measurement / Data	Derived Data / Related Instrument
Primary for hydrogen scenario		
SAS (drill)	depth, torque, drill rate, temperature rise	*SHS*
SHS	depth, volume, sample temperature	*TEGA, SAS*
BNeuP	neutron energy flux spectrum, volume pattern, depth	hydrogen concentration *SNeuP, TEGA*
TEGA	temperature rate, heating curve, depth, mass spectrum or absorption spectrum, sample volume	phase change, molecular species, concentration *BNeuP, SNeuP*
SNeuP	neutron energy flux spectrum, location, measurement volume	hydrogen concentration *BNeuP, TEGA*
Secondary for hydrogen scenario		
EPP	depth, electrical conductivity measurement volume	dielectric constant, ice content *GPR, BNeuP, TEGA*
TCDP	depth, temperature time history	thermal conductivity, diffusivity *BNeuP, SHS*
DCAM	depth, color	grain-size, water distribution *BNeuP, SHS*
GPR	Layer depth, location, measurement volume	Dielectric properties *EPP, SHS, SAS*

The data fusion objective for the integrated CRUX system implies requirements during both instrument and Mapper/DSS development. It also requires the development of analysis models, that tie together the information in Table 1 for example. For example, following the list of data products above, the analysis models need to include, among others

(a) ratio calculations of water and hydrogen and distribution calculations for those species to match concentration with depth with total concentration,
(b) matching EPP from the drill hole with GPR to correlate depth with GPR travel time returns,
(c) matching GPR depths with estimated depths of hydrogen and water to determine to determine local suitability fo using GPR depths to recalculate hydrogen/water maps.

Equally, the design of the DSS tool displays needs to be tailored to the expected applications. Some examples of operationally useful displays include

(a) surface map of hydrogen from SNeuP,
(b) GPR profile of depth to layers versus position,
(c) selectable borehole plots of EPP, TCDP, TEGA, BNeuP data as function of depth, which should be overlain on SNeuP and GPR data to provide contextual information,
(d) interpreted display of the 3D distribution of a selected resource (water or hydrogen), with a function that allows comparison of 3D distributions of different resources

As previously stated we envision that the tools in the Mapper/DSS can be the basis for semi-autonomous LPSO, or human-directed LPSO with astronauts using the tools in the lunar environment.

8. OUTLOOK

The CRUX architecture will be an enabling technology for LPSO with benefit to future solar system exploration. The central Mapper-DSS subscribes to lunar and planetary data from CRUX Prospector/Surveyor instruments, and other historical or near real-time data sources. The Mapper stores, fuses, interprets and displays data layers. The DSS creates and displays data products derived from model analysis, analytical data interpretation, and intelligent data mining to facilitate the planning and conduct of LPSO. CRUX instrument operations can be semi-autonomous and interactions will be in near real-time to facilitate LPSO support. This combination of regolith property data

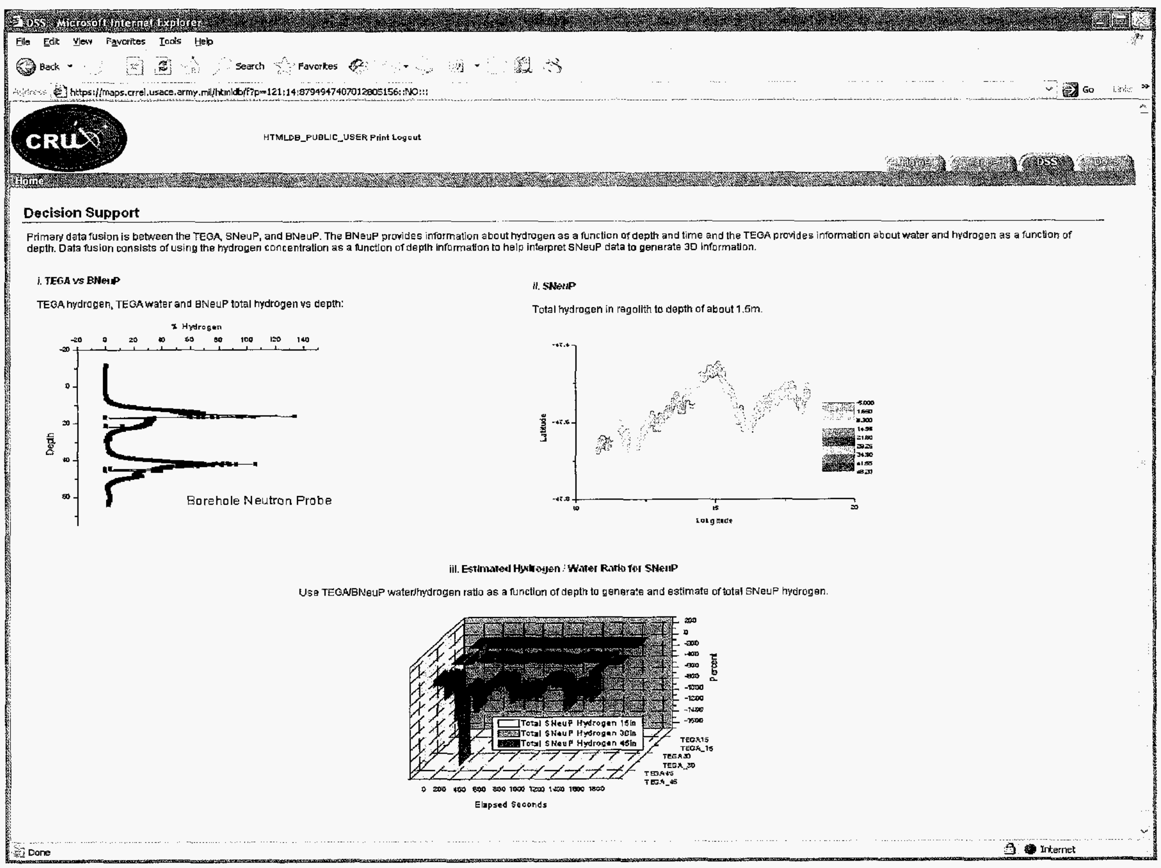

Figure 7. Example display showing DSS support using data fusion between SNeuP, BNeuP, and TEGA measurements to derive water/solar wind hydrogen ratios and using that information to interpret SNeuP data to estimate regional water and solar wind hydrogen distribution.

measurement, data fusion methods, DSS tools, and display functions provide a robust decision support system in which location-referenced raw and interpreted data from the CRUX instrument suite, along with other (e.g., lunar satellite) data, can be rapidly visualized, updated, and communicated to guide further site investigations or LPSO activities, or to plan future LPSO activities.

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BIOGRAPHY

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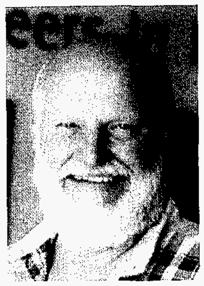
Jerry Johnson *is the CRUX Principal Investigator. He has been a research geophysicist for 27 years, and works at the U.S. Army Corps of Engineers Engineering Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL), based in Fort Wainwright, Alaska. He is specialized in the physical and mechanical properties of snow, ice, permafrost and granular media, with experience in instrument development (he holds 3 instrumet patents). He obtained his Ph.D. in 1978 from the University of Washington, and has worked on geophysical problems of shock waves, penetration mechanics, physical and mechanical properties, and metamorphism of snow and granular media, with applications on Earth and also on Mars.*

Rick Elphic *is a CRUX Co-Investigator, and is responsible*

for the Surface and Borehole Neutron Probe instruments (SNeuP and BNeuP) for CRUX. His specialty is nuclear remote sensing in planetary science with experience from Lunar Prospector, Mars Odyssey, and with NASA's Mars Instrument Development Program. Rick received his Ph.D from UCLA in 1982 and now works at the Los Alamos National Laboratory.

Bill Boynton *is a CRUX Co-Investigator, and is responsible*



for the Thermal Analyzer instrument for CRUX. He has been a Professor at the University of Arizona for 28 years in the Department of Planetary Sciences. Bill obtained his Ph.D. from Carnegie-Mellon University, and since then has specialized in studies of volatile compounds in the Solar System, notably water and carbon dioxide on Mars. He has been the PI for four instruments on NASA spacecraft: Mars Observer, Mars Polar Lander, Mars Odyssey, and Phoenix Polar Lander.

John Wetzel *is the CRUX project system engineer. He is a*

senior engineer with Applied Research Associates, Inc. providing support to ERDC-CRREL for the CRUX project. His experience includes robotic mine detection and neutralization system development, integration and management; robotic mine countermeasure system integration of six subsystems; and International Space Station dynamic analysis for the microgravity environment.

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