WORKSHOP ON EARLY ROBOTIC MISSIONS TO THE MOON

Lunar and Planetary Institute

Houston, Texas

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TO: Distribution

FROM: X/Associate Administrator for Exploration

SUBJECT: Lunar Planetary Institute Workshop

The attached report from the Lunar and Planetary Institute (LPI) is the result of a three day workshop that was conducted at the request of the NASA Headquarter's Office of Exploration. We are making the widest possible distribution of this report to allow all interested parties to keep abreast of the thinking going into our evolving exploration program. This report will form the basis from which we will be making instrument selections for our proposed orbital precursor missions and ultimately will drive the requirements placed on the bus we will be selecting for these missions.

On behalf of the Office of Exploration, I would like to take this opportunity to again thank everyone who was involved in making this workshop a success and in particular, Dr. David C. Black and the entire LPI staff, the members of the workshop, and all of those who took the time to submit papers for this most important gathering.

As the exploration matures we look forward to meeting with and exchanging ideas with as many members of the community as possible. We will do our best to keep everyone up to date with our evolving plans.

Michael D. Griffin
Office of Exploration

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EXECUTIVE SUMMARY

The purpose of the Workshop on Early Robotic Missions to the Moon, held at the Lunar and Planetary Institute on February 4-6, 1992, was to provide an assessment of instruments that might be candidates for flight as part of NASA's Office of Exploration (Code X) early unmanned missions to the Moon. The focus of the assessment was mainly scientific, that is, an evaluation of the candidate instruments from the perspective of the scientific relevance and quality of the data set that they would return if they were flown as part of a Code X flight program. However, we also reviewed instruments from the perspectives of resource exploration, processing and observational studies from the lunar surface.

Instruments were also associated as much as possible with one of the four Code X themes of lunar robotic missions. Those themes are (in no priority order): resources, terrain, gravity, and lander missions. The term "terrain" here implies both topography (altimetry) and surface morphology (imaging). Orbital payloads were also categorized according to the prioritized list of global data sets and measurement requirements that have been established by the Lunar Exploration Science Working Group (LExSWG), a standing advisory group to the Solar System Exploration Division of NASA's Office of Science and Applications (OSSA). A comparable list for landed science payloads does not currently exist, but is under development by the LExSWG.

Instruments were also evaluated from the perspective of their maturity. Each instrument was reviewed to determine whether it was a paper concept, breadboard, some flight hardware, or an "off the shelf" instrument. Additionally, the workshop attempted to identify specific concerns or issues that each instrument faces in order to meet a launch date in early CY 1995. **It cannot be overstressed that for any instruments to be ready in this time frame, it is imperative that instrument selection be made and development begun as rapidly as possible.**

It was the concensus of the Workshop that the missions currently envisioned by the Office of Exploration offer the opportunity to do outstanding science, and that there are high-quality instruments which could be flown within three years. It was also the feeling of the Workshop that while landed science instruments are in general less mature than are orbital science instruments, there are numerous quality instruments that could be flown on the baseline common lunar lander concept (ARTEMIS).

While the focus of the Workshop was on an overall assessment of the proposed instruments, there were a number of ancillary conclusions and associated recommendations that were reached. Those are summarized here.

The Workshop reached a clear consensus that the missions currently being envisioned by the Office of Exploration offer the opportunity to do first-rate scientific research, and that there are available, or soon could be available, instruments which would ensure that the opportunity was realized.

The Workshop also concluded that as a consequence of the lack of any lunar focus to the space program over the past decade and a half, the queue of instruments that could be flown quickly would also empty quickly. If any form of continuing program of lunar exploration is envisioned, the Workshop recommends that the Office of Exploration take steps, perhaps in concert with other Offices within NASA, to initiate a healthy instrument development program for use in lunar exploration.

Regarding the specific mission opportunities that are being considered by the Office of Exploration, that is, two orbital missions and one landed mission, the Workshop recommends the following:

Orbital Mission 1

A gamma-ray/neutron spectrometer with a germanium detector (if development concerns arise regarding this detector, we recommend use of a NaI detector with subsequent flight of a germanium system). A soft X-ray fluoresence instrument of the type to be flown on the ALEXIS spacecraft. A visible-infrared imaging spectrometer, with the first choice being the LUMIS- or MINMAP-type system. However, the Workshop recognizes that there may be a problem with development of LUMIS or MINMAP for a 1995 launch. Should that be the case, a multispectral imager (CompMap) could be used on the first mission. As with the germanium detector, we would urge that a LUMIS- or MINMAP-equivalent be flown later even if is necessary to fly CompMap early in the program.

Orbital Mission 2

A laser altimeter. A number of quality laser systems were proposed at the Workshop, and the selection appears to rest mainly on engineering issues. The same can be said for a gravity experiment, which the Workshop endorses for this mission. Gravity proposals for global coverage require two spacecraft, and various orbital geometries were advanced. An imaging camera is recommended for this mission as well. The synergy between altimetry, gravity and imaging is strong. The highest rated imaging system considered by the Workshop was that submitted by JPL, with the Malin and Mercator concepts close behind and tied for second rating.

Landed Mission

Mobility, at least for these early missions, is strongly recommended, and the Workshop was impressed with the apparent capabilities of rovers (such as that proposed by JPL) to accomplish this. The instruments that we recommend are an alpha-proton backscatter spectrometer, a Mossbauer backscatter spectrometer, and stereo and high-resolution cameras. If resources on the rovers permit, other instruments, such as an evolved gas analyzer, should be added.

I. INTRODUCTION AND BACKGROUND

The purpose of the Workshop on Early Robotic Missions to the Moon, held at the Lunar and Planetary Institute on February 4-6, 1992, was to provide an assessment of instruments that might be candidates for flight as part of NASA's Office of Exploration (Code X) early unmanned missions to the Moon. The focus of the assessment was mainly scientific, that is, an evaluation of the candidate instruments from the perspective of the scientific relevance and quality of the data set that they would return if they were flown as part of a Code X flight program. However, we also reviewed instruments from the perspective of resource exploration and processing, along with observations from the lunar surface.

Instruments were also identified as much as possible with one of the four Code X themes of lunar robotic missions. Those themes are (in no priority order): resources, terrain, gravity, and lander missions. The term "terrain" here implies both topography (altimetry) and surface morphology (imaging). Orbital payloads were also categorized according to the prioritized list of global data sets that has been established by the Lunar Exploration Science Working Group (LExSWG), a standing advisory group to the Solar System Exploration Division of NASA's Office of Science and Applications (OSSA). A comparable list for landed science does not currently exist, but is under development by the LExSWG.

Instruments were also evaluated from the perspective of their maturity. Each instrument was reviewed to determine whether it was a paper concept, breadboard, some flight hardware, or an "off the shelf" instrument. Additionally, the workshop attempted to identify specific concerns or issues that each instrument faces in order to meet a launch in early CY 1995.

The Workshop examined whether there were synergies between data sets that could be obtained with various instruments. This included synergy between landed instrument data sets and orbital instrument data sets, as well as synergies among landed and orbital data sets.

Candidate lander payloads were assessed from the following additional perspectives (provided by the Exploration Program Office):

Do they need to get off of the lander?

Do they need access to "pristine" samples (i.e., uncontaminated by lander exhaust gases)?

Do they need mobility, and if so, do they need power and communications associated with that mobility?

Do they operate only in daytime, and if so, must they arrive at the start of lunar day or can they survive lunar night?

These additional perspectives were used to provide input to the Exploration Program Office at the Johnson Space Center and were not used in the mission-related recommendations which appear in Section IV of this Report.

The schedule for the Workshop was extremely tight. Formal announcement of the Workshop occurred in early December 1991, with the deadline for proposed concepts being January 10, 1992. The Workshop was advertised through an existing and well-worn network of individuals who have a long-standing interest in lunar science. It was also advertised via an announcement in the Commerce Business Daily. Sixty instrument or mission concept proposals were received and considered by the Workshop. The instruments were roughly equally divided between orbital and landed operation. The strength of the response for landed operation is both surprising and encouraging, as there has been only modest thought given to landed payloads in recent years (in contrast with the situation for orbital payloads).

Proposed concepts were circulated to Workshop members in advance of the meeting, with each member being assigned specific concepts to advocate at the meeting. The function of the advocate was to review a given concept, interact with technical consultants associated with that concept, and then present a summary of the concept in the context of the perspectives which were the focus of the Workshop. This approach was taken in an effort to create a relatively "level playing field" for the concepts.

A discussion of the orbital payloads is given in Section II, followed by a similar discussion for landed payloads in Section III. The major conclusions and recommendations of the Workshop are set forward in Section IV.

II. ORBITAL PAYLOADS

General Remarks

The LExSWG has spent considerable time in developing a prioritized list of global data sets that are desired from lunar orbital missions. Associated with each of these data sets are specific quantitative measurement requirements. The data sets and associated requirements are presented in priority order in Table 1, along with comparisons of the performance for each data set from the Apollo program or from Earth-based studies. The existence of this thoughtful list was very significant as it is deeply rooted in the traditional science advisory process of NASA's scientific programs, including input from the National Research Council's Committee on Planetary and Lunar Exploration, and as such has a strong pedigree.

The Workshop used the LExSWG data set and measurement requirements as the basis for assessing the scientific merit of the data products for each of the proposed concepts. Specifically, each candidate is rated relative to the LExSWG requirement according to whether it "Exceeds", "Meets", or is "Below" that requirement. Some of the engineering requirements/attributes associated with each instrument concept (e.g., mass, power, data rates) are also discussed, although it should be borne in mind that the degree of certainty on these numbers varies significantly between existing flight packages and paper concepts.

Assessment of Specific Instrument Concepts

The thirty orbital instrument concepts that were reviewed by the Workshop are summarized in Table 2. It is noteworthy that there are excellent candidate instruments from the perspective of the value of their data sets to the thematic emphasis of the Office of Exploration as well as to the high priority scientific objectives for the study of the Moon as set out by the Office of Space Science and Applications. We return to this in Section IV.

TABLE 1: LUNAR EXPLORATION SCIENCE WORKING GROUP DATA SET REQUIREMENTS

Priority	Measurement	Apollo/Earth-Based (*) Data	Requirement
1	Surface Composition (Elemental)		
	Geographic Coverage	~22% Global	Global
	Ground Resolution	~100 km	$\leq$ 100 km
	Measurement Accuracy	$\pm$ 20%	$\leq$ 20%
2	Topography and Gravity		
	Topography		
	Geographic Coverage	10%	Global
	Ground Resolution	$\geq$ 1 km	$\leq$ 1 km
	Measurement Accuracy	$\geq$ 100 m	$\leq \pm$ 10 m vertical
	Gravity Field		
	Geographic Coverage	45%	Global
	Ground Resolution	$\geq$ 100 km (80% $\geq$ 200)	$\leq$ 100 km
	Measurement Accuracy	$\pm$ 2 mgal	$\pm$ 1mgal
3	Surface Composition (Mineralogical)		
	Geographic Coverage	Landing Sites Only, Nearside*	Global
	Ground Resolution	5-10 km (*)	<500m
	Spectral Coverage		0.3 to 2.4 m, 4 to >30 m
	Measurement Accuracy	$\pm$ 0.5%	$\leq$ 0.5% (Instrument) $\pm$ 5% (Mineral Abundance)

Priority	Measurement	Apollo/Earth-Based (*) Data	Requirement
4	Surface Imagery		
	Geographic Coverage	Apollo 8% Lunar Orbiter 99% Telescope (*) 55%	Global
	Ground Resolution	Apollo 2-10 m Lun.Orb.-nearside 100m Lun.Orb.-farside 300m	15±5 m/pixel
	Positional Accuracy	Telescopic 500m - 3 km Apollo 50-300 m Lun.Orb.-farside 3 - 15 km Telescopic 1 - 3 km	100 - 300 m
5	Vector Magnetic Field (Induced Dipole, Surface)		
	Geographic Coverage	<8% Global	Global
	Ground Resolution	100 km	Features ≤30 km
	Measurement Accuracy	± 0.1 nT	± 0.1 nT
6	Atmospheric/Ionosphere		
	Geographic Coverage	<20% Global	Global
	Ground Resolution	N/A	≤100 km(30-100km)
	Sensitivity	$\sim 10^{11}$ cm^{-2}	10^{7-8} cm^{-2}
	Measurement Accuracy		± 10%
	Measurement Types		Comp. Neutral and Ion) Source/Sink Rates (N-I) P, T, Density (N-I)
7	Surface Thermal Properties/Heat Flow		
	Geographic Coverage	Two Landing Sites (*)	Global
	Ground Resolution		≤ 100 km
	Measurement Accuracy		0.5 K, ≤ ±4mW/m^2

TABLE 2. WORKSHOP CHARACTERIZATION OF ORBITAL INSTRUMENTS

Instrument [1]	Code X Theme/LEXSWG Priority	Performance[2]	Maturity	Development Issues
X-ray Fluorescence Imager (LANL)	Resources/1	Sensitivity: exceeds Spatial Res: exceeds	Flight Approved Components	No Issues Apparent
Gamma-Ray Neutron Spectrometer (LANL)	Resources/1	Sensitivity: meets Hardware	Some Flight	System Integration and test with active cooler
Secondary Ion Mass Spectrometer (LANL)	Resources/1	Sensitivity: meets Spatial Res: below	Derivative of existing flight hardware	No hardware issues, but an extensive testing and validation process technique
Gamma-Ray Spectrometer (Martin)	Resources/1	Sensitivity: meets Spectral Res: below	Modify Mars Observor Inst.	Passive Cooler
Topography and Gravity (Martin)	Terrain,Gravity/2	Topography: exceeds Gravity: N/M	Modified Mars Observer Inst.	Proposed laser less mature than MO system; telescope redesign
Near IR Spectrometer (Martin)	Resources/3	Spectral Coverage: meets Spatial Coverage: below	Concept	Technology is mature. Possible major concern re: system integ. & perform.
COMPMAP (Brown Univ)	Resources/3	Spectral: below Spatial: exceeds	Relatively mature	No major issues apparent
GEOMAP (Brown Univ)	Terrain/2	Spatial Res: below Coverage: meets	Breadboard	No major issues apparent
MINMAP (Brown Univ.)	Resources/3	Spatial: meets Spectral: meets	Advanced prototype (similar to Cassini)	Detector cooling & alignment - need study

1 Proposing Institution given in parenthesis
2 Performance relative to LEXSWG requirements

TABLE 2. WORKSHOP CHARACTERIZATION OF ORBITAL INSTRUMENTS

Instrument [1]	Code X Theme/LEXSWG Priority	Performance[2]	Maturity	Development Issues
LUMIS (Ball,Wash.U)	Resources/3	Spatial: exceeds Spectral: meets	Advanced prototype (soon to fly on airplane)	Detector cooling & alignment - need study
TES (ASU-Hughes)	Resources/3	Spatial: below Spectral: meets	Version on Mars Observer	No Major Issues Apparent
MERCATOR (LPI-Ball)	Terrain/2	Spatial Res: meets Coverage: meets	Flight components and test needed	System integration
Lunar Mapping (Malin's)	Terrain/2	Meets Reqs.	Some flight Components	System Integration & Test
Digicon Imager (SAIC)	Terrain/2	Exceeds Req.	Flight Instrument Available	None (See "Maturity")
Magnetics/ Gravity Mapper (LPL)	Gravity/2	Below (Gravity) meets (Magnetics)	S-band link & magnetics have strong heritage	None
Terrain Mapper (JPL)	Gravity Terrain/2	Meets Grav. Exceeds Terrain	Strong heritage Mod. Existing Hardware	None
Resource Mapper (JPL)	Resources/3	Below spectral meets spatial	Advanced prototype	Design changes to meet spectral coverage
Si(Li)GRS (NASA/AMES)	Resources/1	Meets	Concept	Nothing specific, but low maturity level
Wide Angle Camera (APL)	Terrain/2	Below	Flight exper. in SDI program	None

1 Proposing Institution given in parenthesis
2 Performance relative to LEXSWG requirements

TABLE 2. WORKSHOP CHARACTERIZATION OF ORBITAL INSTRUMENTS

Instrument [1]	Code X Theme/LEXSWG Priority	Performance [2]	Maturity	Development Issues
Narrow angle Camera (APL)	Terrain/2	Exceeds	Flight Exper. in SDI program	None
Gravity from USO (APL)	Gravity/2	Meets	Modified MO inst.	Extent of modifications unclear
Near IR Spect. (APL)	Resources/3	Below	Modify flight hardware	Extensive modifications likely
Resource Ident. (McD)	Resources/1	Below	Concept	Concept too immature to evaluate
Lunar Scout Topo. mapper (GSFC)	Terrain/2	Exceeds	Modify MO Inst.	System integration for mods., not major issue.
Lunar Scout Gravity (GSFC)	Gravity/2	Meets	Some flight hardware	No major issues apparent
Laser Altimetry (McD)	Terrain/2	Exceeds	Modified MO Instrument	Insufficient Information to evaluate
GRS (GSFC)	Resources/1	Meets	Breadboard	Large (5-7 cm) HgI_2 crystal not yet produced
Low Freq. Radio Telescope (NMSU)	N/A	N/A	Breadboard	Dipole encoding & system integration
MEV (SWRI)	N/A/5	N/A	Strong heritage	No major issues apparent
GEV (SWRI)	N/A/5	N/A	Strong heritage	No major issues apparent

[1] Proposing Institution given in parenthesis
[2] Performance relative to LEXSWG requirements

III. LANDED PAYLOADS

General Remarks

There is at present no prioritized listing of data sets that would be expected from payloads landed on the lunar surface. Such a list is being developed, at least for planetary science objectives, by the LExSWG. Therefore, the Workshop was unable to assess a given landed instrument against specific performance requirements, as was done for orbital instruments.

An additional and significant diversity exists for proposals dealing with landed payloads; several of them dealt with resource characterization or utilization. While the Workshop possessed expertise in this area, there are no quantitative requirements of the type that have been developed by the LExSWG. Also, there were a small number of proposed instruments that capture the inherent strength of conducting astronomical studies from the Moon (this strength has been recognized in the recently released Astronomy Survey Committee Report by the National Academy of Science.

While there is no set of specific requirements for astronomical data sets, the Workshop was impressed with the quality and diversity of the proposals that were submitted. Demonstrating the capabilities of a lunar observatory and developing operational experience with telescopes in the lunar environment is important if we are to realize the long-term promise offered by observatories on the Moon. This class of payloads should be considered as strong candidates for future landed missions.

Discussions of landed payloads were carried out in the context of the proposed "common lunar lander", also known as ARTEMIS. A very brief presentation was given on the ARTEMIS concept at the Workshop, with the focus on delineating the capabilities that are currently being planned for the lander. There have been workshops earlier dealing with ARTEMIS, but it was clear at this workshop that the current design thinking regarding the lander was significantly different from that which most of the landed payload people had assumed.

Most significant in this sense were the payload and resource provisions once the lander was on the surface. The Workshop was told that the payload capability would be around 65 kilograms for the first lander, whereas most were anticipating a capability in the 200 kilogram category (that increased capability is being investigated for subsequent versions of the lander). Also, most payloads had assumed that the lander would provide a modest level of power and communications once landed, but the baseline for the prototype has no provisions for power or communications. This mismatch between expectations and current planning within the program is an area for further discussion (see Section IV for specific recommendations in this area). It did not, however, affect the Workshop's assessment of the various landed instruments that were under consideration.

Assessment of Specific Instrument Concepts

A summary of the Workshop assessments of the landed instrument concepts is presented in Table 3. It is apparent that while landed payloads in general lack the degree of maturity that is found for orbital payloads, there are nonetheless a wide and interesting range of concepts that offer the potential to be of great value scientifically as well as for the more practical resource-oriented aspects of exploring the Moon.

Table 3. Workshop Characterization of Landed Instruments

Instrument	Code X Theme	Maturity	Development Issues
Laser Induced Breakdown Spectroscopy (LANL)	Resources	Some Flight Components	System Integration and Calibration
X-Ray Fluorescence/X-Ray Diffraction (LANL)	Resources	Some Flight Components	System Ingegration
Magnetometer (U. of AZ)	N/A	Significant Flight Experience	None Apparent
Lunar Crater Explorer (Carnegie-Mellon U.)	N/A	Ground-based Systems Only	Concept is an Adaptation of One or More Ground-based Mobility Systems; Significant Work Needed to Fly
Mossbauer/X-Ray Fluorescence (JSC)	Resources	Working Prototype Available in 6 Months	Cooled Detectors for the XRF
Diffraction Tomography (ORNL)	Terrain	Acoustic System Well Tested on Ground	Radar Component Has No Flight Hardware
Radio Frequency Glow Discharge ORNL)	Resources	Prototype Exists	Major Effort Needed
Micro-Raman Spectrometer (ORNL)	Resources	Some Terrestrial Applications	No Flight Components
Integrated Regolith Analyzer (Martin)	Resources	Prototype Systems	Too Little Information to Assess
X-Ray Fluorescence Spectrometer (Martin)	Resources	Some Flight Heritage	Cooled Detector on Lander, and Rover System Integration
Lunar Traction and Drilling Test (Martin)	N/A	Drill Exists	Traction Data Already Exist. No Issue Concerning Drill
Spectral Analysis of Surface Waves (LGI)	Resources/ Terrain	Some Flight Hardware	Soundwave Source Needs to be Developed (Not a Major Concern)

Table 3. Workshop Characterization of Landed Instruments

Instrument	Code X Theme	Maturity	Development Issues
Geophysical Station Network (Rice U.)	Resources/ Terrain	Individual Instruments Space Qualified	Minor at Instrument Level. Some System Integration Issues on Artemis
Sample Return (U. Houston)	Resources	Proposal Too Vague to Assess	Proposal to Vague to Assess
Moon-Earth Radio Interferometer (NMSU)	N/A	Concept Mature	No Specific Hardware Available
LUTE (Ultraviolet Telescope) (U. of AZ)	N/A	Functioning Ground Prototype	Meter-Class Beryllium or Light-Weight Mirror (1997 Earliest Flight)
Small Lunar Optical Telescope (Ames)	N/A	Concept	Defined by Further Studies
Solar Flare Forecasting Experiment (NSO)	N/A	Flight Components	System Integration, but Nothing Major Noted
Surface Magnetometer (APL)	N/A	Technically Mature	System Integration with Artemis or Mobility System
Volatile Gas Analysis System (Lamar U.)	Resources	Lab. Prototype	No Flight Qualified Components and Integration
Cosmic Ray Dose In Regolith (JSC)	N/A	Concept at System Level	The Workshop Felt that the Relevant Data Already Exist and that There is no Need to Conduct this Experiment
Lunar Resource Rover (JPL)	Resources	Rovers at Prototype Test	Integration of Rover with Artemis
Geotechnical Probe (LGI)	N/A	Concept	Data Not Needed; Provided by Apollo
Dust on High-Voltage Systems (Lewis)	N/A	Shuttle Flight Upcoming	Much of Data Already Avaliable
Lunar Oxygen Demonstration (Carbotek)	Resources	Proven Laboratory Concept	No Flight Hardware

Table 3. Workshop Characterization of Landed Instruments

Instrument	Code X Theme	Maturity	Development Issues
Oxygen Production (SERC)	Resources	Full-Scale Prototype Being Constructed	No Flight Hardware
Concentrated Solar Flux (MACDAC)	N/A	Concept	Too Early to Characterize
Power Beaming Demonstration (U. Houston)	N/A	Mature Concept; No Flight Hardware	Requires Two Landers Separated by at Least 100 km
Alpha Backscatter (APL)	N/A	Mature Concept	Flown on Surveyor; System Integration and Hardware for New Model Needed

IV. CONCLUSIONS AND RECOMMENDATIONS

General Conclusions and Recommendations

It was the consensus of the Workshop that the missions currently envisioned by the Office of Exploration offer the opportunity to do outstanding science, and that there are high-quality instruments which could be flown within three years. It was also the feeling of the Workshop that while landed science instruments are in general at a less mature state of development than are orbital science instruments, there are several quality instruments that could be flown on the baseline common lunar lander concept (ARTEMIS).

The Workshop noted that appropriate flight-ready, new generation instruments are not immediately available, and some of the more promising instruments that were reviewed, while not new in concept, are still at the advanced concept testing and bread-board stages. This reflects the fact that relatively little lunar instrument development has gone on over the past decade and a half. Thus, most of the state-of-the-art instruments that were reviewed at the Workshop were developed for non-lunar missions, or their components have been qualified for space flight in other contexts. We are confident that the suite of instruments that we recommend here can be flown within three years, as long as prompt and adequate funding is made available to the instrument teams. As a corollary to this, we strongly recommend that Code X take the lead in establishing a flight instrument development program.

This situation is present not just in the science oriented payloads, but in the resource-oriented payloads that were reviewed at the Workshop. Some of these latter payloads were considered to be potentially quite useful to achieving the goals of a permanent presence on the Moon. The maturity of the proposed resource processing concepts as a class is not currently as high as many of the proposed science instruments. With the exception of the carbothermal reduction process for oxygen production, none are in flight hardware design stage.

The hydrogen reduction experiments are relatively mature having been demonstrated on lunar samples, but none of the proposed landed instrument concepts involve flight hardware. The acoustic sub-surface regolith mapper would provide considerable science information as well as engineering information, and it has a solid history in terrestrial use. Again, no flight hardware is available.

As is the case with science instruments, there is a critical need for NASA to initiate a resource instrument development activity. Resource instruments could be flown in a timeframe following the more mature science instruments, provided that instrument development starts soon.

The Workshop concluded that the present ARTEMIS concept requires some additional interaction between the design engineering team and potential users of the lander. The absence of power and communications on the lander were the major points of concern, as was the payload mass. One of the issues is whether it is more economical to have the instrument builders provide for power and communications, or have those resources available on the lander. We recommend that this issue be explored more.

The Workshop identified a very strong need for mobility associated with early landed science missions. While not choosing a specific mode of mobility, it was clear that the JPL mini-rover concept is relatively mature and does address most of the mobility needs for early lunar surface exploration. Whether other rover concepts, or other engineering solutions to the fundamental requirement for mobility, are developed is something that we would urge Code X to examine.

We note that many of the instrument concepts make use of state-of-the-art microprocessors to simplify their design, or to reduce data rates. If these microprocessors cannot be qualified for space flight, some instruments may not be able to fly, or substantial costs will be incurred to re-program/design for old technology microprocessors. As an example, several CRAF/Cassini investigators tried to get an 80386 qualified for deep space but were not able to do so. The project-approved microprocessor is a 1750A, for which the software development tools are crude by current standards. The Workshop therefore strongly urges Code X to take positive steps to assure that capable and up to date technology can be qualified for flight in the context of its early missions to the Moon. Such a posture would be in keeping with the Office's efforts to do things in new ways.

An aspect of landed instruments that became clear during the Workshop is that there is a significant number of non-planetary payloads, most notably payloads associated with astronomical studies. While the Workshop had some expertise in these areas, it was limited relative to that present from the planetary science community. Further, it was evident that a far larger response from other science disciplines would have occurred had there been more time for them to respond. This leads to the recommendation that Code X initiate a more thorough outreach to these other disciplines, in the same manner as was done in this Workshop, to assess instruments that individuals in those disciplines might wish to propose. This outreach can and should be well-coordinated with the relevant Divisions within Code S.

Conclusions and Recommendations regarding Missions

Three instruments proposed during this workshop, working in combination (but not necessarily on the same orbiter), can provide global maps of chemical and mineralogical information that should serve as an adequate base for the above purposes and for additional studies for the indefinite future. We believe that given adequate and timely resources, flight-ready versions of these instruments can be developed to meet the proposed launch schedules. Also, the combined mass, power, data-rate requirements for these instruments are reasonable for orbiters of modest capacity. The instruments are the following:

A gamma-ray/neutron spectrometer **with a germanium detector**. Such an instrument would provide analyses with sufficient accuracy over the entire Moon with a low-resolution footprint. This type of instrument is the only one that senses chemical composition to depths greater than several microns. The scientific return from this type of instrument is very high, but the Workshop notes that there may be some development issues associated with the detector. Should these turn out to preclude the availability of the instrument in time for a 1995 launch, we would recommend flight of a similar instrument using a NaI detector. Such an instrument would provide valuable data, particularly given global coverage, but the data provided by the higher spectral-resolution Ge detector would still be needed.

A soft X-ray fluorescence instrument. The proposed instrument uses detectors of the type to be flown imminently on the ALEXIS spacecraft, and it can provide accurate data for all of the major elements and with high spatial resolution. This instrument would yield far more definitive constraints on ideas about regolith characteristics, origin, and evolution than was thought possible from an orbital mission until very recently.

A visible to near-infrared imaging spectrometer. Data from the gamma-ray/neutron and soft X-ray instruments provide elemental abundances. However, those instruments cannot of themselves provide definitive information on the kinds and compositions of the minerals that are currently in the rocks and soils. That type of information is provided by an instrument such as a visible/near-infrared spectrometer (e.g., LUMIS or MINMAP). Visible and near-IR systems provide compositional information at the highest spatial resolution. While a visible/near-IR system is of high priority from a scientific perspective, there is some concern regarding whether a system can be flight ready by 1995. An alternative type of instrument, which returns a more limited, but still valuable, range of data is a multispectral imaging system (such as CompMap) that produces co-registered images. There is little question that such an instrument could be ready for a 1995 flight. One of these types of instruments should be a part of the first orbital mission.

The choice between these types of systems is a matter of technical readiness; fly a visible/near-IR imaging spectrometer if it can be ready, and fly a CompMap-type instrument if it cannot be ready. If a CompMap-type instrument were flown, data provided by the higher spectral resolution LUMIS- or MINMAP-type instruments would still be needed.

The study of volatiles on the Moon is not high on the LExSWG priority list, but it is an issue of scientific signficance, and it could be of great value to the efforts of the Office of Exploration. An ultraviolet spectrometer of the type proposed by the SWRI meets the scientific requirements, and would provide a global survey of the volatile inventory. The significance of assessing the abundance of volatiles in the lunar environment is mentioned also in connection with landed science instruments.

Instruments for a second orbiter focus on gravity and terrain as the objectives. The specific instrument recommendations are:

A laser altimeter. A number of the proposed laser altimeters have some degree of flight hardware associated with them, much of that deriving from the Mars Observer program. A decision as to which of these devices to select is more an engineering issue than a scientific one, as long as the performance of the selected instrument meets or exceeds the LExSWG requirements (Table 1).

A gravity experiment. Here again, several options were presented to the Workshop. Global coverage is considered essential, and that in general suggests the use of two spacecraft to determine the gravity field (the near side can be done with one spacecraft). The most rapid characterization of the field would come from a so-called "low-low" orbit of the type suggested in the Goddard proposal, but any of the two spacecraft schemes would provide the data in a reasonable interval of time. An assessment of readiness from the perspective of engineering is probably the determining factor here.

An imaging camera. Coupling of imaging with altimetry and gravity is a solid package from the perspective of the science return as well as from the perspective of operational information that would be of long-term use to the Exploration Initiative. The imaging system rated most highly by the Workshop was that proposed by JPL, with the Mercator and Malin concepts being rated in a tie for second. Any of these systems would provide quality data and all have some flight hardware. It is again principally a matter of engineering readiness that should be the deciding factor.

The two mission payloads outlined above would provide the highest quality science, and all of the instruments appear to be capable of meeting the rather tight launch opportunity. Where there are doubts as to schedule, we have pointed them out along with alternatives.

The situation with regard to landed payloads is less clear, but nonetheless, it is the conclusion of the Workshop that a very solid suite of instruments can be available to fly using the prototype ARTEMIS lander concept. These instruments, which must be mounted on one or more rovers (such as were proposed by JPL) are the following:

An alpha-proton backscatter spectrometer. This device would provide excellent elemental information on the lunar soils.

A Mossbauer backscatter spectrometer. This device would complement the alpha-proton instrument and would provide high-quality mineralogical data (particularly important would be data relevant to soil maturity).

Stereo and high resolution cameras.

The above list is a minimum that would return excellent scientific data as well as site characterization through the imaging capability. Other instruments (e.g., an evolved gas analyzer) should be added as resources permit.