Lunar Outpost

The Challenges of Establishing a Human Settlement on the Moon

Erik Seedhouse

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Contents

Preface

My intention in writing this book was to write a narrative of the key mission architecture elements comprising NASA's plan for returning astronauts to the Moon. Although this book is by no means an exhaustive account of the many steps required to enable a manned lunar mission, my goal was to present as much detail as possible. To that end I relied extensively on a vast number of documents ranging from Power-point presentations, briefings, plans, press conferences, and technical articles.

Only a generation ago, the United States abandoned its own pioneering space exploration program. Even as the Apollo 17 astronauts returned from the Moon in 1972, the Nixon Administration was closing the hatch on missions beyond low Earth orbit. The Saturn V fleet, together with all the technological wonders developed by NASA to fly astronauts to the Moon, were mothballed. Since the end of Apollo, thousands of scientific papers and popular articles have been written on the topic of returning humans to the Moon. But how will we actually return? The book you are now holding answers that question and is written for those who wonder how NASA's new fleet of Launch Vehicles are developing, what the new class of astronauts will do on the surface of the Moon, and how mission profiles are designed.

As I write these words, a Presidential election is looming and it would be remiss not to address the historic choices faced by the two candidates. Whether driven by political tactics or strategic statesmanship, the space policy decisions made by either Senator Barack Obama or Senator John McCain may well determine the direction the United States takes in its second half-century of manned spaceflight. Whereas under the Bush Administration manned spaceflight has been ascendant, comments made by Obama, such as those below, suggest job losses in the human spaceflight business to be almost a certainty.

> "I think it is important for us to inspire through the space program, but also have the practical sense of what investments deliver the most scientific and

> technological spinoffs, and not just to feel that the human space exploration—actually sending bodies into space—is always the best investment.''
>
> Senator Barack Obama speaking during a call-in interview with the Editorial Board of the *Houston Chronicle*

In contrast to Obama's position on space, McCain's space policy favors a return to the Moon and preparations for manned missions to Mars, a policy reflected on his website which carries an artist's rendering of the Orion Crew Exploration Vehicle. For seven years, between 1997 and 2005, McCain was Chairman of the Senate Commerce Committee, which oversees space and commercial aviation, a position that provided him with experience critical to shaping NASA's future. As a strong supporter of NASA and the space program, McCain is proud to have sponsored legislation authorizing funding consistent with the President's VSE and he believes support for a continued American presence in space is crucial to re-establishing the country's pre-eminence over the Russians in space technology.

While some may worry about the potential ramifications of a possible Democratic Administration for manned spaceflight, the reality is that no matter who wins the White House in November 2008, both John McCain and Barack Obama will be long gone, or well into a second term, before any policy changes can be implemented that could seriously affect the Constellation Program. With fuel prices spiraling out of control, an economy in recession, and a commitment to overhaul the education system, the newly elected President will need to focus his attention on more pressing concerns.

The Constellation Program, which is the focus of much of this book, is more than just a proposal. It represents nothing less than the next logical phase in the evolution of space exploration and the first step to creating a space-faring civilization. The Vision for Space Exploration, announced by President Bush in January 2004, is a vision that plans to send astronauts not only to the Moon but also onward to Mars and beyond. It is a vision whose scope is vast. Far from being speculative, the plan described in this book is being realized as you read these words.

Although the Constellation Program has its critics, NASA detractors would be wise to remember that the agency invented the American manned space program. The agency put humans on the Moon, built the International Space Station, and regularly sends sophisticated probes billions of kilometers to Mars, Titan, and other moons and planets with unerring precision and accuracy. All these accomplishments are achieved under intense public scrutiny. Paradoxically, the successes of contemporary probes such as the Mars Exploration Rover and the joint NASA–ESA Cassini–Huygens Saturn missions have prompted some of the white suits to argue a case for a strictly robotic paradigm which, they claim, is cheaper and holds more promise than human exploration. In reality, nothing could be further from the truth since, although the aforementioned missions represent a *tour de force* of exploration, robots have many more limitations than humans. A manned lunar outpost is smart not just because the Moon is close but because it offers a unique location from which to parameterize human ecology on the high frontier, a goal that could not be achieved by simply

sending robots. Furthermore, the Moon is the stepping stone to an understanding of the practicalities of human survival for ever-longer periods in artificial ecosystems. Such goals can only be achieved by putting humans on the lunar surface for an extended timescale. Thanks to its cadre of superb engineers and can-do attitude NASA will take us to the Moon again. Here's how the agency will do it.

Acknowledgments

My first and greatest thanks go to my wife, Doina, for her patience and support during the writing of this book. Without Doina's exceptional grammatical talents and the endless hours she spent editing, this book could simply not have been written.

Once again, I am grateful to Clive Horwood of Praxis and the enthusiasm of the book's copy editor and typesetter, Neil Shuttlewood, is acknowledged. Likewise it has been a pleasure to work with my agent, Stephanne, and I look forward to the next book.

Along the path to writing this book, a unique group of colleagues and friends have supported my interest in manned spaceflight. My Ph.D. supervisors Professors David Grundy and Paul Enck constantly supported me in my research endeavors and have been instrumental in my being able to pursue a research career. Dr. Andrew Blaber kindly offered me a post-doctoral position at Simon Fraser University's Environmental Physiology Unit.

Finally, to those friends who read my first book and provided encouraging comments and to those friends who assured me they have the best intentions of reading my book: Julian Wigley, Tim Donovan, Gita Nand, Tania Meloni, Calvin Sandiford, Lee Williams, Tom Rodgers, Nancy Westrom, and Simba. Also, Dan Baouya—if all else fails, there is always Plan B!

Finally, thanks must go to our two cats, Mini-Mach and Jasper, and the constant welcome distraction they provided.

To my parents

About the author

Erik Seedhouse is an aerospace scientist with ambitions to become an astronaut. He experienced his first taste of microgravity while working as a research subject during the European Space Agency's 22nd Parabolic Flight Campaign in 1995. He gained his Ph.D. in Physiology while working at the German Space Agency's Institute for Space Medicine in Cologne between 1996 and 1998 and recently worked as an astronaut training consultant for Bigelow Aerospace in Las Vegas. He is a Fellow of the British Interplanetary Society and a member of the Aerospace Medical Association. When not writing books about space Erik flies his Cessna, races Ironman and Ultraman triathlons, climbs mountains, and spends as much time as possible in Kona and on Hapuna Beach on the Big Island of Hawaii.

Erik lives with his wife and two cats on the Niagara Escarpment in Canada.

Figures

Tables

Acronyms and abbreviations

ACES	Advanced Crew Escape Suit
ACLS	Advanced Cardiac Life Support
ACTS	Advanced Crew Transportation System
AETB-8	Alumina Enhanced Thermal Barrier-8
AIAA	American Institute of Aeronautics and Astronautics
ALARA	As low as reasonably achievable
ALHAT	Autonomous landing and hazard avoidance technology
AOD	Automatic opening device
APG	Advanced Programs Group
APMC	Agency Program Management Council
AR&D	Automated rendezvous and docking
ARC	Ames Research Center
ARPCS	Atmosphere Revitalization Pressure Control System
ARS	Acute radiation syndrome
ARS	Air Revitalization System
ASI	Artemis Society International
ASI	Augmented Spark Igniter
ASM	Aft Service Module
ATCO	Ambient temperature catalytic oxidation
ATCS	Active Thermal Control System
ATHLETE	All-Terrain-Hex-Legged Extra-Terrestrial Explorer
ATO	Abort to orbit
ATS	Aft Thrust Structure
ATSS	Advanced Transportation System studies
AUS	Advanced Upper Stage
AV	Ancillary Valve
BFO	Blood-forming organ
BLSS	Biological Life Support System

BMD	Bone mineral density
BMI	Bismaleimide
BMU	Battery Module Unit
BPC	Boost Protective Cover
BUAA	Beijing's University of Aeronautics and Astronautics
C&C	Command and control
C&N	Communications and navigation
C3I	Command, control, communication, and information
CAD	Computer-aided design
CAD	Coronary artery disease
CAIB	Columbia Accident Investigation Board
CaLV	Cargo Launch Vehicle
CAM	Computer-assisted manufacturing
CARD	Constellation Architecture Requirements Document
CAS	Chinese Academy of Sciences
CBO	Congressional Budget Office
CC	Cargo Container
CCB	Common Core Booster
CCDH	Command, control, and data handling
CDE	Carbon dioxide electrolysis
CDF	Concurrent Design Facility
CDM	Crew Descent Mission
CDMKS	Crew Descent Mission Kick Stage
CDR	Critical Design Review
CDS	Crew Descent Support
CDV	Cargo Delivery Vehicle
CE&R	Concept Exploration and Refinement (program)
CEV	Crew Exploration Vehicle
CFD	Computational fluid dynamics
CG	Center of gravity
CH_4	Methane
CHeCS	Crew Health Care System
CLL	Cargo Lunar Lander
CLV	Crew Launch Vehicle
CM	Crew Module
CMC	Center Management Council
CME	Coronal mass ejection
CMO	Crew Medical Officer
CMRS	Carbon Dioxide and Moisture Removal System
CNS	Central nervous system
CNSA	China National Space Administration
CONUS	Continental United States
COTS	Commercial Orbital Transportation System
CP	Center of pressure
CPDS	Charged Particle Directional Spectrometer

CRaTER	Cosmic Ray Telescope for the Effects of Radiation
CRC	Crew Re-Entry Capsule
CRS	Congressional Research Service
CSA	Canadian Space Agency
CSHL	Cargo Star Horizontal Lander
CSSS	Constellation Space Suit System
CTM	Crew Transfer Module
CVO	Cargo variant of Orion
CXV	Crew Transfer Vehicle
DAEZ	North Atlantic Downrange Abort Exclusion Zone
DASH	Descent Assisted Split Habitat
DAU	Data Acquisition Unit
DC-X	Delta Clipper Experimental
DCR	Design Certification Review
DCS	Decompression sickness
DDT&E	Design, development, testing, and evaluation
DIRECT	Direct Shuttle Derivative
DoD	Department of Defence
DoF	Depth of field
DOI	Descent orbit insertion
DPT	Decadel Planning Team
DRM	Design Reference Mission
DSB	Double-strand break
DS	Descent Stage
DSE-Alpha	Deep Space Exploration-Alpha
DSE	Deep-space exploration
DSM	Direct Staged Mission
DSS	Deep Space Shuttle
DSS	Deceleration Subsystem
DTA	Drop Test Article
DTE	Direct to Earth
ECLSS	Environmental Control and Life Support System
EDS	Earth Departure Stage
EELV	Evolved Expendable Launch Vehicle
EES	Emergency Egress System
EH	Escape Habitat
EIRA	ESAS Initial Reference Architecture
ELPO	Exploration Launch Projects Office
ELV	Expendable Launch Vehicle
EML1	Earth–Moon Lagrange Point 1
EMLR	Earth–Moon Lagrange rendezvous
EMS	Electronic Meeting System
EMU	Extravehicular Activity Mobility Unit
EOI	Earth orbit insertion
EOR	Earth orbit rendezvous

EOR–LOR	Earth orbit rendezvous–lunar orbit rendezvous
EPS	Electrical Power System
ERO	Earth rendezvous orbit
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
ESTEC	European Space Research and Technology Centre
ESTRACK	European Space Tracking
ET	External Tank
ETDP	Exploration Technology Development Program
ETO	Earth to orbit
EUS	Expendable Upper Stage
EVA	Extravehicular activity
FAS	Flight Analysis System
FAST	Flight application of spacecraft technologies
FBR	Fixed Base Radio
FIRST	Flight-oriented Integrated Reliability and Safety Tool
FLO	First Lunar Outpost
FOM	Figure of merit
FRR	Flight Readiness Review
FS	First Stage
FSAM	First Stage Avionics Module
FSM	Forward Service Module
FSO	Family Support Office
FSRCS	First Stage Roll Control System
FSS	Fixed Service Structure
FTI	Fusion Technology Institute
FTV	Flight Test Vehicle
GAO	Government Accountability Office
GCR	Galactic cosmic radiation
GGI	Gas generator ignition
GHe	Gaseous helium
GLOW	Gross lift-off weight
GN&C	Guidance, Navigation & Control
GOX	Gaseous oxygen
GPC	General purpose computer
GPS	Global Positioning System
GR&A	Ground rules and assumption
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
Gy	Gray
H-Suit	Hybrid Suit
HCM	Habitat Crew Module
He-3	Helium-3
HEAT	High-fidelity environment analog training

HGDS	Hazardous Gas Detection System
HHFO	Habitability and Human Factors Office
HLLV	Heavy Lift Launch Vehicle
HLM	Habitat Logistics Module
HLR	Human Lunar Return (study)
HLV	Heavy Lift Vehicle
HM	Habitation Module
HMD	Head Mounted Display
HMM	Habitat Maintenance Module
HPDE	High-density polyethylene
HPS	Human Patient Simulator
HPUC	Hydraulic Power Unit Controller
HSM	Habitat Science Module
HSSV	Helium Spin Start Valve
HSVG	Human Spaceflight Vision Group
HTPB	Hydroxyterminator polybutadiene
HUD	Heads Up Display
ICES	Integrated Cryogenic Evolved Stage
IEB	Ion Exchange Bed
ILOB	Icarus Lunar Observatory Base
IMLEO	Initial mass in low Earth orbit
INS	Inertial Navigation System
InSAR	Interferometric Synthetic Aperture Radar
IPT	Integrated Product Team
IRED	Interim Resistive Exercise Device
ISEMSI	Isolation Study for European Manned Space Infrastructure
ISP	Integrated Space Plan
I_{SP}	Specific impulse
ISRU	*In situ* resource utilization
ISS	International Space Station
ITV	Interplanetary Transfer Vehicle
IUA	Instrument Unit Avionics
IVA	Intravehicular activity
JAXA	Japan's Aerospace Exploration Agency
JCC	Jupiter Common Core
JLS	Jupiter Launch System
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JUS	Jupiter Upper Stage
KSC	Kennedy Space Center
L/D	Lift to drag (ratio)
L1	Lagrange Point 1
LAD	Liquid Acquisition Device
LADAR	Laser detection and ranging
LAMP	Lyman Alpha Mapping Project

LandIR	Landing and Impact Research (NASA Langley facility)
LAS	Launch Abort System
LAT	Lunar Architecture Team
LBNP	Lower-body negative pressure
LCD	Liquid crystal display
LCG	Liquid Cooling Garment
LCH_4	Liquid methane
LCROSS	Lunar Crater Observation and Sensing Satellite
LCT	Lunar Communication Terminal
LCT	Long Duration Cryogenic Tank
LEB	Lunar Exploration Base
LEM	Lunar Excursion Module
LEND	Lunar Exploration Neutron Detector
LEO	Low Earth orbit
LES	Launch Escape System
LEV	Lunar Excursion Vehicle
LExSWG	Lunar Exploration Science Working Group
LH_2	Liquid hydrogen
LIDAR	Light detection and ranging
LIDS	Low Impact Docking System
LiOH	Lithium hydroxide
LLAN	Lunar Local Area Network
LLO	Low lunar orbit
LLOX	Lunar liquid oxygen
LLPS	Lunar Lander Preparatory Study
LM	Lander Module
LM	Logistics Module
LMM	Lunar mission mode
LOC	Loss of crew
LOI	Lunar orbit insertion
LOLA	Lunar Orbiter Laser Altimeter
LOM	Loss of mission
LOR	Lunar orbit rendezvous
LOX	Liquid oxygen
LPMR	Lunar Polar Mission Rover
LPRP	Lunar Precursor Robotic Program
LRC	Langley Research Center
LRC	Lunar Resources Company
LRL	Lunar Reconnaissance Lander
LRO	Lunar Reconnaissance Orbiter
LRO	Lunar rendezvous orbit
LROC	Lunar Reconnaissance Orbiter Camera
LRS	Lunar Relay Satellite
LSAM	Lunar Surface Access Module
LSE	Lunar Surface Explorer

LSMS	Lunar Surface Mobility System
LSS	Life Support System
LTO	Lunar transfer orbit
LTV	Lunar Transfer Vehicle
LUT	Launcher Umbilical Tower
LV	Launch Vehicle
M^3	Manned Mission to the Moon
MAF	Michoud Assembly Facility
MAH	Mission Ascent Habitat
MAV	Minimum volume Ascent Vehicle
Max-ATO	Maximized abort to orbit
Max-TAL	Maximized targeted abort landing
MBR	Model-based reasoning
MCMI	Million Clinical Multiphasic Inventory
MCP	Mechanical counter-pressure
MDR	Major Design Review
MDU	Manufacturing Demonstration Unit
MECO	Main engine cut-off
MIT	Massachusetts Institute of Technology
MLAS	Max Launch Abort System
MLI	Multilayer insulation
MLP	Mobile Launcher Platform
MLUT	Minimal Launch Umbilical Tower
MM	Mission Module
MMH	Monomethyl hydrazine
MMO	Mission Management Office
MMOD	Micrometeroid/orbital debris
MMPI	Minnesota Multiphasic Personality Inventory
MPSS	Main Parachute Support System
MRR	Manufacturing Readiness Review
MSFC	Marshall Space Flight Center
MTV	Mars Transit Vehicle
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection
NEEMO	NASA Extreme Environment Mission Operations
NExT	NASA Exploration Team
NOAA	National Oceanic and Atmospheric Administration
NPR	NASA procedural requirement
NSBRI	National Space Biomedical Research Institute
NSD	NASA Standard Detonator
NTO	Nitrogen tetroxide
OBS	Operational Bioinstrumentation System
OExP	Office of Exploration
OMB	Office of Management and Budget
OML	Outer mold line

OMS	Orbital Maneuvering System
OBS	Operational Bioinstrumentation System
ORN	Osteoradionecrosis
OSC	Orbital Sciences Corporation
OSP	Orbital Space Plane
OTIS	Optimal trajectories via implicit simulation
OTV	Orbital Transfer Vehicle
P/LOC	Probability of loss of crew
P/LOM	Probability of loss of mission
PBAN	Polybutadiene acrylic acid acrylonitrile
PCA	Pneumatic control assembly
PCC	Pressurized Cargo Carrier
PCR	Pressurized Crew Rover
PCU	Power control unit
PDI	Powered descent initiation
PDR	Preliminary Design Review
PE	Polyethylene
PEG	Powered explicit guidance
PFTE	Poly-tetrafluorethylene
PICA	Phenolic-impregnated carbon ablator
PLSS	Portable Life Support System
PM	Payload Module
PMAD	Power Management and Distribution (system)
PNT	Position, navigation, and timing
POD	Point of departure
PPA	Power Pack Assembly
PPO_2	Partial pressure of oxygen
PSG	Psychological Services Group
PV	Photovoltaic
R&D	Research and development
r.m.s.	Root mean square
RATS	Research and Technology Study
RCS	Reaction Control System
RCT	Reaction Control Thruster
RDM	Robotic Descent Module
REI	Rear Entry I-Suit
REID	Risk of exposure-induced death
REM	Radiation equivalent man
RFA	Request for action
RFC	Regenerative Fuel Cell
RLV	Reusable Launch Vehicle
RM	Re-entry Module
RM	Resource Module
RMS	Remote Manipulator System
ROC	Resnick, O'Neill, Cramer

RSC	Rocket and Space Corporation
RSRB	Reusable Solid Rocket Booster
RSRM	Reusable Solid Rocket Motor
RSS	Rotating Service Structure
S&MA	Safety Mission Assurance Office
SAEH	Support Ascent Escape Habitat
SAGES	Shuttle and Apollo Generation Expert Services
SAR	Synthetic Aperture Radar
SARSAT	Search and rescue satellite-aided tracking
SBIR	Small Business Innovative Research
SCA	Spacecraft Adapter
SCR	Solar cosmic ray
SEI	Space Exploration Initiative
SEM	Space Exploration Module
SF	Factor of safety
SFINCSS	Simulation of Flight of International Crew on Space Station
SH	Surface Habitat
SLS	Saturn Launch System
SM	Service Module
SOHO	Solar and Heliospheric Observatory
SORT	Simulation and optimization of rocket trajectories
SPACE	Screening Program for Architecture Capability Evaluation
SPE	Solar particle event
SPM	Surface Power Module
SPWE	Solid Polymer Water Electrolysis
SQM	Strange quark matter
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SRR	System Requirements Review
SS	Satellite and storage
SSB	Single-strand break
SSC	Stennis Space Center
SSC	Systems and Software Consortium
SSME	Space Shuttle Main Engine
SSRB	Space Shuttle Solid Rocket Booster
SS	Satellite and storage
SSTO	Single stage to orbit
Sv	Sievert
SYZ	Soyuz
TAL	Targeted abort landing
TEI	Trans-Earth injection
TEPC	Tissue Equivalent Proportional Counter
TIM	Technical Interface Meeting
TLI	Translunar injection
TO	Thrust oscillation