Human Spaceflight
Space System Design, MAE 342, Princeton University
Robert Stengel

• Historical concepts and mis-concepts
• Manned spacecraft and space stations
• Extravehicular activity
• Physiological and metabolic issues
  – Health and space medicine
  – Radiation exposure
  – Life support systems
• Control capabilities and human error

Copyright 2016 by Robert Stengel. All rights reserved. For educational use only.
http://www.princeton.edu/~stengel/MAE342.html
A Voyage to the Moon
Cyrano de Bergerac
(1619-1655)

- Hercule-Savinien Cyrano de Bergerac
- “Comical History of the States and Empires of the Moon”, written about 1649, published 1656 or 1657
- English translation, 1687
- In Firestone Library (below & left)
Cyrano's Voyage to the Moon and Back

1952 Rocket Ship/Space Station Concept
Trouble in the Spacecraft: Ejection Capsule

Why Humans in Space?

• Exploration
• Scientific discovery
• Engineering development
• Construction, maintenance, and repair
• Pilots, tourists, and tour guides
Man vs. Machine
(Handbook of Astronautical Engineering, 1961)

Table 26.4. Superiority of Man and Machine in Various Activities

<table>
<thead>
<tr>
<th>Man</th>
<th>Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>Physical strength and power</td>
</tr>
<tr>
<td>Multipurpose adjustment</td>
<td>Speed of sensing</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Speed of recognition</td>
</tr>
<tr>
<td>Multipurpose sensitivity</td>
<td>Speed of certain performances</td>
</tr>
<tr>
<td>Communication</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>Learning</td>
<td>Speed of computation</td>
</tr>
<tr>
<td>Judgment</td>
<td>Constancy of performance</td>
</tr>
<tr>
<td>Inductive reasoning</td>
<td>Repetitive performance</td>
</tr>
<tr>
<td>Understanding of essentials</td>
<td>Reliability</td>
</tr>
<tr>
<td>Establishment of hypotheses</td>
<td>Endurance</td>
</tr>
<tr>
<td>Taking risks</td>
<td>Stability of memory</td>
</tr>
<tr>
<td>Problem solving</td>
<td>Short-term storage capacity</td>
</tr>
<tr>
<td>Pattern interpretation</td>
<td>Complete press capability</td>
</tr>
<tr>
<td>Decision making</td>
<td>Conformity</td>
</tr>
<tr>
<td>Ingenuity and intuition</td>
<td>Reaction time</td>
</tr>
<tr>
<td>Invention of new things</td>
<td>Sensitivity to certain environmental conditions</td>
</tr>
<tr>
<td>Utilization of subjective experiences</td>
<td>Simultaneous activity</td>
</tr>
<tr>
<td>Design and construction of machines and equipment</td>
<td></td>
</tr>
<tr>
<td>Integration of internal and external stimuli</td>
<td></td>
</tr>
<tr>
<td>Concluding</td>
<td></td>
</tr>
</tbody>
</table>

Performance Issues for Manned Spaceflight

- Flexibility, learning, and judgment
- Information bandwidth, display, and communication
- Pre-flight training
- Performance variation
- Extra-vehicular activity
- Physical labor
- Physical labor
- Endurance
- Ergonomics
- Control systems
- Re-entry systems and recovery
- Tools and equipment
- Recycling
Cooper-Harper Pilot Opinion Rating
(NASA TN D-5153, 1969)

DEFINITIONS FROM TN-D-5153

COMPENSATION
The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

PERFORMANCE
The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE
The function or purpose that defines the primary use of an aircraft.

TASK
The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD
The integrated physical and mental effort required to perform a specified piloting task.
Human Space Experience to April 2016

- Continuous human space presence since Oct. 31, 2000
- Total people in space: 544
- Total person-days: 47,930
- Most space flights: Jerry Ross and Franklin Chang-Diaz (7)
- Cumulative spaceflight record: 878 days (Gennady Padalka)
- Single mission record: 438 days (Valeri Polyakov)
- Total ISS EVAs (2/16): 193
- Total ISS EVA time (2/16): 1205 hr
- EVA record: 16 (Anatoliy Solovyov)
- Longest EVA: 8hr 56 min (Susan Helms and James Voss)

Physical Issues for Manned Spaceflight

- Physiology
  - Loss of bone and muscle mass
    - Intensive exercise regimen
  - Fluid redistribution to upper body
  - Disruption of vision due to intracranial pressure
- Life support
  - Breathing and pressurization
    - Exposure to vacuum
  - Nutrition and hydration
  - Rest and work cycles
  - Thermal environment
    - Temperature extremes
  - Acoustic noise level
  - Waste disposal

Physical Issues for Manned Spaceflight

- Acceleration level during launch and re-entry
- Effects of weightlessness
- Angular rate and orientation
  - Motion sickness
- Radiation hazards
  - Cosmic radiation
  - Van Allen belts

Human Acceleration Tolerance
(NASA TN D-337, 1960)

Figure 10.- Time tolerance to acceleration boundaries.
Effect of Drag/Mass on Direct Reentry Deceleration

(Handbook of Astronautical Engineering)

Flight path angle = constant
Lift = 0

Effect of Flight Path Angle on Direct Reentry Deceleration

(Handbook of Astronautical Engineering)

$C_D S/m = 0.1$
Mercury

- One crew member
- Command module
- 1,935 kg
- Conical reentry capsule
- Large-radius heat shield
- Negligible reentry crossrange capability
- Parachute recovery of capsule and astronaut
- 9-g reentry
- Low earth orbit

Vostok

- One crew member
- 2,460 kg
- Command + service modules
- Spherical reentry capsule
- Small-radius heat shield
- Negligible reentry crossrange capability
- Parachute recovery of capsule
- Cosmonaut lands on personal parachute
- 8-g reentry
- Low earth orbit
Effect of Lift/Drag on Reentry Deceleration

*(Handbook of Astronautical Engineering)*

$L/D = 1$ to $3$

Gemini

- 2-person crew
- 10 manned missions
- Up to 7 days in orbit
- Low reentry crossrange capability
- Extravehicular activity
- Rendezvous and docking
- Formation flying

Apollo’s Return to Earth

Reentry of Apollo 13 Service and Lunar Modules

Command Module Splashdown

Radiation Exposure

Dose Equivalent (millisieverts)

- Annual Cosmic Radiation (sea level)
- US Annual Average, All Sources
- Abdominal CT Scan
- DOE Radiation Worker Annual Limit
- 6 Months on ISS (average)
- 180-day Transit to Mars
- 500 Days on Mars

~Annual Limit
~Lifetime Limit

Indicated limits are controversial
Psychological Issues for Manned Spaceflight

• Psychology
  – Egocentricity ("autonomization")
  – Isolation and monotony
  – Increased holistic respect for Earth

• Psychiatry
  – Transient anxiety or depression
  – Fatigue, irritability, sleep disorder
  – Readjustment on return to Earth

• Sociology
  – Bonding of vehicle crew
  – Importance of supportive mission commander
  – Lack of confidence in ground personnel
  – Misunderstandings among crew from different cultures

Space Medicine

• Cardiac rhythm disturbance
• Decompression sickness
  – Transition from air to oxygen for EVA ("nitrogen purge")
  – Barotrauma
• Decreased immune response
• Medications
• Health and medical emergency
  – Procedures and protection
  – Use of ultrasound diagnostics in space
  – Intervention, e.g., robot-assisted surgery
X-15: The First US Spaceplane

1st powered flight: 1959
Maximum altitude: 108 km, 1963
Maximum speed: 7,273 km/hr, 1967
USN Commander Forrest Petersen, Princeton AE, 4th X-15 pilot, 1960

Project Mercury Flights (manned)

Redstone
- 5/61, Shepard
- 7/61, Grissom

Atlas
- 2/62, Glenn
- 5/62, Carpenter
- 10/62, Schirra
- 5/63, Cooper
Project Gemini Flights

Unmanned | Manned

Apollo

APOLLO LAUNCH CONFIGURATION FOR LUNAR LANDING MISSION
Similarities Between Verne’s *Columbiad* and *Apollo*

- Launch from Florida at Cape Canaveral’s latitude
- Size of capsule
- Number of astronauts
- Required launch velocity
- Time of flight
- Weightlessness
- Capsule recovery at sea

**Apollo Command and Service Modules**

- 3-person crew
- Upper and lower decks
- Autonomous guidance and control capability
Saturn IB, 1966-1975
- 9 launches
  - Uprated S-I and S-IV stages
  - AS-201, -202: sub-orbital
  - AS-203: orbital
  - AS-204: Apollo 1: Block 1, Jan 1967, no launch, loss of crew (Grissom, White, Chaffee)
- No Apollo 2 or 3
- Apollo 5: Jan 1968, LM test (unmanned)
- Apollo 7: Block 2, Oct 1968, 1st manned flight, (Schirra, Eisele, Cunningham)
- 3 flights to SkyLab, 1973
- Docking with Soyuz, 1975

Saturn V, 1968-1975
- New 1st and 2nd stages
- S-IVB became 3rd stage
- Apollo 4, 6: Unmanned
- Apollo 8: 1st to the Moon
- Apollo 9: orbital
- Apollo 10: 2nd to the Moon
- Apollo 11: 1st lunar landing
- Apollo 12: 2nd lunar landing
- Apollo 13: aborted lunar mission
- Apollo 14-17: successful lunar missions
- Skylab launch (2 stages)
Space Shuttle

- 5 operational vehicles, 1 experimental vehicle
- 135 missions
- Retired in 2011
- *Challenger* and *Columbia* losses

Pilot-Induced Oscillations

Uncommanded aircraft is stable but piloting actions couple with aircraft dynamics to produce instability
Space Shuttle Crew Compartment

- Flight deck
- Middeck
- Lower level equipment bay
- Airlock

Space Shuttle: Spacelab Module

- Modular space station supplied by ESA
  - Spacelab module provides main laboratory
  - Spacelab pallet provides mounting base for experiments
  - Instrument pointing system
  - Tunnel to lower deck
  - Pressurized "igloo" for pallet-only missions
- Components flown on 25 Space Shuttle missions
Space Stations: Skylab

- On orbit from 1973 to 1979
- 77,088 kg
- Station based on refined S-IVB stage
- Launched on modified Saturn V
- Damaged during launch
- Two of 3 crews commanded by Princeton alums
  - 1973: "Pete" Conrad, '53
  - 1973: Gerald Carr, '62

Charles "Pete" Conrad, '51
(1930-1999)
Space Stations: Skylab

- 6 stations successfully orbited
- 31 crews launched to stations

Russian Space Stations

Salyut 7

Mir

Almaz (Military)
International Space Station

- 4 laboratory modules orbited, 3 to follow
- ESA viewing cupola scheduled for 2009
- Docking cargo module scheduled for 2010

http://iss.astroviewer.net/
Today’s ISS Sighting Time

<table>
<thead>
<tr>
<th>Date</th>
<th>Visible</th>
<th>Max Height</th>
<th>Appears</th>
<th>Disappears</th>
<th>Share Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fri Apr 15, 9:29 PM</td>
<td>2 min</td>
<td>45°</td>
<td>21° above WNW</td>
<td>45° above SW</td>
<td>![ ]</td>
</tr>
<tr>
<td>Sat Apr 16, 8:37 PM</td>
<td>3 min</td>
<td>86°</td>
<td>35° above NW</td>
<td>20° above SE</td>
<td>![ ]</td>
</tr>
<tr>
<td>Sun Apr 17, 9:21 PM</td>
<td>2 min</td>
<td>18°</td>
<td>13° above W</td>
<td>17° above SSW</td>
<td>![ ]</td>
</tr>
<tr>
<td>Mon Apr 18, 8:23 PM</td>
<td>4 min</td>
<td>36°</td>
<td>27° above W</td>
<td>10° above SSE</td>
<td>![ ]</td>
</tr>
<tr>
<td>Wed Apr 20, 8:21 PM</td>
<td>3 min</td>
<td>15°</td>
<td>13° above WSW</td>
<td>10° above SSW</td>
<td>![ ]</td>
</tr>
</tbody>
</table>

Space Station Regenerative ECLSS
Flow Diagram (Current Baseline)

Environmental Control and Life Support System, 2008
ExtraVehicular Activity

- Manned Maneuvering Unit included
  - Cold-gas attitude and translational control system (24 thrusters)
  - Astronaut hand controls
  - Used until 1986 Challenger accident
- Extravehicular Mobility Unit provides life support
- SAFER: simplified MMU for rescue

Soyuz Spacecraft and Launch Vehicle

- Orbital, reentry, and service modules
- Spinoff from Soviet manned lunar program
- 3-person crew
- Apollo-Soyuz at NASM
Orion Crew Vehicle

- Command Module (reusable)
- Service Module (expendable)
- 4-6 crew members

Orion/Ares vs. Space Shuttle

<table>
<thead>
<tr>
<th></th>
<th>Orion</th>
<th>Space Shuttle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload to LEO, kg</td>
<td>1,000 (est)</td>
<td>24,400</td>
</tr>
<tr>
<td>Payload from Orbit, kg</td>
<td>Neg. 6</td>
<td>12,700</td>
</tr>
<tr>
<td>Crew + Passengers</td>
<td>30</td>
<td>8 (11)</td>
</tr>
<tr>
<td>Reentry Cross-Range Capability, km</td>
<td>No 30</td>
<td>2,010</td>
</tr>
<tr>
<td>EVA Capability</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Reusable
US and Foreign Manned Spacecraft

NASA Orion  SpaceX Dragon  Blue Origin

Boeing CST-100

Indian Concept  Russian Soyuz  Chinese Shenzhou

Space Tourism

SpaceShipTwo  New Shepard  British Ascender

EADS Spaceplane
SpaceShipOne

Flown above 100 km twice in 2 weeks in 2004 to win the Ansari X-Prize.

Princeton SpaceShipOne Test Pilot and Astronaut

- Brian Binnie, MAE, MSE ’78, exceeded M1.2 in 60-deg climb on December 17, 2003, 100th anniversary of the Wright Brothers first flight.

- Brian won Ansari X-Prize and astronaut wings by flying to 367,442-ft altitude and broke X-15 record on October 4, 2004.
Colonization of the Moon and Planets

... or L4 or L5

Bernal Sphere, 1929

O'Neill Cylinders, 1975

https://en.wikipedia.org/wiki/Space_colonization
Next Time:
System Engineering and Integration