Dr. Shamim Rahman
Panel Member

Apollo Lessons for Young Professionals

AIAA P&E Forum 2019
Lunch & Learn Panel

20 AUGUST, 2019

AIAA Associate Fellow, and AIAA Board of Directors 2010-16
NASA Professional, Lead for Orion to SLS Interface Management
INSPIRED BY -

Lunar Mission Apollo 11 (US, 1969)

Apollo 11 changed my life vector.

Professor Dr. Hermann Oberth, left, congratulates Rahman, at right, during the 34th International Astronautics Congress in Budapest, Hungary, in 1983. Rahman presented a student paper on wind tunnel subscale testing (at Texas A&M)

The 34th IAC reinforced that vector.
INTRO (Rahman) -

- LONG JOURNEY (INDIA, BAHRAIN, College Station, Los Angeles, New Orleans)
- WORK: NASA **Stennis** (SSC), and now NASA **JSC** (Houston)

Born ← Here
School (Bahrain)

And there the (PhD PSU)
Apollo - Rocket Propulsion


5 F-1s (1.5 M-lbf ea)

5 J-2s (200 K-lbf ea)

1 J-2s (200 K-lbf)

1 SPS (20 K-lbf)

16 Thrusters 4 x 4 Config. (100 lbf ea)

1 LEM (Ascent) (3.5 K-lbf)

1 LMDE-Descent (10.5 K-lbf)

LEM = Lunar Excursion Module
LMDE = Lunar Module Descent Engine
SPS = Service Propulsion System
“Lessons” and Learning – 4 Examples

- Rocketry requires **Hardware & Testing** Savvy (F-1, J-2, LMDE)
  - Combustion Stability (F-1, LMDE); Stress testing; ..
  - more

- **Valves** will “eat your lunch” (SPS, RCS, etc.)

- Expect tough **Non-Technical problems** (contracts, suppliers)

- **Redundancy** (system-level and/or hardware level)

“Lessons” / Learning 1 - Examples

Hardware & Testing Savvy (F-1, J-2, SPS, LMDE, …)

- Development* (Scale-up in Size, Pressure, new propellant)
  - Technology maturation (e.g. J-2 LH2 Prop)
  - Proto-Flight-Like “All-Up testing” (e.g. F-1, J-2, LMDE, etc.)
  - Scaling up Design (e.g. LMDE 0,5K to 10K, SPS 2K to 10K)
  - Hardware “rich” $$$ (e.g. Ascent engine, LMDE, f-1, J-2**)

- Qualification / Certification Tests (of flight design)
  - Flight Engines (non-flight sampling), Stage demo

- Acceptance Tests (Flight Hardware)
  - Unit-to-Unit variation & buyoff (engine/stage)

- Flight Demonstration
  - Real use data (J-2 restart failure investigated by test)

Even “evolutionary” mods carry hidden risks
(e.g. J-2 startup design; F-1 LOX Pump vanes)

F-1 is largest Ever built (1.5 Mlbf)

*Even “evolutionary” mods carry hidden risks
(e.g. J-2 startup design; F-1 LOX Pump vanes)

**J-2 had many test stands
(Calif., MSFC, AEDC, SSC); So did the Ascent engine.

AEDC = Arnold Engineering Development Center
SSC = Stennis Space Center
MSFC = Marshall Space Flight Center
# Having Hardware Really Helps

<table>
<thead>
<tr>
<th>APOLLO / SATURN</th>
<th>Development Engines</th>
<th>Qualification Engines</th>
<th>Flights</th>
<th>Contract Award</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascent Engine</td>
<td>4 (209 firings)</td>
<td>6 (308 firings)</td>
<td>6 Flown</td>
<td>July ’67</td>
</tr>
<tr>
<td>LMDE 10:1 throttling</td>
<td>47 Engines (2809 firing)</td>
<td></td>
<td>9 Flown</td>
<td>July ’63</td>
</tr>
<tr>
<td>SPS (In space)</td>
<td>27 Engines (4000 firings)</td>
<td></td>
<td>19 flown</td>
<td>April ’62</td>
</tr>
<tr>
<td>RCS (In space)</td>
<td>45 (R-4C) + 22 (R-4D) (thousands)</td>
<td>469 (R-4D)</td>
<td>Feb. ’62</td>
<td></td>
</tr>
<tr>
<td>J-2 (Stages 2 &amp; 3)</td>
<td>36 (1700 firings)</td>
<td>2 (30 firings)</td>
<td>86 flown (150 engines built)</td>
<td>April ’60</td>
</tr>
<tr>
<td>F-1 (Stage 1)</td>
<td>56 (2805 firings)</td>
<td>2 (34 firings)</td>
<td>65 flown</td>
<td>January ’59</td>
</tr>
</tbody>
</table>

AIAA Monography 45: Rahman, S., on Apollo Rocket Propulsion Development.
Valves & Injection are tricky (SPS, RCS, J-2, LMDE)

- **SPS 20 Klbf Engine**
  - Valve Manufacturing – complex, time-consuming valve casting
  - Valve actuation – switch from hydraulic to pneumatic due to constraints at SM interface (SM to Engine)

- **Injector System Development** (e.g. LMDE Pintle, F-1 baffles)
  - Most engine development programs begin with injector development to achieve the performance & combustion characteristics desired
  - Scaling to higher thrust is a risk-driver (F-1 instability, and LMDE throttling)

- **Injection Challenges for small thrusters**
  - 100 lbf RCS engine injection ignition delay (pulse-mode operation)
  - RCS Injection Inner manifold “ZOTS” explosions
“Lessons” / Learning 3 - Example

- **Some Non-Technical Challenge (SPS, LEM)** - Ref. Monograph 45.
  - Pay attention to the Supplier base [Engine Subs, and even Engine Prime]
    - SPS Sub – **Gimbal Actuator**: Halfway through, **supplier Siegler got bought by Lear and relocated** to Cleveland (minus Siegler engineers); had to develop alternate supplier Cadillac Gage ASAP
    - SPS – **Senator from Maine** request … outcome was serendipitous [First large Titanium nozzle challenge was solved by Maine* boat-hull maker of Norwegian descent (bargain price/schedule, with great quality)]
    - SPS Sub – **Nozz saga continues**: must incorporate Columbium/Titanium combo nozzle thanks to supplier Wah Chang Co. who makes nuclear reactor rods
    - Ascent Engine (Prime contract) – **Late switch** (Bell to Rocketdyne) for 3500 lbf engine; Bell hardware limitations in early dev. came back to bite them; Rocketdyne backup proposal of July 1967 became primary

- Moral of the story? Who knows…. “expect the unexpected.”

*Reason for sourcing from Maine was at request of Maine Senator wanting some Apollo work in her state.*
“Lessons” / Learning 4 - Example

Redundancy is a Must (Apollo system/hardware)

- Apollo 13 – the ultimate example
  - LMDE ended up saving the Crew; brought them home
- F-1/J-2 instances
  - Engine out scenarios allows success to ETO
- SPS Engine instance
  - Dual-redundant valves needed to ensure startup/shutdown
- Ascent Engine: Sometimes not possible
  - Ascent engine HAD to work, so its design was simplified to ensure its reliability was maximized (e.g. no pumps, hypergol prop...)

“Redundancy was really a major hallmark of the Apollo Program.” said Harmon (2006)

Many more example strewn throughout the Apollo literature held by NASA and AIAA.
Quotable Quotes -

- **Harmon**: “I was in charge of [Ascent Engine] stability testing, which was run in two shifts. The first shift and second shift were stability testing. The third shift cleaned up the mess we made in the first and second shifts; then, it started all over the next day.”

- **Boyle**: “We were scratching our heads about what to do [about Nozzle] when one of those fortuitous events occurred.” [found better supplier.]

- **Elverum**: “Testing was key to demonstrating high engine reliability.”
AUDIENCE FEEDBACK

Ballistic Missile Rocket Programs (liquids, solids)

GOVT. KNOWLEDGE & OVERSIGHT

R&D/DDTE

APOLLO (NASA)

SHUTTLE (NASA)

ELVs (USAF)

GOVT. KNOWLEDGE & INSIGHT

DDT&E

FUTURE ORION & SLS PROGRAMS

USAF LAUNCH

COMMERCIAL SPACE (new)

United States - INDUSTRIAL BASE EVOLUTION
EM-1 Near Term (next year)

- 2014-2018: Integrate the Designs of Orion to SLS
  - Loads, Environments, Electrical, Flight Performance, & more

- 2018-2019: Orion & SLS Test, Analyze, Certify their Systems

- 2019-2020: Integrate & Assemble the Orion & SLS, at KSC

- 2020: Conduct first Flight EM-1 of the new vehicle

Thank you for your interest!!
NASA Work -

- Orion to SLS INTEGRATION (since 2014)
- EM-1 (No Crew) - 2020
- EM-2 (4 Crew) - 2022

ROCKET GROUND TEST (SSC)
- Flight Engine - SSME (now RS-25)
- Flight Engine - Delta 4
- R&D Engine - IPD

SHUTTLE (Earth Orbit)
- Retired Orbiter (KSC)

EXPLORATION BEYOND* EARTH-ORBIT
- *Access to Gateway
- EM-1 Patch
- 2018

SLS Block 1
- SLS Block 1B
- SSC PAO Release
- Rockwell Thermal Group (JSC)

An actual F-1 Engine is shown in the background; a display model in front of the NASA SSC onsite visitor center, April 2006.
AR's Role on Saturn V / Apollo Missions

63 Aerojet Rocketdyne engines powered Americans to the Moon and brought them safely back to Earth.

Apollo Service Module
- AJ10 Service Module System (SPS) engine supported Lunar Orbit Insertion, and Earth Orbit Insertion for the return flight
- 16 R-4D bipropellant RCS engines provided reaction control

Saturn V Third Stage
- A single J-2 engine powered the third stage
- Two SE 7-1 engines were used to settle the propellants prior to the J-2 firing

Saturn V Second Stage
- Five J-2 engines powered the second stage
- Four RS-U-601 engines to settle propellants

Saturn V First Stage
- Five F-1 main engines powered the Saturn V Rocket

Launch Escape System

Apollo Command Module
- 12 SE-8 RCS engines guided the Command Module back to Earth

Lunar Excursion Module
- 16 R-4D bipropellant RCS engines provided reaction control
- Lunar Ascent Engine
List of References

- NASA Monograph 45 (2009) – Remembering the Giants: Apollo Rocket Propulsion Development

Lessons are captured implicitly or explicitly in published document -- one should review those documents --

Recent Propulsion designers studied Huzel/Huang - 😊