Dr. Shamim Rahman

Panel Member

Apollo Lessons for Young Professionals

AIAA P&E Forum 2019 Lunch & Learn Panel

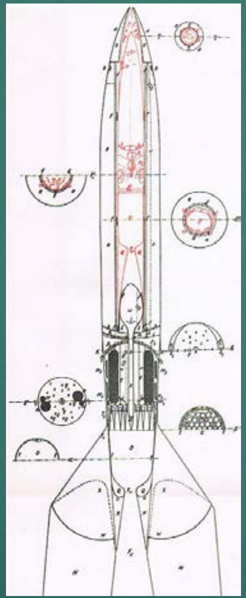
20 AUGUST, 2019

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)

PROF. OBERTH (PIONEER) --Conceived Modern Rocketry



1923

46 yrs

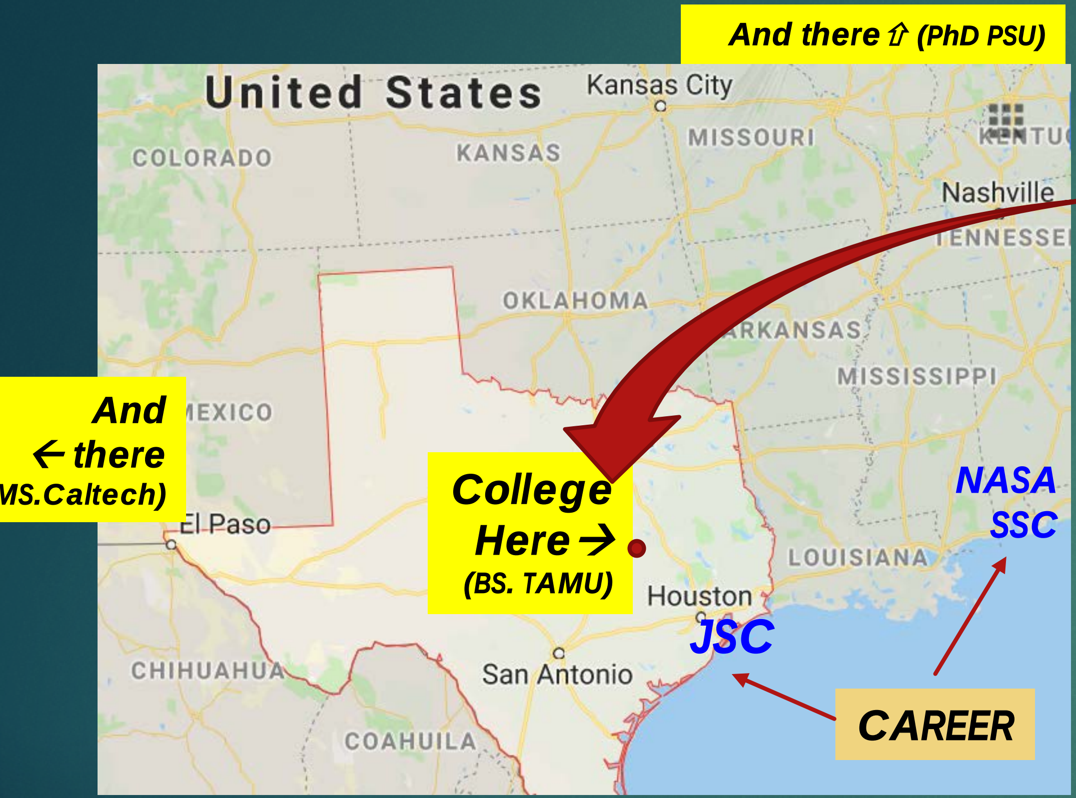
Apollo 11 changed my life vector.

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.

⇧ *Int'l Space Conference 1983*

INTRO (Rahman) -

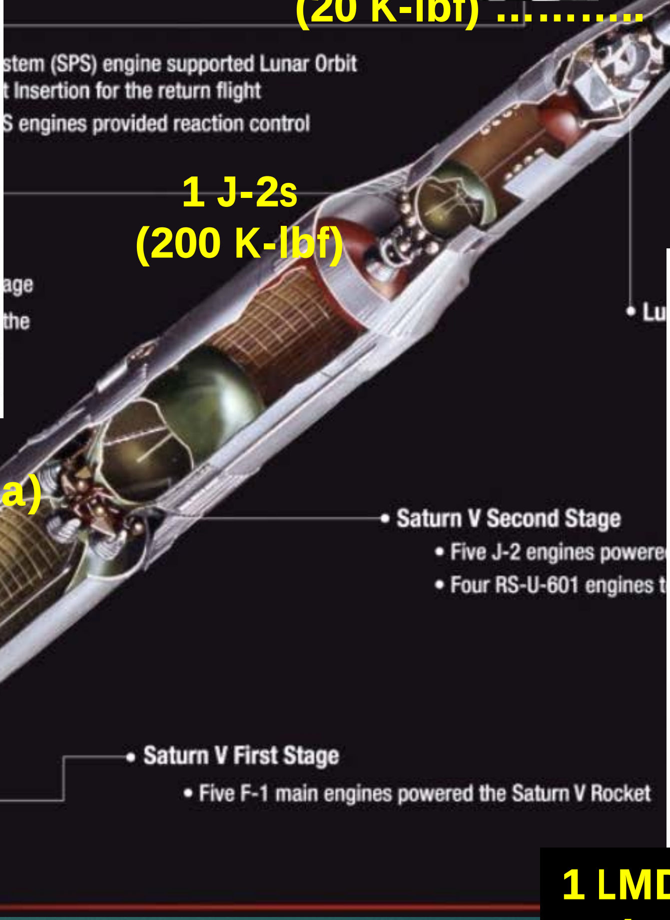


- LONG JOURNEY (INDIA, BAHRAIN, College Station, Los Angeles, New Orleans)
- WORK: NASA **Stennis** (SSC), and now NASA **JSC** (Houston)

Apollo - Rocket Propulsion

Source:
NASA History Monograph 45:
Fisher & Rahman (Eds.) –
Apollo Rocket Propulsion Development (2009)


One of the J-2 engines that power the upper stages of Saturn V liquid

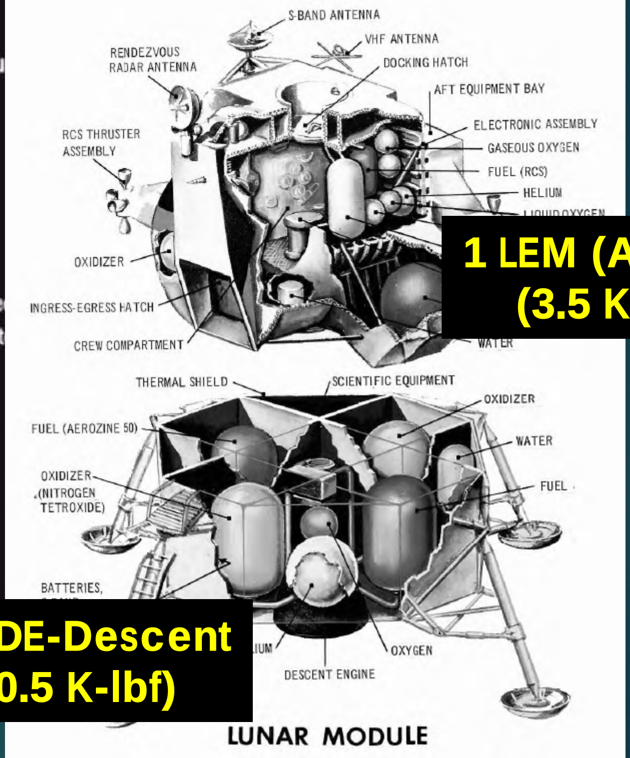


1 SPS
(20 K-lbf) ……….

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

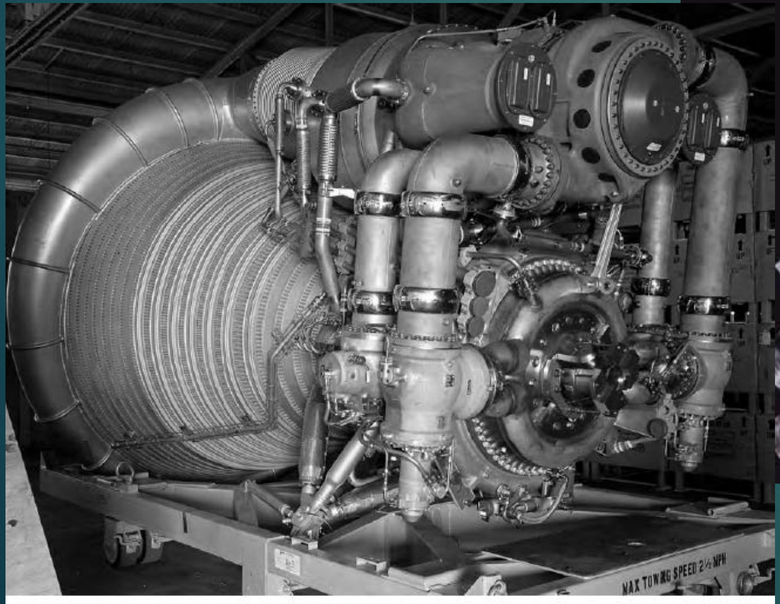
1 J-2s
(200 K-lbf)

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



1 LEM (Asc
(3.5 K-lbf

1 LMDE-Descent
(10.5 K-lbf)

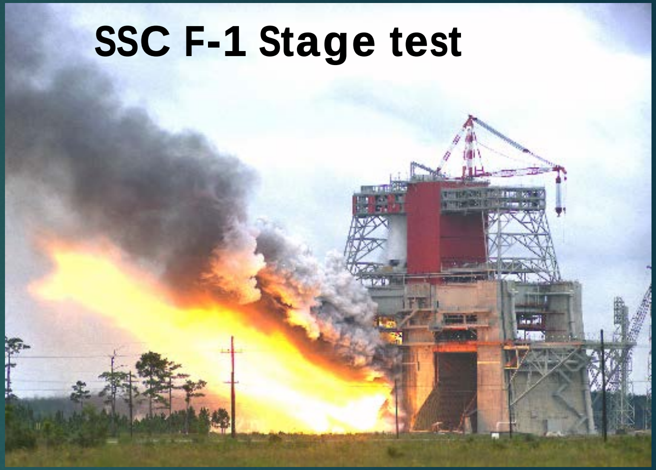

F-1 Engine (NASA image number: MSFC-6413912)

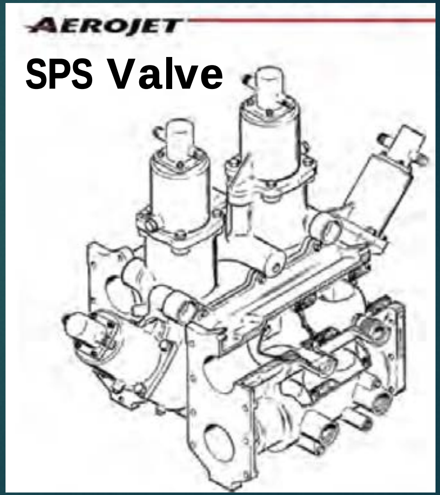
5 F-1s
(1.5 M-lbf ea)

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)



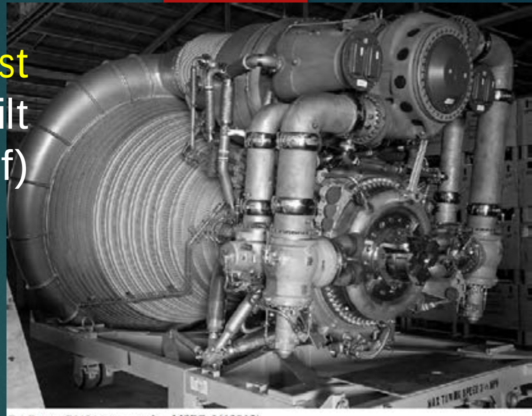


NASA History Monograph 45: Fisher & Rahman (Eds.) – Apollo Rocket Propulsion Development (2009)
NASA SP 125: Huzel & Huang – Design of Liquid Propellant Rocket Engines (1971)

"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)

F-1 is largest Ever built (1.5 Mlbf)



F-1 Engine (NASA image number: MSFC-6413912)

One of the J-2 engines that power the upper stages of Saturn V liquid

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

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

AEDC = Arnold Engineering Development Center
SSC = Stennis Space Center
MSFC = Marshall Space Flight Center

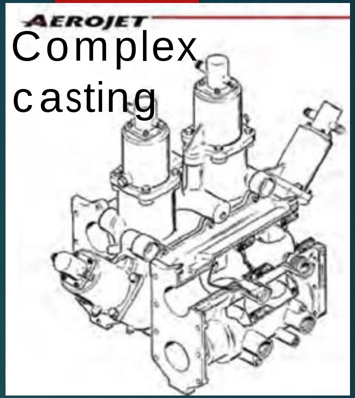
Having Hardware Really Helps

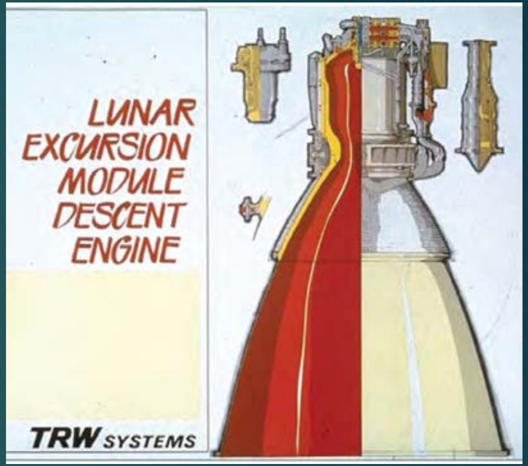
APOLLO / SATURN	Development Engines	Qualification Engines	Flights	Contract Award
Ascent Engine	4 (209 firings)	6 (308 firings)	6 Flown	July ’67
LMDE *10:1 throttling*	47 Engines (2809 firing)		9 Flown	July ’63
SPS (In space)	27 Engines (4000 firings)		19 flown	April ’62
RCS (In space)	45 (R-4C) + 22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

AIAA Papers 2001-0749 & 3985: Emdee, J., on LOX/RP and LOX/LH engines DDT&E history.
AIAA Monography 45: Rahman, S., on Apollo Rocket Propulsion Development.

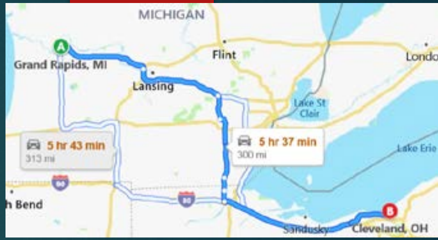
"Lessons" / Learning 2- *Example*

- **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





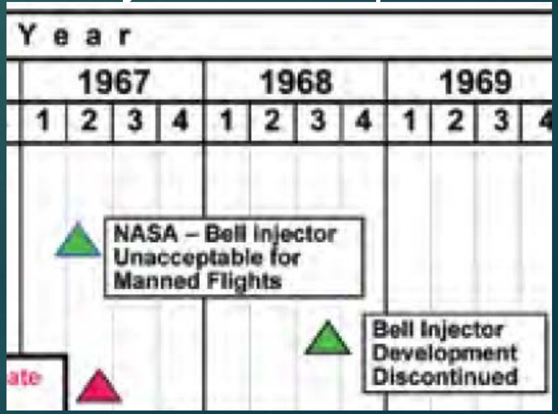
"Lessons" / Learning 3 - *Example*



- 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."

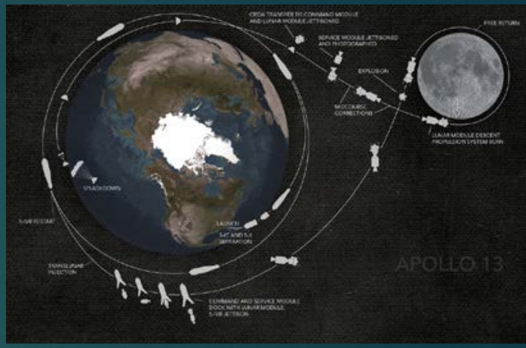
*Reason for sourcing from Maine was at request of Maine Senator wanting some Apollo work in her state.



Bell out (1967); Rocketdyne in.

"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 it's design was simplified to ensure it's 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"*

- Boyce: *"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."*

2006 AUDIENCE

Marshall Expert

White Sands Expert

Biggs (F-1)
Rocketdyne

Coffman (J-2)
Rocketdyne

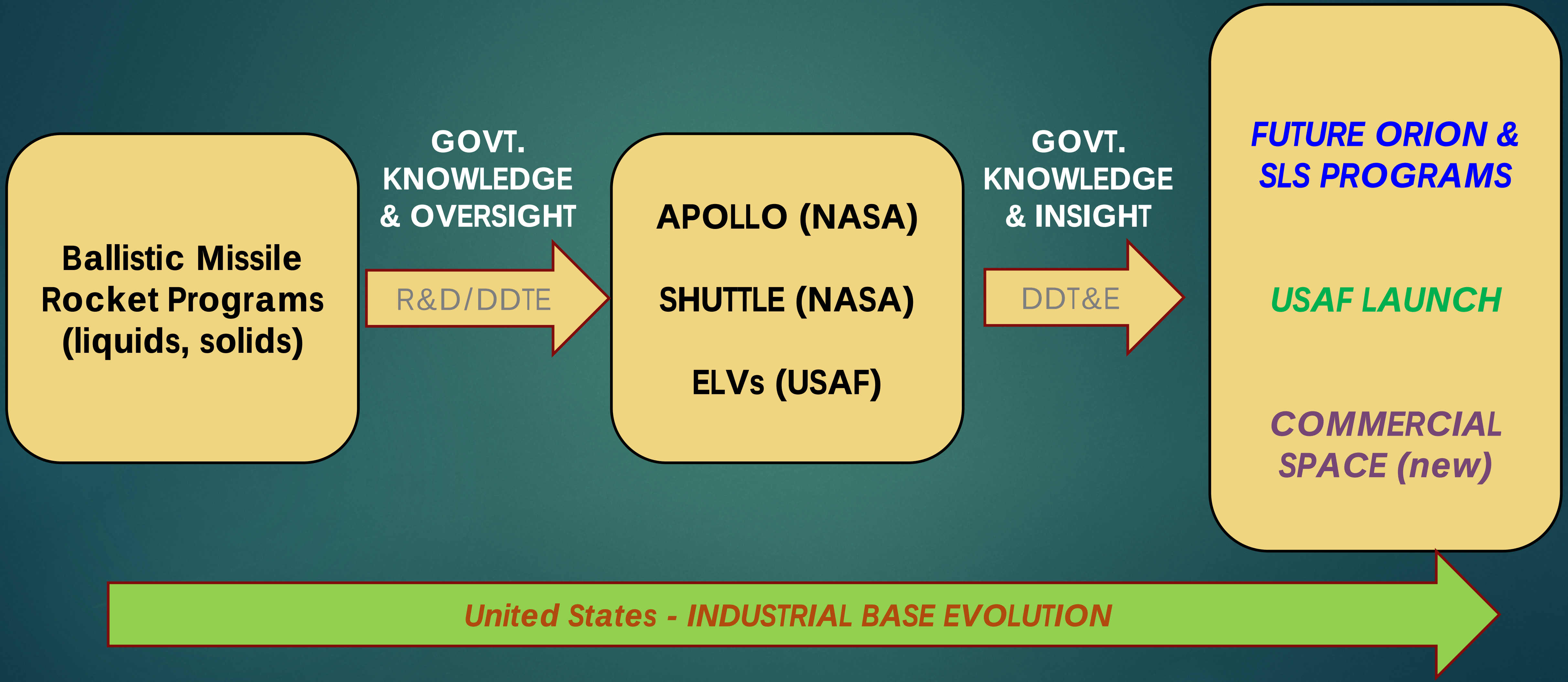
Pfeifer (RCS)
Aerojet

Harmon (Ascent)
Rocketdyne

Boyce (SPS)
Aerojet

Elverum (LMDE)
TRW

AUDIENCE FEEDBACK



EM-1 Near Term (next year)

ARTEMIS 1
(Exploration Mission 1)

- 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**

www.nasa.gov/Orion
www.nasa.gov/SLS

Simulation Image of EM-1 Ascent (uncrewed)

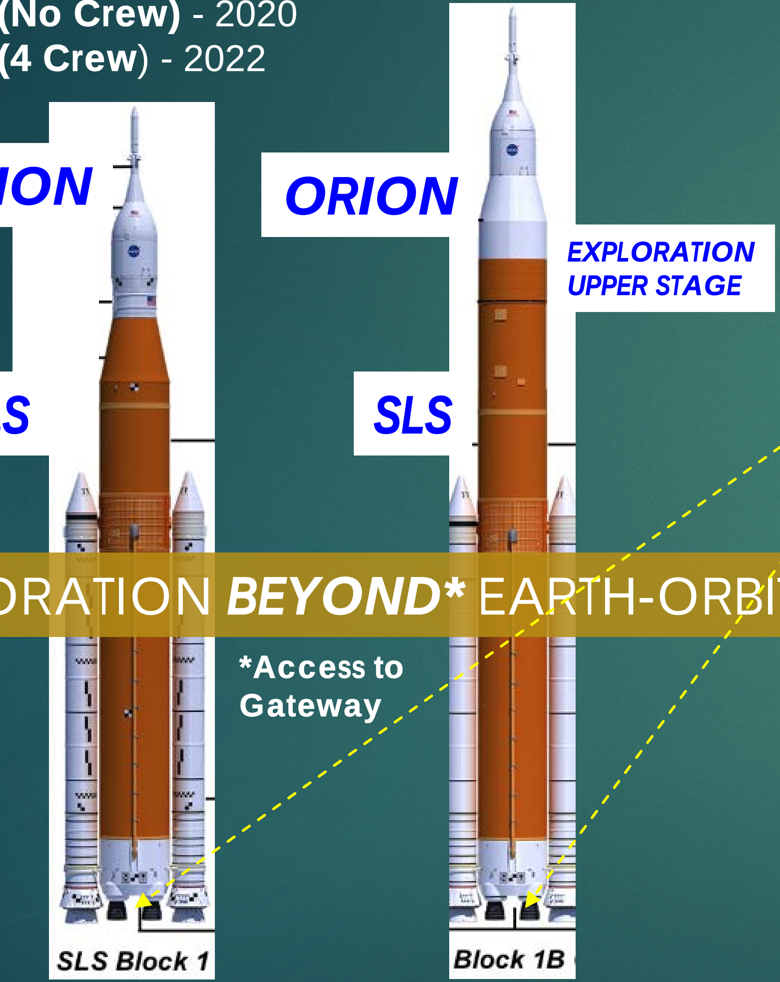
Thank you for your interest !!

NASA Work -

EM-1 Patch

EM-1 (No Crew) - 2020
EM-2 (4 Crew) - 2022

EM-3 (4 Crew)



EXPLORATION ***BEYOND**** EARTH-ORBIT

***Access to Gateway**

2018

- Orion to SLS INTEGRATION (since 2014)

ROCKET GROUND TEST *(SSC)*

Flight Engine – SSME (now RS-25)

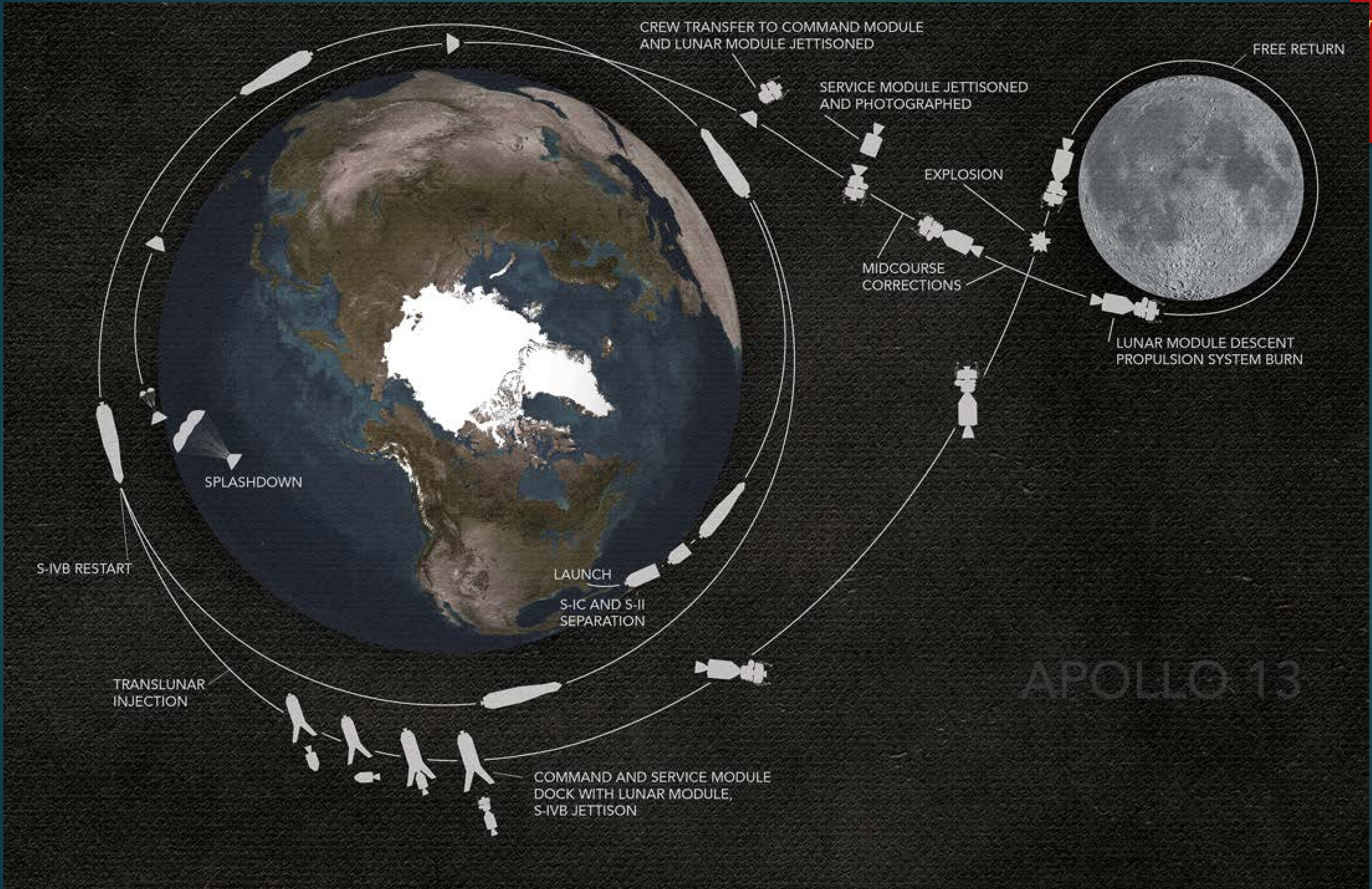
Flight Engine – Delta 4

R&D Engine - IPD

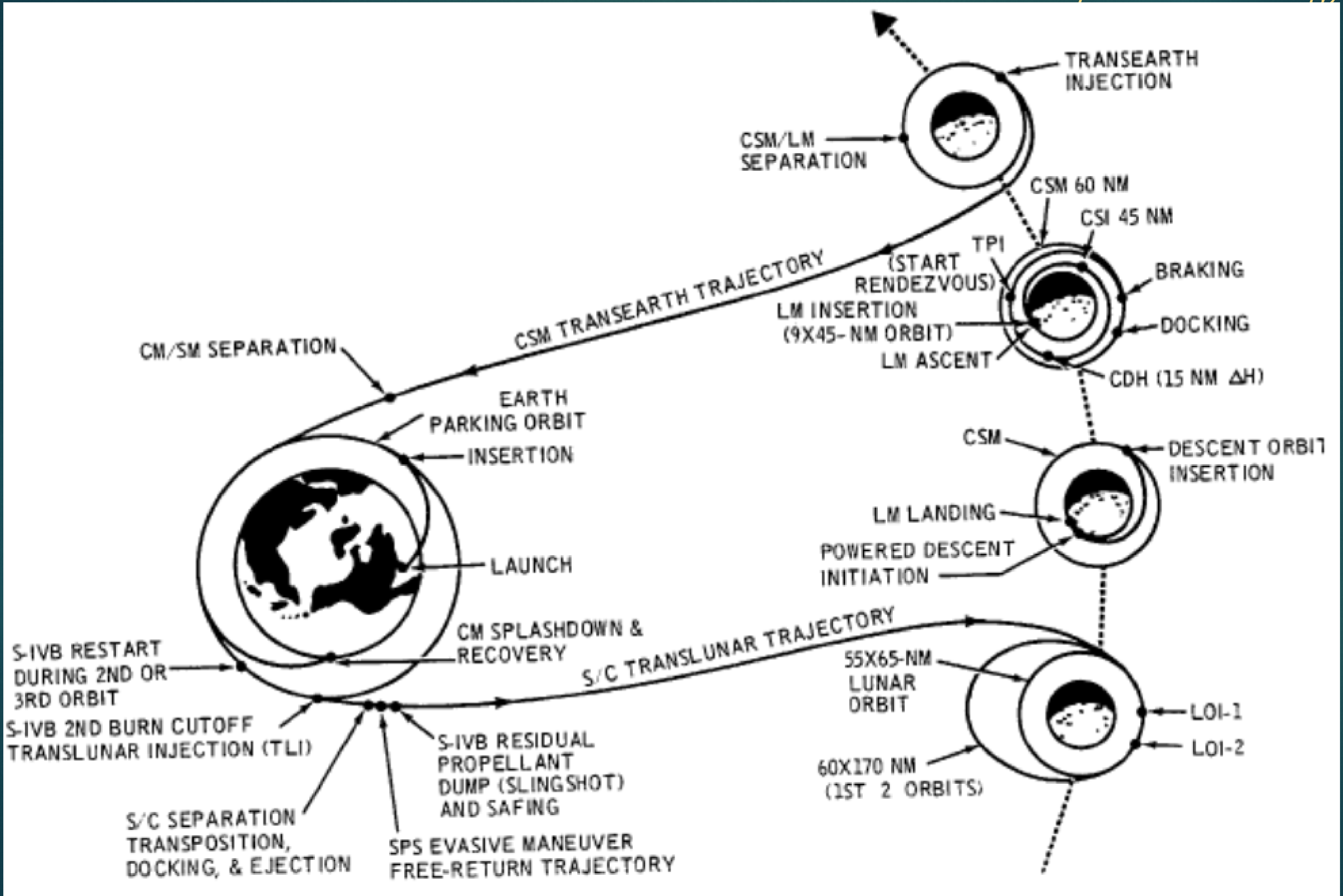
SHUTTLE *(Earth Orbit)*

1981 Intern

Rockwell Thermal Group (JSC)

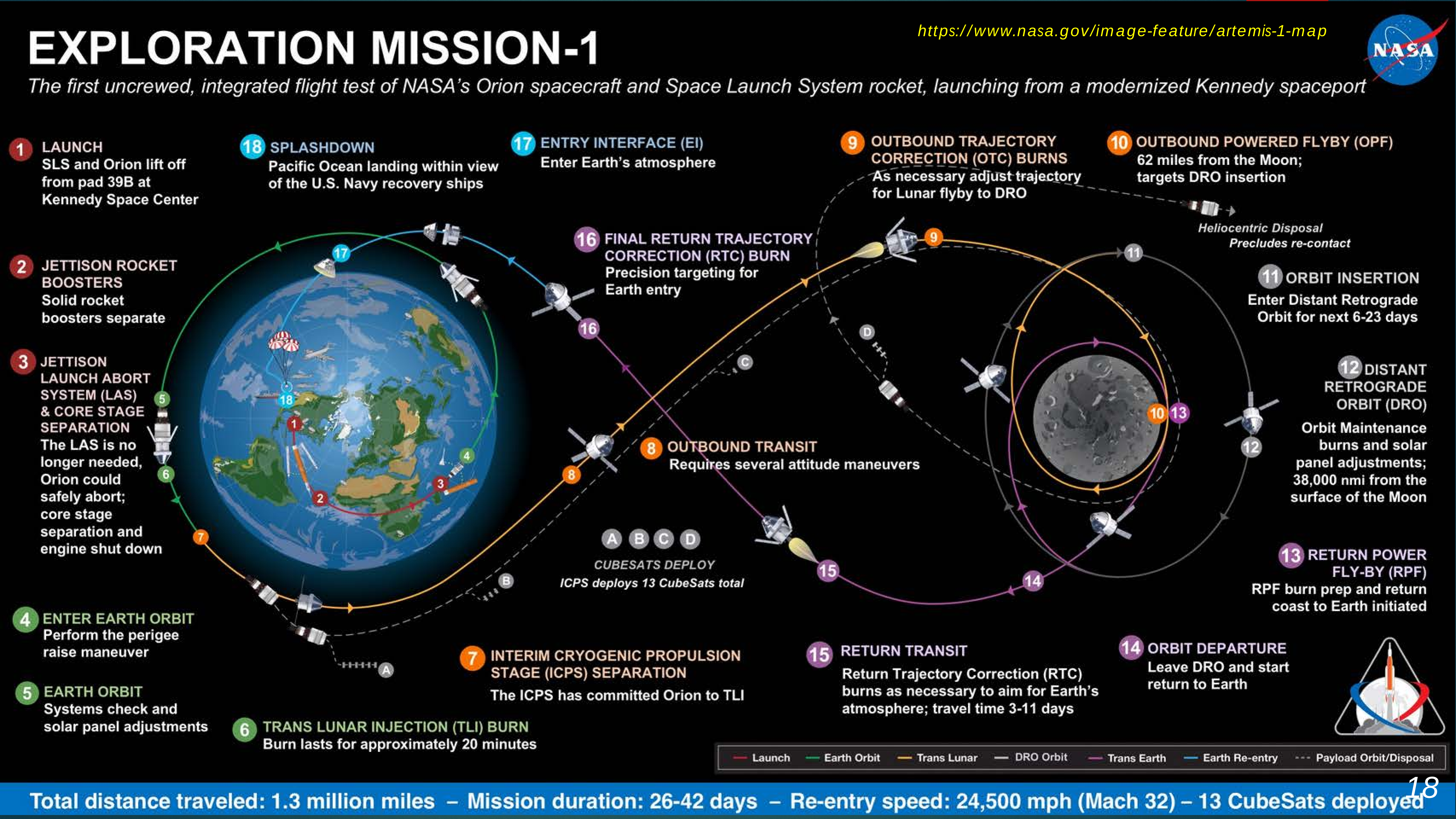


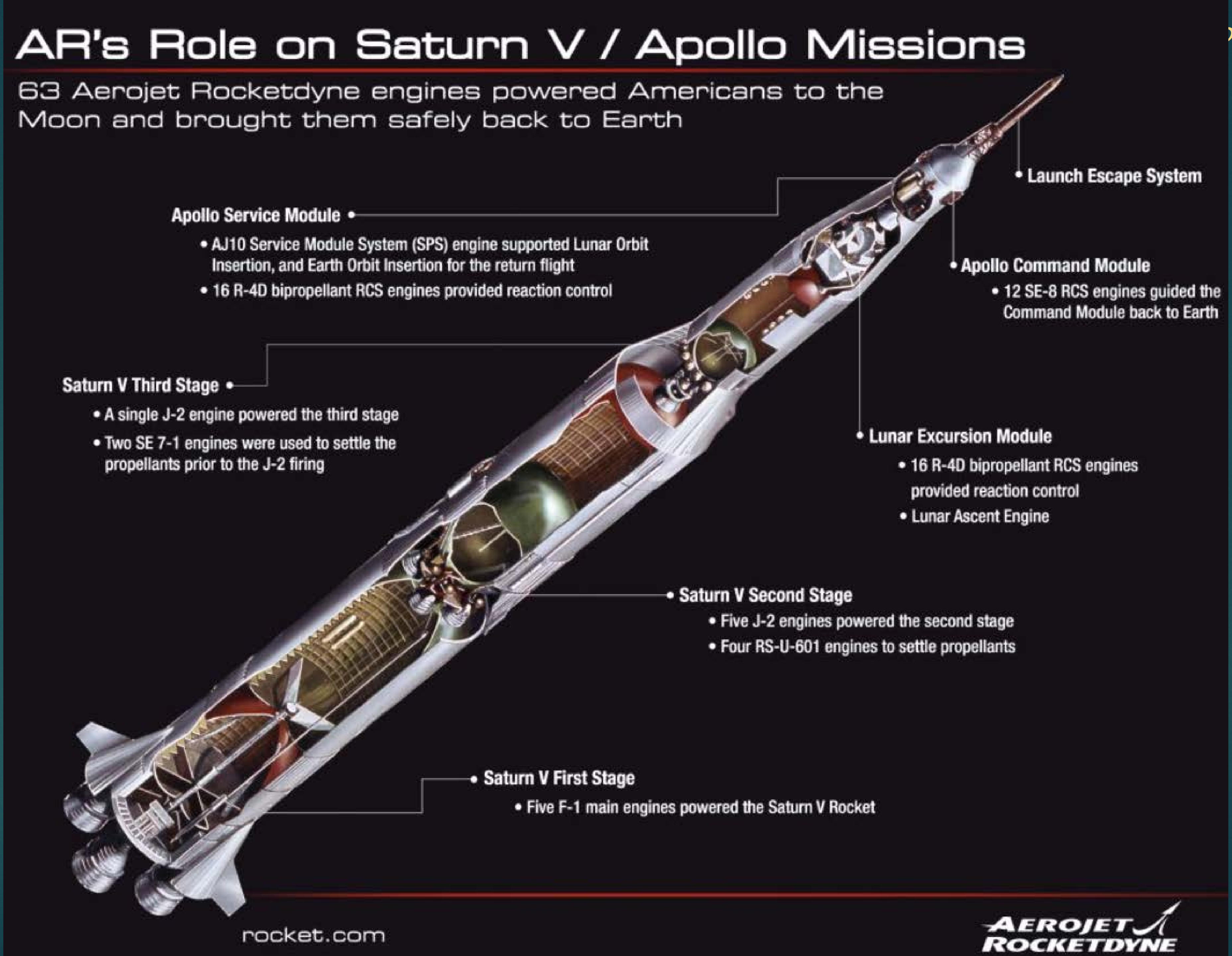
CREW TRANSFER TO COMMAND MODULE
AND LUNAR MODULE JETTISONED
FREE RETURN
SERVICE MODULE JETTISONED
AND PHOTOGRAPHED
EXPLOSION
MIDCOURSE
CORRECTIONS
LUNAR MODULE DESCENT
PROPULSION SYSTEM BURN
SPLASHDOWN
S-IVB RESTART
LAUNCH
S-IC AND S-II
SEPARATION
TRANSLUNAR
INJECTION
COMMAND AND SERVICE MODULE
DOCK WITH LUNAR MODULE,
S-IVB JETTISON
APOLLO 13


TRANSEARTH INJECTION
CSM/LM SEPARATION
CSM 60 NM
CSI 45 NM
TPI (START RENDEZVOUS)
BRAKING
LM INSERTION (9X45-NM ORBIT)
DOCKING
LM ASCENT
CDH (15 NM ΔH)
CSM TRANSEARTH TRAJECTORY
CM/SM SEPARATION
EARTH PARKING ORBIT
INSERTION
CSM
DESCENT ORBIT INSERTION
LM LANDING
POWERED DESCENT INITIATION
LAUNCH
CM SPLASHDOWN & RECOVERY
S/C TRANSLUNAR TRAJECTORY
S-IVB RESTART DURING 2ND OR 3RD ORBIT
55X65-NM LUNAR ORBIT
LOI-1
LOI-2
S-IVB 2ND BURN CUTOFF TRANSLUNAR INJECTION (TLI)
S-IVB RESIDUAL PROPELLANT DUMP (SLINGSHOT) AND SAFING
60X170 NM (1ST 2 ORBITS)
S/C SEPARATION TRANSPOSITION, DOCKING, & EJECTION
SPS EVASIVE MANEUVER FREE-RETURN TRAJECTORY

Pictured (left to right): Steve Fisher, Clay Boyce, Bob Biggs, Gerald Pfeifer, Tim Harmon, Gerard Elverum, Paul Coffman, and Shamim Rahman.

An actual F-1 Engine is shown in the background; a display model in front of the NASA SSC onsite visitor center, April 2006.


EXPLORATION MISSION-1
https://www.nasa.gov/image-feature/artemis-1-map
NASA
The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport
1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center
2 JETTISON ROCKET BOOSTERS
Solid rocket boosters separate
3 JETTISON LAUNCH ABORT SYSTEM (LAS) & CORE STAGE SEPARATION
The LAS is no longer needed, Orion could safely abort; core stage separation and engine shut down
4 ENTER EARTH ORBIT
Perform the perigee raise maneuver
5 EARTH ORBIT
Systems check and solar panel adjustments
6 TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes
7 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION
The ICPS has committed Orion to TLI
8 OUTBOUND TRANSIT
Requires several attitude maneuvers
9 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for Lunar flyby to DRO
10 OUTBOUND POWERED FLYBY (OPF)
62 miles from the Moon; targets DRO insertion
Heliocentric Disposal
Precludes re-contact
11 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-23 days
12 DISTANT RETROGRADE ORBIT (DRO)
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon
13 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated
14 ORBIT DEPARTURE
Leave DRO and start return to Earth
15 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days
16 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry
17 ENTRY INTERFACE (EI)
Enter Earth's atmosphere
18 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships
A B C D
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total
Launch
Earth Orbit
Trans Lunar
DRO Orbit
Trans Earth
Earth Re-entry
Payload Orbit/Disposal
Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed


AR's Role on Saturn V / Apollo Missions
63 Aerojet Rocketdyne engines powered Americans to the Moon and brought them safely back to Earth
Launch Escape System
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
Apollo Command Module
• 12 SE-8 RCS engines guided the Command Module back to Earth
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
Lunar Excursion Module
• 16 R-4D bipropellant RCS engines provided reaction control
• Lunar Ascent Engine
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
rocket.com
AEROJET ROCKETDYNE

List of References

- NASA Monograph 45 (2009) – Remembering the Giants: Apollo Rocket Propulsion Development
- AIAA Papers 2001-0749 & 3985 (2001) – on LOX/RP and LOX/LH Engines DDT&E history.
- NASA SP 125 (1971): Huzel & Huang – Design of Liquid Propellant Rocket Engines
- USAF SMC Standard SMC-S-025 (2017) – Evaluation & Test Requirements for Liquid Rocket Engines
- JANNAF-GL-2012-01-R0 (2012) – Test & Evaluation Guidelines for Liquid Rocket Engines

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

Recent Propulsion designers studied Huzel/Huang - ☺