Activities at the CSNR for the NTR, Mars Hopper and a Mars Sample Return

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Nuclear technologies in space require launching radioactive sources

- **Fission Surface Power (FSP) – deemed ENABLING by the NASA Mars Architecture Team (2008)**
- **Multi Mission Radioisotope Thermoelectric Generators (MMRTG) and Advanced Stirling Radioisotopic Generator (ASRG) are ENABLING for all long duration missions beyond Mars**
- **Nuclear Thermal Rockets (NTR) – deemed the PREFERRED technology by the Mars Architecture Team for the human mission**

A Universal Encapsulation method that is qualified for launch allows all of these applications

Today's Topics

- **Universal encapsulation of radioisotopes**
- **Mars Hopper**
- **Nuclear Thermal Rocket (NTR)**
- **NTR Driven Mars Sample Return Mission**
- **Student programs at the CSNR**

Universal Encapsulation - Common technology for reactor fuels and radioisotope sources

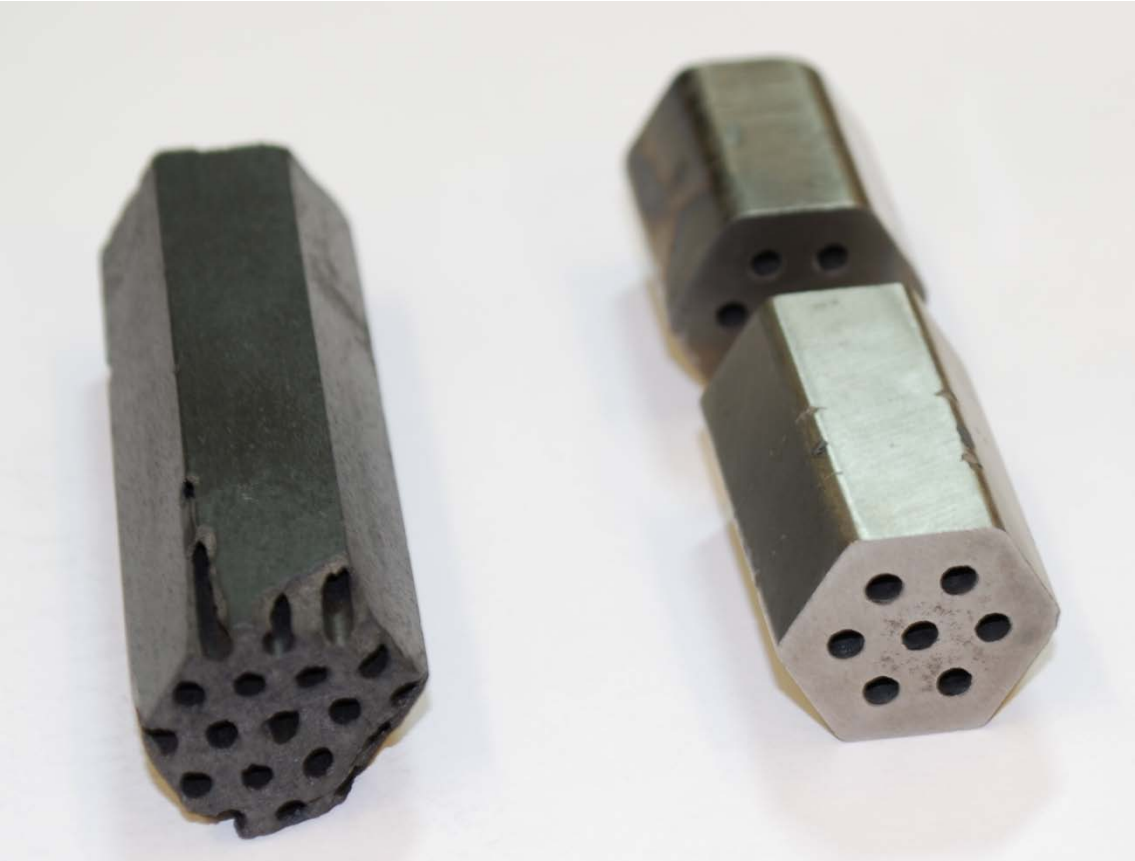
- **The distribution and encapsulation of radioisotope materials and nuclear fuels in an inert carrier matrix will address several issues and requirements for space power applications:**
  - Potential to address non-proliferation security requirements.
  - The ability to survive re-entry into Earth's atmosphere and impact under accident conditions.
  - Assembly & handling safety
  - Reduction in material self interaction such as α-n reactions.
  - Self-shielding properties.
- **The SPS acquired with a INL LDRD grant enables fabrication of tungsten parts at nearly full theoretical density**

Tungsten Cermet Fuels

- **Ceramic-Metallic (cermet) matrix composed of ceramic fuel (UO_2 or UN) and tungsten alloy carrier**
- **Provide mechanical retention of nuclear fuels and fission products**
- **Provide good thermal conduction paths to coolant or propellant (NTR)**
- **Provide resistance to hot-hydrogen erosion and embrittlement.**
- **High melting temperature temperature (3422ºC)**
  - **high operational temperatures**
  - **resistance to atmospheric re-entry**
- **Investigated under 710-Program (Hot pressed)**
  - **- Fabrication process crucial to production success**

Fuel Element production by SPS

- (Left) NERVA graphite fuel element
- (Right) Leicester / CSNR tungsten fuel elements upon removal from die (no machining required)



Several applications will benefit from a qualified Universal Encapsulation

- **Advanced radioisotope sources**
- **Mars Hopper**
- **Nuclear Thermal Rocket**
- **Nuclear surface reactor**

Mars Hopper:
A radioisotope powered, long-lived, long-range mobile platform using in-situ resources

Initiated in the 2009 CSNR Summer Fellows program

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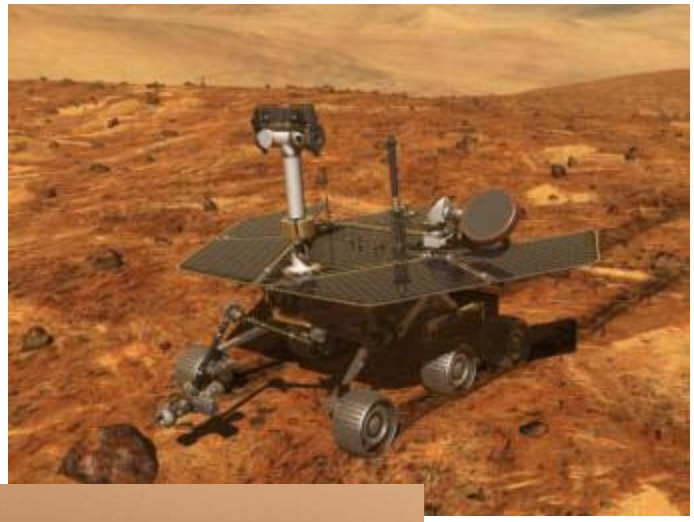
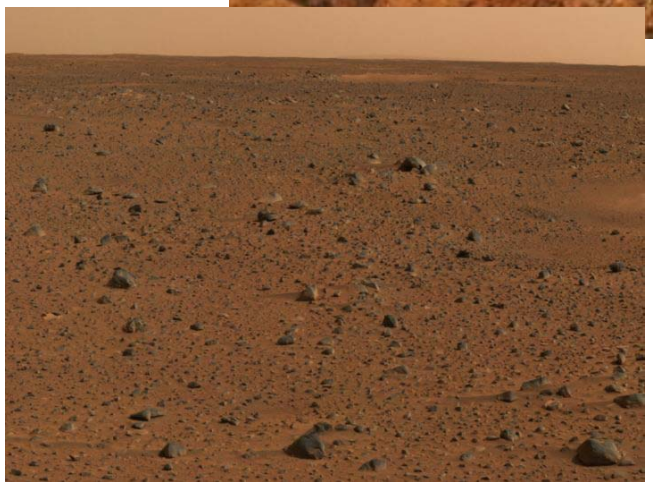
Planetary exploration is getting tougher

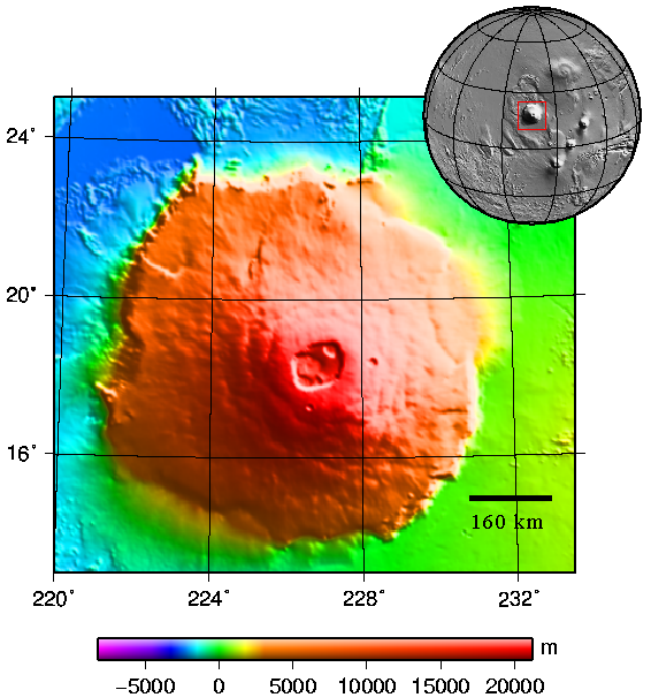
- **Planetary exploration is getting expensive**
- **Orbital good but still don't know subsurface constituency or water to high resolution**
- **MERs did great but only 15 km total after 5 years**
- **Surface landings necessitate flat, safe landing site**
- **Need more science per $**

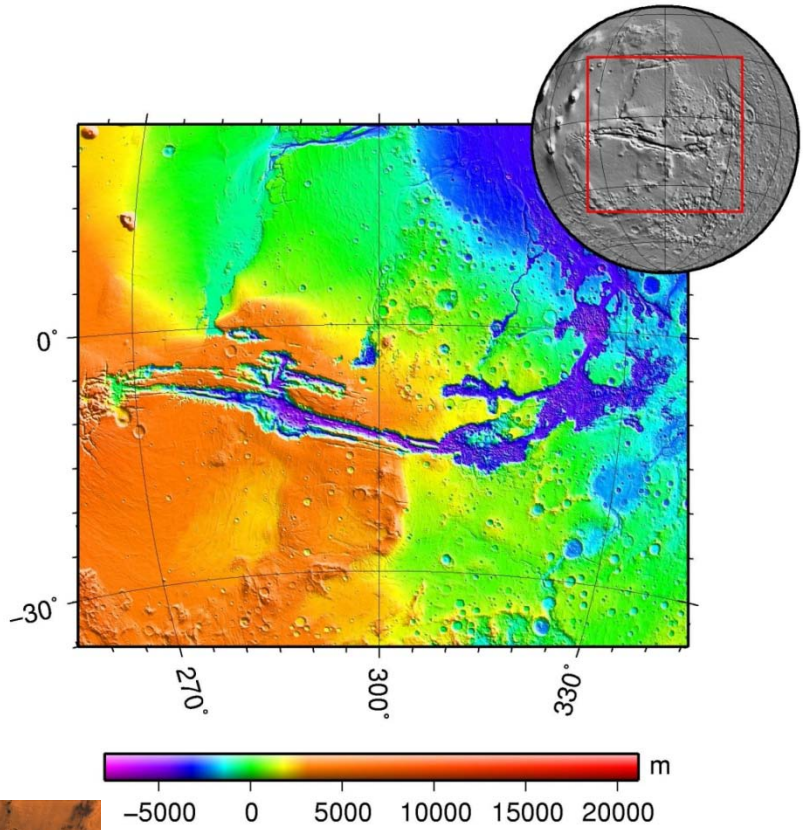


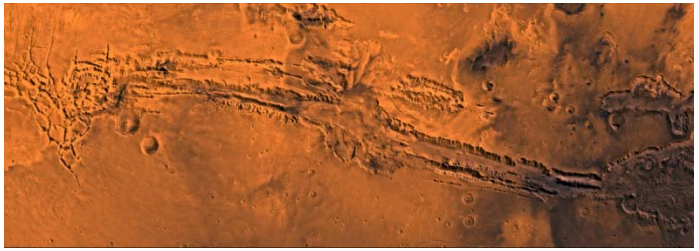


Interest in canyon walls, mountainsides, deep canyon bottoms

Olympus Mons







Valles Marineris

Concept

- The Mars Hopper concept utilizes energy from radioisotopic decay in a manner different from any existing RTGs, i.e. as a thermal capacitor.
  - Radioisotope sources have very high specific energy, j/kg, while having rather low specific power, w/kg.
    - Pu-238 has a specific energy of 1.6×10^6 MJ/kg which is 160,000 times the specific energy of chemical explosives.
    - Factoring in the 25% conversion to electricity, the system may have 4×10^5 MJ/kg of electrical energy compared to the 0.72 MJ/kg for Li-ion batteries.
  - By accumulating the heat from radioisotopic decay for long periods, the power of the source can be dramatically increased for short periods.

Concept

- **The basis for the concept is to utilize the decay heat from radioactive isotopes to heat a block of material to high temperatures.**
  - While the heating is taking place, some of the thermal power is diverted to run a cryocooler.
  - The cryocooler takes in the Martian atmosphere and liquefies it at 3 MPa.
  - Once the tank full, the power convertor is turned off and the core is allowed to increase in temperature.
  - After a peak temperature of 1200 K is reached, the liquid CO2 is injected into the core, heated, expanded through a nozzle, and allowed to produce thrust.
  - Part of the CO2 propellant is “burned” for ascent. After a ballistic coast, the remaining propellant is used for a soft landing.
  - Once landed, the process repeats.

Concept – Predicted performance for two payload masses

Characteristic	case 1	case 2	case 3
Mass payload (kg)	200	10	10
Total Energy stored (J)	1.0e8	1.0e8	1.5e7
Isotope power (W)	1000	1000	1000
Mass Pu-238 (kg)	2.0	2.0	2.0
Mass Beryllium (kg)	55.	55.	6.07
Mass flow(kg/s)	16.6	13.36	1.07
Mass initial (kg)	1061	852	75.7
Mass propellant (kg)	580	580	25.
Mass final/mass initial	0.45	0.32	.67
Ascent burn time (s)	16.45	22.6	23
Initial Thrust (N)	20115	16157	1436
Thrust at Burnout (N)	11854	9094	511
Burn Out Vel (ms^{-1})	230	327	213
Range (km)	15.9	30.9	6.2

Ultimate goal is the Mars Sample Return

- **High priority mission**
- **Difficult to accomplish due to ascent/descent requirements**
- **Conflict between safe landing site and getting samples from interesting regions**
- **Desire many samples from all over the planet**
- **Requires a long lived, highly mobile craft to acquire samples and accumulate them at a centralized location**

NTR Development - Strategic Issues

- **Performance sufficiently superior to justify "perceived" risk**
- **Radioactivity emitted during operation**
- **Risk for "proliferation"**
- **Sub-criticality on launch abort**
- **Cost of development**

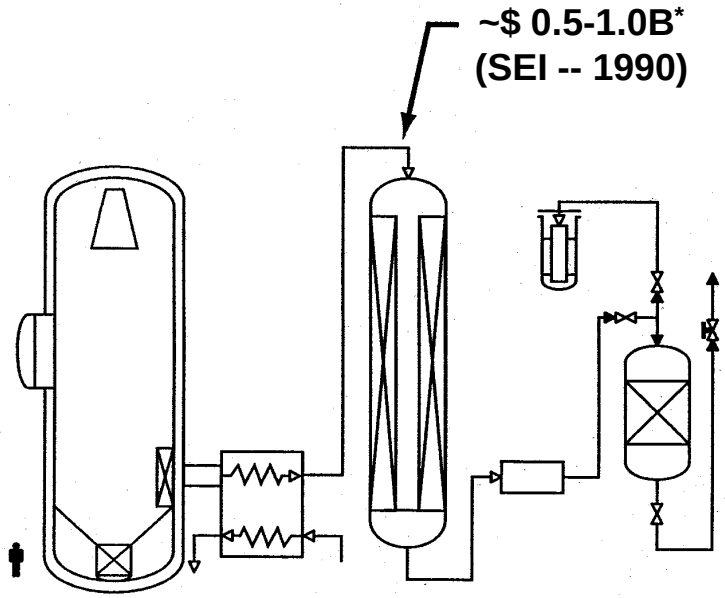
Benefits of the NTR have been shown for several missions

- **Moon - Reduce costs of implementing a Lunar Outpost**
- **Mars - Faster missions for humans; reduced radiation exposure; lower costs for cargo; adaptability to hazards**
- **Good Asteroid - rendezvous**
- **Bad Asteroid/comet - rapid interception; destruction**
- **Outer solar system – time to "first science" within a decade for orbitor missions to outer planets and to Kuiper Belt fly-through**

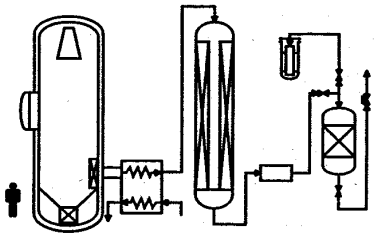
In short, the NTR opens up access to the entire solar system for humans and robotic probes

Cost of Development -- NTR Exhaust Treatment System (ETS) Size Scaling with Thrust Level

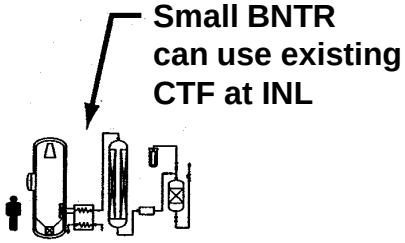
NOTE: Size of the ETS scales with hydrogen exhaust gas throughput from the engine. Small engines can be tested in the Contained Test Facility (CTF) at substantially lower cost than the large engines developed during the Rover / NERVA programs. Detailed cost estimates being prepared by INL and DOE for NASA GRC.



80 klb_f



40 klb_f



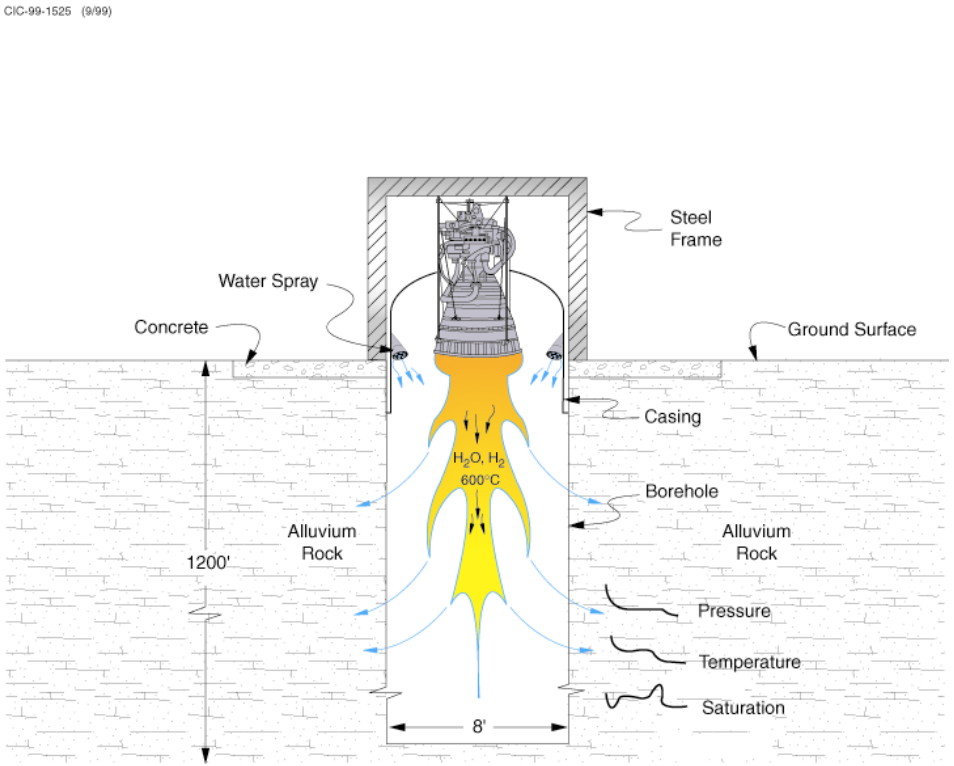
10-15 klb_f

* NOTE: Not shown above is the large containment structure that would enclose the engine & ETS and that is included in the cost number

Source: Idaho National Laboratory (INL)

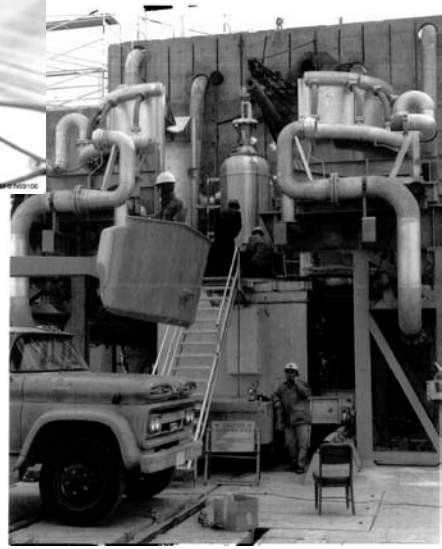
Cost fo Development- Sub-surface Active Filtering of Exhaust (SAFE) may enable much cheaper ground tests

- **Nuclear furnace proved ability to scrub exhaust**
- **Scaling to full power engines implies a costly facility**
- **SAFE offers one cheaper option if proven feasible**
- **If fuel doesn't leak fission products, then test facility is only for off-nominal conditions**



Pewee was a lessons learned test of a small NTR

- **The goal was to produce a reactor with 500 MW thermal power (corresponding to around 25,000 lbsf of thrust (estimated) and a thrust to weight ratio greater than 4).**
- **A major design change was the incorporation of lithium-hydride into the tie-tubes. This softened the neutron spectrum somewhat and enabled a smaller mass core.**
- **The ratio of fuel elements to tie-tubes was decreased from the 6:1 value in the Phoebus engines to 3:1.**
- **The chamber pressure in the Pewee was designed to be around 800 psia. This enabled a higher power density of around 1.4 MW per fuel element, 50% greater than the power density in the NERVA engine.**
- **The Pewee I was tested at the Nuclear Rocket Development Station at the Nevada Test Site in December of 1968.**
- **The reactor operated at full power for 40 minutes at 503 MW with an estimated specific impulse of 845 s. Estimated thrust would have been just over 27,000 lbf.**
- **Total engine mass was 2570 kg indicating a thrust to weight potential of 4.8. Maximum power density was 5200 MW/m3.**



Aerojet contract

- **Aerojet has contracted with the CSNR**

- **1) to fabricate samples in the SPS**
- **2) purchase a glove box to be integrated onto a new Thermal Technologies' SPS furnace being purchased by the INL (Dr. O'Brien's initiative)**
  - Joint effort- 400K inl, 150 k aerojet
  - Enables the fabrication using DU
  - 7 times current of current SPS
  - Longer displacement

Mars Sample Return Mission Architecture Utilizing a Nuclear Thermal Rocket

CSNR 2010 Summer Fellows

Ross Allen, Regal Ferrulli, Brian Manning

Center for Space Nuclear Research

September 9th, 2010

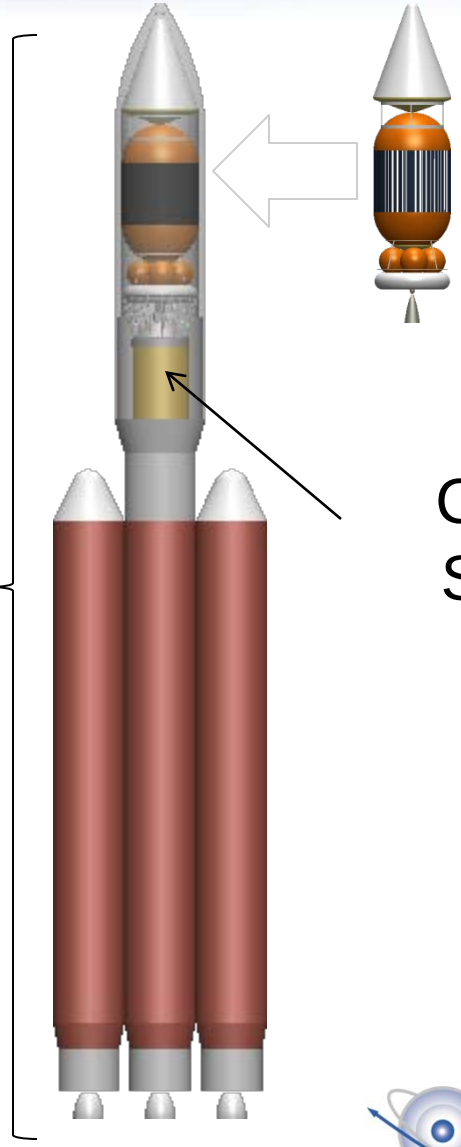
Basic Mission Design:

- **Place entire craft in LEO with ONE Atlas V Heavy**
- **Conjunction class transfer to Mars with H_2**
- **Mars arrival**
  - Burn with H_2 and enter highly elliptical orbit
  - Aerobrake return rocket/tank
- **Descend lander vehicle with NH_3**
- **500 day stay on Mars**
- **Collect 100 kg of Martian samples from hoppers**
- **Ascend with CO_2 to 200 km orbit**
- **Rendezvous with main vehicle and transfer samples**
- **Transfer to Earth with H_2**
- **Jettison sample entry capsule to Earth**

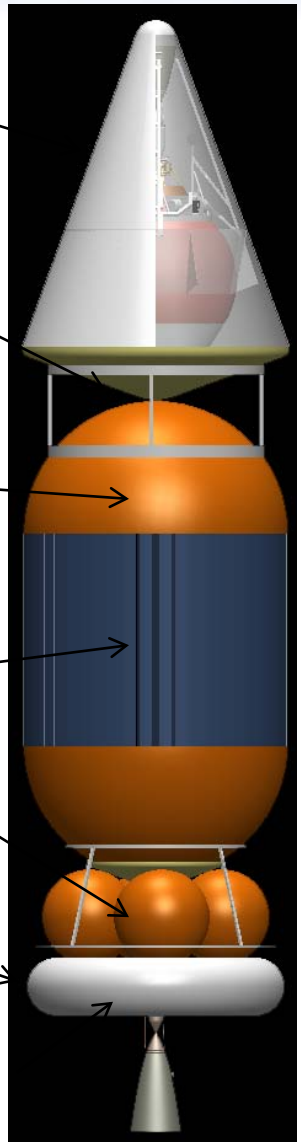
Spacecraft Configuration

Atlas V Heavy Lift Vehicle

- Places main craft in low Earth orbit (LEO)

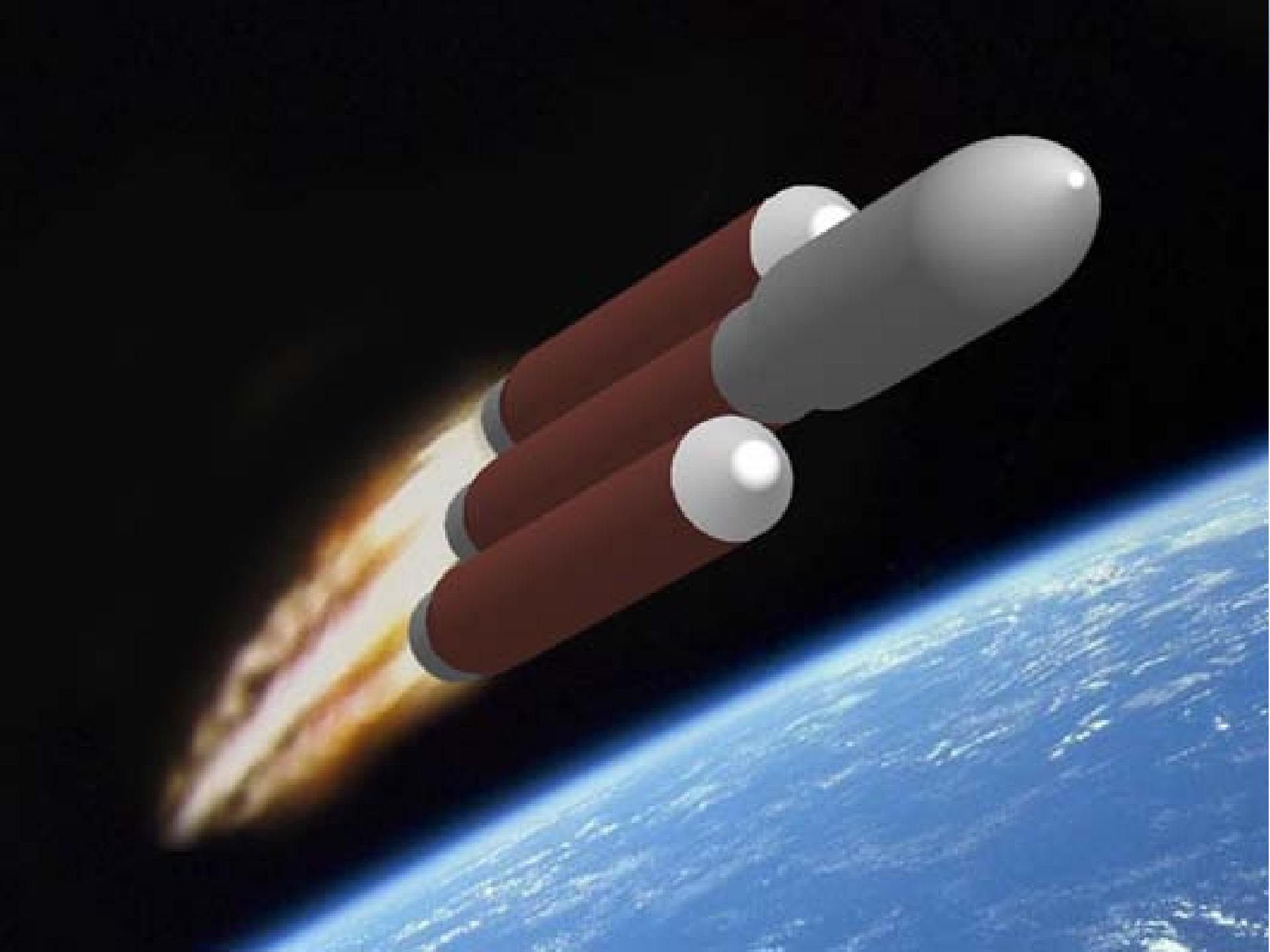


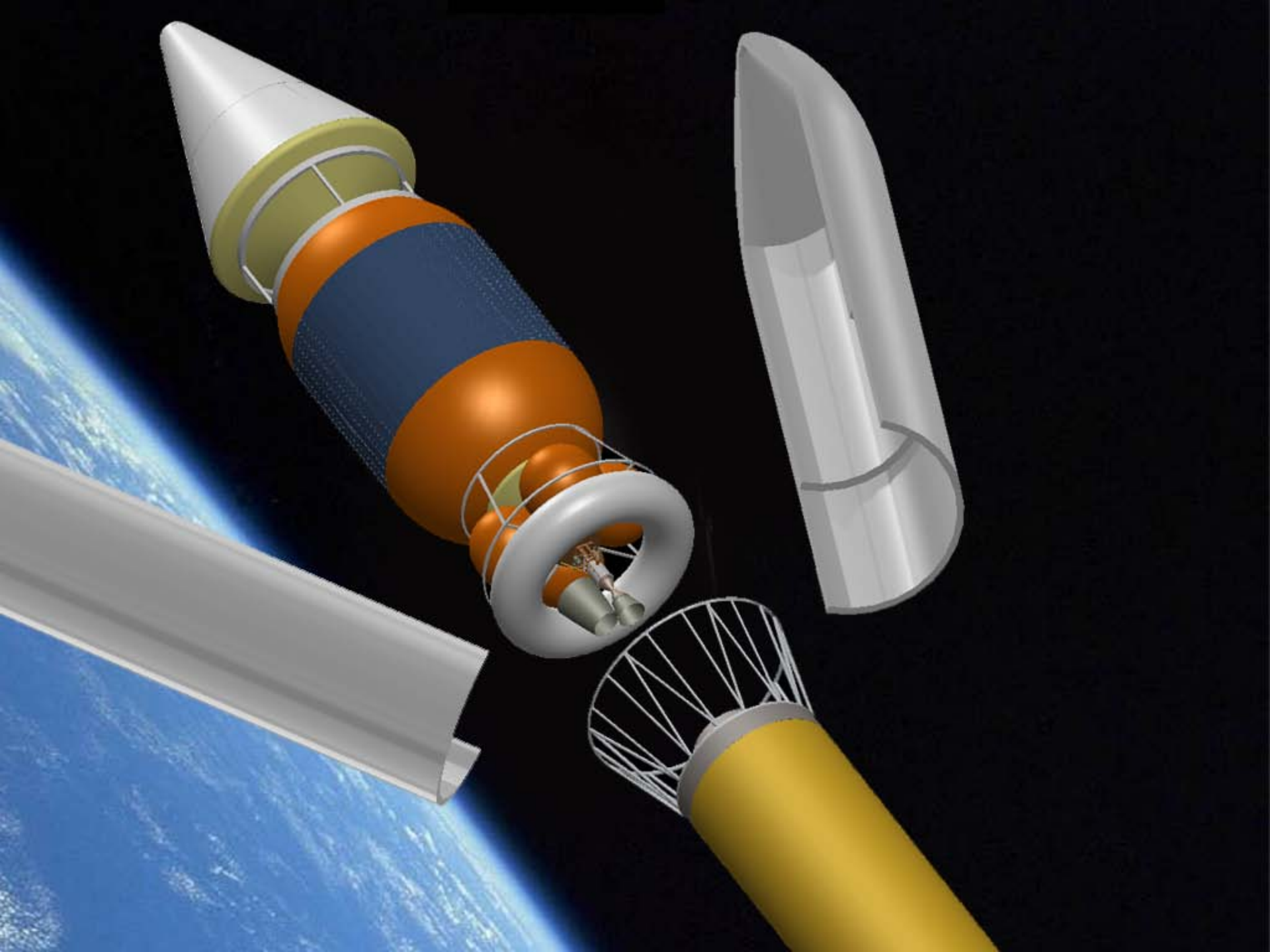
Spacecraft Configuration

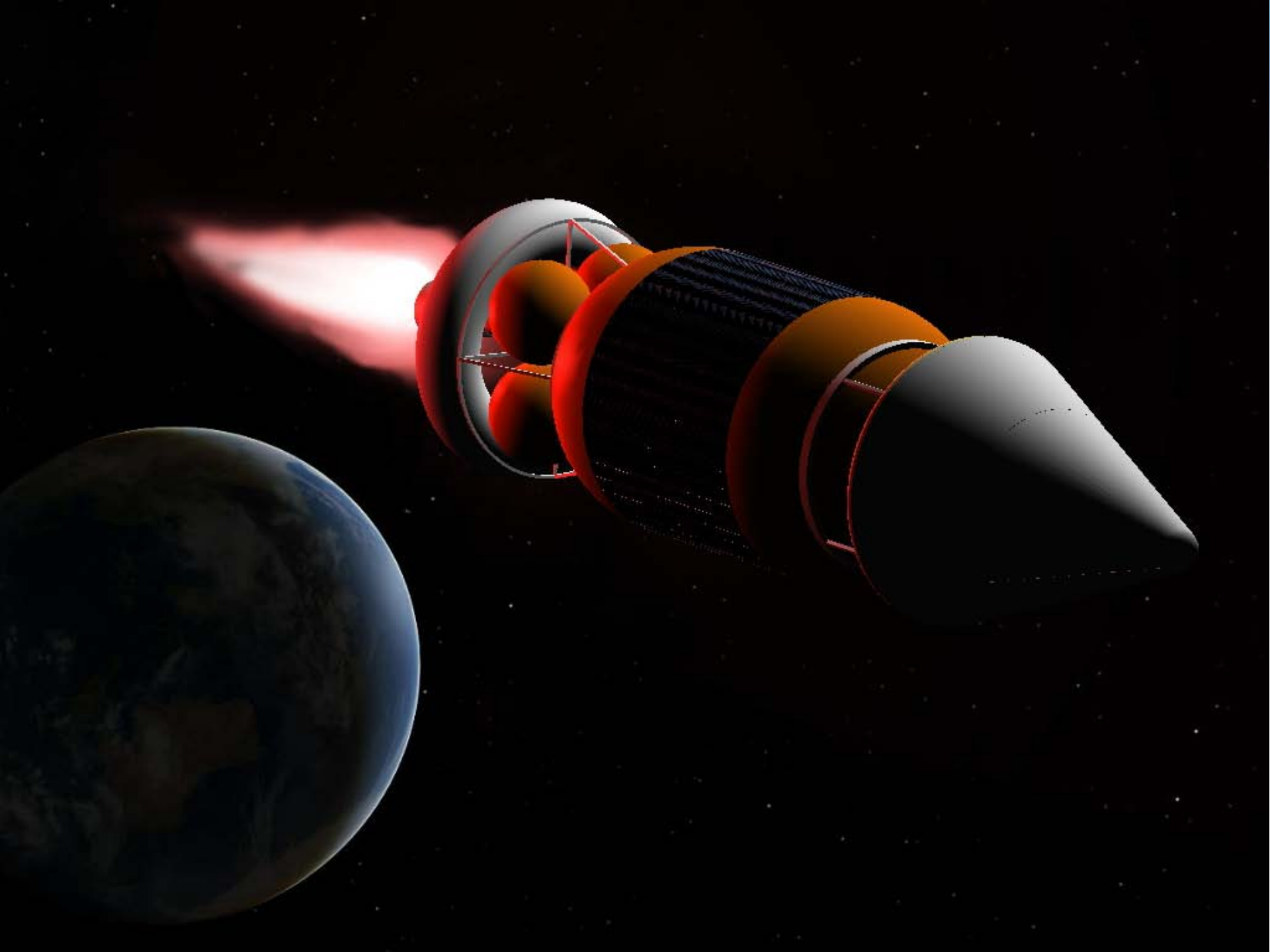


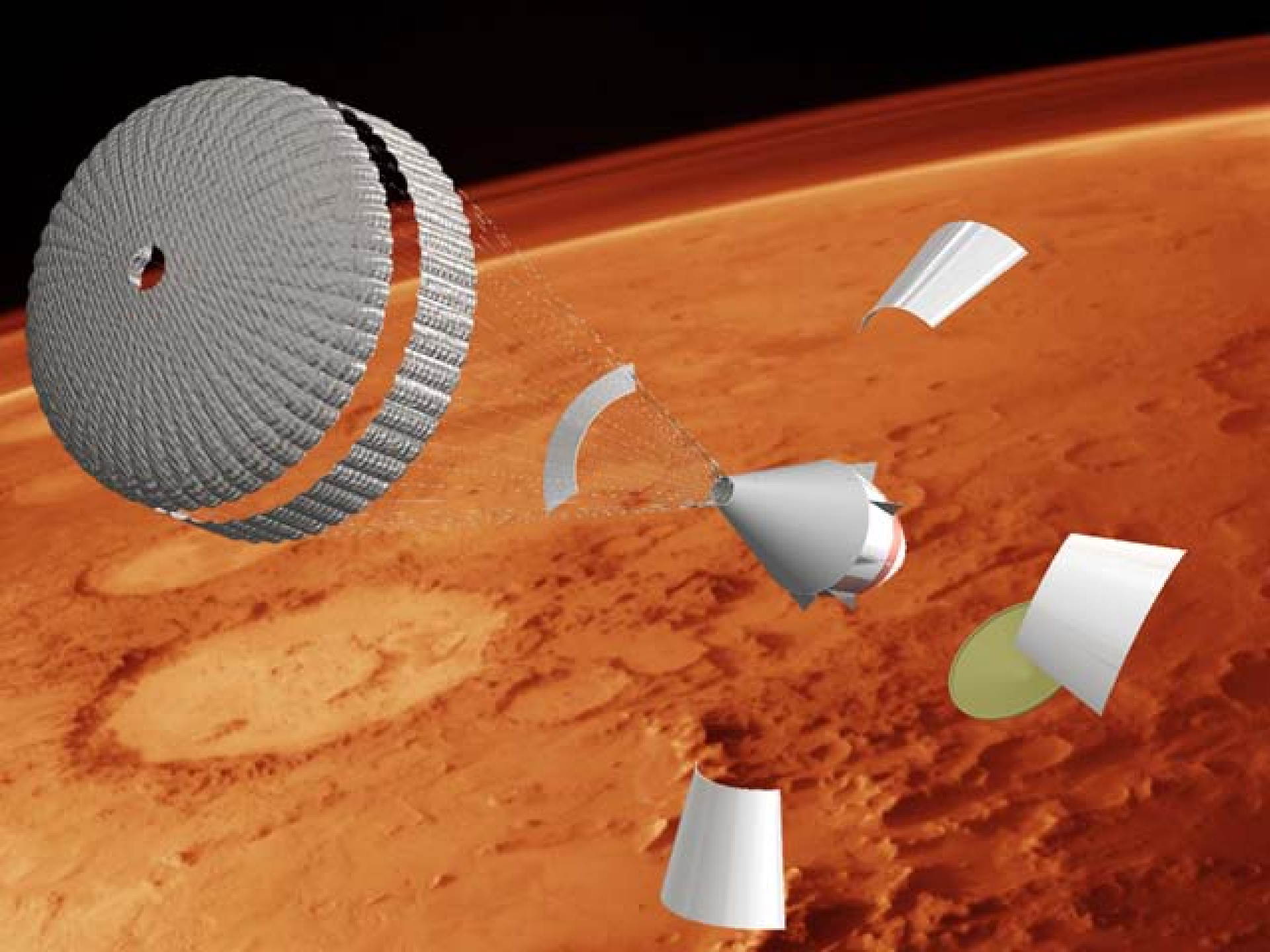
Main Craft

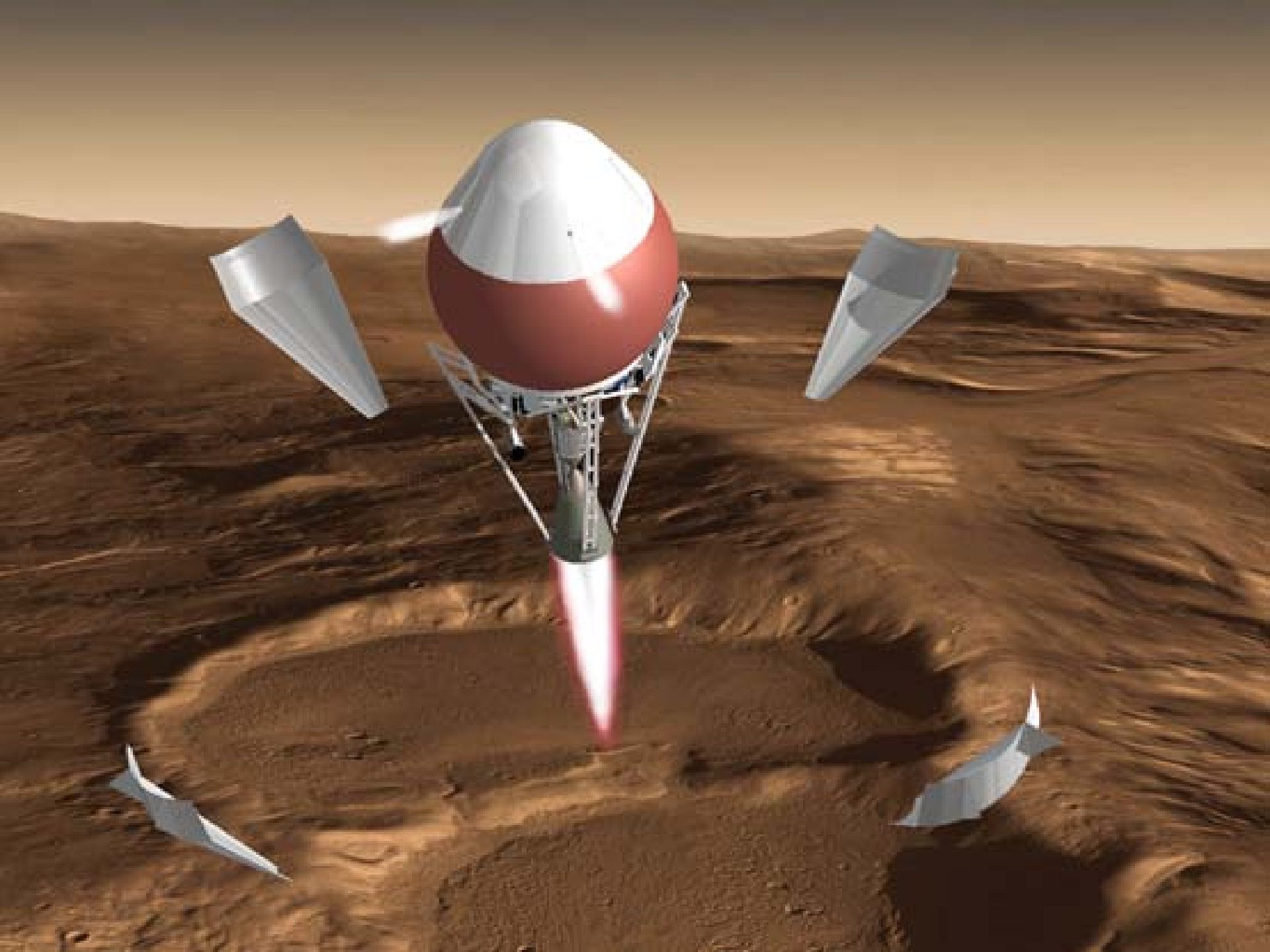
- Transports to Mars
- Orbits Mars during collection
- Rendezvous with ascent vehicle
- Transits back to Earth

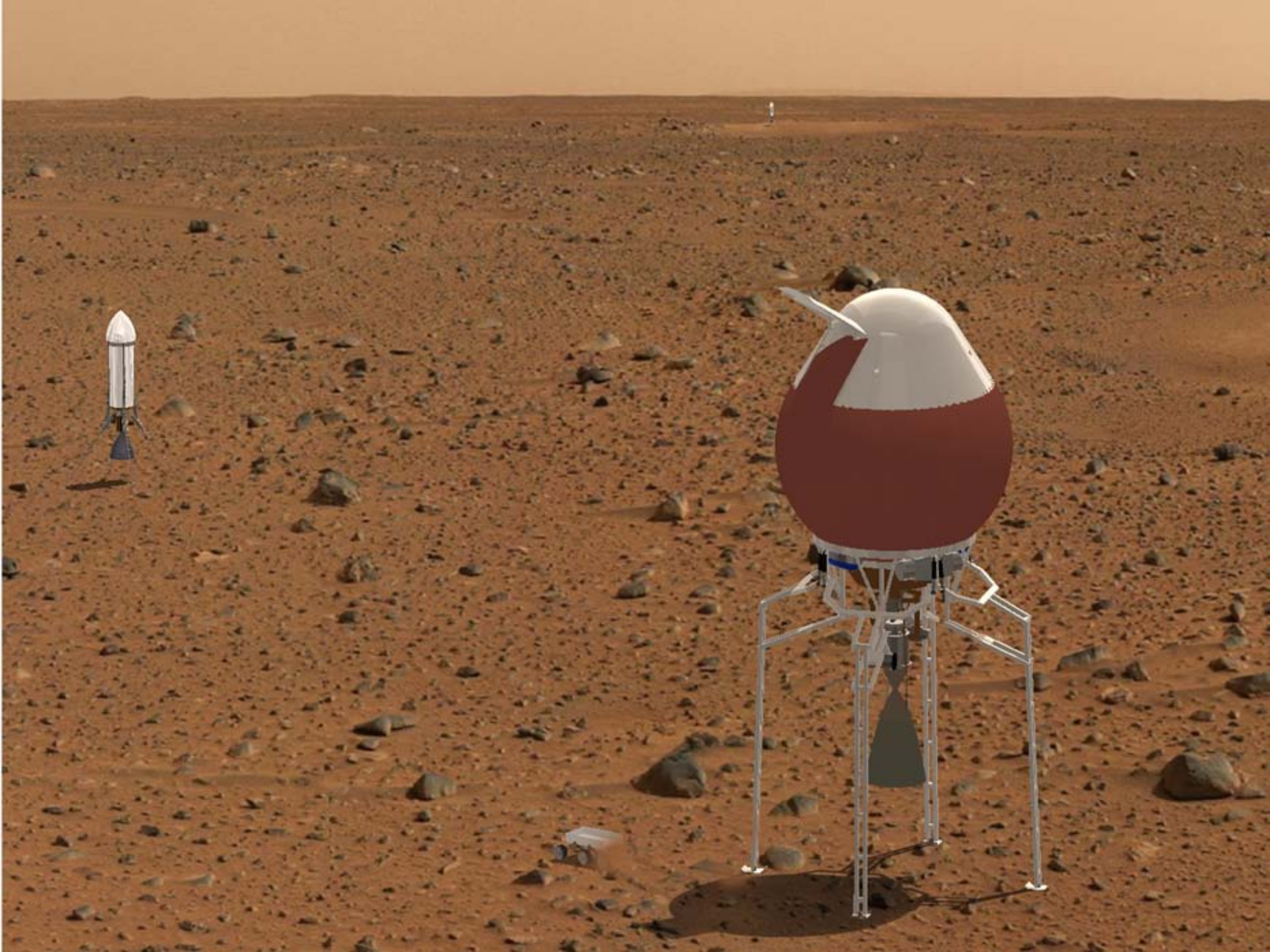


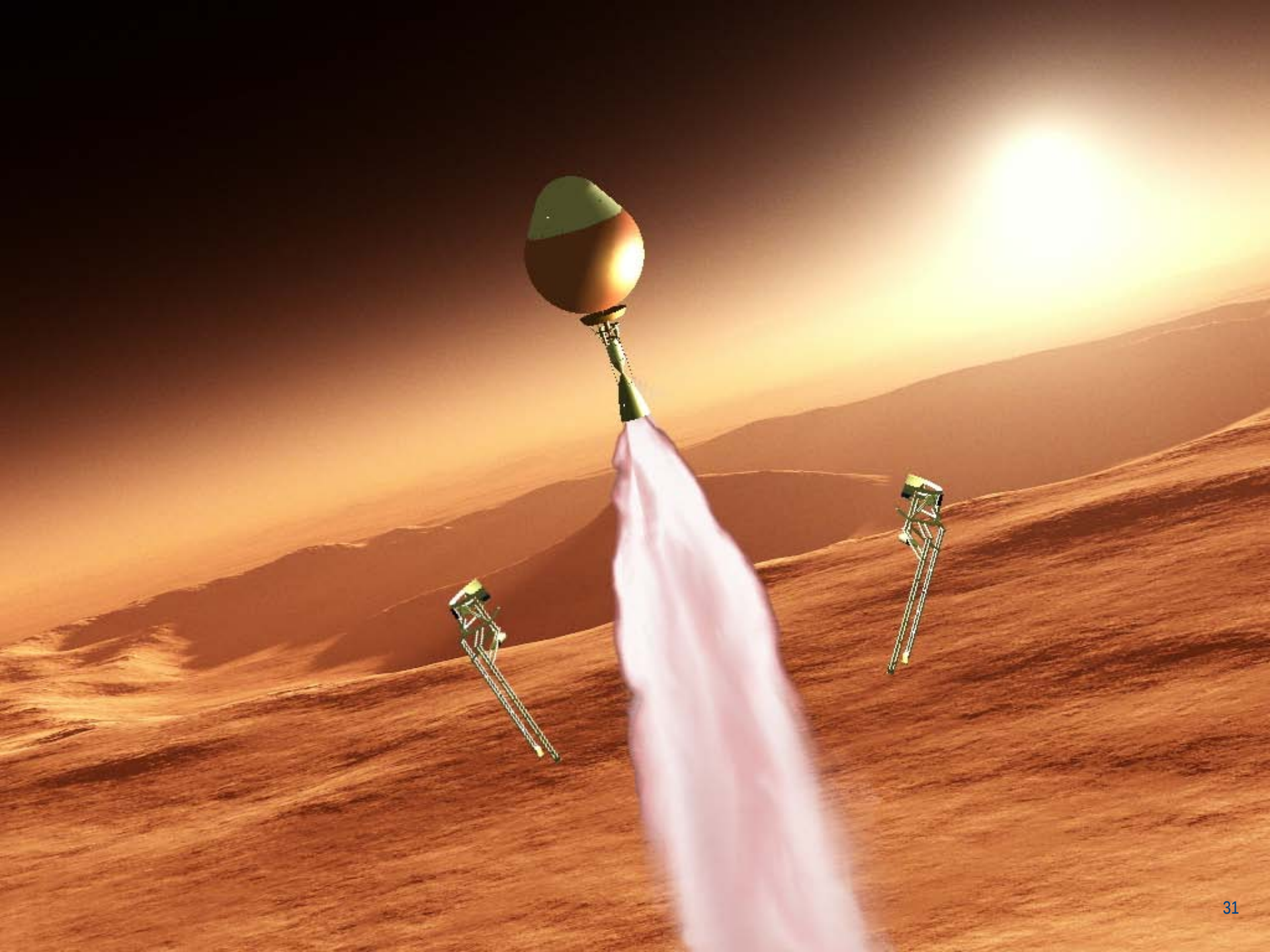


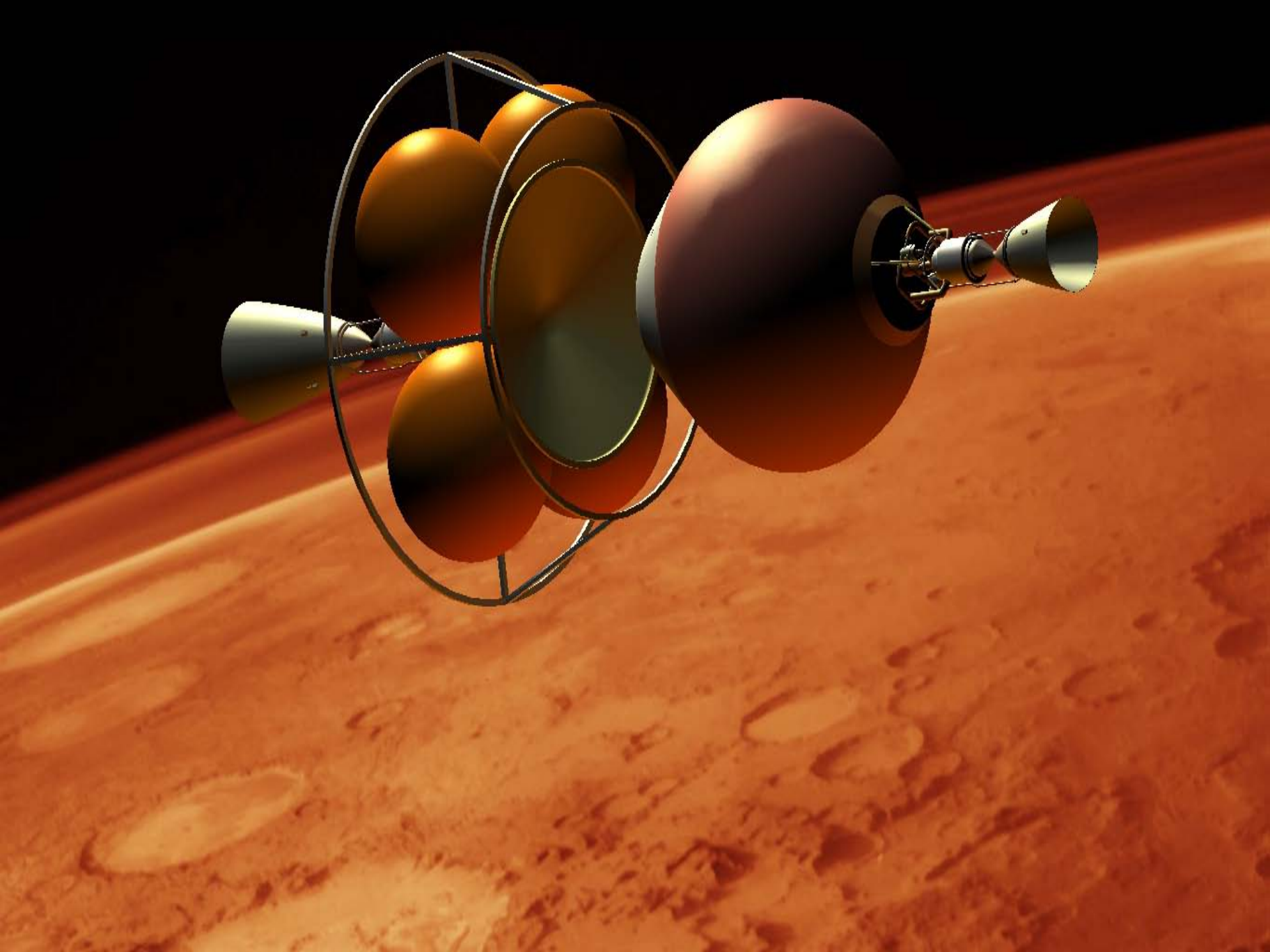


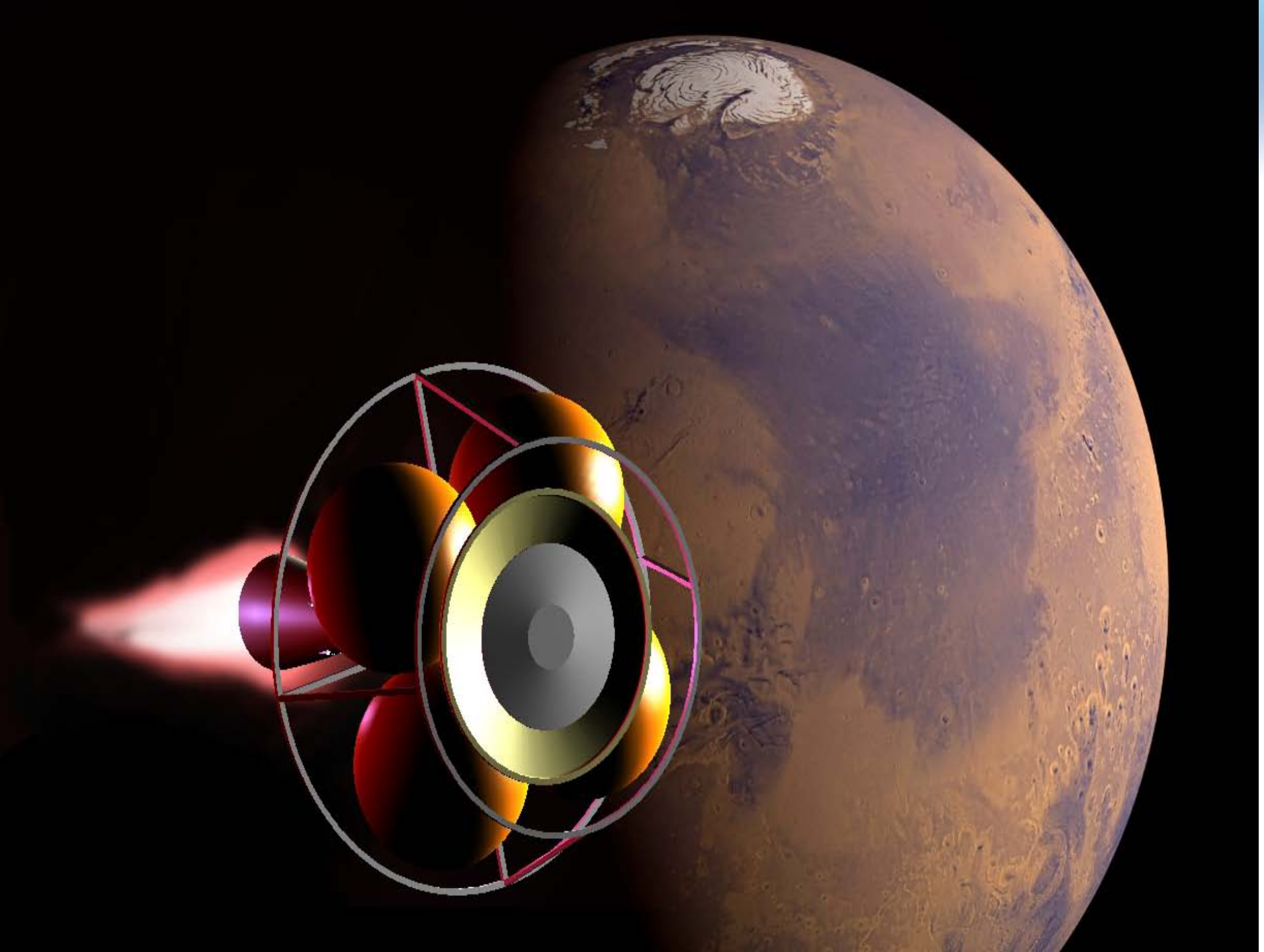












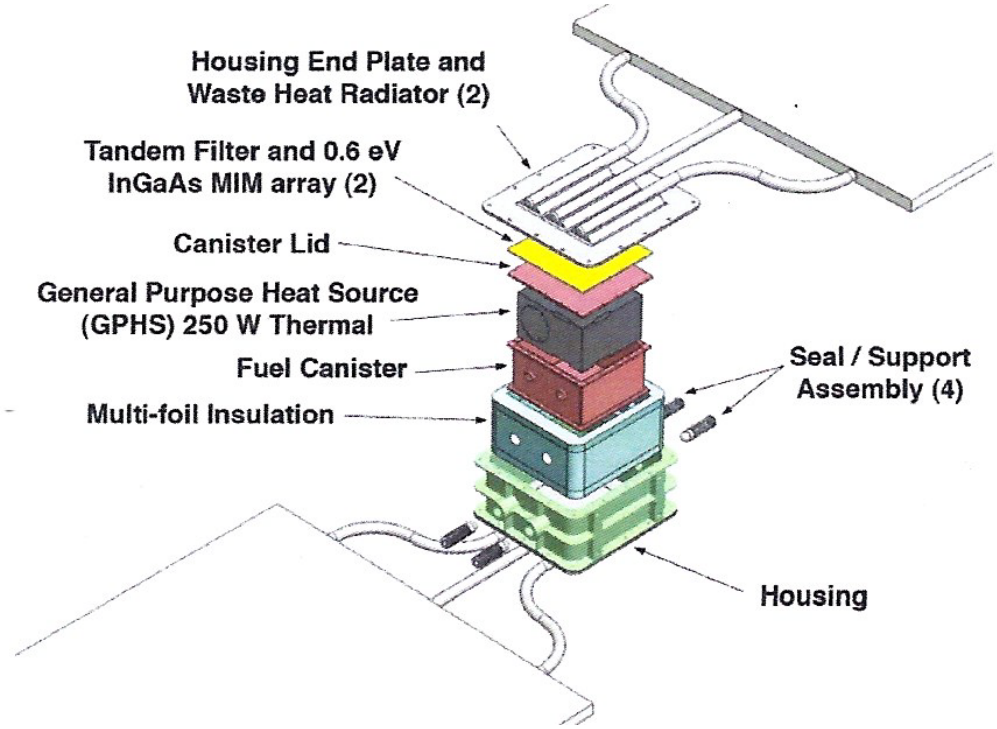
New LDRD project -- RTPV

•Radioisotope Thermo-Photo-Voltaic (RTPV) conversion offers the possibility of a very low specific mass power source

•NASA GRC has designed a RTPV system based on a GPHS brick – 15 % efficient, 167 kg/kw

•Tungsten encapsulation offers 5 times the power density and variable shape

•CSNR Summer Fellows' study implies the possibility of a 2-3 reduction in mass to around 50-70 kg/kw



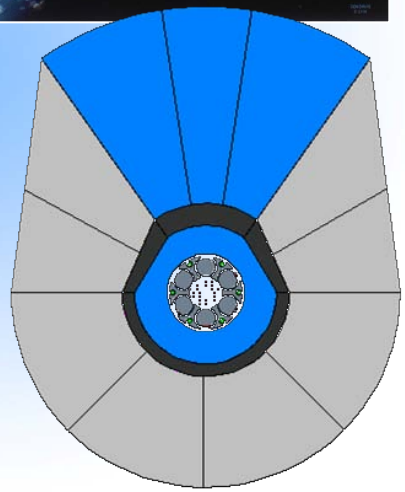
NASA NIAC award

- **Roughly 1000 proposals**
- **CSNR submitted 6**
- **Awarded "Economical Production of Pu-238"**

  will investigate the feasibility of private venture production

2011 CSNR Summer Fellowships

- **58 applications – due to USRA broadcast to members**
- **Accepted 14 Fellows represent 11 states and 14 universities**
- **2 PhD, 8 MS, 4 seniors**
- **Disciplines**
  - 3 Nuclear eng.,
  - 7 mechanical eng.,
  - 4 aerospace eng.,
- **Working on "challenging" topics attracts the students**
  - Mobile lunar base, nuclear rockets, decoupled fast reactors, isotope powered UAVs and UUVs, "smart" shields, comet interceptors, Mars Hopper



2011 Projects

- **NTR/MSR** -- One of the great goals for space exploration is a Mars Sample Return (MSR). The team will extend the work initiated in 2010 to increase the fidelity of a nuclear thermal rocket (NTR) driven MSR mission components. The team will also try to optimize the size of the NTR to minimize the initial mass in low earth orbit.

- **Tungsten cermet fabrication** -- The CSNR is pursuing development of a "universal encapsulation" for all radioactive sources that are to be launched from Earth – including radioisotope sources, nuclear rockets and nuclear reactors for surface power. The basis of the encapsulation is fabrication of a tungsten matrix to contain the isotopic material. The team will assist CSNR staff in developing and diagnosing tungsten cermet samples using the Spark Plasma Sintering furnace.

- **Radioisotope Thermo-Photo-Voltaic (RTPV) power –** The CSNR proposes to design a new configuration of the Radioisotope Thermal Photo-Voltaic (RTPV) system. The design will optimize the diameter, size and thickness to achieve the maximum efficiency for a given power level. The CSNR will also investigate the fabrication of titanium samples and examine the feasibility of diffusion bonding the titanium to tungsten or tantalum.

- **Muon Catalyzed Fusion (MuCF) propulsion System**-- A new direction for fusion power has predicted that under certain low temperature conditions in a DT plasma, a single muon could catalyze ~1500 fusions. This would give the process a significant energy surplus, thus making muon catalyzed power producing reactors a realistic prospect for "game changing" in-space propulsion. The team will design a MuCF propulsion system, assess masses of components, and estimate performance for deep space missions.

- **High Performance NTR (bi-modal, high T/W) --** The reduced mass of the engine, the thermal conductivity and strength at high temperatures allows the tungsten fueled NTR to be considered for bi-modal operation. Operation in this mode allows high-thrust departures from the gravity wells of planets and low-thrust, high-Isp propulsion during the long transit times. A bi-modal NTR would enable fast missions to the outer planets and the Kuiper Belt and orbital rendezvous with the gas giants. We propose to examine the design of a high T/W NTR using U-233 as a fuel, the issues entailed in surface launch of a NTR, and the design of a NTR that can operate in a dual bi-modal state, i.e. at low power levels for ship power and high power levels for Electric Propulsion.

Summary

- The CSNR is developing new Universal Encapsulation technology that is applicable to several nuclear systems
- The Mars Hopper concept can revolutionize planetary exploration and provide dramatically greater science per launch dollar
- The Hopper requires several capabilities that directly overlap the ability to design and test a NTR
- The CSNR has performed several mission studies that show the benefit of the NTR and the tungsten-cermet fuel
- The CSNR has developed a industrial funded effort in NTR fuel development
- Just awarded a new NIAC grant from NASA
- Initiated a new LDRD project in RTPV

- The CSNR continues to progress in the development of front edge technologies for space exploration