SEVENTH FRAMEWORK PROGRAMME
Theme 9: SPACE

WE LOOK AFTER THE EARTH BEAT

SPACE TRIPS SUMMER SCHOOL

# Integration of thermo acoustics into space missions

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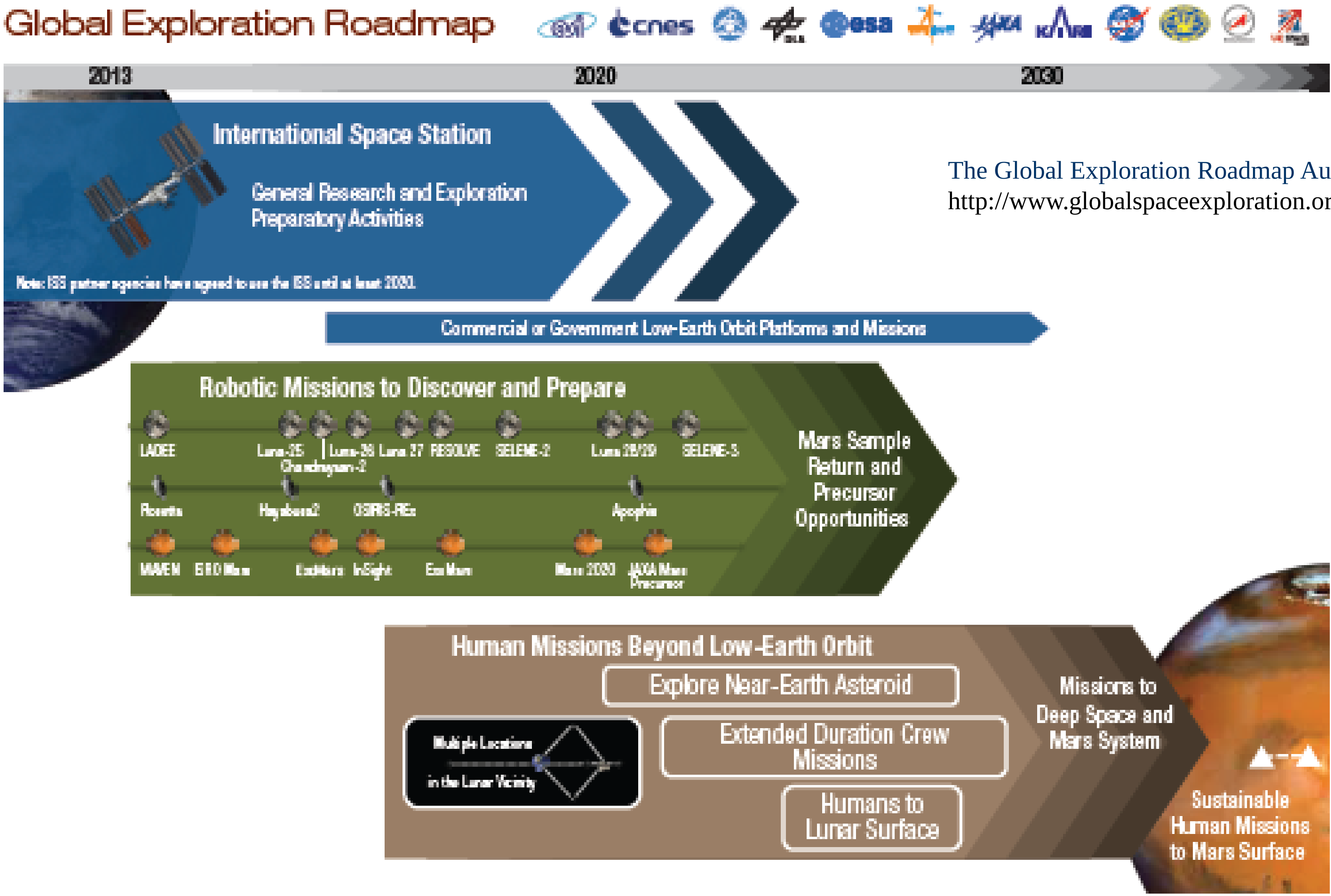
# Introduction

- Exploration and Scientific objectives:
  - Prepare for human and robotic exploration of destinations where humans may someday live and work (see Global Exploration Roadmap). This includes exploring both from on-orbit and on the surface.
  - Go beyond Mars – deep space missions
- Commercial Space Exploitation:
  - Space Tugs for servicing and maintenance
  - In orbit infrastructures




The Global Exploration Roadmap August 2013
http://www.globalspaceexploration.org

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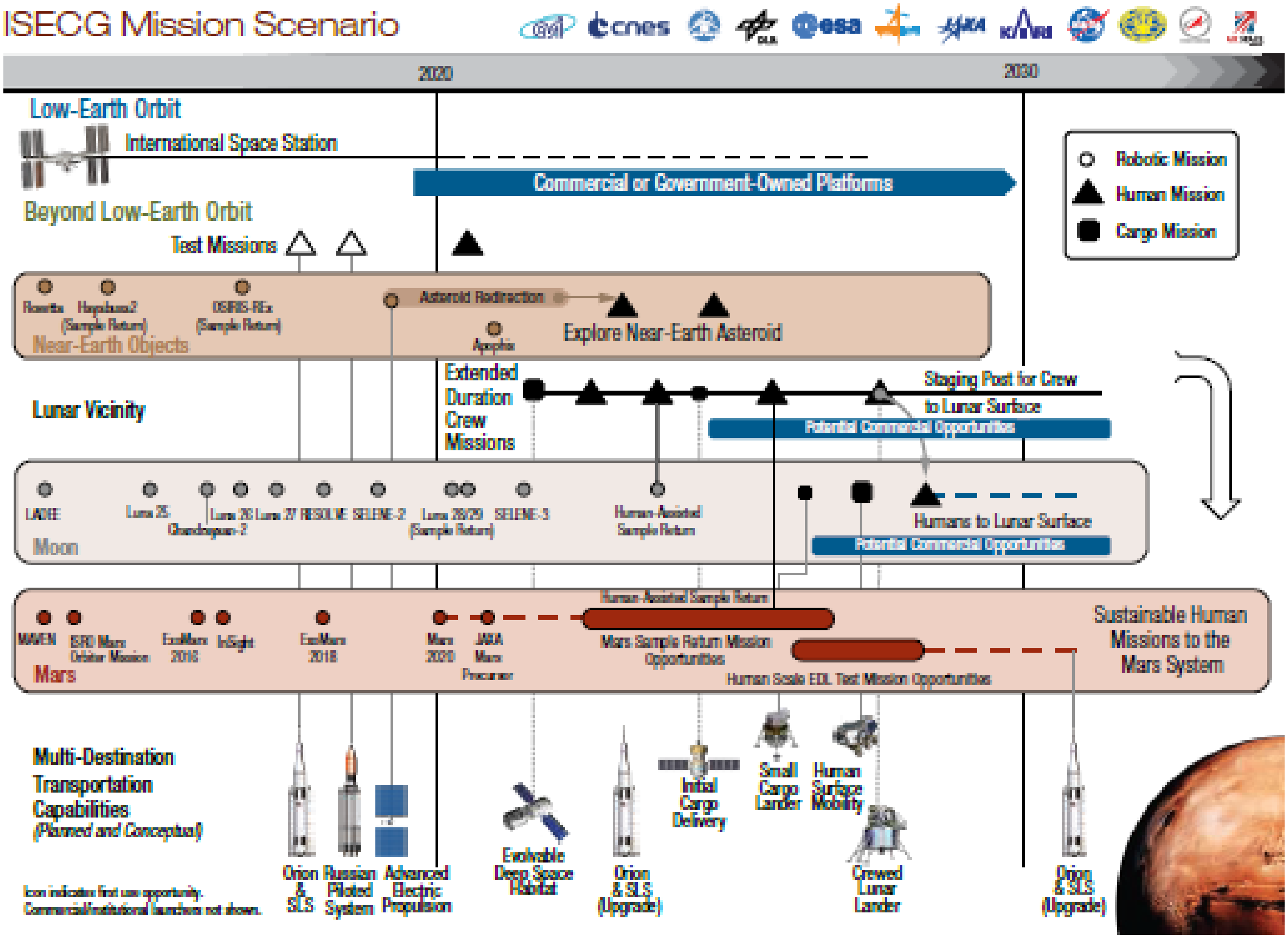


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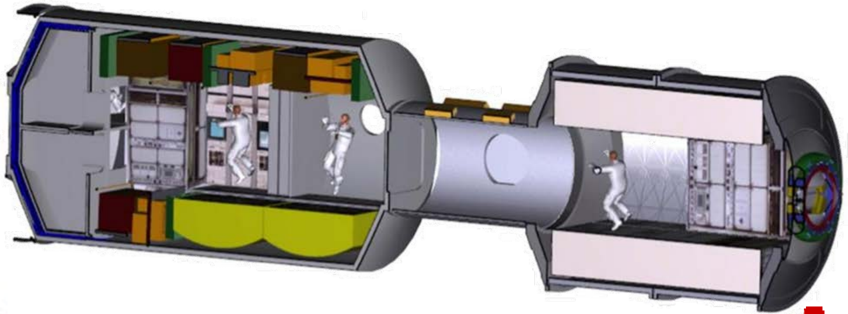
*From wikipedia*: For Earth / Mars trips the energy needed to transfer between planetary orbits hits a low point every 26 months. A typical Mars mission plans have round-trip flight times of **400 to 450 days**. A fast Mars mission of **245 days round trip could be possible**.

BUT

Estimates of Safe Days in deep space defined as maximum number of days with 95% CL to be below 3% REID Limit. Calculations are for **solar maximum and one SPE similar** to the event that occurred in Aug 72, with 20 g/cm2 Al shielding. This for a module of the size of those of the present ISS translate in more than 26 Tons of Aluminium.

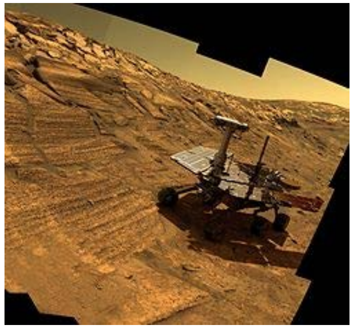
| Age at Exposure | NASA 2012 US Average | NASA 2012 Never Smokers |
|---|---|---|
| MALES | | |
| 35 | 306 (357) | 395 (458) |
| 45 | 344 (397) | 456 (526) |
| 55 | 367 (460) | 500 (615) |
| FEMALES | | |
| 35 | 144 (187) | 276 (325) |
| 45 | 187 (232) | 319 (394) |
| 55 | 227 (282) | 383 (472) |

Values in parenthesis are for the case where a storm shelter is available to reduce the SPE exposure to a negligible amount.
Source: Cucinotta, "Space Radiation Cancer Risk Projections and Uncertainties – 2012"



NASA next-generation Space Habitat – courtesy of http://wordlesstech.com

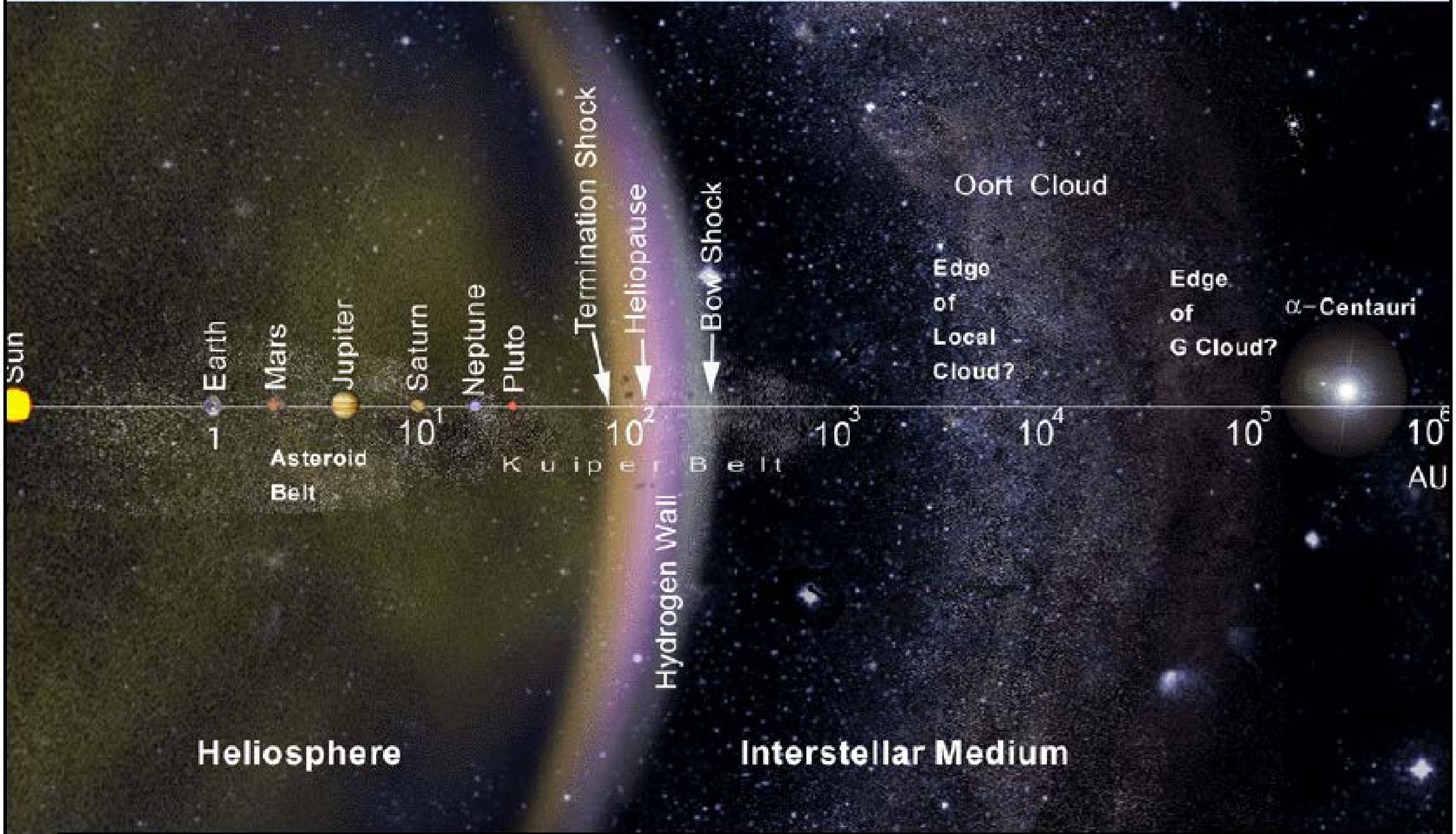
*Mars Rovers from wikipedia:*



- Opportunity (2004): mass 180 kilograms, 1.6 meters long by 2.3 meters wide by 1.5 meters high. Power source: solar-powered Maximum speed is 180 meter per hours although average speed is about a fifth of this i.e. 32 meter per second. Distance travelled 24.49 miles (39,412.83 meters).

- Curiosity (2012): mass of 899 kg including 80 kg of scientific instruments. The rover is 2.9 m long by 2.7 m wide by 2.2 m high. Power source: Curiosity is powered by a radioisotope thermoelectric generator (RTG) fuelled by 4.8 kg (11 lb) of plutonium-238 dioxide. It can travel up to 90 metres per hour but average speed is about 30 metres per second. Distance travelled up to at the beginning of 2014 5000 meters approximately.

# Where is deep space ?




Deep space : observe the solar system from the outside, far from solar influence

From: Roland Lehoucq CEA-Saclay DSM presentation

Source: http://www.heavens-above.com/



| | Pioneer 10 | Pioneer 11 | Voyager 2 | Voyager 1 | New Horizons |
|---|---|---|---|---|---|
| Distance from Sun (AU) | 110,999 | 90,440 | 104,912 | 127,919 | 29,618 |
| Speed relative to Sun (km/s) | 12.010 | 11.336 | 15.406 | 17.022 | 14.847 |
| Speed relative to Sun (AU/year) | 2,533 | 2,391 | 3,250 | 3,591 | 3,132 |
| Ecliptic latitude | 3° | 14° | -35° | 35° | 2° |
| Declination | 25° 53' | -8° 36' | -56° 39' | 12° 27' | -20° 45' |
| Right ascension | $5^h\ 8^m$ | $18^h\ 48^m$ | $19^h\ 58^m$ | $17^h\ 11^m$ | $19^h\ 1^m$ |
| Constellation | Taurus | Scutum | Telescopium | Ophiuchus | Sagittarius |
| Distance from Earth (AU) | 111.987 | 89.646 | 104.306 | 127.101 | 28.815 |
| One-way light time (hours) | 15,52 | 12,43 | 14,46 | 17,62 | 3,99 |
| Brightness of Sun from spacecraft (Magnitude) | -16.5 | -16.9 | -16.6 | -16.2 | -19.3 |
| Spacecraft still functioning? | no | no | yes | yes | yes |
| Launch date | 03/03/1972 | 06/04/1973 | 20/08/1977 | 05/09/1977 | 19/01/2006 |

10 Km/s = 2.1 AU/year

Speed of light = 63240 AU/year

# One of the big problems power!

*Two solutions: solar panels or nuclear (RTG or Nuclear Reactors)*

## Solar Panels:

- Distance from the Sun: beyond Mars solar panels efficiency drops too much
- Surface operations constrained by not continuous exposure, atmosphere reduction effects and degradation caused by dust/environment
- But safe and modular

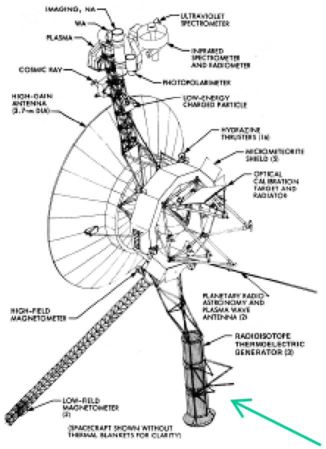
## Nuclear Power:

- Not affected by distance from the Sun
- No operations constraints
- But Safety, efficiency and reliability in conversion issues



# Nuclear fuelled spacecraft (not providing power to propulsion)

- Suited for missions to the outer solar system (where power is also needed to keep the spacecraft warm).
- Ensures a stable, compact and long lasting power source in particular, the long half-life of americium dioxide.
- Ensures a continuous intrinsic and highly predictable generation of thermal power.
- One example Voyager MHW-RTG:




| System mass (Kg) | Generator power (W) | Target |
|---|---|---|
| 722 | 160 We - 2400 Wt | Jupiter and beyond |

| Generator power (We) | Generator mass (Kg) | Generator size (L, W, T; mm) | | |
|---|---|---|---|---|
| 158 | 37.69 | 397.3 | 397.3 | 583.1 |

Possible mission for nuclear fuelled spacecrafts (not for propulsion)

- target body: Mars;
- duration: 20 yrs;
- gross mass: 3000 Kg;
- maximum power: 200 We;
- generator installation: self-contained chassis (case) offering simple interfaces to the SC, figure of merit (electrical power over mass Voyager was 4.19) of ~7 W/Kg and fit in an overall envelope of ~1000 mm x 700 mm x 700 mm.

# Environment:

- Assembly Integration and Test, handling and transportation environment
- Launch environment
- Mission environment
- Bio-burden reduction environment
  i.e. we have to protect Mars environment
  from Earth contamination
  especially biological

| Environment | Earth | Mars |
|---|---|---|
| **Pressure** | 1 atm (101325 Pa) | 600 Pa |
| **Composition** | 78.08% Nitrogen<br>20.95% Oxygen<br>0.93% Argon<br>0.04% Carbon dioxide | 95.3% Carbon dioxide<br>2.7% Nitrogen<br>1.6% Argon |
| **Temperature (average)** | + 14 degrees C | - 63 degrees C |
| **Lenght of Year** | 365 days of 24 hours | 687 days of 24 hours + 37 minutes |
| **gravity** | 1 g | 0.375 g |

# Space-worthiness:

- Compatibility with SC and payload:
  - EM cleanliness;
  - vibration behaviour;
  - radiation shielding;
  - phase separation in microgravity.
- Reliability – long mission timeline required. Nuclear Modules are well developed. It is not the case for Thermo-acoustic Engine (wear; gaseous contamination; helium leakage) and Magnetohydrodynamic Generator (mechanically very simple) only structural fatigue should be considered (no moving mechanical parts).
- Safety; mainly concern exposure of human to radioactive contamination especially in case of launch failure. Usually fuel modules inside the generator are designed to withstand extreme accidental conditions

# Integration of SRPS into spacecraft.

- Interfaces:
  - electrical;
  - mechanical;
  - thermal (for architecture improvement: SC finish to minimize thermal backload on generator's radiator, decoupling between generator and bus, thermal energy harvesting to improve overall system efficiency).
- Late integration aspects: specific support equipment may be required

User needs:

- Provide power where human intervention, maintenance, and servicing are not possible;
- Provide power for the outer solar system (Mars and beyond), where limited solar irradiation makes photovoltaic (PV) ineffective;
- Provide power for very long term missions, where degradation of performances limits the useful life of other power sources;
- Provide power when in very aggressive environments, where PV would be subject to early failure or performance degradation, (e.g. Earth's Van Allen Belt, Jupiter's radiation belt, dusty planetary surfaces);

User needs:

- Provide power substituting conventional “static TE conversion” RTGs (Seebek effect) with higher efficiency generators this is also linked to the need to minimize risks through reduction of the amount of nuclear fuel required to enable a given power output;
- Provide power substituting new-generation “dynamic TE conversion” RTGs (Stirling cycle) with higher reliability generators (i.e. no moving parts);

# Present Solution:

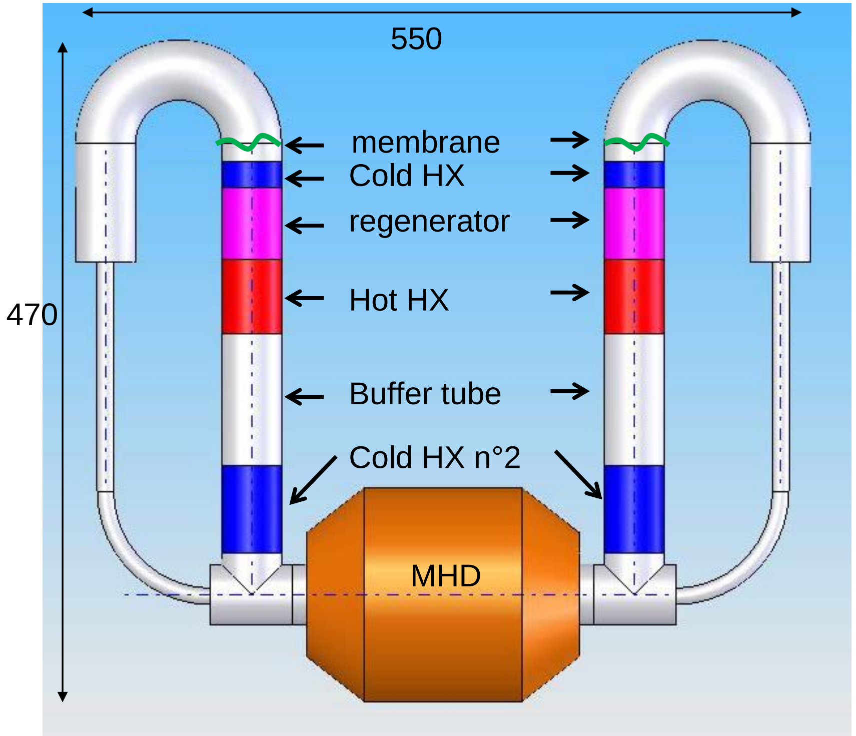
- Radioisotope power generators already flown were based on static thermo-electric conversion through thermocouples working on temperature difference between space (cold side) and "nuclear fuelled" hot side.
- The hot side has been obtained in two ways:
  - through natural decay of Pu238;
  - through fluid heat harvesting from a real reactor fluxed with eutectic NaK.
- Two additional alternative concepts are recently being developed in US, but never flown: HEPS (TASHE/TARPS) and ASRG. Both with dynamic TE conversion based on Stirling cycle with a mechanical alternator (piston).

# TA + MHD Solution:

- Based on the coupling of a thermo acoustic (TA) engine with a magneto hydrodynamic (MHD) generator. The thermo acoustic engine converts thermal energy into mechanical energy, and then the MHD generator converts the mechanical energy into electricity.
- The bare generator (nuclear modules + TA converter + MHD converter) may have a dimensional envelope which is approx. 1000 mm x 700 mm x 700 mm. Therefore, the generator in itself could be accommodated inside a SC bus.
- To increase flexibility it has been suggested to group the generator and its control systems in a self-standing container, providing well-defined interfaces for coupling with the main system.
- Currently, 8 modules are foreseen to provide the required 1160 $W_{th}$, from which the machine extracts ~200$W_e$ (approx. 17% overall efficiency).

# TA + MHD Solution:

- The hot heat exchanger is connected with all the 8 nuclear modules, maximizing contact area, minimizing thermal losses;
- Both cold heat exchangers are connected with the cold sink, namely a radiating area, which can be the external fairing;
- A thermal control system dedicated to integration and launch phases is included.
- To reduce development costs the power source design must be compatible with multiple missions.



With respect to each one of the aforementioned related power systems, the TA-MHD generator can offer the following two advantages:

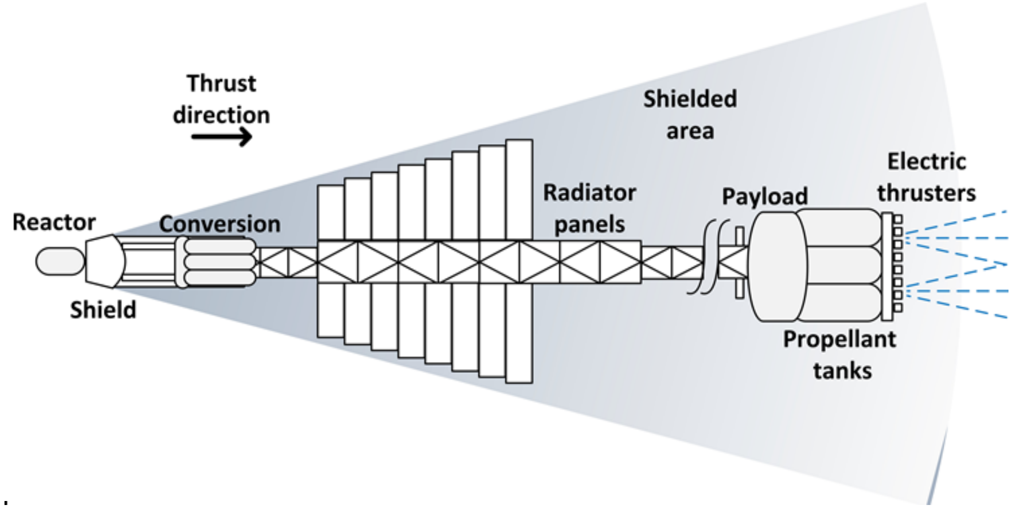
- higher efficiencies (>20% vs. ~7%);
- higher reliability (no moving parts which could wear, jam, leak etc.)

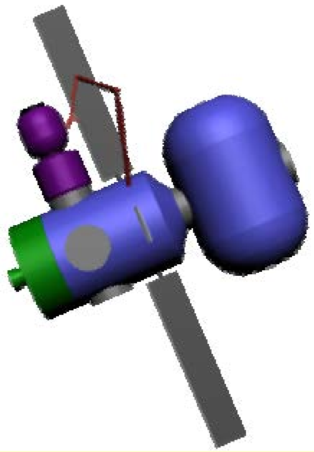
It could power future missions which have one or more of these characteristics:

- target site with insufficient solar irradiance (too far from Sun, long eclipse times, clouds/storms);
- target site with environment not suitable for PV (LILT, high radiation levels, drag generation, high risk of dust deposition, need for high electrostatic cleanliness, particle or micrometeoroid bombardment);
- extremely long mission duration, thus posing a challenge on power supply duration and reliability (the absence of moving parts could contribute to higher dependability, like with Seebek conversion, while at the same time offering fourfold efficiency).

# Future use Nuclear Power for propulsion:

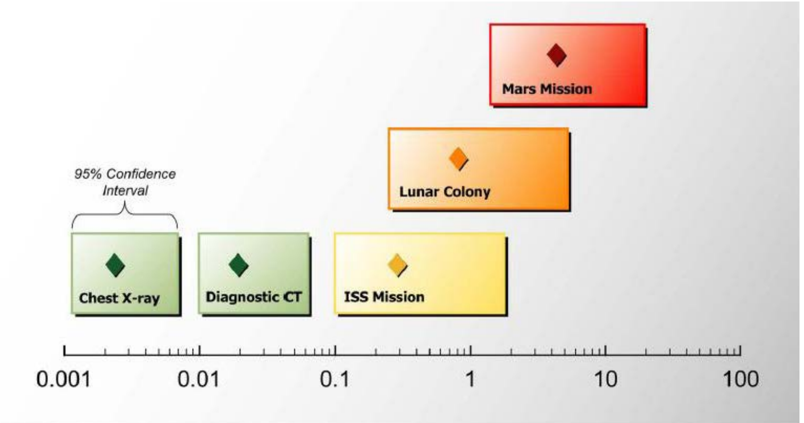
- Nuclear Electric Propulsion (NEP) can offer multiple advantages in regards to space exploration. Significant gains can be realised in flight time, on-board power availability and payload mass delivered to the selected target.
- Using the power source of a nuclear core (5MW) i.e. power in the range of 1MW can be achievable that can then utilised by the spacecraft for advanced electric propulsion, using clustered ion or hall thrusters.





# Future:

- Nuclear Electric Propulsion (NEP) can also make possible manned mission to Mars by reducing travel time i.e exposure time or enable quicker scientific mission




| Isp (sec) | 459 | 1,100 | 4,590 |
|---|---|---|---|
| WR | 10.70 | 7.23 | 3.38 |
| Jupiter | 2.69 | 1.70 | 0.793 |
| Saturn | 4.92 | 3.12 | 1.45 |
| Uranus | 8.14 | 5.16 | 2.40 |
| Neptune | 11.15 | 7.07 | 3.29 |
| Pluto | 13.75 | 8.72 | 4.06 |
| Kuiper Belt | 16.29 | 10.34 | 4.81 |
| Heliopause | 27.86 | 17.67 | 8.22 |

Increasing Isp Reduces Transit Time [**years**] and Weight Ratio

EP can provide theoretical Isp up to $10^5$

Weight Ratio = wet/dry mass

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# Acronyms

| | |
|---|---|
| ASRG | Advanced Stirling Radioisotope Generator |
| EM | Electromagnetic Compatibility |
| HEPS | High Efficiency Power Source |
| Isp | Specifc Impulse |
| LILT | Low Intensity Low Temperature |
| MHD | Magneto Hydro Dynamic |
| NEP | Nuclear Electric Propulsion |
| NaK | Sodium-Potassium alloy |
| PV | Photovoltaics |
| REID | Risk of Rxposure-Induced Death |
| RTG | Radioisotope Thermoelectric Generator |
| SC | Space Craft |
| SPE | Solar Particle Event |
| SPRS | Space Radioisotopic Power System |
| TA | Thermo Acoustic |
| TARPS | Thermo-Acoustic Radioisotope Power Source |
| TASHE | Thermo-Acoustic Stirling Heat Engine |
| TE | Thermo Electric |