University of Padua – Industrial Engineering Department

Aerospace engineering degree

Final report «KRUSTY: a new power source for future horizons»

University tutor: *Prof.ssa Roberta Bertani*

Student: *Fuser Giovanni*

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Index

INTRODUCTION AND REPORT GOAL

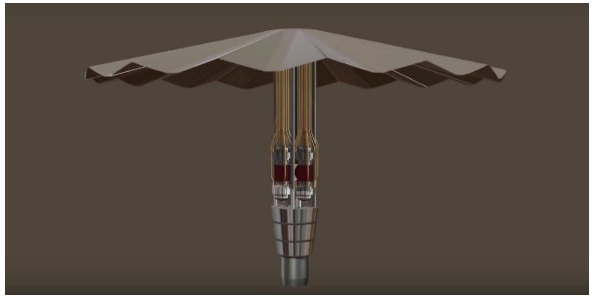
Goal of this report is to analyze and comprehend new generation portable reactor KRUSTY. Starting with nuclear reactors design overview, continuing exploring game-changing technologies and milestone sets with it.

What is KRUSTY?

Acronym for **Kilopower Reactor Using Stirling TechnologY** is an experimental project verging to engineer and test a new *portable modular nuclear reactor for space exploration*.

Relevant strengths of *KRUSTY* are:

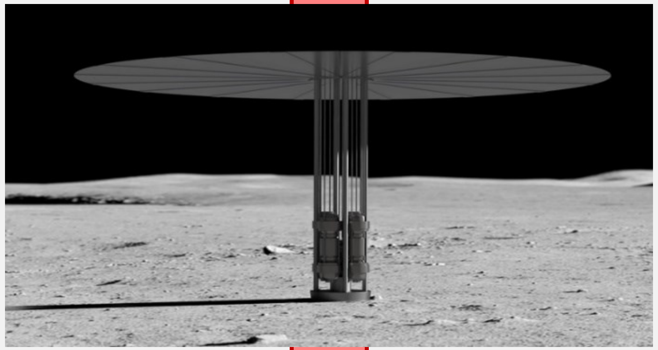
- Compact and low-cost portable fission nuclear reactor ***scalable*** from 1 to 10 kW, lasting decades
- Provides 10 to 100 times the power of the last generation RTG (MMRTG from NASA) with power/mass ratio nearly ***tripled*** in biggest sizes.
- Integrates a passive safety control that gives an operational high-level security



Where are we now?

Nowadays space exploration trusts in energy supplier as : batteries, solar panels and thermoelectric generators.

These devices can cover a **limitate** number of necessities , with boundaries in time duration of supply, power supplied and site of supplying. There's also troubles in dimensioning power unit, that need to have **wide ranges** of working and energy supply capabilities, in very different conditions and needs of operations.



Where are we going in the future?

KRUSTY at its final glance:

- ✓ Modular power supplier running more than 10 years
- ✓ Versatility/Interchangeability of use; supplying spacecraft and outposts with power reaching **tens of kW** (very high value)
- ✓ Liability thanks to high **operational safety** and continuous production of energy

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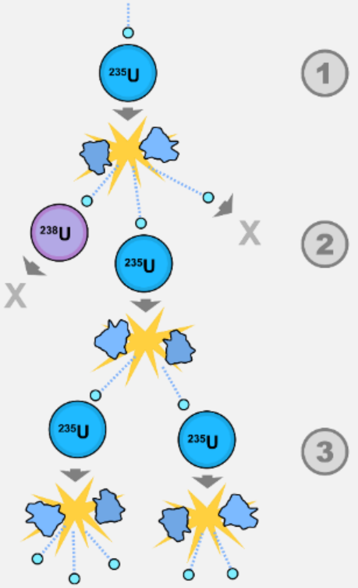
FISSION REACTION PRINCIPLES AND ITS EXPLOITATION

Nuclear fission consist in a chain reaction of heavy elements nucleus that, hit by neutrons, release energy, heavy nucleus and neutrons again.
Chain reaction is given thanks to **unstableness of heavy elements** like Uranium or Plutonium that absorbing a neutron, like the drop that overflows the jar, split its selves starting the chain and releasing energy.
A single stage of this reaction use a Uranium 235 + neutron as input, obtaining «2,5 neutrons», two fragments (Ba and Kr) and 200 MeV.



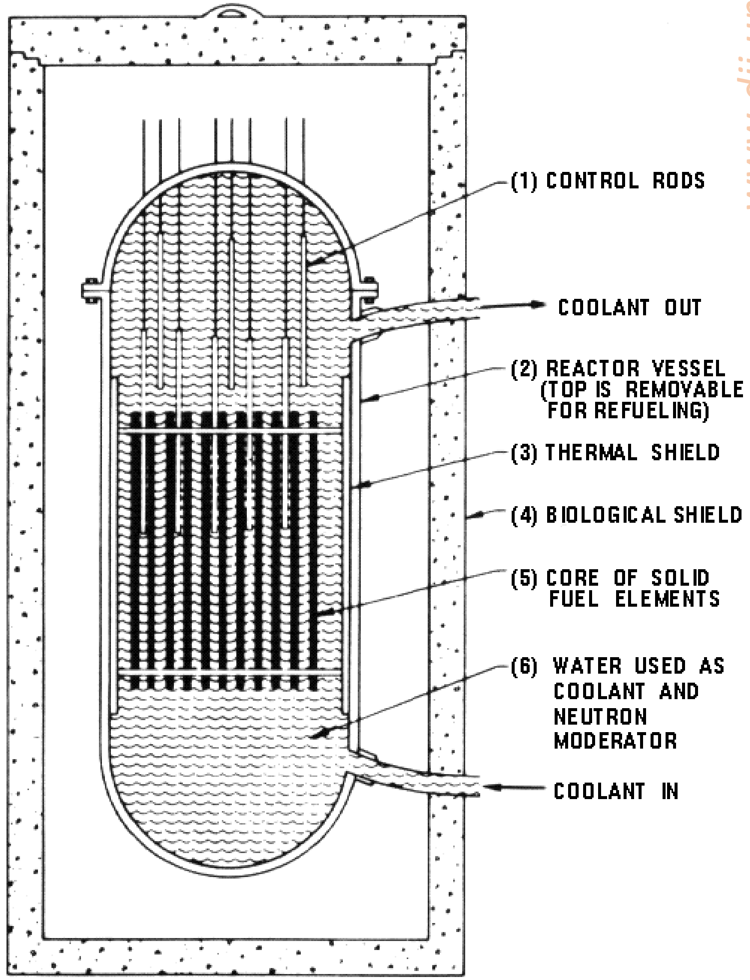
NUCLEAR FISSION REACTOR COSTITUENTS

Every reactor has fundamental constituent

A. Energy source *(CORE)*
- Nuclear fuel assembly
- Control rods assembly
- Moderator
- Various shielding

B. Energy transfer
- Primary loop (core cooling)
- Intercooling loop (optional)
- Secondary loop (optional)

C. Energy converter
- Steam turbine generator *(most common)*
- Others



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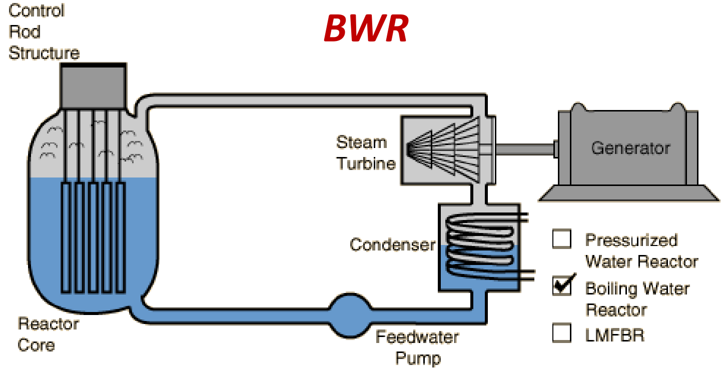
NUCLEAR FISSION REACTOR DESIGN

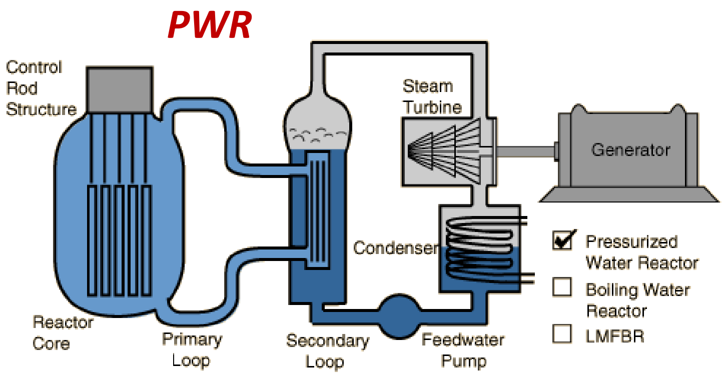
Simplest one is a single loop called **BWR** (*Boiling Water Reactor*) uses hot water turned into steam due to high temperature, directly feeding converter.

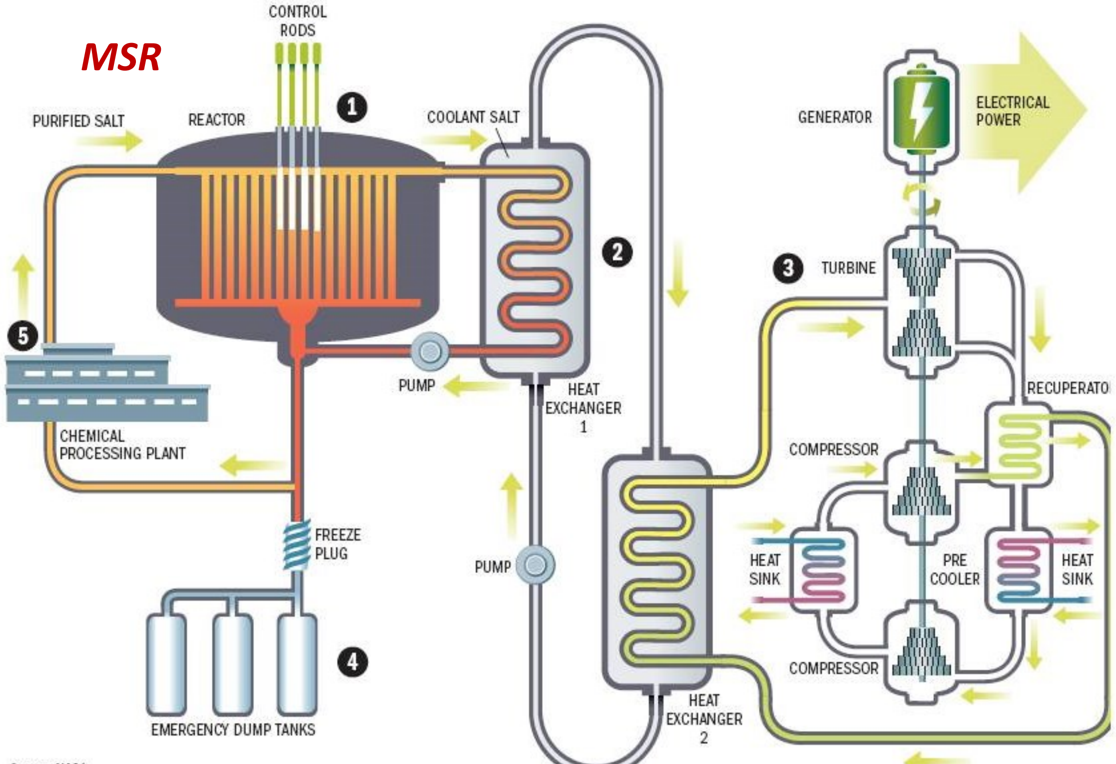
Second one, called **PWR** (*Pressurized Water Reactor*), has primary and secondary loop, so core water doesn't feed directly turbine, but exchange heat trough second loop, that feeds converter.

Last one is more complex, called **MSR** (*Molten Salt Reactor*), implements 3 loops and uses molten salt in primary and intercooling loops. Molten salt gives advantages in engineering and designing structure and material, impacting positively in cost, efficiency of process and safety.

Mentioning these designs is fundamental to understand differences between them, and figure out the hybrid concept of ***KRUSTY***, that use a single loop concept *(for its feasibility)*, with molten salt *(for its advantages and safety, especially in space environment)* and Stirling engines *(for its efficiency in energy conversion)* as energy converter.







Source: NASA

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KRUSTY REACTOR: DESIGN AND FUNCTIONING

1. RADIATORS (COLD LOOP)

Big surfaces on top are **titanium radiators** and they work as heat exchangers in order to regulate the reactor temperature and give cold pole to Stirling engines. The operative fluid used is **water**. Integrated with deploying technology for on-site activities, radiators can make KRUSTY "blooms like a flower" in its open position.

2. POWER GENERATOR UNIT

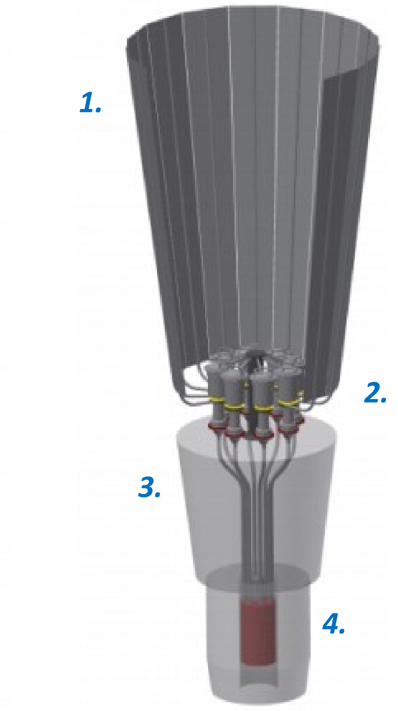
Stirling engines are implemented for producing electrical power exploiting cold and hot poles gives by core and radiators, situated in the middle of reactor.

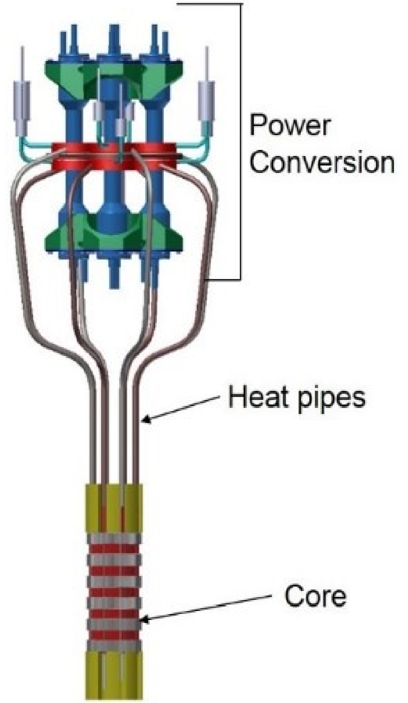
3. HEAT PIPES (HOT LOOP)

Heat transfer is actuated by the movement of **liquid sodium** stored in heat pipes. Through these pipes, heat from core melt salt stored inside of pipes, reaches Stirling engines through exchange with salt and creates the hot pole.

4. CORE

At the bottom we have the **radioactive core**, composed by a shielding all around, a moving control bar and neutron reflective material shell. Bottom configuration is strategical, because on-site core section could be buried underground, giving additional shielding proprieties and operational safety.





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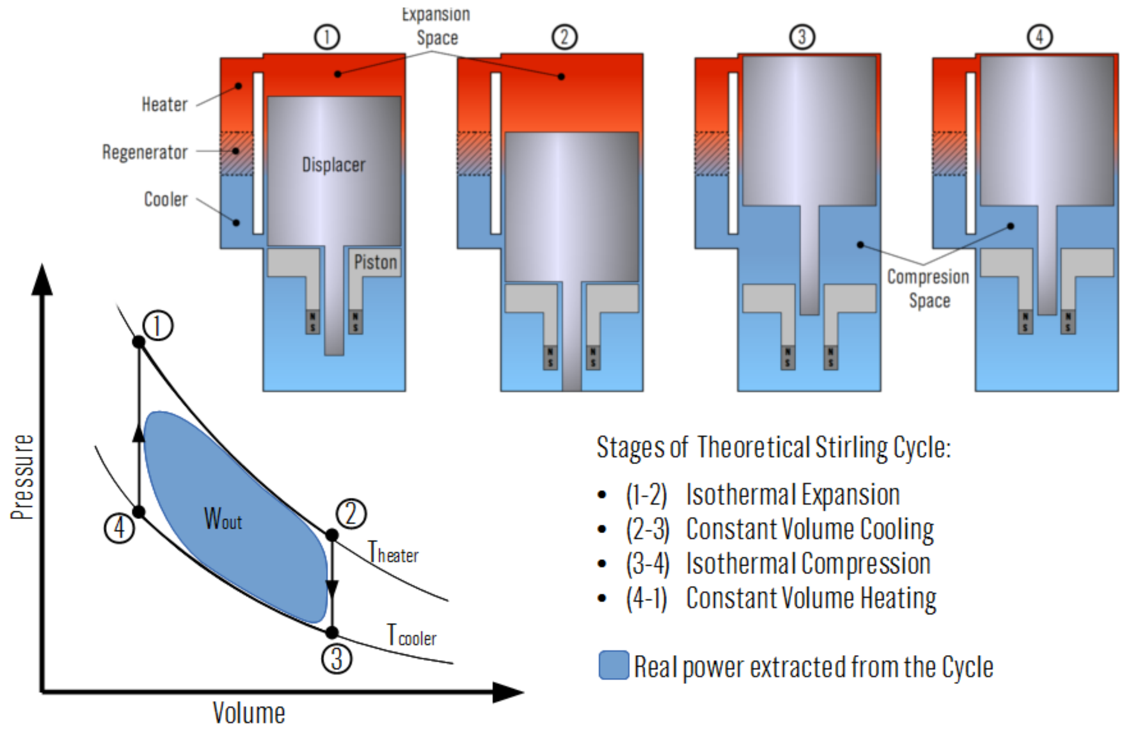
KRUSTY REACTOR: DESIGN AND FUNCTIONING

ENERGY FLOW

All starts from core, where fission is running, producing a large amount of thermal power, reaching temperatures around *1000 K*. This energy needs to be drained out of core and addressed to the hot pole of Stirling engines. These thermodynamic machine uses a ***Stirling cycle***, that need hot and cold pole in order to generate electrical power trough movement of a piston. Hot pole is made by heat pipes bringing thermal energy from the core, cold pole is originated from another loop, situated on top of *KRUSTY* module, ending with radiators that cool-down the process fluid on that side. Key factor to *high power production* is to get as large as possible range of temperature between two poles, in order to reach relevant efficiency conversion. It's possible to understand this implication observing the cycle graphed in *Clapeyròn plane*.



Modularity of KRUSTY gives wide range of sizes for any situations and needs

Sizing of reactor	*Multi-Mission size*	*Surface size*
Power supply (kW)	1-3	3-10
Gross weight (kg)	400	1500
Core mass (kg)	28	44

Stirling cycle theoretical efficiency

$$\eta_{STIRLING} = 1 - {T_{COLD}}/{T_{HOT}}$$

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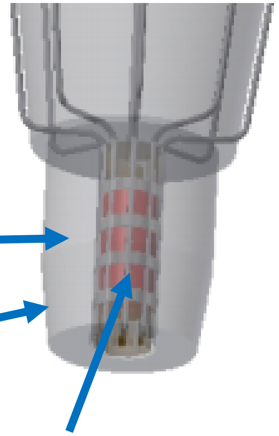
KRUSTY REACTOR: MANUFACTURING AND MATERIALS

Natural form of Uranium (principally isotope-238) isn't adapt to fission. Reactor uses *enriched Uranium 235* pellets, inserted in a **molybdenum alloy frame** chosen for its feasibility and simplicity on engineering. **TMZ alloy** (Titanium Molybdenum Zirconium), is a kind of alloy that compared with pure molybdenum, Titanium Zirconium Molybdenum has a more stable crystalline structure and higher recrystallization temperature. This is due to the small amount of zirconium and titanium doped into the molybdenum substrate. Composite carbides like Mo_2C, TiC, and ZrC help refine and restrain the crystalline grain of molybdenum, which in turn helps the alloy become more creep resistant.



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TZM Molybdenum Physical Properties		TZM Molybdenum Mechanical Properties	
Density	0.37 lb/in3 10.22 gm/cm3	Tensile Strength	110 (760) ksi (Mpa)-RT
Melting Point	4753 °F 2623 °C	Elongation	15% in 1.0".
Thermal Conductivity	0.48 Cal/cm2/cm°C/sec	Hardness	220 dph
Specific Heat	0.073 Cal/gm/°C		
Coefficient of Linear Thermal Expansion	2.50 micro-in/°F x 10-6 5.20 micro-in/°C x 10-6	Modules of Elasticity	46000 ksi 320 gpa
Electrical Resistance	6.85 micro-ohm-cm		

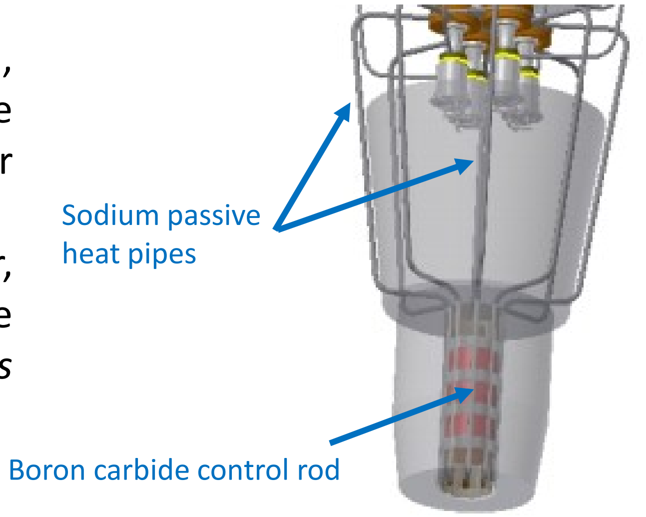
Moderator activity is operated by a **beryllium oxide shell**, decelerating neutrons. **Beryllium oxide** is obtained from heating up to 650 K beryllium hydroxide. It has a peculiarity decelerates neutrons and high energy radiations, improving fission reaction.

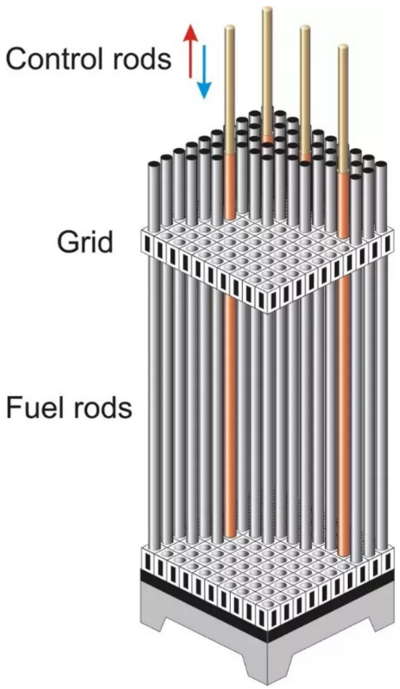
Thanks to **lithium hydride tungsten shielding**, all of dangerous radiation, for both human and electrical devices, are kept inside core.

KRUSTY REACTOR: MANUFACTURING AND MATERIALS

Control of nuclear reaction is supplied by a **boron carbide rod**, also called **neutronic poison**, because of its neutron absorbing proprieties, inserted into core to disinhibit the reaction before reaching site of production. When fission starts this rod can give a regulating mechanism for power production and temporary emergency shutdowns.

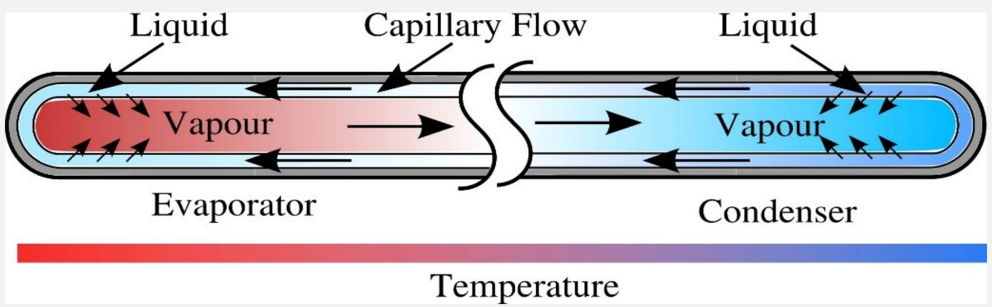
Boron carbide is a molecule that constitute very hard *ceramic aggregates*, used for tank armor, bulletproof vest, and big number of industrial applications. The complex icosahedral structure organized in a rhombohedral grid gives relevant *strength, hardness and intense catching neutrons proprieties*.





Passive heat pipes filled up with **liquid sodium** transfer heat from core to the Stirling engines, thanks to convective movement of fluid, inducted by capillary proprieties. They represent the first cooling loop.

KRUSTY runs at *1000 K,* so sodium with $T_{fusion} = 340\ K$ can transmit heat and flow easily.



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ENERGY SUPPLY: FUELING SPACE SETTLEMENT AND SPACE PROPULSION

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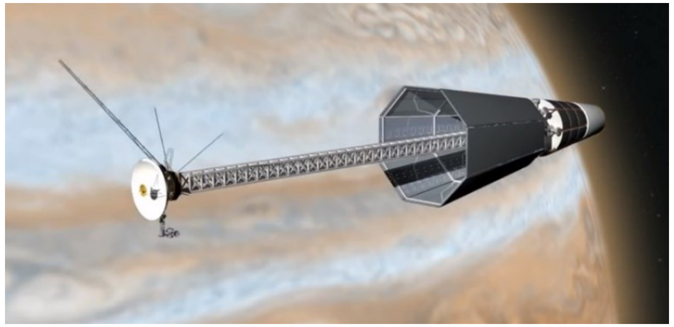
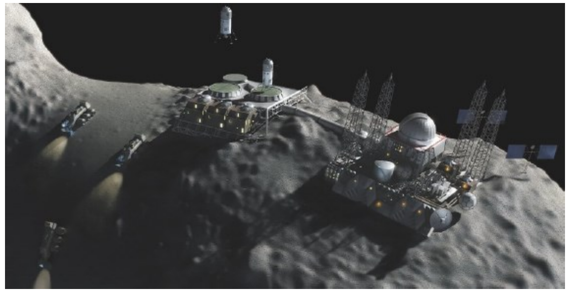
Future space missions will need energy for a lot of the activities as critical safety system or peculiar activities. Reaching lunar or martian outposts would be challenging, regarding duration and resources spent . Giving ***self-sufficiency*** is a key factor to success of the mission.



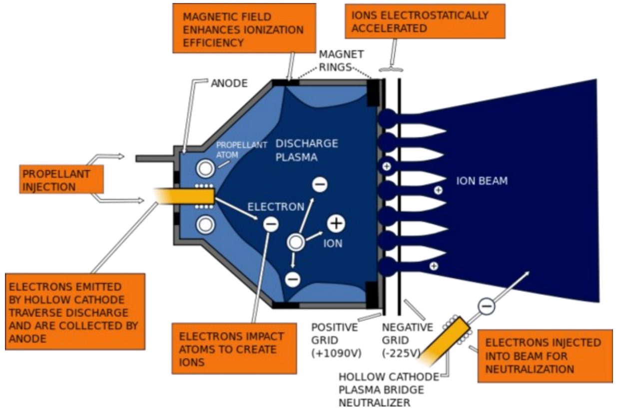
Government and commercial profile missions

- Deep Space Gateway: lunar surface operations
- Planetary orbiters and landers
- Space power utility (pay-for-service)
- Asteroid/space mining
- Lunar/Mars settlements



Projected crewed-missions power needs
40 kW day/night continuous power (*4 KRUSTY modules*)
Powering landers, habitats, life support, rover charging
Source needs to be compact
Several activities of an outpost
drilling, sample collection, material processing, manufacturing, radar, telecomm, rover recharging

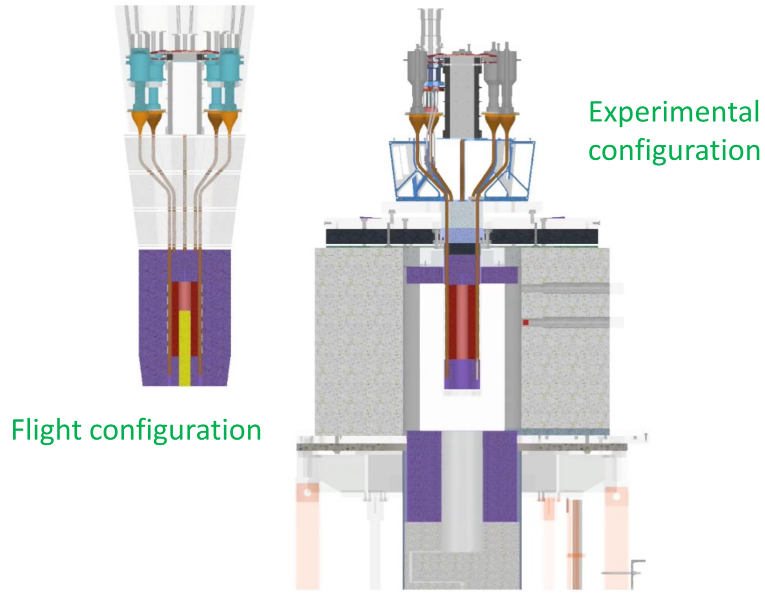
Frontier of deep space propulsion is headed by **ion propulsion**, a new innovative concept, that uses *electric potentials* to drastically accelerate ions to get thrust. It is the *most efficient* way to get propulsion in outer space for **long lasting travels**. **Next-C** is the acronym for **NASA Evolutionary Xenon Thruster Commercial** an ion thruster using grid technology. Electric potentials are generated by the amount of energy available, so, the more energy available, the more thrust generated. Here it comes another big advantage of **KRUSTY**, consisting in the quantity of power that it could provide compared to actual technologies. KRUSTY would be double used, propulsion generator and settlement generator, reflecting high versatility of this device.



IS IT SAFE TO HAVE A NUCLEAR REACTOR IN SPACE?

Aim of KRUSTY experiment was to simulate several operative parameters needed for deep space missions or lunar/martian outposts. With those tests we get a **complete qualifications** of materials, thermal components and passive controls. In 2018 with a 28 kg core, were reached 28 hours of continuous power supply at 5,5 kW overcoming all expectations, ***exceedingly almost every performance metric requested***. At launch, the reactor wouldn't be operating and would be activated only in a trajectory leaving Earth or in-situ. During operations reactor is already sufficiently shielded and won't cause any *damage* to the crew. Design and self regulation gives the ability to **prevents** every kind of uncontrolled dangerous scenarios.

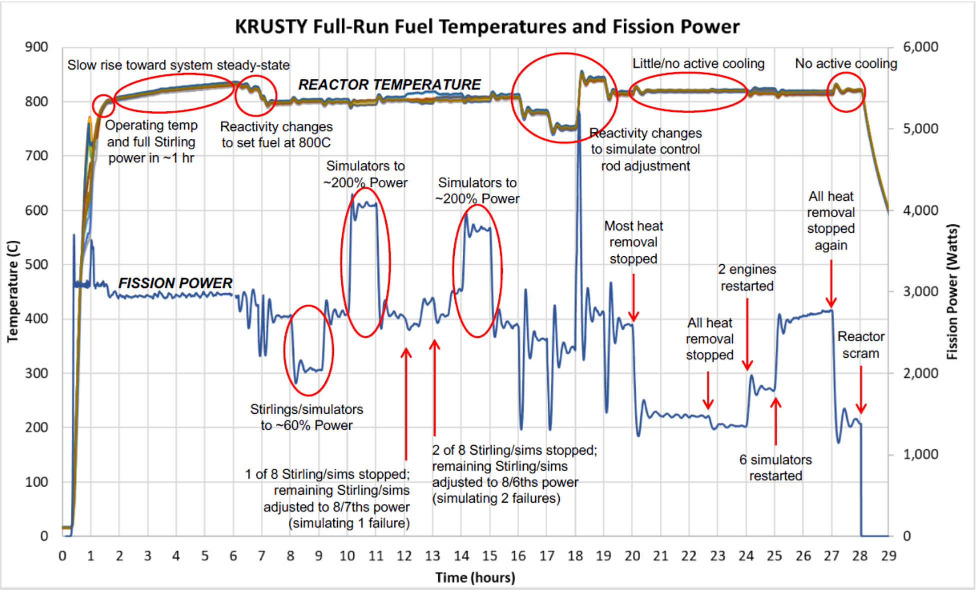
Event Scenario	Performance Metric	KRUSTY Experiment	Performance Status
Reactor Startup	3 hours to 800 deg. C	1.5 hours to 800 deg. C	Exceeds
Steady State Performance	4 kWt at 800 deg. C	> 4 kWt at 800 deg. C	Exceeds
Total Loss of Coolant	< 50 deg. C transient	< 15 deg. C transient	Exceeds
Maximum Coolant	< 50 deg. C transient	< 10 deg. C transient	Exceeds
Convertor Efficiency	> 25 %	> 35 %	Exceeds
Convertor Operation	Start, Stop, Hold, Restart	Start, Stop, Hold, Restart	Meets
System Electric Power Turn Down Ratio	> 2:1 (half power)	> 16:1	Exceeds



*Experimental configuration consists in a platform with vacuum chamber, a mechanism called COMET for moving reflectors from bottom, and shielding sideways. Testing like that create a space like ambient with vacuum, thermal power, operating temperature, system dynamics. This for facing some event scenarios that could happen during operational times. It is to be noticed that all **critical components** like core, neutron reflector, regulating rod were tested and qualified even alone to measure reactivity.*

Testing configuration misses some things that haven't been already tested in a full integrated set up (Radiators, full suite of Stirling engines).
Furthermore, **final configuration** lack of zero-g tests, launch approval, flight hardware, launch loads tests, flight qualification and spacecraft integration.

IS IT SAFE TO HAVE A NUCLEAR REACTOR IN SPACE?

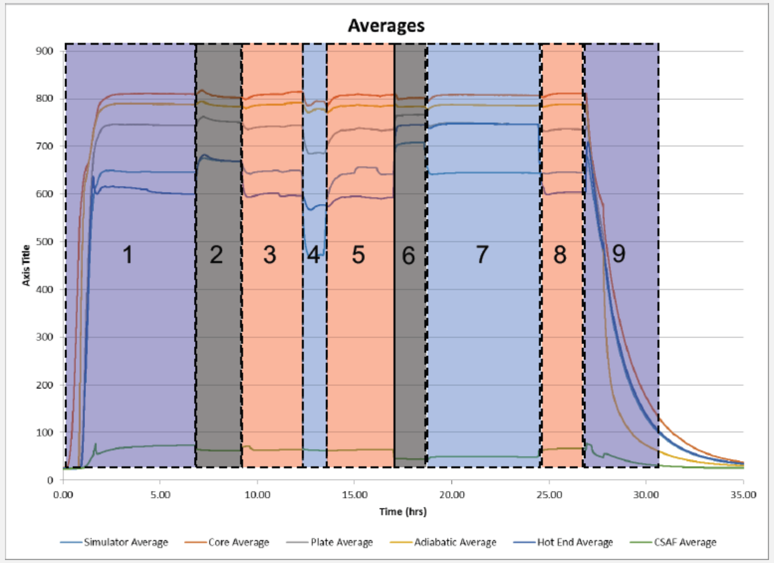


Full power tests consist in a regular mission profile, including startup, ramp up to full power, steady state operation, several operational transient and “shutdown”. It also evaluates every kind of scenarios, including *shutdown* of Stirling engines, *failure* of the regulating rod, *failure* of heating pipes recirculation. That was a **big success**, in 2018, achieving all milestone sets and proving rewardable operational safety on **controlling failure** of systems and **avoiding leakages** of radioactive material and radiations.

Looking at the diagrams we can see how several procedure were made during testing. Safety and control system work very efficiently maintaining temperature always under *850 degree*, self-managed by control unit its selves, without any active action by any operators.

TEST PHASES

1. Heat up and steady state operation, simulators set to match Stirling heat input
2. Half power Stirling operation
3. Return to steady state
4. Full thermal power
5. Return to steady state
6. Turn off Stirling engines and cooling (Simulators), adjust core power to simulate temperature feedback
7. Add additional cooling to Simulators, up core power, engines still off
8. Turn Stirling engines back on, return to steady state
9. Cut core power, GN2 backfill to chamber



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How about sustainability?

Reduced amount of radioactive waste (around 50 kg in 10-15 years), totally excluded radioactive leakages during operations

KRUSTY produces an amount of radioactive waste 5 g/W, compared to ***MMRTG*** *generates 27 g/W(10 yrs. duration).*

Time stiffness device, *multiple usages*, ***no necessity*** of using other power suppliers.

Key factor for space energy implant is getting more energy from less mass, wide energy disposal. ***KRUSTY*** *7,2 W/kg* ***MMRTG*** *2,8 W/kg*

High operational safety and **self regulation**, elevated environment integrational characteristic on-site

Self regulation permit to operate ***safely*** *without any feedback needed or peculiar active systems running.*

Manufacturing cost reduction (time and money), thanks to modularity and already qualificated components.

Cost reduction is ***mandatory*** *for spreading, giving availability for common usage and implementing it in various missions.*

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CONCLUSION: NUCLEAR SOLUTIONS

There are some **boundaries** that actual technologies cannot overcome. For example, space exploration and expansion of human being is stopped by difficulties like ***energy supply*** in low-solar light sites, and **insufficient *propulsion systems*** to satisfy necessities of a manned space travel.

Nuclear technologies permeate a more accessible and safer aerospace sector. We will face new problems for sure, but a lot of nowadays boundaries could be overcome by implementing machine and devices using **nuclear reactions technologies** like ***KRUSTY***.

Thanks for attention

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