Space Nuclear Power

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NASA artwork

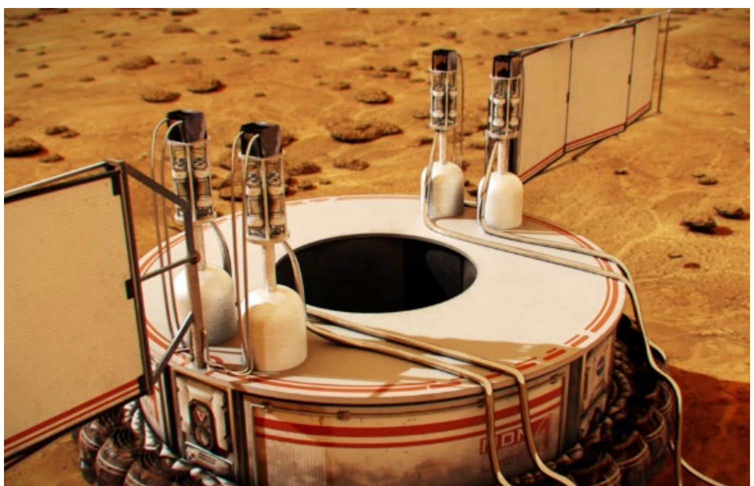
Space Nuclear Power Corporation

SPACENUKES

A power-rich architecture is needed for Human exploration and habitation of Mars

- **Electricity (and heat) is needed…**
  - To create oxygen
  - To create a source of water
  - To power habitats and rovers
  - Drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, telecomm, etc.
  - We (human civilization) have developed an infrastructure that uses electricity as the energy “middleman” for almost everything

International Mars Research Station – Shaun Moss



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- **Abundant electricity is also needed to make propellants**
  - Liquid Oxygen
  - Methane
- **In-situ propellant production is what makes near-term transportation to/from Mars efficient and affordable**

Why Nuclear for Mars Surface?

- **Solar power on Mars surface presents major challenges**
  - ~1/2 solar insolation of Earth
  - Long-term dust storms (months to years in length)
    - Huge increase in optical depth has been experienced many times in the “short” time we’ve had a presence on Mars
    - Note: diffuse light helps keep output above zero, but diminishes output to a relatively small fraction of the full power level.
  - Much colder (and slightly longer) nights than Earth
    - Which complicates batteries or other storage techniques, in addition some of the stored energy might have to be used to prevent things from getting too cold
  - Highly dependent on latitude and season
    - The “easy” water is at high latitudes, with low sun angle, long winter nights
  - Craters/gullies/cliffs/etc. can block/diminish sunlight
    - This might also be where the easy water will tend to be
    - Also, many locations might not have a large “flat” area for deployment
  - Deployment of huge arrays, and ability to deploy and keep them clean.
- **The Moon can be as (or more) challenging**
  - 14 days of darkness, the storage system itself might be more difficult than a reactor, and heavier
  - Huge temperature swings, from warm to extremely cold temperatures
  - Power needed in permanently shaded craters to extract water ice.

Viking Optical Depth Data

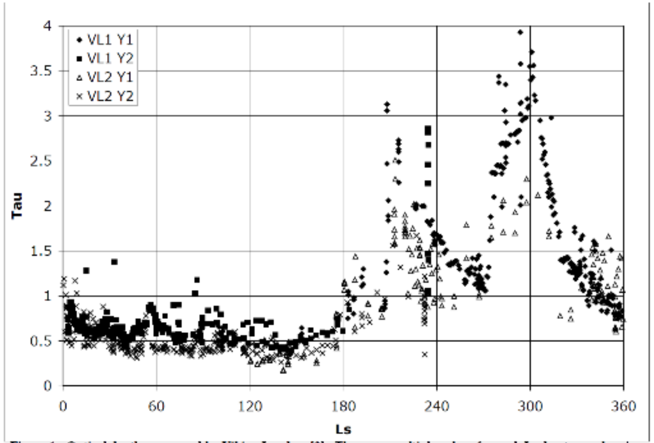
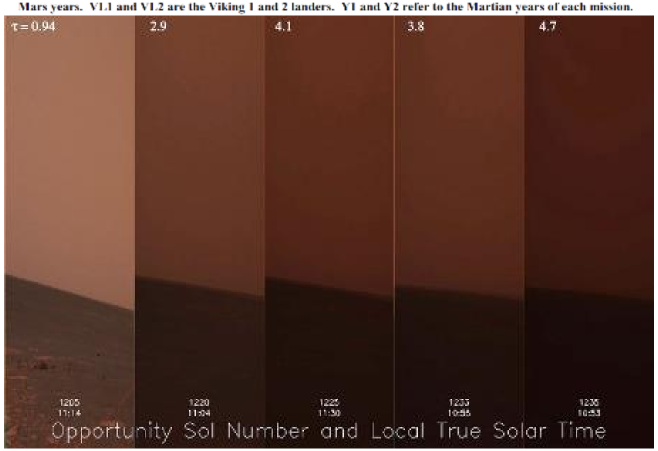


Figure 1 - Optical depths measured by Viking Landers [2]. There are multiple values for each Ls due to overlapping Mars years. VL1 and VL2 are the Viking 1 and 2 landers. Y1 and Y2 refer to the Martian years of each mission.



Why Fission for Mars Surface?

Energy Source	Energy Density	Max Power Density
LH2-LOx Combustion	15 MJ/kg	limited only by engineering
Pu-238 Decay	2,100,000 MJ/kg	0.54 kW/kg
U-235 fission	82,000,000 MJ/kg	limited only by engineering
D-He3 fusion	354,000,000 MJ/kg	limited only by engineering
Antimatter	90,000,000,000 MJ/kg	limited only by engineering

- Nuclear power sources offer enormously higher energy densities than chemical systems
  - Power density limits Pu-238 to lower power applications (~1 kW), and Pu238 is scarce/expensive
- Fission, fusion and antimatter can all provide energy and power densities beyond what we could feasibly utilize in the foreseeable future.
  - Fission has proven and easy to utilize physics -- our limitation is engineering the balance of system to utilize an extremely high temperature/energy-density power source.
  - Until we can develop the capability to engineer such systems, discussions of fusion and antimatter for space are essentially moot (for at least several decades, and that's only if we actually start making real progress today).
- It is possible, and perhaps likely that once we establish large scale settlements on Mars or elsewhere, that we could shift away from nuclear power to an available in-situ power source
  - perhaps solar power with cells made on mars and an in-situ energy storage mechanism, geothermal power, wind power, and maybe nuclear if we could mine thorium, uranium, D, He-3, etc.).

How much energy potential does uranium have?

One KRUSTY Piece = 10.7 kg U8Mo
This piece = ~8.1e8 MJ if all U atoms are burned

the hard part of fission is
not creating the energy,
it is utilizing the energy.

= 121 X

1 piece of KRUSTY fuel contains the energy equivalent of 121 fully-fueled Falcon Heavies

One fully-fueled Falcon Heavy (both stages)
~156 mT RP-1, ~43 MJ/kg = ~6.7e6 MJ

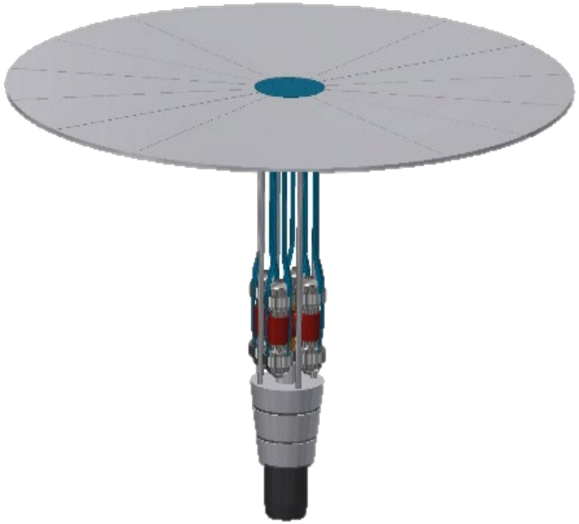
If Space Reactors are so great, why don't we have any??

- **The perception of new reactor technology is stronger than reality**
  - Today. there is a persistent media bombardment of new "advances" or reactors "set to start up in ~5 years", which install a false belief that progress is being made.
  - This situation is no different than it has been for the past 40 years, except that social media now makes the "we're making progress myth" more pronounced.
  - Actually, there is progress being made in China, just not the US
- **In reality, no tangible progress has been made in reactor power systems over the past 40 years (except for KRUSTY in 2018)**
  - Not unique to space reactors – the US hasn't built any new type of reactor in >40 years.
  - Things continue to get "harder" for new reactor development because solar power/battery technology have raised the bar by significantly advancing (which is actually awesome)
- **We've spent billions on space reactor programs, why have they failed?**
  - Programs lost support because too expensive and/or dragged on with insufficient progress.
    - Reason 1: Over-sold paper concepts – there's always someone that claims they can provide a higher-performance system to woo a customer.
    - Reason 2: The traditional NASA/DOE model of spreading the money and continually pursuing advanced technologies and paper studies instead of reactor system development.
  - Lack of capability
    - In the 50s and 60s ~100 new reactors built and tested. All reactors in use today utilized several ground tests prior to success: "INL" tested >50 reactors: National Reactor Testing Station (NRTS)
    - This knowledge/capability is gone: 40+ years of no new reactor concepts tested (until KRUSTY)
- **We need to focus on getting a simple first generation system deployed!!**

SNAP-10A, launched 1965

Kilopower Reactors offer the best chance to finally get something flown.

- Reactor concepts produce from 1 to 10 kWe at low mass, or up to 25 kWe for an LEU system.
- Reactor easily adapted to operate in space or on surface, and for robotic or human missions – power system accommodates modular shielding blocks
- The reactor technology/approach evolves up to > 1 MWe without significant change/risk from a nuclear perspective.



10 kWe, 1500 kg concept

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Kilopower Reactors: Simple, Safe, Reliable, and Testable

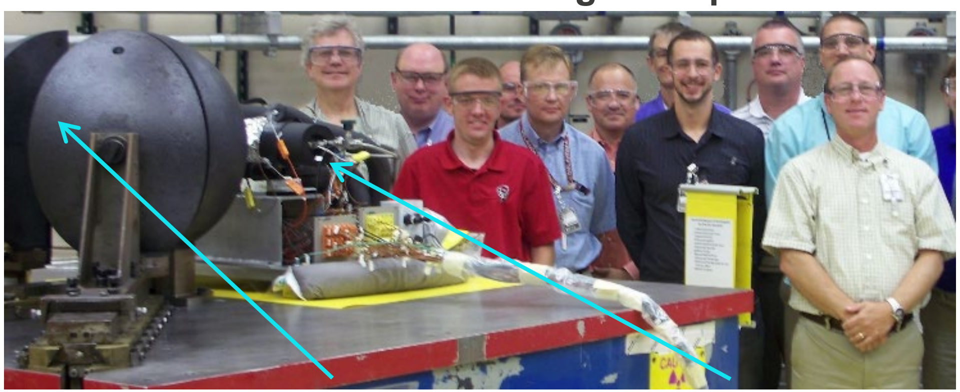
- **In 2012, we envisioned and performed the DUFF experiment to break the repeated cycle of failure of NASA/DOE space reactor programs**
  - Billions of dollars had been spent without progressing to a single nuclear-powered proof of concept test in over 50 years.
- **DUFF was based on our prior LANL/NASA work, which had convinced us that heat-pipe-cooled reactors provide the best combination of performance, ease of development, and affordability**
  - Simple, passive reactor operation, high reliability, ease of electrical testing
  - The use of metal-fuel provides low reactor mass (high uranium density), high temperature, and the only existing infrastructure for rapid, low-cost fuel fabrication.

photos courtesy of NASA MSFC, JPL, and LANL

NEP demo: heat-pipe reactor coupled to Stirling engine, providing electricity to ion engine.

Electrically-heated heat-pipe reactor coupled to gas heat exchangers to power Brayton cycle

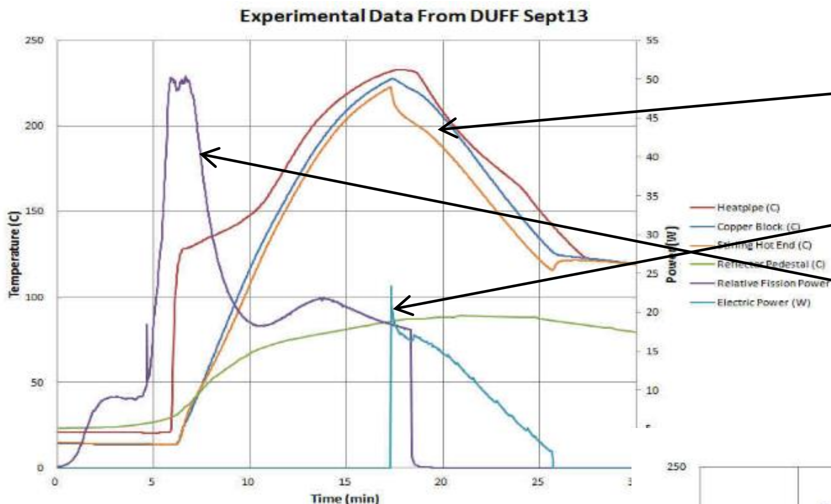
DUFF: Demonstration Using Flattop Fissions



LANL HEU Flattop Core and reflector   GRC Stirlings

- **DUFF Objectives – Proof of Concept**
  - Generate electricity (light panel) from fission heat
  - Demonstrate predictability of basic reactor physics
  - Show a path to affordable space reactor development
- **Significance of DUFF**
  - First-ever use of heat-pipe to transfer reactor power
  - First-ever Stirling engine operation with fission heat
  - Modeling tools predicted the simple physics extremely well
  - Renewed NASA interest in space reactors

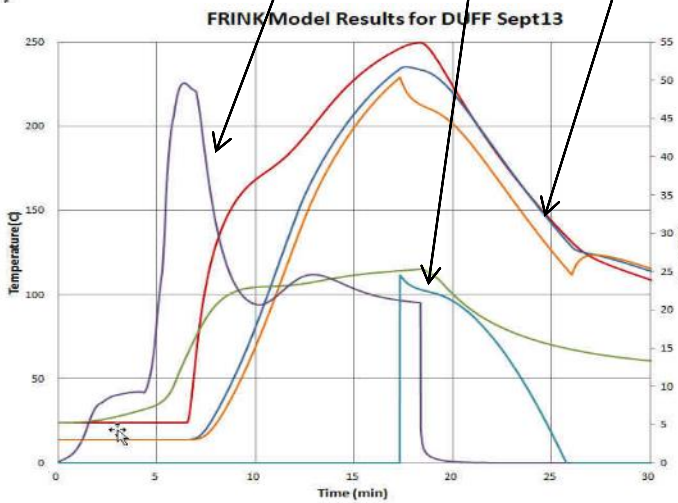
DUFF Results Compared with FRINK System Model



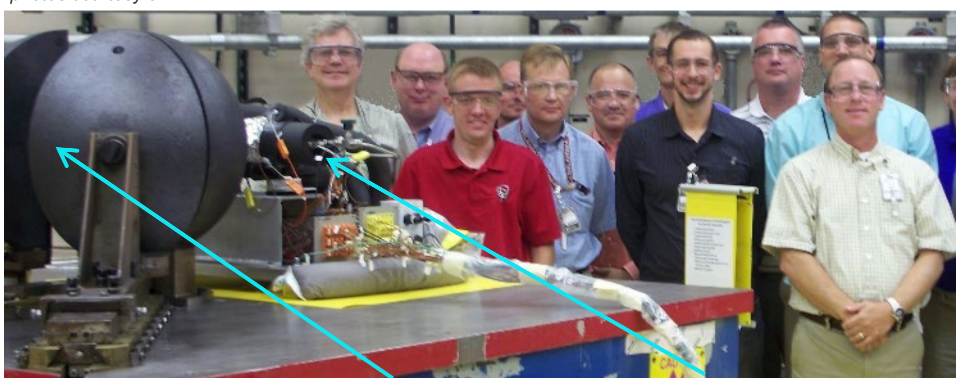
Power Conversion System Temperatures

Electrical Power

Reactor Thermal Power



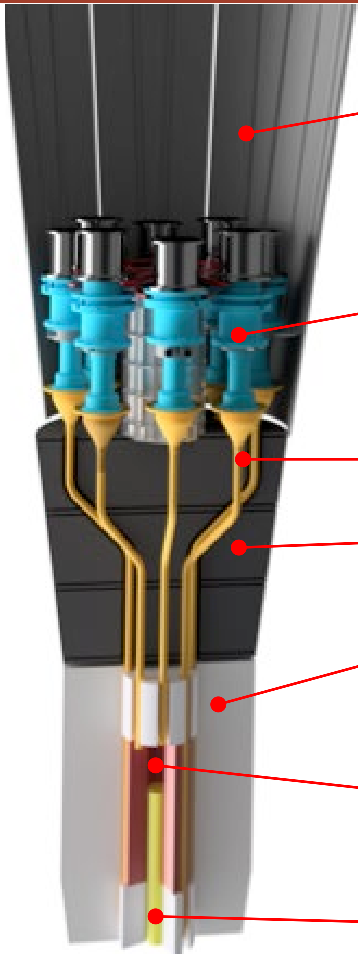
photos courtesy of LANL



Core and reflector

Stirlings

Kilopower Reactor Using Stirling TechnologY (KRUSTY)



Titanium Heat Pipe Radiator

Stirling Power Conversion System

Sodium Heat Pipes

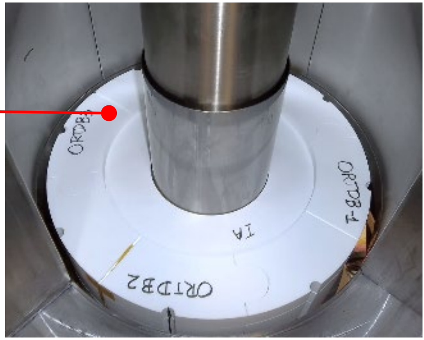
Lithium Hydride, Tungsten Shielding

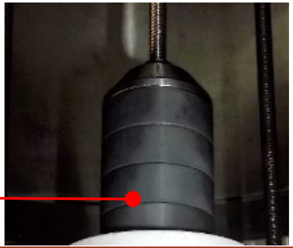
Beryllium Oxide Neutron Reflector

HEU U-Mo Cast Metal Fuel

B_4C Neutron Absorber Rod

System enclosed in vacuum





photos courtesy LANL and NASA GRC

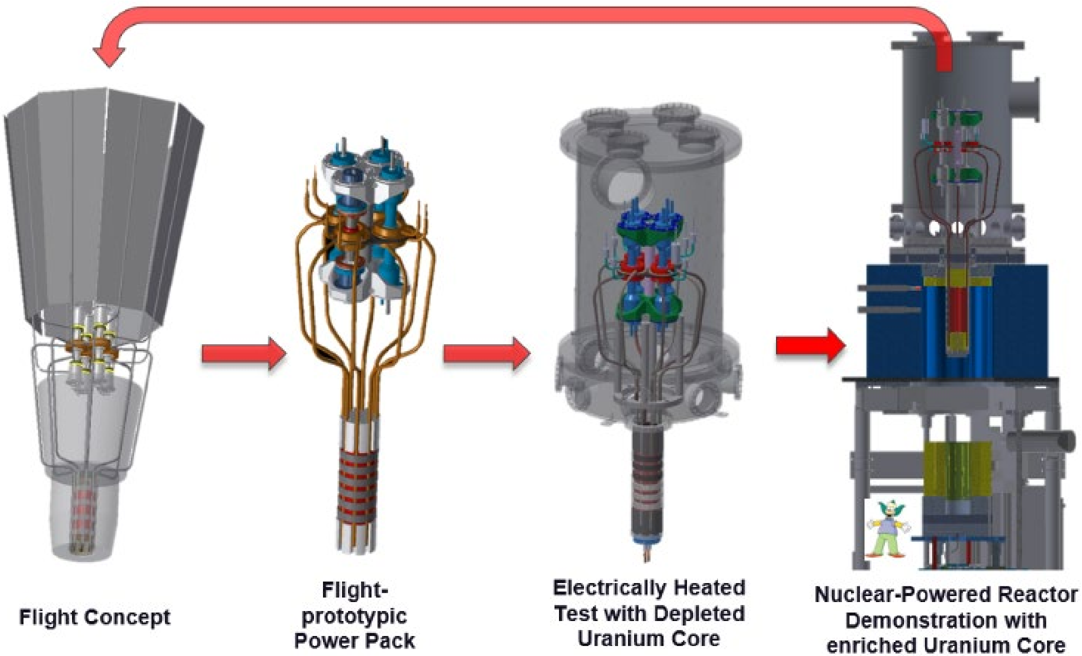
KRUSTY Core and Reflector Assemblies

photos courtesy of NASA/LANL

Note the thermocouple wires in middle photo, under the core clamping rings, and the TC placed in the BeO reflector on right photo.

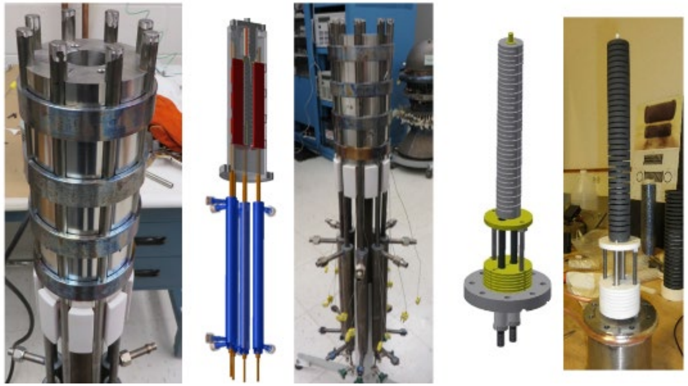
How KRUSTY Succeeded

- **Hardware-focused program with key milestones every year (similar to what we are proposing)**
  - Year 1: Design and hardware prototyping, begin conversations with DOE regulator, begin procurements.
  - Year 2: Electrically-heated test demonstration with depleted uranium, combine our models and testing to gain regulator confidence.
  - Year 3: Final component delivery and assembly, gain regulator approval, full system electrically-heated and nuclear testing.
- **Key to success -- Integrated Simplicity!**
  - Finding/following the simplest path through design (physics, engineering, technologies), development, fabrication, safety, and testing.

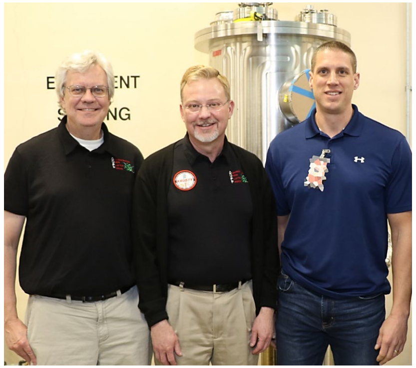


Successful completion in 2018 for $18M

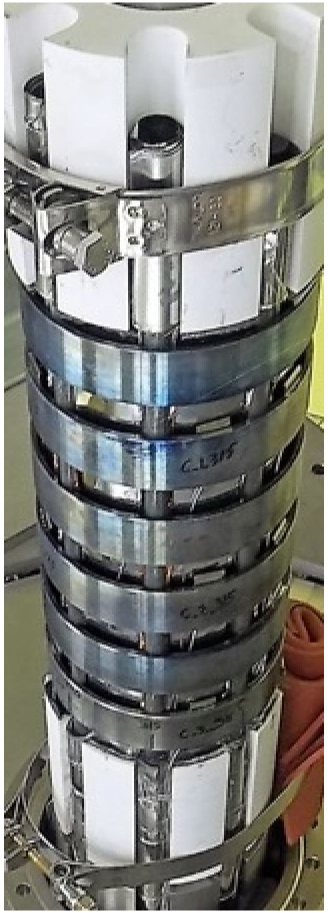
This was not a space-qualified system, but testing a nuclear reactor on Earth can be just as hard, or harder.



KRUSTY Test Results Demonstrated Simple and Predictable Control and Operation



photos courtesy of NASA/LANL

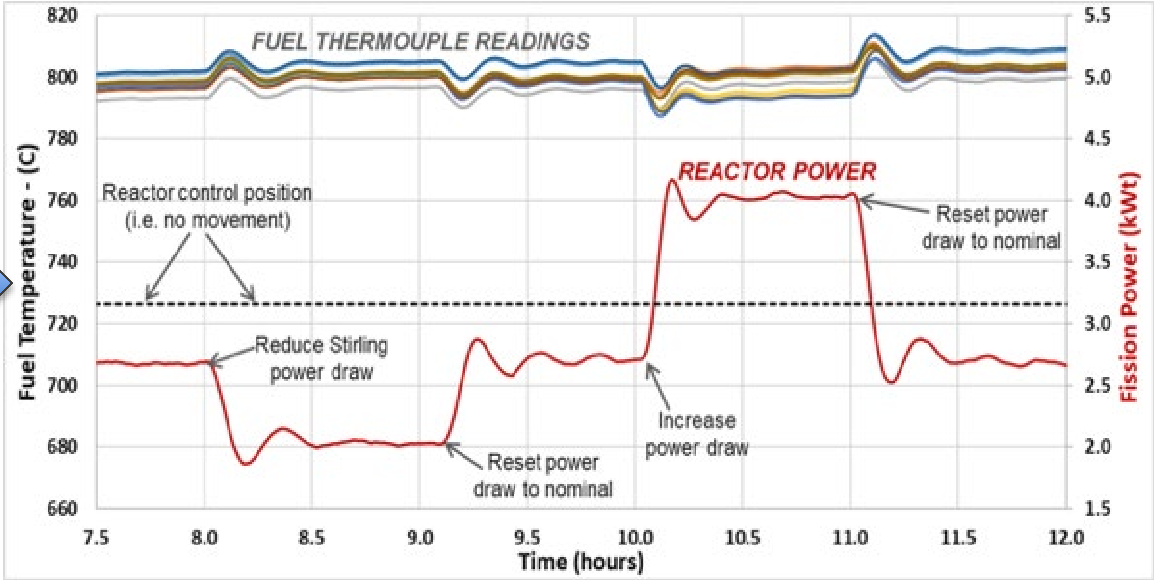


The KRUSTY reactor was highly prototypic of our flight reactor

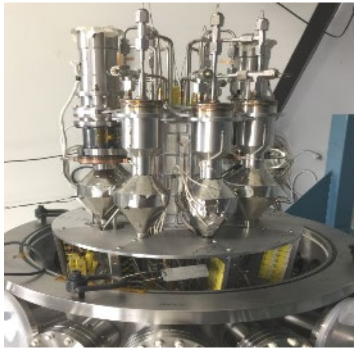
First operational data from a new reactor in US in 40+ years

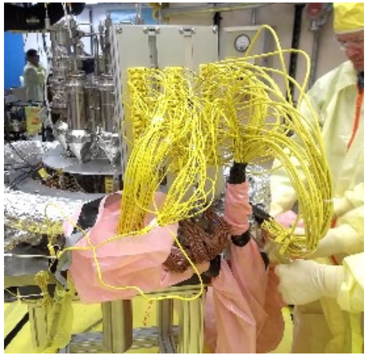
Load Following and self regulation: proven with actual reactor test data.

No other reactor power system that operates like this has ever existed.



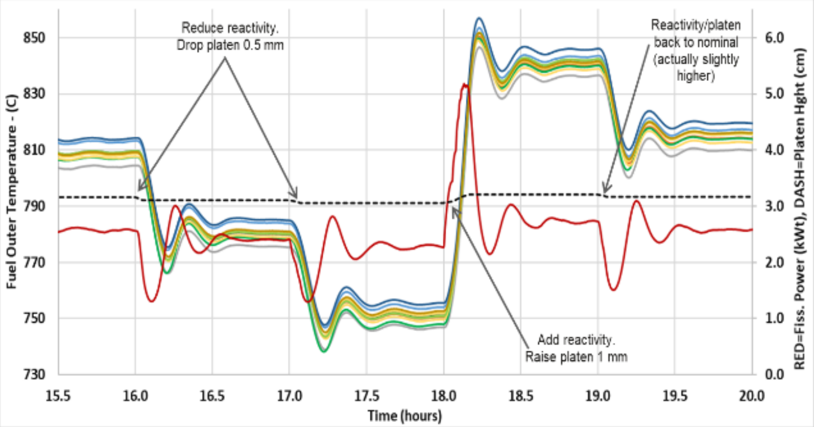
Nuclear-Powered Operation of Prototypic System Demonstrated in a Prototypic Environment.

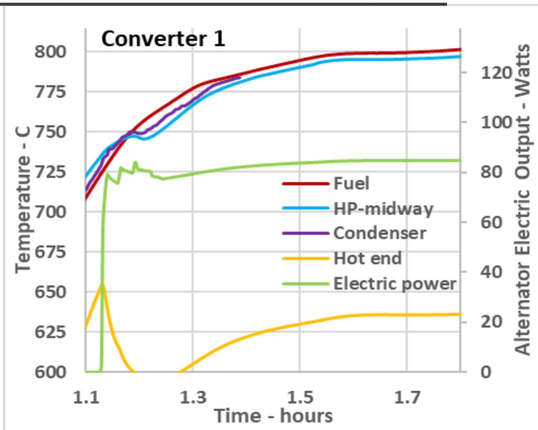


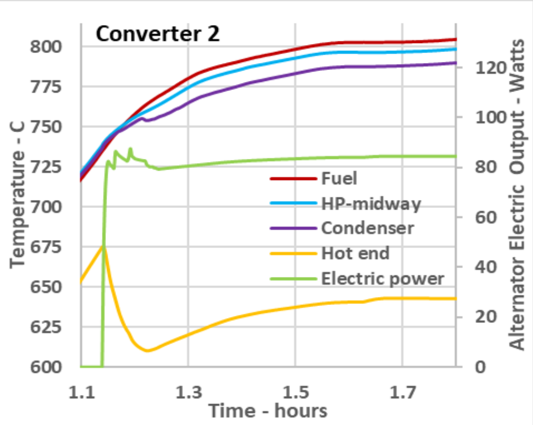




photos courtesy of NASA/LANL

Actual System Data from KRUSTY Nuclear-Powered Test





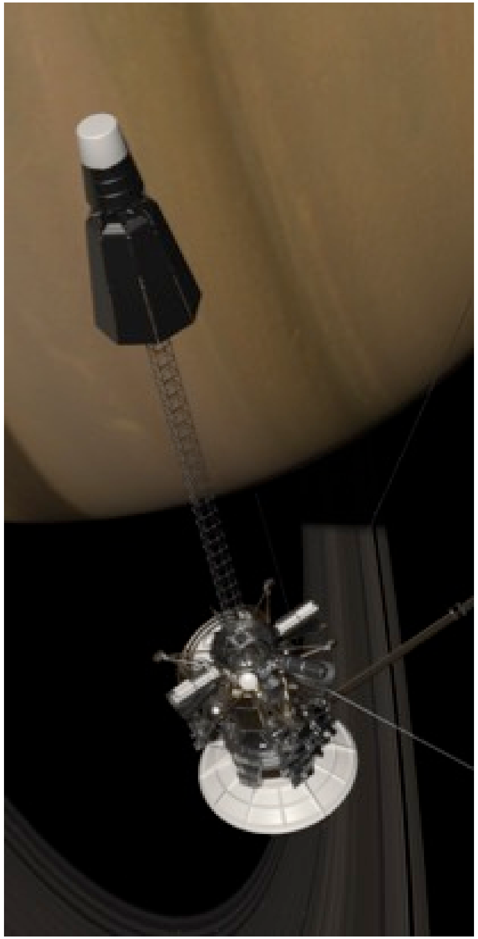


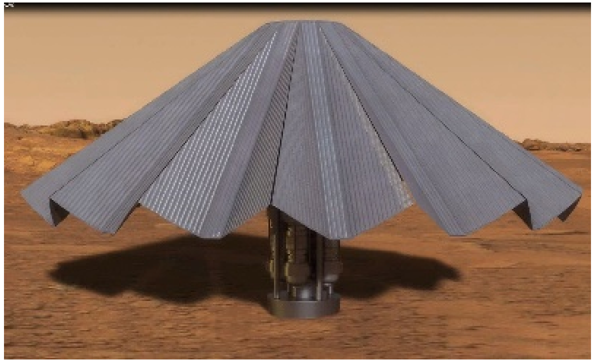
Kilopower reactors operate as a thermostat. The control rod sets the desired temperature, and the fission power passively increases or decreases to maintain the thermostat temperature.

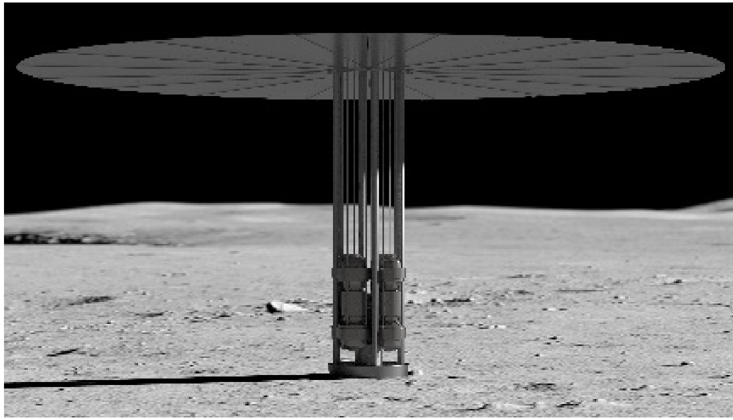
The reactor and each of the 80 kWe-rated Stirling convertors performed without a glitch; including restart where hot-end was soaked >800 C (well above spec).

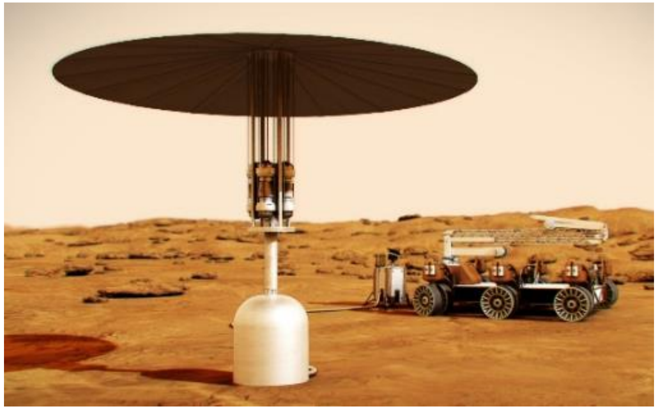
Read the ANS Journal Nuclear Technology for details about KRUSTY.

Possible Near-Term Deployment of Kilopower Reactors









NASA artwork

Kilopower Reactor Evolution to Several Megawatts

- **Kilopower reactors are ideal for higher power evolution because the physics, control, and operation do not change significantly as power increases (core neutronics and heat transfer characteristics remain the same).**
  - This is the most important attribute with respect to power scaling, because it allows the possibility to develop the next evolutionary step without nuclear-ground-test development program (i.e. electrically-heated system testing combined with zero-power physics tests will provide high confidence).
- **KRUSTY provided sufficient experience/data to provide high confidence in the operation of a 1 to 30 kWe Kilopower flight concept. Once completed, the first Kilopower flight concept will do the same for a 100 to 300 kWe system, and so on to > 1MWe systems.**
- **Three technology changes will be required to reach Megawatt levels: fuel type, core structure, and reactor technology**

Kilopower Reactor Evolution - when do we need a technology changes (noting that reactor physics and dynamics changes are small and predictable, difference from KRUSTY in right column)

	1 kWe	up to 3 kWe	up to 10 kWe	up to 30 kWe	up to 100 kWe	up to 300 kWe	up to 1 MWe	up to 3 MWe	up to 6 MWe		KRUSTY Dynamics
Fuel Type	HEU ~700 kg lighter up to 10 kWe, then has diminishing benefit with power.									Fuel Type	
UMo block				As long as fuel lifetime looks good						UMo block	100%
UMo rods				Lowest mass pellet option, easiest fab, need for coatings/liners, swell/FG release problematic is burnup increases						UMo rods	99%
UO2 pellets					Very robust, well understood to high burnup, good with SS or Haynes and maybe someday Moly.					UO2 pellets	97%
UN pellets					Lower mass, fab risk, risk in cladding iterations (coatings/liners?), less certainty in performance					UN pellets	98%
Core Structure										Core Structure	
Kilopower				Transition point depends on experience with...						Kilopower	100%
Megapower				UMo lifetime and SS/HP block fabrication issues						Megapower	95%
				Higher temperature options to SS316 block are possible, super-alloy or refractory, depend on performance vs risk profile.							
Technology										Technology	
HP-Stirling: 1-to-1				If integration OK						HP-Stirling: 1-to-1	100%
HP-Stirling: IHX				If Stir best, but integration gets tough						HP-Stirling: IHX	98%
HP-Brayton				If lowpow Brayton looks better than Stir.		Default as long as HP experience continues to be good				HP-Brayton	95%
GC-Brayton					Go to gas cooled once reliability risk is deemed ok relative to increased pain of HPs with higher power					GC-Brayton	80%
LM-Brayton							"Best" non-"Kilopower" path if GC unreliable or too heavy			LM-Brayton	20%

Each step above does not have to be taken, but at least 3 are recommended.

For sure	
Probably	
Good chance	
Perhaps	
Unlikely	

SpaceNukes Concepts: Schedule and Risk Projections

SpaceNukes KRUSTY/Kilopower Derived Systems

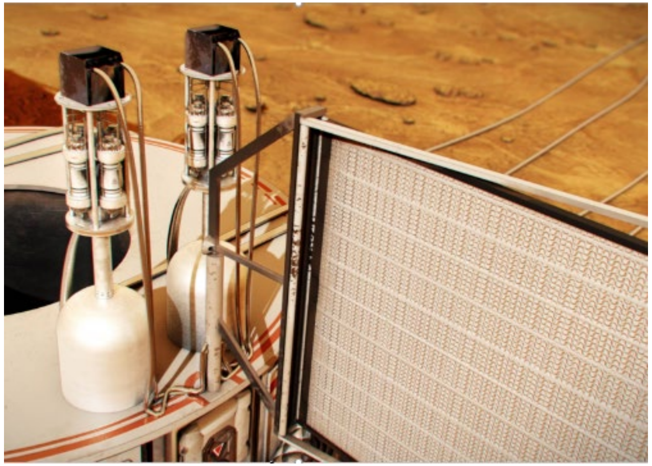
Power	Mass	Fuel	Deployment Schedule	Cost, Sched., Tech. Risk
1kWe-space	400 kg	HEU	3 years	Very low
5kWe-space	700 kg	HEU	3 years	Very low
20kWe-surface	~2300 kg	LEU	5 years	Low
200kWe-surface	~7500 kg	LEU	~7 years	Modest
2MWe-surface	~32000 kg	LEU	~10 years	High

Cost, risk, and schedule of higher performance systems will decrease substantially with the successful completion of any earlier generation.

Masses and risks depend on architecture, reliability, and dose requirements (listed surface power mass includes modest 4pi shielding).

Other options are possible, these power levels span most of the design space.

Costs depend on mission specifics and customer requirements, but in general, very low ~$100M, low ~$200M, modest ~$500M, and high ~$1B for delivered flight reactor and all reactor/nuclear related ATLO/approval costs. *More important is that the cost and schedule risks are much lower for the low cost systems – thus more certain to succeed.*



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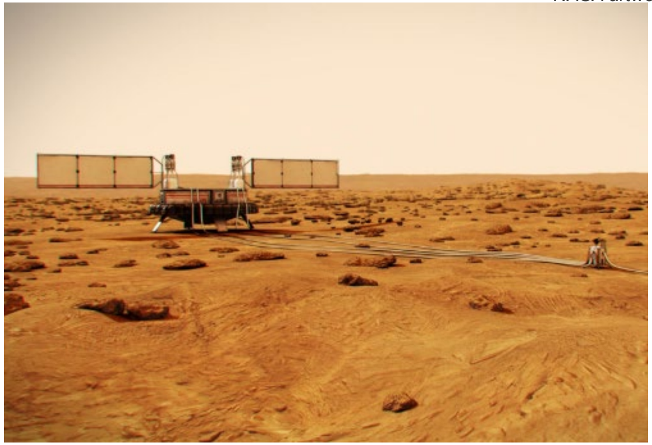
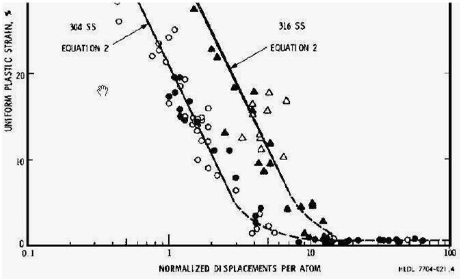
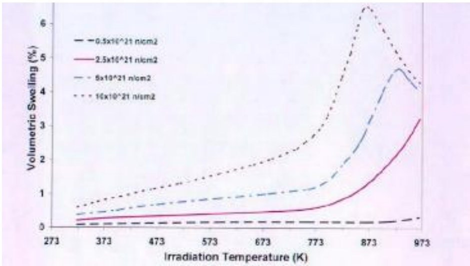


Reactor issues that get more difficult with higher powers

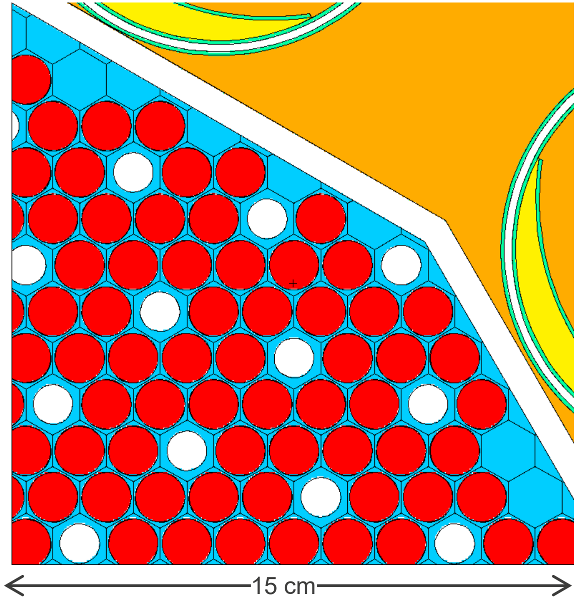
- **Maintaining neutronic reactivity control for nominal and safety conditions**
  - Higher power system loses more reactivity with burn, is “thicker”, and experiences burnup of control material (B10)
  - More coolant area makes water immersion tougher.
  - At some level (~20 MWt) requires internal control elements
    - External control (e.g. drums) simplifies design: system integration, cooling of control elements, boundary penetrations, irradiation damage, mass, shielding
- **Fuel fission gas release and swelling**
  - Fission gas can create block stress issues, via higher pressure and lower conductivity gas-gap
  - Swelling of fuel increases risk of pellet-clad material interactions (PCMI)
- **Irradiation damage to structure**
  - SS316 loses ductility, adding some risk as the system ages
- **Reflector/shield cooling**
  - High power more difficult integration of cooling paths, and the use of cold (pre-compressor) coolant hurts efficiency
- **Beryllium swelling**
  - Higher power increases Be temperature and fluence – both increasing swelling
- **Shielding**
  - Higher power requires a deeper hole, plus increased launched shield mass
- **Regolith overheat potential**
  - The low conductivity regolith has harder time rejecting the heat with higher power density and/or deeper hole.



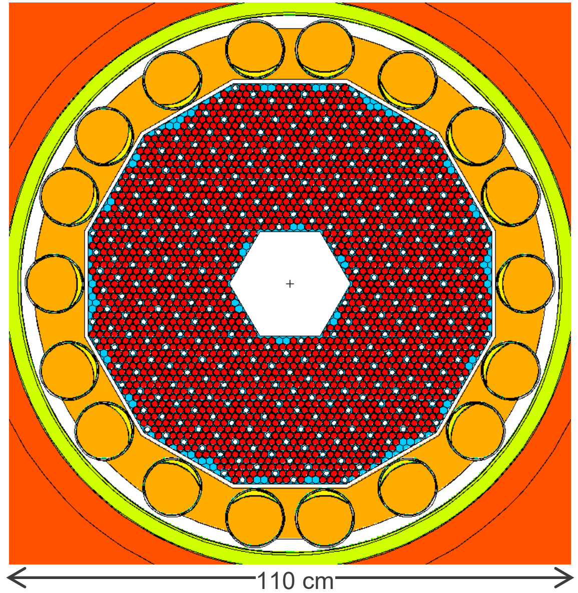


2.5-MWt Megapower Reactor for 650-kWe Power System concept

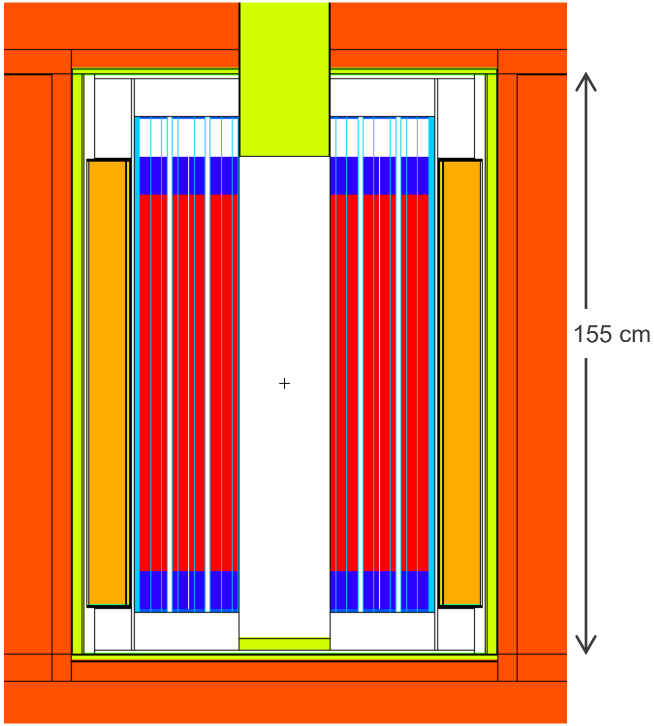
Core is a solid block/monolith of SS316 (light blue), with several holes that contain HALEU UO2 fuel pellets (red), and other holes that contain flowing HeKr gas (white). (could be heat pipes, tbd)



Core is surrounded by beryllium (orange) reflector and rotating control drums that contain an arc of boron carbide neutron absorber (yellow). The central hex filled with B4C safety rod during launch



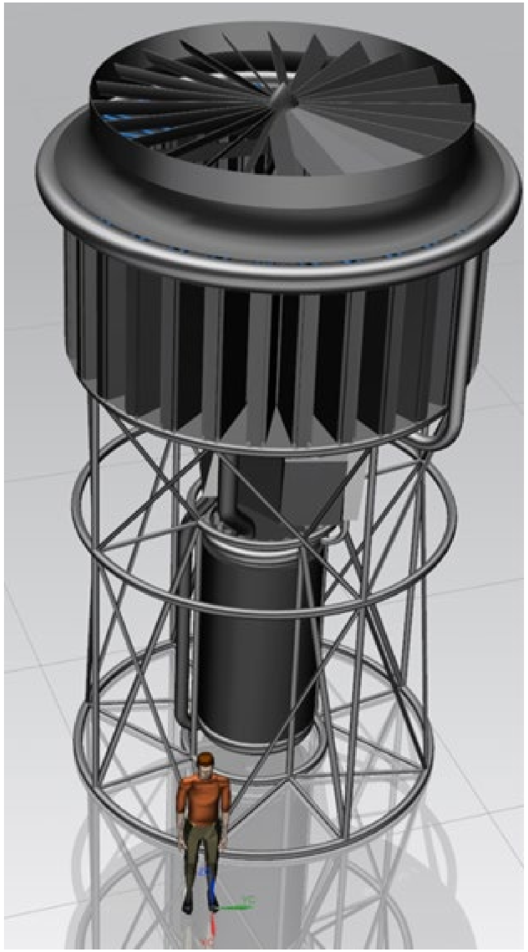
BeO reflector pellets (dark blue) inserted above and below the UO2, with fission-gas plenum above.



Red = UO2, Dark Blue = BeO, Light-Blue = SS316, Orange=Be, Yellow = B4C, Dark Orange = Regolith

650 kWe Megapower Mars Surface Concept

	Mass (kg)
Fuel	3885
Axial reflectors	119
Monolith	2002
Radial Reflector	324
control drum sleeve	113
control drum B4C	61
control drum Be	527
control drum can	113
Reflector Structure	47
Reactor manifolds	84
motor drives	47
safety rod	102
misc. hardware	23
Bypass Reflector Cooler	160
Total Reactor	**7607**
Shield	**875**

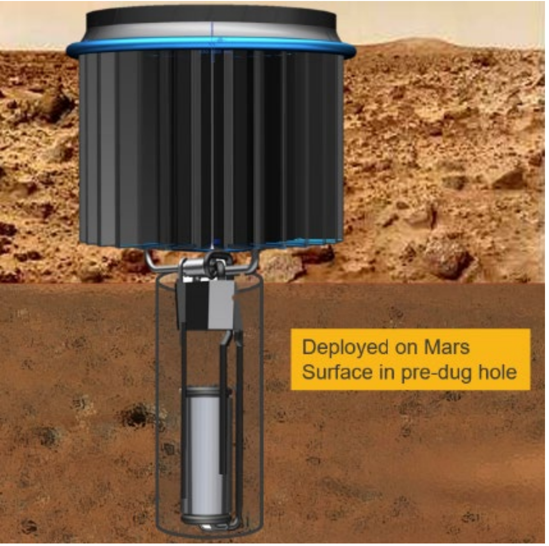


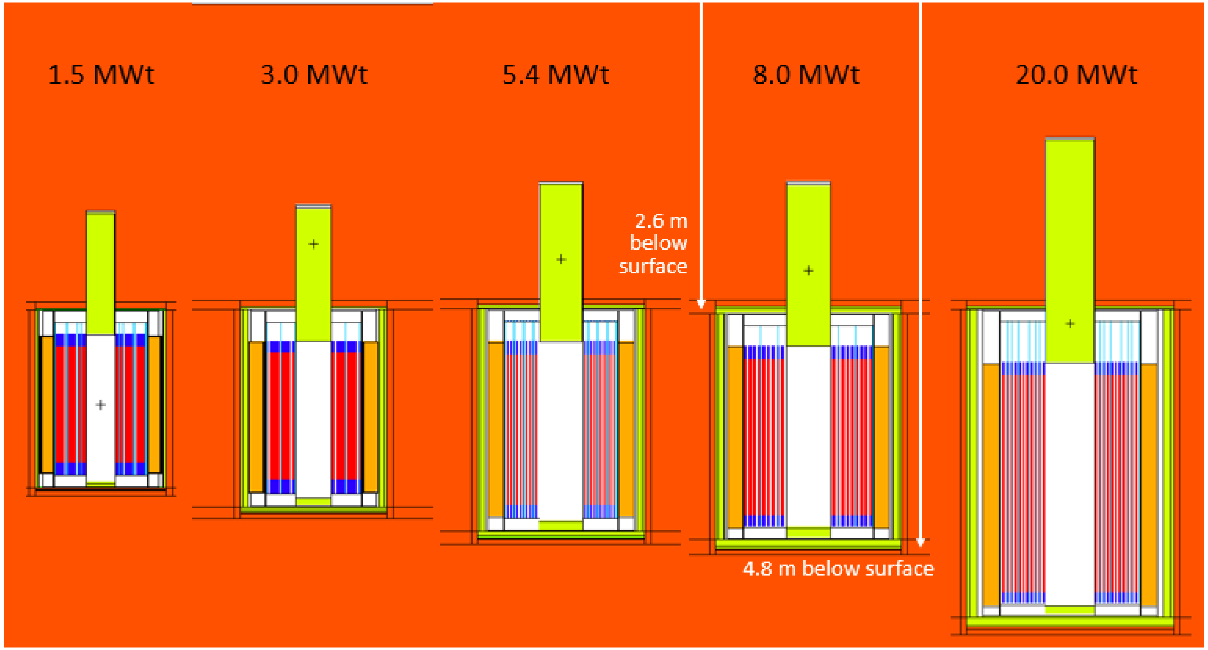
750 kWe Brayton	586
Recuperator	1872
System Piping	159
PMAD	468
Waste Heat Radiator	62
Total Power Conversion	**2896**
Intercooler	3056
Fan, motor, and Shroud	232
Total Intercooler	**3288**
System Structure	**223**
System Instrumentation and Control	**175**
Total System Mass	**15064**
Total System Electrical Power (kWe)	650
Total Energy over Mars Year (GWh/Mars yr)	10.4
Specific Power (W/kg)	43
Total System Specific Energy (kWh/kg)	692
Total Power System Volume (m^3)	55
Specific Volume (kW/m^3)	11.8

Power is dependent on atmospheric temperature and pressure: nominal = 600 to 700 Pa. Range from 1155 Pa at Hellas Planitia to 30 Pa on the top of Olympus Mons.

A system designed to operate at 950 Pa vs 700 Pa could produce 10% more specific power (W/kg).

Buried configuration allows nearby habitation and power system maintenance



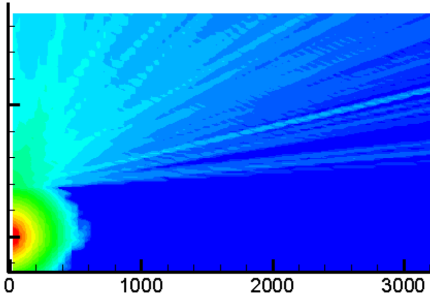


<u>Buried configuration allows:</u>

Huge savings on shield mass.

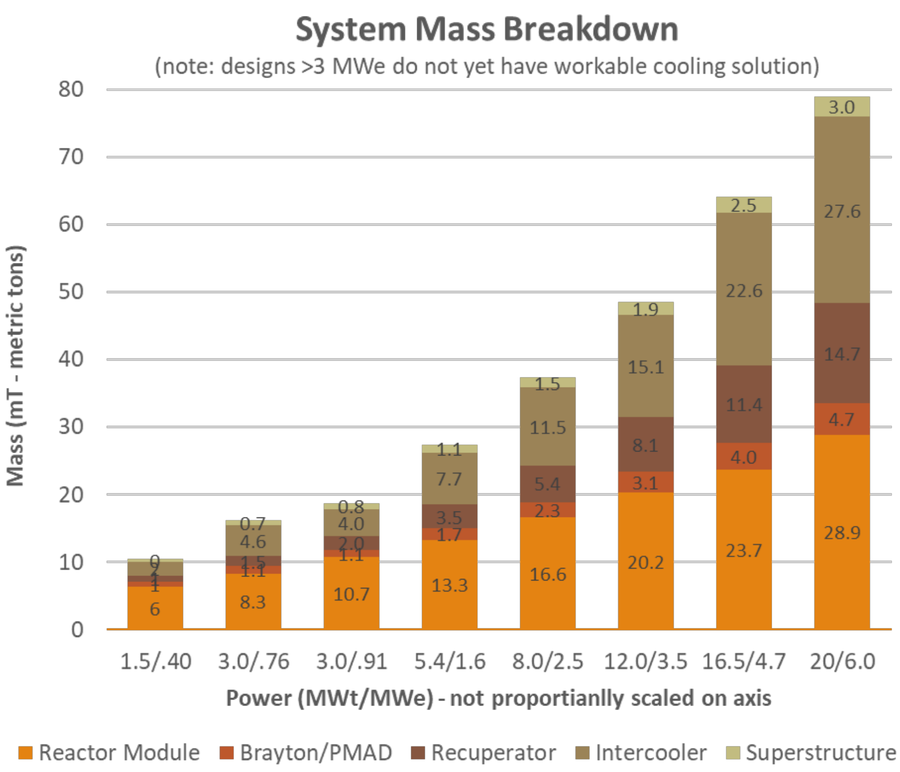
Habitation nearby.

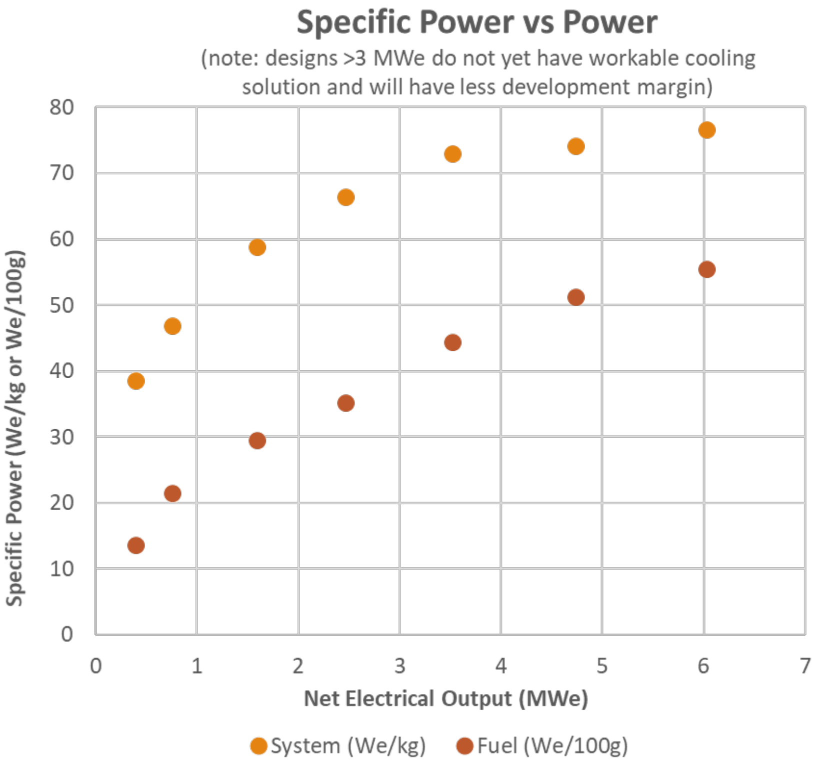
Maintenance on all above surface components.



Dose from an operating 8 MWt/2.5 MWe reactor = Mars background at 30 m, and is 10x lower @100 m.

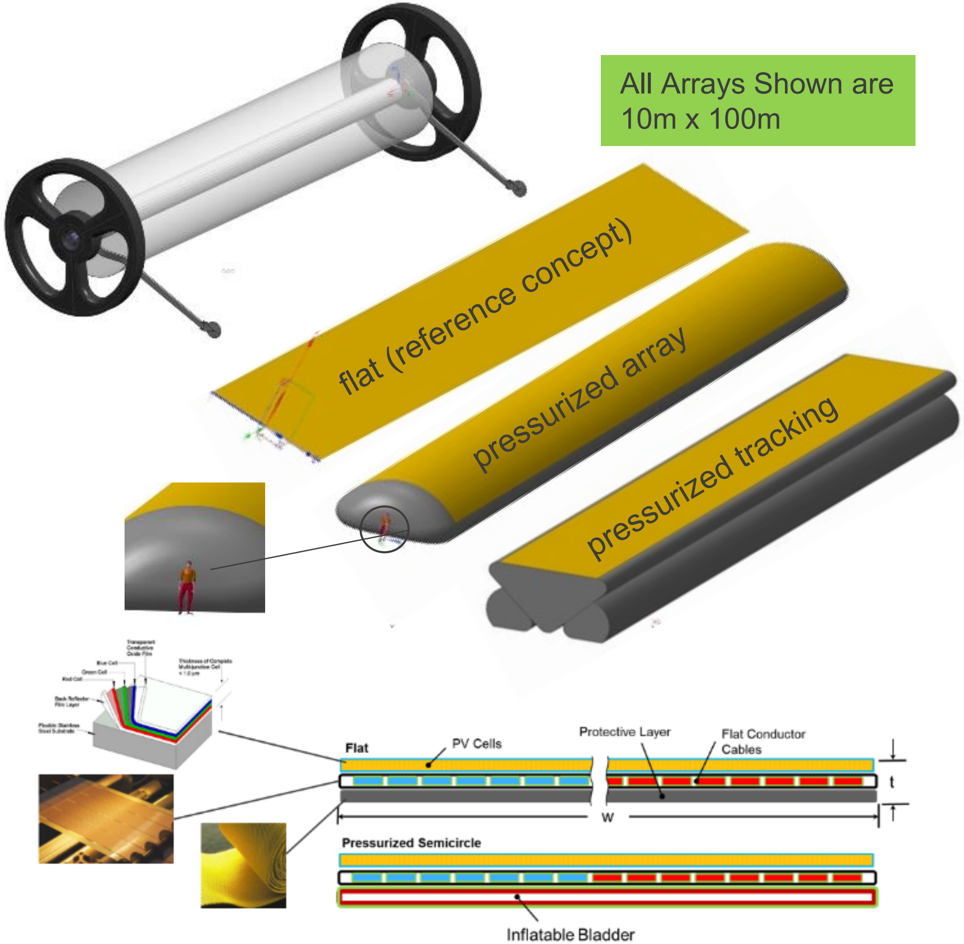
SpaceNukes High-Power Mars Surface Reactors





Above 3 MWe, the intercooler will not fit within Starship's 9m diameter faring. This limit is pressure dependent; i.e. intercooler size could allow a 3.5 MWe power system at low elevations, and only 2.5 MWe at relatively high elevations. Above ~3 MWe there is also little mass benefit of going to higher powers. so ~3 MWe might eventually the place to transition from space reactors launched from Earth, to reactors built in-situ on Mars (perhaps with only fuel coming from Earth), or other in-situ power sources. Note: All of these numbers are based on "simple" Megapower technology, and could be improved upon with more advanced technology (especially with higher temperature materials), and thus offer to higher system powers at similar size/mass.

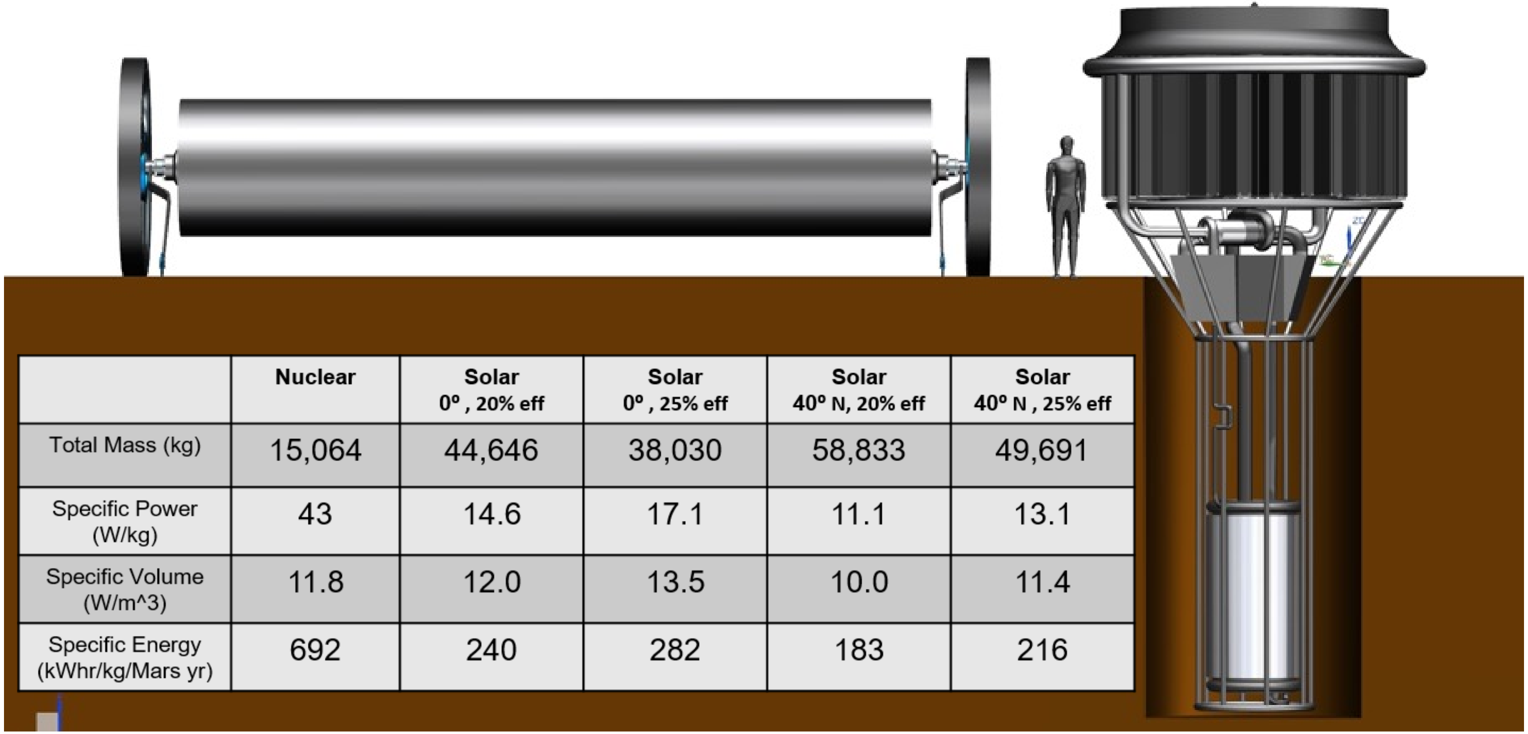
SpaceNuke Design of 650kWe Rollout Solar Array



Array Length	m	2586	2069	3548	2839
Max PV converted Power	kW	2680	2680	3123	3123
PV Voltage	V	600	600	600	600
Joule Heat Losses	kW	23	23	20	20
Distributed Power	kW	628	628	631	632
Yearly average Hab Power Available	kW	596	597	600	600
Total PV blanket Mass	kg	29429	23543	40536	32429
Deployment Vehicle Mass	kg	925	925	925	925
PMAD Mass	kg	6585	6516	8014	7893
Mars Latitude	deg	0	0	40	40
PV cell efficiency	%	20.0%	25.0%	20.0%	25.0%
PV Array Area	m^2	24571	19656	33707	26966
Max daily solar energy	MWh/sol	18.64	18.64	26.91	26.91
Min daily solar Energy	MWh/sol	14.64	14.64	4.77	4.77
Battery Mass	kg	4168	4168	4400	4400
Total Energy over Mars Year	GWh	10.74	10.74	10.74	10.74
Average Power over Mars Year	kW	651	651	651	651
Total Launch Mass	kg	41107	35152	53874	45647
Total Deployed Mass	kg	40182	34227	52949	44722
Growth	%	10%	10%	10%	10%
CBE launch mass	kg	**44646**	**38030**	**58833**	**49691**
mass per unit area (Array only)	kg/m^2	1.2	1.2	1.2	1.2
Yearly average System Specific Power	W/kg	14.6	17.1	11.1	13.1
System Specific Energy (1 Mars yr)	kWh/kg	240	282	183	216
Stowed Volume (Spooled Array)	m^3	54	48	65	57
Yearly Energy/Volume	MWh/m^3	198	223	164	187
Specific Volume (Spooled Array)	kW/m^3	12.0	13.5	10.0	11.4

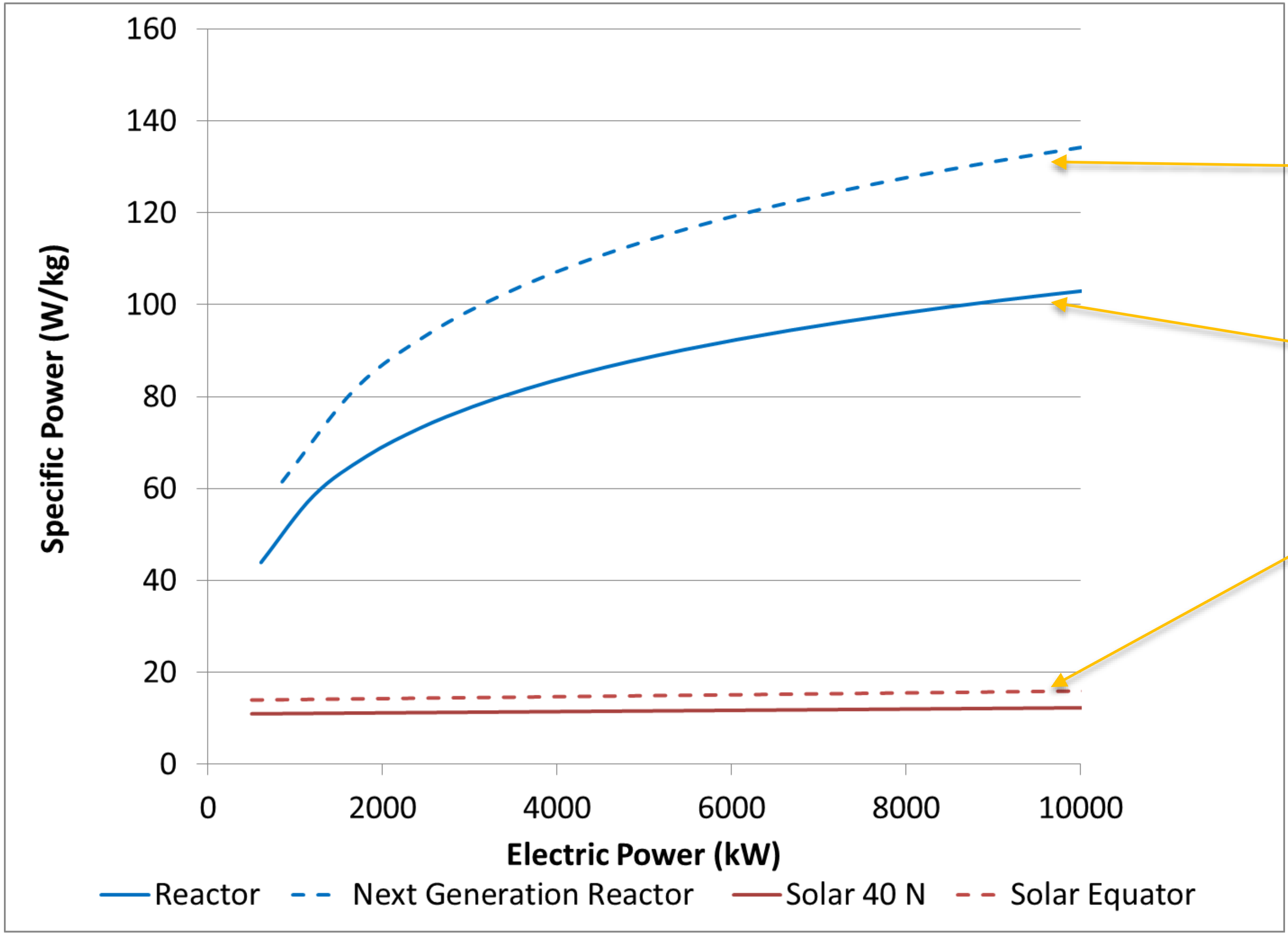
Comparison of Solar-to-Fission on Mars

The table below shows a comparison of solar and reactor 650 kW power systems for Mars. The solar power system includes battery storage for night, and can provide life support power (20% of nominal) during a significant dust storm (optical depth of 3). During daytime nominal conditions, the excess power will be used for ISRU processing, etc.



	Nuclear	Solar 0º , 20% eff	Solar 0º , 25% eff	Solar 40º N, 20% eff	Solar 40º N , 25% eff
Total Mass (kg)	15,064	44,646	38,030	58,833	49,691
Specific Power (W/kg)	43	14.6	17.1	11.1	13.1
Specific Volume (W/m^3)	11.8	12.0	13.5	10.0	11.4
Specific Energy (kWhr/kg/Mars yr)	692	240	282	183	216

Specific Power Comparison vs Power System Size



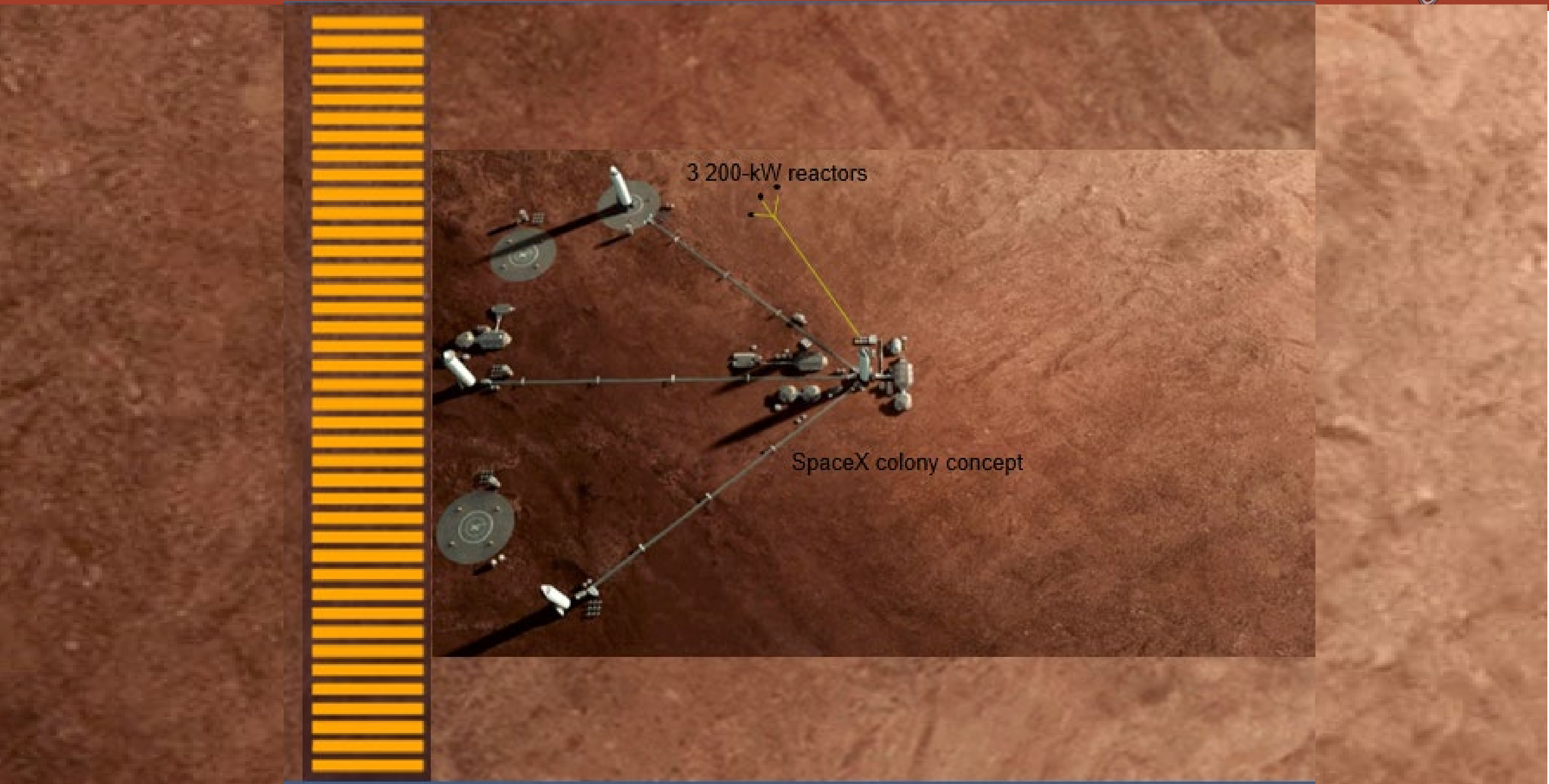
2nd Generation Reactor: With higher U-density fuel and higher temperature core and power conversion system

Megapower Reactor: With simple technology development path from KRUSTY and Kilopower

Solar at equator and 40 N: 25% efficient cells rolled over flat terrain and no dust buildup. Array and battery capacity to give 20% power during dust storm (strong storm, but not severe, optical depth =3)

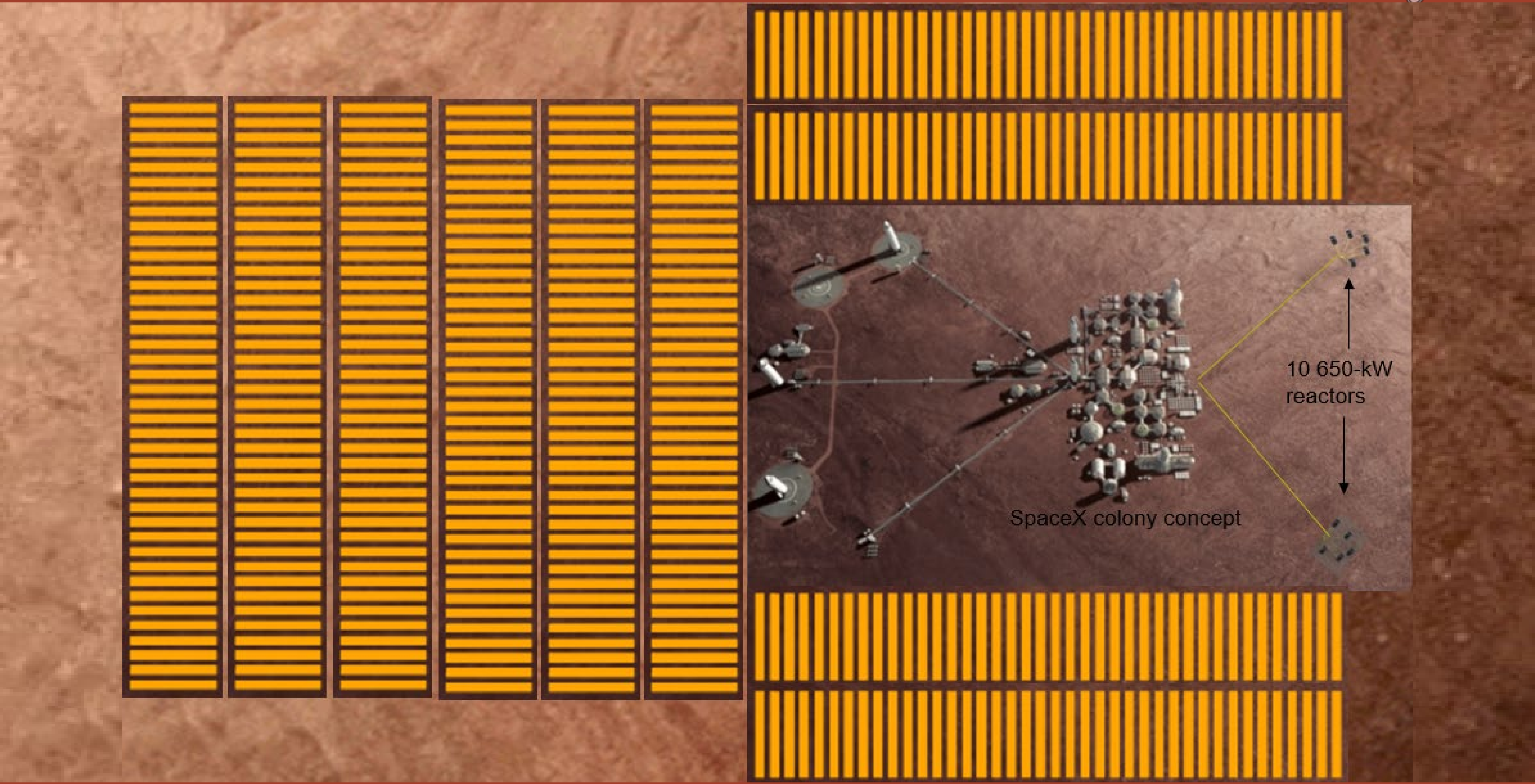
20 people on Mars: 600 kW (600-kW solar versus 3 200-kW reactors)

Estimated Mass at equator: 41 mT solar versus 22 mT reactor



300 people on Mars: 6 MW (10 650-kW solar versus 10 650-kW reactor)

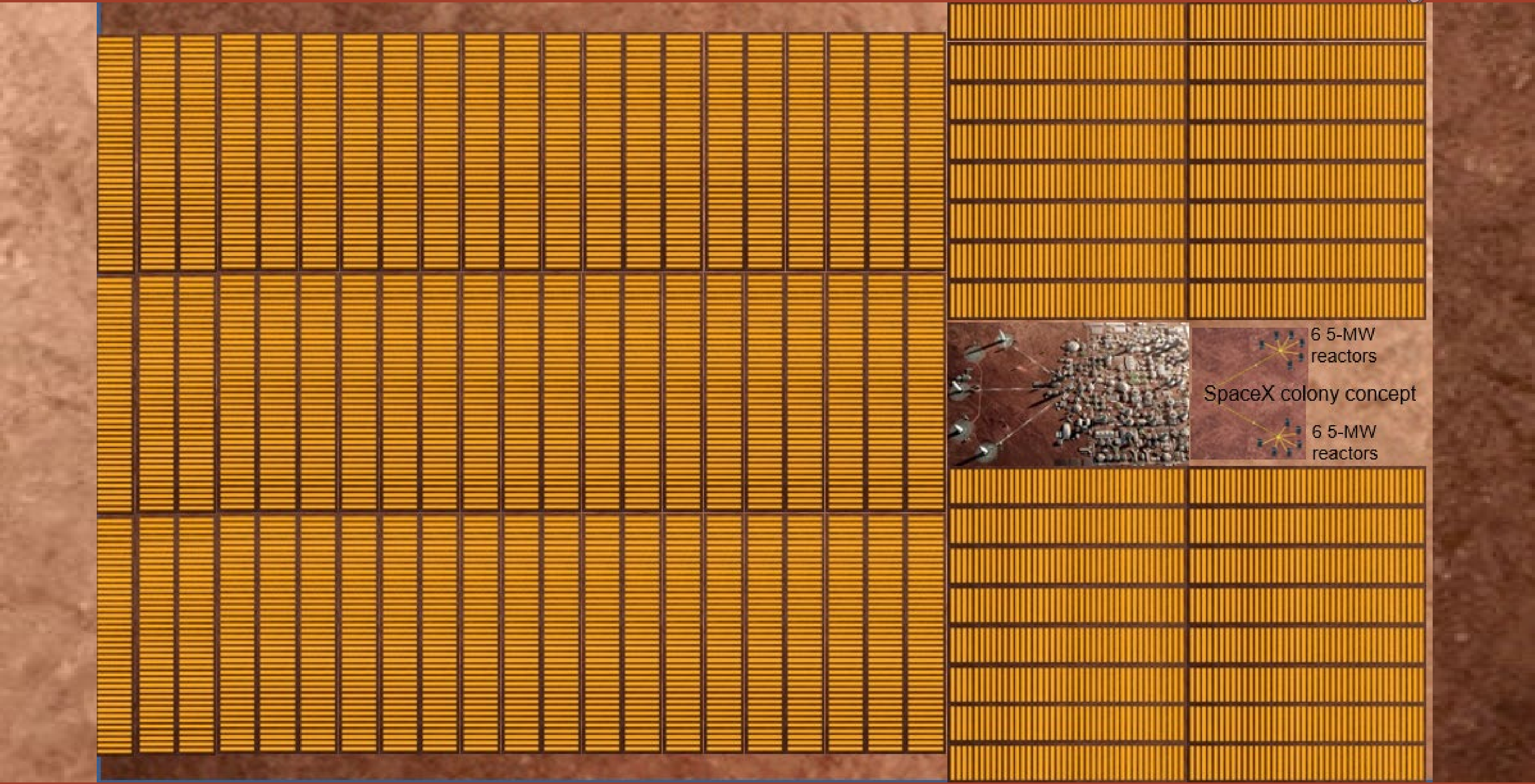
Estimated Mass at equator: 440 mT solar versus 150 mT reactor



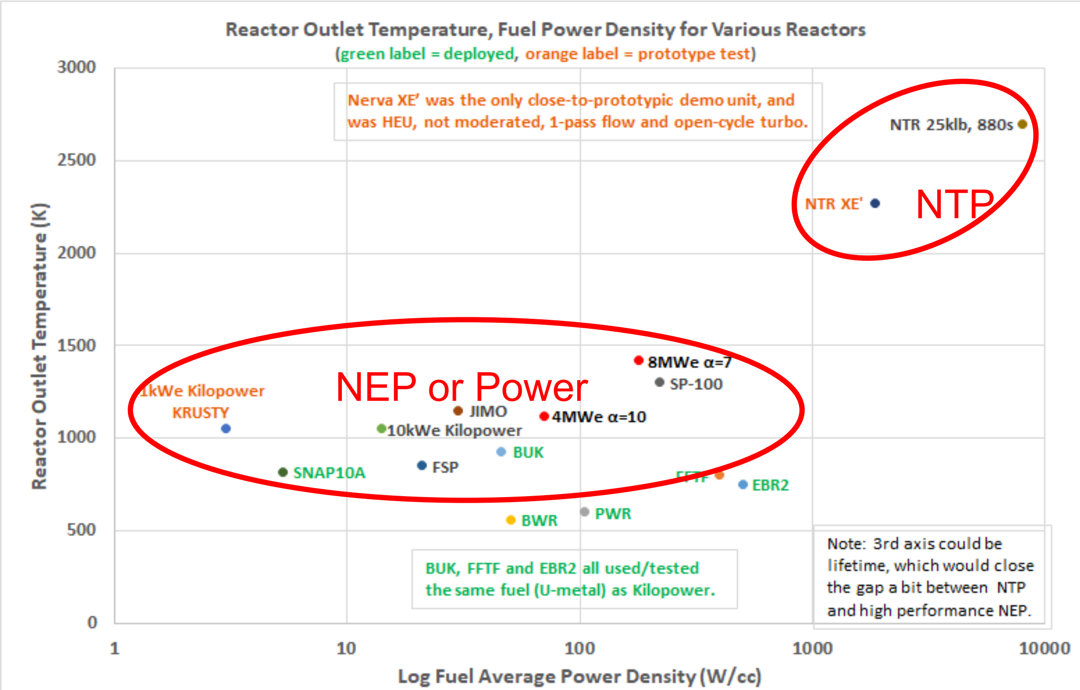
3000 people on Mars: 60 MW (95 650-kW solar versus 12 5-MW reactor)

Estimated Mass at equator: 4100 mT solar versus 780 mT reactor

Solar mass will be even higher because of cabling and/or perhaps transforming the electricity.



What about propulsion? NTP risks are vast and unique



Space Reactor Development Risks

- Neutronic and dynamic complexity
- Reactor "outlet" temperature
- Power density
- Lifetime (if high power density)

There are dozens of risks, but most are a strong function of the above (e.g. adiabatic heat-up rate, power, fluence, chemistry, burnup, erosion, instabilities, etc.)

Power/NEP: Allows system risk to be distributed amongst a "conventional" reactor design and other technologies (power conversion, heat rejection, thrusters) that can be developed in a traditional "non-nuclear" manner. The system risk is largely decoupled from integrated nuclear system testing.

NTP has higher power densities (>100x) and temperatures (>2x) than any conventional reactor, and is cooled by hydrogen traveling though the core at ~1 km/s. A long list of nuclear-thermal-mechanical risks are all integrated and cannot be resolved without repeated design, build, nuclear test iterations.

Useful NTP systems will require a >>SLS size effort: Rover/NERVA spent >$10B ($2021) with 19-ground nuclear test units, and did not get close to flight. Furthermore, all of today NTP programs are pursuing reactors that are higher performance than, and are far more technically complex than NERVA *(see backup slide for more).*

Useful power/NEP systems (surface power, deep space exploration, cislunar awareness) can be flown now (Kilopower), and evolve with manageable steps to high performance systems (cargo/asset movement, human exploration).

Nuclear Thermal Propulsion

History tells us how hard it is, rather than showed that it worked.

- **The progress made during the Rover/NERVA program still represents the most impressive achievements in the history of nuclear reactor engineering.**
  - However, after 19 different reactor tests they were still a long way from a ready-to-fly system.
  - Furthermore, the systems were substantially different and of lower specific impulse (I_{sp}) than what NASA and DoD are expressing interest in today.
  - The tested NERVA (i.e. rocket-like) systems were much simpler than any concept being pursued today because they:
    - used HEU,
    - did not use a neutron moderator,
    - did not attempt in-core axial cross flow (i.e. in both directions),
    - did not fundamentally rely on “exact” thermal insulation,
    - did not use a closed-cycle turbo-pump (simpler dynamics, lower system pressures)
    - had relatively low hydrogen reactivity worth (compared to SNRE),
    - were operating at relatively low pressure and temperature.
- **The only reactor test that resembled an NTR and used a turbopump (albeit open-cycle) was XE’, which had a rated I_{sp} of 710 seconds.**
  - This after >$10B (todays dollars) spent in a regulatory environment we can only dream of today.
  - It would take $10Bs just to reestablish a test capability if we decide to seriously pursue NTP.
    - And flight development is essentially impossible, unless perhaps we pursue a system as simple as NERVA.

High power Nuclear Electric Propulsion (NEP)... IS the future, but requires evolution

- **From where we stand today, an Human Mars NEP system (~10 MWe, 10 kg/kW) is almost as difficult as a 25-klb 850-s NTP system.**
  - Most people are better able to grasp the difficulty in balance of plant than the reactor.
- **Two characteristics of NEP make it much more likely to be the advanced propulsion method to be used for future Mars missions.**
  - Caveat: unless SpaceX makes Earth-to-orbit costs and in-space fueling so easy/cheap that we don't need anything better.
- **1) NEP can evolve via useful smaller systems**
  - There is a clear evolution from small Kilopower reactors to the kind of low-mass multi-megawatt systems.
  - Work on electric propulsion, power conversion, heat rejections technologies continues to advance with or without reactor development.
  - Reactor development and operation is largely decoupled from the balance of the system; this greatly simplifies design and minimizing the need for extensive full-system testing.
- **2) NEP offers truly game changing performance**
  - NEP offers a specific impulse (Isp) increase 5 to 10x higher than NTP, and perhaps maybe more.
  - NTP increases Isp a factor of 2 over chemical, which is very beneficial, but it does not have enough enabling potential to sustain 10s of billions dollars of funding.

NASA artwork

Space Fission Power -- Bottom Line

- **KRUSTY and Kilopower have shown that space reactor development is not inherently expensive or lengthy.**
  - $18M for 3 years to design, build and test a prototypic 1-kWe fission power system.
    - The first nuclear test of a new space reactor system in over 50 years!
- **Human propulsion will require several development steps**
  - Starting from scratch, high performance NTP and NEP would be ~equally difficult.
  - However, NEP systems can benefit greatly from the development of surface power systems (and SEP systems) and are easier to test and evolve.
    - Additionally, NEP systems have lots of headroom to improve, while NTP is limited.
- **We need to continue to take manageable steps (cost and schedule) to evolve fission power and propulsion systems.**
  - Kilopower technology is now available to provide surface power for small human outposts.
  - The path is clear to evolve from Kilopower to Megawatt power systems on the surface of Moon and Mars.
  - Unfortunately, NASA/DOE-NE have reverted to their old ways, exploring “better” paper reactors.
- **Good news may be coming?**
  - DoD’s Defense Innovation Unit has recently shown interest in simple 1st generation space reactors!

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