Space Nuclear Power for Mars

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2020 Mars Society Convention

Space Nuclear Power Corporation

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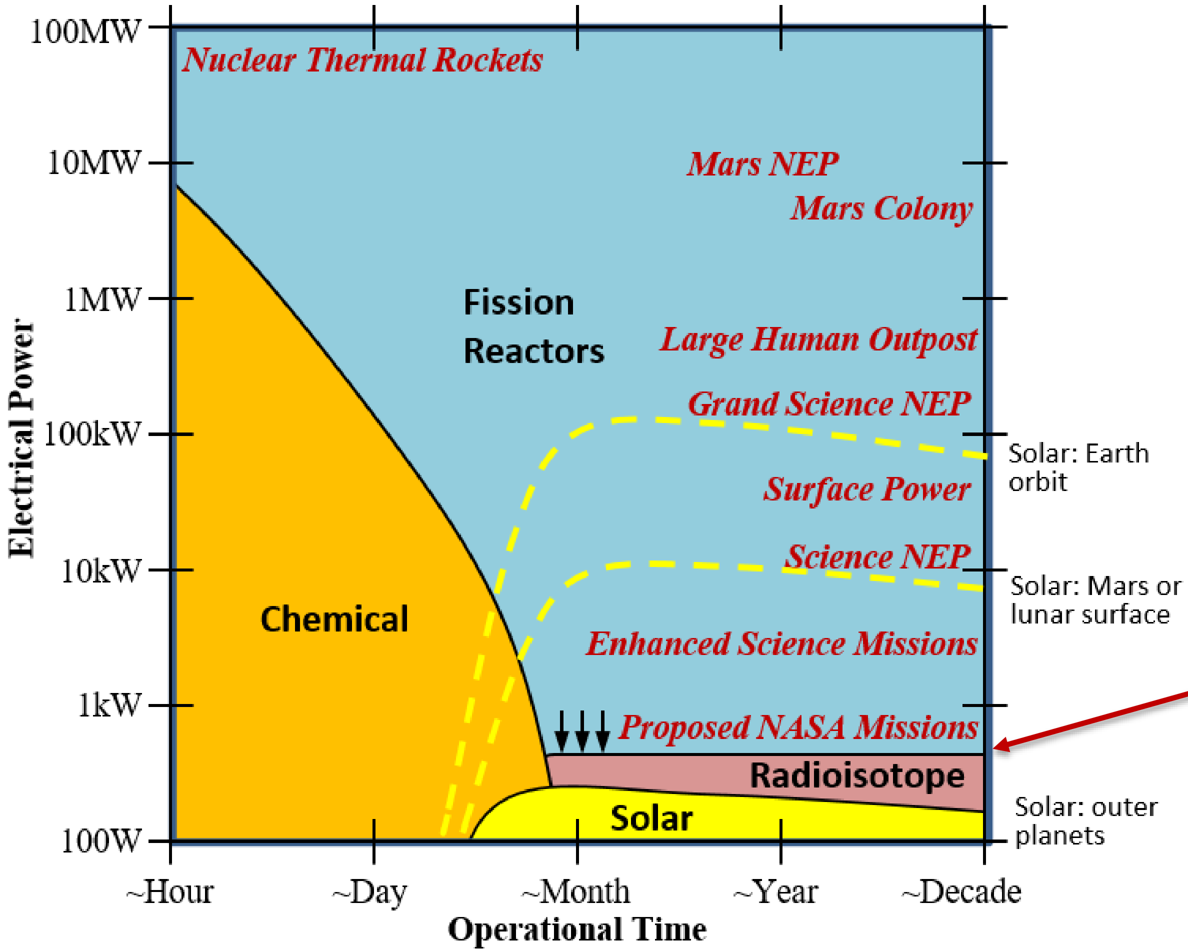
Potential Space Power Sources



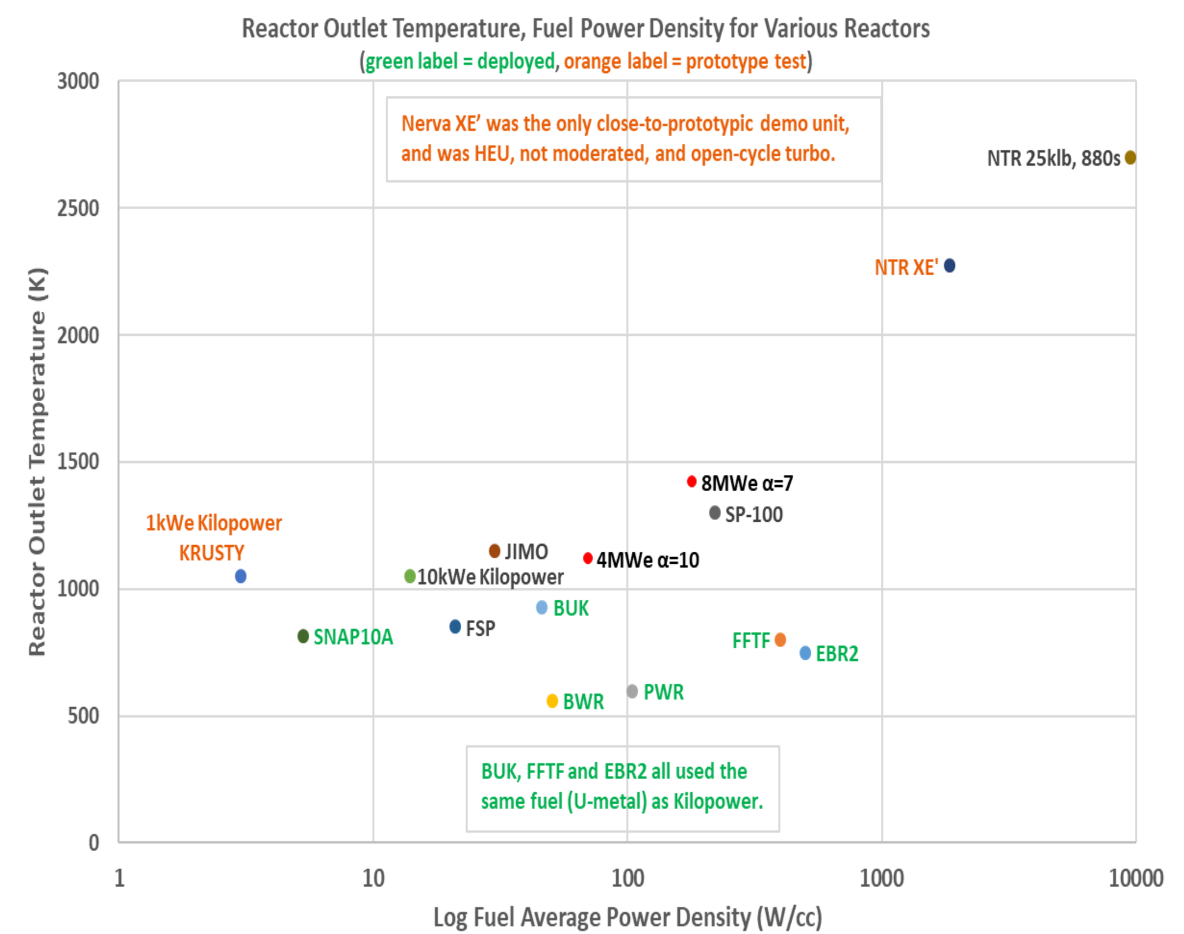
This chart includes very rough estimates of mass, practicality and utility of each power source.

The utility of solar power is obviously dependent on distance from sun and/or possibility of day-night cycle.

Yellow curves are estimates of solar utility, but are highly dependent on the specific mission or applications.

Limited 238Pu supply has lowered the threshold for entry-level fission systems.

Development risks need to be put in perspective when programs are being considered.

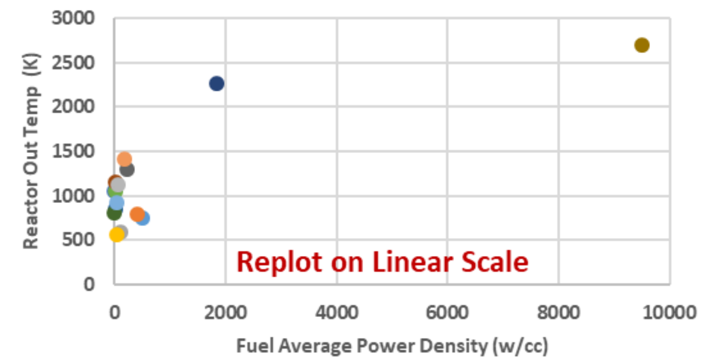


Biggest Reactor Development Risks

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

The above are in general order of importance, and can vary by concept. There are dozens of risks, but most are a strong function of the above (e.g. adiabatic heat-up rate, power, fluence, chemistry, burnup, etc.)

Neutronic/dynamic complexity is listed as #1 because nuclear system dynamics/control is generally the hardest, most expensive, and riskiest part of space reactor development (due to the difficulty of nuclear-powered testing in today's environment)



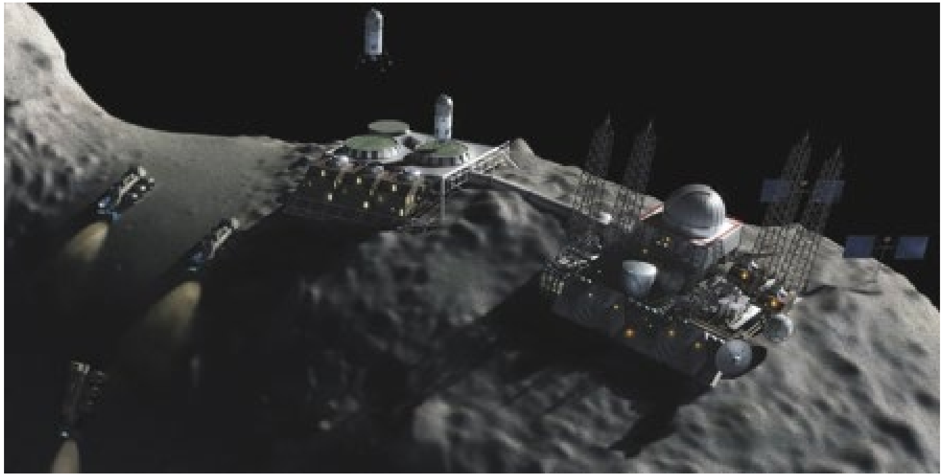
Nuclear Thermal Propulsion? Unlikely.

- **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) 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,
    - 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.

Nuclear Electric Propulsion (NEP)...
IS the future, but be patient.

- **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.**
- **Two characteristics of NEP make it the likely advanced propulsion method to be used for future Mars missions.**
  - Caveat: unless Elon 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.

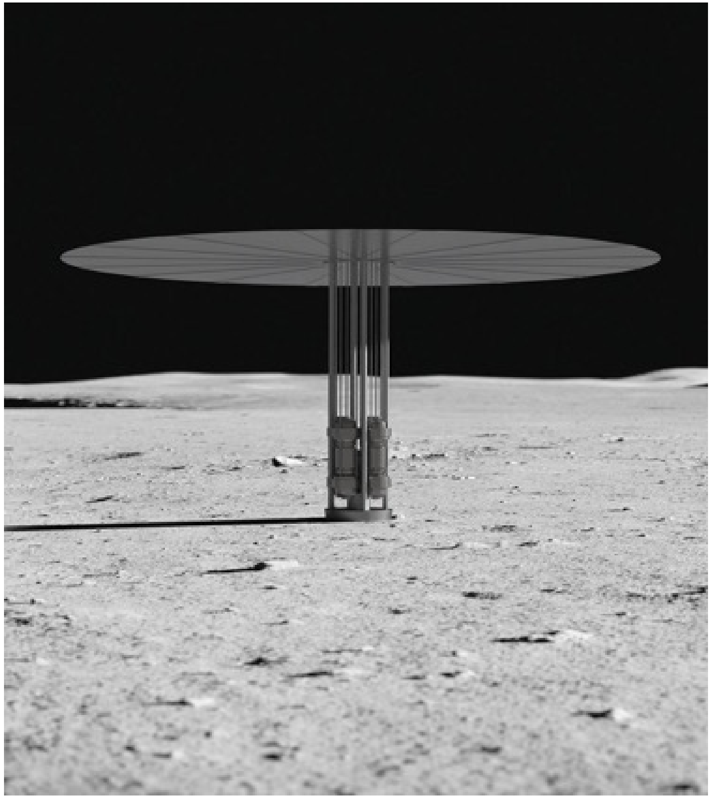
Until then, Space Reactors Can Enable Other Applications



- **NASA Missions**
  - Human Mars surface missions
  - Lunar (moon) surface missions
  - Deep Space Science
  - NEP planetary orbiters and landers:
    - Europa, Titan, Enceladus, Neptune, etc.
  - Asteroid exploration and deflection
- **Commercial Missions**
  - Space power utility
  - Asteroid/space mining
  - Lunar/Mars settlements
- **Power uses**
  - drilling, melting, heating, oxygen/propellant production, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging
- **Defense Missions**
  - Fission power might play a role in a potential space race
- **Simple evolution of Kilopower to higher power reactors (>1 MW)**
  - Electric propulsion for large cargo or human missions
  - Surface power for larger lunar or Martian settlements.
  - “Microreactors” for use on the Earth

Challenges for Solar Power on Surface

- **Mars surface presents major challenges**
  - ~1/2 solar insolation of Earth
  - Slightly longer night than Earth (batteries)
  - The “easy” water is at high latitudes, with low sun angle, long winter nights
  - Long-term dust storms (months to years in length)
  - Deployment of huge arrays, and ability to keep them clean.
- **The Moon can be even 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.

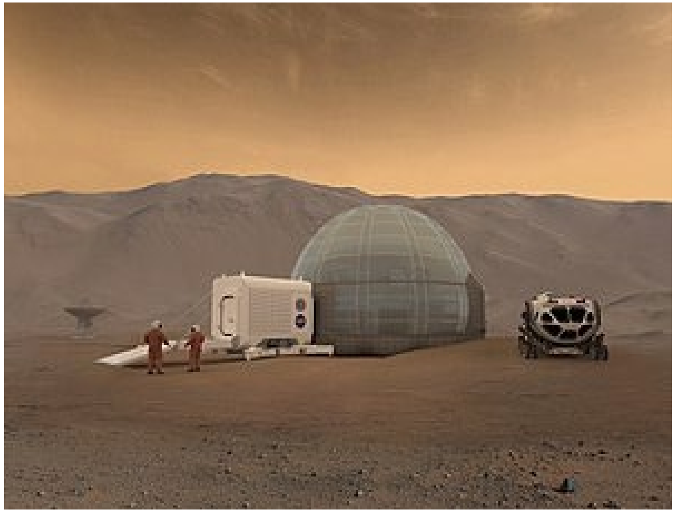


NASA rendition of a Kilopower reactor on the Moon

What is needed for Humans to go to Mars

- **Electricity would be used to make:**
  - Propellant to leave Mars
    - Liquid Oxygen
    - Methane

International Mars Research Station – Shaun Moss



Mars Base Camp – NASA Langley

- **Electricity is needed for:**
  - Oxygen, water, etc. for astronauts
  - Power for habitats and rovers
  - Drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, telecomm, etc.

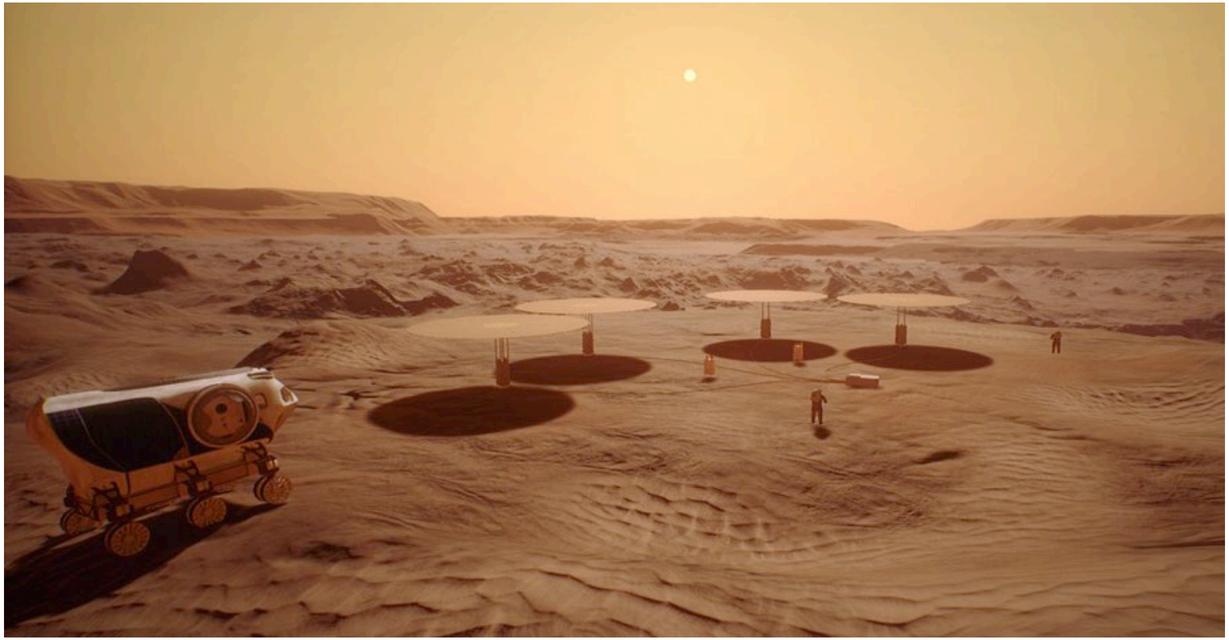
Unfortunately, we've had 40+ years of reactor stagnation

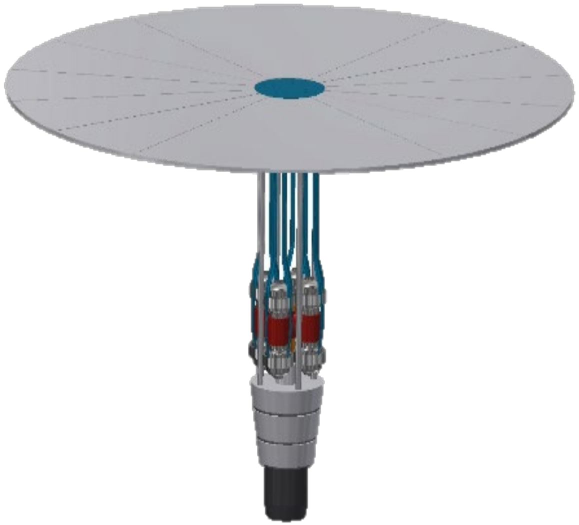
- **Space fission power programs have been ongoing (at various levels) since the 1950s, but to date the US has flown only one space fission system, SNAP-10A, in 1965.**
  - SP-100 and JIMO accounted for well over $1B with no significant progress.
    - Programs did not come remotely close to testing a prototype.
    - Countless of other space reactor programs have resulted only in paper.
  - Things are even worse for terrestrial reactors.
    - Since its formation in 1977, the DOE has 10s of billion dollars on advanced reactors technologies and concepts, with nothing significant to show for it.
- **Why have these previous programs failed?**
  - Programs lost support because they became 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 paper studies instead of system development.
      - Public and political bias against nuclear have not played a major role – i.e. we continue to launch Pu-238.
      - Regulation has not been a "first-order" factor in preventing progress on the government side either, but it might be if they advance far enough to test a system.

SNAP-10A

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.





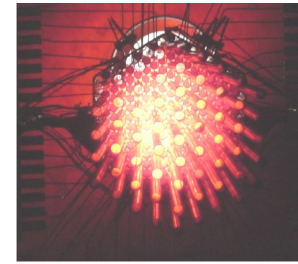
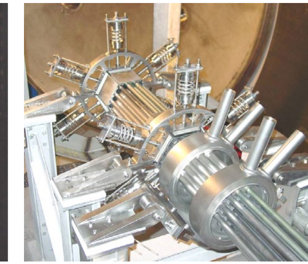
10 kWe, 1500 kg concept

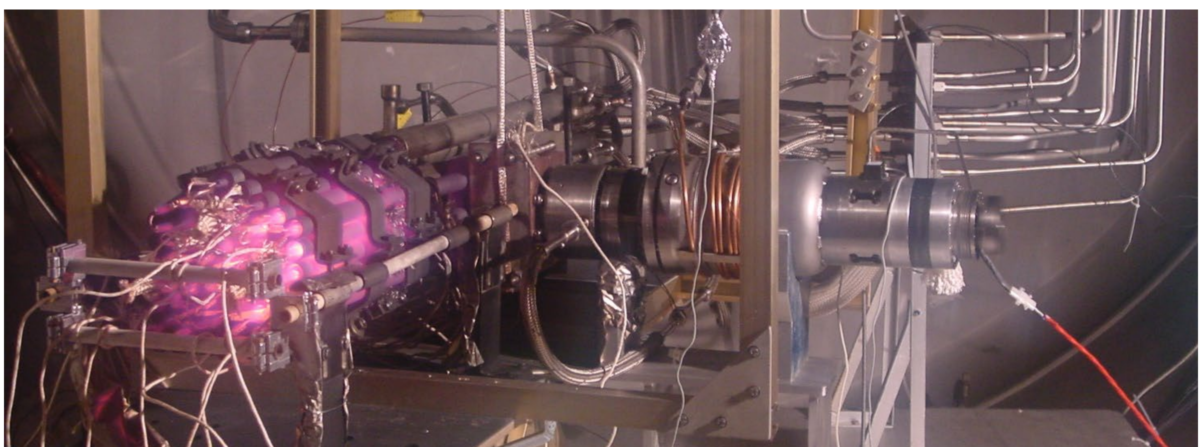
Space Reactor Launch Safety

- **A reactor that has not undergone fission, (been turned on), has very very low safety concerns. It will have from 1 to 10's of curies of naturally occurring radioactivity**
- **This is 1,000s to 10,000s times lower radioactivity than in current radioisotope systems already flown in space**
- **Full dispersal launch accidents would have consequences <u>100's of times less</u> than background radiation or radiation from a commercial plane flight**
- **After the reactor has fissioned, it will become radioactive**
  - Reactors would only be used in deep space, very high Earth orbit (long term decay) and on other planets.
  - Kilopower reactors are designed to stay subcritical in all accident conditions (water, sand, fire, etc.) – the only way the reactor can generate power is if the radial reflector is intact and the B4C rod is withdrawn.

How Did We Arrive at Kilopower, DUFF and KRUSTY?

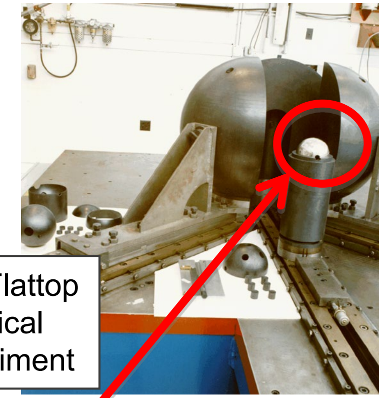
- **We wanted to find a space reactor concept that could be…**
  - 1) Attractive to NASA for flight
  - 2) Proven with a rapid turnaround, low-cost nuclear test.
- **Past work (HOMER/SAFE) convinced us that heat-pipe-cooled reactors provide easiest path to near-term, low-cost concept.**
  - Simple, passive reactor operation, high reliability, ease of testing
  - Stirling engines allow simplest reactor (low thermal pow, simpler reactor control)

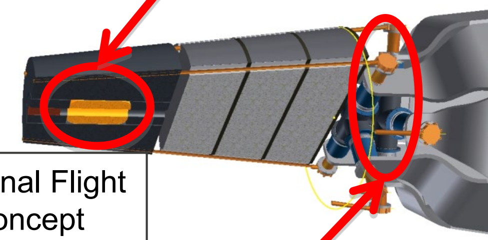



Demonstration Using Flattop Fissions = DUFF
A "Critical" Starting Point – completed in 2012

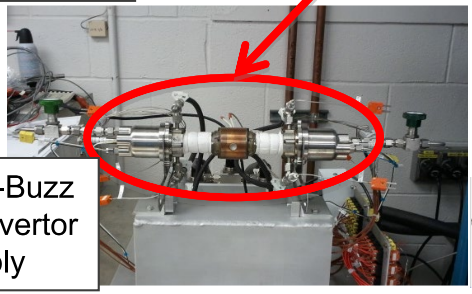
- **Proof-of-Concept Test – Objectives**
  - Use electric power generated from nuclear heat to power a load (light panel)
  - Demonstrate that basic reactor physics is well characterized and predictable using current analytic tools
- **Test Configuration**
  - HEU core with central hole to accommodate heat pipe
  - Heat transfer via single water heat pipe
  - Power generation via two opposed free-piston Stirling Engines
- **Significance**
  - First-ever use of heat-pipe to transfer reactor power.
  - First-ever Stirling engine operation with fission heat
  - Demonstrated nuclear reactivity feedback was predictable
  - Demonstrated that powered nuclear testing is not inherently expensive or time consuming – simplicity is paramount.



DAF Flattop Critical Experiment

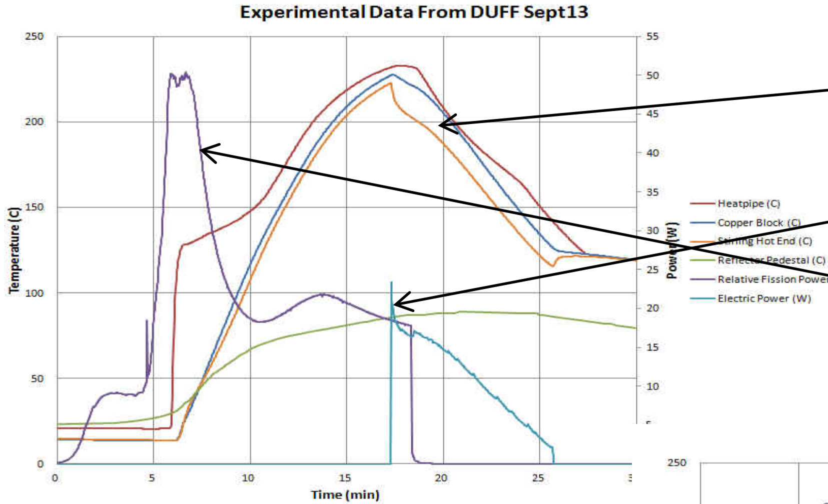


Notional Flight Concept



GRC EE35-Buzz Stirling Convertor Assembly

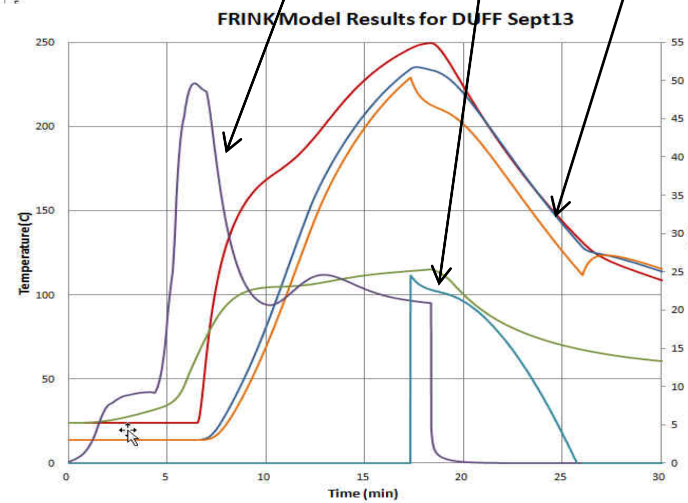
DUFF Results Compared with FRINK System Model

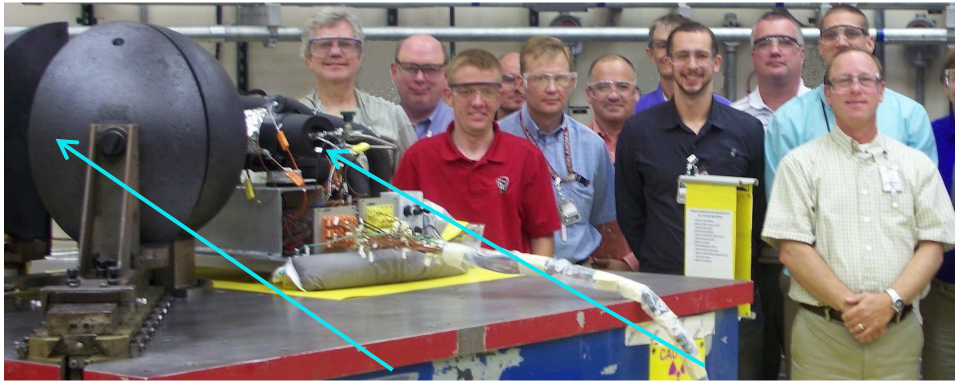


Power Conversion System Temperatures

Electrical Power

Reactor Thermal Power

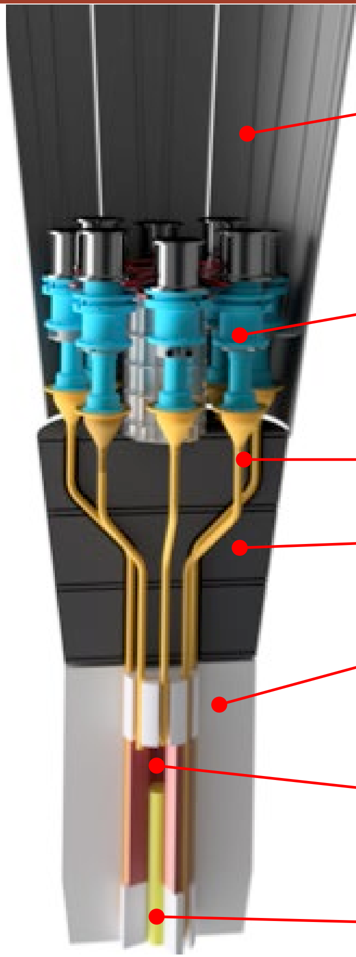




Core and reflector

Stirlings

Basic 1-kWe Kilopower Concept and Actual KRUSTY Components



Titanium Heat Pipe Radiator

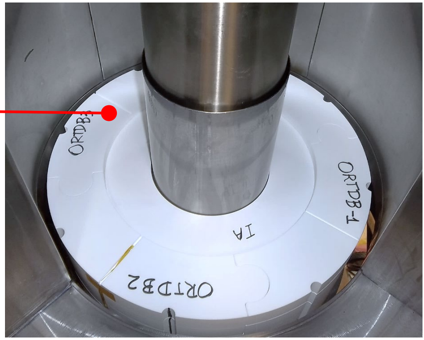
Stirling Power Conversion System

Sodium Heat Pipes

System enclosed in vacuum

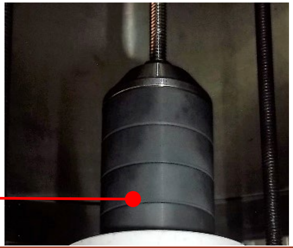
Lithium Hydride, Tungsten Shielding

Beryllium Oxide Neutron Reflector

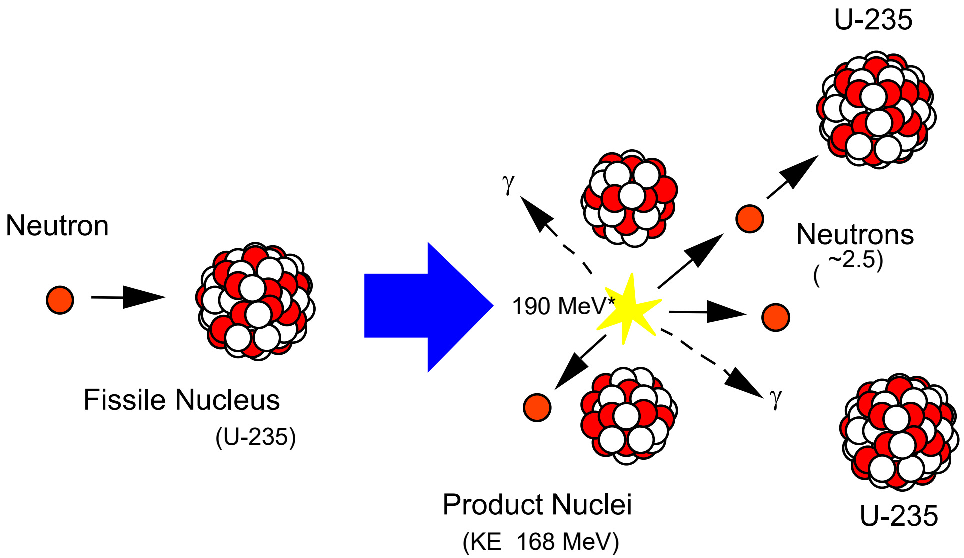


HEU U-Mo Cast Metal Fuel

B_4C Neutron Absorber Rod



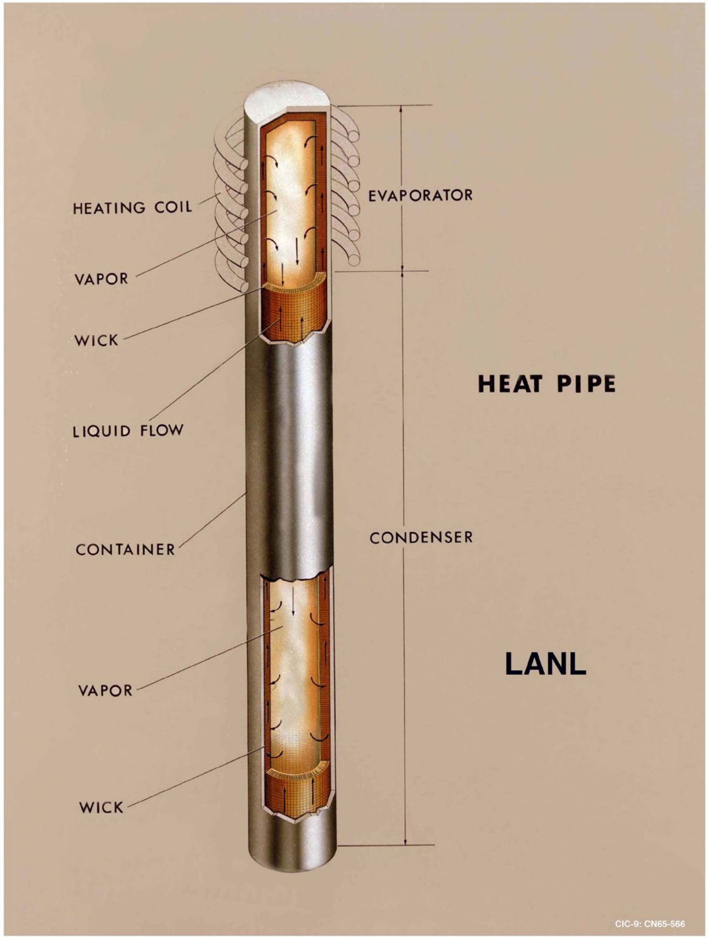
Kilopower Step 1: Nuclear Fission Creates Power



The majority of energy is deposited where the fission occurs within the uranium fuel.

Kilopower Step 2: Heat Pipes Transport the Power

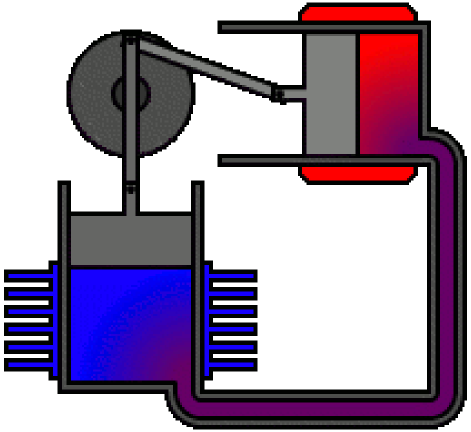
- A heat pipe is a sealed tube with a small amount of liquid that boils at the hot end, the vapor travels to the cold end where it condenses back to a liquid.
- A wick and/or gravity is used to bring the fluid back to the hot end.
- A properly designed heat pipe works in any direction, regardless of gravity or lack thereof
- Heat pipes are an extremely efficient way to move heat.



Kilopower Step 3: Stirling Convertor Creates Electrical Power

- A Stirling engine is a heat engine that turns heat into mechanical motion
- An alternator creates electricity from the mechanical motions.
- Waste heat must be rejected to maintain low temperature on the cold end

Reverend Dr. Robert Stirling
Wikipedia commons



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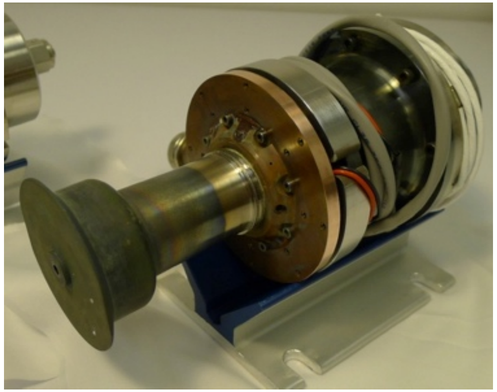
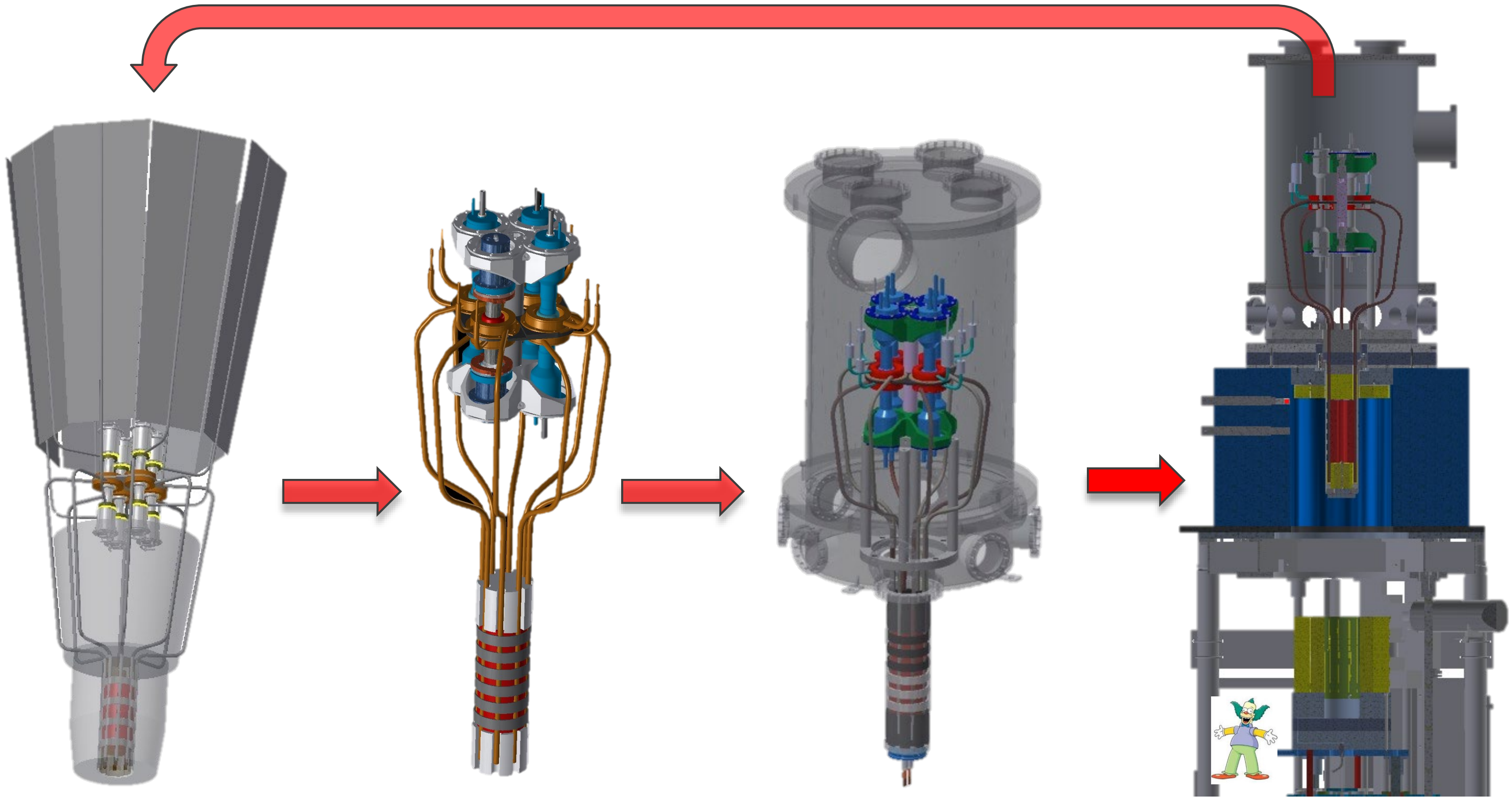


Modern Stirling Engine

KRUSTY Development Path



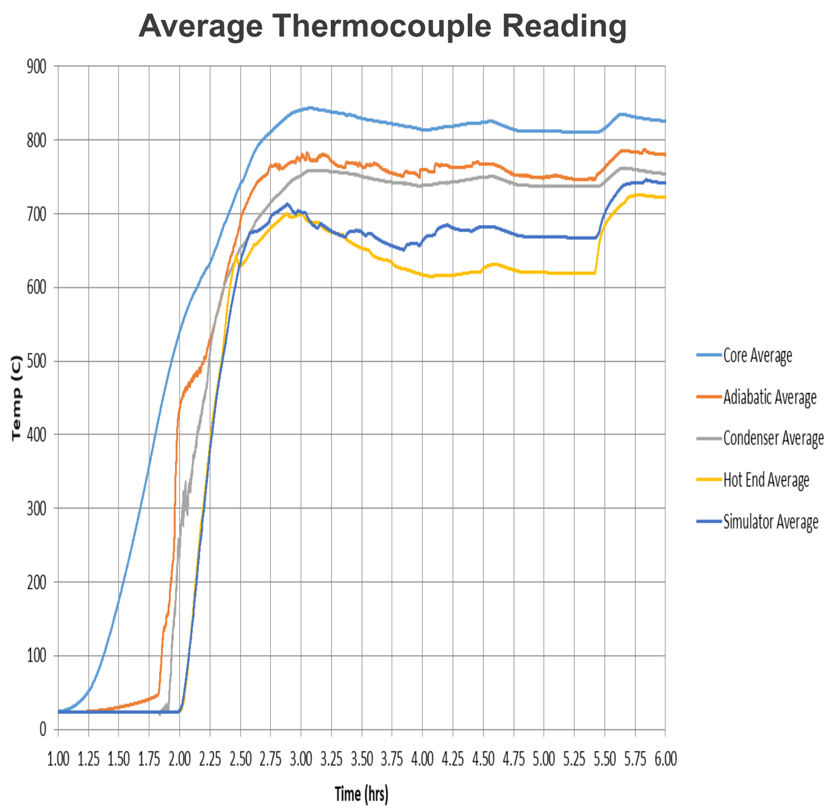
Flight Concept

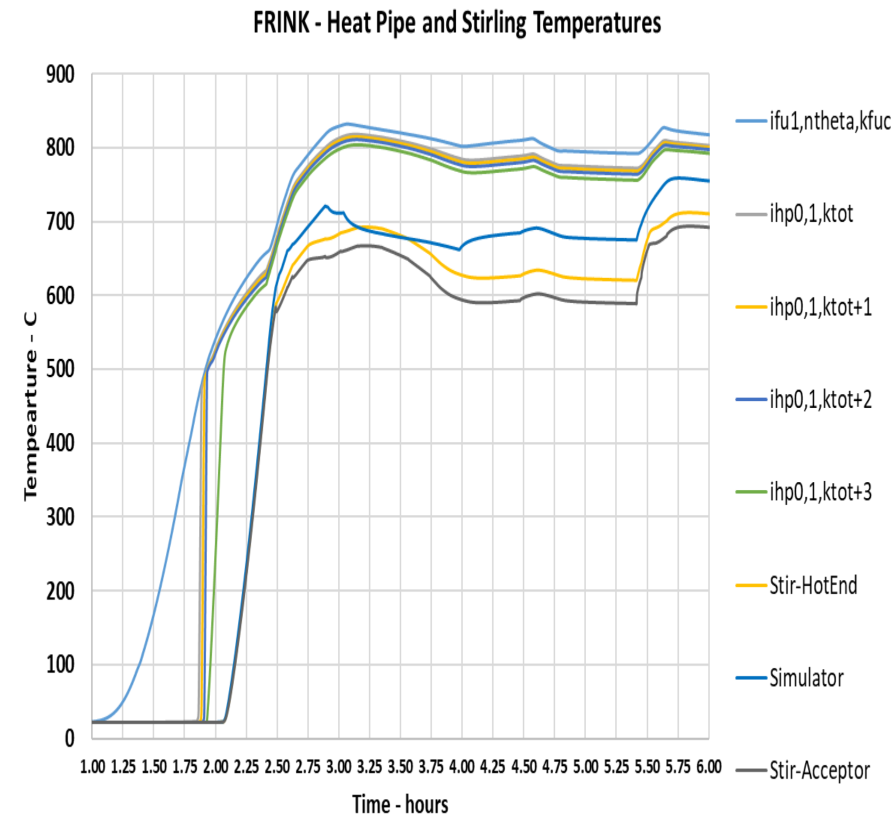
Flight-
prototypic
Power Pack

Electrically Heated
Test with Depleted
Uranium Core

Nuclear-Powered Reactor
Demonstration with
enriched Uranium Core

Benchmarking with Electrical Testing.



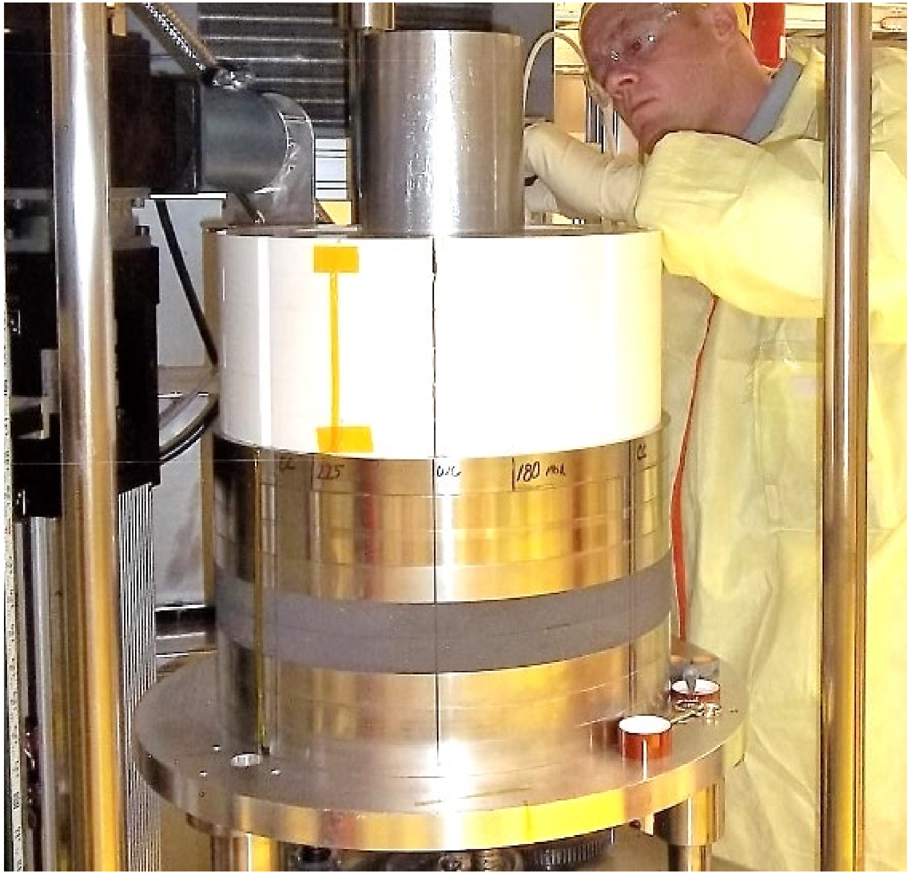


Electrical testing was huge: 1) work out kinks in design, 2) develop instrumentation and control, 3) give regulators confidence in system operation, 4) benchmark the codes that ultimately gained, regulator approval.

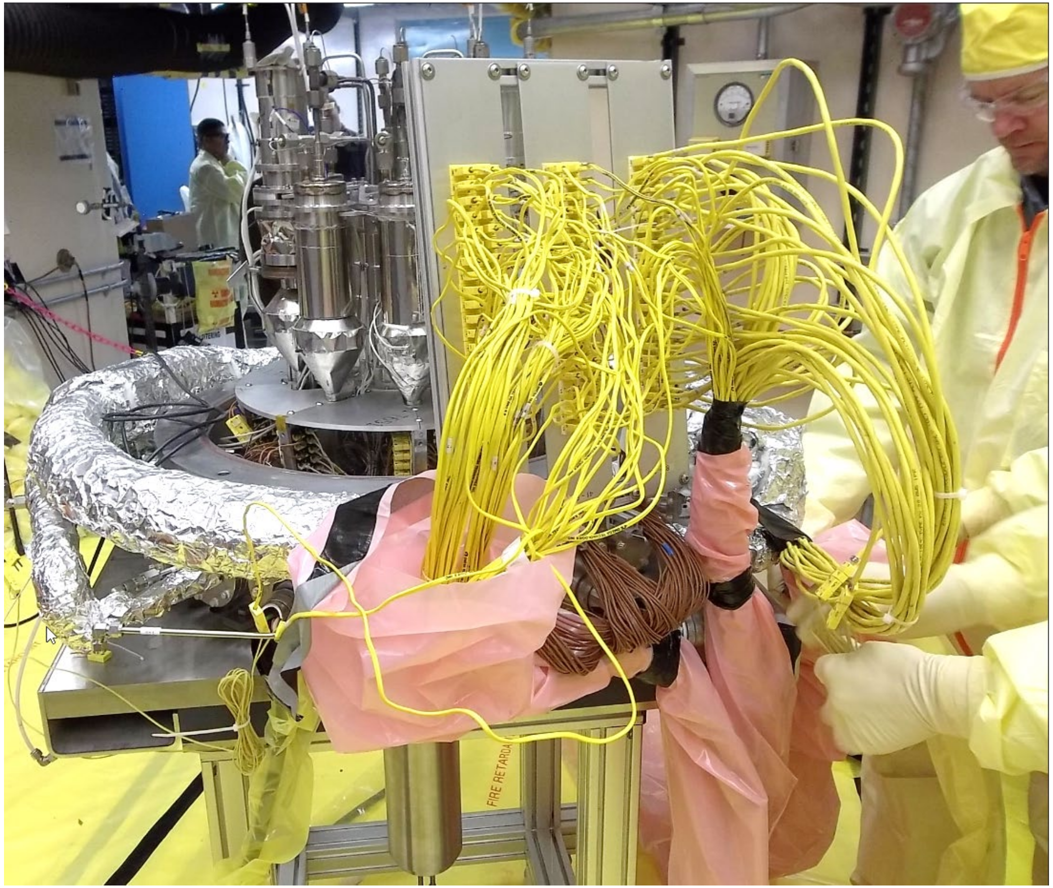
KRUSTY Core and Reflector Assemblies

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

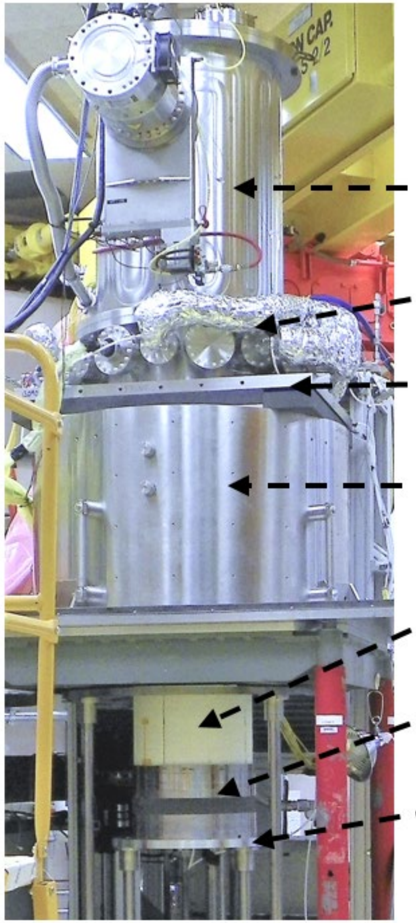
Test Prep in Nevada



KRUSTY Power Conversion

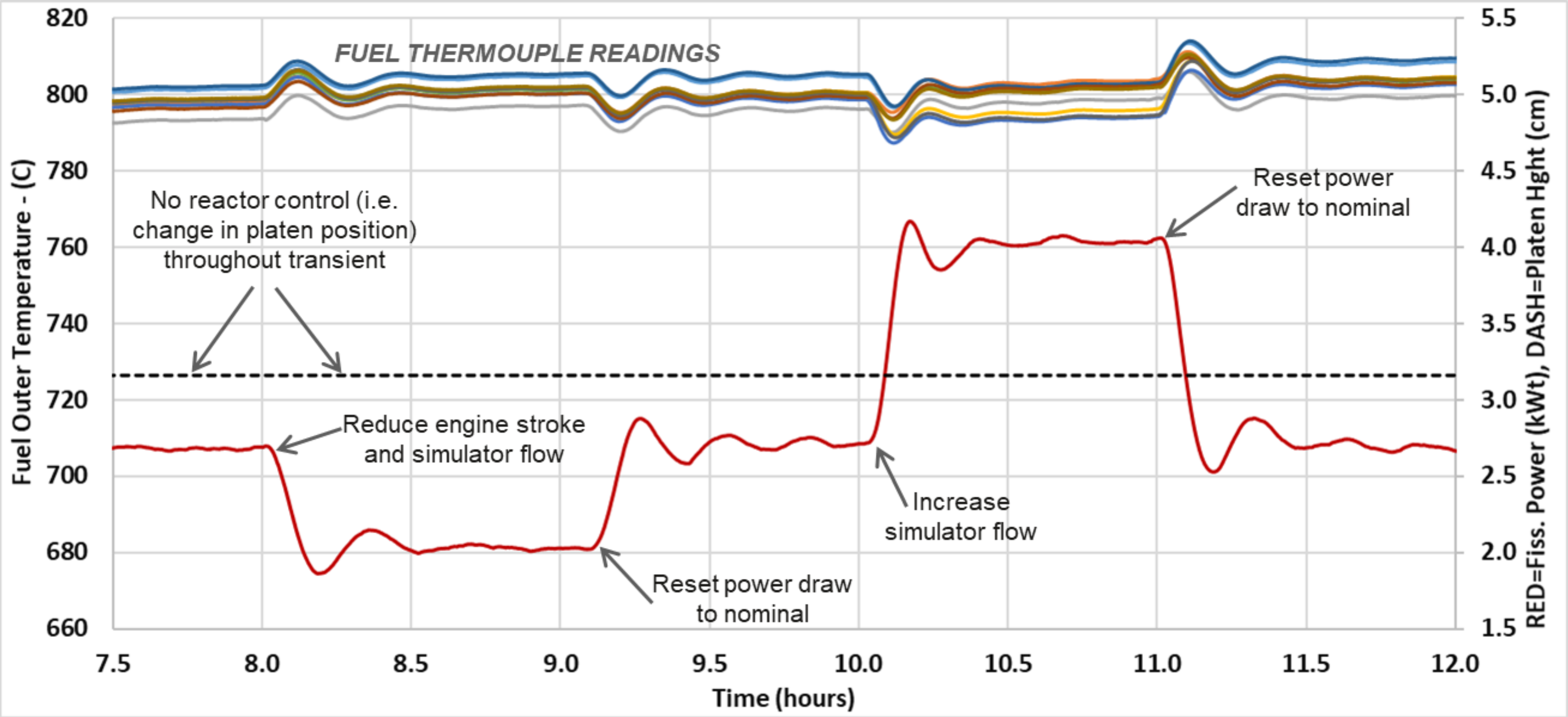


KRUSTY Final Configuration



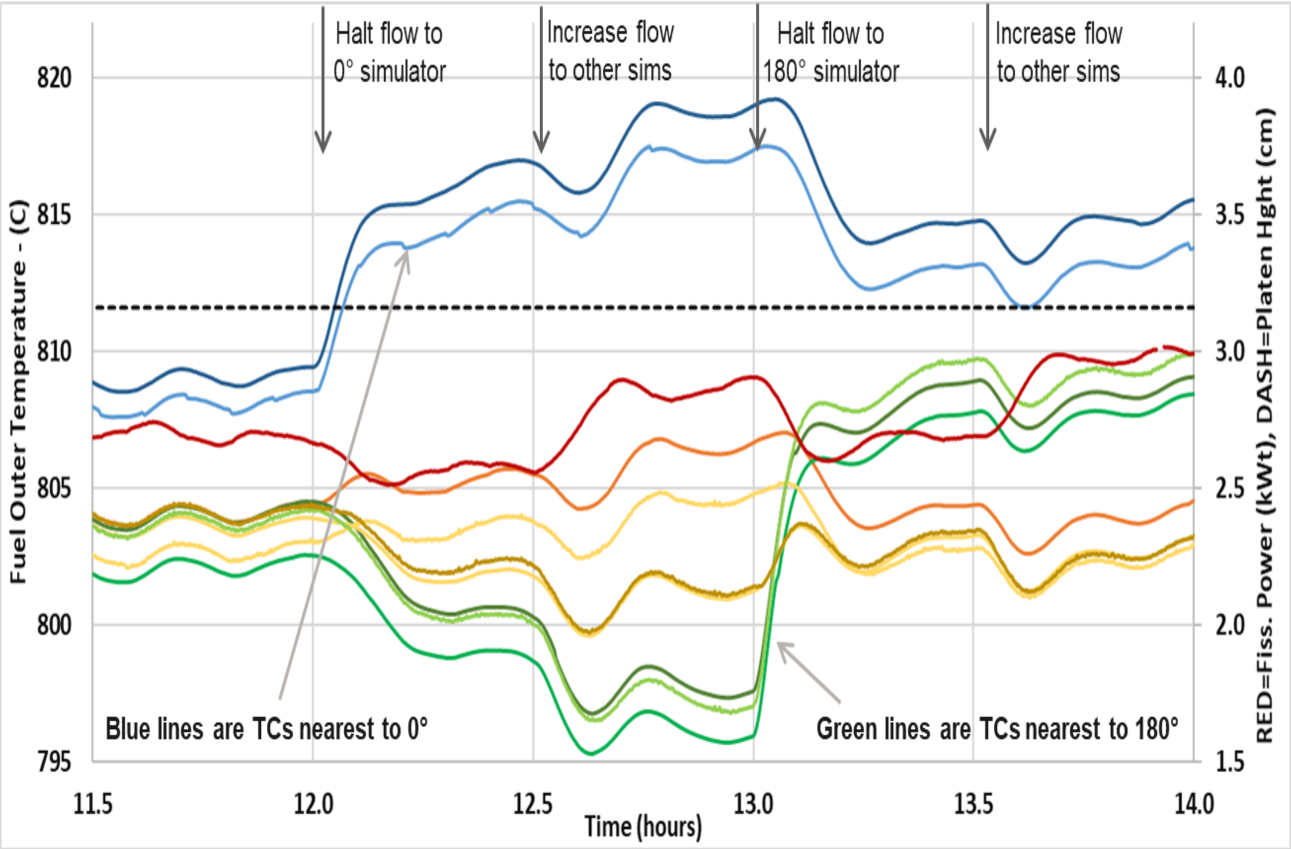
KRUSTY Load Following Transient Data

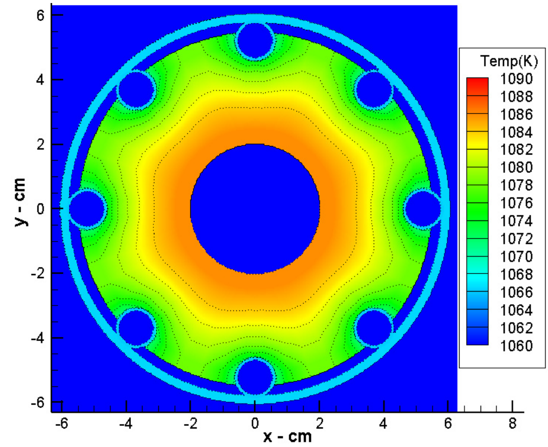
(first operational data from new reactor concept in US in >40 years!)

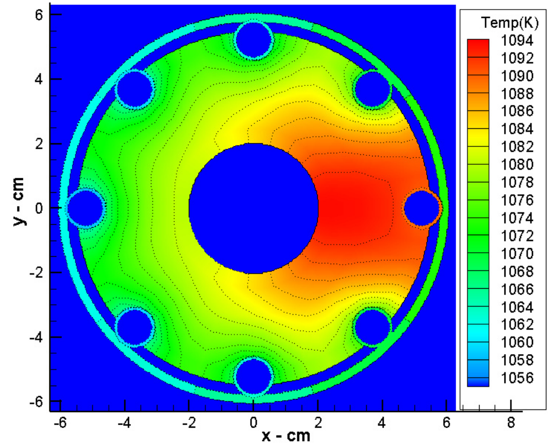


The KRUSTY coup de gras – the reactor thermal power matches the power draw, in order to main the reactivity thermostat set-point (reactivity is zero, k-eff=1 at 800 C, except for minor 2nd order effects).

KRUSTY Fault Tolerance Transient Data



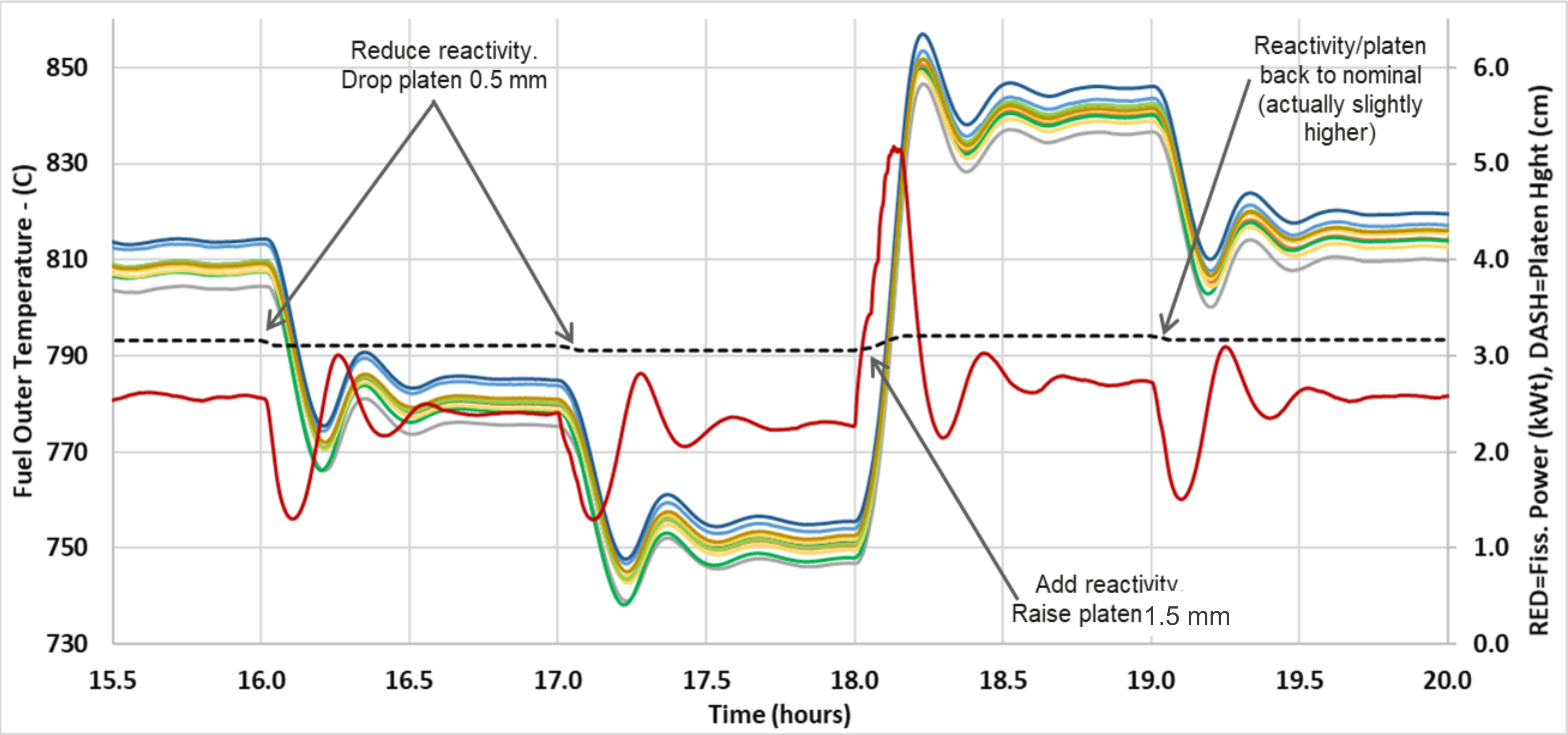




Fault tolerance is proven as expected. A failure in a Stirling "string" (convertor or heat pipe) can easily be tolerated in the core

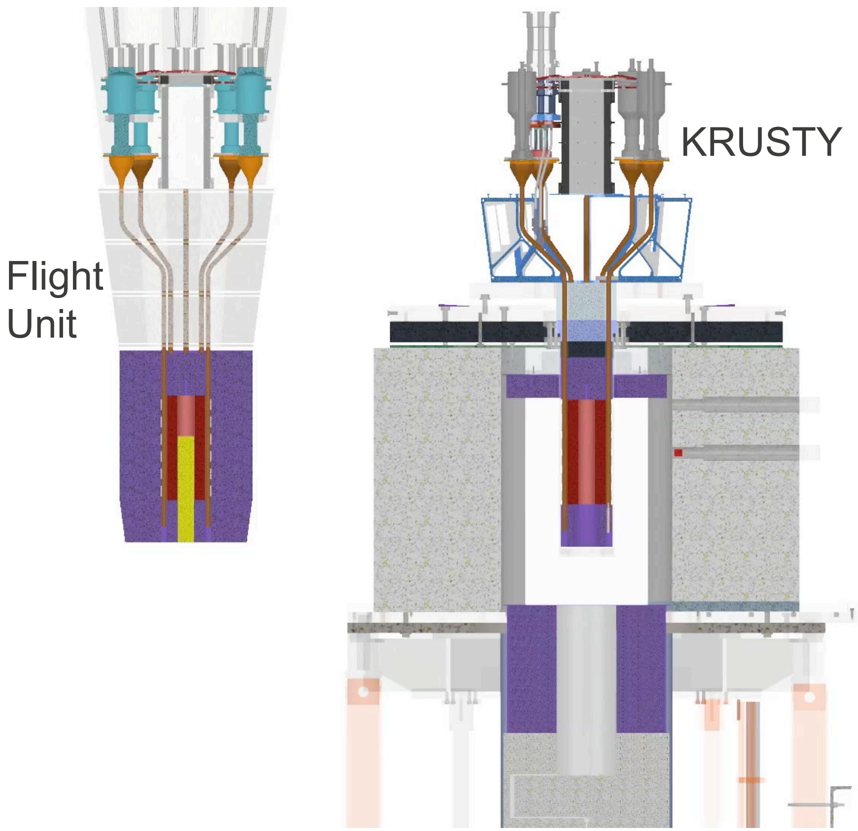
Above plots are from model

KRUSTY Reactivity Adjustment Transient Data



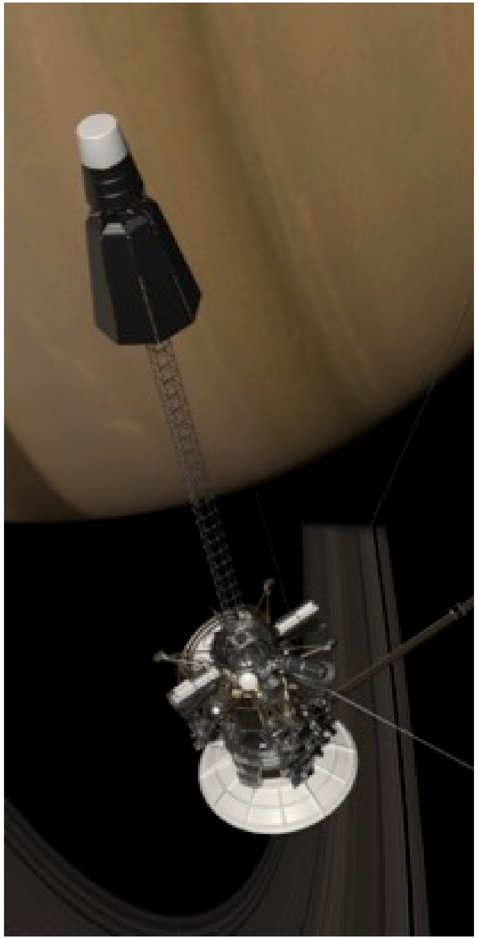
Keep in mind, these plots represent only operational data from a new reactor concept in the US is >40 years!

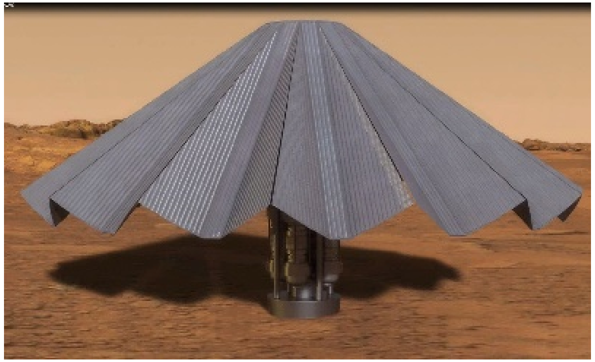
Flight vs. KRUSTY?
Nearly identical reactor performance

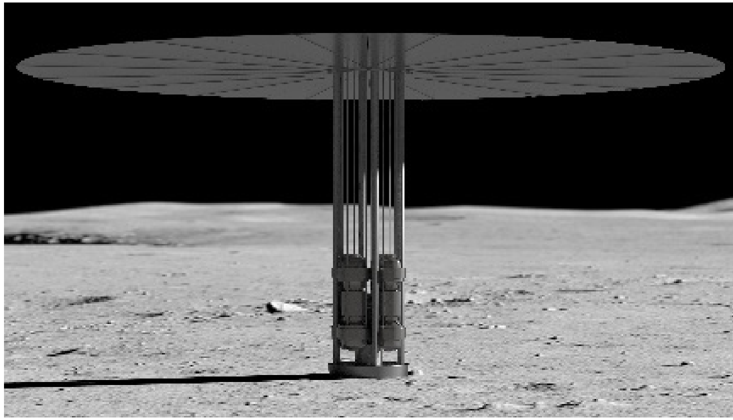


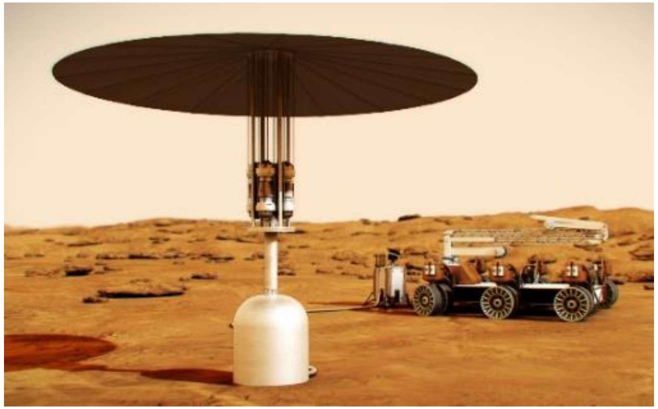
- The raising of the BeO reflector (KRUSTY) increases reactivity by decreasing neutron leakage, while withdrawing the B4C rod (Flight) increases reactivity by decreasing neutron absorption.
- This difference will cause minor effects on power distribution and feedback, but as far as the neutron population (i.e. power) is concerned, there is very little difference between the two reactivity mechanisms.
- This is because KRUSTY is a very good example of a point-kinetic reactor, which occurs when the neutron mean-free-path is a significant fraction of the core geometry. In such a system, all regions of the reactor communicate very well with each other.
- Thus, a 15-cent insertion, or any transient caused by moving the reflector will look almost identical to the same transient caused by moving the B4C rod.
- Also, the coupled thermal-nuclear behavior is nearly identical for a 1 kWe or 10 kWe reactor, or an HEU or LEU reactor, and equally as predictable as KRUSTY.
- **No nuclear-powered testing needed for Kilopower flight unit.**
- **True whether 1 kWe-HEU system or 25 kWe-LEU system.**

Possible Deployment of Kilopower Reactors

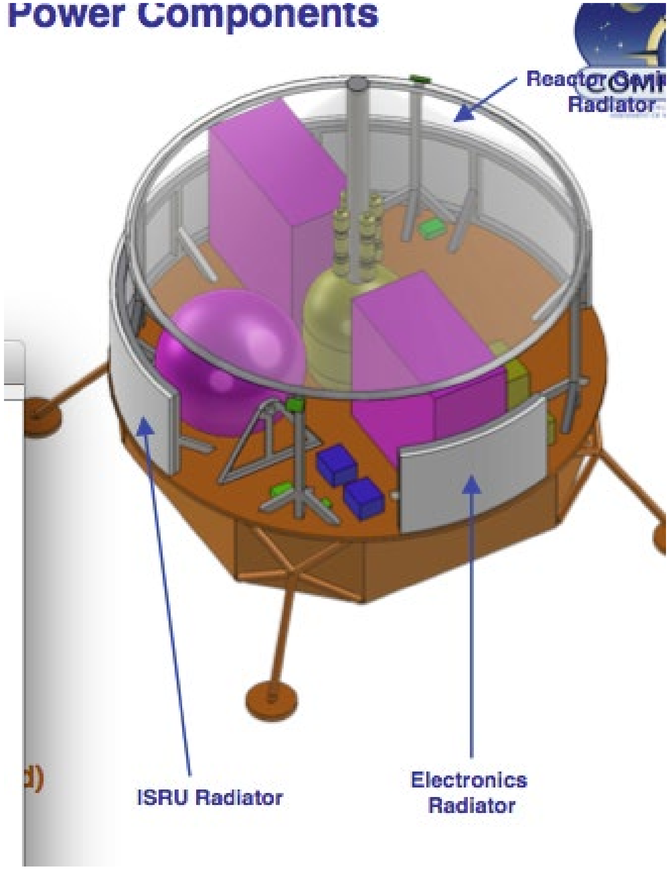


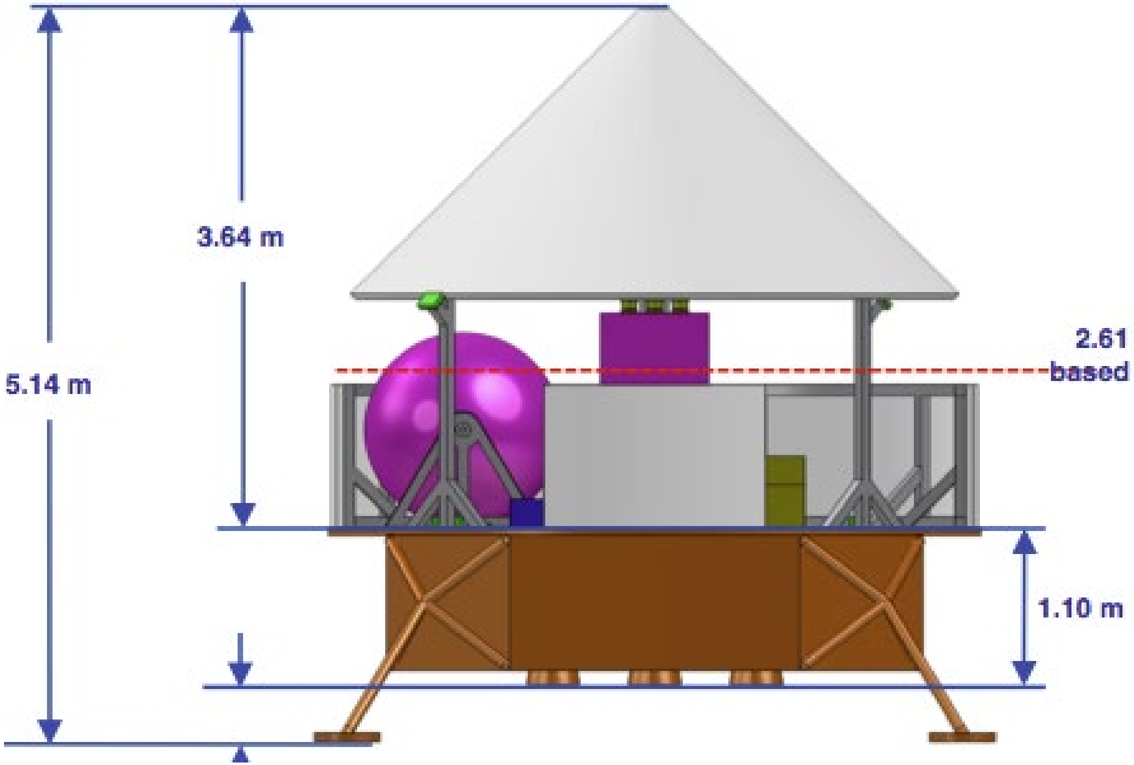






10 kWe Mars ISRU Demo Proposal





Kilopower Reactor Evolution to Several MWe

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 provide the same value for the 100 to 300 kWe system, and so on to a 1MWe system or higher.

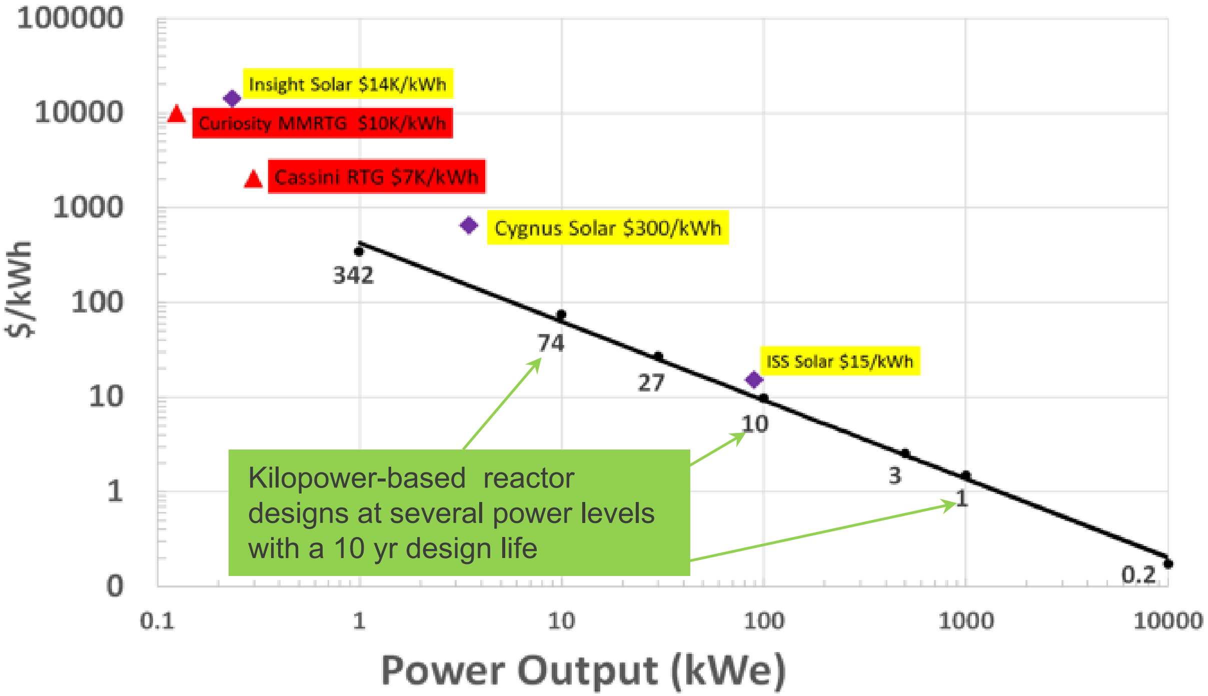
Each step above does not have to be taken, but at least 3 are recommended.

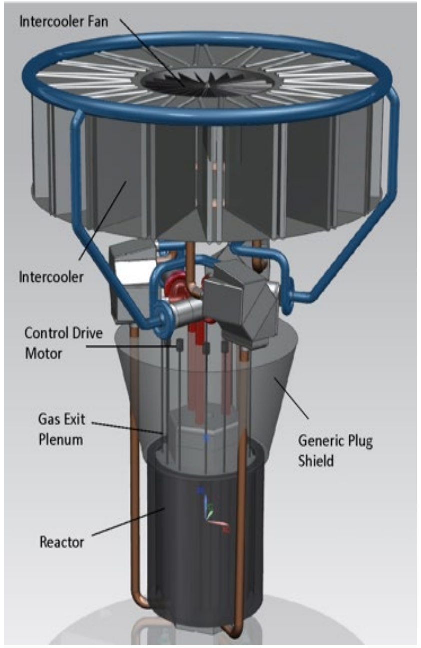
Kilopower Reactor Evolution - when do we need a technology changes (noting that reactor physics and dynamics changes are small and predictable, difference from KRUSTY in right column)

	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%

For sure	
Probably	
Good chance	
Perhaps	
Unlikely	

Cost of fission systems becomes very attractive at higher powers

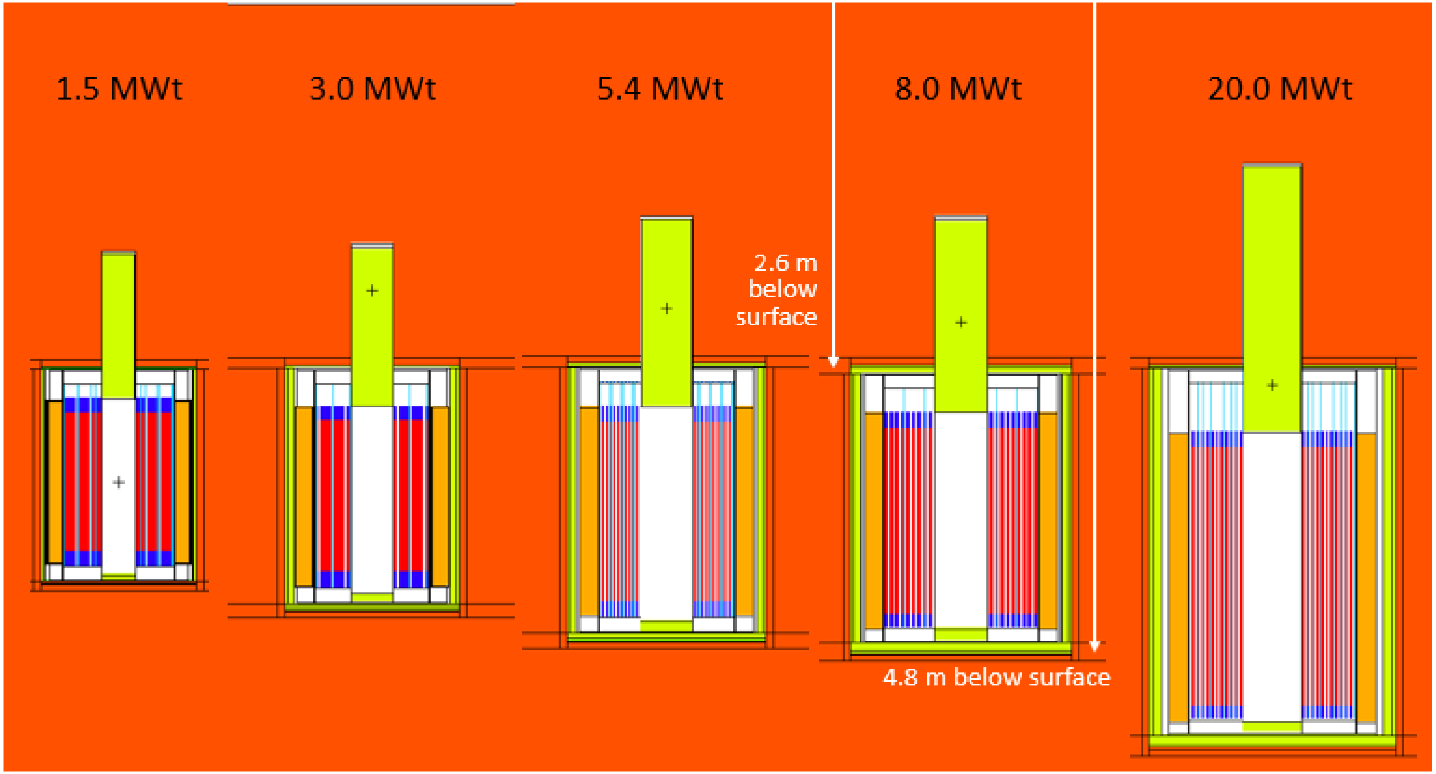




100 to 200 kWe Mars Brayton System

- Per kWh, fission power is competitive with GEO solar power and orders of magnitude more cost effective than RTG’s and solar on Mars, and solar at most locations on the Moon.
- Reactor power does not degrade over lifetime. The core could provide full power for several decades if the balance of plant could be maintained to last that long (we assume 10 year plant life for initial systems).
- A reactor is also a perfect battery, it can be turned off for any period of time and then started when needed.
- No other power systems are cost comparable at higher power and low solar insolation

Buried configuration allows nearby habitation and power system maintenance



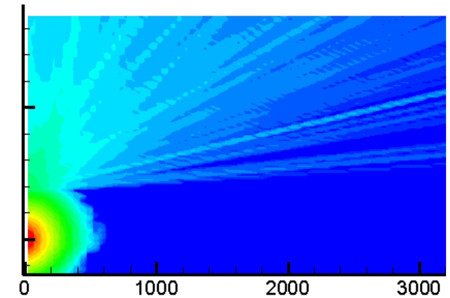
<u>Buried configuration allows:</u>

Huge savings on shield mass.

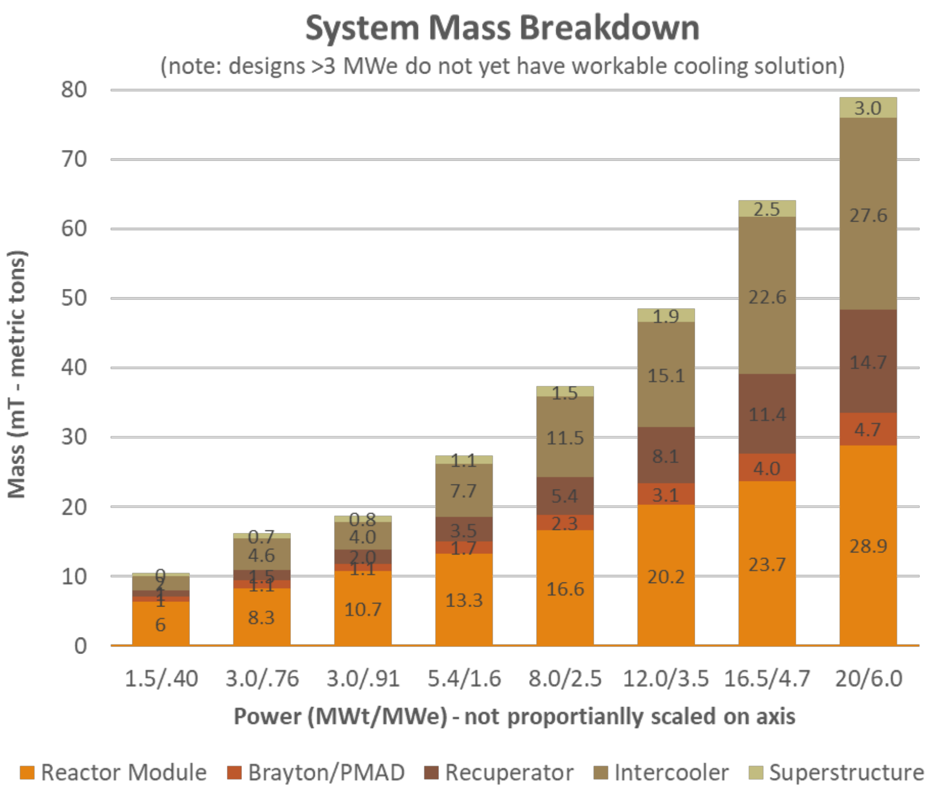
Habitation near by.

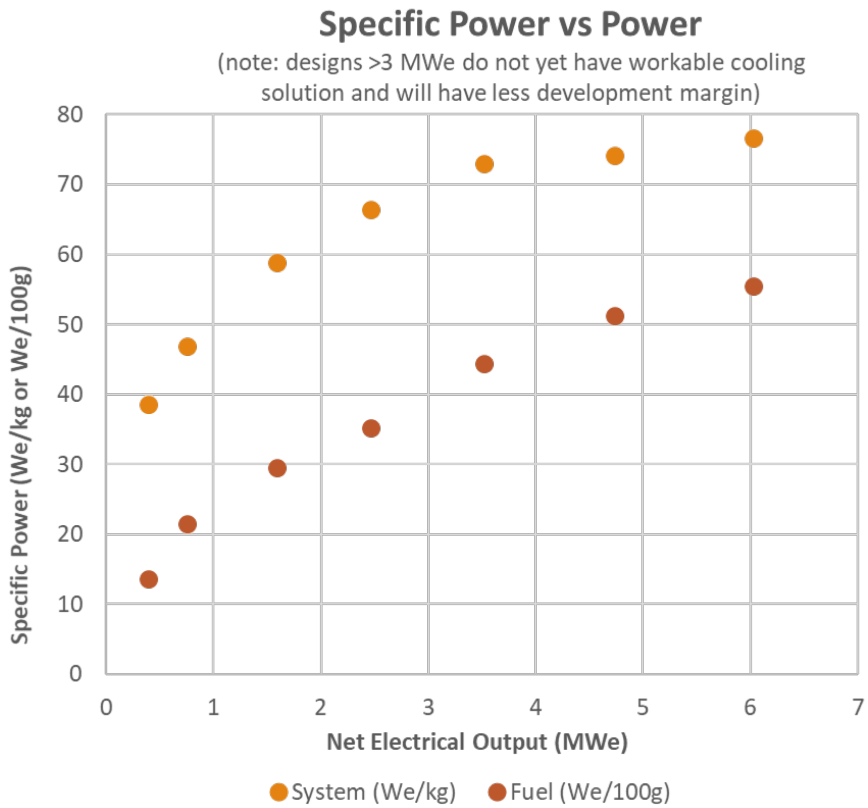
Maintenance on all above surface components.

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



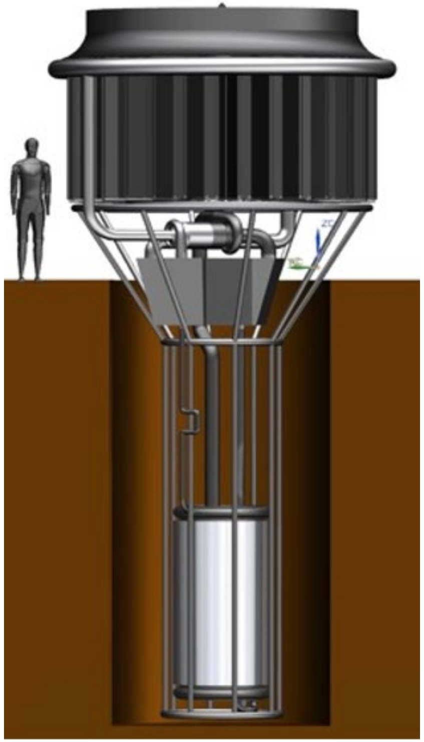
SpaceNukes Mars Surface Power Systems





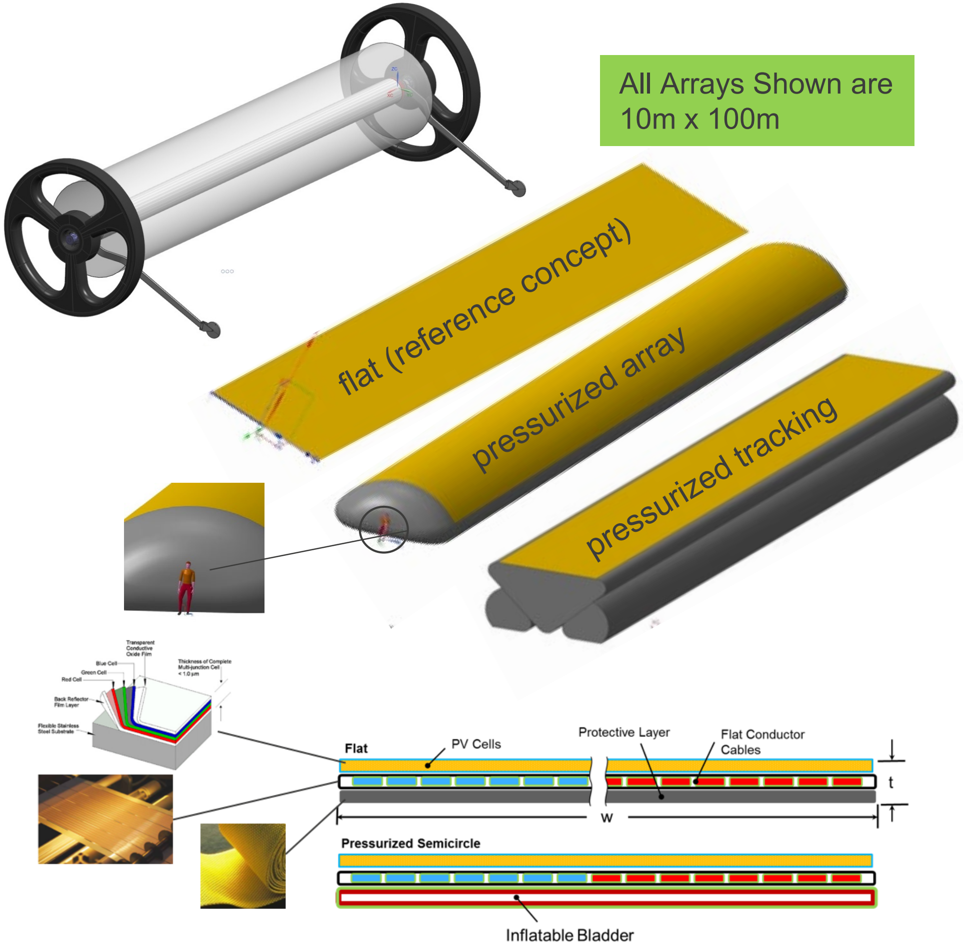
650 kWe Mars Surface Concept

	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

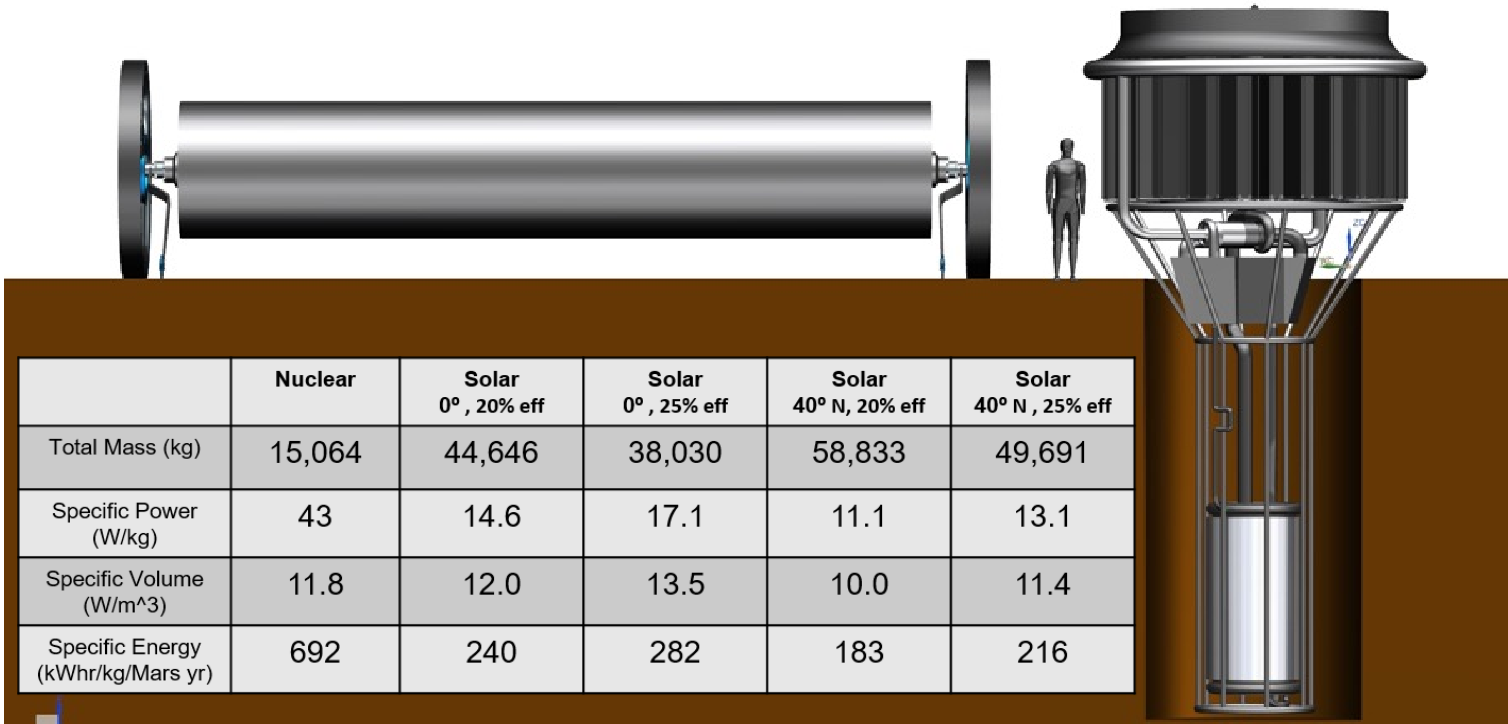
650kWe Rollout Solar Array



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
Distributted 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

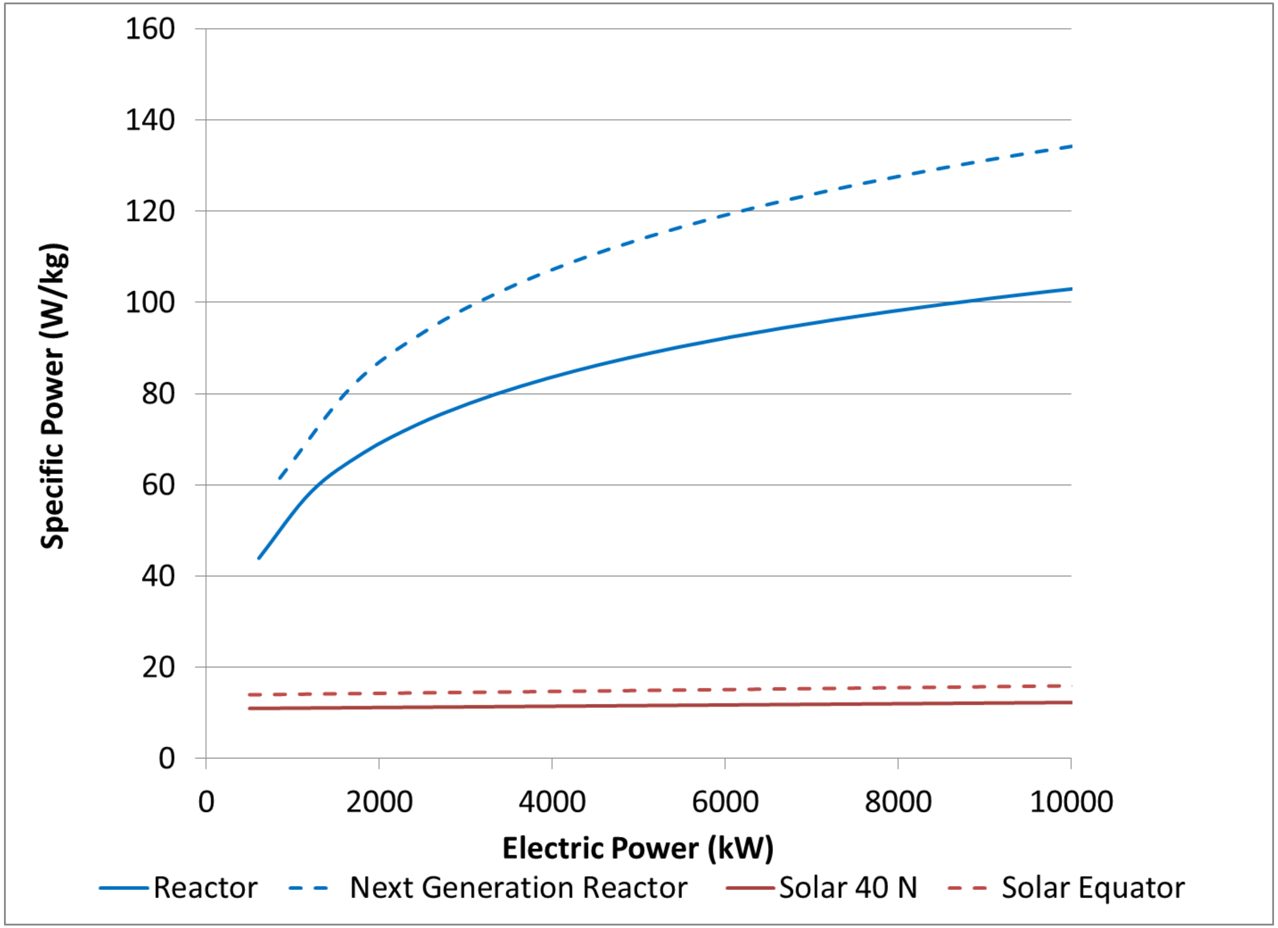
Comparison of Solar to Fission on Mars

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.



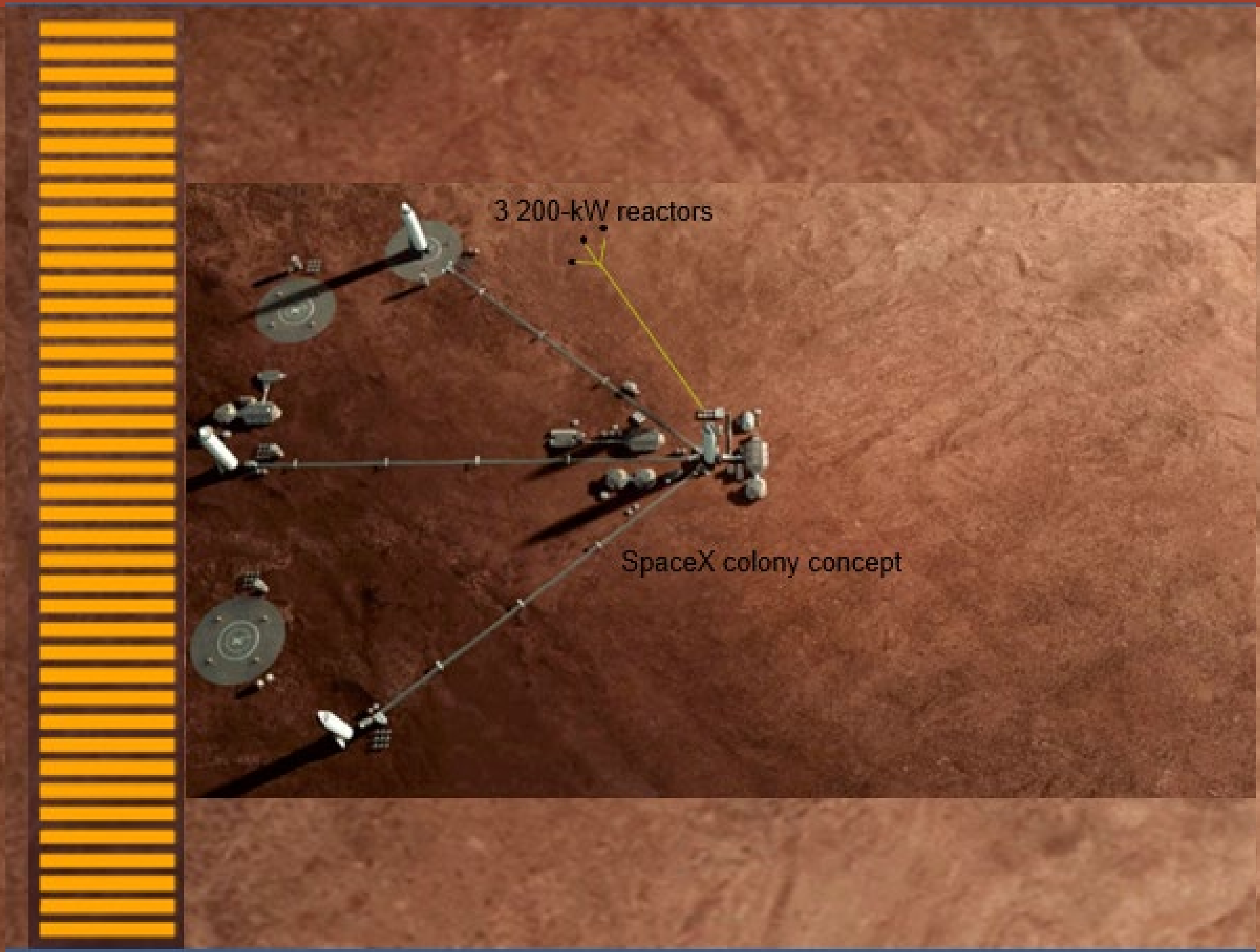
	Nuclear	Solar 0º , 20% eff	Solar 0º , 25% eff	Solar 40º N, 20% eff	Solar 40º N , 25% eff
Total Mass (kg)	15,064	44,646	38,030	58,833	49,691
Specific Power (W/kg)	43	14.6	17.1	11.1	13.1
Specific Volume (W/m^3)	11.8	12.0	13.5	10.0	11.4
Specific Energy (kWhr/kg/Mars yr)	692	240	282	183	216

Specific Power Comparison vs Power System Size



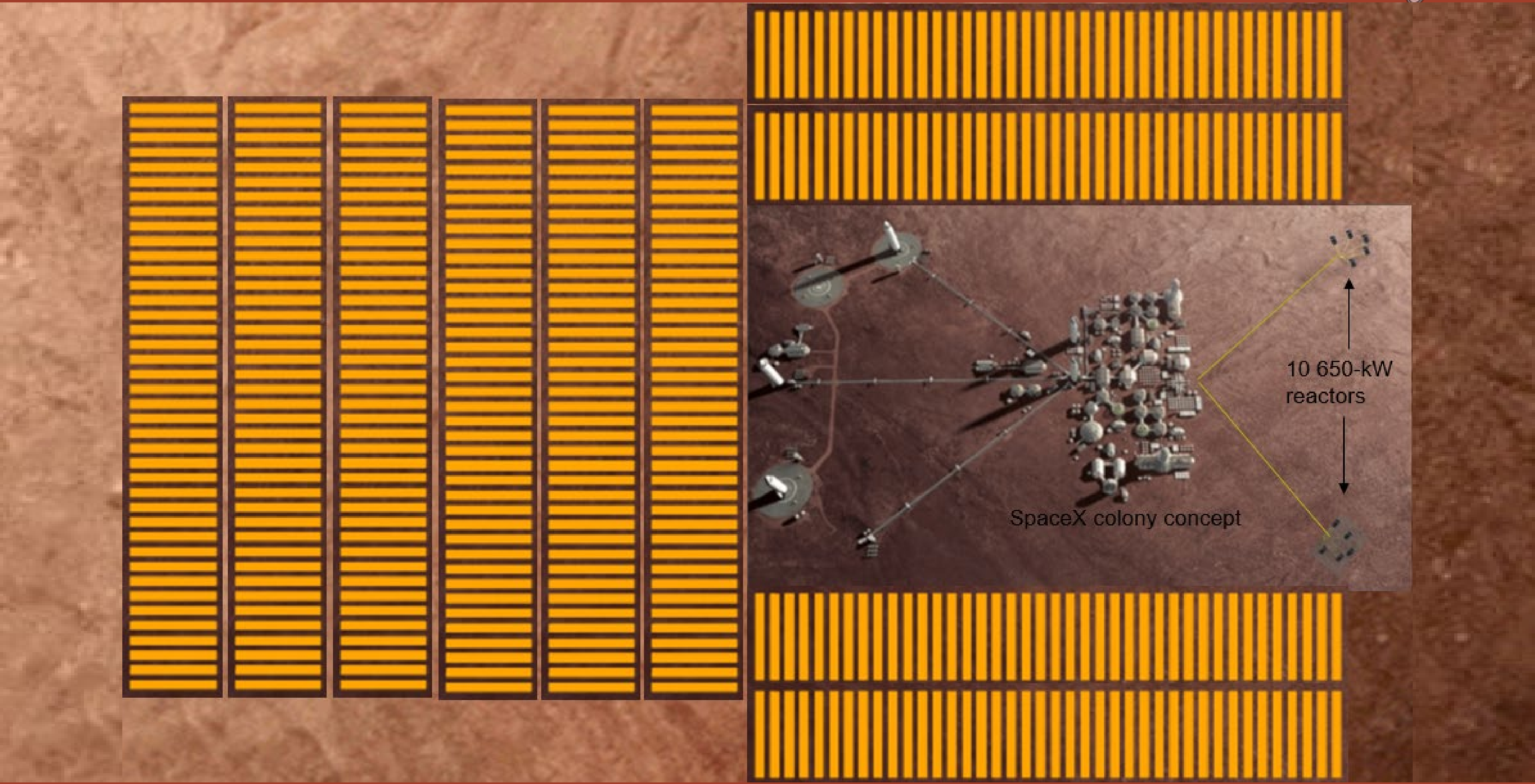
20 people on Mars: 600 kW (600-kW solar versus 3 200-kW reactors)

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)

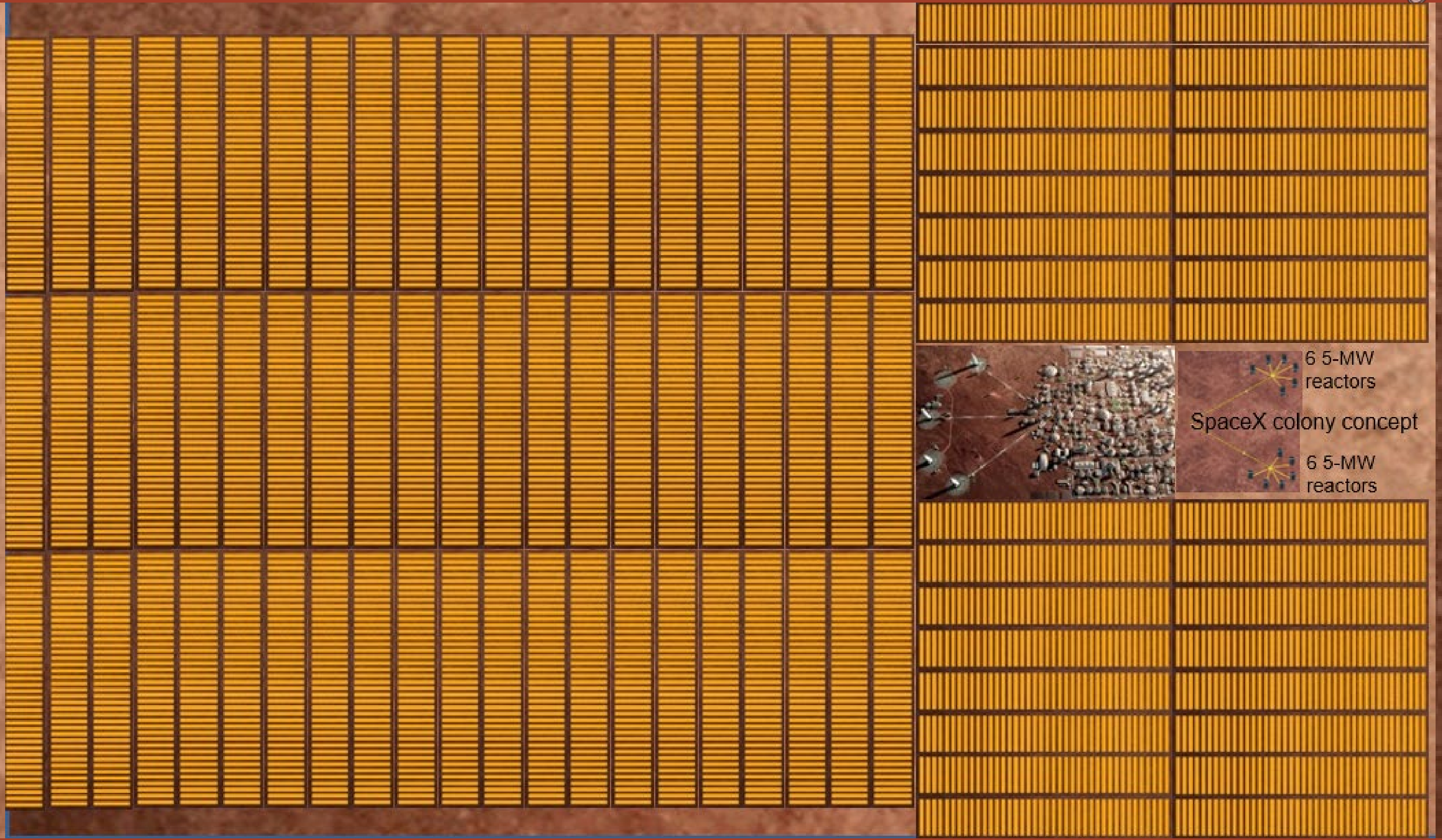
Estimated Mass at equator: 440 mT solar versus 150 mT reactor



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.



Radiation Risk Estimate – 3 Year Mars Mission

Acute Death	Still Alive?	Where?	Event?
0.001	0.999	Earth	Fueling/launchpad accident
0.010	0.989	Earth	Launch to orbit
0.002	0.987	Earth Orbit	On orbit docking/fueling/transfer
0.005	0.982	Earth Orbit	Transfer burn
0.002	0.980	Transit	Loss of facility life support/accident
0.001	0.979	Transit	Lack of hospital: medical emergency
0.010	0.969	Mars Orbit	Capture
0.025	0.945	Mars	Landing
0.003	0.942	Mars	Loss of facility life support
0.002	0.940	Mars	Lack of hospital: medical emergency
0.010	0.931	Mars	EVA accident
0.020	0.912	Mars	Launch to orbit
0.005	0.908	Mars Orbit	Mars docking/transfer
0.020	0.890	Mars Orbit	Transfer burn
0.010	0.881	Earth Orbit	Capture
0.005	0.876	Earth	Landing
	0.876	Earth	~5 to 25 years of satisfaction and hero status
0.0192	0.860	Earth	100 Rem increased cancer death risk
	0.860	Earth	Additional years of satisfaction and hero status

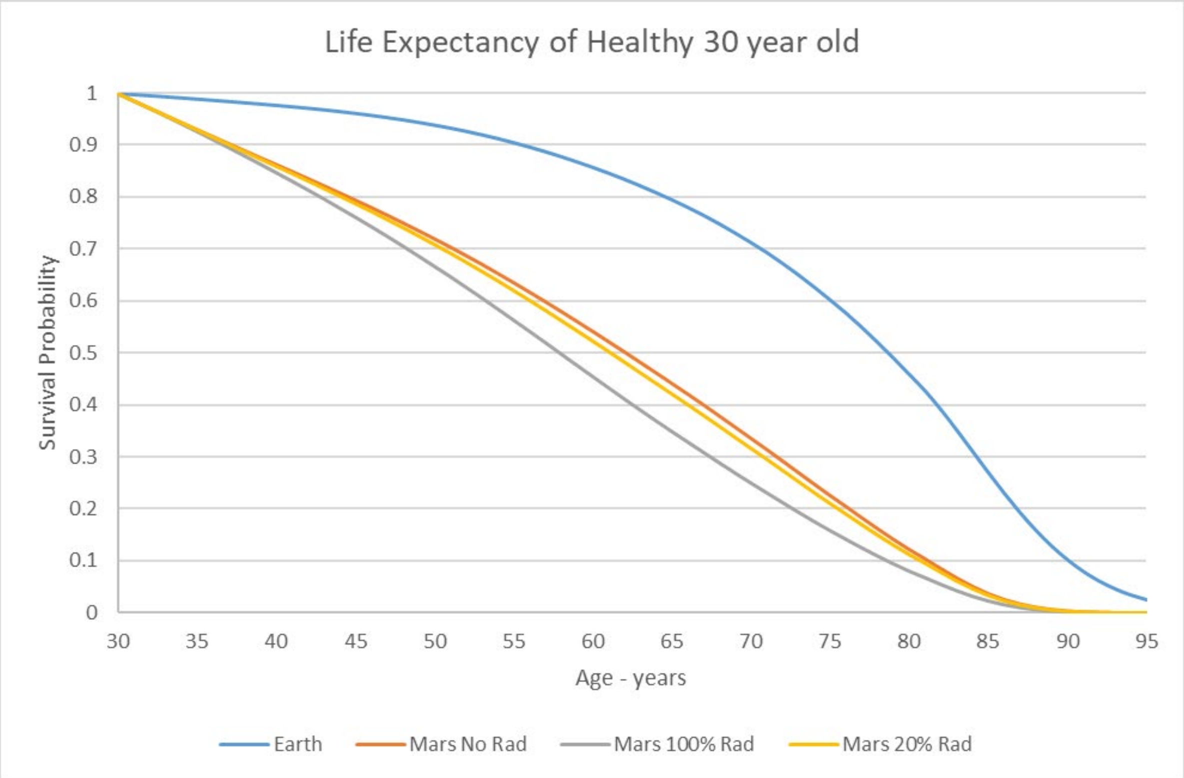
- **Assumptions**
  - All operation failure/death rates are SWAGS, but probably optimistic for initial missions.
    - Loss of facility life support on Mars is likely higher than 0.3%, but kept low because some scenarios might allow mission abort.
    - Return operations are higher risk than outbound because less ability to flight-check, more opportunity for things not to go as planned.
  - 100 Rem of dose over entire mission (rate does not matter in linear-no-threshold (LNT) model).
  - Cancer probability is from National Cancer Institute Radiation Risk Assessment tool, based on LNT
    - 9.6% increase in 35 year old developing cancer over their lifetime.
  - Cancer survival rate on earth will be 80% by 2045
    - 2045 is the expected time an astronaut on a 2030 mission would display significant symptoms. Likely range might be 5 to 25 years after exposure.
    - For reference, survival rate was 50% in 1975 and ~67% in 2010, of course dependent on cancer type.

It's hard to believe that any explorer would change their mind about a Mars mission based on a 2% chance of the mission causing them to die prematurely from cancer, especially since it will almost certainly long after they have provided a great benefit to society.

Why is NASA so hung up on this issue, and almost every media report about Mars harp upon the grave dangers of radiation?

I welcome others to provide alternative numbers, especially those that will have a better feel for acute mission risks (I literally made up these numbers a few hours before my presentation), but I'd be very surprised if the general conclusion changed.

Radiation Risk Estimate – Lifetime on Mars Simple Life Expectancy Model



- **Assumptions**
  - On a health basis, it is assumed that Mars residents have 2x the chance of death per year as an average Earth resident, based on inferior health care, gravity effects, lack of emergency services, etc.
  - On a risk basis, it is assumed that Mars residents have an additional 1% acute chance of death/yr due to failure of life support, food supply, or accident (especially when working outside or traveling away from outpost)
  - Risks will likely be higher than this for initial outposts and hopefully lower when a full colony is established.
  - Cancer risk is standard linear no-threshold model.
  - Cancer survival rate on Mars is assumed to be 50% (the 1975 Earth survival rate, as compared to the 67% in 2010 and the assumed 80% in 2045). If pharmaceutical cancer treatments progress then Mars could become close to Earth.
  - 100% radiation is totally unshielded – 25 Rem/yr
  - 20% radiation assumes habitat is well shielded, but the resident spends 20% of their time outside or in the greenhouse or windowed observation lounge (and that dose might actually extend their life expectancy due to mental health).

Radiation is a comparatively small risk to Mars residents, even with no shielding, no progress in pharmaceutical cancer cures.

Radiation is a minor risk if the habitat is decently shielded.

In addition, these risks are based on the linear no-threshold model, which is likely to be overestimate risk at 25 Rem/yr.

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!
- **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 reasonably simple to get Megawatt power systems on the surface on Moon and Mars.
- **Human propulsion will require several development steps**
  - Starting from scratch, a 900-s-Isp, 25-klb NTP and 10-MW, 5-kg/kWe NEP would be ~equally difficult.
    - Very little of ROVER/NERVA experience applies to the proposed high-performance NTP systems.
  - However, NEP systems can benefit greatly from the development of surface power systems (and SEP systems) and are easier to test and evolve, such that the NEP power system should ultimately be easier.
    - Additionally, NEP systems have lots of headroom to improve, while NTP is limited.