NETS 2021 Panel - Industry Perspectives on Space Reactor Development

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artwork courtesy of NASA

Space Nuclear Power Corporation

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Summary of first 4 slides:
SpaceNukes Perspective on Development

1) A different approach is needed

- The history of space reactor development clearly shows we have been using a bad approach
- Dozens of failures with billions spent in past 50 years
- Our approach for DUFF/KRUSTY appeared to break this cycle, but NASA/DOE reverted to the traditional approach
- We have now founded SpaceNukes because it provides the most likely to succeed path to help NASA/USA fly a reactor

2) This community needs a dose of reality

- Rickover had it right -- decision makers are easily enticed by the touted mass/performance of unrealistic paper reactors
- The experience of Rover/NERVA did not demonstrate anything close to what is being proposed today
- Multi-megawatt, low alpha NEP is also extremely hard, but 1) much of the risk is non-nuclear and 2) the reactor and other components can evolve via useful systems along the way

3) Biggest hurdle: Lack of Knowledge/Capability

- All reactors deployed today based on numerous nuclear tests.
- Reactor is an integrated system, not a technology; i.e. qualified fuel, moderator, coolant does not equate to a working reactor
- The US lacks people or small teams that can effectively <u>identify</u> and <u>balance</u> all system risks: design, development, deployment
- Chicken-and-egg: can't develop knowledge/experience without capability/infrastructure, and vice versa
- The only rational way to break this cycle is to start simple!

4) KRUSTY demonstrated how space reactors should (and can!) be developed

- Integrated Simplicity! The simplest path through design (physics, engineering, technologies), development, fabrication, safety, approvals, testing, deployment, and operation
- STMD/NNSA left all decisions (incl. money) to a lean "hatless" technical team from GRC, MSFC, LANL, Y-12, SNL, and more
- KRUSTY was designed, fabricated, tested in 3 years for <$20M

Summary of last 4 slides:
SpaceNukes Has The Practical Answer

5) Kilopower is the only option that has been demonstrated with nuclear test.

- KRUSTY not only worked as expected, but demonstrated that Kilopower is ideal for remote, autonomous, reliable operation.
- Passive operation with no real-time reactor control needed
- Reactor load following, fault tolerance, restart all demonstrated
- High system efficiency due to thermal power delivered at 800 C

6) KRUSTY was a prototypic test of a Kilopower reactor

- The reactor test was very prototypic (same materials, power, geometry, temperature, in-vacuum, point kinetic reactor, etc.)
- The testing, in combination with the simple physics and models that accurately predicted it, means that no nuclear-powered testing is needed for Kilopower flight unit
- True whether 1 kWe-HEU system or 25 kWe-LEU system

7) Kilopower is most scalable option to >1 MWe

- Evolution via incremental changes using mature technologies (fuel-block-to-rods, Stirling-to-Brayton, UMo-to-UO2)
- The key to Kilopower scalability is retention of the simple reactor physics (thermal-neutronic) through each generation; thus allowing high confidence without nuclear ground tests
- Most important – if it doesn't fly, it doesn't scale!

8) SpaceNukes is the only company with concepts ready for flight development.

- Our 20 kWe HALEU system could be ready to fly in 4 years for <$200M, at a mass of ~2300 kg (depending on shielding, etc.)
- We have aerospace/reactor industry leaders eager to join us
- We have obtained license to the patents we developed at LANL
- We could procure parts tomorrow and start testing soon

Complete Presentation

- **Complete presentation on following slides**
  - Forum only allowed 5 minutes.

"Slide 1": A Different Approach is Needed to Space Reactor Development

Past Space Reactor Programs

>13 Programs, ~$18 Billion Spent, 1 Flight Reactor 55 years ago

Decade	Project	Estimated Cost	Cost Today	Reactors Tested	Flight Units
60s-70s	SNAP	~$380M	$2.40B	~6	1
60s-70s	Rover/NERVA	~$2B	$12.00B	~20	0
70s-80s	SPAR	~$10M	$0.06B	0	0
80s-90s	SP-100	~$1B	$2.50B	0	0
80s-90s	MMW program	~$50M	$0.13B	0	0
90s-00s	NEBA (bimodal)	~$5M	$0.01B	0	0
90s-00s	Topaz	~$50M	$0.09B	0	0
90s-00s	SNTP/Timberwind	~$200M	$0.34B	0	0
00s-10s	Affordable Rx Prog.	~$5M	$0.01B	0	0
00s-10s	JIMO	~$400M	$0.53B	0	0
10s-20s	NCPS/NTP	~$80M	$0.08B	0	0
10s-20s	FSP	~$24M	$0.03B	0	0
10s-20s	KiloPower	$20M	$0.02B	1	0
Total			**~$18.4B**	**~27**	**1**

The most common pitfall for all these terminated programs was "the need to make large performance jumps from what was considered state of the art to satisfy the mission requirements." Nuclear Power Assessment Study, 2015, JHU/APL for NASA

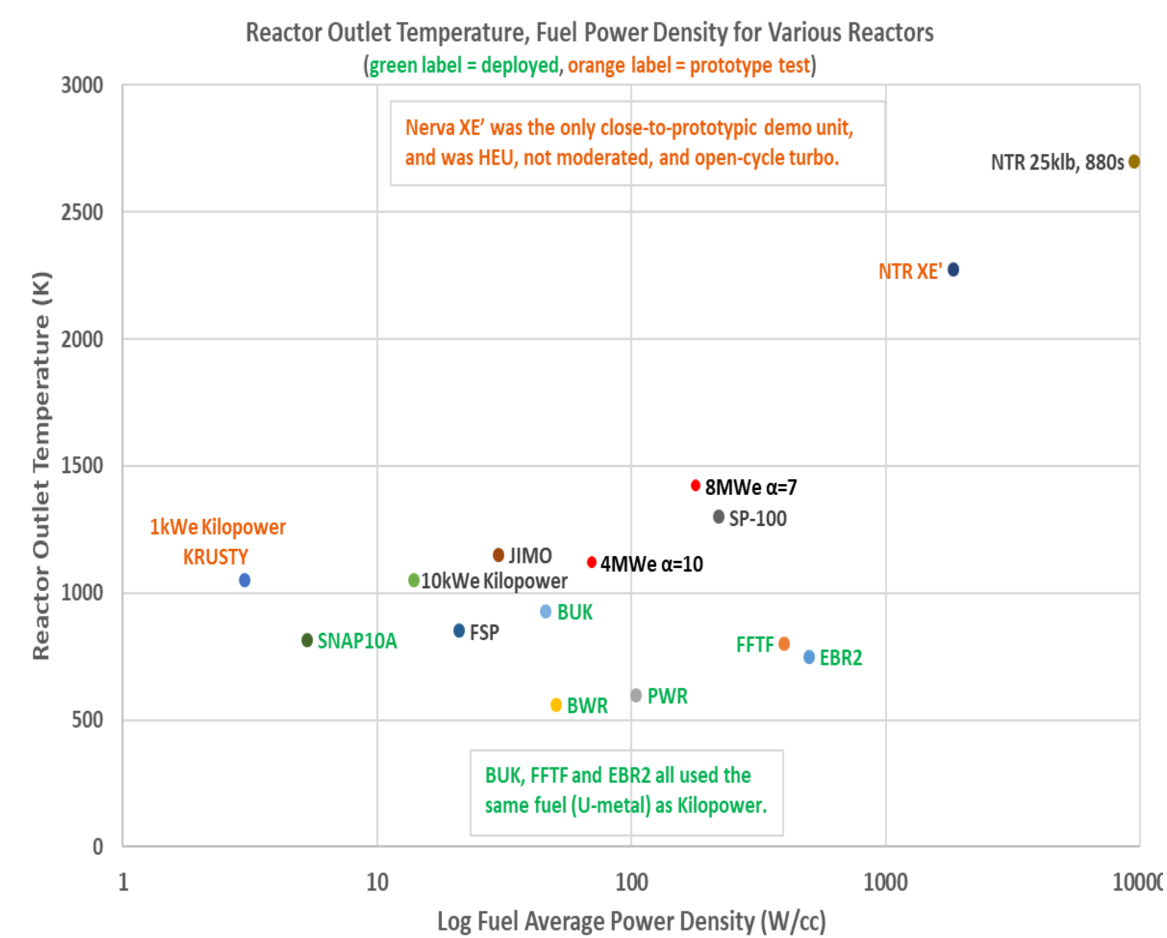
Avoid too large of a first-step

- Over-sold paper concepts – there's always someone that claims they can provide a higher-performance system to woo a customer.
  - Usually a concept is pursued with marginally better performance but a substantially harder development risk.
- Need a path to a successful demonstration within a few years (or every few years depending on how many steps are needed).
  - Eventually arrive at higher performance through evolution.

Everyone has been at fault (my personal opinion of course)

- Congress: White collar welfare – congress has specific Centers/Labs/Large-Corporations to feed.
- Decision makers: Risk aversion; i.e. decision makers seem to prefer "safe" studies to figure out what to do, than risk actually doing anything in fear of potentially making a bad choice.
  - This results in more planning and paper studies
- Bureaucrats: Who the money goes through, and making them feel good, often matters more than progress.
- Labs/Corporations: Follow the cash, no push back on unreasonable requirements/expectations.
- Engineers: Eager to try solve tough problems, instead of recommending more pragmatic, mundane solutions.

"Slide 2": Development risks need to be put in perspective when programs are being considered.

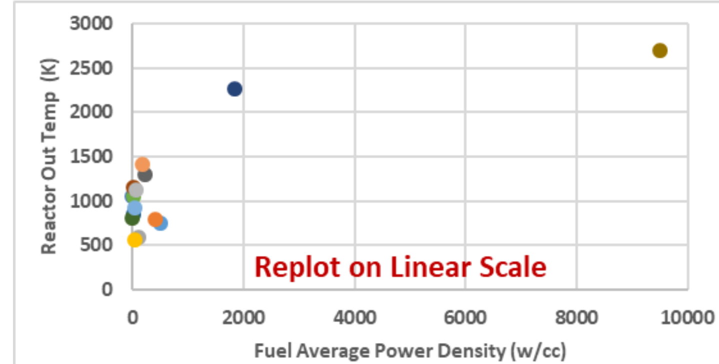


Biggest Space Reactor Development Risks

- 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)



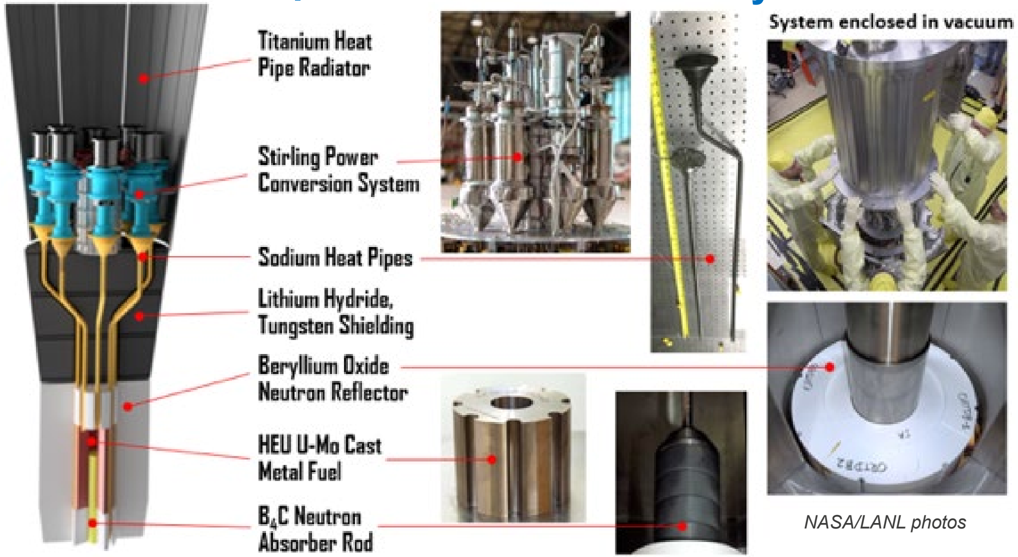
“Slide 3”: Biggest Obstacle: Lack of knowledge and capability – start simple

- **In the 50s and 60s there were ~100 new reactors built and tested (>50 at INL alone, then called the National Reactor Testing Station (NRTS)), which resulted in the reactors we use today**
  - This experience, knowledge, and capability is gone.
  - If we had the NRTS and/or a 70s version of a reactor vendor (GE, BWX, GA, Westinghouse) we’d be much closer to deploying a new type of reactor than we are now.
  - While we have “better” modeling (faster computers), and improved “balance of plant” technologies, these does not come close to filling that gap.
  - There are a lot of current claims about designing/building new reactors, but that has also been the case for the past 50 years, mostly in cycles.
- **A reactor is a system, not a technology**
  - Most of today’s efforts seem to indicate that they key to space reactor development is establishing component technologies
  - However, the difficulty of turning technologies into a reactor is fundamentally dependent on the complexity of the reactor system
    - Not just the complexity of the various thermal-structural-nuclear phenomena, but most importantly the interplay between these phenomena.
  - The complexity of this interplay determines the chances that the reactor will operate as expected (or at all) when it first fires up.
    - In the 50s and 60s, we had the ability to “fire up” lots of reactors, some tests worked and some didn’t, but all of the successfully deployed reactor types utilized several ground tests prior to success.
  - Kilopower reactors simplify this interplay more than any other reactor ever conceived, which is why KRUSTY succeeded.
    - Conversely, externally moderated reactors generally have complex interplay (i.e. many more, uncertain effects on operation)
  - The only way to truly learn how to design, develop, and operate <u>complex</u> reactors is to start by designing, developing and operating <u>simpler</u> reactors – there is no precedent that says otherwise.
- **Overall, the key thing lacking is people or small teams that can effectively 1) identify and 2) balance all technical risks of reactor power system design, development, and deployment**
- **Chicken-and-egg problem: a) can’t develop capability/infrastructure with knowledge/experience, b) can’t develop knowledge/experience without capability/infrastructure – the way to break this cycle is to start simple!**

"Slide 4": Kilopower Reactor Using Stirling Technology = KRUSTY

- **In March 2018, KRUSTY was successfully tested in the Nevada desert**
  - Primary goal met: demonstration of nuclear powered operation of a flight-like space reactor.
- **KRUSTY was a prototype of a 1 kWe Kilopower space nuclear reactor**
  - 1st ever heat pipe cooled reactor, and first nuclear-powered test of a novel reactor in the US in over 40 years.
- **KRUSTY was built & tested in 3 years for $18M (2015 – 2018)**
  - Demonstrated an approach to develop space reactors affordably. NASA/NNSA left all decisions to a "hatless" technical team.
- **Key to success -- Integrated Simplicity!**
  - Finding/following the simplest path through design (physics, engineering, technologies), development, fabrication, safety, and testing.

From Concept… To Reality



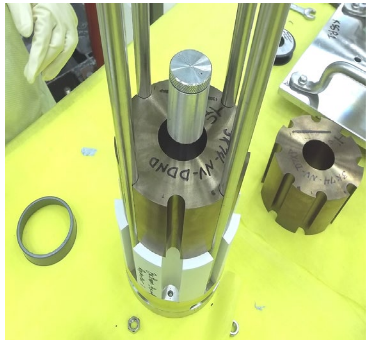
NASA/LANL photos

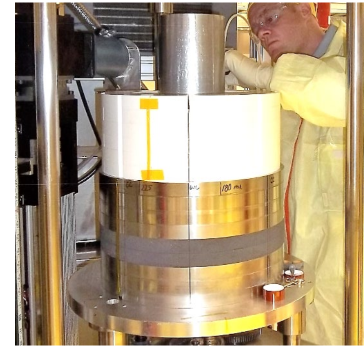
The KRUSTY ground test verified:

- The first successful design, fabrication, assembly & testing of a novel reactor in the US in >40 years
- Passive operation, load-following, and fault-tolerance of the reactor
- Physics & features making design safest reactor ever built
- Unique ability of team to accurately predict reactor performance
- High efficiency thermal to electric conversion
- Team's ability to successfully navigate nuclear Regulations for testing Approval

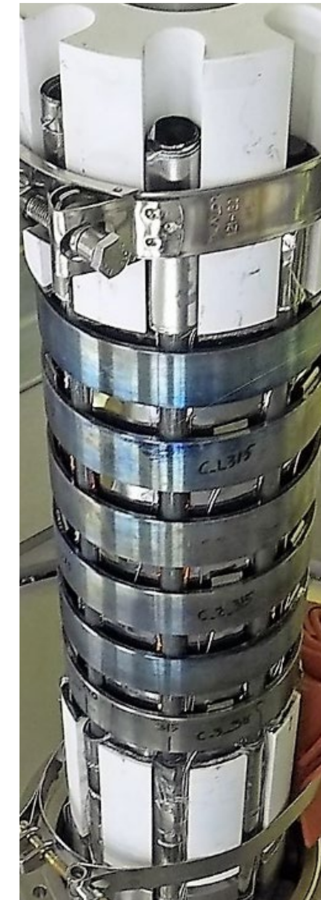
Read ANS Journal Nuclear Technology for details.

"Slide 5a": Kilopower is the Only Space Reactor Concept Being Pursued that has been Demonstrated via Nuclear Testing

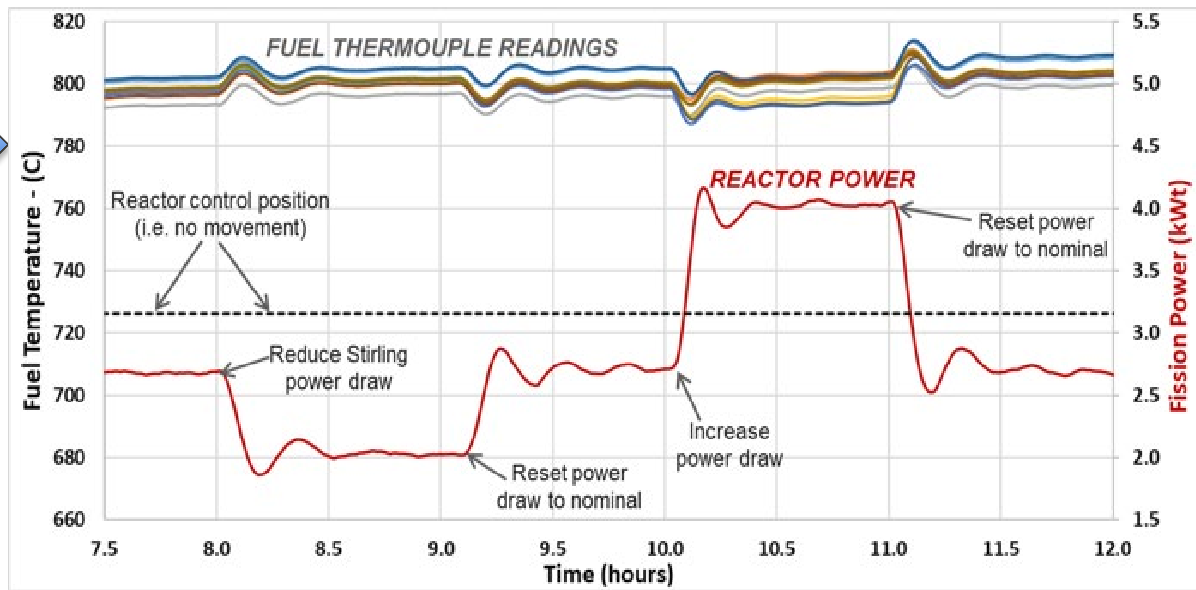





NASA/LANL photos



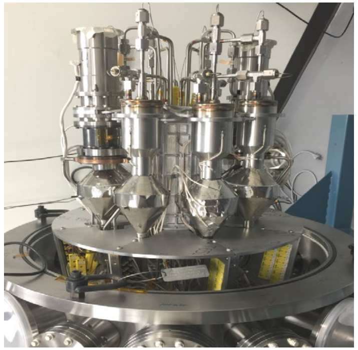
Load Following Proven with Actual Reactor Test Data

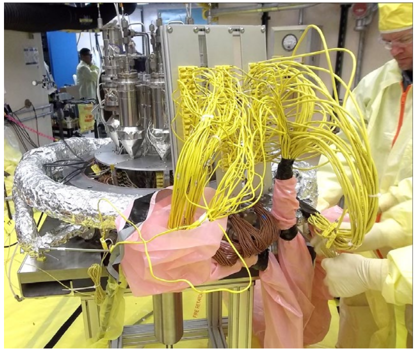


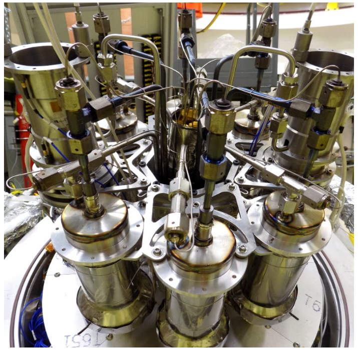
No other reactor, or test data like this has ever existed.

Every other space reactor concept being proposed has zero nuclear test experience.

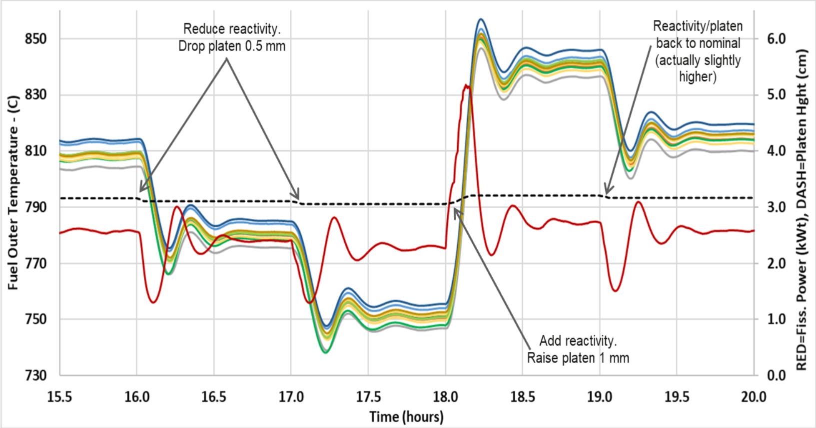
"Slide 5b": Nuclear-Powered Operation of Prototypic System Demonstrated in a Prototypic Environment.

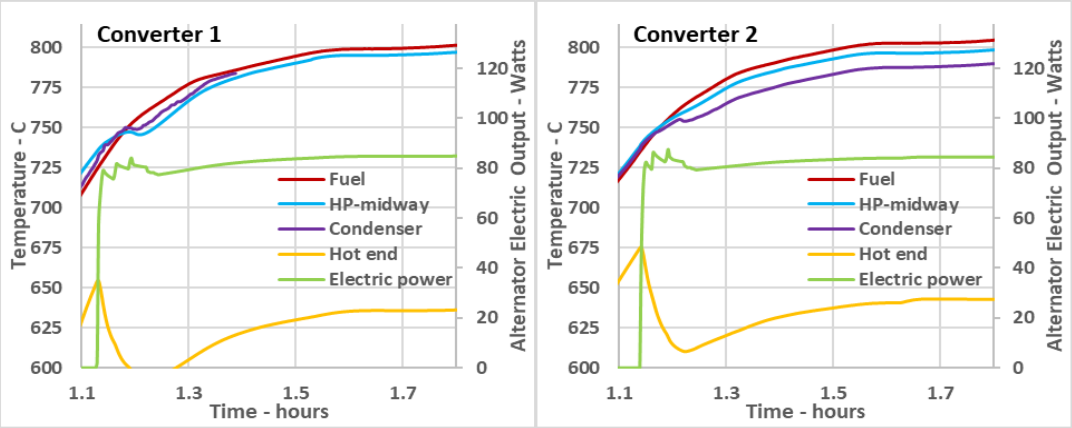






Actual System Data from KRUSTY Nuclear-Powered Test



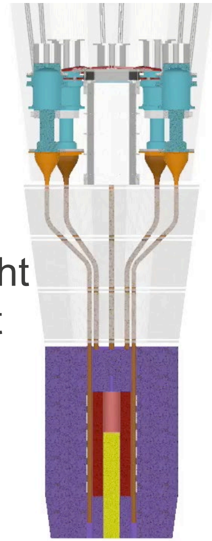


Kilopower reactors operate as a thermostat. The control rod sets the desired temperature, and the fission power passively increases or decreases to maintain the thermostat temperature.

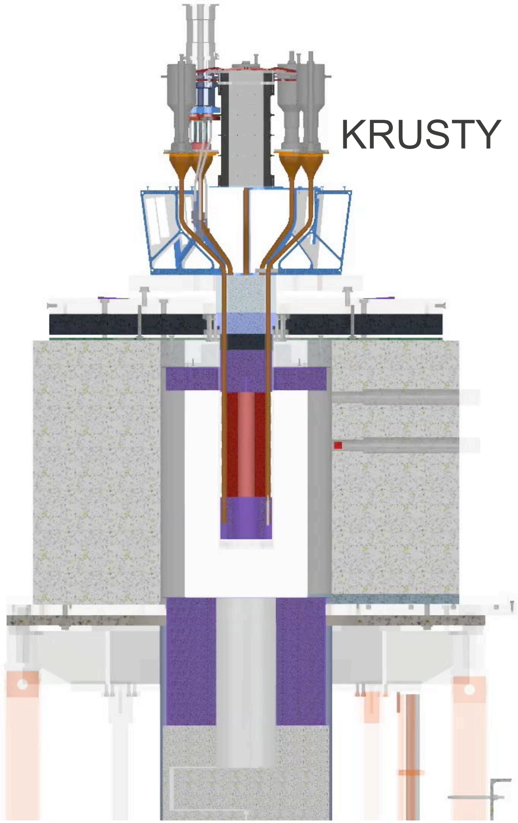
The KRUSTY reactor power system was tested in vacuum. The reactor and each of the 80 kWe-rated Stirling convertors performed without a glitch; including restart where hot-end was soaked >800 C (well above spec).

Nearly identical reactor performance

Flight Unit



KRUSTY



- 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 essentially no difference.
- This is because KRUSTY is a point-kinetic reactor, which occurs when the neutron mean-free-path a significant fraction of the core geometry combined with high neutron velocity. In such a system, all regions of the reactor communicate very quickly 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.
- <u>The coupled thermal-nuclear behavior is nearly identical for a 1, 5, 10, 30 kWe reactor and/or an HEU or LEU reactor, and equally as predictable as KRUSTY.</u>
- **<u>No nuclear-powered testing needed for Kilopower flight unit.</u>**
- **<u>True whether 1 kWe-HEU system or 25 kWe-LEU system.</u>**

Animation synching rod/reflector may not work in all formats

"Slide 7": Kilopower Reactor Evolution to Several MWe

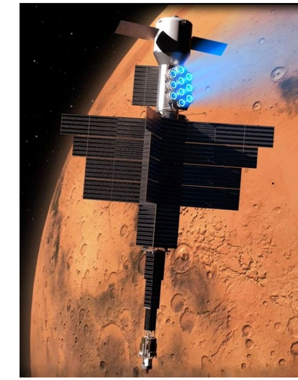
Kilopower reactors are ideal for higher power evolution because the physics, control, and operation do not change significantly as power increases (core neutronics and heat transfer characteristics remain the same), regardless of whether HEU or LEU.

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 can provide high confidence). Uncertain performance/dynamics is also undesirable because the risk is left until the end of a program.

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 >100 kWe system, and so on to >1MWe system.

The same models that accurately predicted KRUSTY can be further improved each generation, with small modifications to address the incremental changes in the system and increase confidence as performance.

Each generation, technology development would begin to guide the next generation, but it's unwise to speculate too much beyond that.



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 does not have to be taken, but several are recommended, depending on where the most useful systems lie along the way.

"Slide 8": SpaceNukes Concepts: Schedule and Risk Projections

SpaceNukes KRUSTY/Kilopower Derived Systems

Power	Mass	Fuel	Development 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	4 years	Low
200kWe-surface	~7500 kg	LEU	~7 years	Modest
2MWe-surface	~32000 kg	LEU	~10 years	High

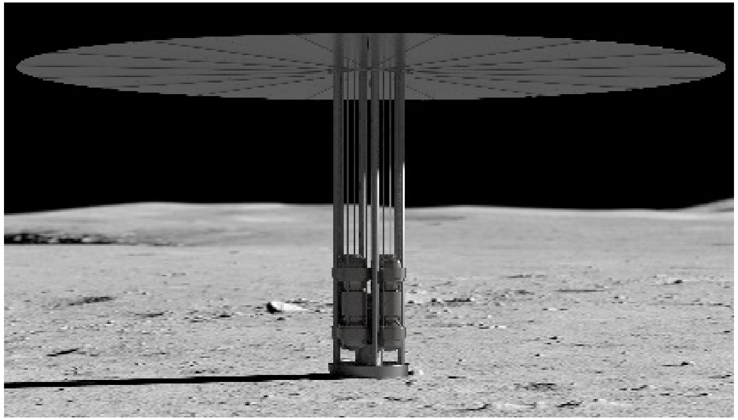
The table above provides our estimated schedule and risk for each concept if we started on them today. Surface power masses depend on architecture and dose requirements (listed includes modest 4pi shielding).

The 1kWe and 5 kWe designs are very low risk because it is directly based on KRUSTY (same core geometry, structure, heat pipe coupling).

The 20 kWe LEU design uses the same physics and technology as KRUSTY but scaled to higher power (allowed due to lower fuel burnup).

The higher power LEU concepts maintain the same thermal-neutronic physics, but require technology changes (SS block, Brayton PCS).

Cost, risk, and schedule of higher performance systems decreases substantially with the successful completion of an earlier generation.



NASA artwork