

# Improvements and Safety Analysis on the Technologies of Current Nuclear Power Systems for Remote Places and Outer Space

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## 1. Introduction

Space nuclear reactors (SNRs) are once again being developed for space exploration. In the last 10 years NASA has successfully developed and tested a new generation of space nuclear reactors in the Kilopower project [1]. The prototype Kilopower Reactor Using Stirling Technology (KRUSTY) was designed with some influence from older Soviet space reactors designs, and is already considered to be ready to deploy [2]

These systems are an alternative for the nuclear batteries in circumstances that demand higher power or more readily accessible power [3]. Despite being of a very different power range, the technologies involved are quite similar, and advances in one of the concepts create synergy with the improvements of the other.

Under the light of the new developments in nuclear space power, it is to be expected to iterate in the current concepts, in search for possible improvements that can either increase the performance and reliability of the reactors or ease their production. This work aims to find such improvements to current space reactors designs using technologies that are readily available.

Such improvements in current space reactor technology have already been investigated in the past, including by the research institutes located in Obninsk [4]. While much has changed since then, the findings are still interesting and can inspire new design ideas.

In order to understand what can be improved, first it is needed to review the current designs and compare then with the older projects that were used in paving the way towards their development. These older projects range from Soviet designs from the late 1960's to current concomitant projects in NASA and different agencies. It also takes into account the latest developments in energy technology as a whole, such as new radionuclide thermoelectric generators (RTGs) designs [5].

This work proposed improvements in the current SNR designs using currently existing technology and near future alternatives under development to investigate whether those designs are viable solutions, through means of calculations, simulations or analysis of similar experiments in the frame of nuclear safety analysis.

## 2. Methodology

The main parameter that will be compared to the other designs is the safety analysis of the nuclear reactor. It was possible to estimate the reliability of the current KRUSTY design using the probabilities of failure (POFs) of the main components. Using probability distributions, the same can be done for the new proposed designs.

The safety of the nuclear reactor was evaluated firstly by calculations using the probability of failures of each component part in a fault tree diagram, and then expanded upon using the SAPHIRE software package. These results were compared between themselves and to the original probabilities of failure calculated for the KRUSTY reactor, the current most well documented reactor using this technology.

Different assessments were tried for the same systems, with different scenarios. These were handled with the respective probability distributions.

A particular useful probability distribution to conduct safety analysis is the binomial distribution mass

function [6]:

$$F = \frac{n!}{k!(n-k)!} p^k r^{n-k}, \text{ for } k = 1, 2, 3 \dots n \tag{1}$$

In which n is the number of attempts, k is the number of failures, p is the probability of success in this attempt and r is the probability of failure in this attempt.

Another tool used for the NSA are the logical diagrams. Logical diagrams used in NSA are often called failure trees, when accessing probability of failure, or reliability networks, when calculating the chance that the system will not fail. The theoretical calculations and logical diagrams were then compared to SAPHIRE fault trees. This software was created by the U.S. Nuclear Regulatory Commission (NRC) with the purpose to draw and analyze risk assessment [7]

### 3. Results and Discussion

The first step was to analyze the reliability of the KRUSTY SNR. The SAPHIRE calculations yielded a result of 5.858E-6 POF per day for the whole system. If this result is multiplied by the 17 years of mission time, it will yield a 3.6% probability of failure, just like the result obtained by NASA and the theoretical calculations.

Compiling the data on other SNRs yielded the Table 1, for post 2000's reactors:

Table 1 – Modern Space Reactors Data [8]

Reactor	Year*	Nationality	Fuel	Reflector	Coolant	Converter	Specific Power (kWe/Kg)
Prometheus	2003	USA	UN/UNO <sub>2</sub>	Be/BeO	He, Xe	Brayton	200/4557
SAFE-400	2002	USA	UN	Be, B <sub>4</sub> C, BeO	Na, He, Xe	Brayton	100/541#
HOMER-15	2002	USA	UN/UNO <sub>2</sub>	BeO	Na	Stirling	3/512##
Rapid-L	2003	Japan	50% UN	Li-6	Li	Thermoelectric	200/4100
TERRA	2011	Brazil	HEU UN/UNO <sub>2</sub>	BeO, B <sub>4</sub> C	Na/NaK/Li	Brayton/Stirling	300
KRUSTY	2018	USA	U <sub>3</sub> Mo	BeO, B <sub>4</sub> C	Na	Stirling	1/400
Zevs	2010	Russia	Unknown	Unknown	He, Xe	Brayton/Thermionic	1000/20000
JANUS	2020	UK	UN	Be	He, Xe	Brayton	800/Unknown
OPUS	2009	France	UNO <sub>2</sub>	Be	He, Xe	Brayton	100/Unknown

Several adjustments were compared to the original KRUSTY design. These designs also had their POF analyzed using theoretical calculations and SAPHIRE. The modifications were separated in two groups: one with very similar specs to the original KRUSTY, but changing the conversion system to an RTG. This version was called KRUSTY-T; and one with a hypothetical thorium reactor, which was labelled Thorium-Uranium-Powered Advanced Airspace Assembly (TUPA<sup>3</sup>). The chosen components are displayed in Table 2. Their POFs over time were also compared, and are displayed in Figure 1. Table 3 compares the performance of each of the proposed models:

Table 2 – Proposed Reactors Overall Components. KRUSTY-T (left), TUPA<sup>3</sup> (right)

Category	Chosen Option	Category	Chosen Option
Reactor fuel	Metal (U <sub>3</sub> Mo)	Reactor fuel	TRISO, 20% U-235, Thorium
Fuel form	Blocks	Fuel form	Plates
Neutron spectrum	Fast	Neutron spectrum	Thermal or Epithermal
Cladding/structure	Stainless steel, superalloys	Cladding/structure	Superalloy N
Control materials	BeO, B <sub>4</sub> C	Control materials	FLiBe (pure Li-7)
Mechanism	Rods	Mechanism	Rods
Heat transport	Heat Pipes	Heat transport	Heat Pipes
Reactor heat transfer fluids	Sodium	Reactor heat transfer fluids	FLiNaK (pure Li-7)
Shield materials	Lithium hydride/DU/Steel	Shield materials	Lithium hydride/DU/Steel
Power conversion	TEG	Power conversion	Stirling engine
Heat rejection	Heat Pipes	Heat rejection	Heat Pipes
Radiator fluids	Water	Radiator fluids	Undefined
Radiator materials	Aluminum	Radiator materials	Aluminum

Figure 1 – POF Over 25 Years of Operation

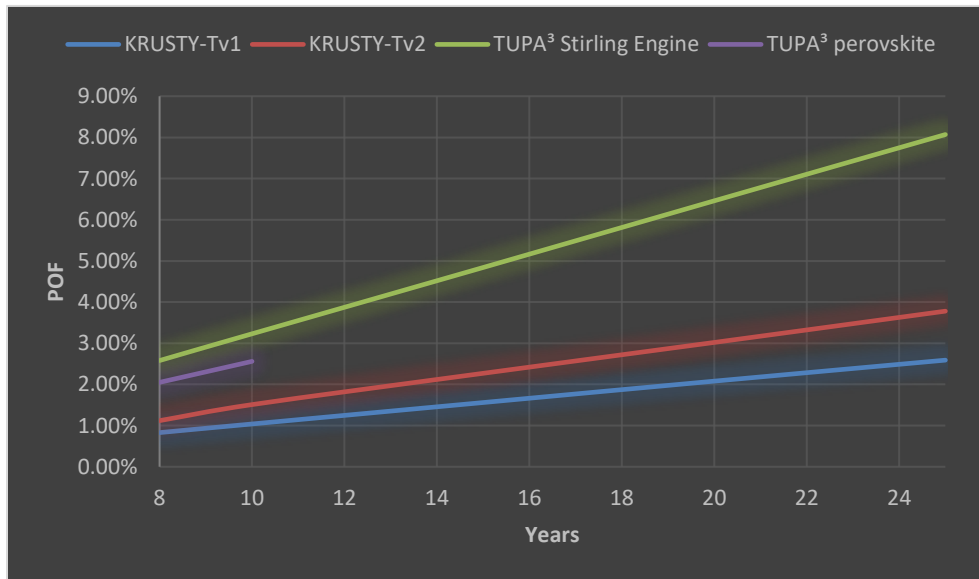


Table 3 – Total Power of Each Proposed Reactor

Case	Power (kW)
KRUSTY-Tv1 Skutterudite TEG	0.6
KRUSTY-Tv2 Perovskite TEG	0.8
TUPA <sup>3</sup> Stirling Engine	75
TUPA <sup>3</sup> Perovskite TEG	60

It can be seen that, while being much weaker compared to the other reactors, the KRUSTY-Tv1 would be the most reliable, and could make up for the low power with 25 years of operation below the 3% POF mark. Also, KRUSTY-Tv1 is the proposed design that is closer to being possible to design currently, as all of the individual component technologies have already been tested successfully. In another light, the thorium designs can't be discarded altogether, as there is still room to improve their technologies and test their results in the next years. These discoveries are aligned with the findings of the Radiant Nuclear Kaleidos reactor, which was found out after the publication of this work [9], and with reports on a new

project from the department of energy, which also leans towards new RTG designs [10].

#### 4. Conclusions

In this work, four alternative preliminary designs to currently known reactors were proposed. Even if not in enough depth, these designs offer some insight on technologies that could be used for the next generation of space reactors. Two of the proposed designs can be developed even by countries that are affected by non-enrichment treaties.

The findings point out that a comeback of the thermoelectric converters might be possible, depending on the mission, and that molten salt reactors might be a good attempt at the future of space exploration. The proposed models range from 0.6 to 75 kW electrical power and all have less than 4% probability of failure over their expected mission times. Future developments might lead to testing those designs and learn whether they are suited for commission.

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