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

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Abstract: A new age of space nuclear reactors is at hand. Current developments in both energy generation and thermal energy conversion are fueling new reactor designs. Some projects have already been tested on Earth, and the results were considered optimistic. This work discusses the latest designs in space nuclear reactors and their surrounding technologies in order to propose new improvements, further expanding their variety and possibilities. The objective was to identify the most promising new designs and propose updates to them that would increase the safety and performance. Furthermore, this work was realized in the scope of the safety analysis of the projects, calculating and simulating in the SAPHIRE software package the consequences of changing parts and comparing the reliability of each possible configuration. At the end, it is discussed which of the designs are considered to be better for new space projects involving nuclear power systems. The work also takes into account new technology that was not available during the development of the older designs. It is possible to conclude that the subject is very dense, and that there are several different aspects that should be taken into account when choosing the ideal space nuclear reactor for each mission, program, and country. Four different concept designs were proposed, by changing around with the pieces of known designs. Two of them by simply changing the converter systems of NASA's KRUSTY design, and two reactors for space based on molten salt reactors. All of them using the KRUSTY systems as a basis, as they are the most well documented ones in the scope of safety analysis. The proposals based on NASA were less efficient, achieving from 0.6 to 0.8 kWe, but were even more reliable, in one of the cases twice as much. The proposals based on the molten salt reactor were more open ended, and the estimates should be considered carefully. The power output for the two molten salt proposals ranged from 60 to 75 kWe, and their reliability was comparable to the KRUSTY design. Even though is only an initial theoretical approach, this work succeeded in proposing new designs and highlighting their safety aspects over the known ones. The data is likely to be refined in the future, but the results are promising.

Keywords: Nuclear Space Power, Small Modular Reactors, Safety Analysis, Probabilistic Safety Analysis.

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Melhorias e Análise de Segurança nas Tecnologias Atuais de Sistemas de Energia Nuclear para Lugares Remotos e Espaço Sideral

Resumo: Uma nova era de reatores nucleares espaciais está começando. Desenvolvimentos atuais tanto na geração de energia quanto na conversão de energia térmica estão impulsionando novos projetos de reatores. Alguns modelos já foram testados na Terra, e os resultados foram considerados positivos. Este trabalho discute os mais recentes projetos de reatores nucleares espaciais e suas tecnologias circundantes, a fim de propor novas melhorias, expandindo ainda mais sua variedade e possibilidades. O objetivo foi identificar os novos projetos mais promissores e propor atualizações que aumentariam a segurança e o desempenho. Além disso, este trabalho foi realizado no âmbito da análise de segurança dos projetos, calculando e simulando no pacote de software SAPHIRE as consequências da alteração de peças e comparando a confiabilidade de cada configuração possível. Ao final, discute-se quais dos projetos são considerados melhores para novos projetos espaciais envolvendo sistemas de energia nuclear. O trabalho também leva em conta novas tecnologias que não estavam disponíveis durante o desenvolvimento dos projetos mais antigos. É possível concluir que o assunto é muito denso e que existem vários aspectos diferentes que devem ser levados em conta ao escolher o reator nuclear espacial ideal para cada missão, programa e país. Quatro diferentes conceitos de projeto foram propostos, alterando as peças de projetos conhecidos. Dois deles simplesmente mudando os sistemas conversores do modelo KRUSTY da NASA, e dois reatores espaciais baseados em reatores de sal fundido. Todos eles usando os sistemas KRUSTY como base, pois é o mais bem documentado em termos de análise de segurança. As propostas baseadas no KRUSTY foram menos eficientes, alcançando de 0,6 a 0,8 kWe, mas sendo ainda mais confiáveis, em um dos casos duas vezes mais. As propostas baseadas no reator de sal fundido foram mais abertas, e as estimativas devem ser consideradas cuidadosamente. A potência elétrica para as duas propostas de reator de sal fundido variou de 60 a 75 kWe, e sua confiabilidade foi comparável ao KRUSTY. Mesmo sendo apenas uma abordagem teórica inicial, este trabalho conseguiu propor novos projetos e destacar seus aspectos de segurança em relação aos conhecidos. É provável que os dados sejam refinados no futuro, e os resultados são promissores.

Palavras-chave: Reatores Nucleares Espaciais, Reatores Compactos, Análise de Segurança, Energia Nuclear no Espaço.

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LIST OF ABBREVIATIONS

DU – depleted uranium
ESA – european space agency
FMECA – failure mode effects and criticality analysis
HEU – highly enriched uranium
HOMER – heatpipe-operated mars exploration reactor
HP – heat pipe
IAEA – international atomic energy agency
JPL – jet propulsion lab
KRUSTY – kilopower reactor using stirling technology
kW – kilowatt
kWe – electrical kilowatt
kWth – thermal kilowatt
MSR – molten salt reactor
NASA – national aeronautics and space administration
NRC – nuclear regulatory commission
NSA – nuclear safety analysis
PDF – probability density function
POF – probability of failure
RPS – radionuclide power system
RTG – radionuclide thermoelectric generator
SAFE – safe affordable fission
SAPHIRE – systems analysis programs for hands-on integrated reliability evaluations
SNAP – systems for nuclear auxiliary power
SNR – space nuclear reactor
TEG – thermoelectric generator
TERRA – Tecnologia de Reatores Rápidos Avançados (Advanced Fast Reactor Technology)
TOPAZ – thermal emission in the active zone (in Russian)
USSR – Union of Soviet Socialist Republics
USA – United States of America
W - watt

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 to 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.

In light of the new developments in nuclear space power, it is expected to iterate on the current concepts in search of 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, it is necessary 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 and thermoelectric materials [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 framework of nuclear safety analysis (NSA).

2. MATERIALS AND METHODS

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 first evaluated 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 among themselves and to the original probabilities of failure calculated for the KRUSTY reactor, the currently 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 particularly useful probability distribution function (PDF) for conducting safety analysis is the binomial distribution mass function [6]:

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

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].

Fault trees in SAPHIRE work by drawing diagrams of interconnected systems, attributing their respective POFs. They work in the same way as logical diagrams, with different forms of connections if the parts, or systems, in the fault tree are dependent or independent between each other and the other parts in the same diagram. The software then uses the associated PDF to automatically calculate the POF of the whole fault tree.

3. RESULTS AND DISCUSSIONS

As part of the review used for this work, Table 1 and Table 2 displays the information for space nuclear reactors designs made until the 1990s. The data of the older models helps to understand the evolution of the newer models that appear in Table 3 and Table 4. Even if many of the components and technology used remain the same, it is possible to spot trends among the different reactors, including among different countries' designs. They were all considered when drafting the adjustments proposed.

It should be noted that many of the properties listed in the tables are estimates or ideal values by design. Many of these designs were never commissioned, and some of the commissioned ones have either dubious, contradictory, or vague descriptions on their records. This is sometimes made on purpose, as most of the designs were under secret of state. Other designs have vague information because they were discontinued before further development, as cited in the paper that compiled the tables [8].

Table 1: Old Space Reactors Data Part 1 [8]

REACTOR	COUNTRY	YEAR	FUEL	WEIGHT (Kg)	POWER (kWe)
SNAP-2	USA	1957	U-ZrH	430	3
SNAP-10A	USA	1965	U-ZrH	0435	0.5
SNAP-8	USA	1963	U-ZrH	2721	15
Romashka	URSS	1964	UC2	0900	0.4
BUK	URSS	60s-70s	U-Mo	1390	1.3
TOPOL	URSS	1987	UO2	1000	7
ENISY	URSS	1989	UO2	<1061	5
SP-100	USA	1983	UN	4600	100
ERATO	France	1986	UN	Unknown	200

Table 2: Old Space Reactors Data Part 2 [8]

REACTOR	COOLANT	SPECTRUM	CONVERTER	EXPECTED LIFETIME (DAYS)	EFFICIENCY (%)
SNAP-2	NaK	Epithermal	Rankine	<500	5.4
SNAP-10A	NaK	Thermal	Rankine	365	1.3
SNAP-8	NaK	Epithermal	Rankine	416	2.5
Romashka	None	Fast	Thermoelectric	625	1.4
BUK	Nak	Fast	Thermoelectric	135#	1.3
TOPOL	NaK	Thermal	Thermionic	1095-1825	5
ENISY	NaK	Epithermal	Thermionic	1095	4
SP-100	Li	Fast	Thermoelectric	3065	4.2
ERATO	Li	Fast	Brayton	3365	20

After reviewing the historical data, the next step was to analyze the reliability of the KRUSTY SNR. The SAPHIRE fault trees were drawn with several different interconnected systems. The biggest of them, the heat pipe (HP) system, consists of 22 blocks of three neighboring HPs, all of which must fail at the same time to cause a malfunction. Because of the mathematical simplicity of this particular problem, it is actually easier to calculate it directly than to use a large fault tree to do so.

Using the binomial probability formula and considering that the POF for each pipe is P = 1% = 0.01, the reliability R = 99% = 0.99 and that there are n = 24 pipes in total, it is possible to separate the failures into groups of k = 3 neighboring pipes. This allows for j = 22 different combinations of 3 neighboring pipes.

It must be taken into account that the POF of these groups is not independent, as a pipe can be part of several groups, but it cannot fail multiple times. Because of this, the binomial coefficient must be dropped from the equation, as it is not correct, to search for all the possible failure groupings of 3 for 24 pipes.

Instead, all that needs to be considered are the possible failure arrangements that have no intersection with the other group. Since all the combinations have the same probabilities, it is only necessary to sum the combined probability for each of them considering all the cases. The probability that the heat pipes will fail to the point that the core will be unable to cooldown efficiently is no higher than 0.0018%, a very similar value to the one found in SAPHIRE.

Since the HPs failure is negligible compared to the other parts of the reactor, they were omitted from the rest of the calculations. The mathematically significant parts for the calculations were: the Stirling Convertor, the Balancer and Controller duo, the Stirling Controller, and the Structure of the reactor. Those are considered to be serially associated, as failure in one of them results in the total failure of the reactor.

Creating a fault tree with those four parts associated in series, along with their respective POFs 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, the same result obtained by NASA [9], demonstrating that both the method and SAPHIRE are solid, and that it is possible to infer the method used by NASA to do their safety analysis by using the same tools and logic applied by them.

Compiling newer SNR data resulted in Table 3 and Table 4 for post 2000’s reactors:

Table 3: Modern Space Reactors Data Part 1 [8]

REACTOR	**COUNTRY**	**YEAR**	**FUEL**	**WEIGHT (Kg)**	**POWER (kWe)**
Prometheus	USA	2003	UN/UO2	4557	200
SAFE-400	USA	2002	UN	541	100
HOMER-15	USA	2002	UN/UO2	512	3
Rapid-L	Japan	2003	50% UN	4100	200
TERRA	Brazil	2011	UN/UO2	300	300
KRUSTY	USA	2018	U8Mo	400	1
Zevs	Russia	2010	Unknown	20000	1000
OPUS	France	2009	UO2	Unknown	100

Table 4: Modern Space Reactors Data Part 2 [8]

REACTOR	**COOLANT**	**SPECTRUM**	**CONVERTER**	**EXPECTED LIFETIME (DAYS)**	**EFFICIENCY (%)**
Prometheus	He, Xe	Fast	Brayton	3365	25
SAFE-400	Na, He, Xe	Fast	Brayton	3365	25
HOMER-15	Na	Fast	Stirling	1683	20
Rapid-L	Li	Fast	Thermoelectric	3365	4
TERRA	Na/NaK/Li	Fast	Brayton/Stirling	2920	Unknown
KRUSTY	Na	Fast	Stirling	6205	25
Zevs	He, Xe	Unknown	Brayton	3365	26
OPUS	He, Xe	Fast	Brayton	Unknown	27

It can be seen from the tables that newer SNRs tend to use a fast neutron spectrum, that they have a diverse list of possible coolants, and that there is a trend to move on from thermoelectric converters. Their expected lifetime and efficiency have also significantly increased, reflecting current age needs for longer missions and more power-demanding tasks. The reasoning for the KRUSTY design is that it is a cheaper, less ambitious device that could be developed using only in-house equipment from NASA. Looking at the tables, however, it is possible to see that there were other options that could improve its performance, given there was enough time for tweaking the design.

Several adjustments were compared to the original KRUSTY design. These designs also had their POF analyzed using theoretical calculations and SAPHIRE. The suggested modifications were separated in two groups: one with very similar specs to the original KRUSTY, but changing the conversion system to a thermoelectric conversion system. These versions were labelled KRUSTY-T; and one with a hypothetical thorium reactor, using TRISO fuel, which was labelled Thorium-Uranium-Powered Advanced Airspace Assembly (TUPA^3).

KRUSTY-T was divided into two versions: KRUSTY-Tv1 equipped with a skutterudite TEG, similar to the ones tested by NASA. The KRUSTY-Tv2 uses a TEG made of perovskite thermoelectrics, which is a promising new technology that requires more field testing to reveal its performance over decades of use [10].

TUPA^3 designs were also divided into two versions: TUPA^3-S, equipped with a Stirling engine similar to the current one used by the KRUSTY prototype. TUPA^3-P also would use a perovskite TEG. The reason for this is that the power output with skutterudite would be smaller, and this would make it less interesting to compare the other designs, as the idea is to showcase different designs that could be better suited for different applications. The fuel of the TUPA^3 could be composed of 20% enriched uranium, and thorium-232. This is based in a compact Chinese reactor design that got discontinued [11].

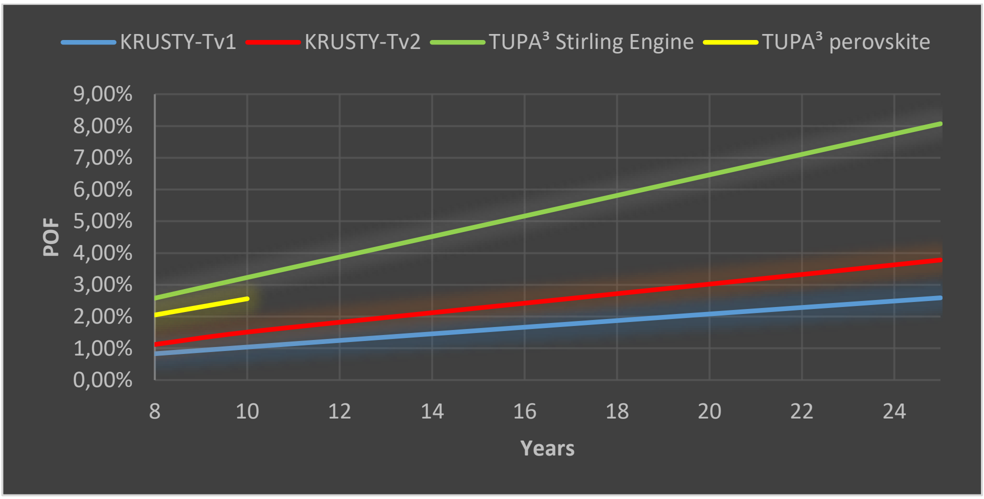
The chosen components for these designs are displayed in Table 5. Their POFs over time were also compared and are displayed in Figure 1. Table 6 compares the performance of each of the proposed models:

Table 5: Suggested Main Reactor Components for KRUSTY-T and TUPA^3

CATEGORY	KRUSTY-T	TUPA^3
Reactor fuel	Metal (U8Mo)	TRISO, 20% U-235, Thorium
Fuel form	Blocks	Plates
Neutron spectrum	Fast	Thermal or Epithermal

CATEGORY	KRUSTY-T	TUPA^3
Cladding/structure	Stainless steel, superalloys	Superalloy N
Control materials	BeO, B4C	FLiBe (pure Li-7)
Mechanism	Rods	Rods
Heat transport	Heat Pipes	Heat Pipes
Reactor heat transfer fluids	Sodium	FLiNaK (pure Li-7)
Shield materials	Lithium hydride/DU/Steel	Lithium hydride/DU/Steel
Power conversion	TEG	Stirling engine
Heat rejection	Heat Pipes	Heat Pipes
Radiator fluids	Water	Undefined
Radiator materials	Aluminum	Aluminum

Figure 1: POF Over 25 Years of Operation



Source : The author.

Table 5: Total Power of Each Proposed Reactor

CASE	POWER (kW)
KRUSTY-Tv1 Skutterudite TEG	0.6
KRUSTY-Tv2 Perovskite TEG	0.8
TUPA^3 Stirling Engine	75
TUPA^3 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, outperforming the current NASA design, which behaves very similarly to KRUSTY-Tv2. Additionaly, KRUSTY-Tv1 is the proposed design that is closest to being feasibly currently, as all of the individual component technologies have already been tested successfully. On the other hand, the thorium designs should not be discarded altogether, as there is still room to develop their technologies and test their results in the coming years. These discoveries are aligned with the development direction of the Radiant Nuclear Kaleidos reactor, which also uses TRISO fuel and was found out after the publication of this work [12], and with reports on a new project from the department of energy, which also leans towards new thermoelectric designs [13].

4. CONCLUSIONS

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

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

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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