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A PWR for a Mars Human Base

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Summary

A preliminary feasibility study of a nuclear fission reactor for space applications is here presented with the following requirements: high reliability, R&D program of moderate cost, development in a reasonable period of time, 10 years without human intervention operability and controllability, terrestrial applicability, or at least common technology sharing, applicability for human settlements on a solar system planet. The driving idea is to extend the PWR technology, by an integral reactor: both Rankine steam cycle and Thermoelectric generator are taken into account to electricity production. The neutronic calculations are based on WIMS code benchmarked with MCNP code. Preliminary reliability assessment vote in favour of the Thermoelectric generator, anyway, both systems appear viable and of reasonable size, well fitting the nowadays space launchers capabilities. Finally, a set of R&D needs has been identified the new generation Light Water Reactors and a research plan interesting the new generation Light Water Reactors is proposed.

Introduction

Near future space exploration programs will require power systems able to provide hundreds of KWe[1,2]. Fission power systems seem to be well suited to provide safe, reliable, and economic power within this range. The goal of this research program, developed within an ESA research contract, is to carry out a preliminary feasibility study of a nuclear fission reactor for space applications. These refer to electrical power production to feed either the electric engines on board of a spacecraft mainly (Nuclear Electric Propulsion, NEP) or stationary settlements, manned or unmanned, on planets or satellites of the Solar system.

Even if this study concerns both applications, the solutions envisaged better apply to the surface one.

Main requirements for the design of the reactor are: the extreme reliability, the moderate cost R&D program, the implementation within a reasonable period of time and the long time operability without intervention.

The first three items mean that the chosen reactor must be already extensively and positively used or tested in terrestrial applications, and then too innovative proposals are a priori excluded, at least in the medium time. The last item too is in favour of simple and reliable solutions.

Moreover it seems reasonable and probable to apply some technologies here suggested for space to terrestrial nuclear and non nuclear systems.

In conclusion the reactor here proposed should be based on the well proven technology of present terrestrial reactors and in principle suitable for propulsion and stationary applications.

Specific requirements, besides the general ones presented above, are:

- electrical power around 100 KW;

- operating life time of around 4000 days, without intervention and fuel supply;
- minimal overall mass and volume;
- high enriched uranium fuel;
- core power density substantially lower than nowadays reactors;
- no leakage of fluids or presence of a recovery system.

Usual safety requirements for terrestrial reactors are to be adopted, able also to assure :no irradiated fuel at launch; core subcriticality in case of launch abort (flooding); radiation protection without impairing mass requirements; easy decommissioning in space.

The reactor considered in this study is the PWR, the HTGR being under study.

As known the Pressurized Water Reactors, PWR, is the most common reactor type for terrestrial power stations, but widely used also for submarines propulsion[3], for which the specifications are not too far from those of space reactor .

In the following a first preliminary classic PWR has been envisaged turning out to be unsatisfying the reliability requirements: an innovative thermeoelectric cogenerative reactor has been designed, that, even if suitable only for stationary applications seems to be an extremely appealing solution.

The PWR Design

The most significant modifications to be brought drawn to a terrestrial PWR to make it fit to space applications are listed below.

Fuel composition adopted is conventional powder of 93 % enriched uranium oxide sintered in very small pellets. Pellet diameter is 1.8 mm, four times lower than the smallest current pellet. The high enrichment imposing a small diameter in order to avoid unacceptable flux depressions inside the pellet. Fabrication process has to be defined. Cladding material is stainless steel, but this choice is a conservative solution. Cladding thickness is 0.2 mm. Fuel rod size has 2.2 mm outer diameter, being the length a design parameter. Fuel bundle is composed by 19 rods assembled in hexagonal geometry and inserted in a hexagonal stainless steel 0.3 mm thick shroud. Fuel burnup has an average value of 60 MWd/kg. Temperatures and pressures: the maximum operating pressure assumed is identical to PWRs, i.e. 15.5 MPa. Maximum temperature has been chosen in order to improve the efficiency and to experiment the saturation temperature at the core exit, in order to use a self-pressurizer. The latter one asking for a gravitational environment. The maximum temperature is set equal to 345 °C, about 15 °C higher than that of PWRs, while minimum temperature at the inlet is assumed equal to 335 °C, 45 °C higher than PWRs. Cold well temperature definition imply a preliminary optimization in order to minimize the overall mass as lower temperature means higher efficiencies, but higher cold well size. Electrical generator has been chosen among two alternate designs, Thermoelectric generator and Rankine steam cycle. Minimum fuel quantity: is known as burnup, operational time and thermal power are given. Core geometry and reflector: the core is assumed to be a cylinder with the diameter equal to the height. Rounded by a 12 cm thick reflector. Primary pumps: spool pumps[4], fully inserted in the primary circuit without any seal, have been considered, being their technology under development.

The neutronic design has been done by the deterministic code Winfrith Improved Multi group Scheme, WIMS. WIMS gives the reactivity in an infinite mean: to obtain the reactivity of a finite reactor, the values of axial and radial buckling, which is a crucial parameter in this small size reactor, are required. Because of the strong dependence of the effective multiplication from the buckling values, WIMS[5] results were compared with a Monte Carlo program, MCNP-4C[6], known as an exact program. The comparison was made in four specific points and namely: infinite lattice and actual reflected reactor at Beginning of Life, cold and hot conditions, different moderation ratio. Monte Carlo results show that WIMS should converge at the End of Life to a reactivity of 1.00, with a reasonable margin.

As the electric power depends on the efficiency of the conversion circuit a classical Rankine steam cycle and a Thermoelectric device are compared. The net efficiency of the Rankine steam cycle in Martian conditions turns out to be 12.5% asking for a 800 KWth and only 61 Kg UO2 minimum fuel mass.

To bring the moderation ratio, in this case 5, to a “safer” 6.5, the burnup has been increased to 80 MWd/kg and the UO2 mass results to be 47 kg.

The integral layout of Rankine reactor places within its vessel almost all the components of the primary system: the reactor core, the barrel, the steam generator, the pressurizer, the circulating pump, the safety valve, the reactivity control mechanism and the instrumentation, in order to guarantee minimum size and mass, together with escaping radiation and fast neutrons fluence reduction on the vessel.

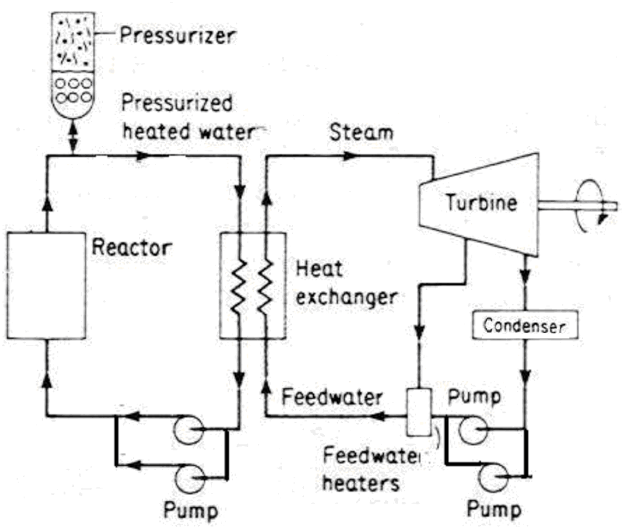

Figure 1 – Conceptual Layout for the Rankine-Cycle-based reactor.

The elements completely innovative of the Rankine reactor are the steam generator and the pressurizer

The steam generator design for the Rankine steam cycle here proposed is a new concept, the main difference being that all the sensible components inside the pressure vessel are compressed instead of being stretched, because the higher primary pressure is acting on the outer surfaces. Taking into account the limited power to be transferred in this case, it has been decided to adopt a single tube in order to eliminate any instability phenomena due to parallel channels. This would imply to choose a reasonable high value of the diameter and the length of the tube. The system has been simulated and sized thanks to the thermalhydraulic code RELAP5. However the thermalhydraulic behaviour of helix was not well studied in past, then an experimental campaign is needed for its development, also to take into account the effect of lack or reduced gravity.

The pressurizer is in direct connection to the vessel (in the upper dome in our case) and bringing the outlet temperature to the saturation value, as here done. The volumes are only a fraction of the upper sphere volume. Besides this free volume we have to foresee the possibility to contain the water expansion between cold and hot conditions Obviously the above pressurizer, integrated inside the vessel, is possible only in presence of a given value of the gravity to separate steam and water. This is the case for surface reactor, but not for propulsion one.

The control of the reactor should have been done using several control rods[7]. As the use of these many rods would have implied a very complex, heavy and voluminous system, a new control strategy have been developed. This proposal is based on the fact that the core is very small and its portions can be probably moved apart rather easily. The core is divided in six moving slices, operated by a single mechanism. By moving apart the slices in outside direction up to a maximum equal to the thickness of the reflector, the reactivity decreases slowly to a minimum equal to that required for the overall control. WIMS and Monte Carlo calculations show that the reactivity first rises, because the core is under moderated, then reaches a maximum and afterwards goes down rapidly: at 12 cm of distance the reactor is no longer critical.

	Mass		**Mass**
UO2	47	**Cold Well**	1840
Cladding + Shroud	32	**Turbine**	200
Water	393	**Steam Generator**	60
Barrel	140	**Contingencies**	200
Vessel	506	**Total 2**	2300
Total 1	1117		

Table 1 – Mass budget of the Rankine reactor. * 5% has been considered as Subsystem mass margin, ** 10% as total mass margin

	Mass	**Mass***	**TOTAL mass****
Total 1	1117	1173	
Total 2	2300	2415	
Entire System	3417	3588	3947

Table 2. Mass budget of the Rankine reactor with margins.

For what concern the cold well for the Rankine reactor the thermal power to be dissipated in the condenser is 700 KW. Only radiation has been considered up to now. A preliminary optimisation study showed that the optimum condenser temperature, minimising the overall weight, is around 165 °C with a total surface of 770 m^2. The condenser geometry is made by a bundle of 269 titanium tubes of ID/OD = 10.4/11.4 mm connected in parallel. If necessary the condenser can be divided in several identical pieces to be assembled on the site.

The mass budget of this reactor is in tables 1 and 2.

The second conversion circuit under analysis, the thermoelectric one, led to the definition of another reactor.

A very low efficiency Thermoelectric device, 2.8%, operating as power conversion circuit has been considered, so that the UO2 mass is 177 kg and the thermal power is 3537 KWth.

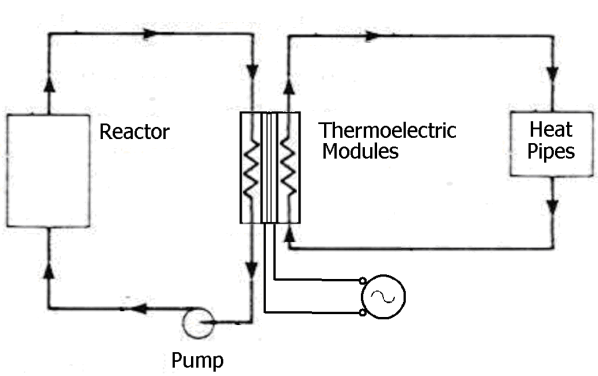

Figure 2 – Conceptual Layout for the Thermoelectric reactor

The primary circuit of Thermoelectric reactor is not completely integral: the reactor vessel contains the reactor core, the barrel, the pressurizer, the circulating pump, the safety valve, the reactivity control mechanism and the instrumentation. The Thermoelectric cells are bonded to hot pipes linked to the core.

Apart from the steam generator, the vessel of the Thermoelectric and the Rankine reactor are almost the same.

The Thermoelectric devices were considered because of their extreme reliability, high portability and small size. They are static elements, generally composed by semiconductors, that using the Seebeck effect, due to the material properties and the temperature gradient, produce electric power. In order to produce 100 KWe, 10000 Thermoelectric cells are needed.

The thermal power to be dissipated in the condenser is 3437 KW. Because of this huge amount of heat to be dissipated a classical radiator would have been too massy. In this preliminary study a heat pipe solution has been adopted as heat pipes have an effective thermal conductivity many thousands of times higher than copper. The chosen heat pipe consists of a sealed aluminium container, a working fluid compatible with the container, Freon and a porous structure in aluminium. An heat pipe can be designed to transport heat between the heat source and the heat sink with very small temperature drops so that a relatively large amounts of heat can be transported by small lightweight structures.

The dimensioning has been realized considering some hypothesis: the sun irradiation is present, each Thermoelectric module produces 10 W, the view factor of each heat pipe is 0.5.

	Mass		**Mass**
UO2	177	**Heat Pipes**	8542
Cladding+Shroud	92	**Thermoelectric**	33
Water	418	**Contingency**	200
Barrel	151	**Total ss 2**	8775
Vessel	565		
Total ss 1	1403		

Table 3 – Mass budget of the Thermoelectric reactor. * 5% has been considered as Subsystem mass margin, ** 10% as total mass margin.

	Mass	**Mass***	**TOTAL mass****
Total 1	1403	1473	
Total 2	8775	9214	
Entire System	10178	10687	11756

Table 4 – Mass budget of the Thermoelectric reactor with margins

The operating temperature is 729 K, resulting from the optimization previously realized for the entire system.

As each heat pipe is mounted on 1 Thermoelectric cell, 10000 heat pipes are considered, the diameter of each of them is 7,5 cm in order to fit with the dimension of the Thermoelectric cell. 10000 heat pipes 1,75 meters high are the cold well of the Thermoelectric reactor.

As clear from the mass budget of the Thermoelectric reactor (table 3 and 4) should be abandoned, if compared with the Rankine one.

Preliminary Reliability Assessment

As easily understandable, system reliability is one of the critical issue in the development of a PWR as a power source for a Mars Human Base.

Due to the mission time frame and to the limited possibilities to perform system maintenance (the reactor likely being the only power source of the base, apart from emergency batteries) a reliability goal of ten years without any fatal accident has been chosen (i.e. mission time of 10^4 hrs).

The first step of any reliability analysis is the identification of all failure modes of the system. This can be done with several standard technique such as the Failure Mode and Effect Analysis (FMEA), a qualitative method, of inductive nature, which aims at identifying those failure modes of the components which could disable system operation or become initiators of accidents with significant consequences.

The analysis starts from a decomposition of the system in functionally independent subsystems, for each of them the various operation modes and configurations must be identified. For each subsystem in each of its operating modes, the analysis must underline all possible failure modes and all consequences of each failure mode on the overall system. In the present case the only operation mode considered is the full power. The basic layout of the two reactors used for the identification of subsystems and components are depicted in Figures 1 and 2. The result of the FMEA is a Fault Tree (FT) for each reactor, the top event being the loss of power generation (see Figures 3 and 4).

Apart from failure modes related with single components (such as pump failures), external and internal events usually identified in standard Probabilistic Risk Assessments (PRA) as Initiating Events (IEs) have been considered as failure modes for the reactor. Typical External Events that cannot be avoided speaking of Mars are dust storms and meteorites. It must be noticed that only those IEs usually related with the nuclear island (such as Loss Of Coolant Accidents – LOCA – and Steam Generator Tube Rupture - SGTR) have been taken in account in this preliminary analysis.

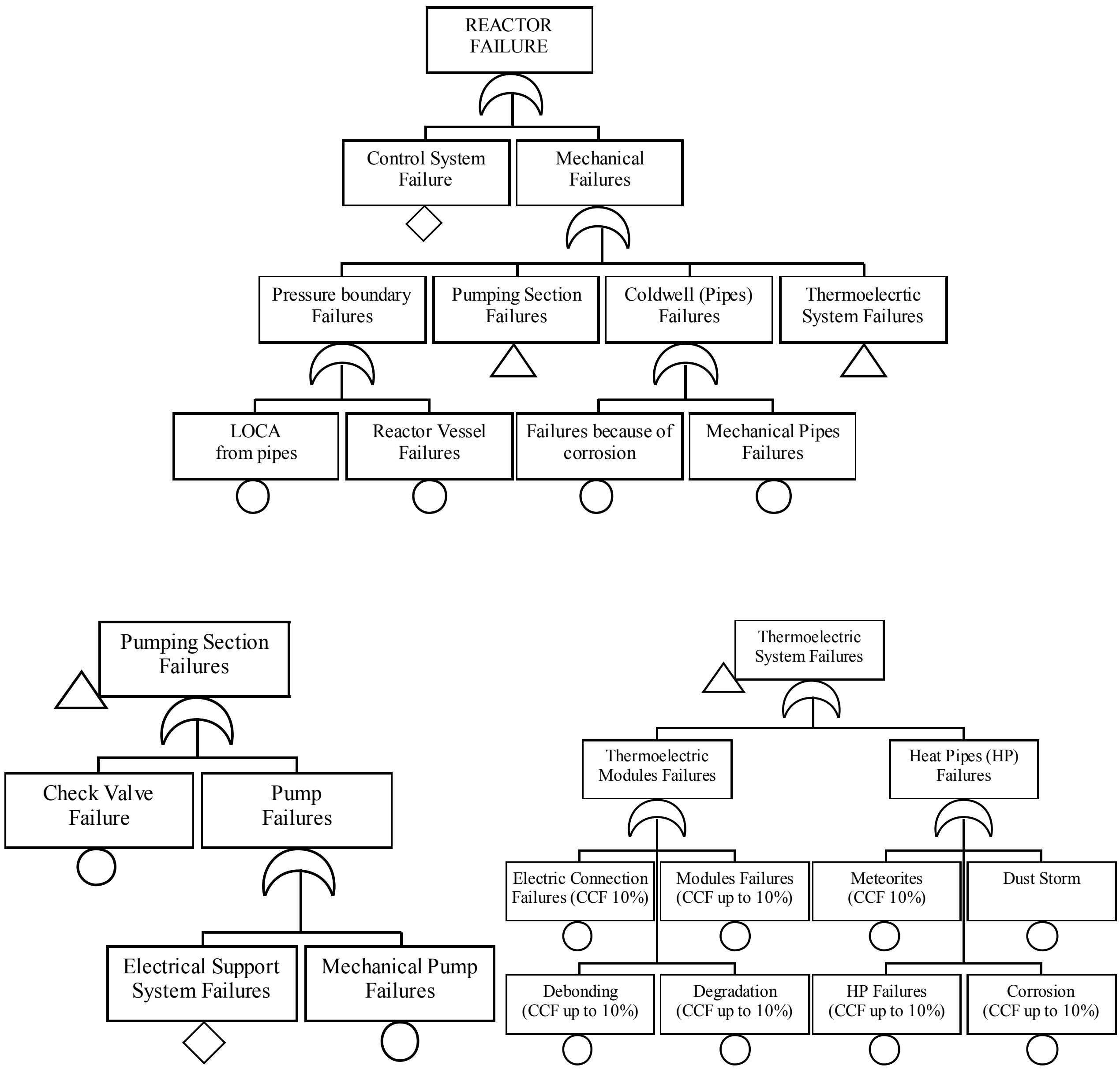

Figure 3 – Rankine reactor fault tree

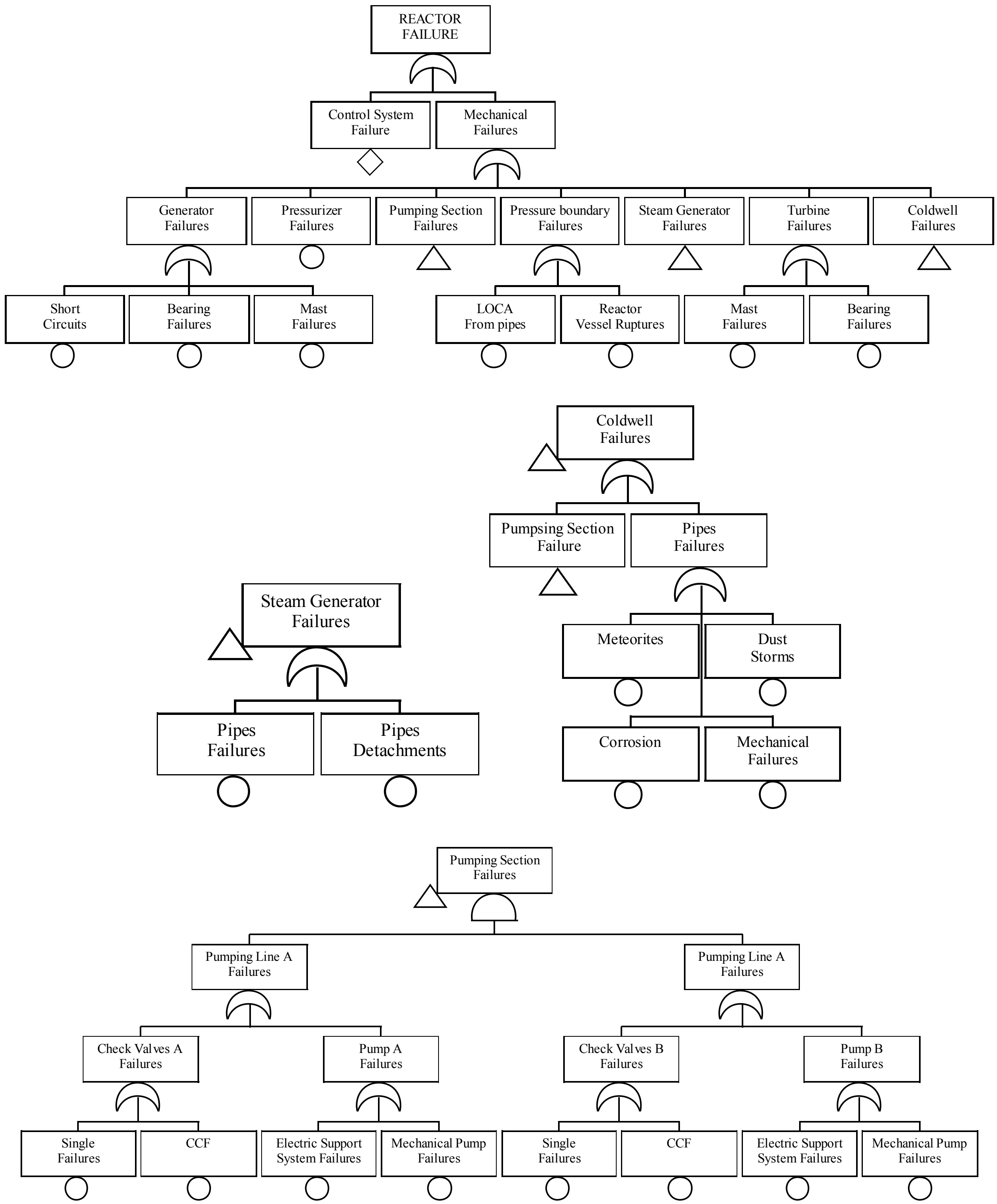

Figure 4 - Termoelectric reactor fault tree

The explanation for this choice is the fact that, in current NPP, an extremely high degree of reliability is requested (and performed) only for safety-related components and systems, usually comprised in the so called nuclear island (i.e. inside containment) whereas in a space mission it is likely that all systems are considered critical for the reliability and the safety of the reactor. Moreover, according to INPO, the nowadays reactor trip rate is about one per year (mainly due to IEs related with systems and components outside the nuclear island), this trip rate is obviously incompatible with the present goal. Therefore, internal IEs such as loss of condenser or loss of offsite power are not included in this analysis, waiting for more realistic information on trip rate originating from this kind of events in similar systems explicitly designed for space applications.
Once the failure modes have all been identified, quantification of the related failure rates is the following step of the reliability analysis. Due to the early stage of the design, with the reactor still in a conceptual phase and all systems and components not yet fully defined, this is a critical step; moreover, due to the uncommon environment of a Nuclear Power Plant (NPP) operating on Mars, the search for numerical values becomes a challenging task. IEs frequency that can be used as failure rate, as well as basic components failure rate (e.g. pumps failure rate) have been taken from official data used in U.S.[8,9] and Japanese[10] PRAs. Historical NASA data[11], well as other available data[12,13,14,15,16] were used to evaluated the probability of meteorites and dust storm fatally impacting the reactor. The search for data regarding turbine reliability was the most challenging due to the lack of available (i.e. not proprietary) data.

	100%	90%
Thermoelectric	0.4055	0.9061
Rankine	0.6143	0.6496

Table 5 – Reliability results for the Thermoelectric and the Rankine reactors, requiring 100% and 90% of the cold well working.

Starting from the FT developed, the minimal cut sets for each reactor can be easily identified. Due to the basic layout available at this stage of the design, almost all the cut set identified are of the first order (i.e. the failure of a single component is sufficient to lead to failure of the entire system).
A simple direct MonteCarlo code has finally set up for the calculation of the reliability of the system, leading to the results summarized in Table 5.
Apart from numerical values, not enough meaningful because of the very preliminary stage of the design and the high value of uncertainties in the numerical sources, the comparison between the two concepts is the most interesting result. As clearly understandable from Table 5, the reduced number of components in the Thermoelectrical concept (with the turbine among them) allows an higher level of reliability. From a preliminary sensitivity analysis, the turbine results as one of the most impacting component in the overall reliability of the system, therefore, also considering a certain degree of lowering of the failure rate due to the fact that components for space application are usually more reliable than those from the industrial world, the absence of this component in the Thermoelectrical design seems to assure a significant benefit for this kind of concept.

The Cogenerative Thermoelectric Reactor

A new concept reactor could be developed for the Martian base, still using the thermoelectric device, because of extreme reliability, as shown in the reliability analysis, but decreasing its mass.

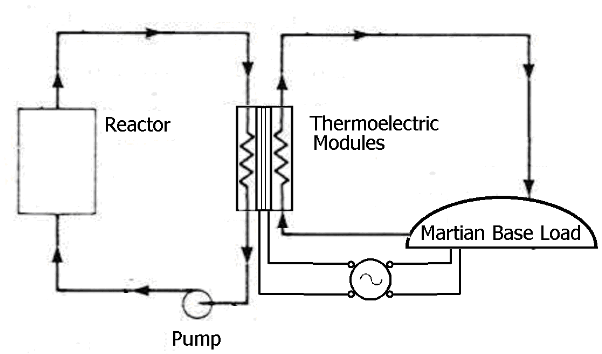

Figure 5 – Conceptual Layout for the Cogenerative Thermoelectric reactor

Subsystem 1	Mass	Subsystem 2	Mass
UO2	47	Thermoelectric	33
Cladding+Shroud	32	Contingency	200
Water	393	Total ss 2	233
Barrel	140		
Vessel	506		
Total ss 1	1117		

Table 6 – Mass budget of the Cogenerative Thermoelectric reactor. * 5% has been considered as Subsystem mass margin, ** 10% as total mass margin.

	Mass	Mass*	TOTAL mass**
Total 1	1117	1173	
Total 2	233	245	
Entire System	1350	1418	1559

Table 7 - Mass budget of the Cogenerative Thermoelectric reactor with margins

The enormous mass of the Thermoelectric reactor, as previously shown, is due to its cold well. On Mars, even at the equator, the temperature conditions are prohibitive for human presence. Most of the electric power furnished by a 100 KWe reactor is used to heat the hab module. The idea is to furnish not only electrical power to the Martian base, but also heat using the Base as 'cold well', reducing the mass of the reactor and the power need of the base.

This new reactor could be a 800 KWth one, with Thermoelectric cells. The temperature on the cold side of the cells in this case is then imposed by the temperature needed by the base. The design of this new reactor has been done considering the water temperature of the reactor-base circuit of 100 °C.

The core is then exactly the one of the Rankine reactor previously described in detail: 47 kg UO_2, burn-up:80 MWd/kg and moderation ratio: 6.5. This vessel should be then linked to the secondary circuit through the Thermoelectric cells (see figure 5).

This type of reactor, the mass budget of which is in tables 6 and 7, demands a base close to its location. This could be possible only if the reactor itself is placed under ground, as already foreseen by other studies[2], linked to the human base only trough the heating tubes and cables.

Conclusion

At the end of this very preliminary feasibility and reliability study about the utilisation of PWR for space applications it can be concluded that no insoluble issues have been evidenced, which would prevent of going on along this route in order to develop a more detailed design. At that point only it will be possible to draw a more justified conclusion. Of the three reactors here presented, the Thermoelectric solution for a 100 KWe PWR reactor is not viable. The two other solutions, entitled to energise a Martian base, are both possible and deserve to be studied in detail: the 800 KWth Rankine reactor, a classical PWR, and the 800 KWth Thermoelectric, a cogenerative reactor that would need a digger-robot on Mars. Even if at a first glance less realistic, this second solution is very interesting because of its extreme reliability.

In the short range, future design activities should address the detailing of many elements here presented and also of some new ones. In fact the conservative assumptions that have been done affect the reactor size, dramatically influencing the overall mass. A better definition of radiation shielding, vessel fluence, vessel material, ancillary circuits for start up, as well as safety criteria, overall layout, containment, leakage, control coolant purification and radiolysis will allow a better definition of entire systems and a preliminary R & D program.

In any case both these reactors seem feasible and their realization would permit a human mission to Mars, allowing mankind to realise the most ancient of its dreams: to reach another world and to live on it in a safe and durable way**.**

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