

Updated Technical Note on 30 kWe Fission Sources for Space Applications

Prepared by C Ferrari, C Bruno



Agreed by C Ferrari, C Bruno



Approved by C Ferrari, C Bruno



Authorized by C. Koppel



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- “Applications” moved in Appendix A
- Details of “Chernobyl Accident” moved in Appendix B
- Point 3.3 Impact of nuclear reactors technology on the radiation risk/ Effects of Ionizing Radiation/ *Terrestrial Radiation* (Added “Calculation of the radioactive decay products time dependence for ²³⁸U, ²³⁵U, ²³²Th series”)

AUTHOR (S) C. Ferrari, C. Bruno		ORGANIZATION (S) ISIS_R&D	ADDRESS <u>Viale Guglielmo Marconi 893,</u> <u>Rome 00146.</u>	
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ABBREVIATIONS AND ACRONYMS

AC.....	Alternating Current
AU.....	Astronomical Unit
BOL.....	Beginning-of-Life
DC.....	Direct Current
EOL.....	End-of-Life
FF.....	Fission Fragments
GCR.....	Gas-Cooled Reactor
GIE.....	Gridded Ion Engine
H.....	PHA's absolute magnitude
HPR.....	Heat Pipe Reactor
HRS.....	Heat Rejection System
ISS.....	International Space Station
LEO.....	Low Earth Orbit
LM.....	Liquid Metal
LOCA.....	Loss-of-Coolant Accident
MHD.....	Magneto Hydro Dynamic
MITEE.....	Miniature Reactor Engine
MOID.....	Minimum Orbit Intersection Distance
MPD.....	Magneto Plasma Dynamic
NEA.....	Near Earth Asteroid
NEC.....	Near Earth Comet
NEO.....	Near Earth Object
NEP.....	Nuclear Electric Propulsion
NR.....	Nuclear Reactor
Nu.....	Nusselt number
P.....	Orbital period
PBR.....	Pebble-Bed Reactor
PCS.....	Power Conversion System
PHA.....	Potentially Hazardous Asteroid
q.....	Perihelion distance
Q.....	Aphelion distance
RBMK.....	Reaktor Bolšoj Moščnosti Kanalnyj (High Power Channel-type Reactor)
RHU.....	Radioisotope Heater Unit
SAR.....	Synthetic Aperture Radar

1 EXECUTIVE SUMMARY

Purpose of this Technical Note is to study a 30 kWe fission power source for space applications requiring fission nuclear power generation. The assessment takes account of past projects and studies and expertise and it also takes account of anticipated future applications and critical technology issues. Important to note is as of today have been designed and operated about 35 space nuclear reactors, all liquid metal cooled. Space assets can provide valuable contributions for very important and demanding issue areas such as, but not limited to, Environments, Energy and Resources. In the Environment sector, space has a crucial role to play in the implementation of sustainable policies. It can contribute to accurate global data measurements and collection, as well as to monitoring greenhouse gases or the melting of the polar ice-cap, thus giving valuable information to fight climate change and to respond to natural disasters, while, as for Energy, space can provide tools for strategic decision-making policies: it can support the planning and monitoring of electrical power grids, pipelines and of the operational needs, including weather forecast, or seismic activity. Remote sensing activities are also useful to assess and monitor exploration surveys. Indeed, referring to Resources, humanitarian response to food problems or the development of water master plans can be benefited from space-based assets. Earth observation systems, as well as space-based communication and information technologies can also enhance the effectiveness of humanitarian responses to food crisis. The growing scarcity of natural resources – mainly water and food – highlights the need for transnational solutions in the management of resources. This area is closely related to environmental concerns, as global warming is threatening food and water sustainability, strongly associated to the need for energy. All these areas are thus tightly linked to the quality of life, that necessitates long lasting and economical energy. In space and for space applications, long lasting and large power can be provided only by nuclear energy. In fact, besides the decay moving farther from the Sun, in LEO solar power is limited to about 1.3 kW/m^2 at best, requiring large and cumbersome structures to gather it.

If the recent statements by the current NASA Administrators can be assumed valid, a human Mars mission should take place around 2030. Ten years of development time for a small reactor translate to a much longer times for reactors and propulsion systems (Nuclear Electric Propulsion, likely, or hybrid nuclear electro-thermal) that must produce power in the 100s of MW to enable fast trips and thus reasonable radiation doses to crew [Durante and Bruno, 2010]. Hard as it is to estimate such time, it cannot be less than 15 years, and that means that development of such systems should start in a few years. The likelihood of this happening seems at this point very low indeed, and is a matter of great concern to space agencies planners.

Nuclear power systems for space will require development times of the order of at least one decade if technologies off the shelf are used. The R&D needed to develop a new fuel or a specific nuclear material will increase significantly that development time. Only good planning of such applications will allow the timely development phases and justify technological road map for Nuclear Power Systems.

The present Technical Note to study a 30 kWe fission power source for space applications will initially focus on the type of reactors that are more likely to lend

themselves to space power generation and propulsion. Because space nuclear reactors are not a current technology, comparing what is needed with what already exists in *commercial* applications is useful. Furthermore, the impact of nuclear reactors technology on the radiation risk posed to crewed interplanetary missions will be illustrated. The nuclear reactor applications in space are largely presented, from applications requiring or benefiting from the use of NRs power generation (ground penetrating radar and high power lasers and surface infrastructures) to space mining (asteroids, moon). The potential usage of the Lagrangian points and their specific peculiarities are also presented.

Requirements for the development of 30 kWe fission power source are outlined in terms of environmental assumptions and constraints, fuel selection, reactor architecture and shielding and power conversion.

In concluding, compactness, flyweight and reliability over lifetimes of order many years pose special problems in space, in part solved by ground applications such as stationary power generation, but where the information is proprietary or classified. To proceed further, whatever information is available should be collected and carefully sifted for application to space systems.

Technologies associated to nuclear power need further investment and much development time. Currently, the ratio power/mass α (kg/KWe) for any commercial NR is high with respect to other chemical power generation systems, and the presence of radiation strongly impacts the trade-off between benefits and risks to environment and human beings in case of an accident. The acceptance by the public of nuclear technologies is, in fact, a very sensitive topic. Hence recourse to nuclear power in space is both an engineering and a socio-political challenge that must be faced with adequate and intelligent resources.

2 REFERENCES

- A. *Project " Disruptive technologies for space Power and Propulsion
" DiPoP - Grant agreement no: 284081 "*
- B. *The Fission Nuclear Power Generator Roadmap Draft
(Dip-Sep-PL-001- D30.1, dated 20th February 2012).*
- C. *Notes of the First DiPoP Advisory Board Meeting
Held at DLR Offices Washington DC Monday 6th February 2012*
- D. *Nuclear Electric Propulsion/Power Processing Unit Report
(Dip-SEP-RP001- D23.2, dated May 2012)*
- E. *Draft Technical Note on 200 kWe Fission Power Source for Space
Applications(DiP-Sep-TN-002 D32.1, dated 7 September 2012)*
- F. *Draft Technical Note 30 KWe Fission Nuclear Power Source for Space
Applications (DiP-Isi-TN-001 D31.1 Draft02_Issue 2, dated 7 September
2012)*

3 BACKGROUND AND SCOPE

The question of building nuclear reactors (NR) capable of operating in space can be preliminarily answered by looking at its mission.

In fact, this type of power generation lends itself to a spectrum of missions, from powering a SAR to a high power laser to melt planetary ice or TLC, to power an electric thruster. The only unifying aspect of this particular nuclear reactor project (and its limitations!) is its power, P , either 30 kWe, or 200 kWe.

Focus for a moment on the obvious application of such power to nuclear *electric* propulsion (NEP): since $P = \frac{1}{2} V_e T$, with $V_e = I_{sp} g_0$, and T thrust, an off the shelf ion thruster (Gridded Ion Engine, GIE) capable of $I_{sp} = 4500$ s (V_e about 45,000 m/s) would produce about 4/3 N *at best* at 30 kWe; about 1.12 N at 200 kWe, and less if one includes the GIE efficiency, currently about 60%.

This is a very small thrust for space missions, requiring extremely long mission times, that is, years or even a decade. Replacing GIE with a Hall thruster hardly changes this estimate: all electric thruster are thrust-limited by the constraint to avoid recombination between ions and electrons, implying pressure must be a small fraction of atmospheric, thus plasma current small, and so the Coulomb or Lorentz force applied to the thruster. Arcjets are less limited, but their specific impulse is lower, of order 1000 - 2000 s (at most). True MPD thrusters, where an externally applied magnetic B field guides and accelerates ions, in principle capable of much larger thrust, are much less developed and prone still to plasma instabilities, so their technology is less mature than that of GIE. Figure 3.1 shows typical electric propulsion systems performance in terms of required power and specific impulse.

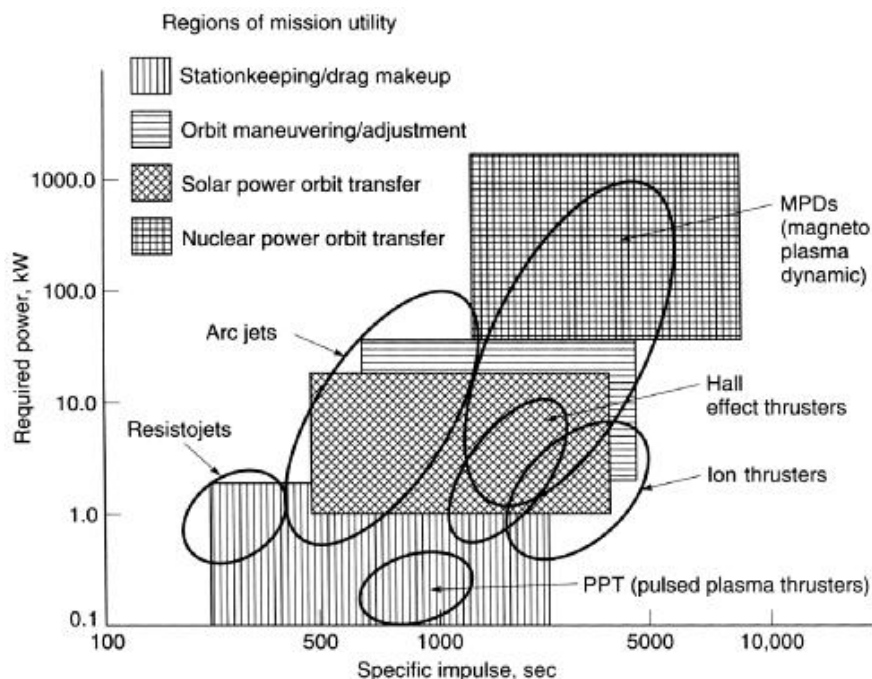


Figure 3.1 - Overview of different electrical propulsion systems in terms of power and specific impulse - Source: Sutton and Biblarz (2010)

This example shows that one of the key issues in space NR is the fact that, whatever their application, the life of the engine must be ensured for years on end, or even a decade for missions to the giant planets. The consequences spread down to all the equipment driven by the nuclear reactor, see below.

3.1 Nuclear Reactor Life

The nuclear reactor technology for commercial power generation and submarines is well developed, and although the requirements for submarines are very stringent, progress in materials and nuclear fuels in both areas has produced reactors with useful lives of order many years to 2-3 decades. Thus there is much to be learned from these two applications, but most critical information is not in the public domain, being either proprietary or classified. This is a serious problem in this project.

A nuclear reactor is the usual engineering compromise among nuclear fuel performance (fission neutron rate/unit mass or unit volume; fuel burnout %; fuel melting point), heat extraction technology (cooling strategy, coolant thermodynamics and heat transfer properties), shielding requirements and thus overall mass per unit volume. Space applications add other severe constraints to mass and volume (both due to the launcher performance, that is, P/L mass and fairing volume), and, for most missions, the demanding constraint that the nuclear reactor must operate unattended or with robotic maintenance for many years or decades. If the space mission is not man-rated, the shielding requirements may be reduced, but electronic equipment must be hardened nevertheless.

An exhaustive discussion of all the issues involved would take volumes. Here the focus is on the type of reactors that are more likely to lend themselves to space power generation and propulsion. Because space nuclear reactors are not a current technology, comparing what is needed with what already exists in commercial applications seems useful.

In commercial applications the burnout percentage of the low-enriched fuel (^{235}U or ^{238}Pu) is of order 5-6%. Above this fraction, poisoning due to fission fragments (FF) implanting themselves in fuel rods (fuel itself and cladding), e.g., in the microcrystals of structural elements, become excessive. The reactivity of fuel also decreases, with negative consequences on reactor control. In commercial applications this fact, and especially deterioration of structural properties, due to physico-chemical effects (hydrogen formation and embrittlement), forces regular reactor shutdown and rod replacement. In space reactors this would be problematic; thus reactor reactivity and control must be carefully studied. With pebble-bed reactors (PBR) technology this is a somewhat less complex process, but still requires reactor shutdown and cooling (in the nuclear sense). Note that cooling is not exponential, but follows a power law, so the longer the reactor has operated, the longer the cooling time (reactor downtime) will be.

Together with rod/pin or PBR pellet re-fueling, the hydraulics of commercial reactors are then checked and parts replaced. All this requires time and specialized expertise.

Residual radiation cool-down forces human intervention to be limited in the time spent in contact with 'hot' material.

Some recent developments in submarine (military) reactors indicate the life of the reactor may be longer than in commercial reactors. This is a positive development in this space context, but obtained with technology that often cannot be applied in space (e.g., using lead as a coolant, moderator and as working fluid for heat extraction and in the thermodynamic cycle).

3.1.1 Key issues in Nuclear Reactor technologies

Power released by a nuclear reactor depends on fuel fission rate, in turn depending on neutron flux and fission cross section; this last depends on neutron velocity. Typical fission neutrons have energies in the 1 to 10 MeV range, and depending on reactor type (fast or slow neutrons), this excessive energy must be reduced or thermalized to a fraction of eV. Note 1 eV energy corresponds to 11,300 K. This can be obtained by a moderator such as graphite or Be, or by the coolant itself, that may slow down not only fission fragments (FF), but also neutrons. Both processes produce heat that must be carried away by the coolant. In most ground commercial reactors the coolant is water; in space, the power density of water reactors is too small, and the mass and volume taken too large. Thus other coolants/extraction concepts must be used. Space reactors must be as light and compact as all other trade-offs can allow. Note that nuclear reactors are not power-limited in the conventional sense: they are *temperature-limited* instead. The key issue in nuclear reactor is how to extract the heat power available without the nuclear reactor melting or breaking by differential thermal dilatation, or working/coolant fluid vaporization or, worse, dissociation due to excessive temperature. To give an example, during the Loss-of-Coolant Accident (LOCA) that caused the Chernobyl reactor meltdown, the reactor power went from 200 MW (~1/3 of peak capacity) to 100 GW (estimated) in 0.4 s. The reactor core melted since (literally) no cooling was available to extract this power. The price of power is of course fuel consumption, since $E = Mc^2$. Note that in such conversion the % of fuel mass that may become energy is limited by the nuclear force potential of the nucleus, and for ^{235}U nuclei this is ~0.09%.

Maximum allowed temperature poses a limit to the bulk power density of reactors: for large reactors (100s of MW_{th} , for which data exist) this density is below 100 MW/m^3 (for water-cooled reactors driven by thermal neutrons fission). For *fast neutron* reactors, using He gas as coolant and graphite moderator, the energy density is about 280 MW/m^3 , and $500\text{-}550 \text{ MW/m}^3$ using liquid Na. The issue with fast neutron reactors is that they can breed fuel, use 10-13% enriched ^{235}U (vs. 2-4% with slow neutron technology) and thus are restricted in their fabrication and use, because of their potential for production of nuclear weapons of sort: the common weapons grade enrichment is $> 20\%$, but at a cost, enrichment from 10% to weapon grade is feasible. Besides, even low grade fuel can be made into a so-called 'dirty' bomb.

The mass limitation and nuclear reactor energy density mean that among the many conversion cycles only a few are of interest to space nuclear reactor. These are gas and liquid metal (LM, that is Na, K, the eutectic NaK alloy, and Li), with heat

extraction by means of two-phase heat pipes. Direct conversion from thermal to electric, via thermoelectric effect or thermoionics, is still very inefficient, although the so-called AMTEC technology, based on solid state electrolytes, has shown in small component tests, direct conversion efficiency of order 25%. Thus most of the tests and concepts to be tested still rely on thermodynamic cycles such as Brayton, Rankine (or Stirling, at the low end of the power spectrum; Stirling is in principle capable of higher efficiency).

Figure 3.2 shows results of a screening analysis comparing different power conversion systems for a 40 kWe class reactor, see Mason et al. (2008). Results for two main parameters are depicted: reactor thermal power and radiator area.

For this class of power, free-piston Stirling has lowest radiator area (A/A_{ref}) while organic Rankine and Stirling have similar reactor thermal power requirements (Q/Q_{ref}).

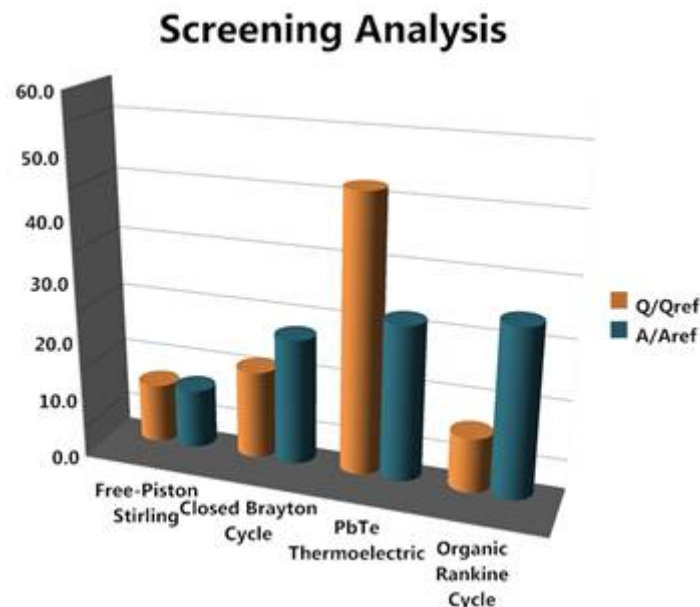


Figure 3.2 - Screening study of different power conversion systems for a 40 kWe nuclear reactor class, from Mason et al. (2008)

The question of efficiency is key to the space radiator. 30% efficiency means that 70% of the reactor heat output must be radiated away. Radiators are cumbersome and massive structures, sometime heavier than the nuclear reactor itself. A 30 kWe nuclear reactor means roughly that 70 kWth must be dumped to space (the characteristic black body space temperature is of order 20K). This fact limits also the 'low' cycle temperature: too high, the power extracted falls; too low, the waste heat cannot be radiated away. This is the most serious drawback, in fact, of all electric propulsion, and will not change until direct conversion with high efficiency will become available (so far progress has been exceedingly slow).

3.1.2 Conversion system and life

For the foreseeable time conversion will be based on thermodynamic cycles, with efficiency up to about 30% max. The components of the conversion system will be (typically), the heat exchanger, the turbomachinery (if a Brayton cycle is used) and the turbogenerator feeding electric power to the thruster.

Commercial power generation turbomachinery (gas turbines) belong to two main types: the first uses massive pieces of machinery ('heavy duty' machines), including compressor, one or more combustion chambers, often water-cooled, and the turbine proper. The second type is called aeroderivatives, based on aeroengine 'cores', that is, missing the low pressure compressor and turbine of the actual aero engine from where they were derived. They are much lighter, and in the recent past were used in the electric grid only for peak power duty. The first class was instead capable of baseline power, with mean time between maintenance of order 8,000 h or higher.

This distinction is changing now. Although the second class is still considered by many utilities for peak power role, the life of both types has been increased over the years, so much so that among utility companies the requirement is a minimum of 8000 h of operation without any maintenance, least of all overhaul. This means in practice 1 year of continuous operation. In space, missions may last several years, posing severe maintenance and reliability issues.

The turbogenerator (or dynamo: in space GIE need DC, not AC current) has a high efficiency and a life limited only by sufficient bearing lubrication. This is still considered a serious issue by many, but magnetic bearing technology is providing a solution, albeit not a cheap one. In fact, current space nuclear power systems using thermodynamic conversion are designed that rotate at 20,000+ rpm. Of course, with increasing rpm the turbomachinery becomes lighter and lighter, a major advantage for space power. Thus, conversion system life of order 3 years or more is feasible, with cycle efficiency close to 30%, account also made for the fact that (unlike ground-based gas turbines) the working fluid will be not reactive.

The heat-exchanger/radiator will have to be manufactured with quality assurance similar to that of the turbogenerators, since the lightness requirement is sometimes contrasting the need to avoid punctures or leaking due to insufficient material thickness. Space debris may become a problem for systems that must function in LEO.

3.2 Space Nuclear Reactor Technology

Ideally one nuclear power generator design could be used for all the applications thus only requiring the development of one set of technologies. This alone would be expensive with the requirement to qualify the system and its various components for the 10 year lifetime. In practice there does appear to be a need for both a lower and a higher power range. It is therefore important to try to identify as many common features as possible as a way to manage development cost and schedule.

Smaller systems appear to be better suited Stirling power conversion and larger systems to Brayton Cycle. Both however need high temperature operation, long 'maintenance free' lifetimes, shielding and control and safety arrangements.

From the description above, space nuclear reactor systems should be designed conservatively and at the same time, with the additional constraints of lightness and efficiency of the single cycle possible in space. To these writers' knowledge, the key issues become then the following:

3.2.1 Gas Cycles

To increase power density and compactness, the cycle 'high' temperature must be as high as feasible. Ground gas-cycle fast reactors (with power ranging in the many 100s of MW) work at less than 1000 K and pressure of order 50-100 atm. For space applications this involves stable (non-corrodible) refractory materials such as ceramics and their composites in the heat exchanger. These materials must survive not only temperature and differential dilatation, when power is turned down or off, but also the radiation damage due to high energy fission fragments (FF). C/C fibers may be expected to perform well in this environment, but there is no experience of their performance over years of use, because they have been introduced relatively later with respect to commercial reactors currently in operation. Gas cycles pose fewer fundamental questions in terms of operation, and (if only in principle) could function as the single working fluid in the cycle, but their heat transfer properties are less desirable (the Nusselt number, Nu , is lower) than that of LM. As in any prime mover, the working gas should have high C_p , with hydrogen being the best by far compared to He and CO_2 , but this requirement is a trade-off with other thermal and chemical properties and with safety constraints. Fast gas-cycle reactors (breeders) have the same restrictions of other breeder cycles due to their need for highly enriched fuel.

3.2.2 Liquid Metal Cycles

Liquid Metals (LM) have very high thermal and electric conductivity, and nuclear reactor design using LM are very compact and efficient. In the power range of commercial nuclear reactor and without any topping cycle, thermodynamic may be as high as 40%. High electric conductivity means that pumping may be MagnetoHydroDynamics (MHD) rather than mechanical, partly reducing seal problems (operation pressure with fast LM reactors is about 10 atm). LM problems are mostly due to reactivity of Li, Na and K, the candidate LM fluids, with Li the least and K the most reactive, and to the presence of oxygen in the LM. Oxygen, in fact, must be limited to < 10 ppm, and purifying LM is increasingly harder going from Na to NaK eutectic to Li. Their melting point decreases in inverse order, and is 180, 97 and 63 °C, respectively. Even though these appear moderate melting temperatures, they pose an obvious start-up problem, and NaK eutectic alloys (K content between 40 and 90%) are far more convenient from this viewpoint, because the melting temperature may be as low as -11 °C. The LM specific volume increases with temperature, but does not follow an equation of state derived from first principles, so

the relationships are semi-empirical and generally hard to get in the public domain. In general, Li is less aggressive than Na or K, but still can chemically erode piping, reactivity invariably increasing with temperature. This fact should be given much consideration in planning high thermodynamic efficiency cycles.

Leak control is a key issue in LM hydraulics, and for space is a critical issue. LM space reactors functioning for extended periods of time must have appropriate leak monitoring diagnostics, since any spill or leak may have destructive effects.

Note also that information on LM corrosion in nuclear reactor is scarce, probably because these cycles are not commercial: most commercial nuclear reactor use light water, pressurized or not, not metals. What is known from the past is that provided the LM temperature is limited to about 1000 K, stainless steels like AISI 316 work fine for long periods of time, in practice, for the life of the reactor. That may be even of order a few decades before decommissioning. The more interesting information regarding nuclear reactor for submarines is normally classified, and their technology may not applicable, since Pb may be now the LM of choice in the latest generation of this class of ships. Portable NR using Pb as coolant are being currently proposed for civilian applications (e.g., SSTAR).

3.3 Impact of nuclear reactors technology on the radiation risk

Radioactivity is the process undergone by unstable nuclei (radionuclides), as well as nuclei in excited states, causing spontaneous changes, or transformations, in composition and/or internal energy of the nucleus. This means that radioactivity may change a chemical element into another, releasing or absorbing energy in the process. Radiation from terrestrial or space reactors is the same, and adequate reactor shielding must protect crew eventually present on a spacecraft. Because of mass limitations, dose to astronauts during long stays in orbit or during interplanetary missions may be significantly higher than on the ground.

What follow is a primer on radiation from nuclear reactors, specifying type and consequences on humans of the kinetic impact of particles and electromagnetic waves generated by reactors. Cosmic/galactic and solar radiation is of course excluded from this discussion.

The most common nuclear transformations ('decays') producing radiation

Alpha Decay - In alpha decay the nucleus of an element with mass number A_1 and atomic number Z_1 emits an alpha particle. Alpha particles are made of two protons and two neutrons, that is, a Helium nucleus. The original nucleus is replaced by a new nucleus whose mass number A_2 is equal to A_1-4 and atomic number Z_2 is Z_1-2 , and an alpha particle.

For instance, ^{222}Rn ($A_{\text{Rn}}=222$, $Z_{\text{Rn}}=86$) decays into ^{218}Po , meaning that the nucleus of ^{222}Rn emits an alpha particle ($A_{\alpha}=4$, $Z_{\alpha}=2$), leaving as remainder a nucleus whose mass number is 218 ($222-4$) and atomic number $(86-2) = 84$, that is, ^{218}Po .

The mass (energy) of the parent nucleus must exceed the sum of the masses (energies) of the daughter nucleus and alpha particle emitted. The condition for α -decay to occur can be expressed as follows:

$$M(A, Z) > M(A-4, Z-2) + M(\text{He}^4)$$

Beta Decay - Beta decay is the spontaneous transformation of an unstable nucleus into a new nucleus with charge differing by $\Delta Z = \pm 1$, because of the emission of an electron (β^- decay) or a positron (β^+ decay) or the capture of an electron (e -capture)

In the first case (β^- decay) one of the neutrons of the nucleus emits an electron and becomes a proton. The mass number A does not change, while the new nucleus has an atomic number higher by 1.

Tritium (^3H , often symbolized by a T), $A_T = 3$ $Z_T = 1$, β^- decays into ^3He , $A_{\text{He}} = 3$ $Z_{\text{He}} = 2$, meaning that one of the two neutrons of the tritium nucleus emits an electron and becomes a proton; the mass number does not change, i.e., $A_T = A_{\text{He}}$, while the positive charge of the new nucleus increases by 1, $Z_{\text{He}} = Z_T + 1$.

The energy condition is that the mass (energy) of the parent nucleus is higher than the sum of the masses (energies) of the daughter nucleus and the electron, and is expressed by:

$$M(A, Z) > M(A, Z+1) + m_e$$

In the β^+ decay the unstable nucleus emits a positron (i.e., a positive electron). The β^+ decay can be treated as the transformation of a proton into a neutron, because also in this case the parent nucleus and the daughter nucleus have the same mass number A , while the atomic number of the daughter Z is lower by 1. The proton mass is lower than the neutron mass (energy). The transformation of the proton into a neutron is possible since the proton is bonded to a nucleus and the excess energy to become a neutron is supplied by the nucleus itself. The energy condition can be expressed in analogy with the β^- case

$$M(A, Z) > M(A, Z-1) + m_{e^+}$$

^{11}C , $A_C = 11$ $Z_C = 6$, decays β^+ into ^{11}B , $A_B = 11$ $Z_B = 5$, and the missing charge of Boron-11 is that of the positron emitted.

The third type of beta decay is the electron capture: it consists in the capture of an electron by a nucleus from its own electron shell. For heavy nuclei with the K-shell close to the nucleus, this phenomenon (also defined K-capture) is quite common; captures from L shell (L-capture), M shell (M-capture), etc. have also been observed. After the capture, the nucleus has the same mass number A , but its atomic number Z decreases by 1: the electron captured and one of the protons of the nucleus become a neutron in the daughter nucleus.

For instance, ^7Be , $A_{\text{Be}} = 7$ $Z_{\text{Be}} = 4$, after capturing an electron from its K shell, becomes ^7Li , $A_{\text{Li}} = 7$ $Z_{\text{Li}} = 3$; the mass number does not change: $A_{\text{Be}} = A_{\text{Li}} = 7$, while the atomic number Z of the lithium is lower by 1.

The mass (energy) condition is that the sum of the masses (energies) of the captured electron and the parent nucleus is higher than the mass (energy) of the daughter nucleus.

$$M(A, Z) < M(A, Z+1) + m_e$$

Because of the vacancy created in the electron shell, there is the transition of one of the shell electrons to that vacancy, accompanied by the photon emission, in the X-ray band.

Gamma Rays - Unstable nuclei going from an excited energy state down to a less energetic, eventually stable, state can emit energy quanta in the γ rays wavelength ($10^{-8} \geq \lambda \geq 2 \cdot 10^{-11}$ cm). There can be single transitions, where the nucleus goes directly from an excited state to the ground, or stable, state following the emission of a single γ quantum, or there can be multiple transitions, i.e., a cascade of transitions bringing the nucleus to the ground state and involving multiple emissions of γ quanta. The energy of the γ quantum emitted is determined by the difference in energy of the two energy levels between which the transition has occurred.

There are different mechanisms responsible for exciting nuclei and leading to gamma radiation. In fact, quite commonly alpha and beta decays can leave the nucleus in an excited state. An alpha decay is usually followed by the emission of low energy γ -quanta (< 0.5 MeV), while after a beta decay higher γ -quanta are emitted (energy up to 2-2.5 MeV).

Radiation and Dose Quantities

Absorbed Dose D (Gy) - When radiation passes through matter it releases energy. The **absorbed dose** is the energy deposited by radiation inside matter per mass unit. Its SI unit is the **Gray** (Gy), equivalent to 1 Joule deposited per kilogram of absorbing target material (1 J/kg). The older unit is the RAD (Radiation Absorbed Dose), defined as the deposition of 100 erg per **gram** (see ICRP, 1991).

Equivalent Dose H (Sv) - Biological effects caused by radiation are not only dependent upon the dose absorbed (in Gy) but also, and above all, by *the kind* of radiation. ‘**Sparsely**’ **ionizing radiations** such as gamma, x-ray or beta rays are less effective in damaging than ‘**densely**’ ionizing radiation such as alpha particles or fission fragments, both possessing a much larger mass. To account for this difference, a weighing factor dependent on the kind of radiation and energy has been introduced. The weighing factor goes from 1 (for photons or electrons) up to 20 (for alpha particles), and is dimensionless, see Table 3.1.

Radiation and Energy	Weighting Factor, W_T
Photons, all energy	1
Electrons, all energy	1
Neutrons, < 10 keV	5
10 – 100 keV	10
100 keV – 2 MeV	20
2 MeV – 20 MeV	10
> 20 MeV	5
Protons, all energy	1
Protons, (not recoil) > 2 MeV	5
Alpha Particles, all energy	20
Fission Fragments, all energy	20
Heavy nuclei, all energy	20

Table 3.1 - Weighting factors (W_T) for different types of radiation, (Mukhin, 1987)

Since W_T is dimensionless, the equivalent dose H has the same dimensions as the absorbed dose D , i.e., Joule per kilogram. Its SI unit is the **Sievert** (Sv). The older unit is the **REM** (or rem) (Roentgen Equivalent Man), whereby 1 Sv = 100 rem.

Effects of Ionizing Radiation

Ionizing radiation interacts with matter changing the state of atoms and molecules. In cells there are two types of consequences after radiation interaction: the cell may die or may be modified. These two different outcomes have different implications for the whole body: in fact, there can be deterministic and stochastic effects.

Deterministic Effects - Radiation may kill cells of a tissue or organ. If the numbers of cells killed is low, the tissue keeps functioning without serious consequences. If the number of cells killed is sufficiently large, the tissue is harmed and may lose its function; eventually, the tissue or even the organ itself may die. Table 3.2 shows thresholds for deterministic effects onset.

Stochastic Effect - If a cell is not directly killed by radiation but somehow modified, the outcome will be different from those included among deterministic effects. In-vitro cellular research shows that damage from radiation to deoxyribonucleic acid (DNA) causes the most of detrimental effects. There are two mechanisms by which radiation may damage DNA: direct or indirect interaction.

In the first case ionizing radiation directly damages a gene, in the second radiation produces active chemical radicals near the DNA. The radicals may diffuse and

interact with DNA, inducing chemical changes. Very efficient mechanisms exist (enzyme actions) that repair DNA, whatever the cause of harm. For instance, if only one of the two symmetric strands forming the DNA is damaged, information on the other strand makes the repair process highly probable and successful, though *not always error free*. It is this repair process that is activated and energized by radiation that is the basis for a field of radiation effects called *radiation hormesis*, to be discussed later. *Radiation hormesis, is actually beneficial to organisms*. If both strands are damaged at the same location, information is lost forever: the repair process is more difficult and genetic changes are likely. Such changes are defined genetic mutations. The very nature of this damage/repair process causes effects that are random and statistical, therefore called stochastic. Stochastic effects can be somatic (i.e., cancer induction), that is, they occur in the individual exposed, or hereditary, when the cells damaged are those whose function is to transmit genetic information to offspring. There is increasing evidence that below a certain dose, the repair process is highly effective, reversing even effects of chemical oxides, peroxides and super oxides within cells. This process is in direct opposition to the linear no threshold (=LNT) concept. However, since stochastic effects may have no dose lower bound, there is no threshold in this case (see UNSCEAR, 1993).

Deterministic Effects	Threshold, Gy
Male temporary sterility	
acute exposure	0.15
chronic exposure (per year)	0.4
Male permanent sterility	
acute exposure	3.5-6
chronic exposure (per year)	2
Female permanent sterility	
single exposure	2.5-6
chronic exposure (per year)	0.2
Depression of blood formation	
acute bone marrow exposure	0.5
long-term exposure (per year)	0.4
Lens opacities (sparsely ionizing radiation)	2-10
Lens opacities (densely ionizing radiation)	1-2
Lens opacities (chronic exposure to sparsely ioniz. rad. per year)	0.15
Dry skin desquamation (3 weeks after exposure)	3-5
Moist desquamation (blistering after 1 month)	20
Tissue necrosis	50

Table 3.2 - Threshold for deterministic effects

Radiation Hormesis Considerations - The Hiroshima/Nagasaki data clearly dispute the Linear No-Threshold (LNT) hypothesis as shown in Figure 3.3.

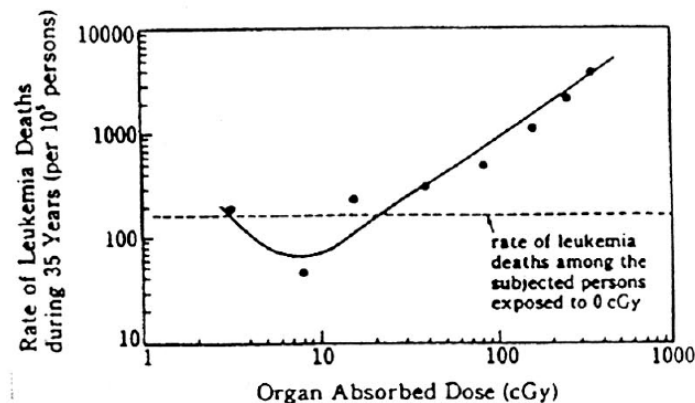


Figure 3.3 - Rate of Leukemia deaths for Hiroshima/Nagasaki population

The above data indicate that the actual leukaemia deaths do not follow the LNT hypothesis, whose intersection at zero dose is shown in the overlay line. The problem with the LNT hypothesis is that it ignores realities of dose in other circumstances. This, when coupled with a no *de minimis* dose can become very problematic. For example, it is well known that 100 aspirin in a single dose can kill. If, in the aspirin case, we would follow the logic of the LNT concept, it means that a person taking one aspirin a week for 100 weeks will die, or out of 100 persons taking a single aspirin, 1 will die (see Frunze, 1999). There exist more data beyond Hiroshima and Nagasaki, that is, data for U.S Naval Nuclear Shipyard workers as shown in Figure 3.4.

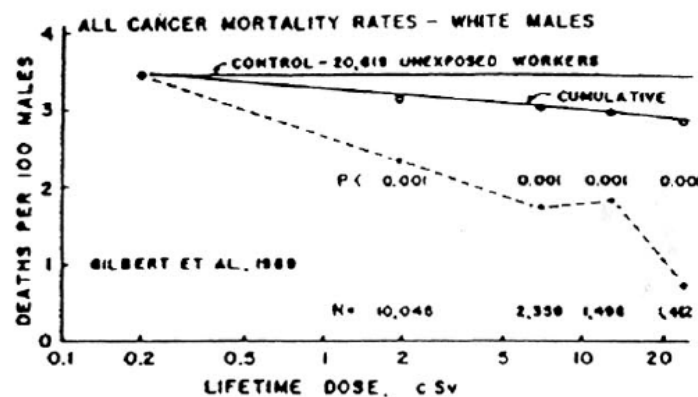


Figure 3.4 - U.S Nuclear Naval Shipyard Workers (Matanowski, 1991)

From Figure 3.4 we note that statistics from the control group of 20419 unexposed workers, and the nuclear naval shipyard workers indicated a *reduced mortality* rate at a given age than did unexposed workers. The same effect is observed to be true for U.S. nuclear weapons workers. It should be a priority for the IAA to establish the importance to cost and risk reduction in adopting the radiation hormesis approach to radiation protection.

Sources of Radiation Exposure on Earth

Natural Radiation Exposure - Natural radiation, also defined **background radiation**, has always existed in nature. Life on Earth has developed and keeps proliferating in a

naturally radioactive environment. There are different sources of background radiation, responsible for either internal or external exposure.

Table 3.3 shows the doses from natural sources.

The **worldwide annual effective dose is 2.4 mSv**. (It varies from very low to 6, depending on location.) and, considering a 7 billion world population, the collective dose is 17×10^6 man Sv.

Cosmic Rays - Cosmic rays are a source of external exposure. They can be divided into primary and secondary radiation. Primary radiation can be further divided, depending on its origin, into galactic and solar, the second being less significant on the Earth ground. Outside the Earth atmosphere the main component of cosmic radiation are positively charged particles, mostly protons, of energy between 10^2 and 10^5 MeV; they constitute the so-called primary radiation (galactic and solar). When these particles approach Earth they are deflected by the terrestrial magnetic field according to their momenta. In their travel toward the ground, primary radiation particles interact with the atmosphere producing many particles such as electrons, photons, mesons, protons and neutrons: these are called the secondary radiation.

Secondary radiation particles themselves can interact with the atmosphere, or decay, producing so-called avalanche ionization: from a single-particle starting event, up to 10^8 particles can be generated. In the atmosphere below 20 km cosmic radiation is constituted almost exclusively of its secondary component. Typical range of effective dose per person per year is 0.3-1.0 mSv, with average effective dose ~ 0.4 mSv [UNSCEAR (2000)]. For locations high above the sea level very large doses are received, e.g., in La Paz – Bolivia (3600 m) the average dose due to cosmic rays is 2.02 mSv per year. Flying at 8000 m altitude results in a dose rate of $2.8 \mu\text{Sv h}^{-1}$ (see Galli and Mancini, 1996). Cosmic rays are an important risk in interplanetary travel (see Parker, 2006).

Terrestrial Radiation - Inside the Earth there are radionuclides whose half life ($T_{1/2}$) is comparable with Earth's age. In fact the Earth's core is still hot thanks to the energy released by radionuclides in their decay processes. The most significant for dose computation are ^{40}K ($T_{1/2}=1.28 \times 10^9$ y), ^{232}Th ($T_{1/2}=1.41 \times 10^{10}$ y), ^{238}U ($T_{1/2}=4.47 \times 10^9$ y); of secondary importance are ^{87}Rb ($T_{1/2}=4.7 \times 10^{10}$ y) and ^{235}U ($T_{1/2}=7.04 \times 10^8$ y). Most radionuclides belong to one of the three families of Uranium, Thorium and Actinium (see Figures 3.5-3.7). In all three families Radon (Rn) is formed. Radon appearance is the clearest evidence that Earth crust is radioactive. Terrestrial radiation can be responsible for internal or external exposure.

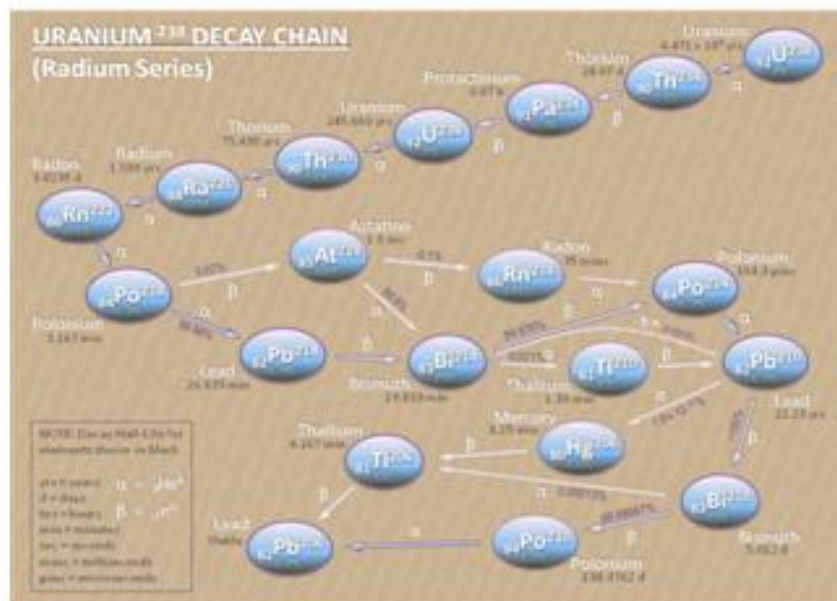


Figure 3.5 - Uranium-238 decay chain

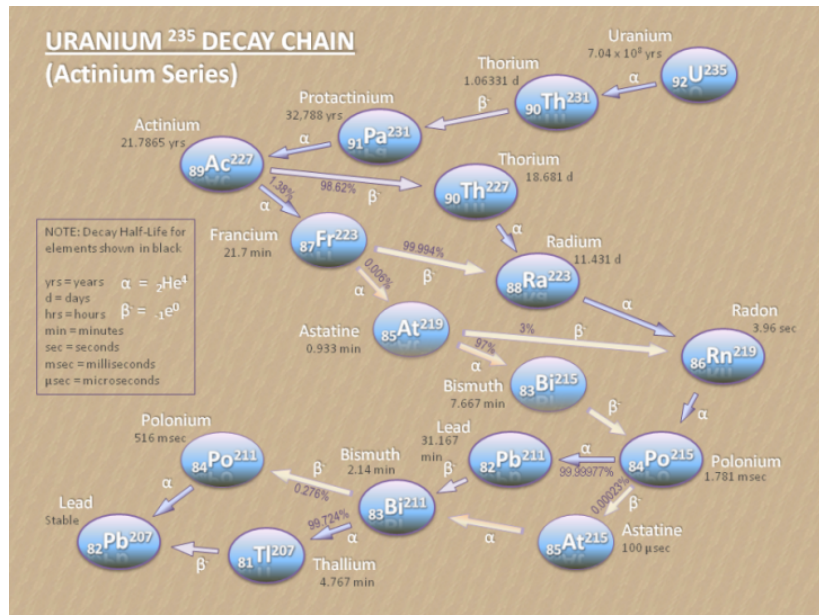


Figure 3.6 - Uranium-235 decay chain

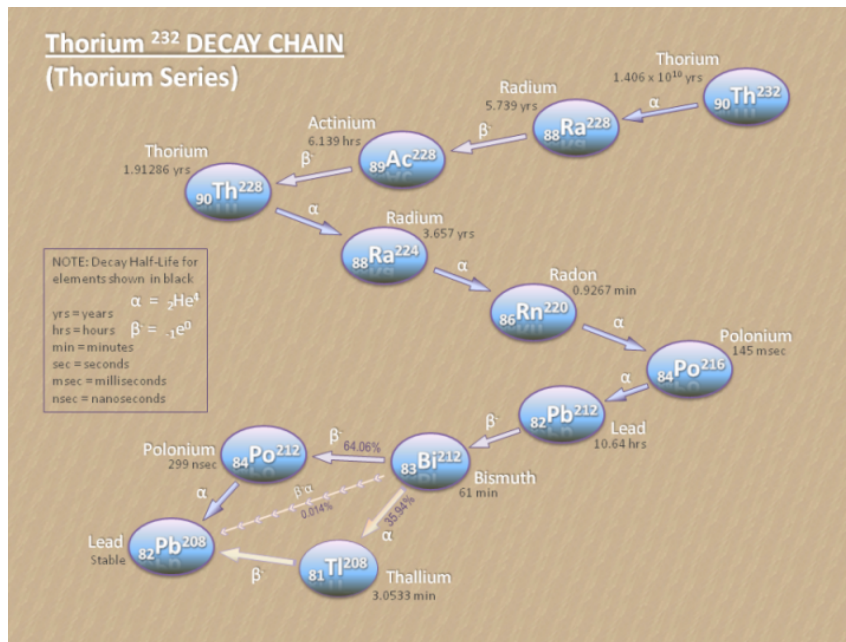


Figure 3.7 - Thorium-232 decay chain

The calculation of radioactive decay products time for ²³⁸U, ²³⁵U, ²³²Th series has been performed by implementing an in-house developed Java code. Mathematical results are generally applicable to all those processes in which the transition of the parent nucleus to a daughter nucleus i.e. the process of radioactive decay, is governed by purely statistical processes.

This process of decay is equivalent to the degree of instability of the parent nucleus. Each radioactive nuclide has its specific degree of instability which is expressed by the half-life ($T_{1/2}$, period of time in which half of the element radioactive nuclei has decayed) assigned to this nuclide.

The radioactivity of a sample, however, is more complicated if it consists of two or more components, such as: (i) in the case of a mixture of independent activities, (ii) if one specific type of nuclide shows two modes of decay, so-called branching decay, and (iii) if in the nuclear decay series also the daughter nuclides are radioactive; these last two characteristics are present in the studied cases.

Figure 3.8 shows the decay curves for the initial and final (stable, ²⁰⁷Pb) element nuclei for the ²³⁵U series. Data for the number of nuclei have been scaled with respect to the initial number of ²³⁵U nuclei (N_0), while time has been scaled with the half-life ($T_{1/2}$). Figure 3.9 shows the same curves but, in this case, the simulation has been stopped after $T=10 \cdot T_{1/2}$, corresponding to about 7 billion (!) years, when the number of ²³⁵U radionuclides has decreased to about 1/1000 of the initial number.

Since all curves representing initial and final elements time dependence for the ²³⁸U, ²³⁵U, ²³²Th series would overlap if represented in terms of scaled time and nuclei number, in Figure 3.10 the scaled time is substituted by the simulation time. In this way, the influence of order-of-magnitude differences among half-life of elements ²³⁸U, ²³⁵U, ²³²Th can be clearly detected: while after $T=1.41 \cdot 10^{10}$ y, half of the initial number of ²³²Th radionuclides is still present, the number of ²³⁵U radionuclides is less

than $1/10^6$ of the initial number and the number of ^{238}U radionuclides is about 1/10 of the initial one.

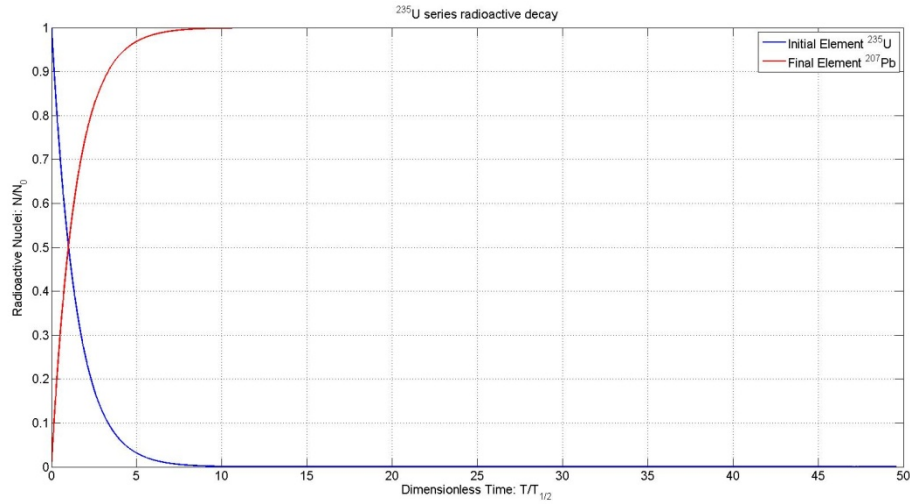


Figure 3.8 - Decay curves for ^{235}U series: initial element (^{235}U , blue curve) and final element (^{207}Pb , red curve)

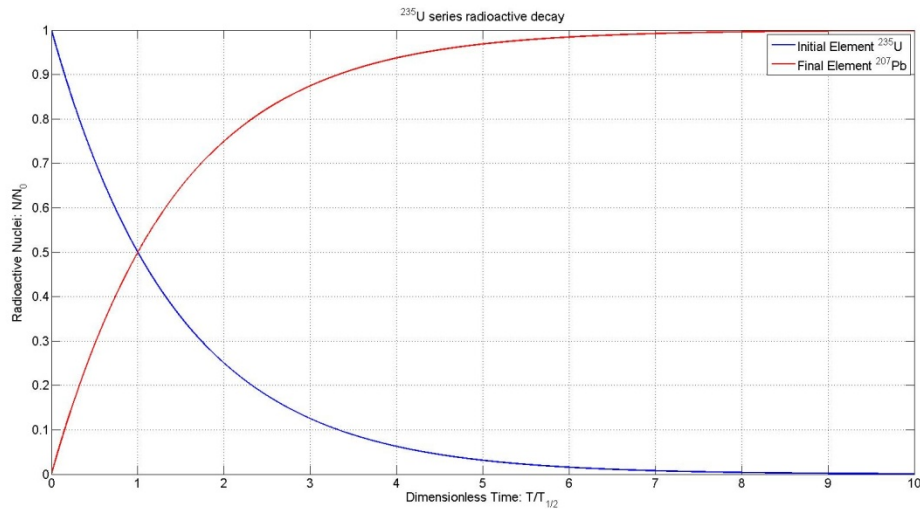


Figure 3.9 - Decay curves for ^{235}U series: initial element (^{235}U , blue curve) and final element (^{207}Pb , red curve); simulation has been stopped after $T=10 \cdot T_{1/2}$

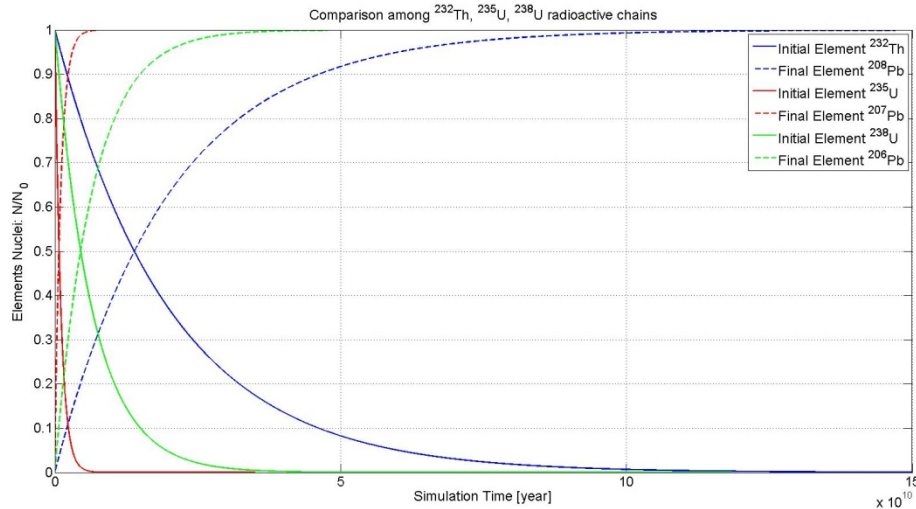


Figure 3.10 - Decay curves for ^{232}Th (blue curves), ^{235}U (red curves), ^{238}U (green curves) series: to be noted the effects of order-of-magnitude difference in half-lives of ^{238}U , ^{235}U , ^{232}Th radionuclides.

Figures 3.11, 3.12 and 3.13 show the curves representing the time dependence of the number of element nuclei (with initial condition $N(T=0)=10^{15}$) for some of the elements of the ^{238}U , ^{235}U , ^{232}Th decay chains shown in Figures 3.5, 3.6 and 3.7.

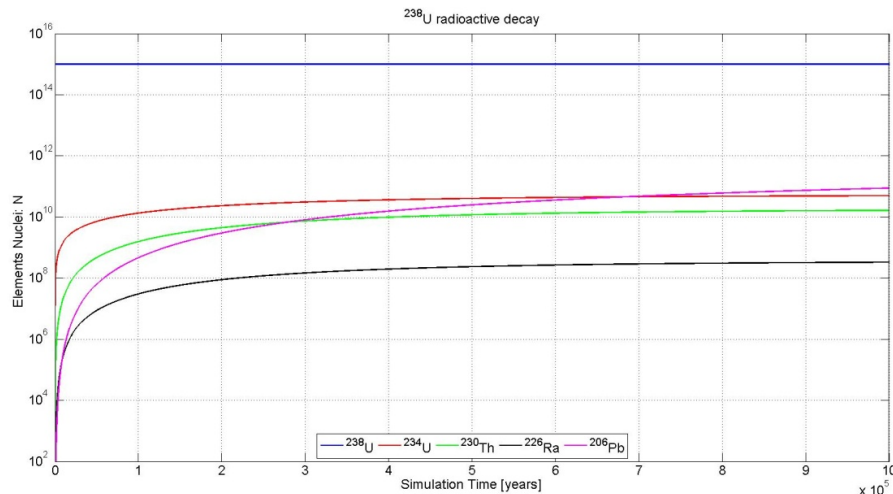


Figure 3.11 - Curves representing time dependence of the number of element nuclei of ^{238}U , ^{234}U , ^{230}Th , ^{226}Ra , and ^{206}Pb , elements of the ^{238}U radioactive decay series

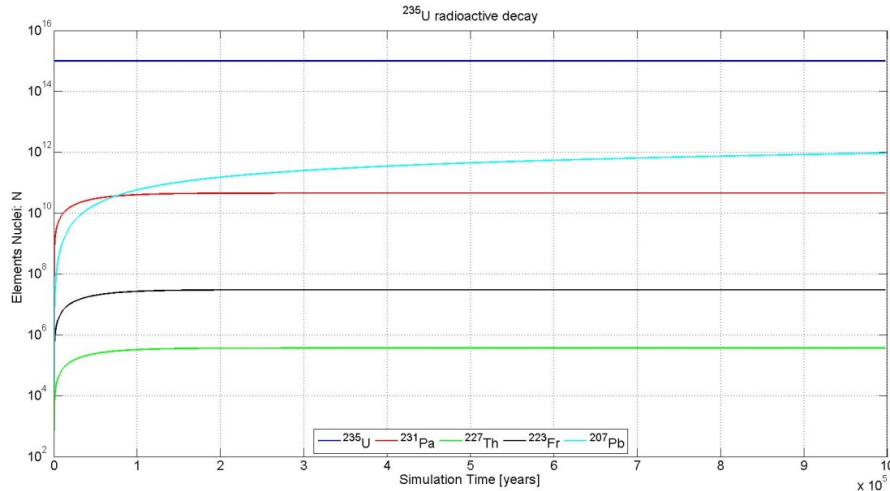


Figure 3.12 - Curves representing time dependence of the number of element nuclei of ^{235}U , ^{231}Pa , ^{227}Th , ^{223}Fr , and ^{207}Pb , elements of the ^{235}U radioactive decay series

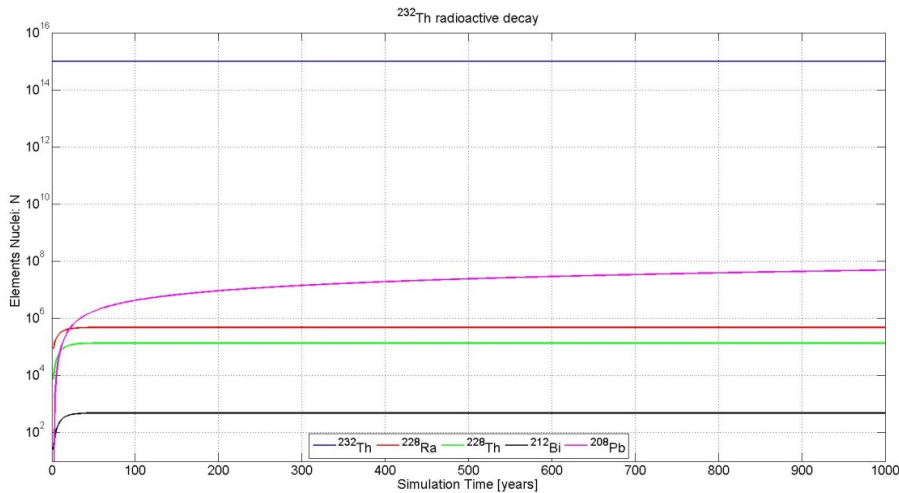


Figure 3.13 - Curves representing time dependence of the number of element nuclei of ^{232}Th , ^{228}Ra , ^{228}Th , ^{212}Bi , and ^{208}Pb , elements of the ^{232}Th radioactive decay series

In Figures 3.11 and 3.12 the simulation time has been stopped after 10^6 years: longer time would have compressed too much the initial portion of the curves. For the same reason, in Figure 3.13 the simulation time has been stopped to 10^3 years.

There are order-of-magnitudes differences among the half-lives of the initial element and of the product elements of the decay process. Just to give an idea, while ^{235}U half-life is equal to $7.04 \cdot 10^8$ y, for ^{227}Th the half-life is equal to about 18.5 days which corresponds to about 0.05 years. This characteristic of decay process is linked also to another aspect that can be observed from the charts: the curves for the initial elements of the three series appear as straight lines (note charts in Figures 3.11-3.13 are semi-logarithmic) with an almost null slope.

This type of relation between parent and daughter activity which occurs when the half-life of the parent nuclide is extremely longer than that of the daughter nuclide is called **secular equilibrium**.

Figures 3.14-3.16 shows the same curves of Figures 3.11-3.13 but with even shorter simulation times: 1000 years for ^{238}U , 100 years for ^{235}U , and 30 years for ^{232}Th : different dynamics of various product elements can be more clearly detected.

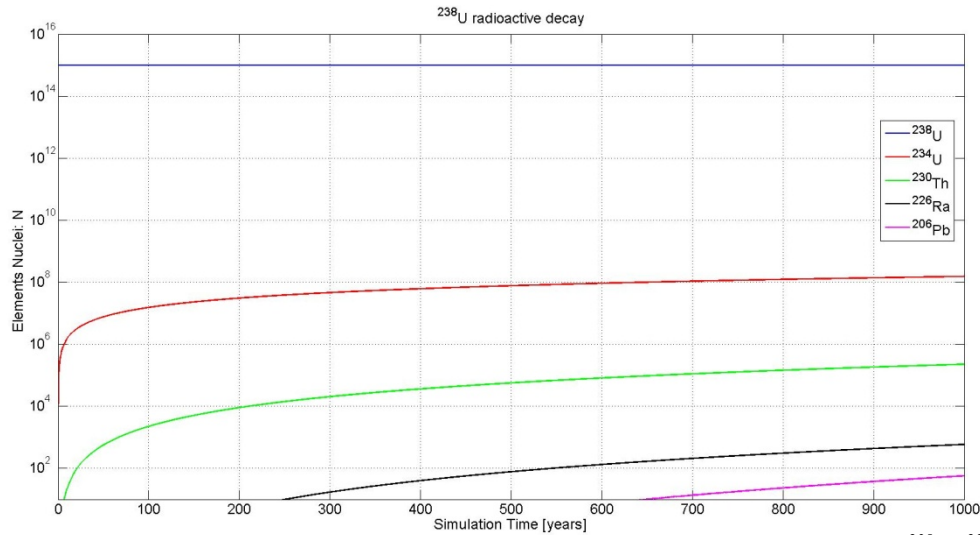


Figure 3.14 - Curves representing time dependence of the number of element nuclei of ^{238}U , ^{234}U , ^{230}Th , ^{226}Ra , and ^{206}Pb , elements of the ^{238}U radioactive decay series: simulation stopped after 1000 y

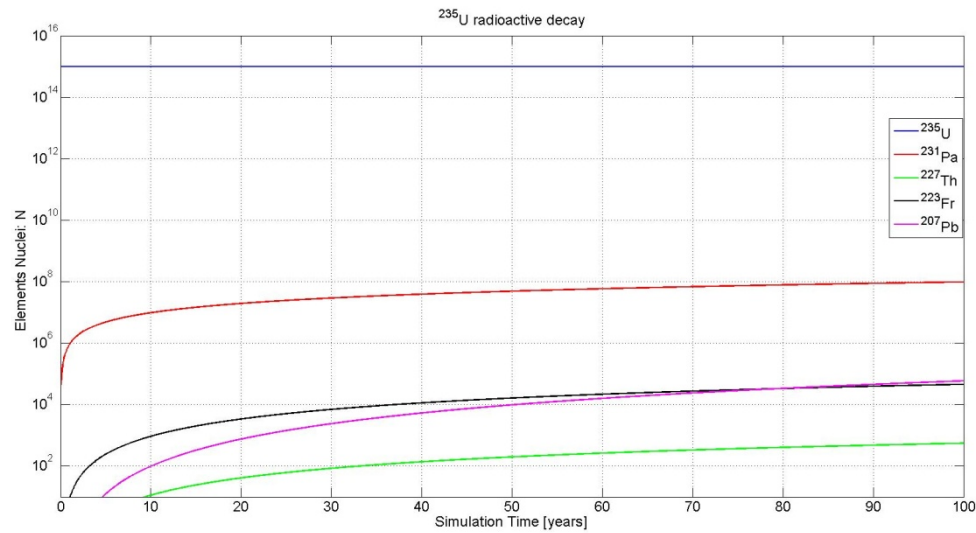


Figure 3.15 - Curves representing time dependence of the number of element nuclei of ^{235}U , ^{231}Pa , ^{227}Th , ^{223}Fr , and ^{207}Pb , elements of the ^{235}U radioactive decay series: simulation stopped after 100 y

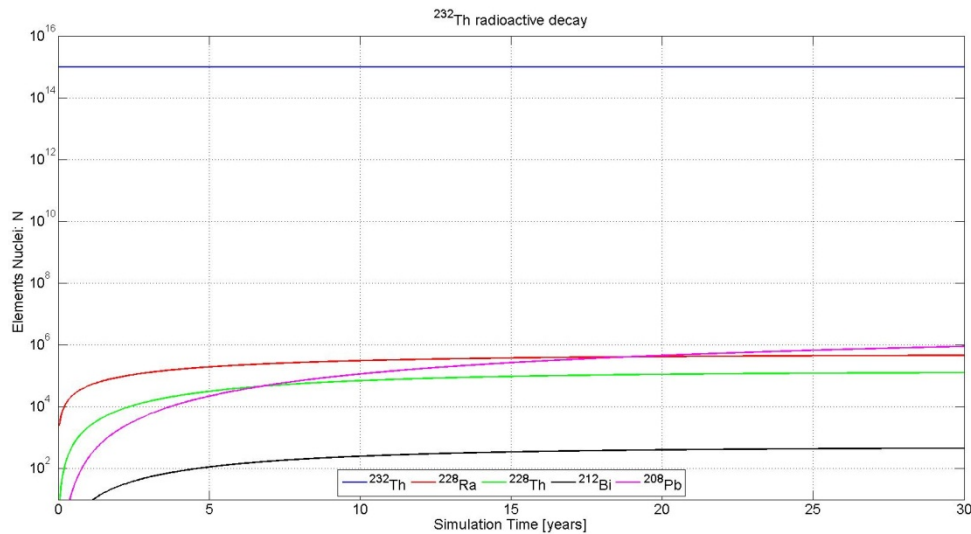


Figure 3.16 - Curves representing time dependence of the number of element nuclei of ^{232}Th , ^{228}Ra , ^{228}Th , ^{212}Bi , and ^{208}Pb , elements of the ^{232}Th radioactive decay series: simulation stopped after 30 y

External Exposure from Terrestrial Radiation

External exposure to gamma rays from natural radionuclides can occur both outdoor, since radionuclides are present in the Earth crust, and indoor, as they may be present in construction material, or seep through building foundations. Combining outdoors and indoor exposure, for a person spending 80% of time indoor, a range of $0.3 - 0.6 \text{ mSv per person per year}$ is typical. Worldwide-averaged annual effective exposure is estimated $\sim 0.5 \text{ mSv}$ [UNSCEAR (2000)].

Internal Exposure from Terrestrial Radiation

Potassium isotopes are present in the human body with a weight percentage 0.18%; the isotope ^{40}K has an isotopic abundance 1.18×10^{-4} , and its main decay mechanism is beta. The annual dose from ^{40}K is estimated 0.165 mSv. Some isotopes (the most significant ^{210}Pb and ^{210}Po) can be ingested through food and water. The typical range of the annual effective dose is $0.2 - 0.8 \text{ mSv}$, but higher values are detected in South America (due to large quantity of ^{210}Po present in 'yerba mate', an herb used in drinks) and arctic and sub-arctic areas (where ^{210}Po and ^{210}Pb tend to accumulate in moose meat). The worldwide-averaged annual effective dose is 0.3 mSv

Some radioisotopes may be inhaled, the most significant in this case being ^{222}Rn and, much less importantly, ^{210}Po (smoking 10 cigarettes a day doubles ^{210}Po introduction). Typical range of inhaled dose is $0.2 - 10 \text{ mSv}$. The range is so wide because the contribution is mainly given by radon and its contribution depends on its indoor accumulation. The worldwide-averaged annual effective dose due to inhalation is 1.2 mSv.

The summary of background radiation sources is in Table 3.3 [UNSCEAR (2000)].

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External Exposure		
Cosmic rays	0.4	0.3-1.0
Terrestrial gamma rays	0.5	0.3-0.6
Internal Exposure		
Inhalation (mainly radon)	1.2	0.2-10
Ingestion	0.3	0.2-0.8
Total	2.4	1-10

Table 3.3 - Mean dose value for background radiation

Comparison of Exposures

The doses received by an individual living on Earth from the main different sources (updated to the year 2000) are summarised in Table 3.4. Their values are given in annual pro capite effective dose (mSv). The values are averaged, meaning that there are significant variations in exposure to individuals, depending on location, diet, personal habits and so forth.

The largest contribution to total dose is from the natural background: 2.4 mSv, but typical values may range from 1 up to 10 mSv, with large groups of population receiving a dose of 10-20 mSv. The second most important source, 0.4 mSv, from the medical use of radiation. It has an increasing trend, thanks to increasingly available medical radiation facilities. The third cause is the fallout from past weapons tests; i.e., 0.005 mSv. The value has been decreasing thanks to the Treaty Banning Nuclear Weapon Tests, the maximum value being reached in 1963, when it was 7% of the natural background. Other man-made sources, like the Chernobyl accident and nuclear power production, are much smaller, 0.002 mSv and 0.0002 mSv, respectively.

Source	Worldwide annual per caput dose (mSv)	Range or trend
Natural background	2.4	Typical range 1-10 mSv. Sizeable population also 10-20 mSv
Diagnostic medical use	0.4	Typical range 0.04-1.0 mSv at lowest and highest level of health care
Atmospheric nuclear testing	0.005	Has decreased from a maximum of 0.15 mSv in 1963. Higher in northern hemisphere and lower in southern hemisphere
Chernobyl accident	0.002	Has decreased from a maximum of 0.04 mSv in 1986. Higher in locations near the accident area
Nuclear power production	0.0002	Has increased with expansion of plants but decreased thanks to improved practice

Table 3.4 - Annual pro capite doses in the year 2000

Nuclear Reactors : Accident Risks

Using the information above, at the time of the Rubbia's Engine project doses were estimated in case of a nuclear accident. They were also compared for a similar compact power reactor devised by physicists at the **US Brookhaven Nuclear laboratory** (originally designed for the US Navy nuclear torpedo program) and then space-engineered (becoming the so-called MITEE engine). In both cases the thermal power of the reactor was similar, about 40 MW.

The individual dose commitments for 250 years arising from a rather improbable total 'crash' of Rubbia's engine, 1.8×10^{-6} mSv, and MITEE (Miniature Reactor Engine), 1.6×10^{-8} mSv, are insignificant compared to all the other sources of exposure shown in the discussion and calculations above. Should a **Rubbia's engine 'crash'**, a hypothetical individual, born in the year of crash and dying at age 250, would have received during his entire life **a dose of 3×10^{-5} mSv**, much lower than the dose imparted by a dental examination (0.03 mSv); the same would be true for a **MITEE accident** of the same type. The average dose from natural background to each individual is 2.4 mSv in one single year. **Table 3.5** shows contribution to dose compared to other sources.

The contribution to individual average dose from the crash of such space reactors is therefore not a reason of concern to public health.

Source	Effective Dose/Dose Commitment (mSv)	Comment
Rubbia's Engine Accident → Catastrophic LEO Re-entry	$1.8 \cdot 10^{-6}$	Dose committed for 250 years (per kg fuel)
MITEE Accident → Catastrophic LEO Re-entry	$1.6 \cdot 10^{-8}$	Dose committed for 250 years (per kg fuel)
Natural Background	2.4	Average effective dose in 1 year
Dental x-ray examination	0.03	Average effective dose from a single examination
Flying at 8 km for 10 hours	$2.8 \cdot 10^{-8}$	1 hour gives $2.8 \cdot 10^{-8}$ μ Sv

Table 3.5. Comparison of doses from different sources

We note that nuclear thermal propulsion and nuclear electric propulsion are exceptional enablers to space exploration, and that **doses from nuclear reactors in space are insignificant compared to the radiation space environment itself**. In fact, the *greatly reduced trip times* enabled by the use of nuclear propulsion will enhance crew safety, due to reduced exposure not only to zero gravity but, especially, to the cosmic ray environment (and dose received) of space [Durante and Bruno, 2010]. We note that there is extensive data supporting the radiation hormesis approach to radiation health effects as opposed to the linear no threshold hypothesis, and that should guide the radiation safety doctrine for space nuclear power and propulsion systems, including ground testing. **It is likely that no other single event will assist the technical development of nuclear power and propulsion than the reduction in costs and regulatory burden** generated by eliminating the linear no threshold hypothesis as the basis for radiation health effects.

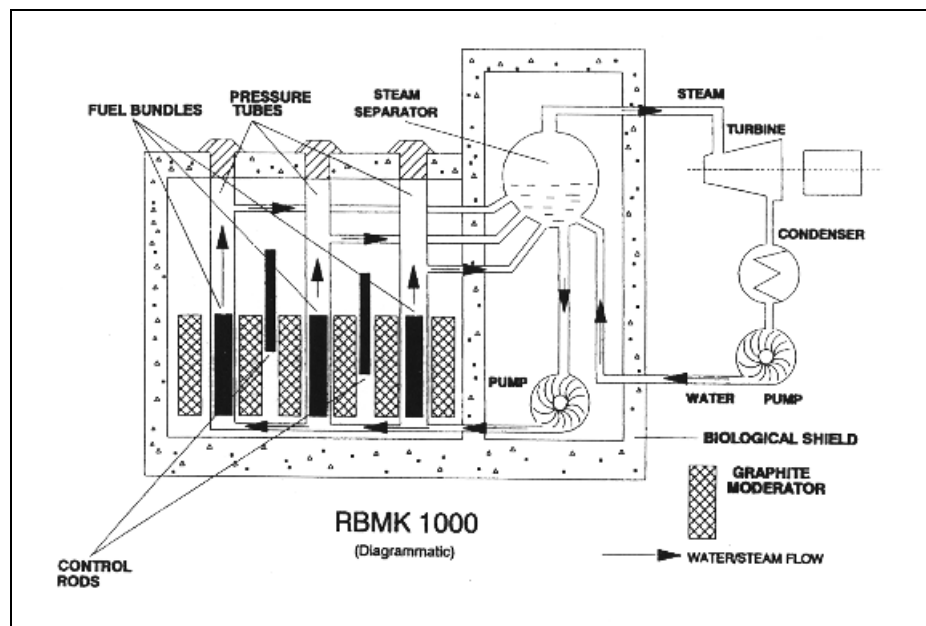
3.4 From The Chernobyl Accident - A Detailed Account [A. Del Rossi and C. Bruno]

One of the major obstacles the nuclear reactors development encounters is the fear that people feel when hearing about 'nuclear' in any of its application such as propulsion or energy production. This fear is born mainly after Chernobyl disaster on April 26, 1986 in Ukraine, formerly in the USSR. The accident renewed worries about the use of nuclear sources. We attempt to explain causes and show consequences of the event, in order to clarify ideas about use of nuclear power in space application as well.

The UNSCEAR report to UN in 2000 [UNSCEAR (2000)] reported the consequences of Chernobyl accident that can be considered the most serious ever happened in

nuclear industry. The radionuclides released from the reactor that caused exposure were mainly iodine-131, caesium-134 and caesium-137.

Reactor Design - The reactor used in Chernobyl was a soviet-designed 925 MWe RBMK (Reaktor Bolšoj Moščnosti Kanalnyj (High Power Channel-type Reactor), see Figure below). RBMK reactors are pressurized water reactors [World Nuclear Association Web Site, <http://www.world-nuclear.org>]. The main purpose of the reactor was to produce weapon grade Plutonium, not energy.



For completeness, refer to Appendix B hereinafter.

4 REQUIREMENTS for 30 KWe FISSION POWER SOURCE

Some preliminary conclusions about what is needed in order to start seriously considering space nuclear reactor can be drawn.

There are two aspects to R&D on nuclear power for space power generation and propulsion: the scientific missions that such technology would enable, and dual mode commercial applications.

Space science is right now limited by the fact that in-space power is based on solar panels, thus with power rapidly decaying with the distance from the Sun, and limited in what they can accomplish once the target is reached. In all history of human exploration the key bottleneck and limitation has been the time taken to reach destination. Time means resources to be carried on-board (food, water, spare parts when using ships, for instance), higher chances to get sick while away from help, chances of incurring accidents, and more generally, unexpected events. The latter

were partly due to unknowns, and partly due to 'unknown' unknowns (e.g., among the first was scurvy, among the second the presence of reefs along the unexplored routes, hostile inhabitants, or drought in transit).

Space exploration is not exactly similar, but still there are unknown unknowns. There is a tremendous advantage to being able, for instance, to travel to Mars in two months rather than eight or nine. With chemical propulsion travel time is restricted to Hohmann trajectories, ruled by gravitation. Nuclear propulsion would revolution and broaden the spectrum of orbits available and shorten their duration. Furthermore, steady and significant on-board power enables long range, high bit rate TLC with Earth, and although real-time GNC becomes unfeasible when increasing distance from earth, TLC is a must to rapid downloading of exploration data. Melting planetary ice(s), drilling and excavating use much power, that cannot be supplied by solar panels but that are enabled by nuclear on-board power.

The second aspect of nuclear space power is that development of such systems can, and should politically wise to, be combined with commercial applications. To be practically useable, pace NR will be compact, durable, and require minimal or no maintenance. There are numerous commercial applications that could benefit from these features and that have a potential market. This market is now almost totally controlled by combustion and IC engines and thus by the price of oil. With its inevitable long-term increase, and its geopolitical consequences, there is a point in looking at compact NR in the tens of kW to MW range. Dual-mode applications, and their perspective, are the enablers of such technology for space missions. Space is a miniscule fraction of the world business, power generation is not, thus it is inevitable to look for nuclear technology that can be applied to both, and that can be easily transferred from one to the other.

The current problem with such approach is obvious: it is the risk that such applications may be used by terrorists. That should not prevent starting investigating dual mode use. The initial customers are likely to be military, but in the high end range industrial applications can be envisaged, e.g., in seabed floor mineral exploration using robotic submarines, or shipping.

Thus a vigorous effort should be started in making contact with EU organizations and the military concerning R&D of this technology for dual-use. The fragmentary state of EU coordination on strategic issues makes such an initiative hard to start, but it is at the same time necessary.

4.1 Mission power impact on nuclear reactor design

There is hardly any public information on ground or space nuclear reactor in the 30 kWe range, an important aspect of this project. What is known of the SNAP reactors in the US, and of the Romashka, BUK and Topaz soviet reactors indicates this power level was never planned: P was either below 10 kWe or above, in the 100 kWe. In the lower range very compact, U-based fuel reactors were built by the US (e.g., the SNAP-10A), and Topaz-1 and -2 in the former Soviet Union, and conversion was

thermoionic or thermoelectric. With a conservative conversion efficiency of order 25% for a thermodynamic Brayton or Rankine cycle, the thermal power of a nuclear reactor producing 30 kWe should be at least 120 kWth. The same thermal power fed a thermoionic/thermoelectric system that should work for many years (efficiency of order 6-7%) would produce only 7 kWe. Thus the first order of business would be to choose between tried thermoelectric systems and thermodynamic cycles. In the first case the nuclear reactor proper would have to be in the 1.5 MWth range, a solution never envisaged before, let alone tried. In the second, the thermal power has been approached before in the US and Russia as far as the reactor, but not as far as the thermodynamic conversion, and implies novel solutions, possibly based on long life microturbine technology. In this context this situation may be summarized by saying that there is no baseline to start from.

The case of 200 kWe is different, since there is no realistic solution (in terms of acceptable weight and efficiency) that could work using the low-efficiency thermoelectric conversion. With a thermodynamic cycle the thermal power of the nuclear reactor should be at least of order 1 to 1.5 MWth. This power has already been explored in designs at NASA and SANDIA, and information is available, see for instance [Lenard, 2008] for gas and LM cycles and compact, high power extraction via heat pipes using Na vapor.

4.2 Action Items

The recommended action in both cases starts with the need to ensure a life of order 5 to 10 years. Peak performance must yield to this requirement, thus peak cycle temperature should be matched to materials capable of withstanding up to 900 – 950 K at most practically indefinitely, and designing a cycle with the compromise between lower T and space radiator T. At this stage is hard to choose between LM and gas reactors, or even to make a recommendation, except that of investigate both. Likewise, unconventional fuels (low critical mass) are probably still unproven in EU or unobtainable. Because there is a requirement for long life power system and components, fuel consumption, and thus possibly in-space refueling, are very important issues and might even become a showstopper. Most experience with high power nuclear reactor goes back to the ROVER/NERVA project, when nuclear thermal rockets (NTR) were successfully ground tested, but also with reactor/propulsion system lifetimes of order hours to days: this because the thrust that can be obtained by NTR is a factor 10^5 or more that of the most powerful GIE in existence or conceivable in the near term. Thus the nuclear reactor was supposed to last a few hours and then discarded. With NEP the situation is just the opposite, and this suggests that an alternative to the long life requirement could consist of clustering together many hundreds or even thousands of individual modules, so that sufficient thrust can be maintained for a much smaller fraction of the total mission time. This of course implies space nuclear reactor in the 100 MWe range, presumably subdivided into a certain number of nuclear reactor modules to increase mission chances of success.

The specific technical issues to address and resolve are those deriving from the previous discussion of space nuclear reactors working continuously in space for years: structural life, thermal fatigue, choice of architecture and neutron reflector, neutronics and its control, heat exchanger and turbine blade design, together with their potential corrosion by impurities due to wear, seals (also an issue in gas turbines and rocket engines), lightweight turboelectric generators and space radiators. Some of these activities require access to information already available in France and the UK from national industry and atomic energy agencies (RR, AREVA, CEA and Harwell, for instance).

Paramount in this scenario (really, the bottleneck) is the materials issue. Whatever the materials used, they will be subject to radiation from fission (neutrons, alpha, beta and gamma, plus FF) affecting their thermal and mechanical properties. It is inconceivable to test materials under the same conditions (besides cost and practicality, not even the LHC at CERN can simulate the energy of a portion of the spectrum of energy possessed by space particles). This is indeed so especially since information already exists in industry and government labs in EU, CIS states and the US as far as fission radiation effects. Thus partnership with EU industry knowledgeable in this area is critical, as is to establish collaborations with other countries.

5 TECHNICAL NOTE

The development and safe and effective implementation of a fission reactor module is a key goal of any space nuclear power project. In addition to providing a significant level of power reliably for over a number of years, perhaps ten years, the reactor module must satisfy numerous requirements regarding nuclear safety and integration with the rest of the spacecraft (or user loads for surface power applications) while simultaneously minimizing both programmatic risk and system mass.

It has been recognized from the earliest days of the fission era that the application of nuclear fission energy to space power and propulsion needs could provide a number of advantages. The very high energy density achievable with fissile fuel leads to compact, high power, long-lived systems that have great advantages in space use. In recognition of these advantages, a number of programs have been undertaken in the U.S. and in the former USSR to capitalize on these technologies for space use (see Section 2). In addition, a large number of study and evaluation programs funded worldwide have resulted in numerous plausible designs for a range of missions and suggested many mission enhancing or enabling features of nuclear systems.

The following sections describe technical aspects and considerations for the design of a 30 kWe nuclear reactor.

The reactor module consists of several subsystems: the core, reflectors, instrumentation and control (I&C), shield, primary heat transport system.

The herein presented trade study analyses three different reactor types (Liquid-Metal Reactor (LMR), Heat-Pipe Reactor (HPR) and Gas-Cooled Reactor (GCR)) coupled with three power conversion systems (Brayton, Stirling, Thermoelectric).

5.1 Reactor module requirements and constraints

Analytical efforts approach fission power source design process taking into account the following high-level requirements:

- a) Nuclear safety must be assured for all mission phases
- b) Electric power requirement: 30 kWe
- c) Lifetime requirements: operational for 10 years at full power

In order to perform the analysis in a consistent manner, the high-level requirements are translated to a set of detailed requirements that are necessary for design and trade studies, see Table 11. A number of the numerical values of the requirements necessary for a detailed design are determined at this stage of the work, but will need to be settled prior to start of serious designs.

Several constraints on the reactor performance dictate a set of key *preliminary* requirements, derived from experience with terrestrial reactors:

- *Operational constraint*: The need to remain critical at end of life (EOL), accounting for uncertainty, sets the key requirements of k_{eff} , the reactivity coefficient, at EOL at 1.000 (+0.005 – 0.000);
- *Safety constraint*: In order to ensure sub-criticality under the worst credible accident scenario, the reactors are designed to have a $k_{eff}=0.985$ under those conditions. Accident conditions included immersion in water or wet sand and burial in dry sand. The k_{eff} value of 0.985 is appropriately conservative given the low probability of the event.
- *Resource constraint*: Past designs and the various reactor systems have used different fissile fuel enrichment values. In order to ensure a level playing field for all reactor configurations studied, the fissile enrichment of the fuel is set at 93 percent.
- *Technology constraint*: Recognizing the interest in avoiding significant fuel qualification, the peak fuel burn-up was set at 4 (atom) percent. This is well below the peak value demonstrated for SP-100. The data at the higher burn-up values, however, are sparse, and for reasons of conservatism, the 4 percent value is chosen.

Category	Requirement	Specific Value
Power	Electric Power	30 kW
	Thermal Power	>100 kW
Reactivity	Lifetime	10 full power years
	k_{eff} (EOL)	1.000 (+0.005 -0.000)
	k_{eff} (BOL)= k_{eff} (EOL) + Burnup reactivity + Temperature reactivity + Margins	TBD
Safety	k_{eff} for worst credible accident scenario	<0.985
	Assured safety for all mission phases	>99%
	Minimum shutdown element speed	TBD
Fuel	Peak central temperature	<1600 K est.
	Peak clad temperature	<1350 K est.

	Enrichment	93%
	Burnup	<4%
Operational	Power coefficient over mission life	Negative, all power
	Number of scheduled shutdowns	TBD
	Restart time after unscheduled shutdown	<TBD days
Shield	Lifetime dose at 30 meters	<25 krad
	Lifetime fluence at 30 meters	<10 ¹¹ n/cm ²
	Shadow angle	5°×10°

Table 5.1. Reactor module input requirements

The main requirements in Table 5.1 were taken from practice in ground-based reactors. In this phase, they should be considered estimates, as any future space reactor will be quite different in geometry, architecture, materials and mass from commercial electric utilities reactors. Thus some of the requirements may never be imposed in space reactors, e.g., shutdown. The other requirements listed in Table 5.1 reflect standard constraints on shutdown reactivity, negative power coefficient over entire power range, dose levels at payload, etc. (completion goes beyond the scope). For this study, the dominant assumption or constraint is that all the reactors would be designed to be equally safe, to first order. The dominant hazard involving the reactor is release of radiation to the public during a launch accident. Since a space reactor is not very radioactive before it is operated, this hazard is greatly mitigated by designing the reactor so that it remains sub-critical for all credible launch accidents.

5.2 Reactor options comparison

Past studies have compared various combinations of reactor type and conversion type. The trades have traditionally looked at performance first (as indicated by system mass for a given power) and then tempered the conclusions with qualitative features such as versatility, growth potential, or technological readiness.

During the early days of the SP-100 program (1983), Rockwell performed a technology assessment followed by a power system trade study. That study concluded that the gas-cooled reactor directly-coupled with a Brayton-based power conversion system had the highest overall figure of merit for the originally specified requirement set. But when the requirements and weightings were adjusted, the liquid metal cooled reactor (LMR), with lithium coolant, and a fairly high-temperature Brayton system was the combination selected, with an LMR and thermoelectric option as backup. Later the LMR-thermoelectric combination became the basis for the SP-100 program. What follows in this section and Figure 5.1 and section 5.3 refer to documents pertaining to the DOE SPFT program and reported with further comments in [Lenard (2008)].

The trade study in SPFT was performed for three reactor types: 1) liquid-metal cooled reactor (LMR), 2) heat pipe-cooled reactor (HPR), and 3) gas-cooled reactor (GCR). This trade study takes into consideration coupling these reactors to three conversion systems based on: 1) Brayton, 2) Stirling and 3) thermoelectric (TE).

A brief overview of the three reactor types is shown in Figure 5.1. All three reactor types use uranium nitride (UN) fuel pellets with a Nb1Zr clad containing a Re

(Rhenium) liner. It is also feasible for these reactors to use UO_2 fuel, but its lower density and thermal conductivity make UO_2 less attractive.

The LMR uses pumped lithium to remove the heat from the reactor to a heat exchanger where it is transferred to the power conversion system. The HPR uses sodium-filled heat pipes to transfer the heat from the reactor to a heat exchanger. The GCR uses a flowing helium-xenon gas mixture to transfer the heat from the reactor to the power conversion system. With a Brayton conversion system, the GCR does not use an intermediate heat exchanger. Rather the Brayton working fluid passes through the core and the reactor heat is transferred directly to the gas from the fuel pins.

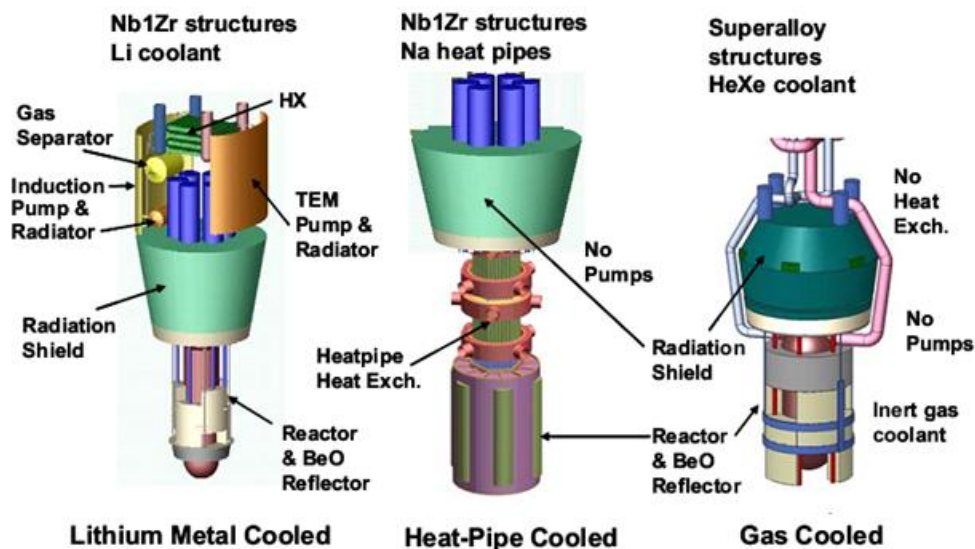


Figure 5.1 - Drawings of reactor options, all with external control elements

All three systems control the reactor with external neutron reflectors rather than internal neutron absorbers, similar to the SNAP-10A approach, as opposed to the SP-100 approach.

The LMR draws upon extensive LMR experience with NaK and Na reactors, is compact because of the excellent heat-transfer capability of liquid metals, and is versatile in working with different conversion systems.

The HPR draws upon extensive design work and electrically heated testing, has passive heat removal from the core via numerous redundant heat pipes, and has an accessible core (no pressure vessel).

The GCR draws upon the High Temperature Test Reactor experience (in Japan) with prototypic temperature and pressure levels, has no freeze-thaw issues and few material interaction concerns (because of the inert-gas coolant), and in the direct-drive configuration employ all-super alloy outer boundaries (which simplifies testing and integration).

Estimates for the reactor module mass have been calculated in order to compare the three reactor types across a broad range of conditions that included various power conversion schemes, reactor thermal power, radiation dose requirements, shield half angle.

The design conditions under which the comparison was performed can be summarized as follows:

- Uranium enrichment is 93.15 percent U-235 (which is generally more available than 97 percent enriched fuel used for SP-100)
- External sliding reflectors for control with BeO as the reflecting material
- Reflectors extending axially to the mid-plane of the top and bottom axial BeO reflectors within the pins, which were approximately 4 cm long
- Pressure drop of He/Xe gas flowing through reactor or reactor heat exchanger is about 3.5 percent of the absolute pressure (for the Brayton conversion system)
- Reactivity at start-up while cold is 1.015 plus projected burn up for 10 full-power years
- Reactivity at beginning of life when submerged under wet sand with no reflectors and flooded internally with water (and inside heat pipes but not inside the fuel pins) is 0.985
- Pressure vessel creep less than 2 percent in 10 years at operating temperature and pressure
- Clad creep less than 2 percent in 10 years at operating temperature and pressure

5.3 Shielding

There are several types of shielding for space systems, however in this context, shielding is needed primarily to protect against damaging radiation resulting from fission and fission product decay emitted by the core. The amount of gamma dose and neutron fluence attenuation that would result from a given shield configuration combined with mass formulae based on geometry yields estimates for shield mass vs radiation attenuation and cone angle for the zone of protection, through which the thicknesses of the Be, W and LiH of the shield can be calculated (see Figure 5.2 for the shield configuration).

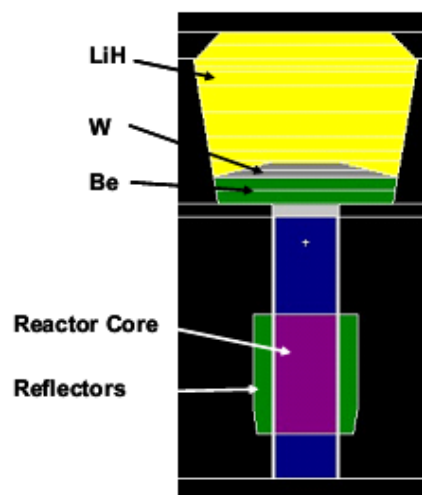


Figure 5.2 - Shield configuration

Each reactor concept exhibits various virtues or liabilities associated with its particular design. The GCR is slightly larger, so the shield mass is somewhat heavier. The reverse is true for the LMR. The HPR requires that the heat exchangers be between the reactor and shield. This increases the distance between the reactor and shield necessitating a larger shield in order to achieve the desired shielded protection area. Moving sensitive payloads closer to the shield makes the shield thicker and more massive. Using an elliptical shield (with half the angle transversely) reduces the mass slightly.

5.4 Instrumentation & Control

The functions of the Instrumentation and Control (I&C) subsystem are broadly categorized as measurement, monitoring, communication, and control. The nature and interrelationship of these functions define the overall architecture. The sensors to measure system performance parameters are assumed to be dispersed mainly on the flow loops and power conversion unit.

5.5 Power Conversion System

The purpose of the power conversion system is to convert thermal energy from the core into usable electricity and then to transfer that power to the user load. To accomplish these tasks, the power conversion system consists of three subsystems. The power conversion unit (PCU) is responsible for the production of electricity. The radiator couple is responsible to transfer removing unconverted energy toward heat rejection system. Finally, the conversion and transmission system has the job of transforming and transmitting electric power.

5.6 Heat Rejection System

The heat rejection system must ensure the dissipation of waste heat from the reactor. The radiators must be compatible with the power conversion rejection temperature and fluid cooling loop, tolerant to the space environment and reactor-induced radiation environment, and stowable, so that the complete nuclear reactor system can be easily packaged in launcher fairings.

The state-of-the-art in large space radiator technology is the International Space Station (ISS) Heat Rejection System. The ISS HRS is a deployable, pumped-ammonia radiator assembly with aluminum facesheets, aluminum honeycomb, and stainless-steel flow channels. The ISS HRS includes eight radiator panels measuring 2.7 by 3.4 m each that extend to a deployed length of 23 m using a motor-driven scissor mechanism as shown in Figure 5.3. The total ISS HRS mass is 1123 kg and the total two-sided deployed area is 147 m² for an effective areal mass of 7.6 kg/m².

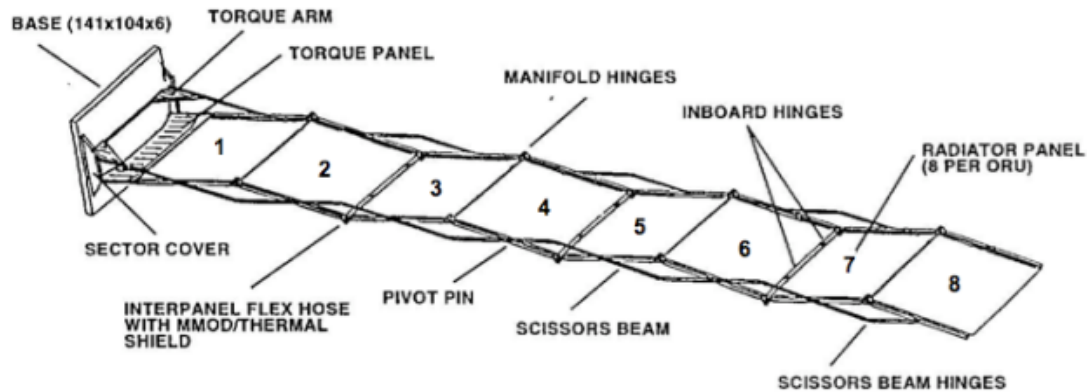


Figure 5.3 - International Space Station deployable heat rejection system

The use of composite materials can reduce the heat rejection system areal mass relative to the ISS design by as much as 50 percent, moreover guaranteeing high thermal conductivity, and high strength.

For a reference system mass budget, refer to Table A.3, where estimates (20% mass margin included) for stainless steel and refractory materials reactor options for Fission Surface Power systems are presented. Three different power conversion system configurations, LM Stirling cycle, gas-cooled (Xe-He) Brayton cycle, thermoelectric conversion are evaluated.

6 CONCLUSIONS

The power level of both the 30 kWe and the 200 kWe nuclear reactor that are the focus of DiPoP find no parallel in the commercial and military world of nuclear reactors. Compactness, flyweight and reliability over lifetimes of order many years pose special problems. Some, especially life and reliability, have already been solved in submarines by means that are in part completely different and partly similar, but where the information is proprietary or classified. Besides the key issues of materials irradiation, reactivity (neutronics), and control, a preliminary key issue is the prompt harvesting of all information necessary to tell which and what are the known critical issues, and which are still potential critical unknowns in need to be explored for space applications.

Bibliography

- Beynon, T.D., Beynon, T.D., (1974), The Nuclear Physics of Fast Reactors, *Reports on Progress in Physics*, **37**, 951.
- Blankenship, D.D. et al., (2010), in *EUROPA*, ed. by R.T. Pappalardo, W.B. McKinnon, K. Khurana (The University of Arizona Press, Tucson), 631–653.
- Bruzzone, L. et al., (2011), Subsurface Radar Sounding of the Jovian Moon Ganymede, *Proceedings of the IEEE*, 99, n 5, 837-857, *SOLAR SYSTEM RADAR AND RADIO SCIENCE*.
- Campbell, M. D., et al., 2009, "Developing Industrial Minerals, Nuclear Minerals and Commodities of Interest via Off-World Exploration and Mining," Paper/Poster at Conference of the American Association of Petroleum Geologists (AAPG), Energy Minerals Division, June 9, Denver, Colorado.
- Chyba, C. F., et al., (1998), Radar detectability of a subsurface ocean on Europa, *Icarus*, **134**, 292-302.
- Del Rossi A., C. Bruno, (2008), *The Chernobyl accident : a detailed account*, in *Nuclear space power and propulsion systems*, ed. C. Bruno, AIAA Progress in Astronautics and Aeronautics, Vol.225, AIAA, Reston, VA, Appendix B.
- Dewar J. A., *The Story of The Nuclear Rocket: Lessons for The Future*. IAC-02-IAA.2.4.06 53rd International Astronautical Congress-The World Space Congress, Oct. 10-19, 2002, Houston, Texas, USA.
- Dewar J. A., *To the End of the Solar System: The Story of the Nuclear Rocket*, The University Press of Kentucky, Lexington, KY, USA, 2002.
- Eckart, P., (2006), *The Lunar Base Handbook*, 2nd edition, McGraw-Hill.
- Elphic, R. C., et al., (2000), Lunar Rare Earth Element Distribution and Ramifications for FeO and TiO₂: Lunar Prospector Neutron Spectrometer Observations, *J. Geophys. Res.*, **105**, 333-346.
- Fission Surface Power Team, (2010), Fission Surface Power System Initial Concept Definition, NASA/TM—2010-216772.
- Frunze, J.W., ISU Engineering, October 28, 1999.
- Galli and C. Mancini, *Esposizione alla radioattività ambientale*, Ingegneria Nucleare e Tecnologie Energetiche, 38, n.1-4, Jan-Aug. 1996.
- ICRP Publication 60. *1990 Recommendations of the International Commission on Radiological Protection*. Annals of the ICRP – Volume 21 n. 1-3, 1991
- Johnson, L., (2010), Opportunities for Near Earth Object Exploration, ESMD NEO Objectives Workshop, NASA HQ.
- Knief, Ronald A., (1992), *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, Hemisphere Publishing Corporation.
- Klein H.A., *The Science of Measurement: A Historical Survey*, Dover, New York, Ch. 49.
- Kofman, W. et al., (1998), Comet nucleus sounding experiment by radiowave transmission, *Advances in Space Research*, **21**, 1589-1598.
- Kordylewsky, K., (1961), Photographische Untersuchungen des Librationspunktes L₅ im System Erde-Mond, *Acta Astronomica*, **11**, 165-169.
- Lawrence, D. J., et al., (1998), Global Elemental Maps of the Moon: The Lunar Prospector Gamma-Ray Spectrometer, *Science*, **281**, 1484-1489.

- Lawrence, D. J., et al., (1999), High Resolution Measurements of Absolute Thorium Abundances on the Lunar Surface, *Geophysical Research Letters*, **26**, 2681-2684.
- Lenard, R.X., (2008), A review of reactor configurations for space nuclear electric propulsion and surface power considerations, in *Nuclear space power and propulsion systems*, ed. C. Bruno, AIAA Progress in Astronautics and Aeronautics, Vol.225, AIAA, Reston, VA.
- Lewis, J.S., (1996), *Mining The Sky*, Addison-Wesley Publishing Co., Reading, MA, 274p.
- Lillie, C.F., (2006), On-Orbit Assembly and Servicing for Future Space Observatories, Proceedings of SPIE, 6265, 62652D, May 24, Orlando, Florida.
- Lipinski, R. J., Wright, S.A., Lenard, R.X., Suo-Antilla, A.J., Vernon, M. E., Marshall, A.C., Jablonski, J.A., and Helmick, P.H., (2004a), CRADA SC03/01673 Final Report: Space Reactor Trade Studies and Conceptual Design, Sandia National Laboratories, November 23, 2004.
- Lipinski, R. J. Wright, S.A., Lenard, R.X., Metzinger, K.M., Nygren, R., Youchison, D.L., Viswanathan, S., Jablonski, J.A., Helmick, P.H., Beard, S.G., Humberstone, M., Rollston, L.R., Potter, D. L., Young M.F., Vehar, D., Berry, D. and Hanson, D., (2004b), CRADA SC03/01670 Final Report: "IRAD Activities for Jupiter Icy Moons Orbiter, Sandia National Laboratories, November 23, 2004.
- Maise G., Personal communication <http://www.nato.int/science/e/grants>
- Mason L.S., (2006), A comparison of fission power system options for lunar and Mars surface applications, *Space Technology and Applications International Forum (STAIF-2006)*.
- Mason L.S., et al., (2008), System Concepts for Affordable Fission Surface Power, *Space Technology and Applications International Forum (STAIF-2008)*.
- McKay, M.F., McKay, D.S. and Duke, M.B., eds., (1992), Space Resources, NASA SP-509, Vols. 1-4, NASA Scientific and Technical Information Program, Washington, D.C.
- Moore, J.C., (2000), Models of Radar Absorption in European Ice, *Icarus*, **147**, 292-300.
- Morbidelli, A., et al., (2002), Origin and Evolution of Near-Earth Objects in *Asteroids III*, edited by W. F. Bottke, Jr., et al. University of Arizona Press, 409-422.
- Mukhin, K.N., *Physics of Atomic Nucleus Volume I*. Mir Publishers, Moscow, 1987.
- Nelson, M.L., et al., (1993), Review of Asteroid Compositions, in Lewis, J.S., et al., (1993), *Resources of Near-Earth Space*, University of Arizona Press, 493-522.
- Oegerle, W. R., (2006), Concept for a Large Scalable Space Telescope: In-Space Assembly, Proceedings of SPIE, 6265, 62652C, May 24, Orlando, Florida.
- Parker, E.N., Shielding Space Travellers, *Scientific American*, **294**, No. 3 March 2006.
- Phillips, R. J. et al., (2008), Mars north polar deposits: stratigraphy, age and geodynamical response, *Science*, **320**, 1132.
- Plaut, J. J., et al., (2007), Subsurface radar sounding of the South Polar Layered Deposits of Mars, *Science*, **316**, 92-95.
- Poston, D. et al. (2003), Notes from Space Reactor 101 Conference. Arcadia, CA.
- Powell J., Maise G. and Paniagua J., *MITEE: An Ultra Lightweight Nuclear Engine for New and Unique Planetary Science and Exploration Missions*. IAF-98-R.1.01

- 49th International Astronautical Congress, Sept. 28-Oct. 2, 1998, Melbourne, Australia.
- Powell J., Maise G. and Paniagua J., *The MITEE Family of Compact, Ultra Lightweight Nuclear Thermal Propulsion Engines for Planetary Space Exploration*. IAF-99-5.6.03 50th International Astronautical Congress, Oct. 4-8, 1999, Amsterdam, The Netherlands.
- Reddy, F., (2008), How Scientists Discovered a Solar System —Superhighway, *Astronomy*, November.
- Safaeinili, A. and Ostro, S. J., (2002), Imaging the interiors of near-earth objects with radio reflection tomography, *Workshop on Scientific Requirements for Mitigation of Hazardous Asteroids & Comets*, September 3, Arlington, Virginia.
- Safaeinili, A. et al., (2005), High-Power Radar Sounders for the Investigation of Jupiter Icy Moons, *Workshop on Radar Investigations of Planetary and Terrestrial Environments*, February 7-10, Houston, Texas.
- Sanchez Cuartielles, J.-P. and McInnes, C., (2011), Asteroid Resource Map for Near-Earth Space, *Journal of Spacecraft and Rockets*, **48**, 153-165.
- Siamidis, J., et al. (2005), Heat Rejection Concepts for Brayton Power Conversion Systems, NASA/TM-2005-213337, NASA Lewis Research Center, Cleveland, Ohio.
- SSP 2010, International Space University Space Studies Program 2010, Asteroid mining Technologies Roadmap and Applications (ASTRA).
- Stokes, G. H., et al., (2003). *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters*. Report of the Near-Earth Object Science Definition Team, NASA, Office of Space Science, Solar System Exploration Division, Maryland, USA.
- Summerer, L., and K. Stephenson, (2011), Nuclear power sources: a key enabling technology for planetary exploration, *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, **225**, 2, 129-143.
- Sutton G.P., Biblarz O., (2010), *Rocket Propulsion Elements*, 8th edition, Hoboken, New Jersey.
- UNSCEAR (1993). United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. UNSCEAR 1993 Report to the General Assembly, with Scientific Annexes. United Nations, New York.
- UNSCEAR (2000). United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. United Nations, New York.
- UNSCEAR (2001). United Nations Scientific Committee on the Effects of Atomic Radiation. *Hereditary Effects of Radiation*. UNSCEAR 2001 Report to the General Assembly, with Scientific Annexes. United Nations, New York.
- Valeska, S., (2005), Chernobyl: poverty and stress pose 'bigger threat' than radiation, *Nature*, **437**, 181.
- Villard, R., (2004), Beyond Hubble The Very Large Space Telescope, *Astronomy*, November.
- Zarka, P., et al., (2004), Jupiter's low-frequency radio spectrum from Cassini/Radio and Plasma Wave Science (RPWS) absolute flux density measurements, *Journal of Geophysical Research*, **109**, A09S15.