Limits of the Advanced Nuclear Power Systems for Space Exploration

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Abstract

Nuclear power as we know it today is in its infancy and has a long way to evolve before reaching its limits. The proposed advanced nuclear systems, based on heterogeneity by design, represent one step forward but surely not the ultimate end. Compact power supplies, based on direct nuclear energy conversion into electricity, a kind of super-capacitor charged by the kinetic energy of product nuclear particles and discharged as electricity, has a major strategic importance. This device will power the electric thrusters of a spacecraft, its directed energy systems, the shielding and all the rest of equipment onboard. One must consider that all this power in part becomes heat, and the spaceship have to deal with it, in part by converting it into electricity, via switched thermo-electric devices, and in part by removing it via heat-pumps to dump it into space. One may immediately see the tradeoff.
Space is a hostile place for life. Novel nuclear materials developed based on nano-technologies can be used as shielding and to create materials that self-repair from radiation damage.

A combination of radiation guides in nano-structure shield tiles and in direct nuclear energy conversion tiles may be used as active shielding and remote power transport and, when combined with classical radiation absorption materials, may create for astronauts a safe habitable zone in the spaceship.

Complex, multi-spectrum nuclear detectors can help in evaluating the environment and study all the aspects of outer space.
The biggest limitation with respect to the range a manned spaceship may reach comes from its propulsion, which requires mass much larger than that of the spacecraft to be ejected in order to transfer momentum. 

*Basically, it does not help to eject into space a small mass with high speed.*

Better propulsion efficiency is obtained if energy is distributed to a mass equal to that of the spaceship.

This is a very strong constraint, implying that, even with the best nuclear power driving the best rocket propulsion, we may reach the outer boundaries of the Solar System, the Oort cloud, but no further than $\frac{1}{2}$ light-year.

**In order to have interstellar spaceships we need to drastically improve propulsion and further use advanced nuclear power in various systems onboard.**
Generations of Nuclear Reactors

PHWR

FBR

**Generation I**
- Early Prototype Reactors
  - Shippingport (Pennsylvania)
  - Dresden (Illinois)
  - Fermi I (Michigan)
  - Magnox

**Generation II**
- Current Commercial Power Reactors
  - LWR, PWR, BWR
  - CANDU
  - VVER/RBMK
  - AGR

**Generation III**
- Evolutionary Reactors
- Advanced Evolutionary & Passive Reactors

**Generation III+**
- System 80+
- ABWR
- APWR
- AP600

**Generation IV**
- New technologies that may co-produce hydrogen

**Timeline**
- Gen I: 1950 - 1960
- Gen II: 1960 - 1970
- Gen III+: 1990 - 2010
- Gen IV: 2010 - 2030

The heated water from the reactor circulates through the steam generator and transfers its heat to the water here. It boils off and pressurized steam moves through pipes to the turbine building. Turbines are driven by pressurized steam forced through them. The generator is driven by the motion of the turbines.
heterogeneity by design
The Idea!

**The METHOD**

is about how to control

moving entity

Range

- fission products, 5-30 microns (fp)
- charged particles, 5-30 microns (cp)
- electrons, 10-1000 nm (e^-)
- recoils, 3-20 nm (R)
- neutral atoms, En dependent (NA)
- molecules, En dependent (M)

by using a plurality of

**elemental modules** made of three components and interfaces

with

**Generic functionality** alone or together

Elemental module

- Generator
- Insulator
- Absorber

Interfaces


cp/cp

**14 μm**

**100 nm**

**10 nm**
5 + 1 Basic developments / Details

Micro-heterostructures

Nano-structured cladding

Radiation damage

Fission products

Nanoclustered structures

Transmutation products

Radiation nano-guiding structures

Space fiber or connection to a subspace?

Shielding and criticality control

Meta-materials

Knock-on electrons

55 Pd

He Recoil

102 110 113Pr

Carrier-Multiplication-Based Fuel
Generation - \( V \)

Higher power density
Longer fuel life
Higher burnup
Enhanced reprocessing
Enhanced fuel cycle

\( T2M - 5-50 \) years

Generation - \( VI \)

Enhance fuel cycle
Improved fuel breeding
Diversified transmutation
Cheaper fuel
Increased nonproliferation
Near perfect burning
Reduced waste

\( T2M - 10-70 \) years

New generations of Nuclear Power Sources

Generation - \( VII \)

Direct energy production
Portable nuclear power
Reduced reactor size
Space and under-water reactors
Advanced Isotopic batteries

\( T2M - 20-80 \) years

Generation - \( VIII \)

Enhanced reactor control
High power densities
Light shielding
Portable reactors
Enhanced safety

\( T2M - 30-100 \) years
Direct energy conversion

Nano-guides

Position, direction, energy, particle detector

Nano-hetero structure

Transmutation probe
Indicates spectrum and flux
Traces fuel breeding and transmutation
Safe-guard detector

T2M- 5-50 years

T2M- 10-70 years

T2M- 20-80 years

T2M- 30-100 years

New generations of Nuclear Detectors
direct nuclear energy conversion into electricity
The novel development of a **direct energy conversion meta-material** based on a plurality of conductor-insulator (C-I) interfaces resembling a **super-capacitor** loaded by the energy of the moving nuclear particles as heavy ions, neutral atoms, alpha particles, protons and deuterons and discharged as electric current onboard has the potential of changing the propulsion system, making them lighter and more efficient.

![Diagram of the energy conversion process](image_url)
During the harvesting of the particles energy in the structure their impulse is also absorbed and transmitted to the shuttle.

Energy conversion principle

The limitation is related to the efficiency of conversion of the particle’s energy
The Dimensions of a Spherical Nuclear Reactor versus the Critical mass

Criticality may be reached in very small structures, 1-2 ft large, Total mass < 50-100 kg

Maximum Power densities are $10^4$ times than the actual nuclear reactors, of $<1$KW/cm$^3$

Nano-layered structure
The novel meta-material may be fabricated in tiles, good for plating parts of the shuttle or satellite by morphing on its surface to serve as active shielding.

The tile has several layers customized on type of particles and energies.

The tile cross section

![Diagram showing tile cross section with layers for different particle interactions.]

- High albedo and absorption material
- Cellular separator
- High density, high cross-section material
- Intermediary layer
- Short ranges and EM absorption layer
- Heavy particle
- High energy light element or neutrons
- Absorption
- Reflection
- Cascade interaction
- Harvesting mosaic

Energy
electric thrusters
A finite amount of energy

\[ E = \frac{m}{2} v^2 = \frac{p}{2} \frac{v}{2} \]

\[ p = mv \]

\[ E_{\text{nucl}} = \text{const} \]

\[ \nu_{\text{ch}} = \text{const} \]

\[ \Delta V = v \ln \frac{m + M}{M} \]
Continuous jet
Deflected trajectory
Spacecraft

ATACMS (Advanced Tactical Missile System);
LASM (Land-Attack Standard Missile);
L/H_TODEV (Low/High Terrestrial Orbit Directed Energy Vehicle System);
ERGM (Extended-Range (Gun) Guided Munitions)
SDEV (Stratospheric Directed Energy Vehicle System)
Radiation Detectors
Position, radiation energy, direction sensitive detectors

Particles hitting a sensitive volume

Impact position

Position addressing electronics

Detection procedure
Shielding and Criticality Control

Shielding is bulky, and requires several ft to stop neutrons. Even the reactor is small the shielding is BIG!

Solution:
Make a nano-structure that to guide inside and bend the radiation (neutrons, gamma) turning back towards the absorbing material.

Nuclear reactor control is slow, based on absorption rods mechanically actuated using mainly the delayed neutrons that represent <0.5%.

Solution:
Use nano-structure neutron guiding effect, adding an electro-sensitive material that may switch the pass, from turning back towards active zone or let pass along into an absorbent material.
This is a supplementary effect predicted to be triggered by the radiation effects in meta-materials, and intended to be studied at direct conversion nano-structured materials.

Nano-structured structural materials

Extremely important to increase the life-time of the reactor structure, to allow for higher burnup without re-cladding or restructuring.
1 - Nano-structured cladding

Radiation damage

Is produced by the gamma and neutron interaction with structural materials – that make them swallow and loss mechanical properties

Solution:
Make a special material
That recovers the radiation damage itself, similar to graphite over 700 k.

It will be a bi/tri- material with defined grain-boundary interface properties, that makes the boundary self-heal.
Types of nano-composite structures

Composite $\text{SiC}_\text{fiber}$-$W,\text{Ti}$ plating

Immiscible solid solutions

Nano-layered

Nano-clustered

Nano-structured immiscible composite-material (NSICM)

Stress [Mpa]

Strain [%]

$T_1 = T_{irr} = 50^\circ C$

316 SS

(NSICM)
Five fundamental developments based on nanotechnologies to improve the fission reactors

1. Nano-structured cladding
2. Radiation nano-guiding structures
3. Shielding and Criticality Control
4. Meta-materials
5. Knock-on electrons

- Micro-heterostructures
- Fission products
- Nano-clustered structures
- Transmutation products
Reactions inside a nuclear reactor

Fission Products (FPs)

Knock-on electrons (Ke)

Recoils (R)

Nuclear space-time

Atomic space-time
Fusion

Total kinetic energy = 10-22 MeV
Total Mass : 8-12 amu
Ratio : reaction dependent
Averaged Speed : 15 000 Km/s

\[ \begin{align*}
\frac{2}{1} D + \frac{3}{1} T & \Rightarrow \frac{4}{2} He (3.5 \text{ MeV}) + \frac{1}{0} n (14 \text{ MeV}) \\
\frac{2}{1} D + \frac{6}{3} Li & \Rightarrow 2 \times \frac{4}{2} He (11.2 \text{ MeV}) \\
\frac{3}{2} He + \frac{2}{1} D & \Rightarrow \frac{4}{2} He (4.3 \text{ MeV}) + \frac{1}{1} H (11 \text{ MeV})
\end{align*} \]

\[ \begin{align*}
2 \times \frac{1}{1} p + 3 \times \frac{1}{0} n &= \left[ (2 \times 938 + 3 \times 940) \frac{\text{MeV}}{c^2} \right] = 4696 \frac{\text{MeV}}{c^2} \\
4 \times \frac{1}{1} p + 4 \times \frac{1}{0} n &= \left[ (4 \times 938 + 4 \times 940) \frac{\text{MeV}}{c^2} \right] = 7512 \frac{\text{MeV}}{c^2}
\end{align*} \]

and the efficiencies are 0.37% respectively, 0.3%.
Tiles are morphed on inner fusion reactor chamber to harvest charged particles energy

Fusion application
Delivers 3 times more energy/mass than fission

Total kinetic energy = 10-22 MeV
Total Mass : 8-12 amu
Ratio : reaction dependent
Averaged Speed : 15 000 Km/s

\[
\begin{align*}
{\frac{2}{1}}D + {\frac{3}{1}}T & \Rightarrow {\frac{4}{2}}He \ (3.5 \text{ MeV}) + {\frac{0}{1}}n \ (14 \text{ MeV}) \\
{\frac{2}{1}}D + {\frac{6}{3}}Li & \Rightarrow 2 \times {\frac{4}{2}}He \ (11.2 \text{ MeV}) \\
{\frac{3}{2}}He + {\frac{2}{1}}D & \Rightarrow {\frac{4}{2}}He \ (4.3 \text{ MeV}) + {\frac{1}{1}}H \ (11 \text{ MeV})
\end{align*}
\]

\approx10^{18} \text{ fusion inducing collisions per second are needed for 1 MW}
Nuclear molecules

Fusion in quantum active environment

Nuclear molecule compaction
The process and the **NEW PHYSICS** beyond

**Stage 1 – Doper-Lattice synergy**

Tunneling tube
OPEN!

**Stage 2 – Non-local nuclear reaction**

Nano-structure and its parameters determines how the energy is released

As kinetic energy

As collective lattice HEAT energy

**Stage 3 – Final products Energy harvesting**
Complex, multi-spectrum nuclear detectors
Cross sections

Spectral n flux measurement

\[ MS = \phi \{EGR\} \approx \phi \{k \times \sigma_f(E) \times \phi(E)\} \]

Measured spectrum

10 Energy group detector response

Spectral n flux measurement

EGR
n-rad Detector features

- N detection efficiency x100
- Pulse shape discrimination between gamma and n
- Pulse or integral mode operation
- N spectra, position and direction

Multi-FMAT detector

n energy sensitive detection volumes

2”

E directions S

N W
1. **n-rad Detector features**

   - N detection efficiency x100
   - Pulse shape discrimination between gamma and n
   - Pulse or integral mode operation
   - N spectra, position and direction

2. **Micro-hetero structured detectors - The operation principle**

3. **Cross sections**

4. **Spectral n flux measurement**

   - MS = \( \varphi \{EGR\} \approx \varphi \{k \times \sigma_f(E) \times \phi(E)\} \)

   - Measured spectrum

5. **Energy group detector response**

6. **Energy group detector response**

7. **Nuclear reactor channel detector**

8. **Portable \((\gamma,n,\alpha,\beta)\) Detector**
Nuclear reactor channel detector

Sensitive material  Scintillator input
Detection sub-sector  Detection sector
Central tube  Transparent tube

Portable \((\gamma,n,\alpha,\beta)\) Detector
Possible outcomes

Pushes the nuclear reactor performances towards the physical limits
Better Shielding + radiation control

The principle of shielding

Body and electronics shielding

Ultra thin, ultra light active shielding for mobile ultra-small reactors

5g$^{239}$Pu/1Mmiles

Nano-waveguides for nuclear radiation advanced shielding
A significant miniaturization may be possible: Without the intermediary thermo-mechanical cycle the reactor may become a solid state fission based battery.
Fusion Battery

Power output $1 \div 100$ kWe**

To computer control

Combustible function

Cooling 1

Burner

Cooling 2

Dozer

Control
The fusion battery

Li-Air battery

Fusion Battery – 10 MW

589 MWh
25 MWDay

P=10 MW
for 2 ½ day

Controller

Electron Flow

Negative Electrode

Li^+

Positive Electrode

Electrolyte

Lithium Oxygen Compound
Lithium Ion
Carbon
Manganese Oxide (the catalyst)

Oxygen

20kV
Fusion – propulsion mixed system

Shuttles payload
The tiles are morphed in specialized antenna arrays used for shuttle’s trust by an external ion beam jet sent in the antenna from a space outpost.

**Space Applications**

**From panels to shielding and antenna**

The energy harvested in nuclear structures, may be returned as beam to the outposts’ antenna by accelerators onboard used in continuous or pulsed operating regime, having a large range of applications. The same energy may be exchanged several times between the space shuttle and outpost multiplying the trust.
limitation
On Earth – Fissile material storage limitation

Reactor masses versus enrichment

$y = -898.32 \ln(x) + 4404.6$

$R^2 = 0.9505$

Fissile mass [kg]

Enrichment [%]

Terrestrial reactors statistics

Fission based systems
The actual fission structures suffer of: "fissile total mass limitation" due to criticality issues on the shuttle and.

**NOTE:** This limitation appears as due to techno-economical reasons.

1 Kg of fissile material \((^{235}\text{U}; ^{239}\text{Pu})\) = 1 GWDay
There is no such physical limit;

5 tons of pure fissile material is the upper limit, but to have 5 tons sub-critical, in long term stability condition, takes 10-20 times more mass of efficient neutron absorber material.

This starts to be an issue for on-board power demand over 100 Mw, that uses 100 kg/year. 5 tons \(\rightarrow\) 50 years

*Not yet there!*  

Fusion systems has *Not this storage limitation*!

1 Kg of fusion product \(\rightarrow\) 3 GWDay
The Power domain versus Operation Temperature

$y = 10873e^{-0.0047x}$

$R^2 = 0.4884$

$P = P_0 e^{-\frac{t}{T_e}} = 10.9[Gw] * e^{-\frac{t}{212.77}}$
Power density and pellet’s radius limitation due to temperature - nuclear to electric conversion efficiency due to thermal limitations in structural materials and fuels that limits the specific power density and energy density, therefore any outside contribution to propulsion and energy is welcomed.

There are very few gas turbines that may work with intake gas over 1200 °K.
**Issue:** Low grade thermal power onboard removal

**Example:** low grade heat of 150 °C → 5 Kw/m²

\[ P = Q = \varepsilon A \sigma (T^4 - T_e^4) \]

\[ Q = \left[ \frac{1 - \varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \left( \frac{1 - \varepsilon_2}{\varepsilon_2} \right) \frac{A_1}{A_2} \right]^{-1} A_1 \sigma (T_1^4 - T_2^4) \]
The tiles are morphed in specialized antenna arrays to be directly used for shuttle’s trust by an external ion beam jet sent in the antenna by a space outpost. The limitation are the efficiency of conversion of beam energy in the tile’s meta-material and of the harvested energy back in the accelerator structure on shuttle to generate the returned beam.

The energy harvested in nuclear structures, may be returned as beam to the outposts’ antenna by accelerators onboard used in continuous or pulsed operating regime, having a large range of applications. The same energy may be exchanged several times between the space shuttle and outpost multiplying the trust.
Propulsion

Courtesy Jet Propulsion Lab.
\[ \nu_s = \sqrt{\frac{2E_p m_p}{m_s (m_s - m_p)}} \]

\[ \eta = \frac{E_s}{E_p} = \frac{m_p}{m_s} \approx 10 ppm \cdots 1 ppb \]
The ion beam based propulsion seems to be among the most mass effective reaction based propulsion systems, but there is a technical-economic tradeoff between ejected mass and its energy that started become visible for nuclear powered systems.

\[ E = \frac{m}{2} v^2 = p \frac{v}{2} \]

\[ p = mv \]

The limitation in nuclear systems is that the fission or fusion products have limited speed inside the non-relativistic domain, but better performances are obtained when the released energy is applied to a supplementary mass.
The ion beam based propulsion seems to be among the most mass effective reaction based propulsion systems.

- There is a techno-economic tradeoff between ejected mass and its energy that started become visible for nuclear powered systems.

The energy \( \{0.1-100 \text{ GWDay}\} \) is used to accelerate the jet and use its thrust.
Ballistic (with DSM)  
Transport to Mars  
Particularities  

N. Summer  
400sols  
30sols  

N. Spring  
Venus  
Sun  

N. Autumn  
Severe weather  
N. Winter  

Dust storms  

56 Gm  
1w  
1.5 mo  
384 Gm  

Deep-space orbits shorter and faster but requires nuclear propulsion  

Mars trip  

Opportunity window  
2018, 2025  

Solar Weather and Distance between Mars and Earth versus Time  

Distance between Earth and Mars in AU  

Stay on Mars  
Transit  
Return
An imaginary travel somewhere to Alpha Centauri

Mission = Impossible!

Possible planets at Alpha Centauri

α Centauri A

α Centauri B

Life zone

Proxima (α Centauri C)

(13,000 astronomical units away from A and B)

11 AU distance at closest approach

2 AU limit for stable orbits

The Sun and its terrestrial planets (on the same scale)

Now $v=1 \text{hl/y} \rightarrow 40 \text{ky 20xfaster}$

$>2,700 \text{y} = 1600 \text{kg}_{\text{fiss}} + \text{CM}$

$\geq 500 \text{y}/R_{\text{only}}$

Energy on board = 100 [M ton TNT]
The intergalactic trips with living crews seem not possible with the best fusion energy and the best jet propulsion envisaged at this time and might be thoughtful to pay more attention to new approaches that gives better grip to space-time handling.

NO !

Now: $10y/1lh$; NPP $\rightarrow 1y/1lh$

The complementary aspect is that this fission-fusion based technologies are good enough for trips inside the solar system, and a special attention has to be given to their development, and to the ability of developing self-sustainable life modules in any position in the solar system.
A new view on nature
Some clues, that something more exists

Easter Island

Mexico Under Sea

Romania, MIG-21 collision 2007

MIG-21 Lancer
Various shapes of spaceships
A 1kg weight suspended over the device could lose 2% of its weight, (1kg = 980g)

Cooled with liquid nitrogen

Superconducting ceramic rim spinning at 5,000rpm

Solenoids create magnetic field around rim

Solenoids allow ring to levitate magnetically

30.4cm

Theoretical anti-gravity device designed by Dr Yevgeny Podkletnov
Zero Point energy?
Reality or science fiction?

Does it matter?

There are so many unexplained encounters, so we might use this information as a challenge to improve the performances of our own system beyond this level.
Potential opportunities:
or potential distractions??:
The UFO phenomena:

TA-51 stories:

Boyd Bushman
Born 1936 in Globe, Arizona
Passed away August 7, 2014 in Tucson, Arizona
Frequent Observations

'Tucson/Phoenix AZ lights

The spaceship

Hovering or parked

Quintonia planet 63 ly

In 45 min reach Solar system

Accelerating

Traveling

Take off

Landing on Earth

LN=37.274147, lg=-115.801373, h=60 km

Spaceship’s Engine

P27
Fermi’s paradox?
Even we might have these leads, our main problems remains analogies! More than an warning!

A captive pilot can not tell how his ship was made!!

Looks like TA51
But; Is it enough?

Suppose:
- We have the best nuclear energy available onboard
-- We have an advanced propulsion system as in the picture;
* Now what?
- The more we learn, the more we realize our ignorance,…

In order to have safe, reliable space travel we have to commit the big step in our evolution from a Planetary to an Inter-galactic civilization.
"Man will not fly for fifty years."
—Wilbur Wright, 1901

"Heavier-than-air flying machines are impossible."
—Lord Kelvin, president, Royal Society, 1895

"There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will."
—Albert Einstein, 1932

"Anyone who looks for a source of power in the transformation of the nucleus of the atom is talking moonshine."
—Ernest Rutherford, 1933

"Space travel is utter bilge."
—Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956

"Airplanes are interesting toys but of no military value."
—Marshall Foch, future WWI French commander-in-chief, 1911

Famous misjudgments
A Nuclear Universe

EM nano-rings absorber

Fusion + Fission + Position = Life

Earth is a Nuclear Reactor too!

Otherwise life might Not be possible

View from the Earth to the galaxies

Flying vehicles