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NUCLEAR WASTE DISPOSAL IN SPACE: A LONG TERM SOLUTION

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As a consequence of the steady increase in energy demand and the economical and environmental problematic associated to the greenhouse gas-emitting fuel burning, there is a worldwide increasing energy dependence on nuclear power sources, resulting in large quantity of radioactive waste to deal with.

Even if effective methods to improve the efficiency of the nuclear reactors and to reduce the amount of radioactive waste generated are currently investigated, the problem of disposing of the already existing waste remains. According to the forecast of experts, the problem must be effectively solved during the next ten years otherwise the nuclear energy growth will slow down and production decrease influencing negatively the economy of many countries.

The way the wastes are disposed today at great depth under unpopulated areas have drawbacks such as the fact that during the long term storage (hundreds or even thousands of years), the integrity of the containers with the high-level activity and «long half-life» radioactive waste is threatened by the tectonic dislocations, by destructions during earthquakes as well as by material corrosion.

The cost of highly reliable burial sites and the cost to support an accurate continuous monitoring of these depositaries to protect them for hundreds of years will probably exceed the cost which is necessary to remove the radioactive waste away from the Earth biosphere using launchers. This is why, since long ago, the disposal of processed nuclear waste in space, especially the longest-life and most toxic isotopes, was considered as a promising, practical and economically viable option in order to maintain a clean Earth for the next generations.

NASA and DOE have intensively studied the space disposal of hazardous waste in the 70's and 80's. As an example, NASA designed payload containers that would survive a worst-case accident for application on the Space Shuttle. Past studies have never succeeded mainly due to the difficulty to demonstrate the overall safety associated with all phases of launching and operation - normal, emergency, abort and accident - of such a system and the affordability of the system, knowing that only unsound and costly space transportation systems could be proposed. However, the launching techniques proposed to make such a system acceptable at the horizon 2020 need to be carefully revisited taking into consideration the launchers available as well as the new developments and possible breakthroughs foreseen with the future launchers. The space-disposal option must be cost effective and must feature, if any, a cost increase limited to a few percent per kW-h to the customer.

Various possibilities for disposing of nuclear waste in outer space are possible. The use of Earth orbit as repository for the nuclear waste was considered, giving attention to the distances of the waste containers from the Earth. The acceleration of the containers to a velocity that is sufficient to ensure that the waste containers will leave the solar system was also taken into account. The solution of transporting and delivering waste containers to the Sun, the planets or moons was studied as well as the use of the lagrangian points of the Earth-moon or Earth-Sun system.

INTRODUCTION

The increase in awareness of the problem of global warming has led many nations to turn their efforts to energy sources that do not produce greenhouse gases. Nuclear energy – fusion and fission – are among the most efficient alternatives. While fusion is still in a research phase and should hopefully become available in the next decades, fission remains the only current alternative.

But nuclear fission produces an important of amount of waste products which need to be treated and stores or dispose of. Traditionally storage on Earth was the only viable alternative for this waste. But the increase in energy prices, another option might become an alternative in the coming years: sending the waste into space.

Therefore, in 2006 the European Space Agency initiated a study with Astrium in France and Yuzhnoye in Ukraine to study this alternative. This paper is a short synthesis of the study and provides the conclusions and recommendations for the future.

OVERVIEW OF THE CURRENT SITUATION

Many types of waste come out of a nuclear power plant today. Among all of them, only some kinds of hazardous waste should be considered for space disposal:

- The waste for which there is no possible treatment to make them less dangerous
- Those which will present a hazard for a very long period (with respect to human life scale)
- Those for which there is no economic terrestrial solution
- Or those for which there is no safe terrestrial solution

The best candidate solution for storage or disposal is space is known as Nuclear High Level Waste (HLW). This is the waste which represents a medium and high radioactivity and for the long term (half life higher than 30 years).

Today, spent nuclear rods coming out from power plants are first vitrified and spend 10 years cooling in swimming pools. These rods are made up for 25% of their mass by HLW. These rods are stored in power plants or dedicated sites (the barrels were dumped in oceans in the 1950's and 1960's).

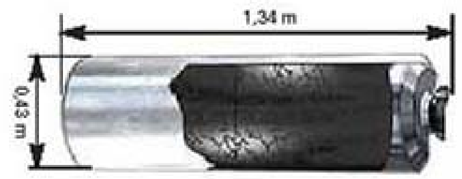

Figure 1 – Vitrified rod with C-type waste R7T7

HLW quantities

The amounts of high level waste that are stored today in various countries are rather high:

- In France, in 2004 there were 1851 m^3

- In Great Britain, in 2005 there were around 2000 m^3
- In the United States there are 52 000 tons of used nuclear fuel and thousands of tons coming from plutonium used for military applications.

Considering the countries that represent the 20 first contributors in terms of nuclear power generation, the situation was the following in 1997: there were 122 000 tons of waste and 12 000 additional tons were produced each year. It was then considered that the existing storage capacity would be full in 2006 (226 000 tons).

Moreover, with the fear of accidents (Three Miles Islands, Chernobyl), HLW are contributing to the low acceptance of nuclear energy by public opinions and are the main obstacles to its expansion. Nuclear energy represents today only 6% of the worldwide energy and 17% of the worldwide electricity consumption. Few nuclear power plants were built in the last decade and some countries have even abandoned nuclear energy: Sweden in 1980, Italy in 1987, Belgium in 1999 and Germany in 2000. The Netherlands and Spain are planning a ban.

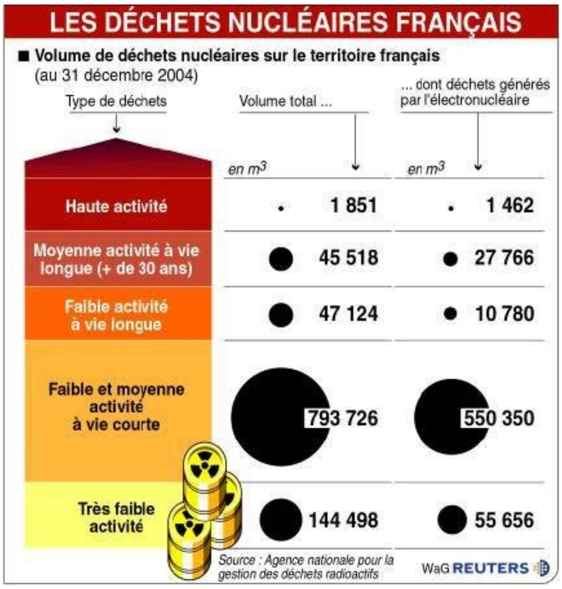

Figure 2 – Nuclear waste situation in France in 2004: Amount of waste as a function of radiation level (vertical axis)

Current solutions for HLW

Several solutions are used or investigated today for HLV.

Transmutation consists in using reactors that consume nuclear waste and transmute it to other, less-harmful nuclear waste. They produce no transuranic waste and could even consume transuranic waste. A fusion reactor where plasma could be "doped" with a small amount of the "minor" transuranic atoms could transmute them into lighter elements. Experimental reactors have not yet demonstrated an industrial feasibility: the Integral Fast Reactor was cancelled by the US, Superphoenix was closed by France, and there are mixed results and accidents in Russia and Japan.

Geological disposal is today the most used solution which can be implemented in different ways.

With **Remix & Return** HLW are blended with uranium mine and milled. When the original radioactivity of the uranium ore is reached, the mix is replaced in empty uranium mines.

Sea-based options for disposal are: burial beneath a stable abyssal plain, burial in a subduction zone that would slowly carry the waste downward into the Earth’s mantle and burial beneath a remote natural or human-made island. These approaches are currently not being seriously considered because of the legal barrier of the Law of Sea and because in North America and Europe sea-based burial has become taboo from fear that such a repository could leak and cause widespread damage.

Deep ground final repositories are being studied and considered by several countries (first decisions expected some time after 2010):

- Switzerland: the Grimsel Test Site is an international research facility investigating the open questions in radioactive waste disposal.
- Sweden: Plans for direct disposal of spent fuel are quite far, since its Parliament

decided that this is acceptably safe, using the KBS-3 technology.

- France: There is a research center for deep geological disposal in Bure. It is considered as the future French HLW final repository site.
- Germany: There are political discussions and protests. Gorleben is presently being used to store radioactive waste temporarily, with a decision on final disposal to be made some time in the future.
- United States: There is a final repository at Yucca Mountain in Nevada, but this project is widely opposed and is a hotly debated topic.
- Finland, China, Taiwan and South Korea are also evaluating sites.

There is also a proposal for an international HLW repository in optimum geology, with Australia or Russia as possible locations. Today there is a worldwide consensus for deep geological burial (« less bad solution »).

But there is no real acceptance of this kind of solution by public opinions because of the existing drawbacks:

- No reversibility (shallow and reversible solutions are emerging)
- Monitoring and security for thousands of years is difficult to demonstrate since our « modern world » is only centuries old and the potential danger is neither visible nor immediate. The closest possible example is sea-wall maintenance: done correctly since 1277 in the Netherlands, budget cuts and delays in New Orleans. Long term nuclear waste monitoring will have a cost without providing revenue.
- Container integrity has not been proven with respect to earthquakes, tectonic dislocation and material corrosion (risks of soil and aquifers contamination).
- New risks are appearing, such as terrorism.

SPACE DISPOSAL SOLUTION

Space disposal could therefore become today a viable alternative. Even if the new world situation today could make this possible, the idea was suggested several decades ago.

Past studies

Reference [R5] in 1978 showed one of the first ideas. Their proposal was based on the following principles:

- Shuttle launch based on the development hypothesis, namely that the Shuttle would perform more than 50 flights per year for a cost of a few tens of M$ per flight.
- Given the launcher’s mass constraint only high activity long half-life non-reusable elements are concerned for economical (high kilo-in-orbit price) and ecological reasons (several tens of tons of toxic propellants used by the Shuttle for one ton in Earth orbit).
- HLW mass can be reduced by a factor of 40 after separation of unused uranium and cladding (75 tons/year in 1997).
- The waste-to-container mass ratio must be maximized, while assuring radiation shielding, thermal control, reentry and impact protection. The ratio proposed was 15% in this study (this leads to a launch mass of 500 tons per year for the yearly production plus 10 000 tons for the already stocked waste).
- The orbits retained for the disposal were: High Earth Orbit (55000 km, LEO+4000

m/s), Lunar Soft Landing (LEO+6053 m/s), Solar Orbit (0,86 UA, LEO+4450 m/s) and Solar System Escape (LEO+8750 m/s).

Another paper was presented ([R4]) in 1999 proposing an alternative to the Shuttle launcher. The main conclusions of this paper were the following:

- The huge amount of spent fuel rods (77 100 tons by 2020 for US civilian reactors) justifies the development of a reliable and low recurring cost launching system (10 000 tons launched per year).
- Ground launch systems are proposed as alternatives: laser and microwave propulsion, electromagnetic rail-guns. These system offer low payload masses but quick turn around times.
- The simplest orbit was considered, namely solar system escape and was assured by a continuous thrust by laser.
- An alternative orbit proposed was a solar orbit inside Venus which would guarantee HLW retrieval by future generations if this was considered valuable.

A paper presented in 1980 the status of the on-going studies ([R1]):

- The waste generation hypothesis commonly accepted were that a 1000-MWh nuclear power plant produces 1,2 tons of HLW per year, which meant that 420 tons were produced worldwide with the 1997 production of 353 GWh.
- There was an ESA Call For Tender on June, 13th 1980 ([R2]).
- It was also commonly accepted that no nuclear power plant expansion could occur without a HLW long term solution.
- High earth orbits were seen as an economical and promising way but all alternatives (into the Sun, outside the solar system, on the Moon or others planets) had to be investigated.

Orbit	**DV**	**Orbit**	**Orbital boosts**	**Plus**	**Minus**	**Rank**
High Earth Orbit	4000	55000-km	2	Easily rescued & recovered, lowest DV	Orbital stability uncertain, public controversy, non-permanent disposal	5
Lunar Orbit	4250	21700-km	5	Possible rescue & recovery, low DV	Orbital stability uncertain, complex flight profile	4
Lunar Soft Landing	6050	Lunar back-side	5	Possible rescue & recovery, permanent disposal on celestial body, no orbital stability problem	Potential lunar contamination, public & scientific controversy, complex flight profile	2
Solar Orbit	**4450**	**0,85 AU**	**2**	**Permanent disposal, excellent orbital stability (> 10^6 years)**	**High subsystem lifetime, difficult rescue**	**1**
Solar System Escape	8750	-	1	Permanent disposal, high public acceptance, operationally simple	High DV, difficult rescue, non recoverable	3
Sun impact	24000	-	1	Permanent disposal, operationally simple	Very high DV, small fraction of waste returns to Earth	6

Table 1 – Possible waste disposal options in space (cf [R3])

<u>Waste container and reliability</u>

One of the critical aspects of the feasibility of the nuclear waste disposal in space is safety in case of launcher failure.

It goes without saying that the container must withstand by means of active or passive systems:

- The heat released by the radioactive source contained during the launch.
- The heat and the mechanical shocks released in case of explosion of the launcher at any time during the launch.
- The heat and the mechanical loads encountered during a high speed reentry into the atmosphere in case of launcher failure just prior to orbital insertion.
- The mechanical loads and shocks encountered upon impact on the ground after a launcher failure and container reentry.
- The extreme conditions that could be encountered on the ground prior to retrieval following a launch failure (extreme heat in case impact in the dessert, extreme pressure in case of impact in deep ocean waters).

These various requirements on the container has led in past studies to the definition of a serious of layers or containers instead of a single one:

- A waste canister which assures the physical integrity of the waste.
- A radiation shield which guarantees the safety of the ground crews during handling and launch preparation.
- A mechanical shield which will guarantee the integrity in case of launcher failure and impact on the ground.
- A thermal protection shield which will protect the previous containers during reentry into the atmosphere.

This last layer could break upon impact on the ground which will actually facilitate cooling during the wait time before retrieval of the container. The studies have shown that in case of fall down in the ocean the mechanical container should withstand the heat coming from the nuclear source thanks to the cooling effect of water. However, the worst case would be the fall and burial in dry ground, in which case the heating coming from the waste will be the sizing effect for the mechanical shield.

Economic feasibility today

The economic feasibility of nuclear waste disposal in space has been studied with the first preliminary figures and hypothesis that are available today.

In the European Union (25-countries) 129,4 GW x year were produced by nuclear power plants in 2006 (35% of world capacity).

Two scenarios were considered:

- a constant European nuclear power plant production and
- an increase of 4% per year in the next 50 years. This yearly increase corresponds to the increase of the nuclear part in the overall electricity production, to the increase of the electricity part in the overall energy consumption and to the increase in the electricity needs. A 1% per year increase was considered afterwards, corresponding to only the increase of electricity needs.

It was considered that the mass of waste to launch per GW x year of electricity produced was 71.4 kg. In this numbers plutonium and reusable uranium components were not considered as waste. It was then assumed that the waste was stored in swimming pools on the Earth for 20 to 30 years for cooling before launch (heat flux reduction).

The study was performed assuming NWD into a solar orbit at 0,85 AU which was considered as the best option in past studies: long term stable orbit between Earth and Venus, « reversible » storage, safe location with respect to terrorist acts, short transfer duration (less than six months), intermediate DeltaV need (with respect to other solutions), no celestial body contamination.

The proposed mission scenario was the following:

- Injection by a launcher into a low Earth orbit of a transfer stage, the container and the waste
- Transfer stage boost for transfer to final orbit
- Transfer stage second boost upon arrival to the storage orbit, for circularization.

Assuming an Ariane 5 ESCB type launcher from Kourou, the following graph gives the performance of the launcher with a perigee altitude of 200 km, free inclination (5,24°) and a launch azimuth of 90°.

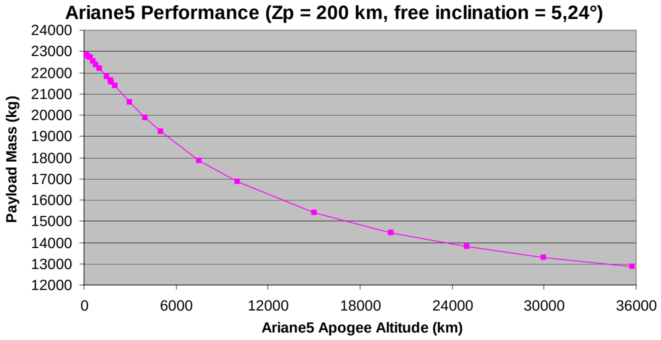

Figure 3 – Ariane 5 ESCB performances

The transfer stage hypotheses were the following:

- Single stage
- Storable propellant. This solution was taken to avoid the thermal constraints of cryogenic propellants and to avoid thrust-to-weight ratio issues that could come with electric propulsion.
- Aestus-2 type of engine (339-s Isp)
- Structural coefficient law ranging from 17,7% for a 5-ton propellant loading to 12,8% for a 10-ton propellant loading
- Velocity Increase needs (based on an Hohman transfer): reach liberation velocity with a 200-km perigee (11,008 km/s), 1,231 km/s to lower the heliocentric perigee to 0,85 AU, and 1,282 km/s to circularize upon arrival at 0,85 AU

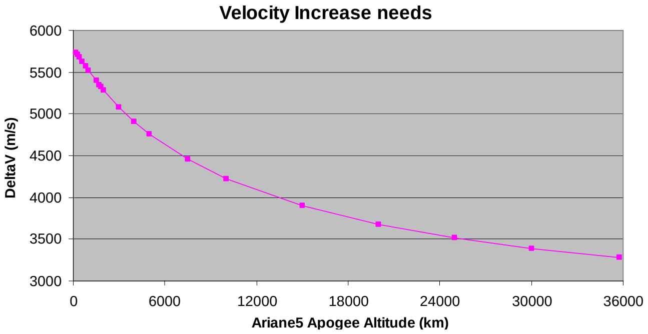

Figure 4 – Overall transfer stage DV needs

Two scenarios were then considered:

- First scenario: the nuclear waste is sent with the container to the final depository orbit, or
- Second scenario: the nuclear waste is extracted from the container after the Ariane 5 injection (limited to Earth orbits) and before departing for the final depository orbit. In this case, containers can be reused (since in any case they are designed to resist reentry in case of launcher failure).

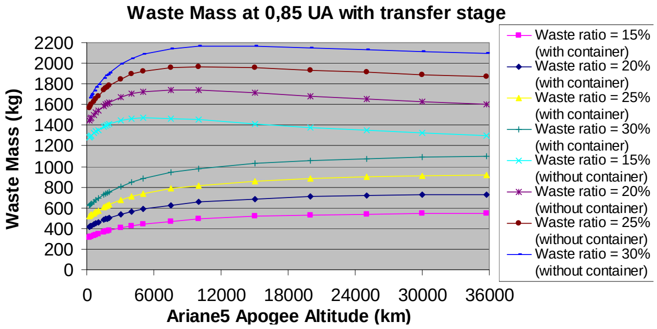

Figure 5 – Waste mass per Ariane 5 launch

Considering the graph above, a reference scenario was considered for the economical analysis:

- Launch by A5/ESCB into a 200 km X 5000 km X 5,24° orbit of a 19200 kg payload composed of :
    - 1470 kg of waste
    - 8320 kg of container (waste to container ratio of 15%)
    - 9410 kg of transfer stage (including 8,3 tons of propellant).
- It was assumed that the container was removed in Earth orbit and reused after controlled reentry (de-orbiting boost at apogee performed by a small solid motor).
- The transfer stage performs a first boost of 3476 m/s to leave the Earth (leading to an Earth departure velocity of 1231 m/s with respect to the Earth velocity around the Sun) and a circularization boost of 1282 m/s upon arrival at the heliocentric perigee of 0,85 AU.

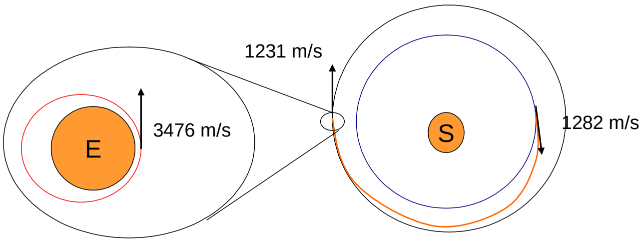

Figure 6 – Transfer stage boosts

The economical analysis was then performed with a launch of 1470 kg of nuclear waste:

- This amount of nuclear waste is produced by the production of 20,6 GW x year of electricity, or in other words, 150 billions of kWh.
- At the current public cost of electricity of 0,1 € per kWh, this represents a cost of electricity of 15 B€.
- Assume a cost of the space mission of 150 M€ (round number used for easy comparison, which would include the launcher, the transfer stage and the recurring cost of the reusable container).

Therefore the cost of space disposal would increase the cost of electricity by 1% (or 0,001 €/kWh). For comparison purposes, the budget allocated today to NWD using ground-based solutions is 0,0015 €/kWh (including disposal of all waste, not only HLW)

Going back to the original nuclear energy production scenarios, if a constant nuclear production scenario is assumed, this would require 6 launches per year to get rid of all the HLW.

With the second scenario, assuming an increase in nuclear energy use, this could go up to the equivalent of 73 Ariane 5 launches per year in 2106 (of course by that time, we should have higher performance launchers and nuclear fusion should be working).

With time, it can also be expected that waste-to-container ratio should increase, and recurring launch cost should decrease with higher launch rates. The contribution of the space disposal to the electricity cost could therefore we expected to go down in the mid-term.

SYNTHESIS AND RECOMMENDATIONS

Launch of Nuclear Waste into Space is a very interesting solution for the space industry (driving force to reduce launch costs and promote new space applications) and a very good long-term solution for nuclear energy.

With the current energy demands and the forecast for the coming years, only nuclear fission energy (and coal) appear as possible solutions in the short to midterm. Even if massive investment is put into alternative energy solutions (like nuclear fusion and renewable energies), the problem of nuclear waste disposal will remain for the existing stock and for the near term production.

Diposal of this waste in space would require the development of a fail-proof container able to withstand any possible mission failure, merging the technologies currently used by the space and the nuclear industries.

Preliminary analysis shows that this could be a very attractive long term solution from a safety point of view and with an accessible cost. Further studies in cooperation between the space and nuclear sectors will be required in the coming years to analyze in detail this solution and its advantages with respect to ground storage.

ACKNOWLEDGEMENTS

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ACRONYMS

A5ECB – Ariane 5 with Vinci cryogenic upper stage
AU – Astronomical unit (~150 million km)
DOE – Department of Energy (US)
ESA – European Space Agency
GW – Gigawatt
HLW – High Level Waste
Isp – Specific Impulse
kWh – Kilowatt hour
LEO – Low Earth Orbit
MWh – Megawatt hour
NASA – National Aeronautics and Space Agency (US)
NWD – Nuclear Waste Disposal
P/L - Payload

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