TITLE: Surplus Weapons-Grade Plutonium -- A Resource for Exploring and Terraforming Mars

AUTHOR(S): Anthony C. Muscatello and Michael G. Houts

SUBMITTED TO: Proceedings of the Case for Mars VI Conference

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Surplus Weapons-Grade Plutonium—
A Resource for Exploring and Terraforming Mars

Anthony C. Muscatello and Michael G. Houts
P.O. Box 1663, MS: A140
Los Alamos National Laboratory
Los Alamos, NM 87545
(email: amuscatello@larfets.lanl.gov)

Abstract
With the end of the Cold War, greater than 100 metric tons (MT) of weapons-grade plutonium (WGPu) have become surplus to defense needs in the United States and the Former Soviet Union. This paper is a proposal for an option for WGPu disposition, i.e., use of the plutonium as a fuel for nuclear reactors for Mars exploration and eventual terraforming. WGPu was used in nuclear weapons because it has a much smaller critical mass than highly enriched uranium, allowing lighter weapons with consequent longer ranges. Similarly, WGPu reactors would also require smaller amounts of fuel to attain a critical mass, making the reactor much lighter overall and resulting in large savings in launch costs. The >100 MT of WGPu would generate about 1000 billion kilowatt hours of heat energy, much of which could be converted into electricity. The waste heat would also be useful to a Martian outpost or colony. A potential way of getting the WGPu reactors into space is a large gas gun like that being developed at the Lawrence Livermore National Laboratory to orbit materials by achieving high velocity at the surface, greatly reducing launch costs and enhancing reliability. Reactor components would be launched on conventional rockets or space shuttles, the reactor fuel rods would be injected into orbit using the gas gun, and the reactor would be assembled in space. Implementation of this proposal would allow disposition of a serious, expensive problem on earth by removing the WGPu from the planet and simultaneously provide a very large energy resource for Mars exploration and terraforming.

Introduction
The end of the Cold War has presented the world with a great dilemma and a great opportunity. Greater than 100 metric tons (MT) of weapons-grade plutonium (WGPu) are now surplus to defense needs in the United States and the Former Soviet Union (1). The U.S. has 38.2 MT of excess WGPu stored at several sites, including 11.9 MT at the Rocky Flats Environmental Technology Site, near Boulder, CO (2), only about 10 miles from the site of the Case for Mars VI Conference. The United States Department of Energy (DOE) has three leading candidates for disposition of the surplus WGPu:
- deep bore hole burial,
- vitrification with high-level radioactive waste from reprocessing nuclear fuel followed by geologic disposal, and
- mixing of the plutonium with uranium and fabrication of mixed-oxide fuel (MOX) for use in existing or future nuclear reactors for power generation, with geologic disposal of the spent fuel.

The leading contenders for excess U.S. plutonium are vitrification of impure plutonium oxide and fabrication of pure plutonium into MOX. All Former Soviet Union nuclear weapons are in the process of being moved to Russia, where excess WGPu will be stored. Russia considers the surplus WGPu to be a national resource and intends to use it for power generation in nuclear reactors. This paper is a proposal for another option: use of the undiluted plutonium as a fuel for nuclear reactors for Mars exploration and eventual terraforming.
Use of Plutonium as a Reactor Fuel

Use of plutonium as an efficient reactor fuel has already been demonstrated (3); a few example reactors are listed below.


Thus, the technology to use plutonium as a nuclear fuel is very well established and would not require long development programs.

Advantage of Plutonium as a Reactor Fuel

Because plutonium has a smaller critical mass than uranium, use of plutonium as a reactor fuel for mobile reactors was studied many years ago, including for rocket propulsion and spacecraft power (4). The same weight advantage was behind the decision to base most nuclear weapons on plutonium instead of uranium. Table 1 shows that the critical mass of WGPu is only about 25% that of uranium-235, which has usually been considered the fuel for space reactors. Before now, WGPu was not available for non-military uses.

Table 1. Critical Masses of Highly Enriched Uranium (HEU) and Weapons-Grade Plutonium

<table>
<thead>
<tr>
<th></th>
<th>Critical Mass (metal sphere, water reflected) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEU (oralloy, 93% U-235):</td>
<td>~25 kg</td>
</tr>
<tr>
<td>WGPu (95% Pu-239):</td>
<td>~6 kg</td>
</tr>
</tbody>
</table>

Purpose of This Paper

This paper proposes the use of WGPu instead of Fuel-Grade Plutonium or Reactor-Grade Plutonium for Mars exploration. Table 2 shows the different isotopic concentrations of plutonium in Weapons-Grade, Fuel-Grade, and Reactor-Grade Plutonium. Most work with plutonium as a reactor fuel has been focused on Fuel-Grade or Reactor-Grade because only these materials were available for investigation for potential commercial applications. The end of the Cold War and recent nuclear weapons treaties have opened up the possibility of using WGPu, which has the weight advantage mentioned above over uranium-235. WGPu also has the advantage of being a smaller source of penetrating gamma radiation on a gram-per-gram basis over the other grades of plutonium. The isotopic composition of heat-source plutonium, which has been used extensively as the fuel of radioisotope thermoelectric generators (RTGs) for spacecraft and lunar surface power sources, is shown for comparison.

Table 2. Isotopic Composition of Grades of Plutonium

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Weapons</th>
<th>Fuel</th>
<th>Reactor</th>
<th>Heat Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-238</td>
<td>88 yrs.</td>
<td>&lt;0.05%</td>
<td>0.1%</td>
<td>1.5%</td>
<td>83.5%</td>
</tr>
<tr>
<td>Pu-239</td>
<td>24,100 yrs.</td>
<td>93.6%</td>
<td>86%</td>
<td>58.1%</td>
<td>14%</td>
</tr>
<tr>
<td>Pu-240</td>
<td>6,600 yrs.</td>
<td>6.0%</td>
<td>12%</td>
<td>24.1%</td>
<td>2%</td>
</tr>
<tr>
<td>Pu-241</td>
<td>14 yrs.</td>
<td>0.4%</td>
<td>1.6%</td>
<td>11.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Pu-242</td>
<td>376,000 yrs.</td>
<td>&lt;0.05%</td>
<td>0.2%</td>
<td>4.9%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
WGPu has the highest concentration of Pu-239, the primary fissile isotope. WGPu also has a low concentration of Pu-240, which is a neutron absorber that impedes nuclear fission. Los Alamos National Laboratory is investigating WGPu as a nuclear fuel (6) because there are several advantages to using WGPu:

- non-fertile fuel—no uranium to breed more plutonium,
- potentially higher plutonium burnups (fission of a higher percentage of the nuclear fuel), and
- lower radiation source than Fuel-Grade or Reactor-Grade Pu during fabrication and storage prior to use.

This proposal would build on this work with a view to apply the fuels to Mars exploration and colonization. To advance this proposal, Los Alamos has designed a compact 100-kilowatt (heat) WGPu-fueled reactor specifically for use for this purpose. Figure 1 shows a cross-section view of the proposed reactor.

![Cross-section of PuO2-fueled reactor for Mars surface missions. Axial dimension of active core region is also 0.30 m.](image)

Fig. 1. Conceptual Weapons-Grade Plutonium Reactor Diagram.

Briefly, space reactors such as this achieve criticality by operation of the control drums, which rotate a neutron reflector, such as beryllium, close to the fuel rods in the center. The reduced loss of neutrons from the core enables a fission chain reaction to initiate, generating heat, which can be converted to power. This reactor design has several advantages for space exploration: compact size, light weight, high power, and long life. The reactor itself is expected to weigh only 130 kg fully fueled, require minimal shielding brought from Earth, fit in a small volume, and generate
power for more than 10 years. Energy conversion devices would require additional weight. For use of the plutonium reactor in Mars surface missions, shielding would be provided by placing the reactor in a crater or by use of indigenous material. Use of the plutonium reactor in space during travel to Mars would, of course, require shielding brought from Earth to protect the crew. The excess WGPu available would allow construction of approximately 2,000 of these reactors, enough for many Mars missions.

Energy Potential

This proposal to use the 100 MT of WGPu for Mars exploration is worthwhile because it is a tremendous energy source:

- Fission of 1 kg of U-235 yields 20 million kWhr of heat energy equivalent
- The energy potential of U-235 is approximately the same as that of Pu-239
- 100 MT = 100,000 kg
- 50% burnup (fission) releases 1,000 billion (10^{12}) kWhr.

By comparison, the daily power generation in the U.S. is about 10 billion kWhr. Thus, fission of the WGPu yields the equivalent of about 100 days of U.S. electrical power. Mars explorers and colonists could use this power for rocket thrust, electricity, and heat. The Martian environment will require compact sources of energy because of the low ambient temperatures. The exploration and colonization of Mars will be a very challenging task. Even though Mars is only half the diameter of the Earth, the surface area of Mars is the same as the dry land surface area of the Earth. Exploration and colonization of this enormous expanse will require large amounts of energy. Mars has few intrinsic sources of energy, only solar (only about half the flux at the Earth) and perhaps some geothermal sources. A compact, portable high energy supply will be extremely useful.

Economics and Environmental Concerns

Because WGPu is a special nuclear material and requires very high security to be protected from theft, one might expect its use to be very expensive. However, the U.S. and Russia must deal with the excess WGPu in any case, and the costs of fabricating fuel elements should not be borne by the Mars exploration program. In fact, the Mars exploration and colonization program would be doing the two countries a favor by getting the material completely off the earth, to a place where there is no one’s “back yard.” International safeguards with oversight by the International Atomic Energy Agency (IAEA) would be used to ensure nonproliferation of the WGPu during fuel fabrication, storage, and use. It may also be desirable to dilute the WGPu with hafnium oxide or other suitable oxides to make it less attractive and gain some reactor control benefits. Such oxides will be tailored to ensure that the temperature coefficient of the reactor is negative (the reactivity goes down as the temperature increases). Details such as this remain to be worked out.

Disposal of spent WGPu fuel on Mars is actually less of a concern than on Earth. The main problem with disposal of radioactive materials on earth is their transport away from the repository by ground water. At least until Mars is terraformed, there is no mobile liquid water near the Martian surface and radioactive materials will stay where they are emplaced. Good records of spent nuclear fuel burial sites would be required to ensure safe storage after terraforming and consequent liberation of large amounts of liquid water. Recent reports that indicate life may have formed on Mars and may still exist do not preclude disposal of spent nuclear fuel. The waste need only be buried wherever no liquid water is likely to exist, now or in the future. Hydrothermal and volcanic areas would have to be avoided. It may become desirable in the future to dispose of radioactive materials on Mars in space because the concerns with launch accidents would be greatly reduced until Mars has a substantial population.
Fuel-Fabrication Facilities

The U.S. DOE has several potential sites for WGPu fuel fabrication:
- a new facility at Hanford (Fuel Manufacturing and Examination Facility, FMEF), in Washington state,
- the Rocky Flats Environmental Technology Site, in Colorado,
- the Savannah River Site, in South Carolina, and
- Los Alamos National Laboratory, in New Mexico.

The Hanford facility was built to handle nuclear fuels and was built to modern safety standards. However, it was never run with radioactive materials and would result in greatly increased decommissioning costs if it were ever contaminated. Rocky Flats produced nuclear weapons components from plutonium during the Cold War and would have the capability to work with WGPu. It is unlikely to be available for fuel rod production because of its proximity to major population centers (Denver) and its current mission, which is to clean up and close the site. The Savannah River Site is a possibility because it is currently operating and is seeking a long-term mission. Los Alamos is also a possibility because of the work there on use of WGPu as a nuclear fuel. Los Alamos is also currently building the plutonium-powered heat sources for use on the Cassini mission to Saturn. Fabrication of WGPu fuel rods in Russia may be a much less expensive option and may be desirable if the U.S. decides not to use WGPu.

Launch Technique

Launch of WGPu reactors into space presents a serious issue because the current reliability of rockets is not sufficient to allow public acceptance of the launch of such materials, which would probably lead DOE to reject this option for disposal of WGPu. A possible solution to this issue is to orbit nonradioactive reactor components on conventional rockets or space shuttles. The WGPu fuel rods, in aeroshells, could then be put into orbit by a future gas gun (also known as the Jules Verne Launcher). Use of the gas gun ensures high-reliability launch because, unlike a rocket, it has testable components. After launch of the components, the reactor would be assembled in space for use during travel to Mars, on the surface, or both.

Hunter and Cartland at Lawrence Livermore National Laboratory (LLNL) have developed a gas gun (Super High Altitude Research Program, or SHARP) for demonstrating launch of materials by achieving high velocity at the surface, greatly reducing launch costs and enhancing reliability (7). The gas gun uses a methane-air detonation to compress hydrogen gas, which propels the projectile through an evacuated tube. For launch into orbit, the projectile would have its own small rocket to achieve orbit after being lofted to high altitude and high speed. A commercial company has been formed recently to scale up the Livermore device (8). The SHARP has also been used to test scramjets at speeds up to Mach 9 (9). Figure 2 is a photograph of the SHARP being fired. (Used by permission of Harry Cartland, Lawrence Livermore National Laboratory. Inclusion of this photograph and the proposal to use SHARP technology does not constitute endorsement of the proposal by Harry Cartland, the SHARP project, or Lawrence Livermore National Laboratory.)

Outstanding Launch Issues

In response to this proposal to use the gas gun for launching plutonium, Cartland (10) has pointed out several potential problems:

"What happens if you do not achieve orbit? A gun is more reliable than a rocket, but the possibility of scattering Pu over a wide area is still finite. With a rocket you have a chance of separating and recovering the payload intact, but our launch velocity is about 6 km/sec. You are far downrange before you know something is wrong, and the aerothermal environment is, shall we say, difficult. Even if the ballistic portion of the trajectory is nominal, what will you do if there is a problem
with heat shield separation or engine start? At apogee you will still have about 4 km/sec velocity - too fast to simply kick out a parachute. These problems are probably all solvable, but I suspect that most of your payload will consist of hardware to protect and recover the Pu if something goes wrong.”

Although these are serious concerns, they have already been resolved for RTGs (Pu-238 heat sources) used on many space missions (Apollo, Voyager, Ulysses, Galileo, etc.) by providing blast and heat shielding for the plutonium. The majority of the launch package will be protective packaging, but, as seen above, the mass of WGPu needed for the reactors will be small. Also, the specific activity of WGPu (the amount of radioactivity per gram) is several orders of magnitude less than that for Pu-238, making the threat from dispersion of WGPu in an accident much less than that from Pu-238 on a gram-per-gram basis. The longer half-life of the WGPu would, however, lengthen the time the material stayed in the environment. Because similar concerns have been satisfactorily resolved, use of Pu-238 in RTGs and General Purpose Heat Sources in graphite aeroshells has been approved by the U.S. Government for the Cassini mission, even in today’s litigious climate.

**Summary**

Implementation of this proposal to use WGPu for nuclear reactors for Mars exploration and colonization would allow resolution of a serious, expensive problem on Earth by removing the WGPu from the planet and would simultaneously provide a very large energy resource. Mars exploration and terraforming would be greatly enhanced by having access to small, high power energy sources.

**References**