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Space nuclear power system accidents: Doses from Pu-238 and Am-241 inhalation

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To address the shortage of availability of Pu-238 for space missions, while new initiatives for Pu-238 production are being undertaken, there is a need for exploration of the use of Am-241 as a possible replacement for Pu-238 since the stockpile of Am-241 from the nuclear weapons program has remained relatively intact. Previously, there have been studies of the risks and consequences of Pu-238 release in postulated accidents including, for example, the Final Safety Analysis Report (FSAR) for the Galileo Mission. Since this report used an ICRP-30 based model, and a later ICRP-66 model has become available, it is of interest to re-evaluate the previous results for Pu-238 and obtain new results for Am-241. We are reporting here the following results of calculations for inhalation doses using our own computational programs (as based on different models). The results include committed equivalent doses for Pu-238 particles using the Galileo FSAR model, the original ICRP-30 model, and the ICRP-66 model. We also calculated committed equivalent dose for Am-241 using the ICRP-66 model. The ICRP-30 and ICRP-66 results were obtained using assumptions of committed time and resuspension taken from the FSAR. We have found that the ICRP-66 predicts lower doses for Pu-238 than those predicted by the Galileo FSAR or ICRP-30. Also we have found that the Am-241 lung doses are lower than those of Pu-238 because of greater clearance of Am-241 from the lungs as compared with Pu-238.

1. Introduction

NASA's supply of radioisotopes for Radioisotope Heat Units (RHU) and Radioisotope Thermoelectric Generator (RTG) power sources (we will refer to these together as Radioisotope Power Systems - RPSs) is facing a crisis due to shortages of Pu-238 for future missions. To address this shortage while new initiatives for Pu-238 production are effected, there is a need for exploration of the use of Am-241 as a possible replacement for Pu-238 since the Am-241 stockpile from the nuclear weapons program has remained relatively intact. It is imperative that the safety of Am-241 and its interactions with the environment be assessed to certify its use in RPS units. This assessment will require:

- Investigation of release and transport mechanisms of Am-241 in the environment and understanding receptor pathways for dose assessments as part of nuclear risk assessments, and
- Developing approaches and methodologies for nuclear risk assessment of space radioisotope power system applications.

The risk from a hazard (potential of an activity to cause harm to an entity or simply exposure) can be defined (Hines et al., 1993; McCormick, 1981; Rasmussen, 1981) as:

$$R\left[\frac{\text{harm}}{\text{unit time}}\right] = f\left[\frac{\text{events}}{\text{unit time}}\right] C\left[\frac{\text{harm}}{\text{event}}\right] \tag{1}$$

or

$$R\left[\frac{\text{exposure(s)}}{\text{unit time}}\right] = f\left[\frac{\text{events}}{\text{unit time}}\right] C\left[\frac{\text{exposure(s)}}{\text{event}}\right] \tag{2}$$

Mathematically, considering n events, $1, 2, \ldots, n$, we can write the total risk R from these events as:

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$$R_T = \sum_i R_i \tag{3}$$

where $R_i = f_i C_i, f_i$ is the frequency of the specific i-type of event, and C_i is its associated consequence. For example, relating to use of RPSs, for an individual subjected to exposure from an accident involving a spacecraft carrying a Pu-238 RPS (Frank, 1999; Goldman et al., 1991; Kastenberg and Wilson, 2004), one could find:

$f = 10^{-6}$ (RPS accident with significant release/launch)
$C = 10^{-5}$ (Excess cancer over the lifetime to an exposed individual/RPS accident)
$R = 10^{-11}$ (Excess cancer over the lifetime to an exposed individual/launch)

By most standards, such a value of R would be considered insignificant considering all of the other risks from various hazards that the individual would be exposed to. Assuming this R to be a mean value for all exposed persons (say about 100,000 near the accident or even spread out worldwide), the excess cancer risk to this total population then be about 10^{-6} to 0.05 over the lifetimes of all exposed individuals and is, again, most likely insignificant.

However, there are admittedly large uncertainties in estimations of both f and C. In launches to date (about 27 launches carrying 46 RPSs, see NAS study (National Research Council Radioisotope Power Systems Committee, 2009)), there has been only one RPS accident involving any release of Pu-238 (Transit 5BN-3 spacecraft). Thus, $f = 10^{-6}$ is just an estimate based on the likely event tree and fault tree type analysis methods (Frank, 1999; Goldman et al., 1991). The estimation of C is likewise based on assumptions regarding release, dispersion, aerosol and dust interactions with Pu-238, inhalation and ingestion of Pu-238, related doses to critical organs, and cancer/dose relationships.

The works by Goldman et al. (1991), Frank (1999), and Kastenberg and Wilson (2004) are particularly informative. Goldman et al.'s panel, which was sponsored by several government agencies, studied potential health risks from postulated accidents involving the Pu-238 RTG on the Ulysses solar exploration mission launched on October 6, 1990. The RTG contained 24.2 pounds of polished cylinders of radioactive Pu-238 (in oxide form) in 18 packaged modules. They addressed the question of "what might have happened to the Pu-238 if an explosion worse than that of Challenger ripped apart this shuttle and caused the Ulysses spacecraft to disintegrate across the sky. Also considered was what might have happened if, after leaving the shuttle's bay, Ulysses accidently reentered the atmosphere and smashed into something as hard as granite?" The authors discuss various accident scenarios and the subsequent release of Pu-238 dioxide, its environmental transport, inhalation and ingestion (inhalation appears to be about 300 times more likely than ingestion), and its health effects. The explanation is bit involved, but Pu-238 leads to smaller particles that dissolve more rapidly in water than those resulting from Pu-239 and, hence, requires a different health effects model than Pu-239. Some of the main understandings from that study can be summarized as:

1. Concerns for the safety of RTGs has always been a part of the U.S. space program, and design of the RTGs has evolved from a health protection philosophy of dilution and dispersion to one of containment. An earlier event involving a Navy navigational satellite (Transit 5BN-3 mission) released about 3 pounds of Pu-238 (17,000 Curies) into the atmosphere in a dilute band around the Earth after accidental atmospheric reentry and burnup. The burnup of the Transit 5BN-3 satellite prompted the development of a four-layer containment system for Pu-238: an iridium jacket around the fuel, further ensconced by two graphite jackets, ultimately placed inside a modular container to provide further protection. Two subsequent accidents, the Nimbus B-1 weather satellite and the Apollo 13 mission, appear to have confirmed the efficacy of this multi-barrier containment philosophy as no subsequent releases occurred.
2. Out of the nine hypothesized accident scenarios, the authors concluded that only two worst case scenarios could (realistically) release Pu-238.
3. In the first scenario (the shuttle exploding on or close to the launch pad with metal shard(s) slicing into RTG container) a small fraction of the Pu-238 would consist of dust-sized small particles (up to 10 to 20 μm in diameter) that would be transported through the atmosphere to be either inhaled or incorporated into the food chain. In the second scenario (metal shards slicing into the RTG at an altitude of about 10,000 ft), some of the Pu-238 would be released in a plume, and by location and design, most of the Pu-238 would likely fall into deep ocean. However, the possibility of release in a heavily populated area does still exist.
4. The first scenario would involve a maximal release of about 380 Curies. Fifty Curies (about one ounce) of Pu-238 in the air and 330 Curies (about 6.6 ounces) in a four-meter puff two feet off the ground. Approximately 700,000 people might be exposed, receiving a collective dose of 3000 person-rem in the first year, and with a committed (50 year) dose of 4100 person-rem. Statistically, one could expect 0.9 excess cancers (to one single person) in a population of 700,000, or, approximately one excess lifetime cancer in a million-people exposed to the radiation, such that $C = 10^{-6}$. We have not found estimates for the second scenario, because it is even less consequential.

Frank expanded upon this work regarding the Cassini mission and provided an in-depth analysis of the frequency of these scenarios using event tree methods and associated uncertainties. Kastenberg and Wilson applied the results of Goldman et al., Frank, and several other government panel reports to the risk equation (perspective) that we have discussed earlier, and emphasized the overall smallness of an $R = 10^{-11}$ excess lifetime cancer risk to an individual from the launch. They also noted that the probabilities for two terms (f and C) are truly independent with each being about 1 in a million, thus the resultant risk is inherently minuscule.

Although the frequency f is very small, and the estimated consequence C is also very small, the perceived societal risk is often not small for nuclear accidents. The focus often remains more on the consequence C, and it becomes necessary to improve our understandings and estimations of it. We should note that although considerable information on the modeling of C is available, it is scattered through several government reports and notes, and is not easily retrievable. Also, as noted by Kastenberg and Wilson, even contemporaneous reports have used different models and data (ICRP-30 in one case and ICRP-60 in another), and it would be useful to have all this information expressed in a single framework.

We have explored this last aspect in some detail in this paper. Of particular interest to us is the Final Safety Analysis Report (FSAR) for the Galileo Mission (General Electric Company, 1988; NUS Corporation, 1989) which describes the consequence modeling in some detail. Therein, it was assumed that Pu particles can be released in accidents through cracks in the RTG containment. The released amounts and particle size distributions were modeled using some small-scale laboratory experiments as guides. For the modeling of the atmospheric transport, the amount of material and its radioactivity available for inhalation by a subject population (directly and from resuspension of particles deposited on ground)