RISK ASSESSMENT FOR THE GROUND LAUNCH OF A SINGLE STAGE TO ORBIT NUCLEAR THERMAL ROCKET.

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Introduction: Recent advances in the development of high power density fuel materials have renewed interest in nuclear thermal rockets (NTRs) as a viable propulsion technology for future space exploration. This study describes a risk assessment for the ground launch of three NTR reactor engines designed for the single stage to orbit launch of payloads from 1-15 metric tons. The risk assessment includes an evaluation of dose rates produced by the NTR reactor as a function of distance from the launch site, an estimate of the types and amounts of activation products produced at the launch pad and in the surrounding soil and air, and a prediction of the quantities of actinides and fission products produced in the reactor core during the ~10-minute operating period.

Nuclear Thermal Rocket Reactor Design: A previous research project [1,2] developed three NTR reactors for a range of payloads between 1 and 15 metric tons. The resulting reactors utilize tungsten cermet fuel composed of W-25wt%Re loaded with 40 vol% uranium nitride fuel enriched to 97 at% uranium-235. Thermal hydraulics calculations determine hydrogen propellant temperatures axially along the approximately 40 cm diameter reactor core. The outlet hydrogen temperatures provided the specific impulses and thrusts for several different reactor lengths and powers. This determined the reactor lengths corresponding to the lowest mass and power requirements for a given payload (see Fig. 1). A 40 cm long reactor is preferred for payloads between 1 and 3.5 MT, a 80 cm long reactor is most appropriate for for payloads between 3.5 and 10 MT, and a 120 cm reactor is indicated for payloads between 10 and 15 MT. All three reactors have $2 of hot clean excess reactivity, $5 of shutdown margin, will remain at least $1 subcritical when submerged in dry sand, wet sand, or seawater with or without the coolant channels flooded with seawater. The rhenium in the 40-cm long reactor is sufficient to keep the reactor subcritical in all postulated submersion accidents. The larger (80 cm and 120 cm) reactors require the addition of up to 0.6 wt% GdN to the UN fuel in order to remain $1 subcritical in all submersion cases. The 40 cm reactor has a 22 cm top axial, a 3 cm bottom axial, and a 24 cm radial reflectors with a B_4C thickness of 1.30 cm. The 80 cm reactor has a 10 cm top axial reflector and a 14 cm radial reflector with a B_4C thickness of 1.25 cm. The 120 cm reactor has a 10 cm top axial reflector and a 12 cm radial reflector with a B_4C thickness of 1.25 cm. The system masses increase with increasing core length (1392, 1765, and 2451 kg for the 40, 80, and 120 cm reactors, respectively).

Risk Assessment: This study provides an initial risk assessment for the surface launch of the three NTR reactors and presents several analyses to bound the risks involved with launching a nuclear thermal rocket from the ground. A multiple sphere model utilizing surface tallies determined potential dose rates from an NTR surface launch. A launch pad with a dedicated controlled area approximately 3.5 km from the launch site would keep dose rates to the public to levels less than natural background (see Fig. 2).

Surface tallies in MCNP5 determined the activation rates in the launch area, including the launch pad, soil, and air. The 40 cm reactor with a 3.5 MT payload resulted in the greatest rate of significant radionuclide production around the launch area. The ^{56}Mn and ^{55}Cr isotopes produced by the launch had the highest levels of activity (5.1×10^8 Bq/cm^3 and 1.2×10^8 Bq/cm^3, respectively) in 304 stainless steel 10 m from the launch site immediately after the launch of the 40 cm reactor with a 3.5 MT payload. The activation analysis classified the activated material by NRC waste classification standards, considering all of the activated iso-

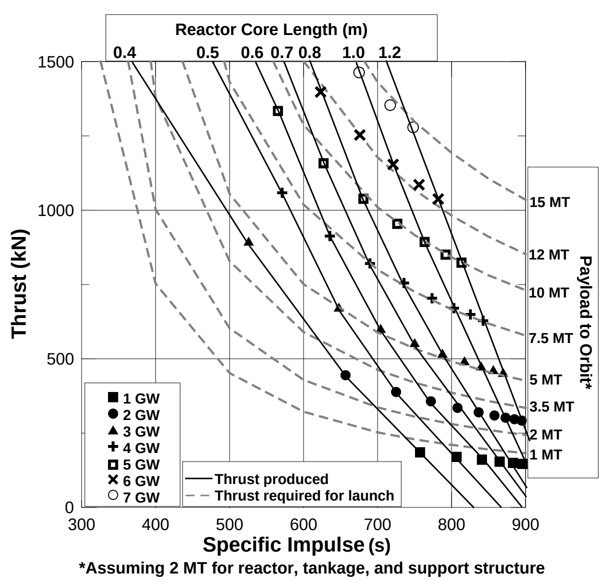

Fig. 1. Thrust produced by an NTR core with an approximate diameter of 0.4 m as a function of core length and specific impulse compared with the required thrust for a 2 g launch as a function of payload and specific impulse.

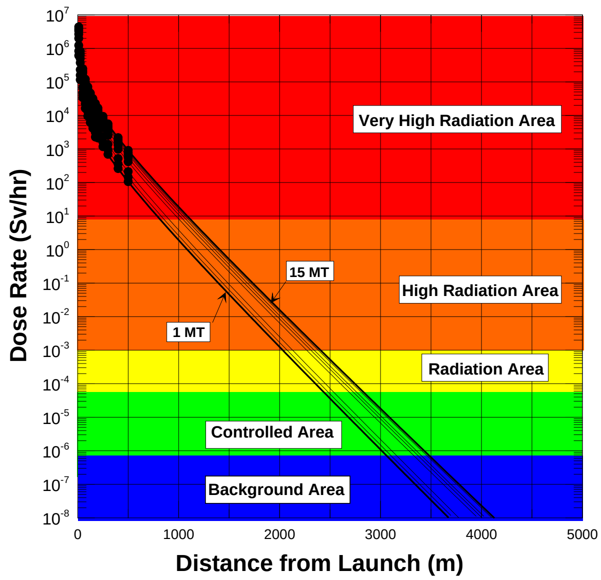

Fig. 2. Dose rates for the launch of all rocket payloads in this study as a function of distance from the launch.

topes one year after the NTR launch, and concluded that all of the resulting material would be Class A low-level waste.

Activated air around the launch area cannot be contained and/or disposed of and the risk limits set for airborne radioactivity are different from those for disposable material. MCNP5 F2 tallies estimated the activity levels of radioactive argon isotopes and ^{16}N resulting from the activation of air. The air activation analysis provided a prediction of the derived air concentration for each isotope at a given distance from the launch as a function of time after launch. After 12 hours, the concentration of radionuclides in air would require less than one day but more than one hour of inhalation to produce a committed dose of 50 mSv. The predictions indicate that a surface launch of an NTR will require a multi-day exclusion zone to allow the activated air around the launch site to decay to safe levels.

MCNPX determined the amount of selected isotopes that would be generated in the core of the 40 cm reactor after 10 minutes of operation at 1 GW. ^{135}I is the most abundant fission product after ten minutes of operation, with 3.3 x 10^{16} Bq of ^{135}I in the core at shutdown. The decay heat after shutdown increases with increasing reactor power with a maximum decay heat of 108 kW after 10 minutes of operation of the 120 cm reactor with a 15 MT payload. A complete failure of the 120 cm reactor in this case (ten minutes at 7.0 GW) would release ^{131}I, ^{137}Cs, ^{133}Xe, and ^{239}Pu in amounts (2.5 x 10^{13} Bq, 1.4 x 10^{12} Bq, 1.5 x 10^{12} Bq, and 5.5 x 10^{8} Bq, respectively) substantially lower than the Chernobyl and Fukushima meltdowns (see Fig. 3). The predicted release would include less ^{133}Xe but more ^{137}Cs and ^{131}I than the Three-Mile Island meltdown. The worst case ^{239}Pu release from the complete failure of the 120 cm reactor after 10 minutes of operation at 7.0 GW would be several orders of magnitude lower than amount of plutonium released by global weapons testing (Fig. 3).

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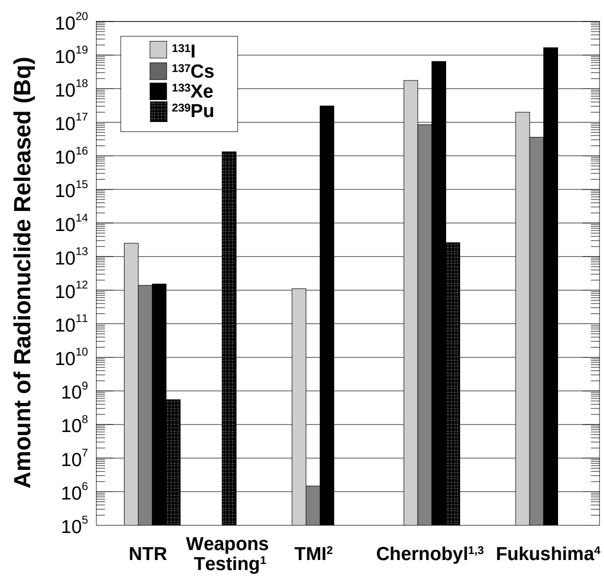

[1] Eisenbud and Gesell, 1997 [3]
[2] GPU Nuclear Corporation, 1986 [4]
[3] Kobayashi et al., 2012 [5]
[4] United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 [6]

Fig. 3. Comparison of the complete failure of the 120 cm reactor after 10 minutes of operation at 7 GW with global weapons testing and three historical nuclear meltdowns.