Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting
Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/

KILOPOWER - MAXIMUM CREDIBLE DOSE FOR A CRITICALITY ACCIDENT

Patrick McClure and David Poston

Los Alamos National Laboratory, Los Alamos, NM 87545, 505-667-9534, pmcclure@lanl.gov

Inadvertent criticality is one end state for a space reactor launch accident. If a criticality were to occur, then consequences of this event must be estimated. This paper uses an estimate for the number fissions combined with estimates of release from historic space reactor criticality tests to estimate the dose to receptors at 100 m and 1000 m.

I. INTRODUCTION

This paper examines potential consequences for the Kilopower small space reactor going critical during a launch accident. The goal of this analysis is to postulate the dose at a distance (100 m and 1000 m) that could be generated during a criticality accident event. This paper does not examine local consequences to an individual who would be close enough to the reactor (within several 10's of meters) to receive a lethal dose from the direct shine of neutrons and gamma radiation present when the reactor is critical.

I.A. Method to Estimate Dose

To calculate the dose, two receptor locations were chosen. The first is 1000 m and the second is 100 m. 1000 m is used as a surrogate value for public standoff. 100 m is used as the distance for a nearby individual. The standard formula for dose (as presented in DOE-HNBK-3010[1] with some unused terms eliminated) is shown below for dose from inhalation of radioactive material.

$$Dose = MAR \times ARF \times RF \times X/Q \times BR \times DCF \qquad (1)$$

Where,

MAR = Material at risk (Curie inventory of core)

ARF = Airborne release fraction

RF = Respirable fraction

X/Q = Atmospheric dispersion coefficient (s/m3)

Br = Breathing rate (m3/s)

DCF = Dose Conversion Factor (Rem/Ci)

The MAR is the radioactivity in the reactor core based on the number of fissions for the accident. All fission products for which International Commission on Radiation Protection (ICRP) has a DCF are included in the MAR. The fission product inventory is calculated by the Los Alamos National Computer code CINDER[2] and Monteburns[3] based upon the burn up of U^{235} from the criticality accident and the reactor cross-section. This means that the MAR is reactor specific and is calculated using the Kilopower reactor design.

The ARF will be accident specific and will be defined later in this paper. The RF will be assumed to be 1 to be conservative.

The atmospheric dispersion coefficient (X/Q) for the 1000 m was estimated from Napier[4], for a ground level releases and a wind speed of 1 m/s and an F wind stability (a very conservative value) as 1.E-4 s/m^3. A ground level release is chosen, since a reactor falling from a launch accident will strike the ground or ocean and then release is assumed to occur with minimal height increase over that of level ground.

The atmospheric dispersion coefficient for the 100 m receptor is from DOE-STD-1189-08[5] and is 3.5.E-3 s/m^3. This is the design value used to calculate dose to a worker for a new facility.

Given that the distance to the two receptors is 100 m and 1000 m, the travel time of the plume (1 min for 100 m and 10 min for 1000 m) is used as the delay time after the accident for the "at the receptor" inventory.

All releases are assumed to be instantaneous. This is a good assumption for burst releases, but is conservative for long-term releases. In the calculations, the receptor is present for the duration of the plume passage.

The breathing rate is the standard DOE[6] breathing rate of 3.3E-4 m^3/s.

Dose conversion factors are from ICRP-72[7], dose conversion factors for adults, with fast absorption, and a 1 micron particle size.

Using equation 1, the dose for each individual isotope was calculated in a spreadsheet. The values are then summed over all fission products to arrive at the total dose to the 1000 m and the 100 m receptor.

I.B. Scenario Description

The reactor fault conditions leading to a criticality have been postulated in previous space reactor studies. From these studies, the most likely generic scenarios for a space reactor going critical during a launch involves the following potential issues:

1. The reactor being surrounded by a medium (such as water or wet sand) that increases moderation or reflection causing a criticality, or
2. The reactor core is deformed into a more favorable geometry causing criticality, or

3. The control mechanism being separated from the reactor by a blast or fire causing an insertion of reactivity, or
4. Some combination of these events.

Reactor criticality accident typically are either a short-term accidents or long-term accidents. A short-term accident is one where the reactor has a step insertion of reactivity (initial burst) and the reactor self disassembles given the thermal shock. These accidents are on the order of milliseconds. A long-term accident is one where the reactor has an initial burst and survives the burst, followed by a longer period with the reactor critical or pulsing critical. Long-term events can last days.

A reactor that is completely submerged in water (say at the bottom of the ocean) may be critical but will not adversely impact the public given that any radiation will not be airborne but instead will be dispersed into the ocean. The primary assumption for scenarios involving the reactor surrounded by water is that the reactor falls onto land near water (say on a beach) such that the reactor is not always complete submerged, but instead is partially cover by the incoming tides or is buried in wet sand.

The cases for criticality events will be divided into four cases, two base cases (short term and long term) and two sub-cases (with and without water present.) These cases are then matched up to the categorization used by the primary sources for binning historic criticalities. The cases and bins are shown in Table I.

TABLE I. Accident Cases and Bins.

Case	Description	Bin
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid
1b	Step insertion by water immersion	Moderated/reflected system
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system

I.C. Assignment of Fission Yields

The accident scenarios in Table I were assigned fission yields using the most bounding values from all historic criticality accidents as summarized by McLaughin[8]. The assignments for fission yields for Kilopower based upon the four cases are presented in Table II. These basis for selection is document in McClure[9].

TABLE II. Fission Assignments for Kilopower.

Case	Description	Bin	Initial yield	Total yield
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	5E17	
1b	Step insertion by water immersion	Moderated/ reflected system	5E18	
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	5E17	1E19
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/ reflected system	5E18	1E20

I.D. Assignment of Airborne Release Fraction, ARF

The release fractions will change for each specific accident case. The two main issues are 1) the amount of fuel damage (associated with a short-term step insertion that destroys the core versus a long-term accident where core is intact) and 2) the presence of water. The short-term accidents are associated with massive fuel damage from a burst event leading to core destruction. The long term-events are associated with minimal fuel damage. Non-water events will be associated with dry/bare systems. Water events will be associated with moderated/reflected systems. The release fractions are then discussed for each case are described below.

I.D.1. Case 1a – Short-term step insertion leading to reactor damage with no water present

A reactor that has undergoes a step insertion of reactivity large enough to self-destruct and shutdown the reactor will also have a significant amount of fuel damage. The destruction of the reactor is cause by a thermal shock-wave traveling through the reactor as portions of the fuel either melt or vaporize. This leads to structural cracking/destruction of the reactor core internals and fuel with a portion of the reactor being ejected outward. Examples of such tests are the SNAPTRAN-2 test and KIWI-TNT test performed in the 1960s.

The SNAPTRAN-2 destructive test was a $5 insertion of reactivity to the SNAP-10A reactor, (a small space reactor), by artificially turning all the control drums at a high speed. No water was present during the test. Cordes[10] describes the radiological releases of SNAPTRAN-2 as follows

"the SNAPTRAN-2 test, 75 percent of the noble gases, 70 percent of the halogens, 45 percent of the tellurium, and 4 percent of the remaining solids were released."

The KIWI-TNT destructive test was a ~$8 insertion of reactivity to the Kiwi reactor, (a thermal nuclear rocket), by artificially turning all the control drums at a high speed. This produced a 3E20 fission event in the reactor that caused an explosion approximately the same as 100 to 150 lbs of TNT equivalent. The reactor core was completely destroyed. Fultyn[11] describes the radiological releases as follows:

"From 5 to 20% of the reactor core was vaporized, with approximately 67% of the products from about 3E20 fissions released to the effluent cloud. Radiation effects from the cloud passage were less than predicted in the pretest safety evaluation report."

Later in the report it is clear that most of the fission products were Xenon, Iodine and Tellurium. Small amounts of Lanthanum, Ruthenium and Barium were also found. This would indicate some agreement with the values measured for SNAPTRAN-2.

For step insertion accidents for Bare/Dry solids (no water), Base Case 1a, the release fractions will be assigned using the values from SNAPTRAN-2. The alkali metals (Cesium) will be assigned the same release fraction as the Halogens (Iodine). Using the grouping of chemical classes from Restrepo[12], the follow release fractions are assigned in Table III.

TABLE III. Release Fraction for Case 1a, Step Insertion – Bare/Dry Metal

Group Name	Elements in Group	ARF
Noble Gases	Xe, Kr, He, Ne, Ar, Rn, H	7.5E-1
Alkali Metals	Cs, Rb, Li, K, Fr, Na	7E-1
Alkali Earths	Ba, Sr, Mg, Ca, Ra, Be	4E-2
Halogens	I, F, Cl, Br, At	7e-1
Chalogens	Te, S, Se, O, Po, N	4.5E-1
Platinoids	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	4E-2
Transition Metals	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	4E-2
Tetravalent	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-2
Trivalent	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	4E-2
Main Group I	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-2
Main Group II	Sn, Ca, In, Ag	4E-2
Boron	B, Si, P, C	4E-2

I.D.2. Case 1b – Short Term step insertion by water immersion with fuel damage

The SNAPTRAN-3 test was, much like the SNAPTRAN-2 test, an experiment to examine reactivity insertion in a small space reactor, SNAP-10A. This test was a reactivity insertion caused by immersing the reactor in water. The SNAP reactor was super critical in water and in the SNAPTRAN-3 test, water caused the reactor to be ~3.60 dollars in excess above delayed critical. This caused an initial burst of 1.2E18 fissions.

Fission product release was very low for this experiment because the water scrubbed a good portion of the fission products that were released. Cordes[10] estimated that 99% of the fission products were retained by the water. Iodine (a Halogen) was not detected in the release plume. Only the noble gases (and their daughter products) were detected in the plume. It is estimated that 3% of the noble gases were released.

For this analysis it will be assumed that 3% of the noble gases are released based upon the SNAPTRAN-3 results. For the more volatile groups of Cs (alkali metals) and I (halogens) the release fraction will be set to 5E-3 (0.5%) for conservatism. This value was chosen because it is an order of magnitude less than the values for heated spent fuel from Restrepo[12]. These values are given in Table IV.

TABLE IV. Release Fraction for Case 1b, Step Insertion – Water Immersion

Group Name	Elements in Group	ARF
Noble Gases	Xe, Kr, He, Ne, Ar, Rn, H	3E-2
Alkali Metals	Cs, Rb, Li, K, Fr, Na	5E-3
Alkali Earths	Ba, Sr, Mg, Ca, Ra, Be	0
Halogens	I, F, Cl, Br, At	5E-3
Chalogens	Te, S, Se, O, Po, N	0
Platinoids	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	0
Transition Metals	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	0
Tetravalent	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	0
Trivalent	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	0
Main Group I	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	0
Main Group II	Sn, Ca, In, Ag	0
Boron	B, Si, P, C	0

I.D.3. Case 2a – Long-term accident, initial burst followed by longer critical period with no fuel damage and no water present

For Case 2a, the main assumption is the reactor remains "relatively" intact. Meaning the fuel is still in a geometry very close to the original. This means the initial burst was not strong enough to break or melt the reactor. For these releases, the DOE Handbook[1] on release fractions recommend the work of Restrepo[12] as the basis for release fractions. These values should be representative of an intact reactor releasing fission products and are shown in Table V.

TABLE V. Release Fractions for Case 2a, Long Critical Period, No Water

Group Name	Elements in Group	ARF
Noble Gases	Xe, Kr, He, Ne, Ar, Rn, H	5E-1
Alkali Metals	Cs, Rb, Li, K, Fr, Na	2E-1
Alkali Earths	Ba, Sr, Mg, Ca, Ra, Be	3E-2

Halogens	I, F, Cl, Br, At	5E-2
Chalogens	Te, S, Se, O, Po, N	7E-2
Platinoids	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	2E-3
Transition Metals	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	3E-2
Tetravalent	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-4
Trivalent	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	6E-4
Main Group I	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-3
Main Group II	Sn, Ca, In, Ag	4E-3
Boron	B, Si, P, C	6E-4

I.D.4. Case 2b – Long-term accident, initial burst followed by longer critical period but reactor is in water during critical periods

For Case 2B, Initial burst followed by longer critical period caused by water immersion, the main assumption is again that the reactor remains "relatively" intact. However, unlike Case 1a, the reactor will be covered by water when it is critical (say by tides coming in and out.) This means that much like Case 1b, the fission products will be scrubbed heavily by the water when it is present. The scenario again is one where the reactor survives the launch accident mostly intact and that the reactor falls onto land near water (say on a beach) such that the reactor is not always complete submerged, but instead is partially cover by the incoming tides. Therefore, it must also be assumed that some fission product release occurs while the reactor is sub-critical, (i.e. fuel is hot enough to release fission products.) This means the release will be somewhere between Cases 1b and Case 2a. For this case, the Restrepo[12] values for heated spent fuel will be divided by 10 as an approximation. This assumption is somewhat arbitrary, but it also brings the release of the noble gases more in line with values seen in Case 1b, for a reactor that burst and is destroyed while covered by water. These values are presented in Table VI.

TABLE VI. Release Fractions for Case 2b, Long Critical Period - Water

Group Name	Elements in Group	ARF
Noble Gases	Xe, Kr, He, Ne, Ar, Rn, H	5E-2
Alkali Metals	Cs, Rb, Li, K, Fr, Na	2E-2
Alkali Earths	Ba, Sr, Mg, Ca, Ra, Be	3E-3
Halogens	I, F, Cl, Br, At	5E-3
Chalogens	Te, S, Se, O, Po, N	7E-3
Platinoids	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	2E-4
Transition Metals	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	3E-3
Tetravalent	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4E-5
Trivalent	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	6E-5
Main Group I	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4E-5
Main Group II	Sn, Ca, In, Ag	4E-5
Boron	B, Si, P, C	6E-5

I.E. Summary Closing Thoughts on Release Fractions

The worst-case release fraction is Case 1a, where the prompt burst destroys the reactor with no water present. However, this case will also be paired with the lowest number of fissions.

For two cases with water Case 1b and 2b, the release will be highly mitigated by the water. This can be shown by the historical use of water as a fission product scrubber to reduce releases in light water reactors.

Longer-term releases will have a high number of fissions, but the intact reactor has lower release fractions and this will mitigate the dose.

I.F. Dose Results

The dose for 100 m and 1000 m receptors is presented in Table VII.

TABLE VII. Dose Calculations for Each Case

Case	Description	100 m Dose (milli-rem)	1000 m Dose (milli-rem)
1a	Step insertion by rod ejection or geometry change	493	9.6
1b	Step insertion by water immersion	4.5	0.1
2a	Initial burst followed by longer critical period	63	1.2
2b	Initial burst followed by longer term pulsing reactor from water ingress	61	1.2

The dose provides insights into the potential doses from criticality events from a space reactor. First the doses at 100 m are in the 10s of millirem to 100s of millirem for that receptor. The doses for the 1000 m receptor are in the sub millirem to single digit millirem range.

The experimental results from the SNAPTRAN program and Kiwi program did not see significant doses downwind either. A summary of the SNAPTRAN test radiological impacts[10] states that:

The SNAPTRAN-2 test confirmed the results of the SNAPTRAN-3 test that a reactivity accident with a "virgin fueled" SNAP 10A/2 reactor does not pose any undue hazard to the general public. The total integrated *radiation exposure dose at the NRTS site boundary (104 meters) was less than 10 mR for both tests. Likewise, the spread of contamination was limited to a radius of 200 meters from the reactor following both tests.*

Summary tables for the SNAPTRAN test have doses less than a rem at 100 m and in the millirem in the 1000 m range. A summary of the Kiwi TNT test radiological impacts[11] states that:

From 750 to approximately 2,000 ft downwind, little, if any, injury or clinical effects would occur, but exposures would exceed 3 rads and would require administrative investigation and reporting. Beyond approximately 1.5 mile, doses even in the path of the cloud would be below a few hundred millirad, and should present no problems.

Note, the difference between the rad and rem is that rad is a measurement of the radiation absorbed by the material or tissue and rem is a measurement of the biological effect of that absorbed radiation. For this study, rad and rem may be considered equivalent. In addition, Kiwi-TNT was a much large number of fissions than the SNAPTRAN test and higher than the number of fissions used for Case 1a by three orders of magnitude. So, doses will be higher for Kiwi-TNT than SNAPTRAN or this study.

ACKNOWLEDGMENTS

This work was funded by the NASA Game Changing Development Program in the Space Technology Mission Directorate.

REFERENCES

1. DEPARTMENT OF ENERGY, “DOE Handbook - Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities,” DOE-HDBK-3010-94 Vol. 1., December, (1994)
2. W. B. WILSON and T. ENGLAND, “CINDER90 V 1.0,” LA-CC-03-048, Los Alamos National Laboratory, (2003)
3. H. R. TRELLUE, “MONTEBURNS, VERSION 2.0,” LA-CC-02-0046, Los Alamos National Laboratory, (2002)
4. B. A. NAPIER, J.P. RASHEL, and N.E. BIXLER, “Final Review of Safety Assessment Issues at Savannah River Site,” August 2011,
5. U.S. DEPARTMENT OF ENERGY, DOE-STD-1189, Integration of Safety into the Design Process, Washington DC, March 2008
6. U.S. DEPARTMENT OF ENERGY, SBT-14BE-32792, Approval of Breathing Rate for Safety Basis Accident Analysis, Los Alamos Site Office, Los Alamos NM, September 3, 2008
7. INTERNATIONAL COMMISSION ON RADIATION PROTECTION, ICRP Publication 72, Age Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5, Compilation of Ingestion and Inhalation Dose Coefficients, JAICRP 26(1), September (1995).
8. T. P. MCLAUGHLIN, et al. “A Review of Criticality Accidents,” LA-13638, Los Alamos National Laboratory, May, (2000)
9. P. R. MCCLURE, “Kilopower Space Reactor Launch Safety,Maximum Credible Fissions for a Criticality Accident”, LA-UR-18-28896, Los Alamos National Laboratory, Los Alamos, NM, May, (2018).
10. O. L. CORDES, et al. "Radiological Aspects of a Reactor Destructive Test,” IDO-17203, Phillips Petroleum Company, Atomic Energy Division, February, 1967.
11. R. V. FULTYN, "Environmental Effects of the KIWI- TNT Effluent: A Review and Evaluation," LA-3449, Los Alamos Scientific Laboratory (1968).
12. L. RESTREPO “Building 771, Sub-team 6 Report, Chapter 7, Criticality Assessment,” EG&G-RF, Golden, CO