*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 FISSIONS FOR A CRITICALITY ACCIDENT

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*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. The first step in estimating consequences is to estimate the source term, which is a function of the number of fissions that have occurred during the criticality. This paper presents a bounding estimate for the number of fissions for a Kilopower space reactor criticality accident based upon values for all historic criticality accidents to date.*

## I. INTRODUCTION

This paper examines potential accident conditions for the Kilopower space reactor going critical during a launch accident. The goal of this analysis was to postulate the total number of fissions that could be generated during an accident event. The total number of fissions is an approximate surrogate for what will be the maximum release (or source term) for the accident. From the source term an approximation of dose (based upon the fission products generated and released) can be estimated.

### I.A. Methods to Estimate Number of Fissions

Several methods are available to estimate the number of fissions. These include

1. Using a generic model for calculating reactivity insertions such as "Bethe-Tait"[1].
2. Using a reactor specific model for calculating reactivity (e.g. a Kilopower MCNP model).
3. Using historic data as a bounding estimate.

Los Alamos has performed calculations to investigate the first two methods. Modeling can provide some insight, but the results are extremely assumption driven even for a reactor specific model and much more so for a generic model. The number of fissions calculated can span several orders of magnitude. A more defensible approach is believed to be an examination of the all criticality events that have occurred and use that information to set a bounding value. That is the approach taken in this paper.

### 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 | Moderated/reflected system |

from water ingress

### I.B. Primary Reference Material and Assignment of Fission Yields

For this paper, three primary reference documents are used and are:

1. Nuclear Regulatory Commission, "Nuclear Fuel Cycle Facility Accident Analysis Handbook"[2]
2. Department of Energy, "DOE Handbook - Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities"[3]
3. McLaughlin, T.P., et al. "A Review of Criticality Accidents,"[4]

The first two references are very important since they represent the current regulatory guidance from the NRC and DOE respectively. And they represent "reasonable conservative estimates" for criticality accidents. However, they are somewhat older and new data has been obtained since they were first published. McLaughlin is the most recent attempt to gather data for all of the known reactor criticality accidents. McLaughlin is considered to be the most up to date reference on all criticality accidents to have occurred worldwide.

### I.C. Assignment of Fission Yields

All of the references were examined to find the most bounding values for criticality using the bin assignments from Table I. All of the most bounding values are from McLaughin. The following assignments were made based on the data from McLaughlin:

- Case 1a – Short Term - Bare/Dry Solid – Pg. 86, Livermore, CA, 26-03-63, 47 kg cylinder with Be reflector, severe fuel damage 3.7E17. Also, Pg. 89, Aberdeen, MD 6-09-68, 123 kgs of U-Mo unreflected, severe fuel damage 6.09E17. A value of 5E17 was chosen. This value is a higher value than both the recommended DOE and NRC values for Bare/Dry Solids
- Case 1b – Short Term - Moderated/reflected system short term – Pg. 95, National Reactor Test Station, 22-07-54, 4.16 kg U(93) as U/Al alloy, fuel/elements in water moderator, 4.68E18 rounded up to 5E18. Again, this value is a higher value than the DOE and NRC values.
- Case 2a – Long Term - Bare/Dry Solid – Pg. 89, Sarov (Soviet Union), 17-06-97, ~44 kg U(90), Sphere with copper reflector, highly damped power oscillations lasting six days before termination, with 1E19 total fissions. The long-term fission total seems appropriate given the assumptions of a long-term criticality.
- Case 2b – Long Term - Moderated/reflected system – Pg. 99, Kurchatov Institute, 26-05-71, U(20) O2 fuel rods, Be reflected in water, 2.E19 fission from approximately 50 pulses. Also pg. 95, Chalk River, 1950, which was 1E20 fission which was also multiple excursions, but number of excursions was not specified. Data is lacking on the Chalk River event. Final assignment was 1E20 fissions. A long-term fission total seems appropriate for this long-term criticality event.

The assignments for fission yields for Kilopower based upon the four cases are presented in Table II.

**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. Comparison to KRUSTY calculations

KRUSTY is the name of the nuclear demonstration experiment of the Kilopower reactor. For the safety analysis of the experiment, two Reactivity Insertion Accidents were performed and documented by McClure[5].

For the first accident, the reactor accident is a prompt insertion of $1.40. The calculated number of fissions was 3E17. Based upon the results, it is assumed that the reactor would disassemble along with some melting of the fuel. The conditions necessary to achieve this condition are unlikely and the probability of occurrence was considered extremely unlikely. This result is comparable to the initial burst yield for a Bare/Dry Solid shown in Case 1a of 5E17. As an additional note, this accident compares well to a LLNL accident of 1963 (47 kg of metal with a Be reflector, p. 86 of McLaughlin). Its fuel made an explosive sound, and it was observed as melting and burning. Its measured yield was 3.76E17 fissions.

The second accident was a longer-term accident where the reactor runs for multiple days. The total number of fissions was calculated to be approximately 3E19 fissions. Again, the conditions necessary for this result are considered beyond extremely unlikely in likelihood. This result is comparable to a total fission yield for a Bare/Dry Solid of 1E19 of Case 2a. In order to achieve the 3E19 result, the launch accident resulting in sustained criticality would have to last days before action is taken to shut-down the reaction.

### I.E. Comparison to Experimental Results

Two different space reactor systems were tested for similar types of reactivity insertion accidents including;

1. the Kiwi reactor (a ground test version of a thermal nuclear rocket) and
2. the SNAP 10A reactor which was the first reactor flow in space.

Each test is discussed below.

#### *I.E.1. Kiwi-TNT*

The Kiwi-TNT test is documented in King[6]. The Kiwi "Transient Nuclear Test" was designed to artificially insert the maximum reactivity possible into the Kiwi Reactor that was built and tested as part of the Rover program. This was accomplished by building control drum motors that spun at as fast a rate as was achievable, with the goal of inserting as much reactivity from the eight control drums as was possible. The test inserted ~7.3 dollars of reactivity into the reactor in a few milliseconds and achieved an initial bust yield of 1.3E20 fissions.

This test is considered not applicable to Kilopower for several reasons. First, Kilopower does not have the excess reactivity that was present in the Kiwi reactors. Kilopower only has approximately ~2 dollars of excess reactivity. Second, this test did not represent accident conditions. The motor on the control drum were made especially for maximum speed and all eight motors turned together in unison. This is outside the failures one would equate to an accident condition. However, the test is interesting for the applicability of fission product release. This portion of the test will be of interest to Kilopower safety.

#### *I.E.2. SNAPTRAN*

The SNAPTRAN tests were also used to examine reactivity insertion accidents for the SNAP 10-A reactor. Three tests were performed for SNAPTRAN:

1. A series of non-destructive reactivity insertion events;
2. A maximum reactivity insertion event (like Kiwi-TNT) where the drums were spun at a very fast rate; and
3. A water immersion test that caused the reactor to go prompt critical.

The tests are documented in Johnson[7] and Kessler[8]. The first SNAPTRAN test is not of interest to this study. The second SNAPTRAN test was an insertion of ~5 dollars using a method similar to Kiwi-TNT. This test is also not of interest to Kilopower for reason similar to Kiwi-TNT in that it has more excess reactivity that Kilopower and does not represent accident conditions (i.e. artificially fast drums turning in unison.)

SNAPTRAN-3 is of interest to Kilopower. The SNAP 10A reactor was not designed to "not" go critical in water. The SNAP reactor was very 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. However, Kilopower is designed to "not" go critical in water and should be sub-critical when submerged. But the accident conditions for this accident are very similar to data for a moderated/reflected systems estimated in Table II. It is very similar to the value of 5E18 for an initial burst yield for water emersion shown in Case1b. So, the SNAPTRAN results do reflect and provide more reassurance that the accident values assigned in this note are good "bounding" values for criticality accidents for Kilopower.

## II. CONCLUSIONS

Using bounding historical data the maximum credible number of fissions can be assigned for the Kilopower space reactor. As the safety analysis processes moves forward the maximum number of fissions will be used to determine the source term and dose to the public for hypothetical inadvertent criticality accidents.


## ACKNOWLEDGMENTS

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


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