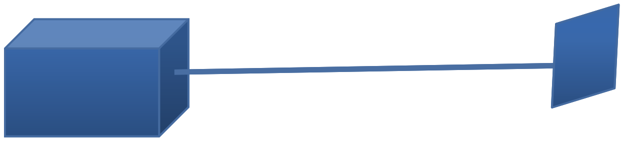
AeroCube 5 Drag Enhancement Device

- In order to comply with the 25-year LEO de-orbit requirement, a passive electrodynamic tether is deployed from AC5 bus.
  - *Orbit decays faster due to electrodynamic force*
  - *Increase in surface area also increases orbit decay rate (atmospheric drag)*

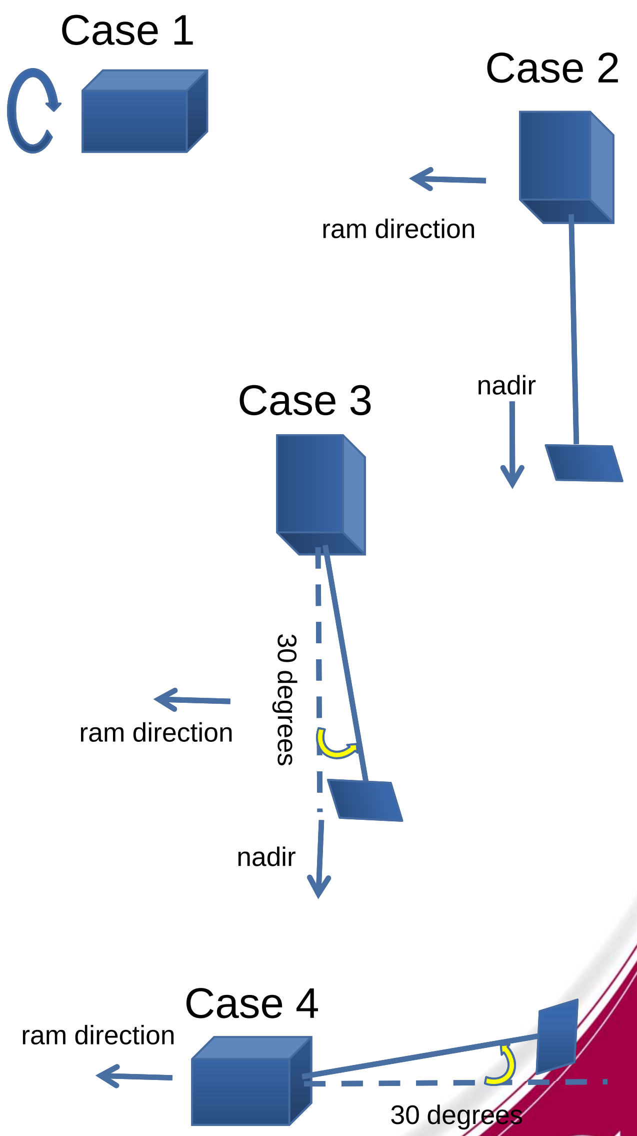
- The tether has an end mass plate for stabilization. The electrodynamic forces should passively stabilize the spacecraft and deployed tether system in a gravity gradient configuration.
  - *Device provided by a commercial company Tethers Unlimited Inc.*
  - *Total device mass = 85 grams*
  - *Tether tape dimensions (12 m length, 75 mm wide)*
  - *End plate dimensions (100 mm x 83 mm x 6.5 mm)*
  - *Deployed two years after spacecraft operations are complete*



A-110513-1

AeroCube 5.0 Case Descriptions

- 4 intact cases were considered:
  1. *AeroCube body only (assumes average tumble configuration)*
     - Assumes tether is not deployed.
  2. *AeroCube and tether device deployed (assumes gravity gradient stabilization)*
     - Tether system is fully deployed and in a gravity gradient stabile orientation until reentry.
  3. *AeroCube and tether device deployed (gravity gradient stabilization with libration of the tether of ~30 degrees from nadir)*
     - Tether system deployed but uncertainty in the stabilization effects
       - *Assumption taken from conversations with Nestor Voronka and Rob Hoyt of Tethers Unlimited*
  4. *AeroCube and tether device deployed (alignment with velocity vector with libration of the tether of ~30 degrees from the velocity vector)*
     - A different orientation to determine the range of lifetimes.



A-110513-1

AeroCube 5.0 Initial Conditions

- Area estimation:

  The AeroCube 5 satellite core body is 10.26 x 10.26 x 17.02 cm

  – *Case 1: AeroCube body (assuming tumble) area = 0.023 m^2*
  – *Case 2: AeroCube body + tether system (gravity gradient alignment) with = 0.596 m^2*
  – *Case 3: AeroCube body + tether system (gravity gradient alignment with 30 degree libration about nadir)= 0.559 m^2*
  – *Case 4: AeroCube body + tether system (velocity vector alignment with 30 degree libration about ram direction) = 0.314 m^2*
  – *All areas with tether take into account twist.*
    - Ref. Noord, J.L., West, B., Gilchrist, B., “Electrodynamic Tape Tether Performance with Varying Tether Widths at Low Earth Altitudes.”, AIAA, 39th Aerospace Sciences Meeting & Exhibit, Reno, NV, 2001
- Mass estimate: 2.08 kg
  – *Includes cubesat + tether drag device*
- Atmospheric Assumption: Considered 50th percentile (nominal) level of solar flux ($F_{10.7}$) and geomagnetic index (A_p)
  – *Used NASA Marshall Space Flight Center monthly predictions (based on NOAA data) from October 2013 to 2030; for years after 2030, repeated last 11-years (2019-2030) of Marshall predicted data*
- Initial orbit (provided by David Hinkley)
  – *469 x 972 km perigee/apogee altitude, 120^o Inclination, Epoch: December 1, 2013*

AeroCube 5.0 Initial Conditions (cont'd)

- NASA Standard 8719.14A requires consideration of the case in which the tether is severed at the half-way point (assumed here to occur right after deployment)
- Severed tether half attached to AC5
  - *Area estimation:*
    - Case 2: AeroCube body + half tether (gravity gradient alignment) with = 0.309 m^2
    - Case 3: AeroCube body + half tether (gravity gradient alignment with 30 degree libration about nadir)= 0.290 m^2
    - Case 4: AeroCube body + half tether (velocity vector alignment with 30 degree libration about ram direction) = 0.161 m^2
  - *Mass estimate: 2.004 kg*
    - Includes cubesat + half tether
- Severed tether half attached to end plate
  - *Area estimation:*
    - Case 2: End plate+ half tether (gravity gradient alignment) with = 0.287 m^2
    - Case 3: End plate + half tether (gravity gradient alignment with 30 degree libration about nadir)= 0.269 m^2
    - Case 4: End plate + half tether (velocity vector alignment with 30 degree libration about ram direction) = 0.153 m^2
  - *Mass estimate: 0.048 kg*
    - Includes end plate + half tether

Long-Term Orbit Propagation

- Precision integration code TRACE was used to propagate the upper stage
  - *MSISE-86 atmosphere model*
  - *70 x 70 modified WGS84 Earth gravity model*
  - *Sun and Moon gravity*
  - *Solar radiation pressure (assumed reflectivity coefficient = 1.3)*
- Primary source of uncertainty is solar activity, which affects atmospheric density and hence drag
  - *Used MSFC monthly predictions (based on NOAA data) from October 2013 to 2030; for years after 2030, repeated last 11-years (2019-2030) of Marshall predicted data*
  - *Used 5, 50, and 95 percentile levels of solar flux ($F_{10.7}$) and geomagnetic index (A_p)*
- Did not model electrodynamic force
  - *Conservative assumption for lifetime*
  - *Tether length is too short too produce significant electrodynamic force*

Collision Probability Assessment

- Used an orbit trace crossing (OTC) method
  - *All crossings of the orbit traces of the primary object (AC5) and the secondary (background) objects as they evolve are determined*
    - Used TRACE evolution results
  - *The collision probability at each crossing is computed assuming the in-track position of the background object is uniformly distributed over 360 deg*
  - *Collision probabilities are accumulated across all OTCs over the probability assessment time interval*

Computation of Collision Radius

- Collision probability at an orbit trace crossing depends on the collision radius
- For AC5 cases with no tether (Cases1, 5, and 9)
  - *The primary (AC5) mean contact radius was computed by randomly picking unit vectors in three dimensions, using a simple rectangle model to represent the surfaces, and computing the root mean square*
  - *For each primary/background object pair, the combined mean collision radius is the sum of the fixed AC5 mean contact radius and the contact radius of the background object*
- For AC5 cases with a tether (Cases 2-4, 6-8, 10-12)
  - *The combined mean collision radius is computed using a formulation that uses the AC5 tether configuration length and width (including cube sat and end plate) and the background object contact radius (assumes 3D random orientation of straight AC5 tether configuration)*
- Contact radii of the secondary objects are from the ADEPT model (see following slides)

Background Objects

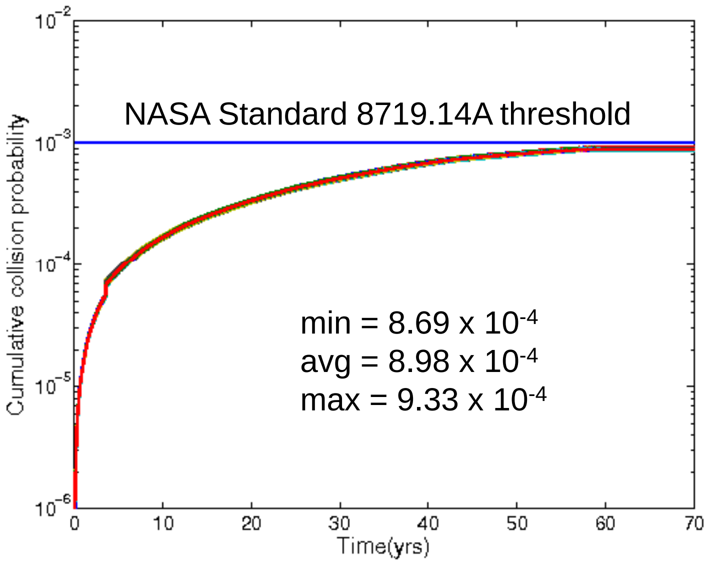
- Used the Aerospace Debris Environment Projection Tool (ADEPT) model of the current and future background population (Ref. 4)
  - *Model includes orbit trajectories and sizes for each object*
  - *Extends from LEO to GEO*
  - *Selected the "Non-Compliance" population (see Ref. 4)*
  - *Retained objects larger than 10 cm for this study*
- Model projects out 200 years and includes the following populations:
  - *0^{th} generation objects: Recent unclassified catalog population, a statistically-derived population of unknown objects (difference between cataloged and tracked populations), and a representation of future launched objects*
  - *1^{st} generation debris from future explosions and from collisions between 0^{th} generation objects (100 Monte Carlo scenarios)*
  - *2^{nd} generation debris from collisions between 0^{th} and 1^{st} generation objects was not included in the upper stage collision probability analysis (contribution is small)*

Collision Probability

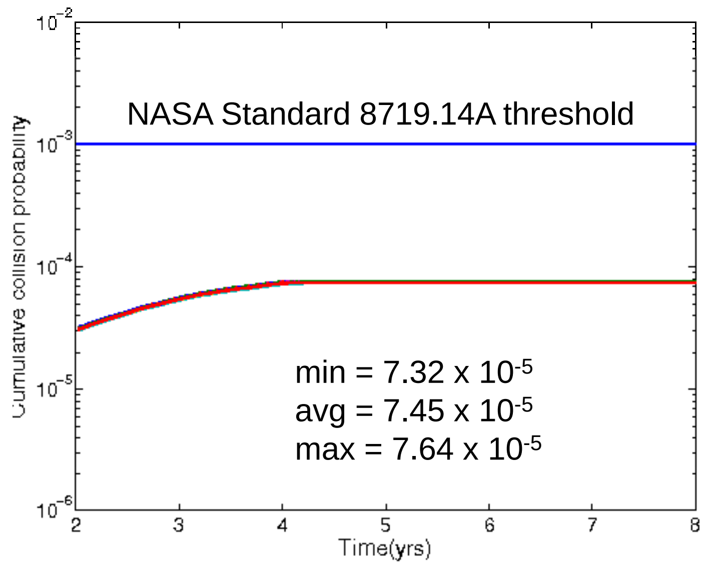
MSFC 5th percentile solar cycle, Cases 1 and 2

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 1 (no tether)



Case 2 (tether in gravity gradient alignment, no libration)



Cumulative collision probability curves become horizontally flat after re-entry

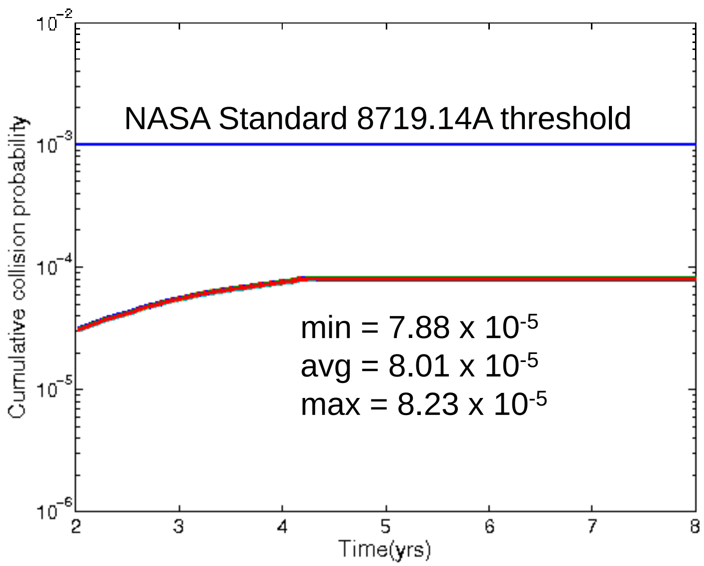
A-110513-1

Collision Probability

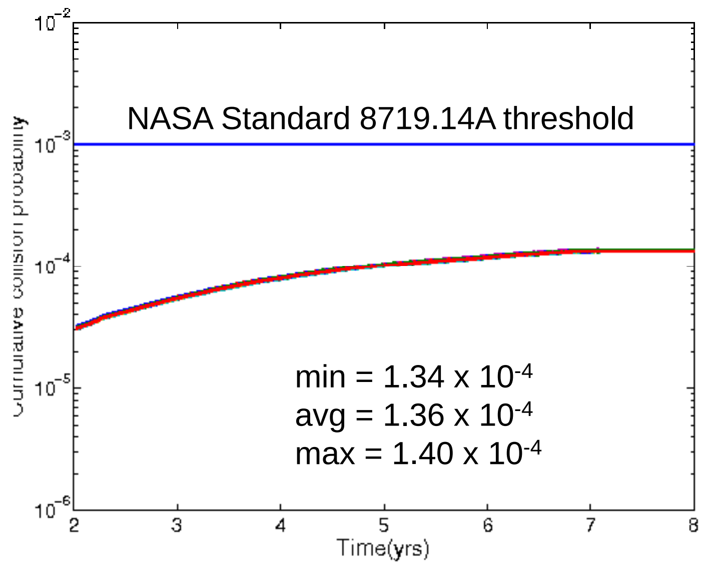
MSFC 5th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



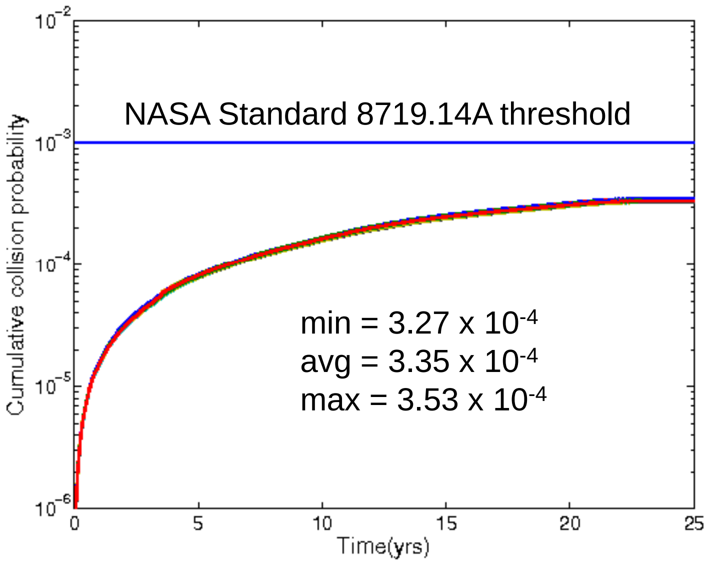
Cumulative collision probability curves become horizontally flat after re-entry

Collision Probability

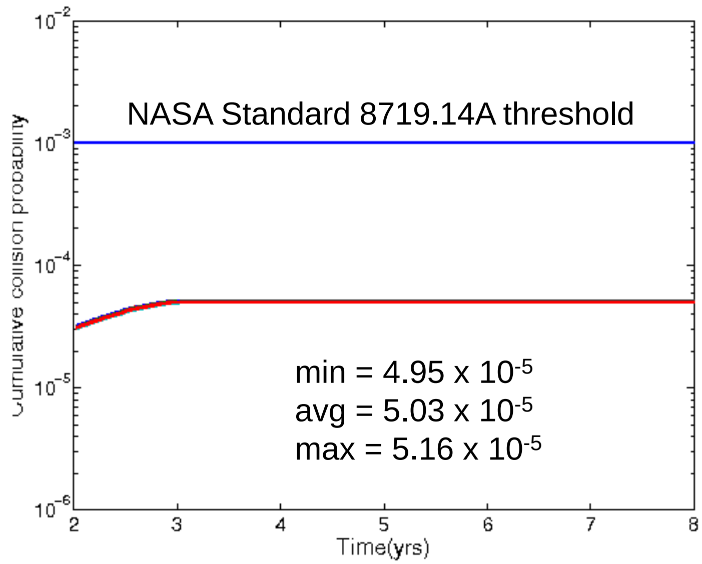
MSFC 50th percentile solar cycle, Cases 1 and 2

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 1 (no tether)



Case 2 (tether in gravity gradient alignment, no libration)



Cumulative collision probability curves become horizontally flat after re-entry

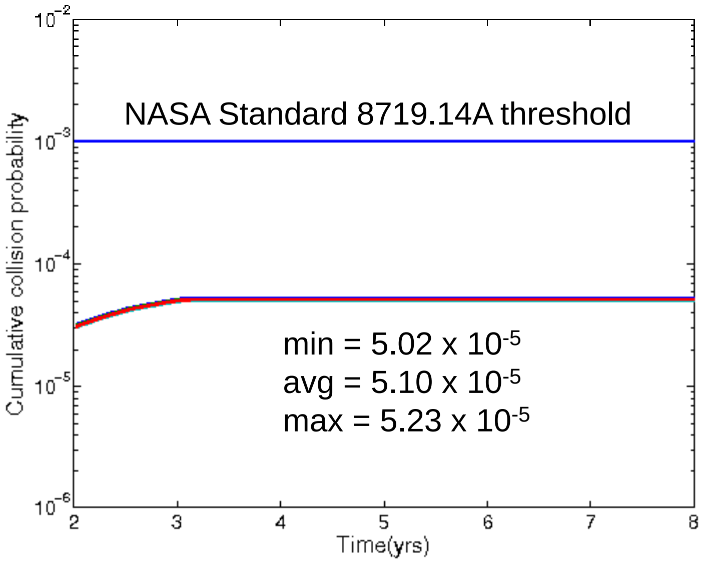
A-110513-1

Collision Probability

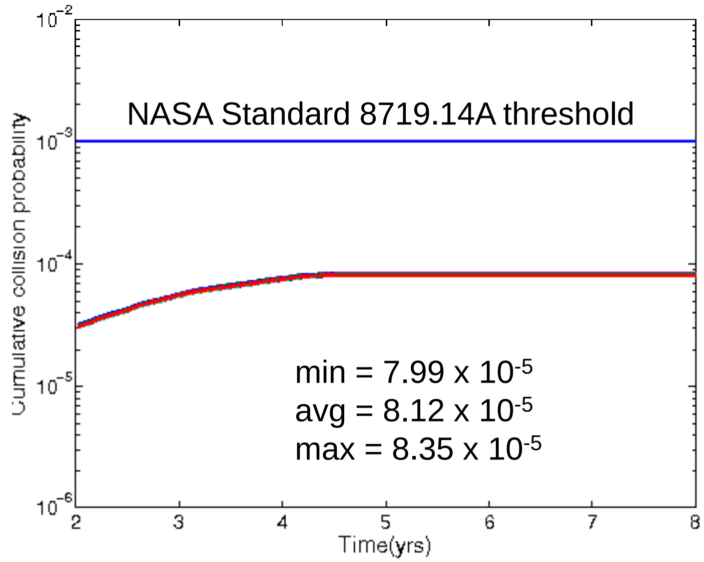
MSFC 50th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



Cumulative collision probability curves become horizontally flat after re-entry

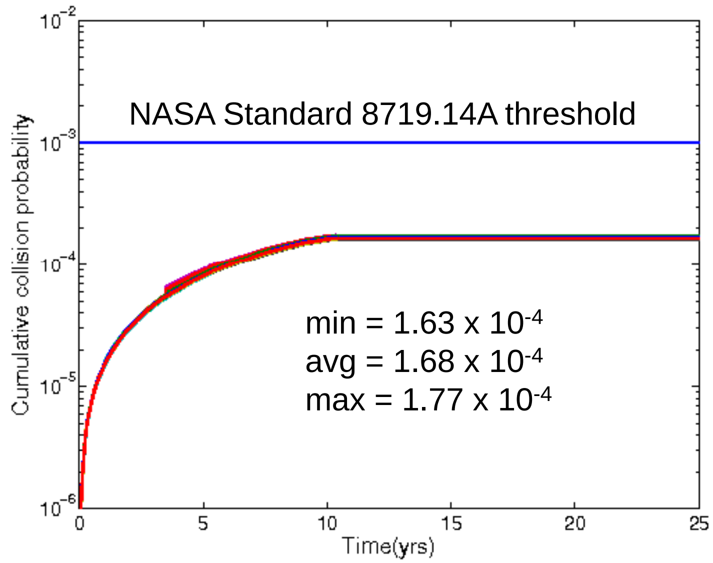
A-110513-1

Collision Probability

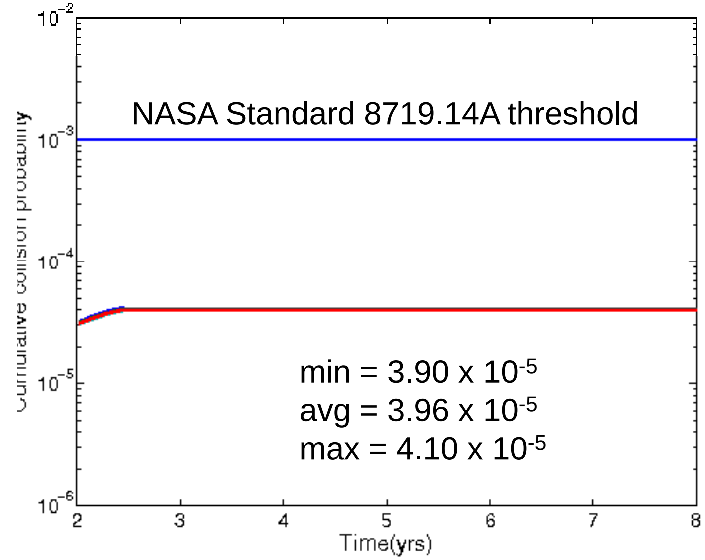
MSFC 95th percentile solar cycle, Cases 1 and 2

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 1 (no tether)



Case 2 (tether in gravity gradient alignment, no libration)



Cumulative collision probability curves become horizontally flat after re-entry

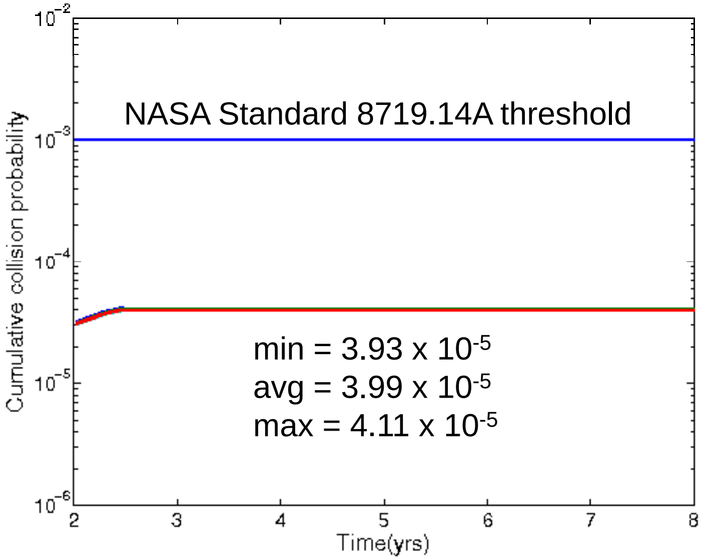
A-110513-1

Collision Probability

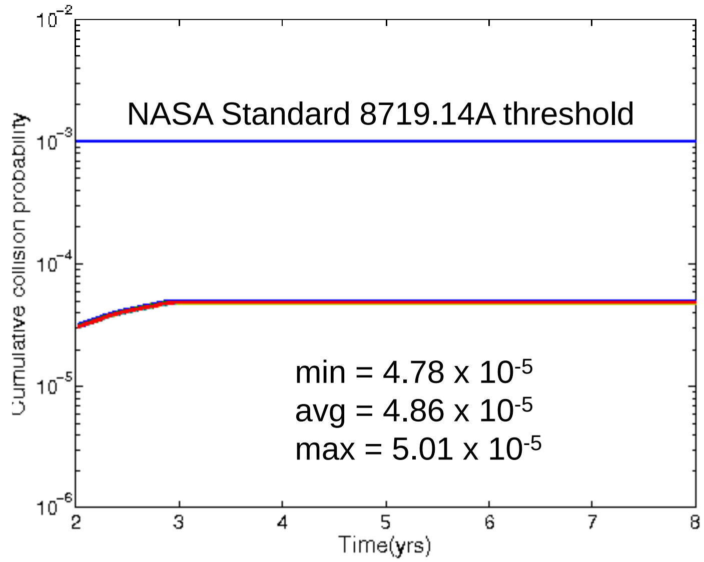
MSFC 95th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for AC5 for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



Cumulative collision probability curves become horizontally flat after re-entry

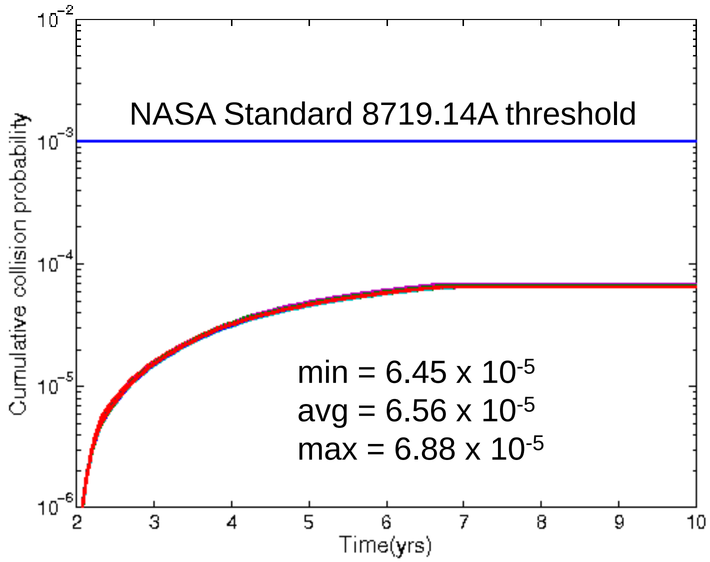
A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

MSFC 5th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001

Case 2 (tether in gravity gradient alignment, no libration)



Cumulative collision probability curves become horizontally flat after re-entry

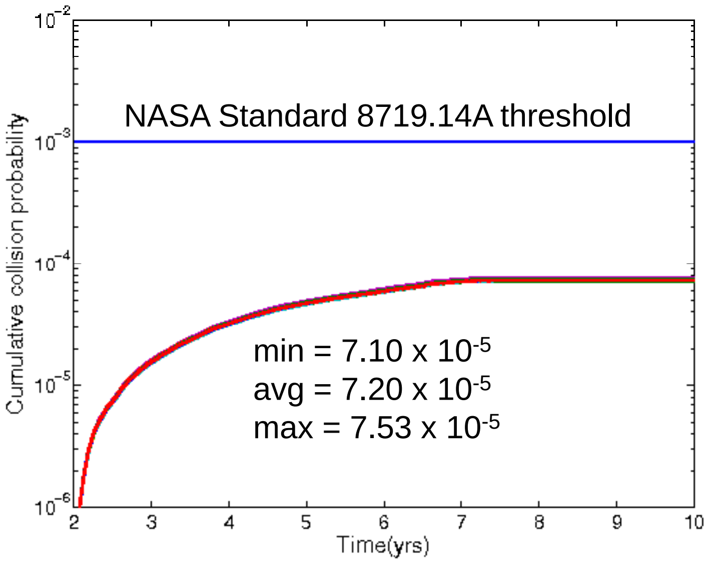
A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

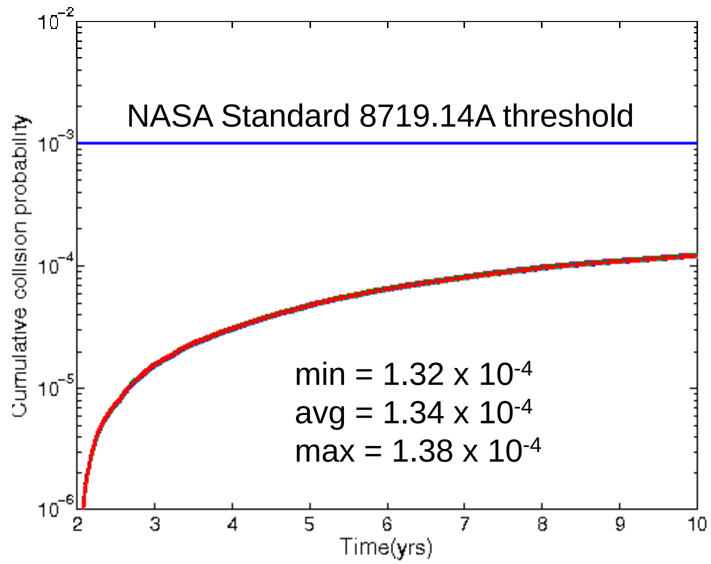
MSFC 5th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



Cumulative collision probability curves become horizontally flat after re-entry

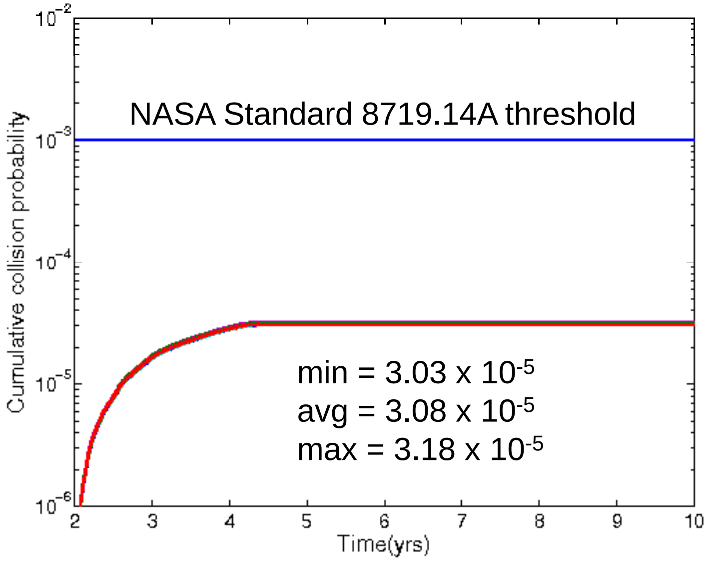
A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

MSFC 50th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001

Case 2 (tether in gravity gradient alignment, no libration)



Cumulative collision probability curves become horizontally flat after re-entry

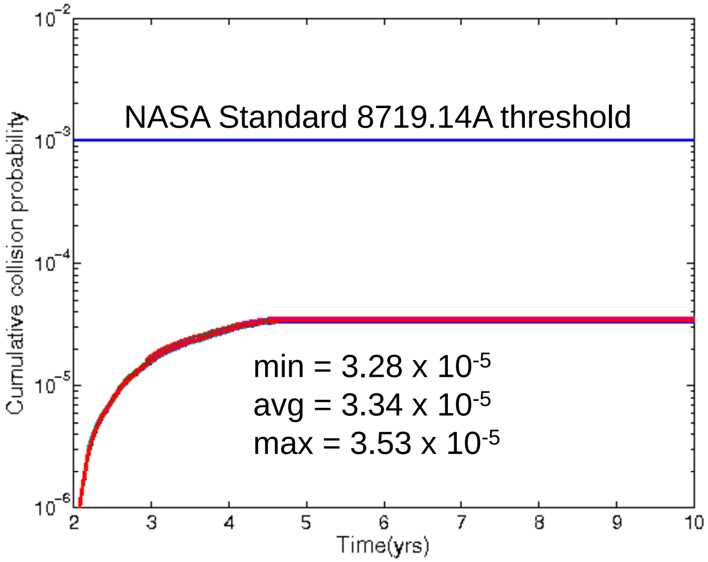
A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

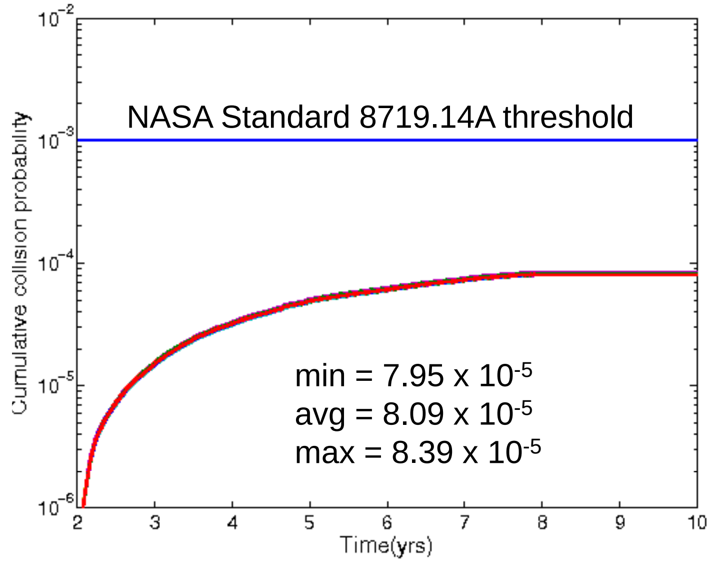
MSFC 50th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



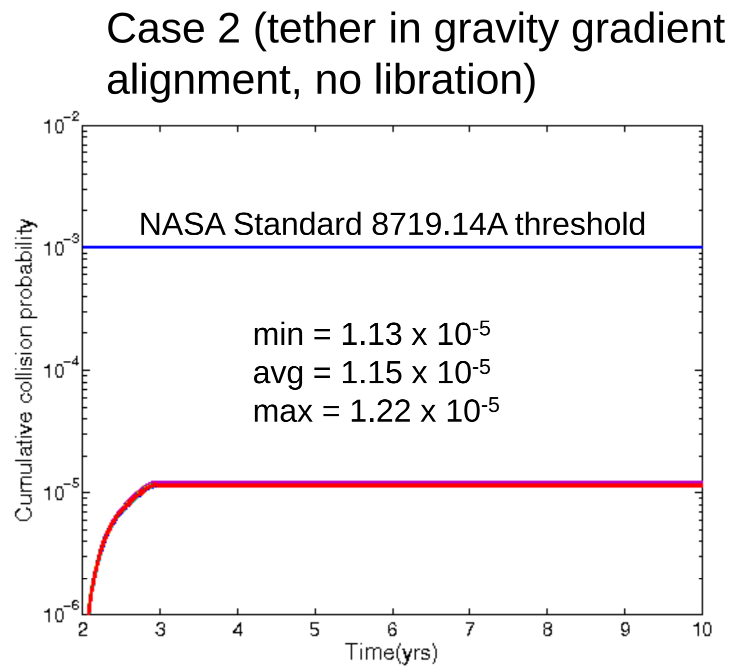
Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

MSFC 95th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001



Cumulative collision probability curves become horizontally flat after re-entry

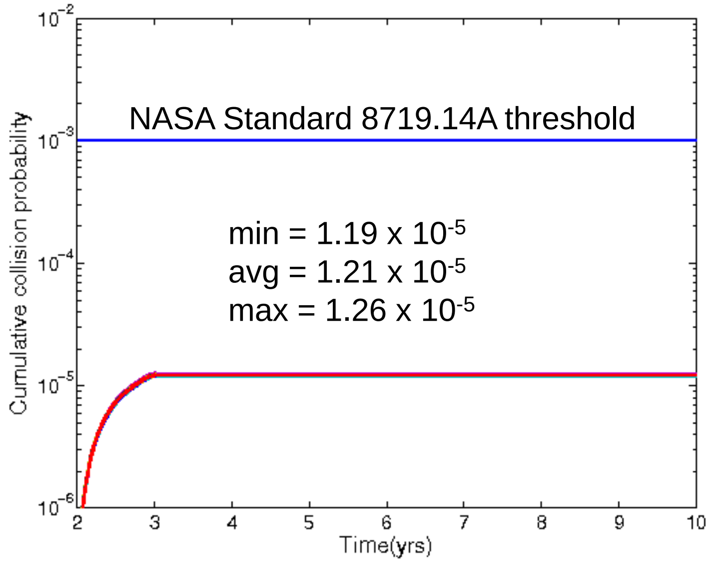
A-110513-1

Collision Probability for Severed Tether Half Attached to AC5

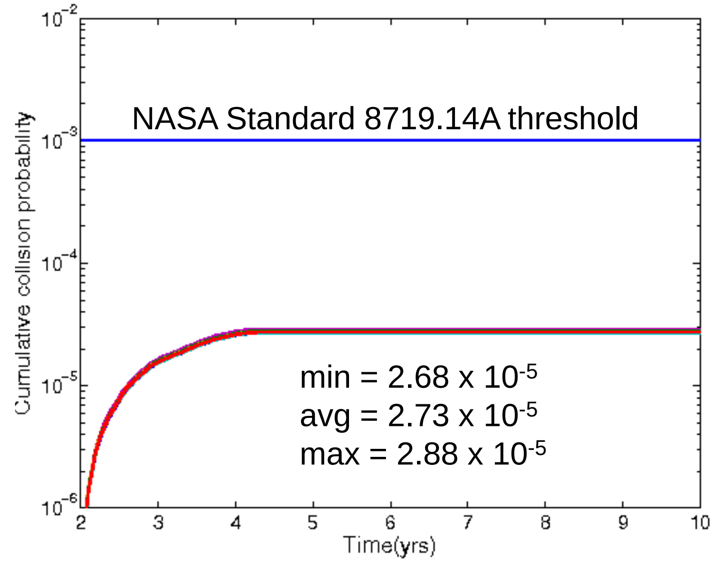
MSFC 95th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to AC5 for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



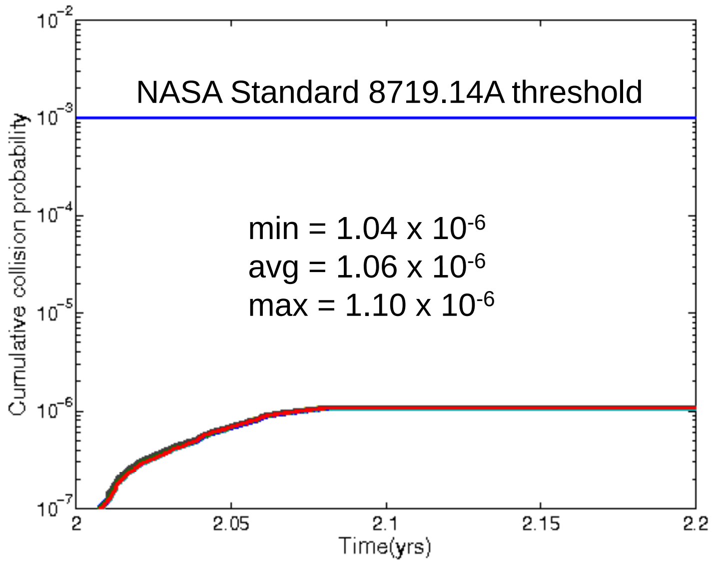
Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

Collision Probability for Severed Tether Half Attached to End Plate MSFC 5th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001

Case 2 (tether in gravity gradient alignment, no libration)



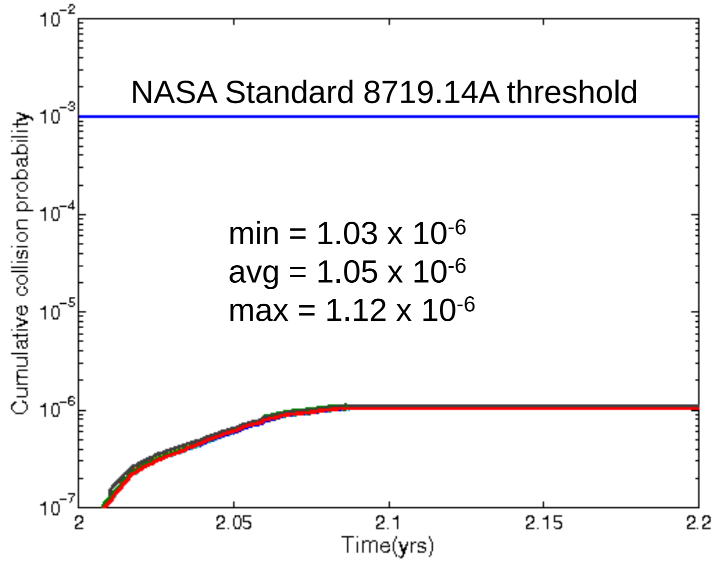
Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

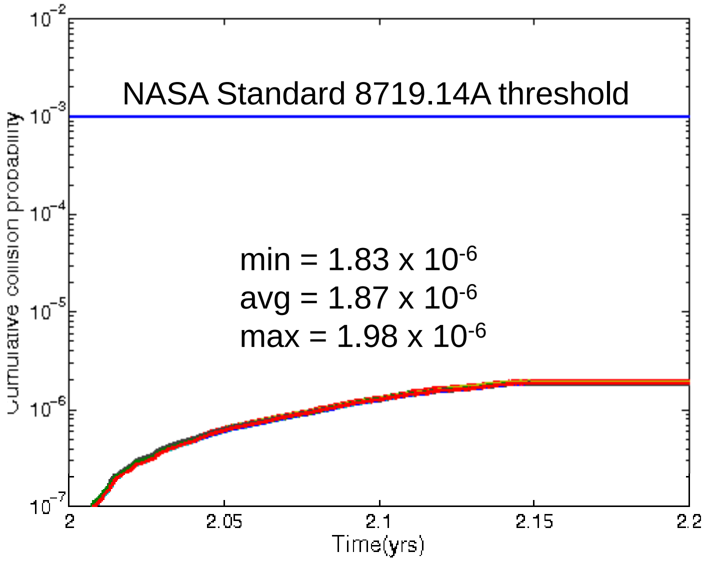
Collision Probability for Severed Tether Half Attached to End Plate MSFC 5th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 5th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)

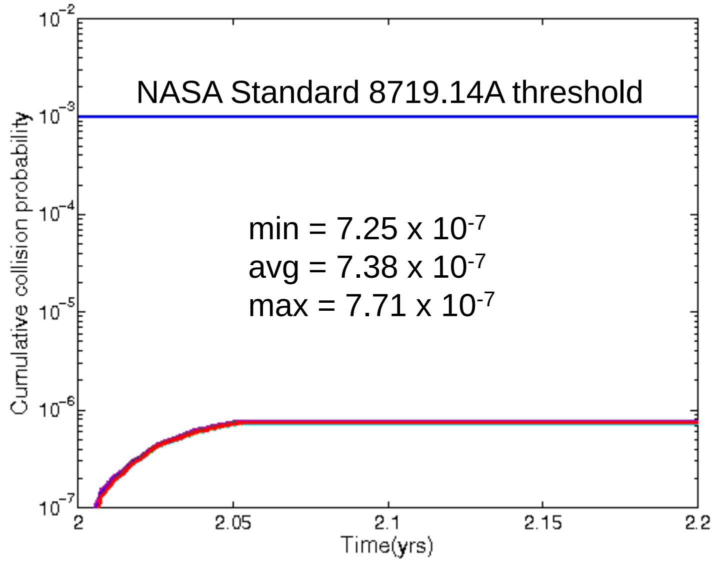


Cumulative collision probability curves become horizontally flat after re-entry

Collision Probability for Severed Tether Half Attached to End Plate MSFC 50th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001

Case 2 (tether in gravity gradient alignment, no libration)



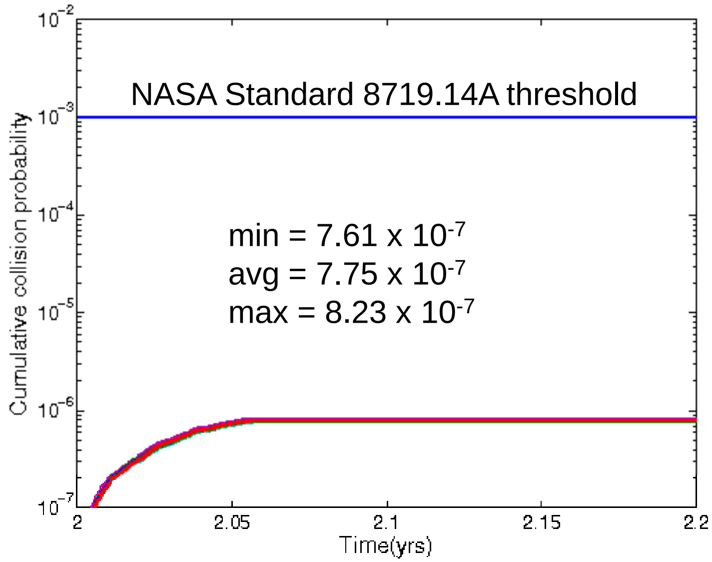
Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

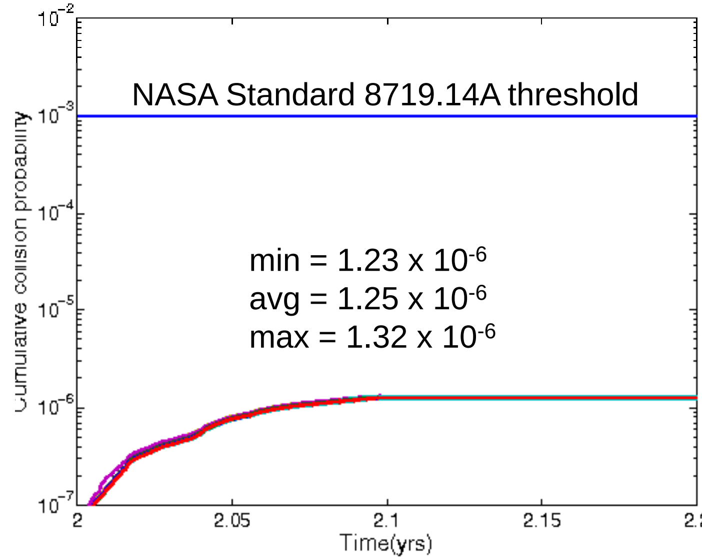
Collision Probability for Severed Tether Half Attached to End Plate MSFC 50th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 50th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)

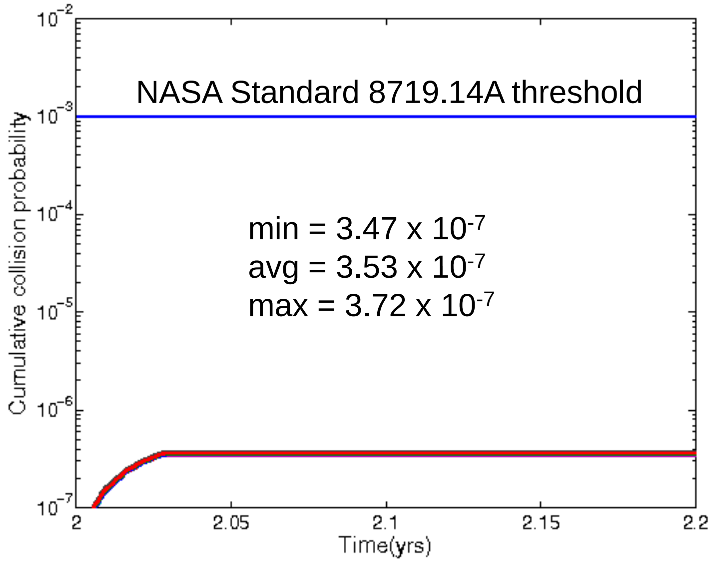


Cumulative collision probability curves become horizontally flat after re-entry

Collision Probability for Severed Tether Half Attached to End Plate MSFC 95th percentile solar cycle, Case 2

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001

Case 2 (tether in gravity gradient alignment, no libration)



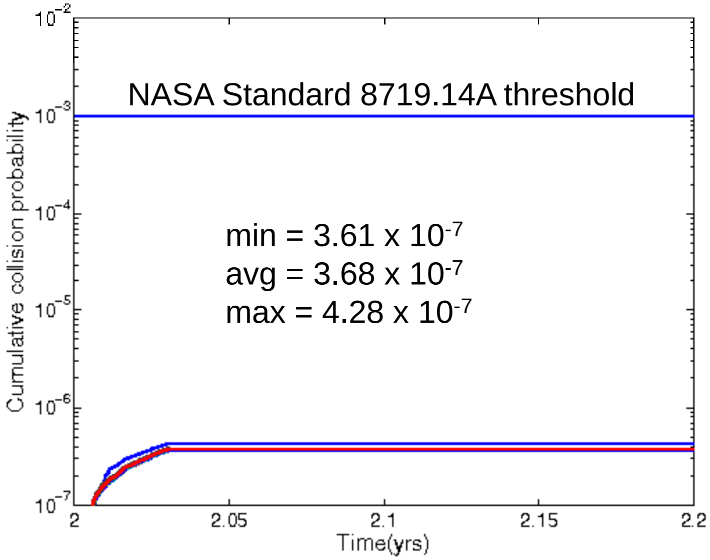
Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

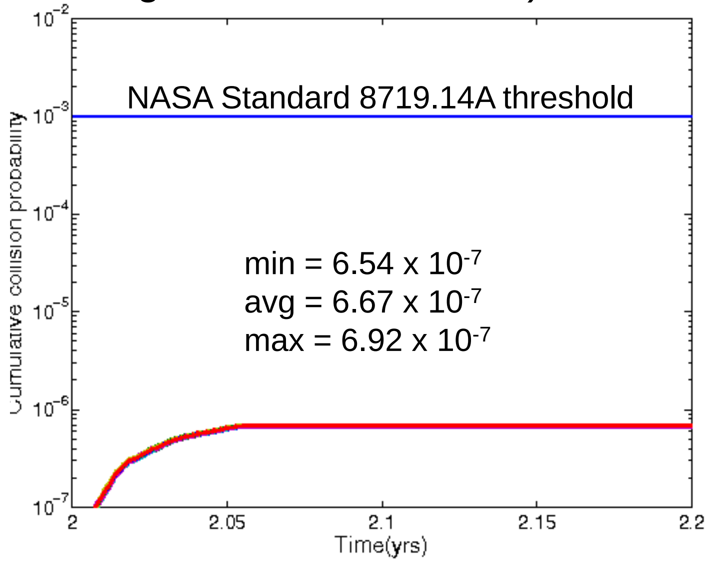
Collision Probability for Severed Tether Half Attached to End Plate MSFC 95th percentile solar cycle, Cases 3 and 4

- The plot shows cumulative collision probability vs. time for the severed tether half attached to the end plate for the MSFC 95th percentile solar cycle profile (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

Case 3 (tether in gravity gradient alignment with libration)



Case 4 (tether in velocity alignment with libration)



Cumulative collision probability curves become horizontally flat after re-entry

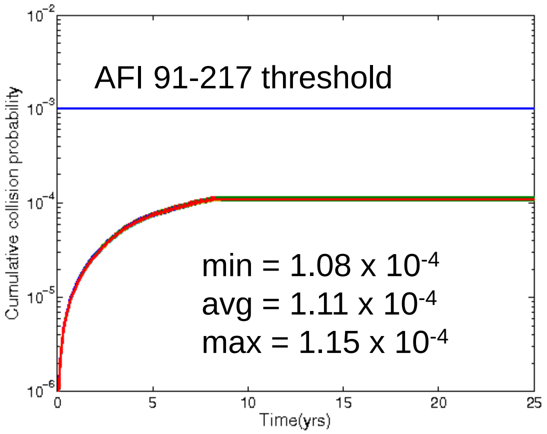
A-110513-1

Collision Probability

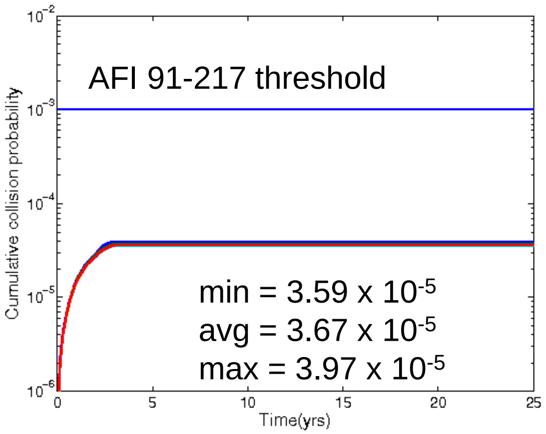
"Peas"

- The plots show cumulative collision probability vs. time for a single "pea" for all three MSFC solar cycle profiles (one curve for each of 100 Monte Carlo debris populations)
- Collision probability < 0.001 for all cases

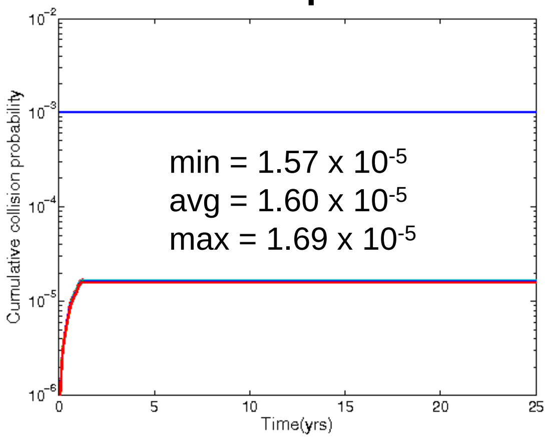
MSFC 5th percentile



MSFC 50th percentile



MSFC 95th percentile



Cumulative collision probability curves become horizontally flat after re-entry

A-110513-1

Conclusions

- The collision probability between AC5 and large background objects for all tether configurations considered is less than the 0.001 threshold in NASA Standard 8719.14A
- The collision probability between the severed tether halves and large background objects for all tether configurations considered is less than the 0.001 threshold in NASA Standard 8719.14A
- The collision probability between the “peas” and large background objects is less than the 0.001 threshold in NASA Standard 8719.14A