Modeling of Radiation Effects on Spacecraft Hardware

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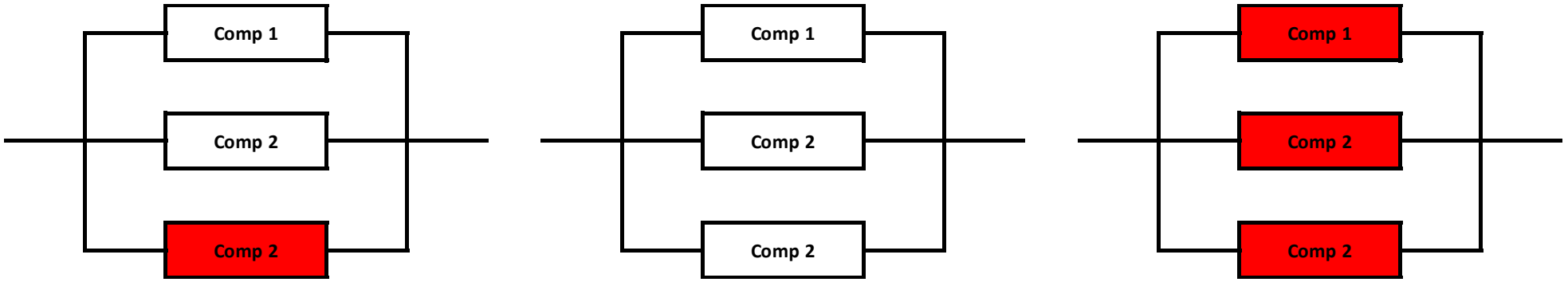

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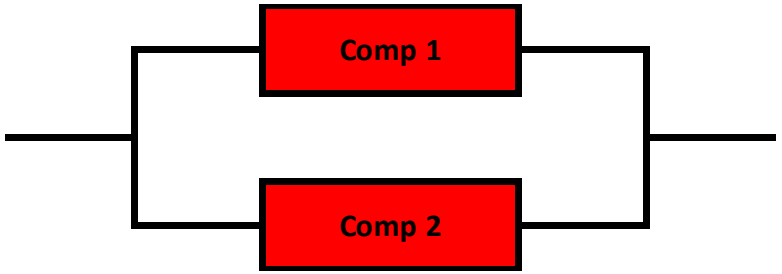
Introduction

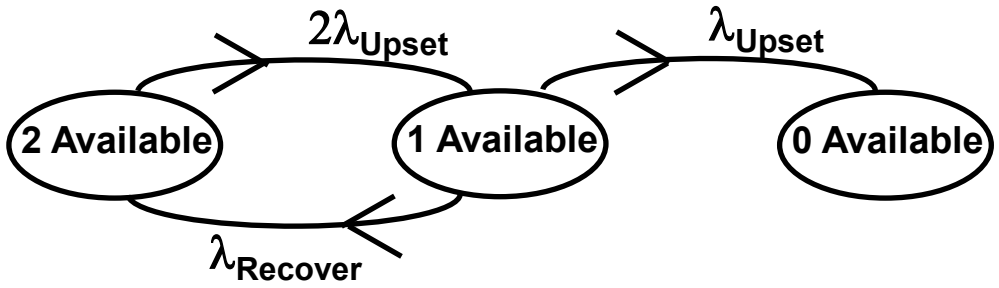
The **probabilistic radiation model** is a discrete event model that estimates the likelihood of system failures primarily due to radiation induced upsets.

- In a space environment, electronic components are subject to **radiation induced upsets**
- During an upset the component is unavailable until it recovers
- The upset time is generally brief
- The components could experience multiple upsets (and recoveries) during a mission
- A system failure can occur when multiple components are unavailable at the same time
- Mission time could be long (years)
- **Standard fault trees are not designed for this type of model**

Simplest Case



State Space Diagram



This would be easy to simulate in Excel or possibly using a Markov Model.

Complications

System complications:

- System size of two or more items
  - Mostly two or three
- Radiation upsets and *random failures*
  - Random failures are likely not recoverable
- Auto reset or manual reset
  - Reset from ground or on board if crewed
  - Human error possible on ground-based manual resets

Radiation complications:

- Regular radiation environment and solar particle events
  - Higher upset rates during solar particle events

Model complications:

- Vehicle crewed part of the time
- Crew can manually do resets
- Crew might be able to fix random failures
- Human error

Component Inputs	
Component Name	Electronic Box
Number of Components	2
Minimum Number Needed	1
Upset Rate (Per Hour)	1.0E-04
Worst Case Rate (Per Hour)	1.0E-03
Auto or Manual	Auto
Auto Recovery Time (Hours)	0.1
Recovery Time Crewed (Hours)	8.0
Recovery Time Uncrewed (Hours)	500.0
Random Failure Rate (Per Hour)	1.0E-05
Crew Random Recovery Time (Hours)	24.0
Global Model Inputs	
Human Error Probability	1.0E-02
Worst Case Frequency (Per Hour)	1.0E-03
Worst Case Duration (Hours)	160
Mission Time (Hours)	8,760
Crewed Portion (Hours)	720
Run Control	
Replications	100
Seed Value	1
Show Output?	Yes
Exclude Random Only System Fails?	Yes
Array Adjustment Factor*	1.5
Run	

Note: All values in this presentation are for demonstration purposes and are not actual data.

The Model

Excel front shows inputs and outputs.

The simulation is done in Visual Basic using the Excel random number generator (Mersenne Twister since 2010).

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Recovery Time Uncrewed (Hours)	500.0
Random Failure Rate (Per Hour)	1.0E-05
Crew Random Recovery Time (Hours)	24.0
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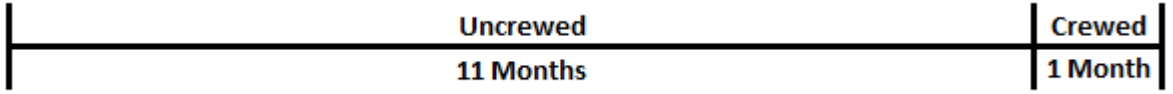
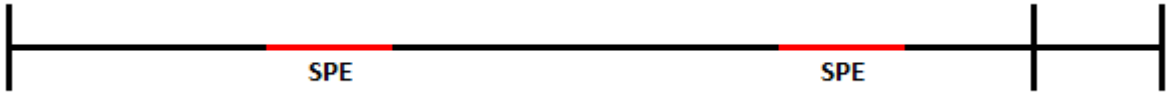
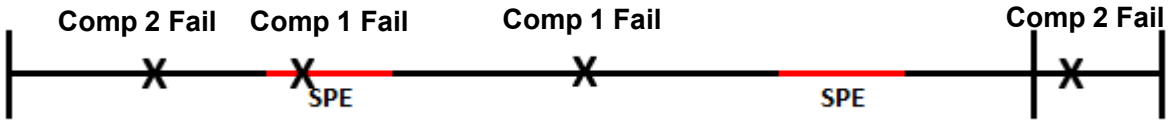
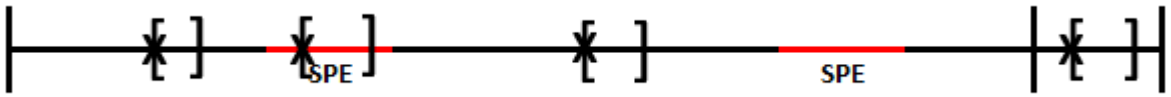
Human Error Probability	1.0E-02
Worst Case Frequency (Per Hour)	1.0E-03
Worst Case Duration (Hours)	160
Mission Time (Hours)	8,760
Crewed Portion (Hours)	720
Run Control	
Replications	100
Seed Value	1
Show Output?	Yes
Exclude Random Only System Fails?	Yes
Array Adjustment Factor*	1.5
Run	
Output	
Run Tim (Minutes)	0.00
System Failure Rate, $\bar{p}$ (Per Mission)	1.3E-01
One in:	8
Human Error System Failure Rate	0.0E+00
One in:	-----
Failure While Crewed Rate	1.0E-02
One in:	100
Convergence	
Desired Confidence	90%

Rep	Comp	Event Time	Recovery Time	Crewed?	Rate Type	Human Error	Simultaneous Failures	System Failure?	System Failure While Crewed?	Random Only System Failure?
1	2	4,525.7	0.1	No	Worst Case	No	1	0	No	No
1	2	4,791.6	3,968.4	No	Random Failure	No	1	0	No	No
1	1	7,103.3	0.1	No	Worst Case	No	2	1	No	No
2	2	1,739.3	0.1	No	Worst Case	No	1	0	No	No
2	2	3,075.3	0.1	No	Worst Case	No	1	0	No	No
2	1	4,209.6	0.1	No	Usual Rate	No	1	0	No	No
3	2	676.9	0.1	No	Usual Rate	No	1	0	No	No
3	2	1,420.1	0.1	No	Usual Rate	No	1	0	No	No
3	2	2,758.4	0.1	No	Usual Rate	No	1	0	No	No
3	1	2,875.9	0.1	No	Usual Rate	No	1	0	No	No
3	2	5,828.7	0.1	No	Worst Case	No	1	0	No	No
3	1	7,474.9	0.1	No	Usual Rate	No	1	0	No	No
3	2	7,803.1	0.1	No	Usual Rate	No	1	0	No	No
4	1	950.3	0.1	No	Worst Case	No	1	0	No	No
4	1	994.7	0.1	No	Worst Case	No	1	0	No	No
4	2	2,232.8	0.1	No	Worst Case	No	1	0	No	No
4	2	3,557.9	0.1	No	Worst Case	No	1	0	No	No
4	1	7,949.5	0.1	No	Usual Rate	No	1	0	No	No
5	2	1,496.5	0.1	No	Usual Rate	No	1	0	No	No
5	1	6,411.8	0.1	No	Worst Case	No	1	0	No	No
6	1	179.2	0.1	No	Worst Case	No	1	0	No	No
6	2	3,473.9	0.1	No	Usual Rate	No	1	0	No	No
6	1	4,040.0	0.1	No	Worst Case	No	1	0	No	No
6	1	4,160.9	0.1	No	Worst Case	No	1	0	No	No
6	2	4,957.7	0.1	No	Worst Case	No	1	0	No	No
6	2	8,133.4	0.1	Yes	Usual Rate	No	1	0	No	No
7	**2**	**175.9**	**8,584.1**	**No**	**Random Failure**	**No**	**1**	**0**	**No**	**No**
7	**1**	**6,954.2**	**0.1**	**No**	**Usual Rate**	**No**	**2**	**1**	**No**	**No**
8	1	643.9	0.1	No	Worst Case	No	1	0	No	No
8	1	741.6	0.1	No	Worst Case	No	1	0	No	No
8	1	1,008.6	7,751.4	No	Random Failure	No	1	0	No	No
9	1	1,205.6	0.1	No	Worst Case	No	1	0	No	No
9	**2**	**1,313.3**	**0.1**	**No**	**Worst Case**	**No**	**1**	**0**	**No**	**No**
9	**2**	**1,429.3**	**7,330.7**	**No**	**Random Failure**	**No**	**1**	**0**	**No**	**No**
9	**1**	**2,715.3**	**0.1**	**No**	**Usual Rate**	**No**	**2**	**1**	**No**	**No**

Methodology

Suppose there are **two components** and the system needs at least one component to function at all times.

Step	One Model Replication	Notes
Start with the base timeline:		Same for every replication
Simulate solar particle event arrival intervals (the upset rate is higher in these intervals):		Exponentially distributed time between SPE arrivals
Simulate upset and random failure times:		Exponentially distributed time between upsets and random failures
Use the recovery time to determine the downtime intervals:		No system failures since failures did not overlap

This is what needs to be done for each of the 100,000 or so replications.

Output

- Output in the table is shown for 10 replications
- Zero-failure replications are not shown
- **The replication ends if there is a system failure**
- Random + Upset combinations are most likely

Run Control	
Replications	100,000
Seed Value	1
Show Output?	Yes
Exclude Random Only System Fails?	Yes
Array Adjustment Factor*	1.5
Run	
Output	
Run Tim (Minutes)	2.18
System Failure Rate, $\bar{p}$ (Per Mission)	8.8E-02
One in:	11
Human Error System Failure Rate	3.0E-05
One in:	33,188
Failure While Crewed Rate	9.4E-03
One in:	106
Convergence	
Desired Confidence	90%
Desired Percent +/- about $\bar{p}$	5%
Lower Bound on $\bar{p}$	8.61E-02
Upper Bound on $\bar{p}$	8.90E-02
Lower Allowable +/-	8.31E-02
Upper Allowable +/-	9.19E-02
Convergence?	Yes

Note: "Worst Case" indicates the solar particle environment.

Rep	Comp	Event Time	Recovery Time	Crewed?	Rate Type	Human Error	Simultaneous Failures	System Failure?	System Failure While Crewed?	Random Only System Failure?
1	2	4,525.7	0.1	No	Worst Case	No	1	0	No	No
1	2	4,791.6	3,968.4	No	Random Failure	No	1	0	No	No
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Pros and Cons

Pros

- Good for non-standard models with several complications
- Shows intermediate result (failures and times) not just summary data
- Anyone with Excel can run it
- It is easy to make changes to the inputs—sensitivity analyses

Cons

- Hard to build
- Hard to change the model structure to add additional features

Key Takeaway

Random failures followed by upsets are the primary risk driver (unless the random failure rate is very low).