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PNNL-SA-138909

Modeling and Analysis of SNF Transportation, a Summary

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NWTRB meeting

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Albuquerque, New Mexico

This Work Relative to other DOE NE R&D Efforts

Conditions and Structural Capacities of Used Nuclear Fuel (UNF)

High Burn up Demo:
- Temperatures are low.
- Good for cladding.

CIRFT (Cladding Fatigue) Testing:
- Fuel contributes.
- Cladding irradiated fatigue strength is better than expected.

Sister Rod Mechanical Testing:
- Cladding properties
- Composite rod properties.

Normal Conditions of Transport (NCT) Shock and Vibration Loads

Multimodal Transportation Test (MMTT) Campaign:
- Recorded NCT shock and vibration environment
- Measured cladding strains
- Validate structural & dynamic models
- Use validated analytical methods to predict response of other systems

All DOE-NE R&D is laying the foundation for this conclusion:

Irradiated fuel rod conditions and structural capacity >> NCT transportation loads, therefore it is safe to ship UNF and to expect it to arrive with no additional damage.

Key DOE NE Reports on MMTT

- McConnell PE, SB Ross, CA Grey, WL Uncapher, M Arviso, R Garmendia, IF Perez, A Palacio, G Calleja, D Garrido, AR Casas, LG Garcia, W Chilton, DJ Ammerman, J Walz, S Gershon, SJ Saltzstein, K Sorenson, NA Klymyshyn, BD Hanson, R Pena, and R Walker. 2018. *Rail-Cask Tests: Normal-Conditions-of- Transport Tests of Surrogate PWR Fuel Assemblies in an ENSA ENUN 32P Cask*. SFWD-SFWST-2017-000004, Sandia National Laboratories, Albuquerque, New Mexico.

- Kalinina, EA, C Wright, N Gordon, SJ Saltzstein, L Lujan, KM Norman. 2018. *Data Analysis of ENSA/DOE Rail Tests.* 2018. SFWD-SFWST-2018-000494, Sandia National Laboratories, Albuquerque, New Mexico.

- Klymyshyn N.A., P. Ivanusa, K. Kadooka, C.J. Spitz, P.J. Jensen, S.B. Ross, B.D. Hanson, D. Garcia, J. Smith, S. Lewis. 2018. *Modeling and Analysis of the ENSA/DOE Multimodal Transportation Campaign. 2018.* PNNL-28088. Richland, WA: Pacific Northwest National Laboratory.
  - *This presentation is a summary of this report. See this report for additional information.*

Presentation Objectives

- Show a selection of the MMTT test results.
  - Select key data for discussion (Westbound Rail).
- Provide context and perspective to the test results.
  - Fuel cladding stress, strain, load, deformation energy are all low.
- Describe the progress of structural-dynamic modeling:
  - Validated structural-dynamic models to predict loads on other transportation system configurations.
  - Fatigue analyses.
  - Next steps.

Strain Energy Perspective:
UNF Rod Shock and Vibration Energy Comparisons

Structural-dynamic models predict that the strain energy implied by the strain values recorded on the fuel cladding is so low that it is comparable to the kinetic energy in one raindrop.

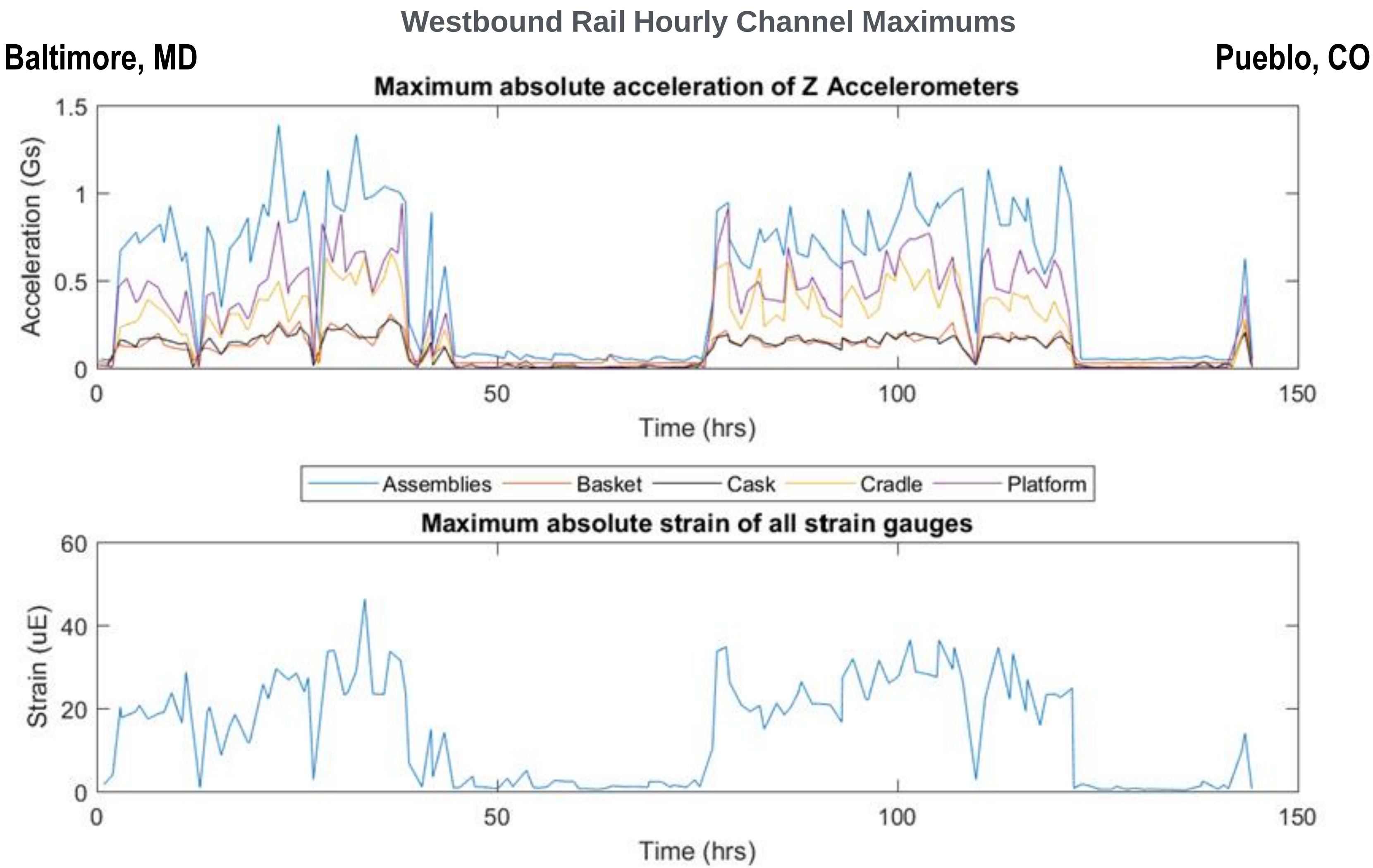
Moving Object	Specific Example	Kinetic Energy (mJ)
Bullet (Muzzle Energy)	AR-15 9 mm Handgun	1,854,000.0 467,000.0
Golf Ball (Off the Tee)	PGA Tour, Male (168 mph) Amateur, Bogey Golfer (131 mph)	129,000.0 77,000.0
Bird Flying	Robin (25 mph) European Swallow (19 mph)	4,400.0 1,200.0
Ping Pong Ball (Table Tennis)	World Record (70 mph) Average (25 mph)	1,300.0 168.0
Single Raindrop	Heavy Thundershower (130 mg, 20 mph) Moderate Rain (37 mg, 17 mph) Light Drizzle (8 mg, 14 mph)	5.2 1.0 0.1
Fuel Rod Vibration (Strain Energy)	Single Rod Model Estimate (50 mph P&B) Gravity	1.3 0.7
Flying Insect	Wasp (15 mph) Housefly (4 mph)	2.2 < 0.1

1 Rod

Select MMTT Results: Westbound Rail Summary

- Rail transportation is the most important mode in the US because that is how the bulk of UNF is expected to be moved.
- Cladding strains are the key measurement because they tell us about the deformation of the rods. Deformation relates to stress, strain, and strain energy.
- Cladding strains are so small that it is convenient to discuss them in units of microstrain (uE).
  - 1 uE = 0.000001 in/in, or 0.0001%

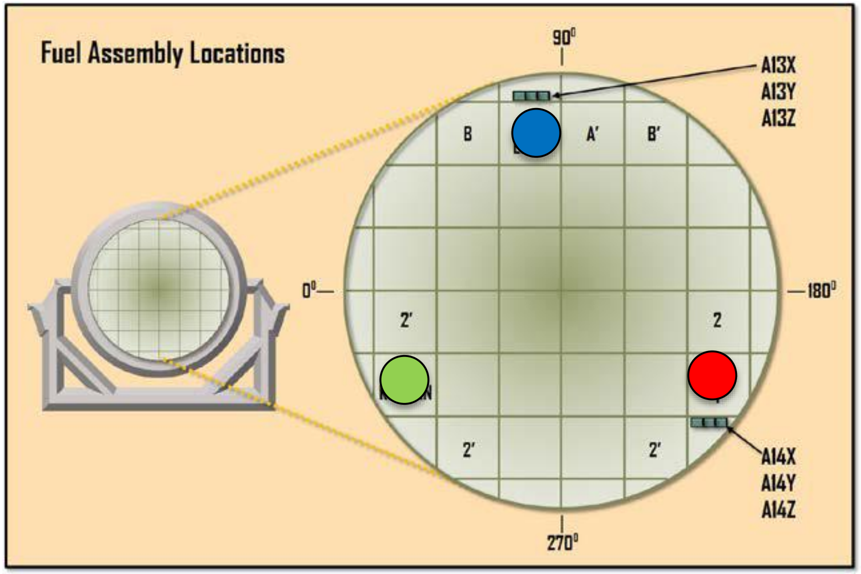
Westbound Rail Transportation Peaks



- The peak strain of 46 uE is attributed to PLN. 37 uE is the peak when PLN is reduced by a PNNL algorithm.
- Platform is the railcar deck center. The corner railcar deck accelerometers are excluded due to excess vibrations.

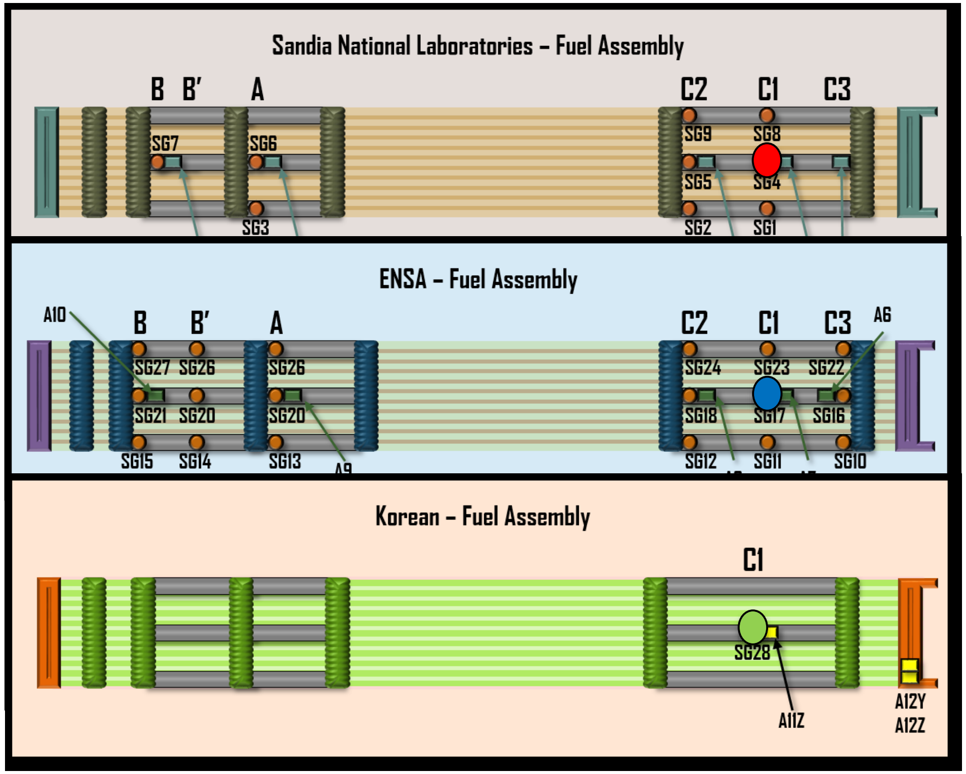
Strain Gage and Assembly Color Key

Three instrumented fuel assembly locations.



- The ENUN 32 P cask used in the MMTT holds 32 fuel assemblies.
- Three instrumented fuel assemblies were used in the test.
- 29 simulated assemblies filled the remaining baskets.

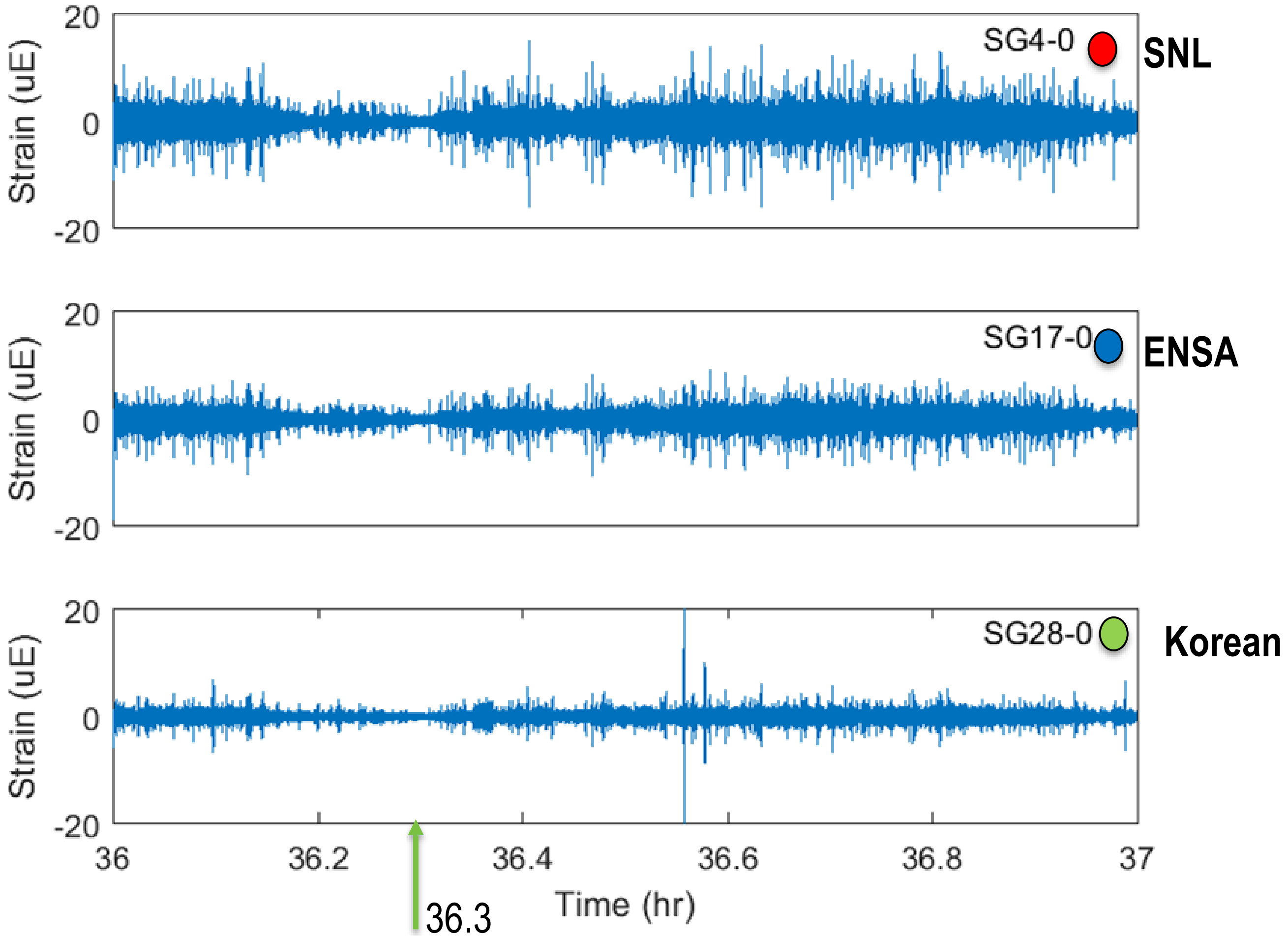
Three common strain gage locations.



- There is one fuel rod location on all 3 fuel assemblies

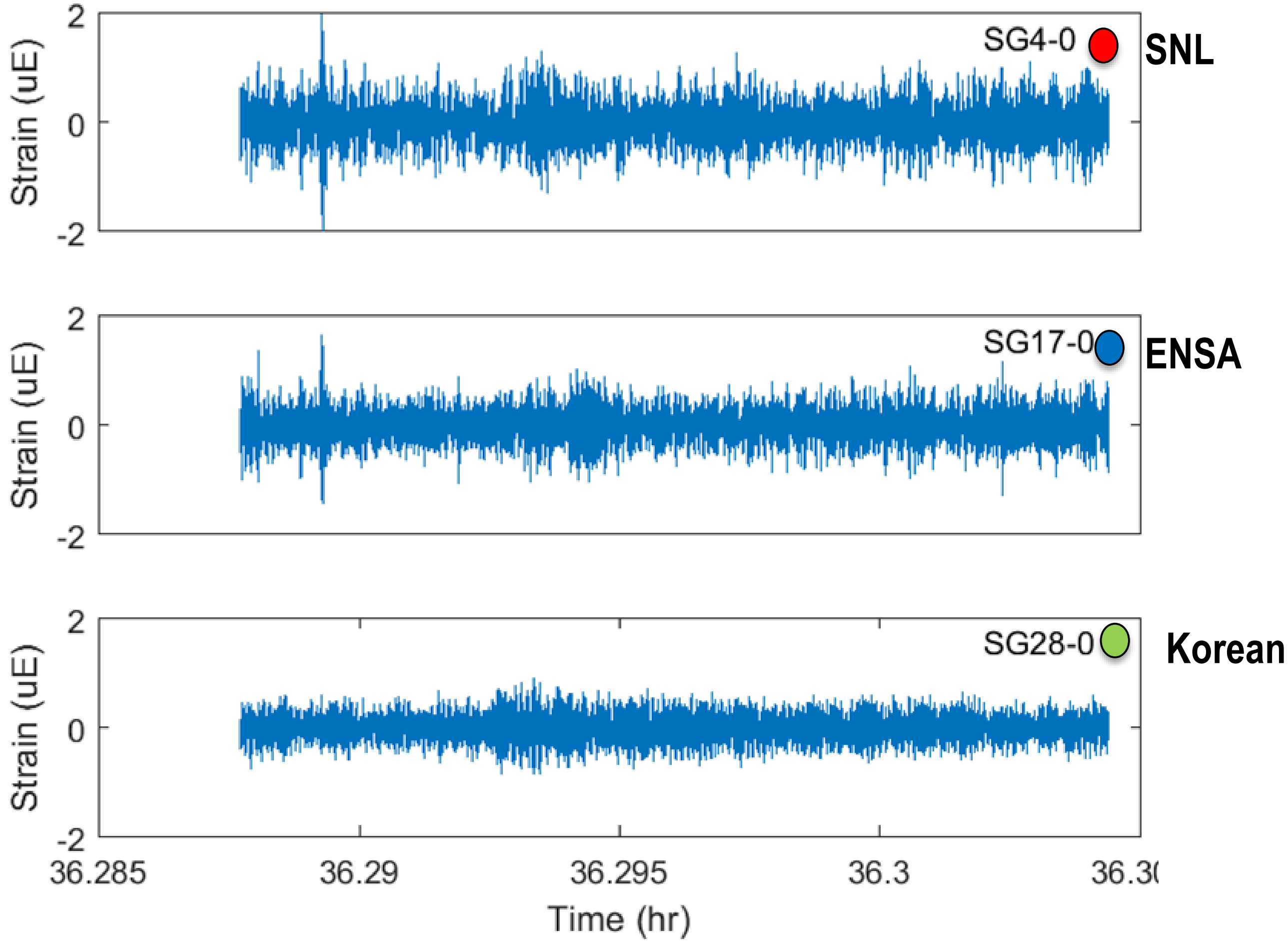
Example Westbound Rail Strain Gage Data (1 hour)

- This 1-hr section of data includes a road crossing that causes the peak recorded cask vertical acceleration. Notice that there is no clear indication of this event in the strain data.
- Strain peaks above 10 uE can be traced to track features, like road crossings.

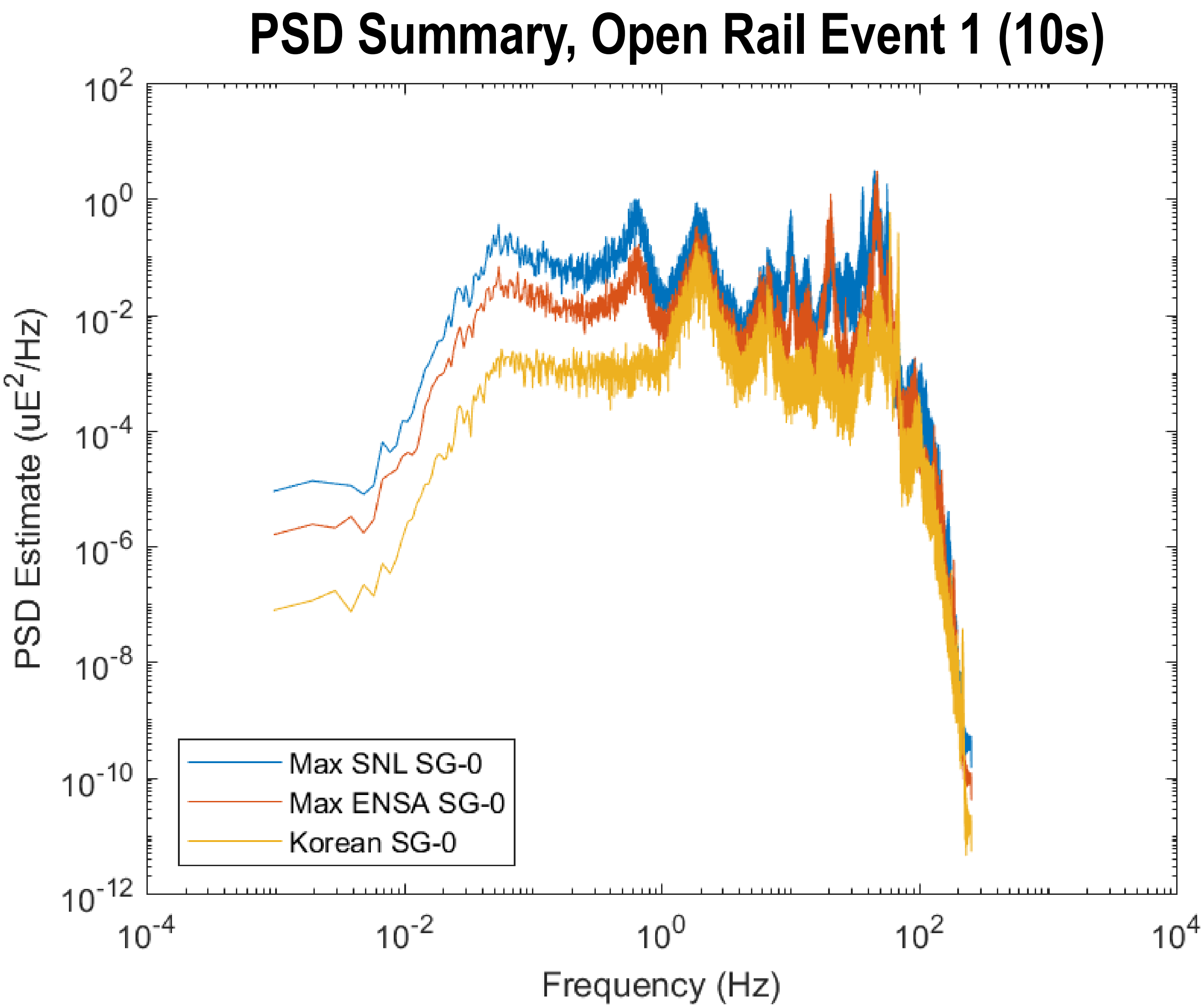


Example Westbound Rail Data between Events (1 minute)

- This 1-minute section of data shows strain cycles with an amplitude less than 1 uE.
- The fatigue discussion will note 50 million strain cycles like these. Note that they are too small to cause any practical fatigue damage.



Strain Gage Frequency Spectra



This graph summarizes the Power Spectral Density (PSD) of the strain gages during an open rail shock event. PSD's for all strain gages were generated, and the maximum value at each frequency is plotted. Strain gages were grouped by assembly.

2 Hz is a strong frequency that aligns with railcar suspension.

Rail Transportation Peak Cladding Strains

Captive Track Test Peak Strains Compared to Open Rail

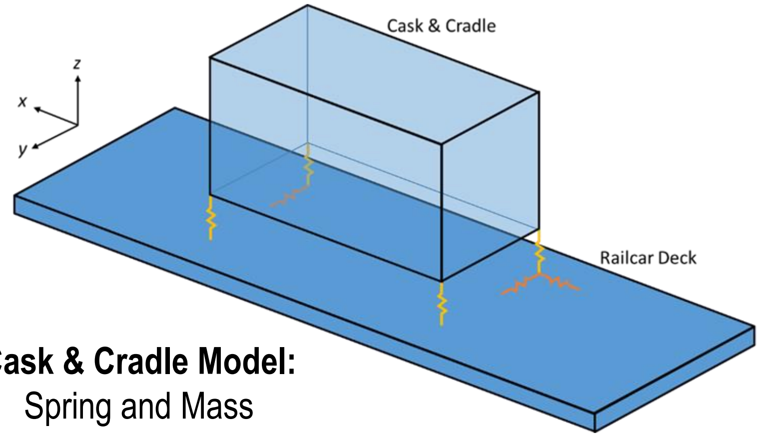
Test	Maximum Strain (uE)		
	SNL Assembly	Spanish Assembly	Korean Assembly
Coupling Impact	96.4	74.1	39.0
Diamond Crossing	32.8	15.5	6.7
Dynamic Curving	36.7	22.3	8.3
Hunting	37.2	18.6	10.4
PCD	32.3	13.6	5.5
Single Bump	37.0	20.2	9.1
Twist and Roll, Pitch and Bounce	29.3	24.8	13.1
All Open Westbound Rail	**36.5**	**27.9**	**36.5**

- PLN is reduced in Open Westbound Rail category
- Captive track tests bound the open rail response.
- Peak strain energy in each rod is small: around 1 mJ
- Amplification of 2-3 orders of magnitude would be needed to challenge fuel cladding strength.

Structural-Dynamic Modeling Progress

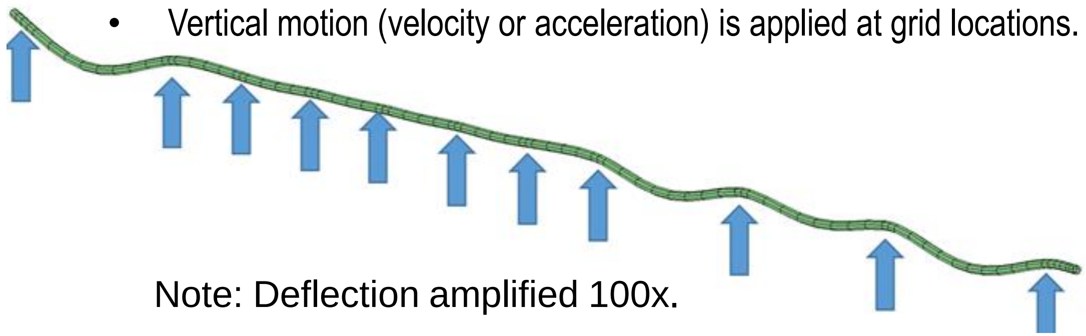
- The test data was used to validate dynamic and structural models:
  - NUCARS rail dynamics models predict conveyance system motion.
  - LS-DYNA explicit dynamic finite element models of a full fuel assembly and a single fuel rod.
- A minimal model architecture was developed to predict cladding strains. This model agrees well with test data and is economical to solve.
  - The minimal model can always be expanded as necessary, but the loads are close to zero.
- Additional analyses were made to investigate conveyance system components and their effect on the test.
  - Simulated fuel assemblies
  - Modal analysis of cask and cradle system.

Minimal Model Architecture – 2 Parts



Cask & Cradle Model:
Spring and Mass Structure

Single Rod Model:
- Arrows indicate grid locations.
- Vertical motion (velocity or acceleration) is applied at grid locations.



Note: Deflection amplified 100x.

NUCARS
Railcar, Cradle, and Cask System Dynamics

→

LS-DYNA
Single Fuel Rod Model Structural Dynamic Response

Calculates the dynamic response of railcar conveyance system.

Valid in relatively low frequency range.

Calculates the structural dynamic response of a single fuel rod.

Valid when strains are low.

Vertical loads are used because they were limiting in the test.

Single Rod Model Validation

50 mph Pitch and Bounce Test Validation Case

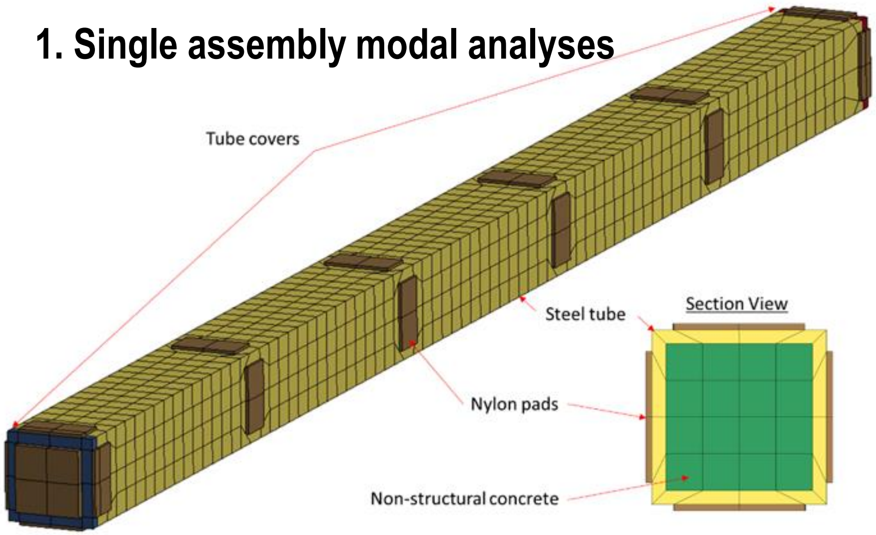
Case	Peak Strain at Gage (uE)	Maximum Strain Cycle Amplitude (uE)	Number of Strain Cycles over 10 uE
Baseline 2-Part Model	29.9	29	167
1-Part Model (A15Zv)	11.9	12	6
Actual SG4	11.3	11	2
Actual SG17	7.3	7	0
Actual SG28	5.3	6	0

- 2-Part Baseline Model: All information comes from models. Pure model estimate of strains.
- 1-Part Model (A15Zv): Cask motion comes from recorded test data. This case represents the ability of the model to calculate strains when cask motion prediction is perfect.
- Actual SG4: Strain gage data. (SNL)
- Actual SG17: Strain gage data. (ENSA)
- Actual SG28: Strain gage data. (Korean)

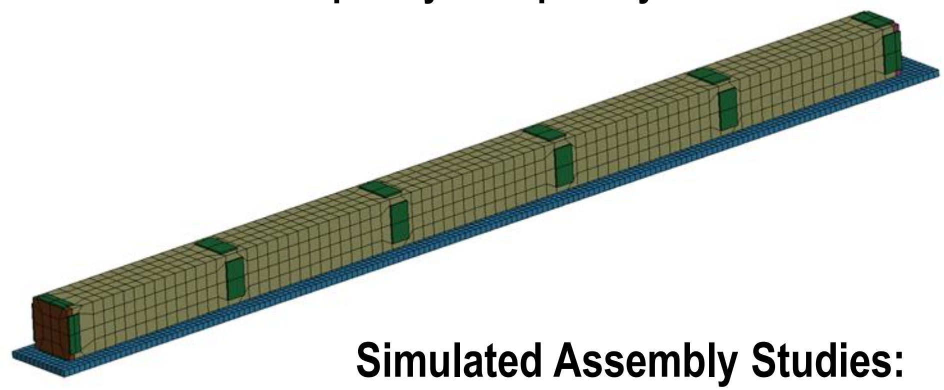
- The baseline 2-part model provides conservative results compared to test data.
- The 1-part model provides better agreement, but it uses test data. There may be room to improve the 2-part model further.

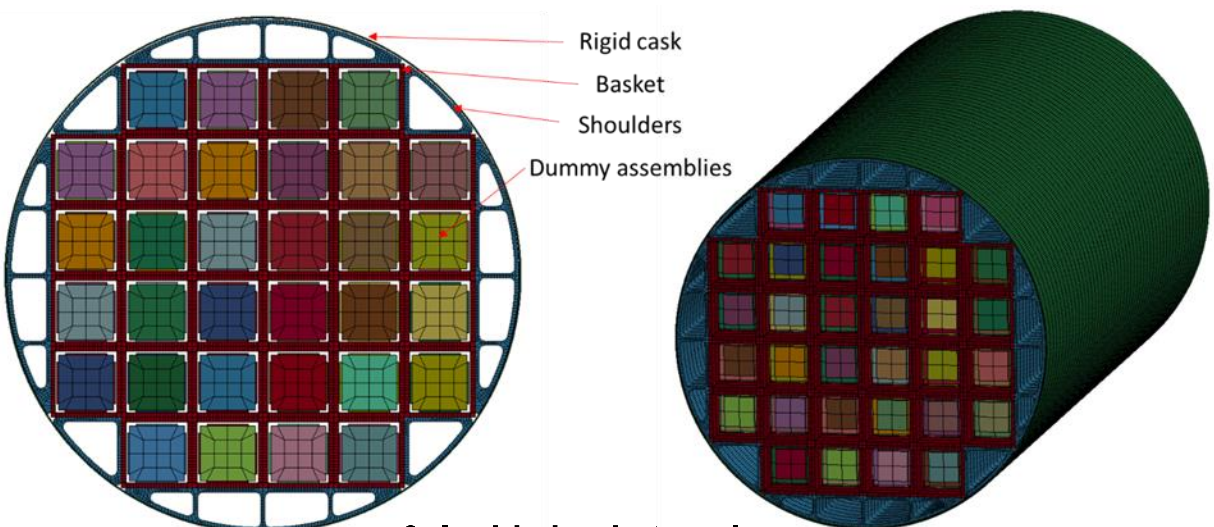
Modeling Study: Simulated Assemblies

1. Single assembly modal analyses



2. Frequency sweep analyses





3. Inside basket analyses

Simulated Assembly Studies:

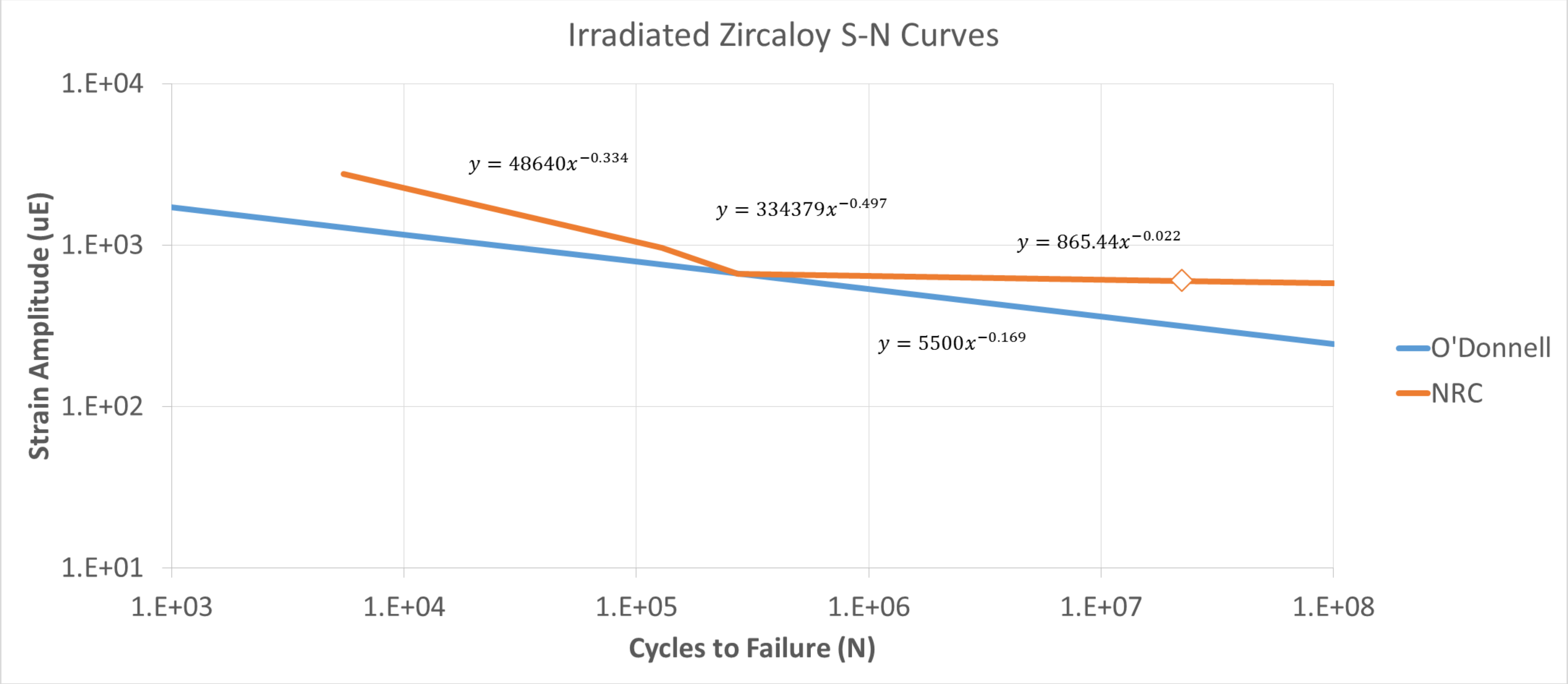
1. **Modal analysis** shows response is similar to real fuel assemblies.
2. **Frequency sweep analyses** demonstrate response frequencies similar to real fuel assemblies in horizontal position. (Damping is low.)
3. **Basket shock pulse analyses** show dynamics expected of real fuel.

Conclusion: Simulated assemblies do not have a strong effect on test results.

Fatigue Evaluation

- Fatigue is a material failure mechanism that can occur during dynamic loading scenarios that involve a cycling, reversing load that continues over a length of time.
- Fatigue failure can occur when the loads are below their normal static failure strength.
- Typical fatigue evaluations assume that fatigue damage accumulates over time according to Miner's Rule.
  - Every strain cycle removes a fraction of fatigue life.
  - S-N curves relate strain amplitudes (S) to number of cycles to failure (N).
- Cladding fatigue evaluations were made using the strain gage data collected in the MMTT.
  - Accounting for real irradiated rods is done by adjusting the fatigue histogram.

Fatigue Curves for Irradiated Zircaloy

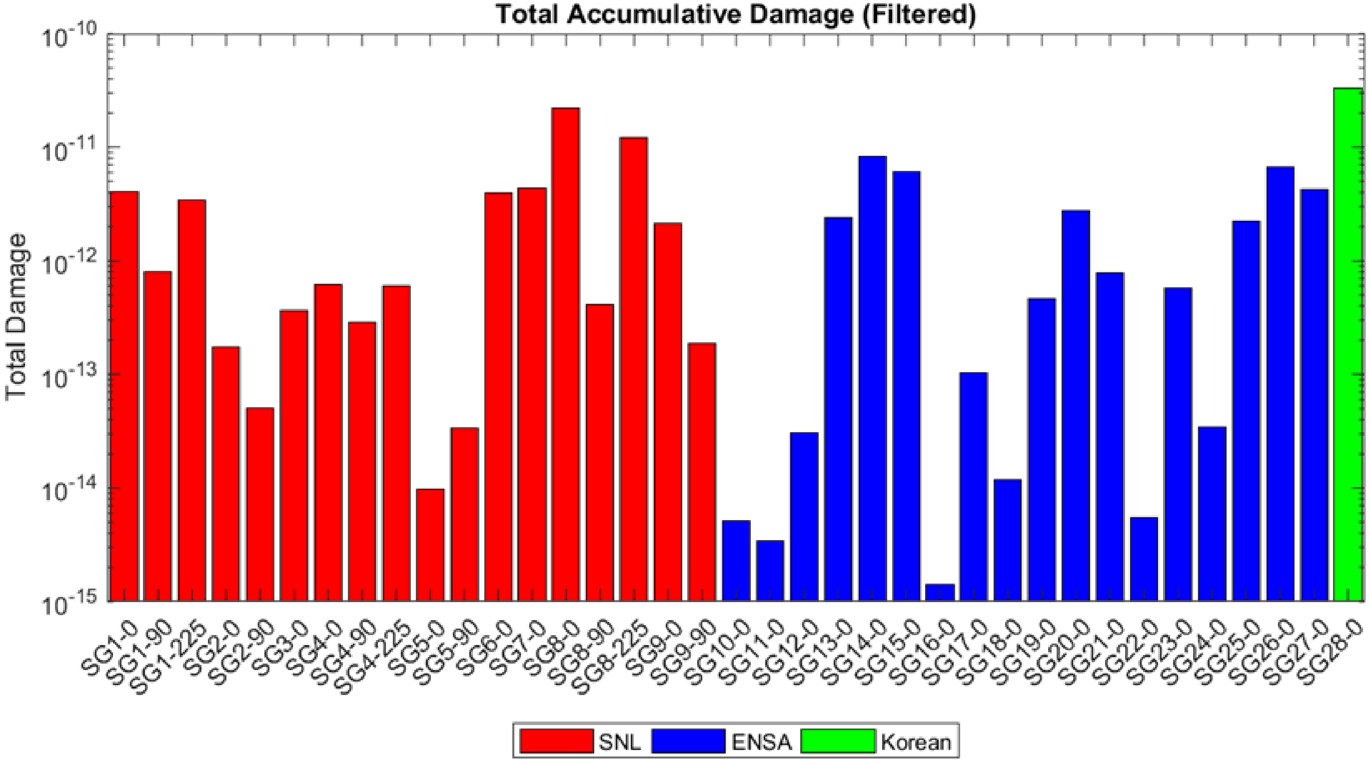


O'Donnell: S-N curve used to define accumulated damage in this work. O'Donnell WJ and BF Langer. 1964. "Fatigue design basis for zircaloy components." *Nuclear Science and Engineering* (20):1–12

NRC: S-N curve based on CIRFT data. Defined in NUREG-2224, Dry Storage and Transportation of High Burnup Spent Nuclear Fuel. Draft for Comment, 2018.

Cladding Fatigue Summary

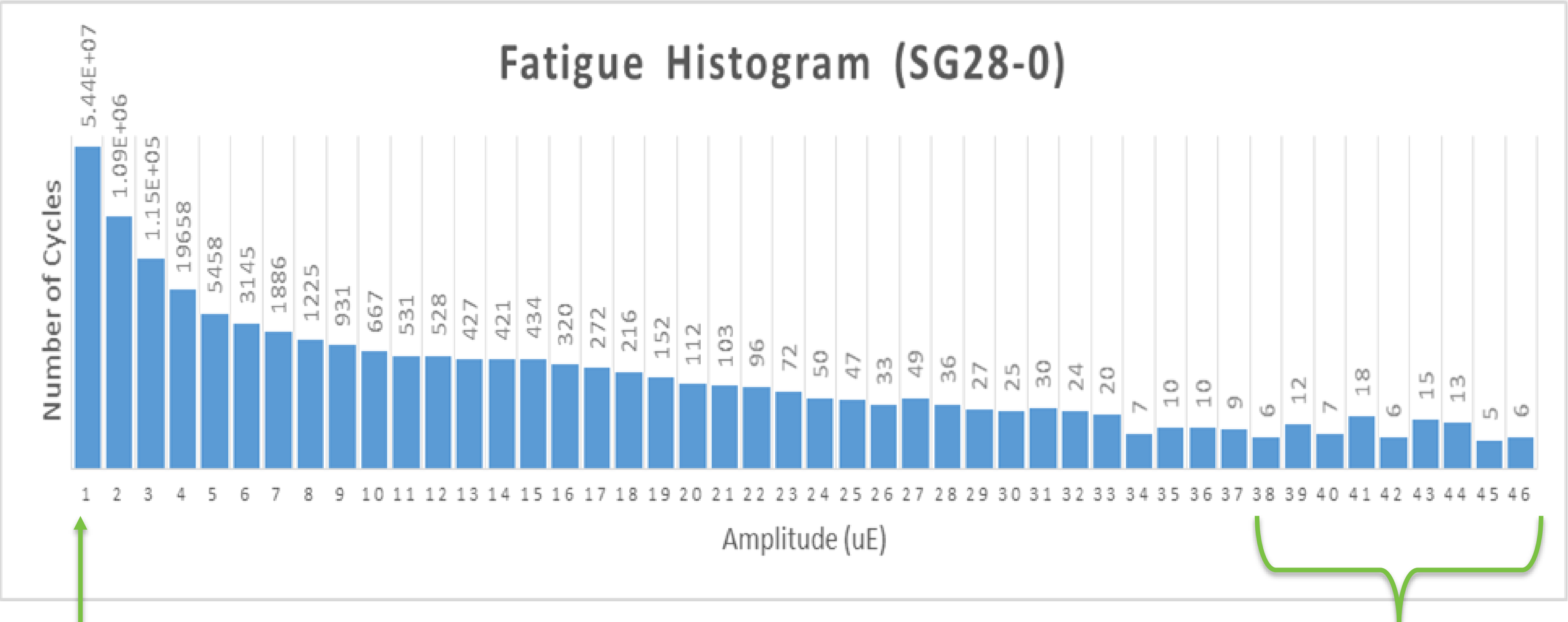
Westbound Rail Accumulated Fatigue Damage



Westbound rail total accumulated fatigue damage for each strain gage. All damage fractions are less than 1E-10, when a damage fraction of 1.0 indicates fatigue failure. Damage is calculated according to Miner's Rule, ASTM rainflow counting, and the O'Donnell irradiated zircaloy S-N curve.

Example Fatigue Cycle Histogram

Full westbound rail strain gage strain cycle counts.



These strain cycles are associated with power line noise.

All strain cycles are rounded up to nearest integer for histogram binning.

How to Account for Irradiated Fuel?

- Test as an Analog
  - Assume the as-tested fuel rods are a perfect analog for irradiated fuel.
- Adjust the Test Data to Account for Differences
  - Stress concentration in cladding between pellets.
  - Change in fuel rod stiffness changes natural frequency.
    - Increase number of cycles.
    - Increase vibration amplitudes.
      - Modeling basis.
      - Transmissibility basis.
- Recognize that adjusting vibration amplitudes too high can lead to impractical fuel rod deflections.
  - Space inside fuel basket is limited, so deflections are limited.

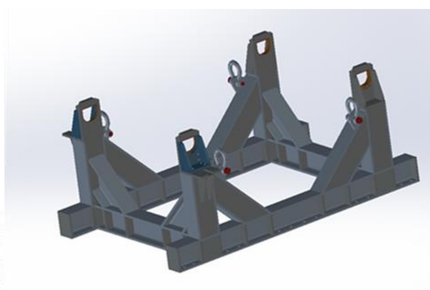
Adjusting Accumulated Fatigue Damage for Irradiated Fuel

	Total Strain Amplitude Adjustment Factor	Cycle Increase Factor	Adjusted Damage Fraction	Notes
Test as Analog	1.0	1.0	4.5E-11	Does not account for irradiated condition.
Model-Based Estimate	2.1	1.5	5.5E-9	Modeling-based adjustments. No practical difference from analog case.
Bounding Estimate Irradiated Fuel	14	1.5	4.1E-4	Bounding because of fuel rod deflection limits.
Resonance 3% Damping	23.8	1.5	9.5E-3	Not practical. Fuel rod deflection exceeds available space.
Resonance 1% Damping	70	1.5	1.6	Not Practical. Fuel rod deflection exceeds available space.

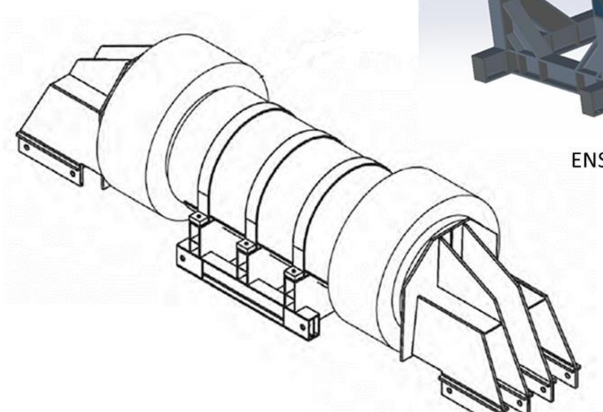
- There is no practical difference in fatigue damage between the test as an analog or adjusting the test data to represent the irradiated condition.
  - The vibration energy is so low, the potential amplification does not make a difference.
- The bounding estimate assumes a higher amplification based on an alignment of natural frequencies.
  - This case would require about 5mm of fuel rod deflection. Available space is less than this.
- The resonance cases are only listed to show how much amplification is needed to challenge the fatigue limits.
  - The 1% damping case needs about 25mm of room to deflect.

Next Steps – FY19 (1 of 3)

- Atlas railcar analysis
  - Apply the modeling experience of the test campaign to the Atlas railcar.
  - Check the dynamic behavior of the many cask and cradle configurations using structural-dynamic modeling.
    - 4 cradle designs, many cask designs with different masses, all with potentially different dynamic responses
    - Confirm that cladding strains are low in these configurations



ENSA Cradle Design



Atlas Railcar, Cradle Family 1

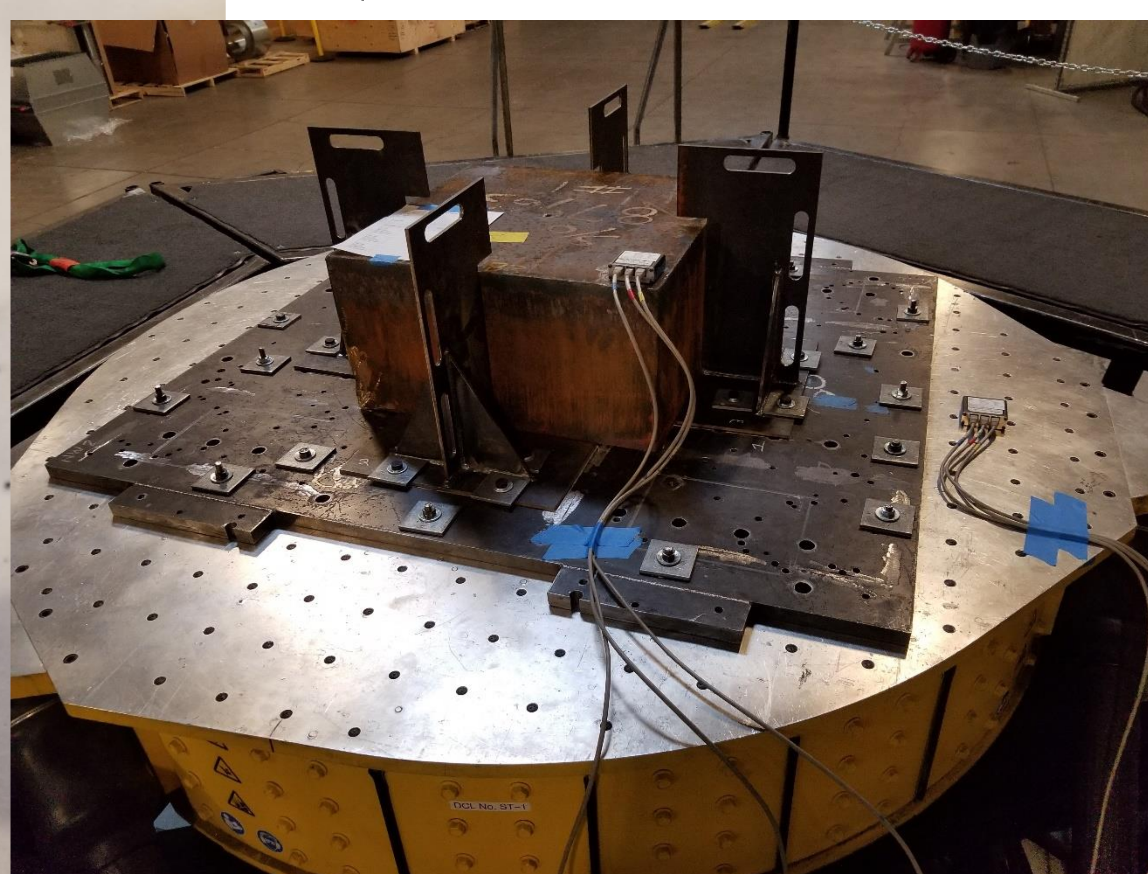
Atlas Rail Car Cradle Configurations

Family 1	AREVA-TN: TN-40, TN-40HT, TN-32B Holtec: Hi-Star 60, Hi-Star 100, Hi-Star 100HB, Hi-Star 180
Family 2	AREVA-TN: TN-68 NAC: MAGNATRAN, NAC-STC, NAC-UMS
Family 3	AREVA-TN: MP197, MP197HB Energy Solutions: TS125
Family 4	AREVA-TN: MP197HB

Next Steps – FY19 (2 of 3)

Evaluate the Effect of Rubber Pads in the Test Configuration.

Shaker table testing, Sparks NV, Sept. 2018. Collected data to characterize dynamic effect of rubber mats in test. To be documented in future reports.



Next Steps – FY19 (3/3)

- Canister system analysis
  - The test used a bare fuel system.
  - Check the dynamic behavior of a fuel canister system with structural-dynamic modeling.
    - Confirm that cladding strains are low in these configurations
- Alternate fuel assembly analysis
  - The test used 17x17 PWR fuel.
  - Check BWR fuel and other PWR fuel with structural-dynamic modeling.
    - Confirm that cladding strains are low in these configurations
- Evaluate information coming from sister rod tests
  - Check potential stress concentrations caused by large pellet gaps with structural-dynamic modeling.

Conclusions

- The shock and vibration loads on the fuel rods recorded in the MMTT are approximately zero.
  - The cladding strains are below normal engineering notice.
  - Cladding fatigue damage is below the practical endurance limit.
  - The peak strain energy in the cladding is comparable to the kinetic energy of a raindrop.
- Structural-dynamic models are validated against test data.
  - Ready to evaluate other conveyance systems and fuel types.
- Ongoing work will evaluate the effect of rubber pads on the test data.
- Ongoing work expected to confirm that changes in conveyance system design or fuel assembly design will not affect these conclusions.

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Irradiated fuel rod conditions and structural capacity >> NCT transportation loads, therefore it is safe to ship UNF and to expect it to arrive with no additional damage.

Questions?

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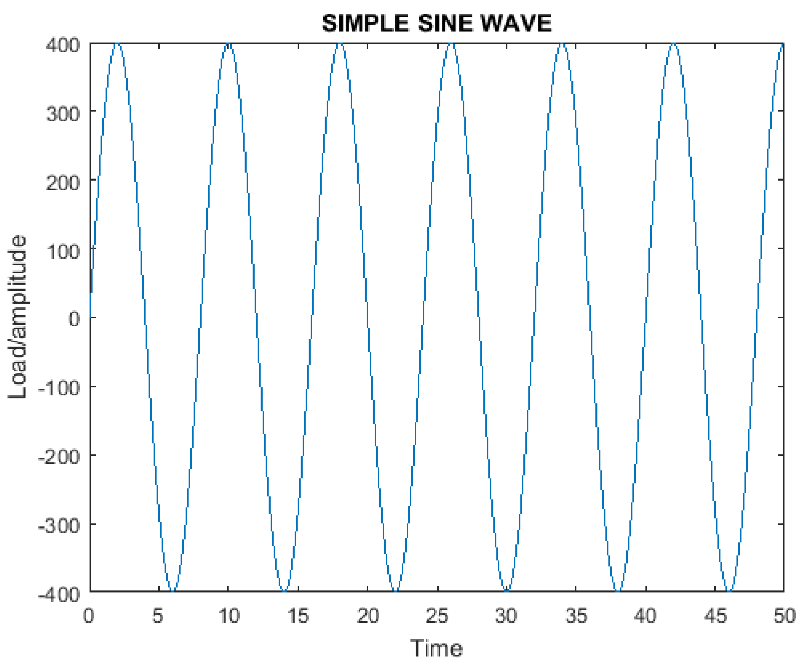
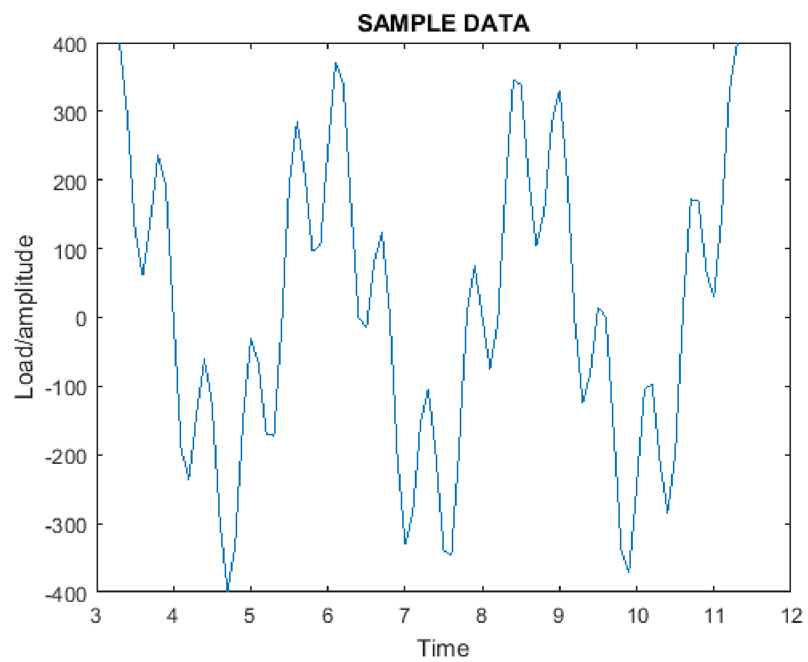
Backup Slides

- These slides are included for potential reference during Q&A.

Rainflow Counting

- Is a method to determine the number of fatigue cycles and amplitudes in a specified time interval for variable loadings
- For simple periodic loadings rain-flow counting is unnecessary
- Developed and validated MATLAB code for Rain-flow counting algorithm last summer
- Simple steps listed in website of American Society of Testing and Materials (ASTM E1049)





Fatigue Damage Calculation

Miner's rule

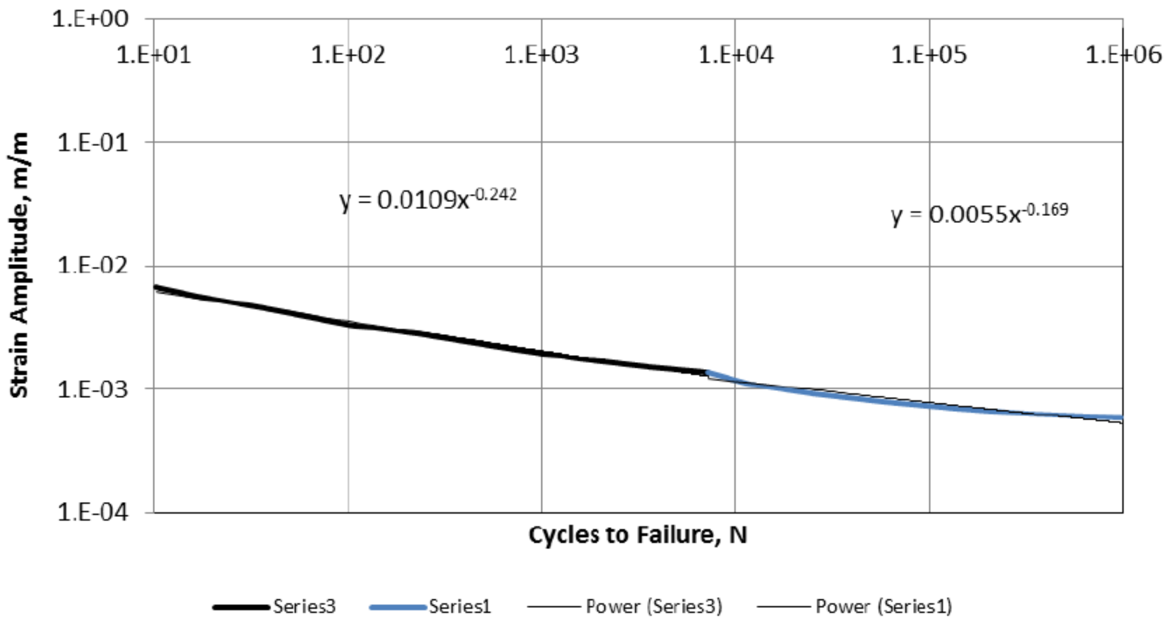
$$D_g = \frac{n}{N} \; (Damage\ for\ Each\ Group)$$

$$D = \sum_{i=1}^{k} D_{g,i} \; (Total\ Damage)$$

$$If \sum_{i=1}^{k} D_{g,i} \; > \; 1 \; (Material\ Will\ Fail)$$

General form of equation

$$S_i = AN^B \rightarrow N = \left(\frac{S_i}{A}\right)^{\frac{1}{B}}$$



Where $A \;\&\; B = \ constants$

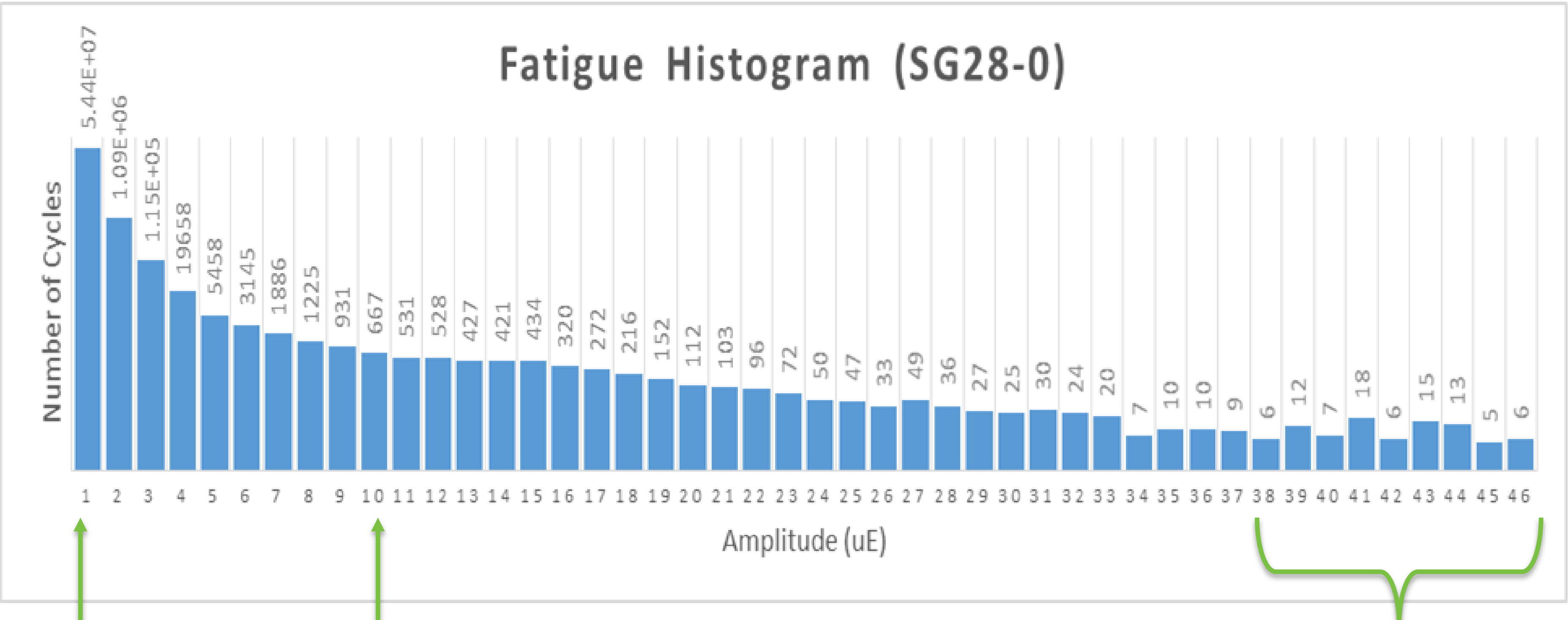
$S_i = strain\ amplitude$

$n = Number\ of\ cycles\ accumulated\ at\ stress\ S_i$

$N = Average\ number\ of\ cycles\ till\ failure\ at\ the\ ith\ stress\ S_i$

Example Fatigue Cycle Histogram

Full westbound rail strain gage strain cycle counts.



All strain cycles are rounded up to nearest integer for histogram binning.

10 uE is a reasonable strain cycle minimum threshold because strain cycles of this amplitude could not possibly contribute a 0.01 damage fraction in a practical cross country trip.

These strain cycles are associated with power line noise.

How Many Relevant Strain Cycles?

3,800 Cycles > 10uE in Westbound Rail

1E+8 Total Cycles in Westbound Rail

(Any amplitude)

# of Strain Cycles (Failure)	Strain Amplitude (uE)	Cycles to Reach a Damage Fraction of 0.01
10,000	1,160	100
100,000	786	1,000
1.0E+06	533	10,000
1.0E+07	361	100,000
1.0E+08	245	1.0E+06
1.0E+09	166	1.0E+07
1.0E+10	112	1.0E+08
1.0E+11	76	1.0E+09
1.0E+12	52	1.0E+10
1.0E+13	35	1.0E+11
1.0E+14	24	1.0E+12
1.0E+15	16	1.0E+13
1.0E+16	11	1.0E+14
1.0E+17	7	1.0E+15
1.0E+18	5	1.0E+16
1.0E+19	3	1.0E+17
1.0E+20	2	1.0E+18
1.0E+21	1.6	1.0E+19
1.0E+22	1.1	1.0E+20
1.0E+23	0.7	1.0E+21

If 1E+8 cycles were 112 uE or higher, the accumulated damage could be affected by 0.01 or higher.

Why count any cycle below 10 uE?

There are not enough cycles to change the damage fraction by any practical amount.

Note: O'Donnell Irradiated Zircaloy S-N Design Curve

Adjusting Accumulated Fatigue Damage for Irradiated Fuel

Adjust As-Tested Rods to Real Irradiated Fuel Rods

	Stress Conc. Factor	El Strain Amplitude Adjust. Factor	Total Strain Amplitude Adjust. Factor	Cycle Increase Factor	Adjusted Damage Fraction
Test as Analog	1.0	1.0	1.0	1.0	4.5E-11
Model Estimate	1.4 [1]	1.5 [2]	2.1	1.5 [3]	5.5E-9
Bounding Estimate Irradiated Fuel	1.4	10 [4]	14	1.5	4.1E-4
Resonance 3% Damping	1.4	17 [4]	23.8	1.5	9.5E-3
Resonance 1% Damping	1.4	50 [4]	70	1.5	1.6

[1] Adkins H, K Geelhood, B Koeppel, J Coleman, J Bignell, G Flores, J-A Wang, S Sanborn, R Spears, and N Klymyshyn. 2013. Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Demonstration of Approach and Results on Used Fuel Performance Characterization. FCRD-UFD-2013-000325, Pacific Northwest National Laboratory, Richland, Washington.

[2] Klymyshyn NA, PJ Jensen, and NP Barrett. 2015. Shaker Table Modeling Support Task 2015. PNNL-24735. Pacific Northwest National Laboratory, Richland, Washington.

[3] Klymyshyn NA, PJ Jensen, and NP Barrett. 2016b "Modeling Used Fuel Response to 30 cm Package Drops." Presented by Ross at 18th International Symposium on Packaging and Transportation of Radioactive Materials PARTRAM 2016, Kobe Japan, Japan. PNNL-SA-120852.

[4] Transmissibility at resonance: see next slide

Transmissibility at Resonance

SHOCK AND VIBRATION RESPONSE SPECTRA COURSE
Unit 8. Transmissibility Function for Acceleration

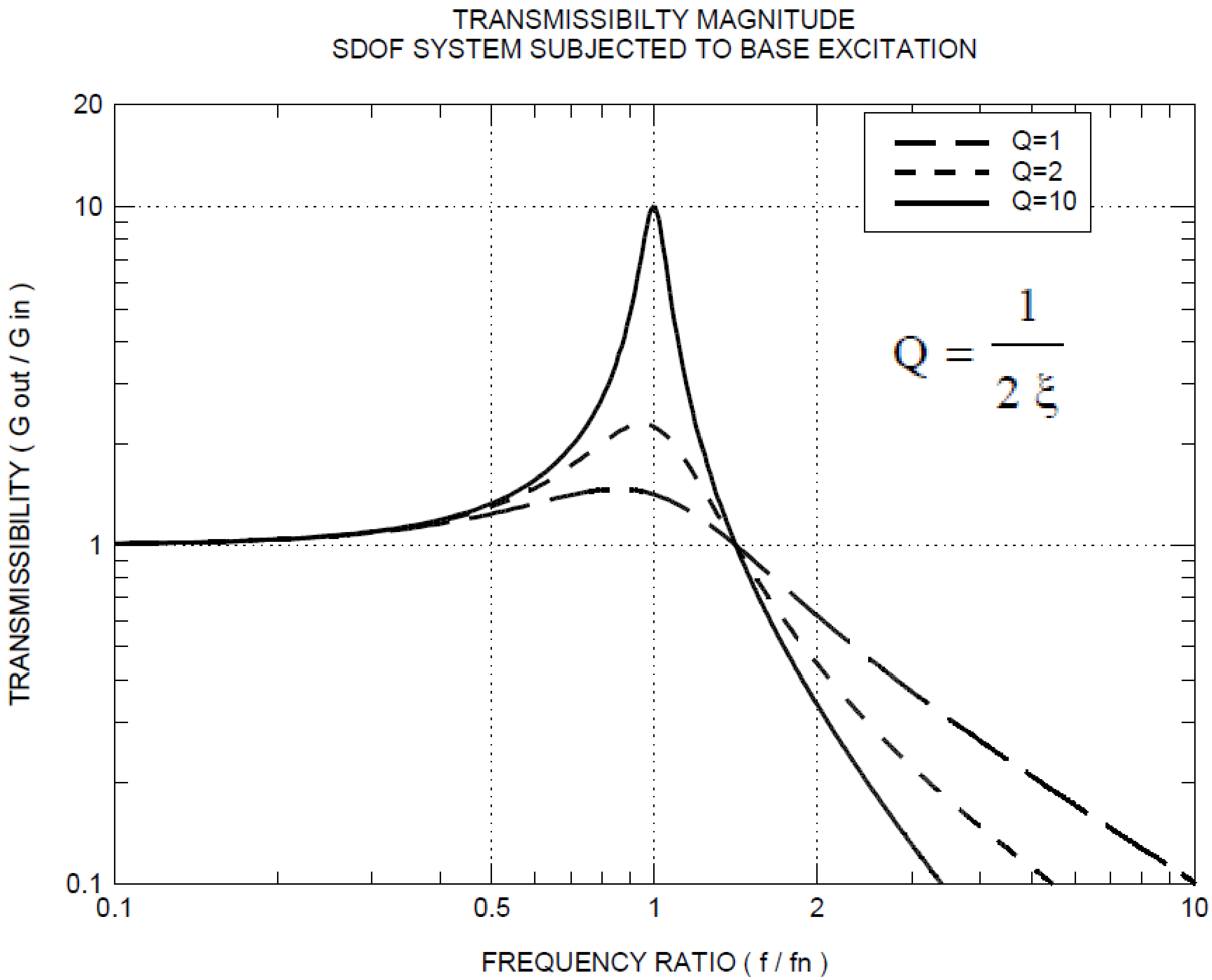
By Tom Irvine

www.vibrationdata.com

Closed-form solution of transmissibility magnitude:

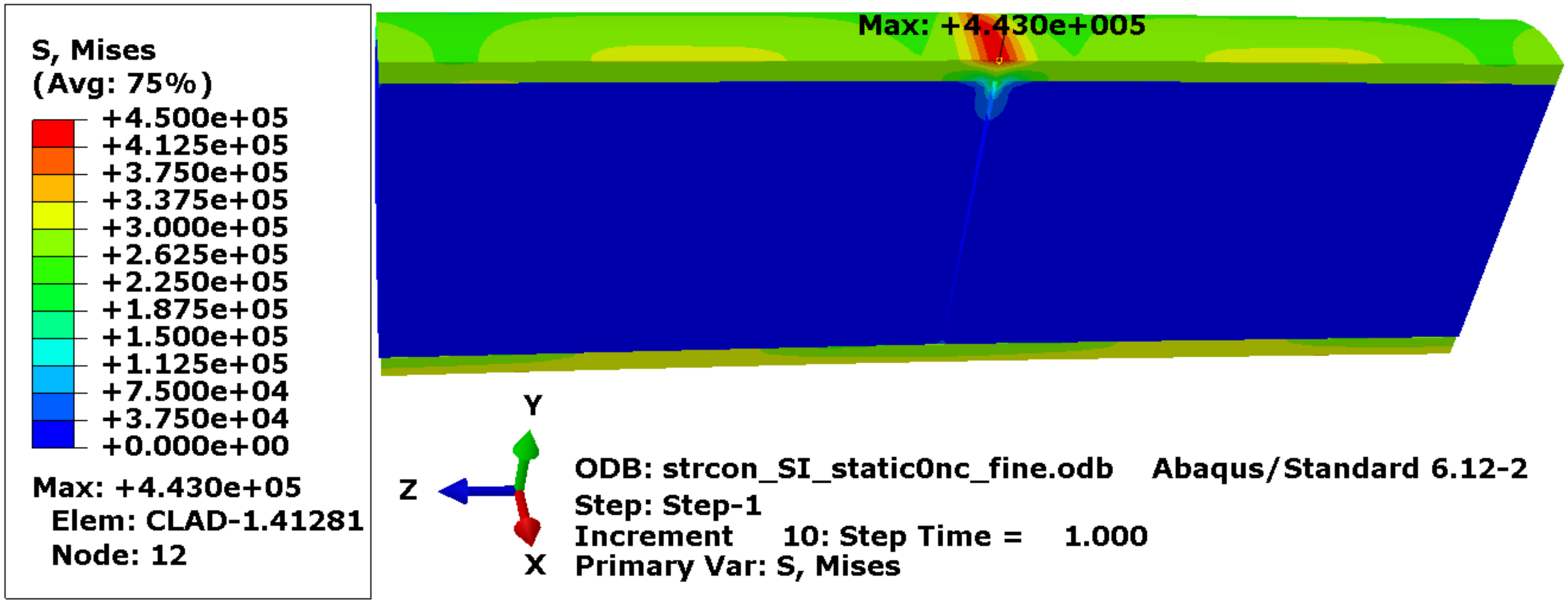
$$\left|\frac{\ddot{x}}{\ddot{y}}\right| = \sqrt{\frac{1+(2\xi\rho)^2}{\left(1-\rho^2\right)^2+(2\xi\rho)^2}},$$

$$\rho = f / f_n$$



Stress Concentrations at Pellet Gaps (1.4x)

We will assume that the strain gages were not placed at anticipated stress concentrations. FCRD-UFD-2013-000325 predicted these stress concentrations could be on the order of 1.4x the nominal strain. Fatigue amplitudes will be increased by this factor. (Image from FCRD-UFD-2013-000325)

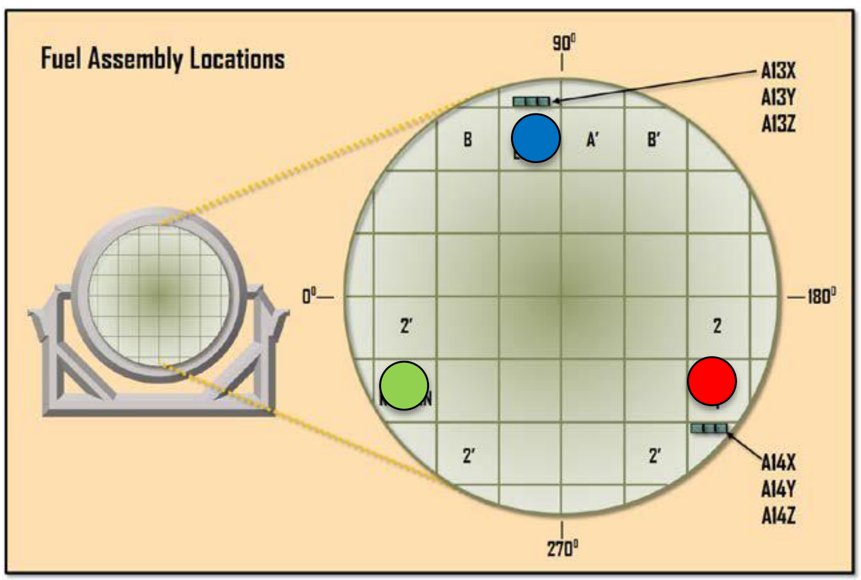


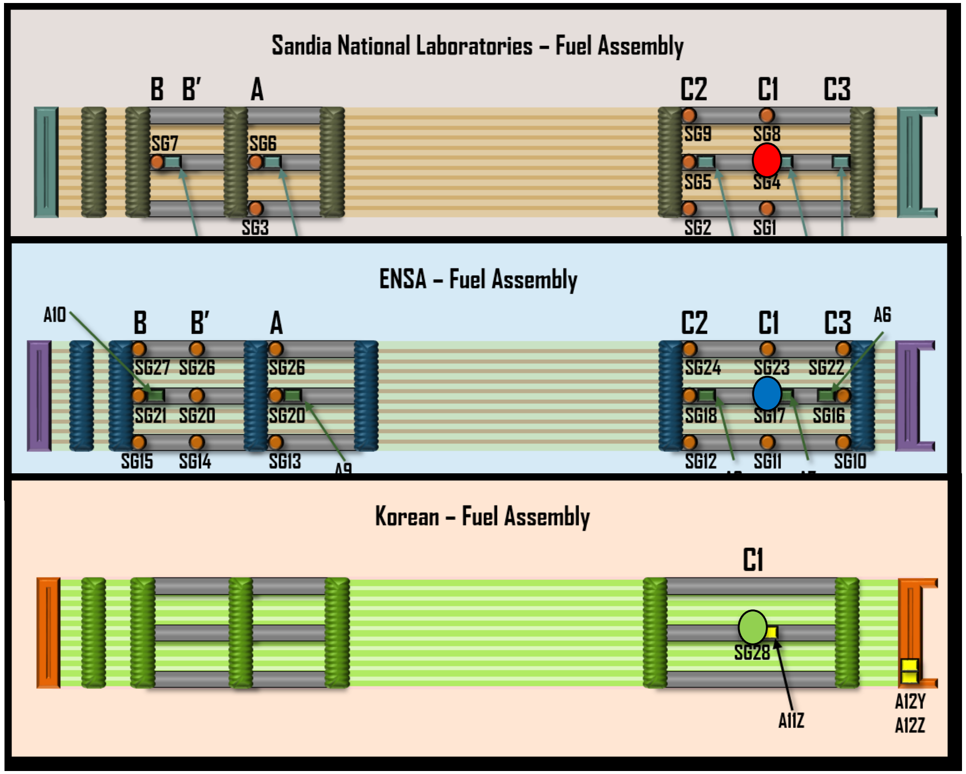
Data Analysis Study:
Strain Gage Response Correlation, by Frequency

Average signal correlation when low pass frequency filter applied to strain gage data.

	15 Hz	30 Hz	45 Hz	60 Hz	75 Hz	90 Hz	Baseline (200 Hz)
Top Mid-Span Strain Gage, All Three Assemblies	0.98	0.93	0.76	0.60	0.54	0.51	0.50

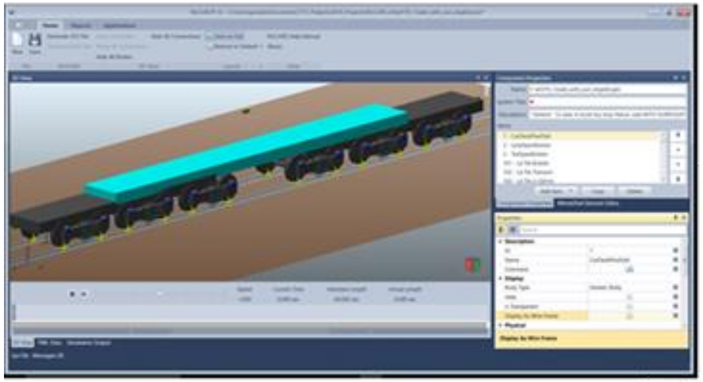
Signal correlation: 3 strain gages in similar locations on all 3 fuel assemblies. 10 second open rail event.



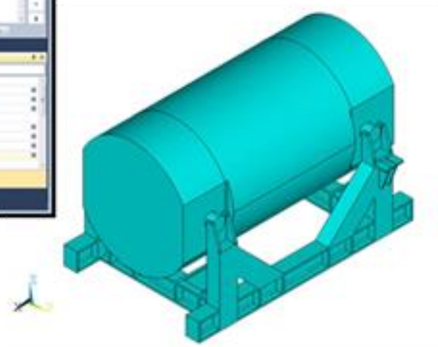


Initial Model Architecture – 3 Parts

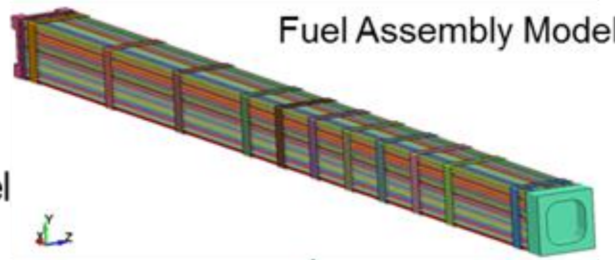
Railcar Model



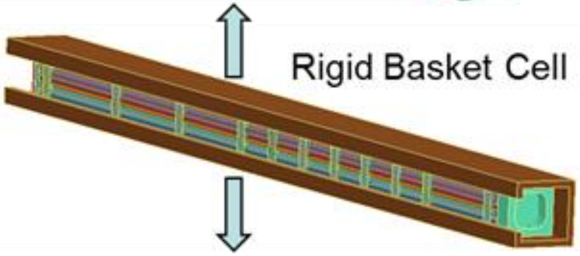
Cask & Cradle Model



Fuel Assembly Model



Rigid Basket Cell



Model Chain ➔

NUCARS	*ANSYS*	*LS-DYNA*
Rail Vehicle Dynamics	*Load Transmissibility*	*Fuel Rods & Assembly*

50 Mph Pitch and Bounce: Test Data Summary

Maximum Recorded Strains (uE) Per Rod
50 mph Pitch and Bounce Test

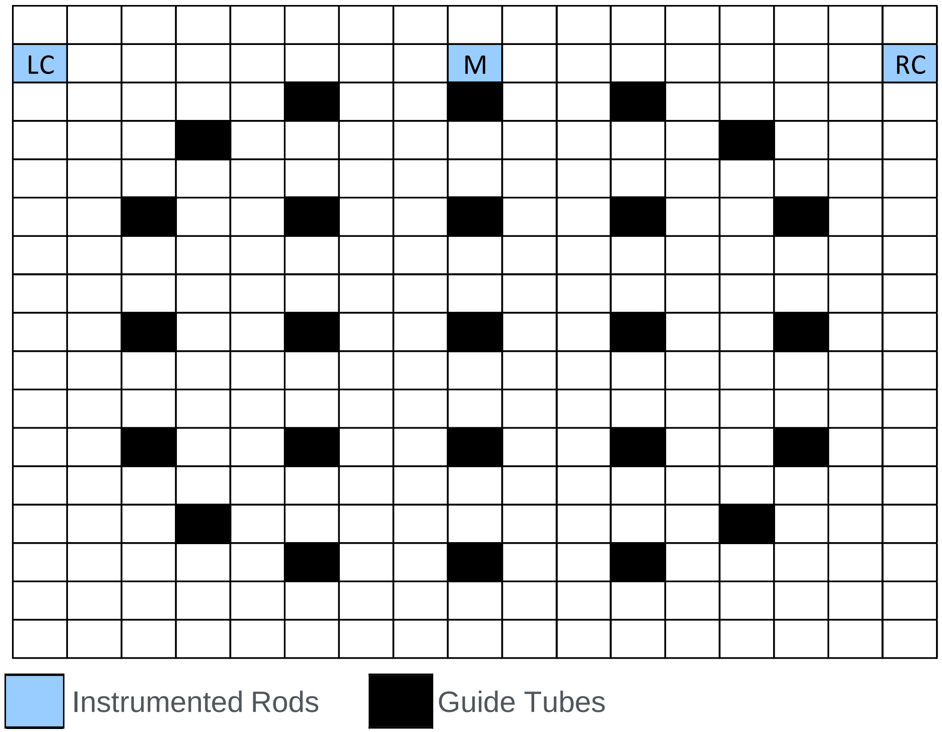
	Max	LC	M	RC
SNL	19	13	18	19
ENSA	10	10	10	10
Korean	5	-	5	-

Irradiated Cladding Yield ~10,000 uE

Strain Data Summary:

- P&B test data is 5 to 19 uE
- SNL assembly is 13 to 19 uE

Instrumented Fuel Rod Map



Model Results: Cladding Strain Pretest Prediction (50 mph P&B)

Model Calculated Peak Strain (uE) Per Rod

102	104	95	101	95	80	87	98	112	91	107	95	85	83	89	102	88
89	92	88	89	99	95	115	101	108	102	91	115	102	79	86	93	92
91	100	111	119	93		116	92		106	106		97	102	106	85	92
98	85	83		106	221	147	100	206	126	93	196	131		99	83	87
89	92	86	106	113	99	79	83	112	102	91	118	119	115	89	102	86
90	90		98	91		83	87		102	89		109	88		115	82
85	85	276	126	118	195	110	88	264	116	89	212	131	85	268	116	87
89	92	107	82	83	100	87	84	86	95	86	101	91	92	93	84	77
81	96		98	85		97	88		109	86		98	85		93	88
85	90	336	156	88	238	124	101	193	130	92	238	131	99	225	122	95
93	95	99	129	87	102	86	93	103	86	91	125	86	88	104	100	89
89	96		93	97		113	84		91	83		99	102		96	92
86	122	150	89	111	318	140	86	172	117	105	226	109	92	97	109	97
89	82	97		89	107	98	91	112	94	94	109	108		103	87	86
111	91	110	174	100		95	108		107	95		104	208	111	93	131
89	116	71	113	109	179	123	104	194	112	119	214	132	89	88	92	112
113	96	102	114	83	80	113	100	94	99	96	83	85	98	87	89	89

Instrumented Rods   Maximum Calculated Strain Rod   Guide Tubes

Results Documented:
- SFWD-SFWST-2017-000035

Model Prediction:
- Most rods about 100 uE
- Max rod is 336 uE (outlier)

Compare to Test Data:
- Test data is 5 to 19 uE
- Add gravity strain (~50 uE)

Review Conclusion:
- Not working as intended

Model Fixes Needed:
- Double Precision Solver
- Damping/Numerical Noise
- Initialization/Gravity

Model Results:
Revised Post-Test Model (50 mph P&B)

Post Test Model Validation:

- **Resolved model flaws and adjusted results for gravity**
- **Peak strain: 33 uE (calculated)**
- **Instrumented rod strains: 12-14 uE (calculated)**
- **Measured Strains: 5-19 uE (measured)**
- **Good model, but not necessary when strains are this low.**

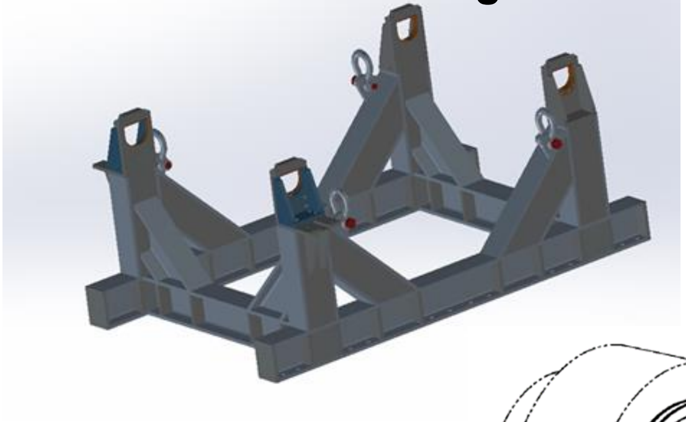
Maximum Recorded Strains (uE) Per Rod
50 mph Pitch and Bounce Test

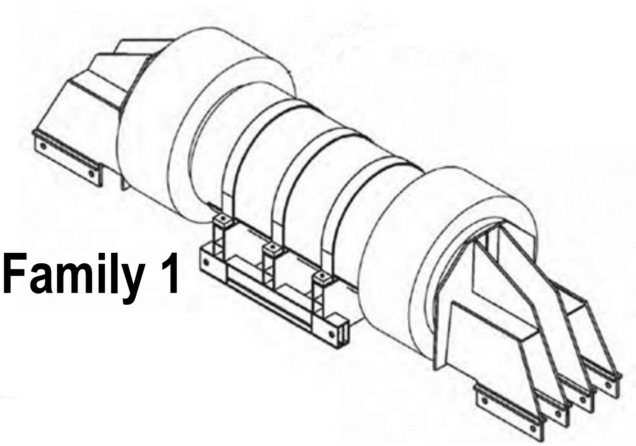
	Max	LC	M	RC
SNL	19	13	18	19
ENSA	10	10	10	10
Korean	5	-	5	-

12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
12	12	12	12	6	17	10	6	**14**	8	6	14	8	12	12	12	**12**
12	12	7	19	8		11	7		8	9		8	17	12	12	12
12	12	12		14	17	25	17	15	23	23	17	8		10	11	11
11	6	5	6	14	19	7	6	19	9	5	16	20	5	7	8	11
11	5		12	7		9	7		8	8		10	5		7	11
11	15	13	19	16	12	23	17	13	20	16	15	23	16	11	18	11
10	6	13	8	7	20	8	7	17	8	6	14	8	6	14	9	11
10	6		9	6		10	7		9	8		9	8		8	10
10	16	8	21	16	9	22	17	12	20	17	9	19	16	7	20	10
10	6	18	9	6	15	8	6	18	8	6	16	8	6	16	8	10
10	5		10	11		12	7		12	10		9	7		8	10
11	14	6	7	13	8	20	18	11	22	17	8	12	7	6	17	11
11	11	7		7	20	15	6	18	12	11	18	6		9	11	11
11	11	15	11	9		12	8		11	10		11	7	18	11	11
11	11	10	11	14	11	$\boxed{33}$	18	11	22	17	8	24	11	10	11	11
11	11	11	11	13	13	12	12	12	13	13	11	11	11	10	11	11

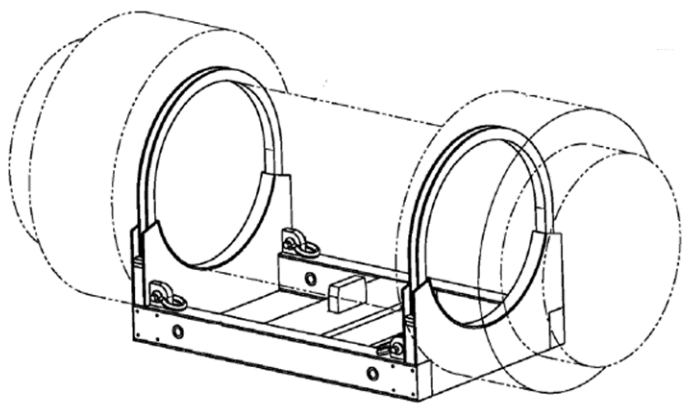
Four Atlas Railcar Cradles

ENSA Cradle Design





Family 1



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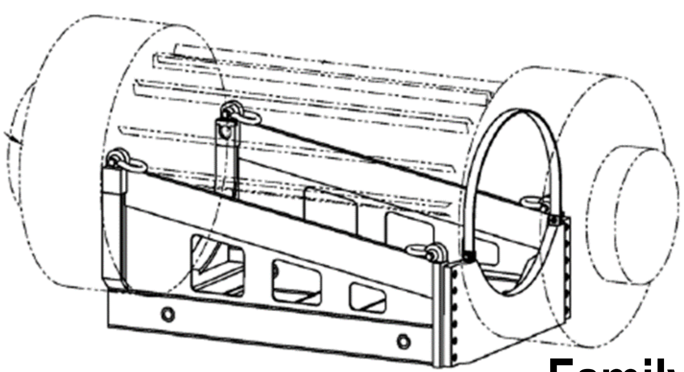

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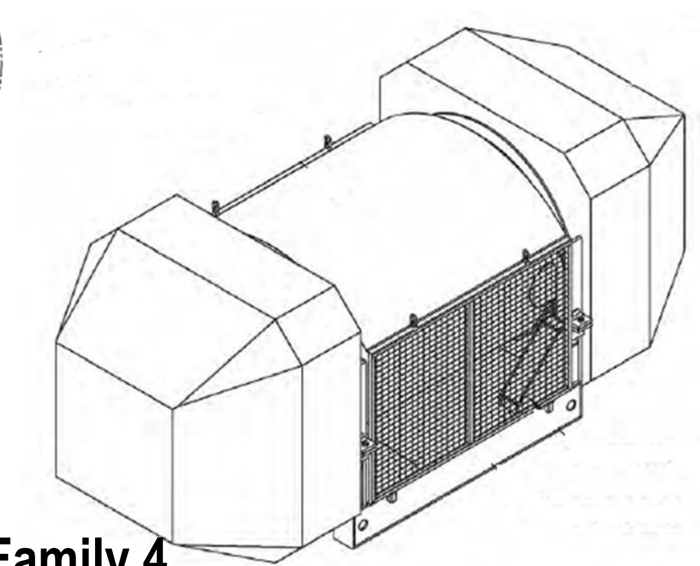

Family 4

NWTRB Questions

1:10 p.m. **ENSA Cask Multimodal Transportation Test and Related Structural Modeling and Analysis**

Sylvia Saltzstein, Sandia National Laboratories, and *Nicholas Klymyshyn*, Pacific Northwest National Laboratory

a. In a summary fashion, what is the progress on the Equipos Nucleares, S.A. (ENSA) cask transportation test?
b. How were the effects of using surrogate components in the ENSA cask test evaluated to determine if the test results can be applied to a real transportation system? How does the use of a pad, which was placed between the cradle and cask in the test, but which may not be present or may be of different material in other transportation operations, affect the applicability of the ENSA test results to different transportation systems?
c. How will the behavior of real irradiated spent nuclear fuel during transport be evaluated?
d. Considering the relatively large transient impulse loads measured during the rail testing at the Transportation Technology Center compared to the actual rail vibration loads, explain how the effects of large transient impulses will be accounted for when determining the fatigue lifetime of spent nuclear fuel.
e. Was the frequency spectrum observed for the surrogate fuel rods in the ENSA cask test consistent with the frequency spectrum used for the fatigue testing at Oak Ridge National Laboratory? If not, what are the implications of the inconsistency for using the fatigue testing results to model actual transportation operations?

1:50 p.m. *Questions, discussion*