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Fuel Assembly Tests under Normal Conditions of Transport

Paul McConnell
Sylvia Saltzstein
Ken Sorenson

Sandia National Laboratories*
Albuquerque, New Mexico USA

Abstract

Tests of a surrogate pressurized water reactor fuel assembly have been conducted simulating normal conditions of truck and rail transport to measure the strains and accelerations on the fuel pins and accelerations on the assembly. The assembly was subjected to vibrations and shocks imposed by shakers and on a truck for an over-the-road test. These tests were performed to assess the strains on individual fuel rods subjected to normal conditions of transport. The magnitude of these strains can be used for an assessment of the margin of safety relative to the elastic limit of the cladding. This is important for predicting the integrity of zirconium-alloy fuel pins that may be degraded due to high burnup or long-term aging in a storage facility.

Results of three sets of tests of the assembly are reported. The strains imposed on the fuel pins for the normal conditions of transport were extremely low. Strains measured on the surrogate fuel rods were consistently very low—well below the elastic limit of irradiated Zircaloy-4. Conclusions based on these results along with a fatigue evaluation are discussed.

Introduction

Nuclear fuel will experience higher burnup and will be stored above ground prior to disposal for longer periods of time than previously assumed. Both of these factors could lead to the zirconium-alloy cladding being embrittled to a degree that needs to be considered for Normal Conditions of Transport (NCT, as defined in Part 71.71 of Title 10 of the U.S. Code of Federal Regulations). If strains applied to the cladding by vibrations and shocks associated with NCT exceed, the elastic limit of the alloy, the cladding may fracture and radioactive material may be released within the transport cask.

Assembly and Basket Used for the Tests

The test unit for all three sets of tests consisted of a 17 X 17 PWR assembly populated with a full array of tubes. Some of the tubes were Zircaloy-4—most were copper.

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The assembly was placed into an aluminum-alloy basket that was based upon the dimensions and weight of a NAC-LWT cask single-PWR basket (Figure 1).

Figure 1 Assembly and basket used for NCT tests

The Tests

Three sets of NCT tests were performed using the assembly/basket unit [1 -3]. The first set of tests used a uniaxial (vertical direction) shaker at Sandia National Laboratories (Figure 2). The inputs to the shaker for this series of tests simulated normal conditions of truck transport. Truck transport is widely regarded as a more severe vibration and shock environment than rail transport. And, accelerations in the vertical direction tend to exceed those for the other axes and are potentially most damaging to a rod within an assembly. The truck NCT accelerations used as input to the shaker were based upon data in [4].

Figure 2 Sandia uniaxial shaker

The second test was an actual truck over-the-road test. The assembly/basket was placed upon a trailer upon concrete blocks whose mass simulated that of a truck cask (Figure 3). The truck was driven over a variety of road conditions and velocities (Figure 4).

For both sets of these tests, all of the tubes were filled with lead “rope” (lead rod) to simulate the mass of actual uranium oxide fuel (Figure 5). The Zircaoly-4 tubes were instrumented with strain gauges and uniaxial accelerometers (Figure 6).

Figure 3 Over-the-road truck test configuration

Figure 4 Typical roads for truck test

Figure 5 Lead “rope” with in copper surrogate fuel tube

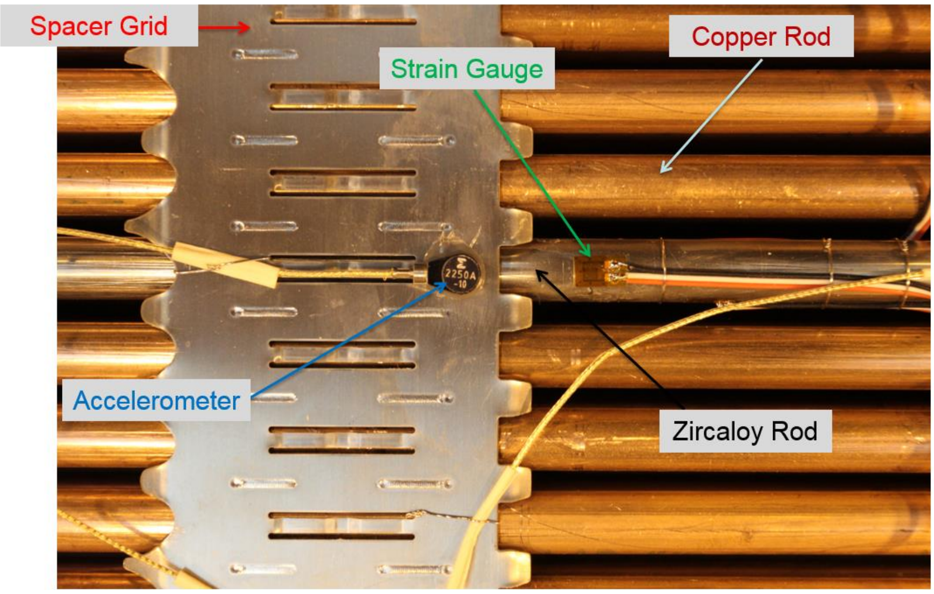


Figure 6 Instrumentation on a Zircaloy-4 tube and spacer grid

The third set of tests were conducted at the Dynamic Certification Laboratories using a six-degrees-of-freedom multi-axis shaker (Figure 7). These tests simulated both truck and rail NCT. The truck NCT input was the same as used for the Sandia shaker tests. The rail NCT inputs were derived from [5].

For the multi-axis truck and rail NCT tests, three Zircaloy-4 rods were instrumented. One of the tubes was filled with lead “rope” as with the other tests; one was filled with lead pellets; and the third was filled with molybdenum pellets.

Figure 7 Multi-axis shaker used for rail and truck NCT tests

The Results

The strains measured on the surrogate Zircaloy-4 fuel rods were very low as shown in Figure 8 which is a plot of the elastic portion of unirradiated and irradiated Zircaloy-4 stress-strain curves (these curves are from [6]). Also shown in that figure are the maximum strains measured in each of the three sets of tests conducted.

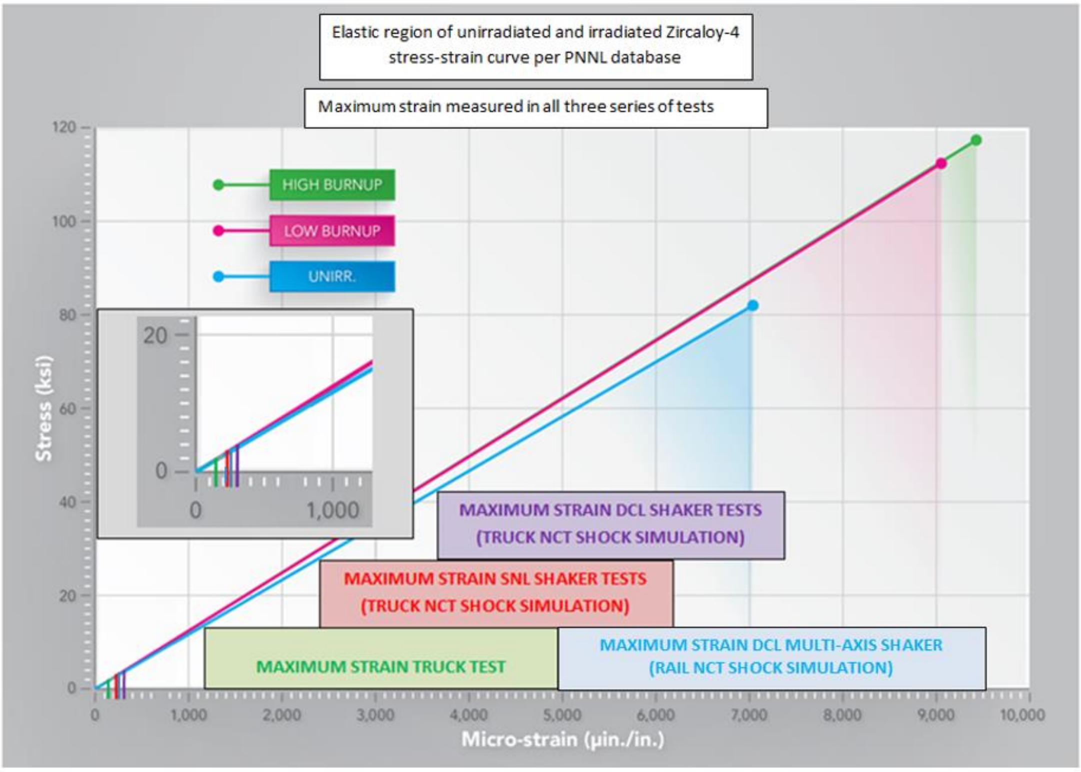


Figure 8 Maximum strains measured relative to elastic limit of Zircaloy-4

The results from all of the many tests were consistent regardless of the various parameters involved in the testing: strains applied to the Zircaloy-4 cladding during simulated conditions of NCT were very low. Table 1 shows the maximum strains measured for each set of the three series of tests.

Table 1 Comparison of maximum measured strains on a surrogate fuel rod for three surrogate fuel assembly test conditions

Surrogate Fuel within Zircaloy-4 Tube	Rod Lateral Location in Assembly (strain gauges adjacent to spacer grid at mid-span of assembly)	Uniaxial Shaker Simulated Truck Shock	Over-the-Road Truck Test	Multi-axis Shaker Simulated Truck Shock
		Maximum Strain (μm/m)		
Pb “rope”	Middle		143	
Pb “rope”	Middle	119		
Pb pellets	Right Edge			160
Mo pellets	Middle			214
Pb “rope”	Left Edge			301

The consistency of the measured low strains is evident from the following observations:

- The strains were low regardless of the axial position of the strain gauges along the length of the rods within the assembly, be it adjacent to a spacer grid or at the mid-span of the rod between spacer grids, or at the end of the rod/assembly or the middle of the assembly.

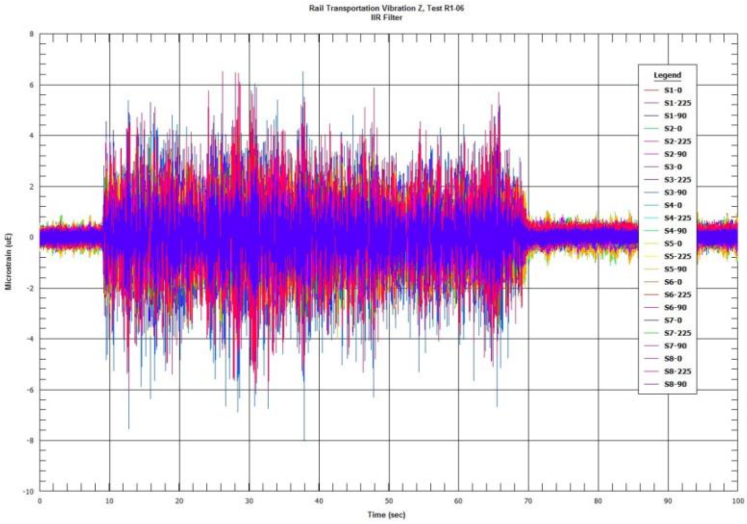
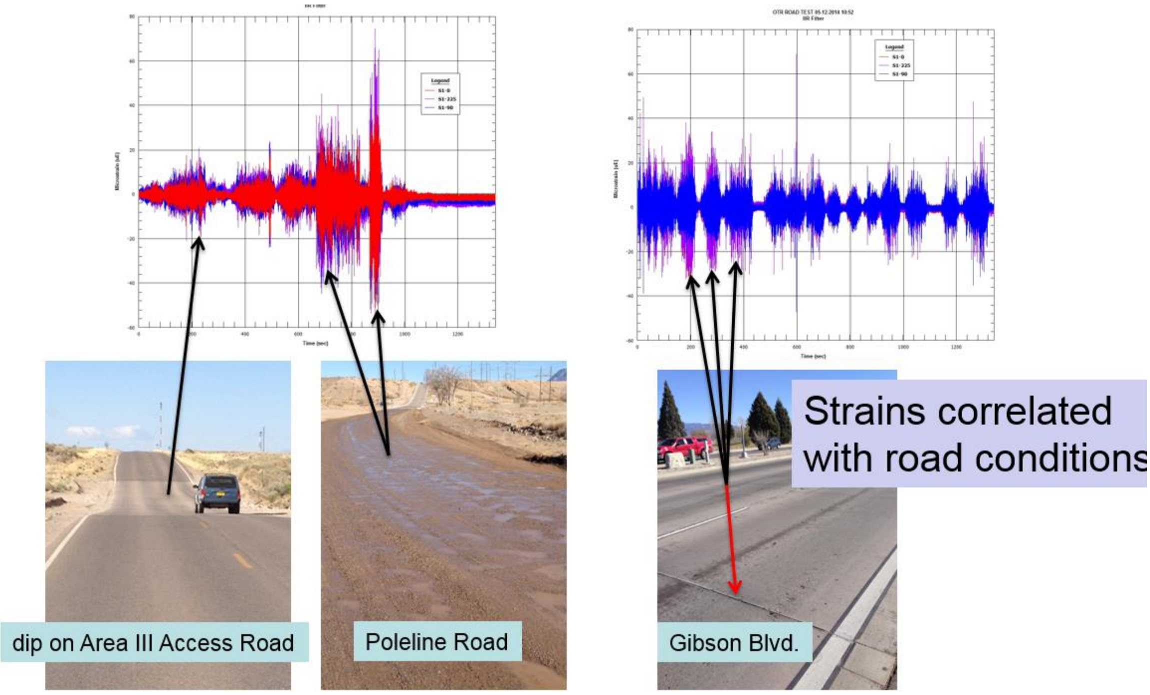


Figure 8. Strains measured during a multi-axis shaker rail vibration test

- The strains were low regardless of the lateral position of the rod within the assembly, be it middle or at the top side or the bottom side of the assembly.

- The strains were low regardless of the circumferential position of the strain gauge around the rod (0º, 90º, or 225º).
- The strains were low regardless of the material within the rod which simulated the mass of UO_2 fuel, be it lead "rope", lead pellets, or molybdenum pellets.
- The strains were low regardless of the simulated NCT loading, be it truck vibration and shock or rail vibration and shock. Simulated truck shock strains exceeded simulated rail shock strains, however.
- And, the strains were very similar—and always low—regardless of the test platform, be it uniaxial shaker, over-the-road truck, or multi-axis shaker.

For the over-the-road truck test, the measured strains could be correlated with features of the road surface as shown in Figure 8.



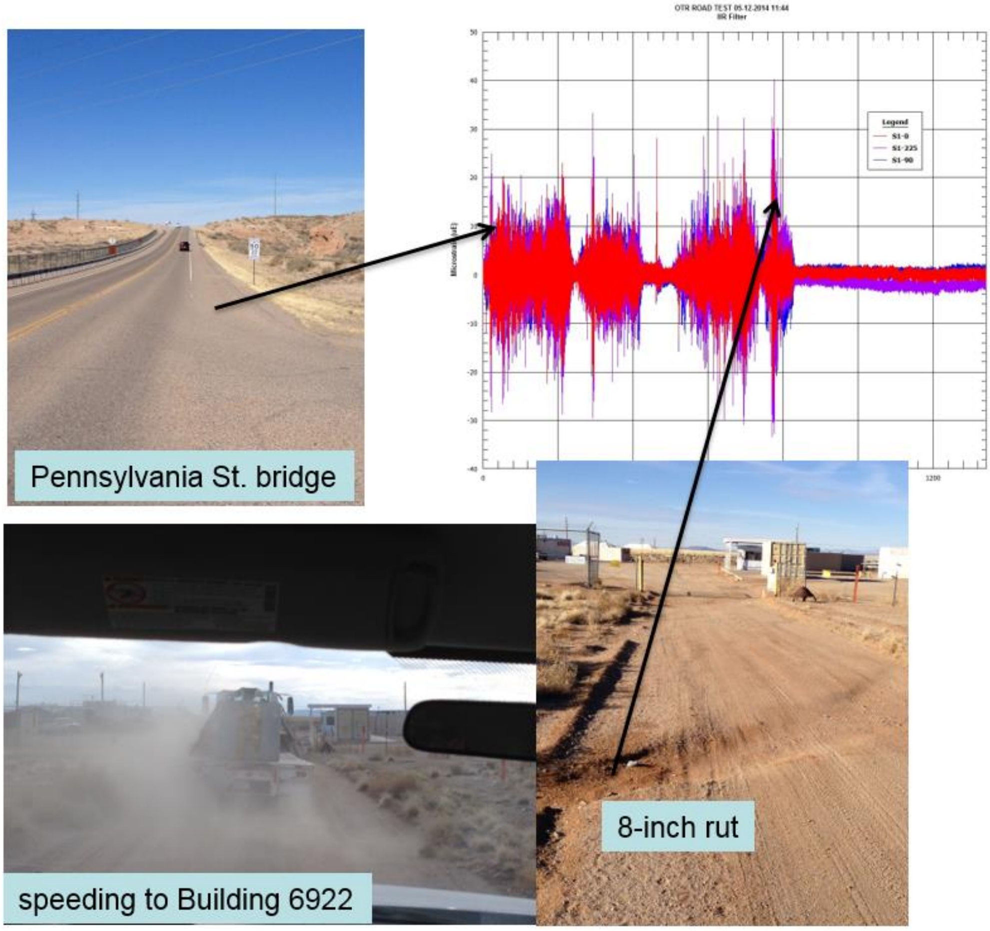


Figure 9 Strains measured on surrogate fuel rods correlated with road conditions

Maximum strains were observed at relatively low frequencies, generally below 100 Hz (Figure 9).

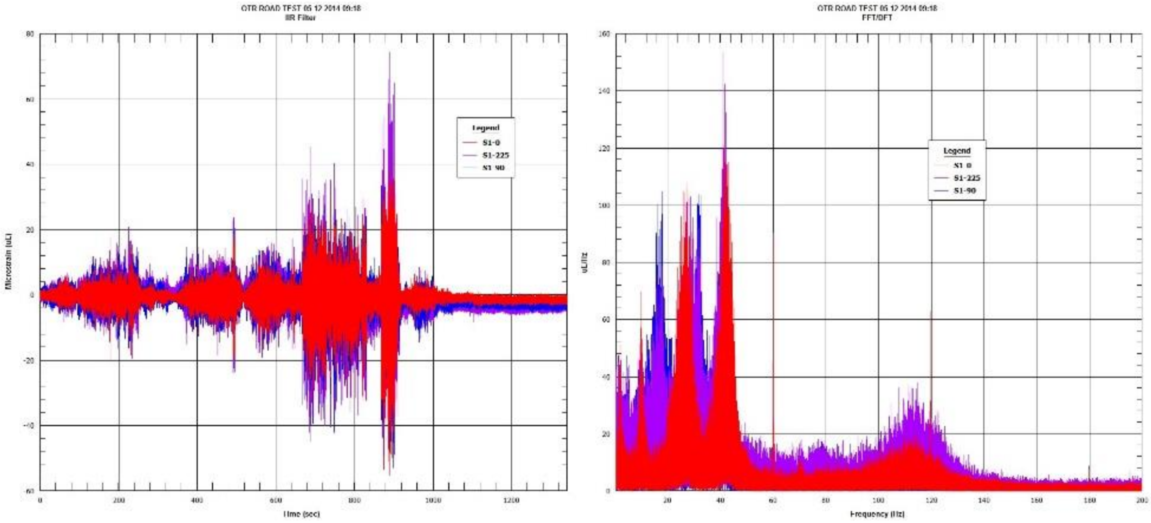
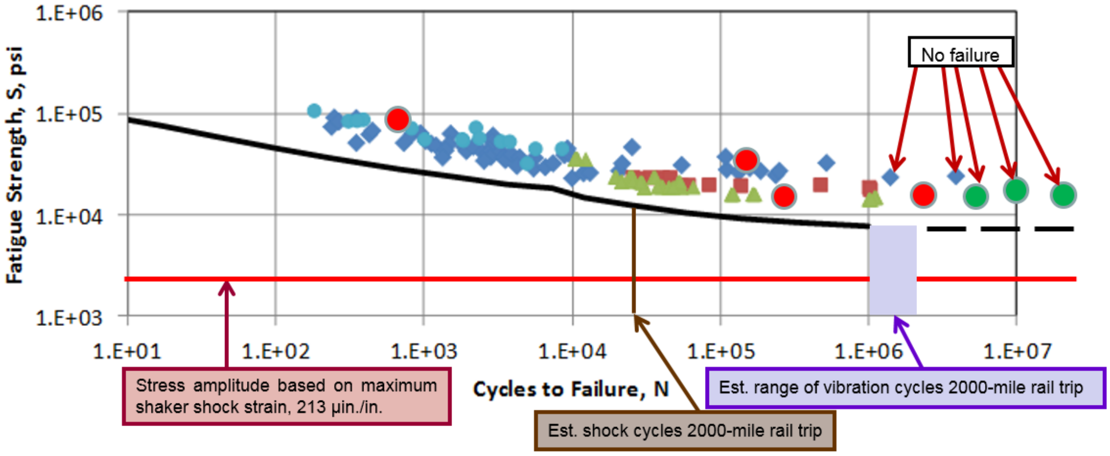


Figure 10 Maximum strains on the surrogate fuel rods occurred at low frequencies

The low strains measured in the simulated NCT tests suggest that fatigue failure of cladding during transport of fuel assemblies is unlikely. Figure 10 shows a fatigue curve for Zircaloy-4 with data points used to construct that curve and data points recently generated by Oak Ridge National Laboratory (ORNL). (Note references cited in the figure). A typical strain measured for shock conditions in the Sandia assembly tests is represented by the horizontal red line.

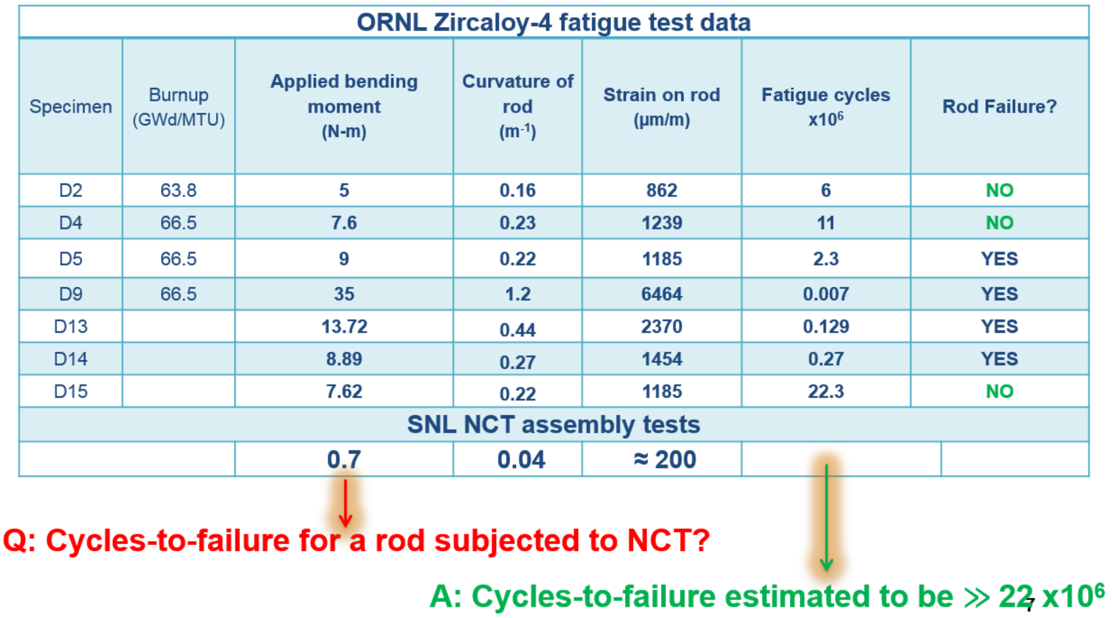


Fatigue design curve (▬) [7]

Data points plotted courtesy of Ken Geelhood, PNNL
The large circles are ORNL irradiated Zircaloy-4 data [8]

Figure 11 Fatigue curve for Zircaloy-4 showing levels of stress measured on surrogate fuel rods in simulated assembly NCT tests

Based upon empirical data of Zircaloy-4 fatigue testing at ORNL [8], irradiated Zircaloy-4 rods withstood in excess of 22.6 million fatigue cycles at the strain levels in excess of those measured in the Sandia tests which simulated normal conditions of transport (Figure 11).



ORNL Zircaloy-4 fatigue test data

Specimen	Burnup (GWd/MTU)	Applied bending moment (N-m)	Curvature of rod (m^{-1})	Strain on rod (µm/m)	Fatigue cycles x10^6	Rod Failure?
D2	63.8	5	0.16	862	6	NO
D4	66.5	7.6	0.23	1239	11	NO
D5	66.5	9	0.22	1185	2.3	YES
D9	66.5	35	1.2	6464	0.007	YES
D13		13.72	0.44	2370	0.129	YES
D14		8.89	0.27	1454	0.27	YES
D15		7.62	0.22	1185	22.3	NO
SNL NCT assembly tests						
		0.7	0.04	≈ 200		

Q: Cycles-to-failure for a rod subjected to NCT?

A: Cycles-to-failure estimated to be ≫ 22 x10^6

Figure 12 Comparison of bending moment and strain applied to Zircaloy-4 rods during ORNL fatigue testing and SNL NCT surrogate fuel assembly tests

Conclusions

- The strains measured on the rods during the NCT test simulations were in the micro-strain levels—well below the elastic limit for either unirradiated or irradiated Zircaloy-4.
- Strains on irradiated fuel rods during NCT may be less than strains measured on the unirradiated Zircaloy-4 due to pellet-clad bonding in the irradiated rod which stiffens the rod.
- Strain- or stress-based failure of Zircaloy-4 fuel rods during NCT unlikely.
- Fatigue failure of Zircaloy-4 rods during NCT does not appear to be an issue.
- Rail NCT results are similar to truck NCT results (truck strains were marginally higher).
- Rod strains when filled with lead "rope" as a surrogate fuel were similar (perhaps marginally more conservative) to strains measured when lead pellets or Mo pellets were used as a surrogate fuel within the Zicaloy-4 tubes.

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