

Structural Integrity Evaluation of an i-SMR Fuel Control Rod Assembly

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1. Introduction

An important requirement in i-SMR nuclear fuel design is flexible operation, including boron-free operation. To satisfy the core subcriticality requirement under this design philosophy, an improved control rod design is required. Accordingly, the number of control rod fingers was increased from 24 to 28, and the CRA (Control Rod Assembly) configuration was revised, as shown in Fig. 1 [1].

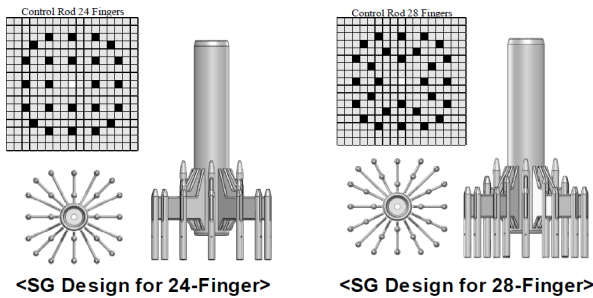


Fig. 1. Comparison of fuel assembly array designs for 24- and 28-finger CRAs

To verify the structural integrity of the revised CRA, a mechanical integrity test program was conducted for the spider pack, which is a critical load-transfer component in the upper region of the CRA. During CRDM operation, the ratchet mechanism generates a discrete axial stepping load. In the present design, this stepping load was conservatively evaluated, which bounds the loads expected during transportation, handling, normal operation, and accident conditions. Based on this design-basis load, a prototype spider pack was tested to verify its mechanical adequacy. The verification program consisted of two categories of tests: (1) axial tensile/compressive loading tests and (2) fatigue tests. Strain responses at critical locations were measured using uni-axial and rosette strain gages.

2. Structural Integrity Test and Results

2.1. Structural Integrity Test

The test specimen and fixtures were prepared in accordance with the reference drawings and specifications for the i-SMR CRA spider pack. A servo-hydraulic testing machine (MTS Landmark) equipped with a 100 kN load cell was used to apply axial loads, and the loadcell and strain gage signals were acquired using a SIEMENS SCADAS Mobile data acquisition

(DAQ) system. As shown in Fig. 2, strain gages were installed at critical locations on the spider pack head, wing plate, surrogate control rods, and selected rosette positions to measure strain responses during testing. The overall test configuration and loading setup are shown in Fig. 3.

For the axial structural integrity evaluation, tensile and compressive loading tests were performed under the conservative stepping load condition. The actuator loading rate was set to 562 lbf/min. A total of five tests were conducted for each loading mode (tension and compression): Tests 1 to 3 were performed at 3,500 lbf, and Tests 4 and 5 were performed at 5,200 lbf, which includes an additional margin of approximately 1.5 times the design load. These tests were conducted to verify the mechanical response and dimensional stability of the spider pack under both design and margin load conditions.

In addition, a fatigue test was performed to assess long-term durability under repeated stepping load conditions. The fatigue loading history was defined based on a 10-year service life assumption, and a total of 10,800,000 cycles was applied. Before and after the tests, the specimen dimensions were inspected using a 3D metrology system and compared with the drawing requirements to confirm structural integrity and compliance with the acceptance criteria.

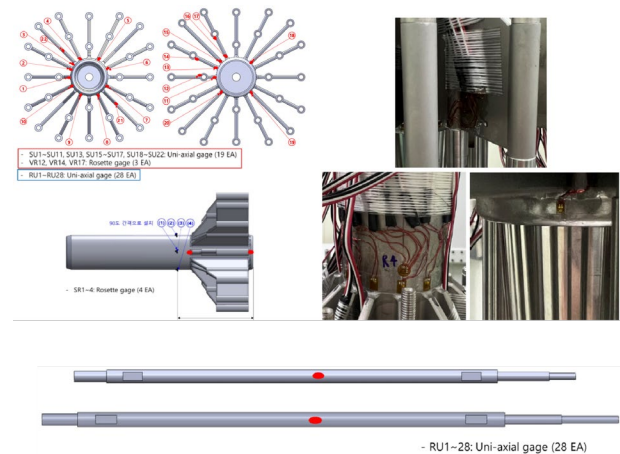


Fig. 2. Stain gage location



Fig. 3. Structural integrity test setup

2.2. Test Results

A total of 68 strain-gage channels were installed on the spider pack head, spider pack wing plate, surrogate control rods, and selected rosette locations to measure strain responses under the applied loads. Across all loading conditions, the maximum strain was consistently observed in the spider pack head region, and the corresponding stress was confirmed to satisfy the allowable stress criterion with sufficient margin. Table 1 summarizes the ratio of the calculated stress at the location of maximum strain to the allowable stress, where the allowable value was determined in accordance with ASME BPVC Section III.

Post-test dimensional measurements also confirmed no permanent deformation, with the overall length, absorber-rod location, and wing plate height remaining within the specified tolerances. Representative strain-gage responses are presented in Fig. 4 for the fourth tensile test and in Fig. 5 for the fatigue test at 1 second.

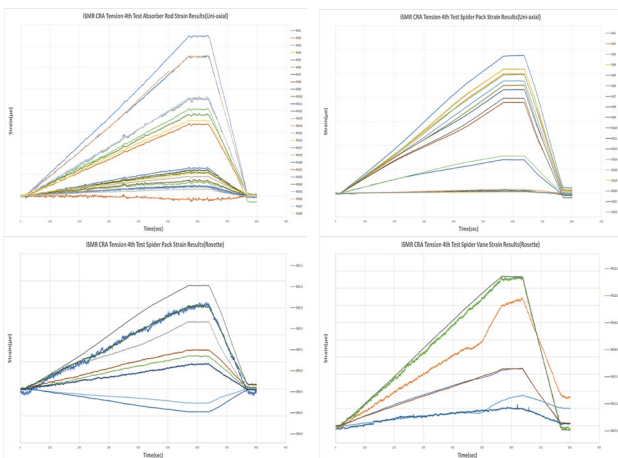


Fig. 4. Strain gage responses in the fourth tensile loading test

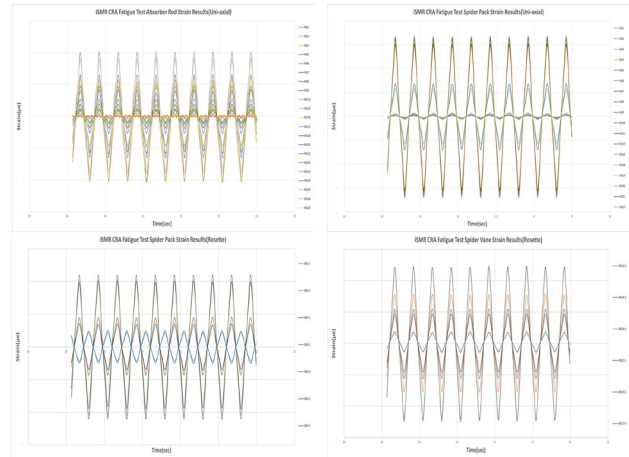


Fig. 5. Strain gage responses at 1 sec during the fatigue test

Table 1. Maximum stress ratio $S_{test}/S_{allowable}$

Condition	Strain gage No.		$S_{test}/S_{allowable}$
Stepping Load	Uni-axial	SU5	0.13
	Rosette	SR3-3	0.09

3. Conclusion

A structural integrity evaluation of the i-SMR CRA spider pack wing plate was successfully conducted under conservative stepping-load conditions, including axial tensile/compressive loading tests and a fatigue test. The measured strain responses showed that the maximum strain occurred in the spider pack head region, and the corresponding estimated stresses satisfied the allowable stress criterion specified in ASME BPVC Section III with sufficient margin. In addition, pre- and post-test dimensional inspections confirmed that no permanent deformation occurred within the acceptance criteria. Therefore, the spider pack wing plate design was verified to satisfy the structural integrity requirements under both the design-basis stepping load and long-term cyclic loading conditions.

ACKNOWLEDGEMENT

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