

PWR rod bow engineering process demonstration

Provisional analysis and evidence report

Process demonstration—unvalidated engineering estimates.

The original maximum 5% DNBR penalty requirement is **not established**. This report records a reduced numerical demonstration and transferred references, not engineering acceptance.

1. Problem and supplied requirements

A peripheral rod in a 5 by 5 segment bows toward its neighbor. This demonstration compares the imposed gap closures and two effective grid-support stiffnesses, and carries native mechanical observations and attributed thermal references into a traceable report.

Supplied quantity	Value
Rod outside diameter and pitch	9.5 mm and 12.6 mm
Nominal wall-to-wall gap	3.1 mm
Coolant pressure and inlet temperature	15.5 MPa and 290 degC
Coolant mass flux	3000 kg/(m ² s)
Bowed-rod linear power	25 kW/m
Effective support stiffness states	50 and 20 N/mm
Requested nominal closure	0%, 50%, 80%, 100%

2. Analysis basis and assumptions

Assumed model parameter	Value
Span	1000 mm
Wall thickness	0.57 mm
Elastic modulus	77420.0375 MPa
Poisson ratio	0.383780271027766
Elements	B32R, native PIPE section; 100 elements, with 50/200-element pilot comparisons
Material reference	Previously retained Zircaloy-4 zero-cold-work/zero-fluence card at 573.15 K; no new material correlation.

One initially straight, homogeneous hollow pipe beam; the neighbor is a geometric reference only. The 25-rod SteveCAD model is retained context, not the finite-element mesh.

Pinned lateral ends; axial datum at first end, free axial motion at other end; planar y displacement restrained, one torsional datum. Bending rotations remain free.

A single bilateral, zero-preload incremental SPRING at $z=500$ mm represents aggregate transverse stiffness. It does not resolve individual springs/dimples, separation or strap clearance.

Prescribed x displacement at $z=500$ mm produces nominal 0/50/80/100% midplane closure against an undeformed neighbor. The actual nodal maximum and gap are checked independently.

A forced-displacement sensitivity calculation, not an irradiation-induced natural-bow prediction. Grid displacement equals closure only because this reduced model explicitly imposes that arrangement.

At the same imposed midpoint displacement, changing a colocated grid spring changes reaction but should not change the elastic beam deformation or bending stress. This is a consequence of the imposed-displacement model, not proof that real rod stress is independent of support stiffness.

Omitted: rod-to-rod contact and load redistribution, grid strap interference, spring/dimple travel/yield, local cladding contact stress, coolant/internal-pressure stresses, pellet interaction, creep and irradiation constitutive response, thermal gradients.

3. Existing tools and artifact handoffs

Retained SteveCAD bundle: geometric context. Existing CalculiX MCP: each independently recorded native solve of an exact reviewed pipe-beam input. Existing ParaView MCP: native result inspection and plots. Retained CoolProp MCP observations: conditional bulk-water properties. Published HTRF rows: explicit thermal substitutes. Wright: durable execution, per-output validation and human reviews. Existing Pandoc MCP: report formats from this same source.

4. Mechanical matrix

Global force/moment equilibrium is **not established**. The original RF-sum screening residual is approximately 0.97677 for bowed 50 N/mm cases and 0.94388 for bowed 20 N/mm cases, versus the unchanged 0.001 screening limit. Exact values accompany the report; this is not a corrected equilibrium measure. Printed midpoint RF is not a verified total actuator reaction. The original failed pilot assessment remains part of the evidence.

All entries below are **native calculations with provisional inputs**. Stress is the maximum paired increment of global axial stress at native integration points; it is not local contact stress or an outer-surface peak.

State	Closure %	Gap mm	Spring force N	Axial stress MPa
50 N/mm	0	3.100	0.000	0.00000
50 N/mm	50	1.550	77.500	6.40682
50 N/mm	80	0.620	124.000	10.25092
50 N/mm	100	0.000	155.000	12.81365
20 N/mm	0	3.100	0.000	0.00000
20 N/mm	50	1.550	31.000	6.40682
20 N/mm	80	0.620	49.600	10.25092
20 N/mm	100	0.000	62.000	12.81365

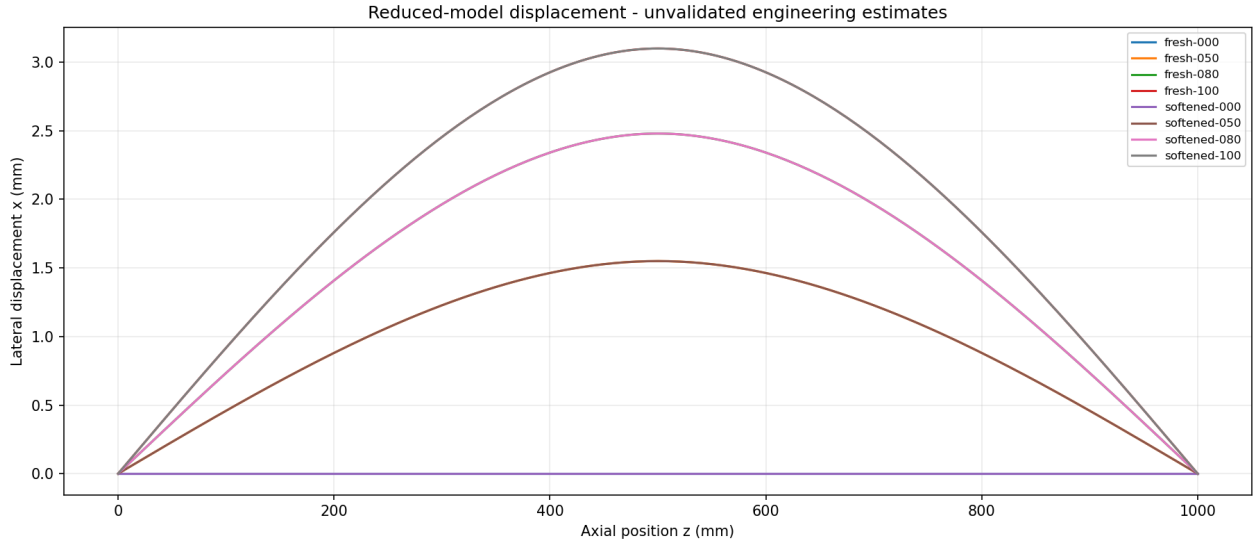


Figure 1: Actual native reduced-model displacement; axes use different scales.

5. Pilot, refinement and numerical verification

The original pilot validator passed 25 checks and failed three force-screening checks. The engineer approved the disclosed demonstration exception at B. The continuation passed 60 checks covering native completion, exact files, finite values, displacement, nominal gap, the spring relation and explicit disclosure of unresolved equilibrium. This does not clear the original force requirement.

The 100-to-200 element axial integration-point stress change is 0.164%; 50-to-200 is 0.544%. The observed stress change meets both the 5% demonstration threshold and the original 2% numerical threshold for this quantity. It does not establish convergence of local contact stress or all quantities in the original V08 requirement.

Mesh elements	Axial integration-point stress MPa	Grid reaction N
50	6.38246	77.5
100	6.40682	77.5
200	6.41734	77.5

6. Thermal references and transfer limitations

63 mm square enclosure; all 25 rods at 25 kW/m; 0.5/1/1.5 m lengths; constant 15.5 MPa; steady adiabatic global balance. Only the bowed-rod power was supplied.

Conditional bulk water observations

Retained native CoolProp calls were reused; no local flow simulation is claimed. At the assumed open area 0.00219695 m², total flow is 6.59084 kg/s and mean rod heat flux is 0.837658 MW/m².

Length m	Backend	Outlet degC	Bulk subcooling K
0.5	HEOS	298.889	45.901
0.5	IF97	298.897	45.895

Length m	Backend	Outlet degC	Bulk subcooling K
1.0	HEOS	307.446	37.343
1.0	IF97	307.458	37.333
1.5	HEOS	315.626	29.163
1.5	IF97	315.638	29.154

The HEOS/IF97 comparison uses two formulations within CoolProp, not independent experimental validation. Bulk subcooling does not establish local single-phase behavior, surface temperature, CHF or DNBR. The all-rods power, enclosure and length scenarios are assumptions adopted for this demonstration.

Published thermal analogues

The HTRF source uses a 16-rod experimental bundle, whereas the requested study has 25 rods. The 85% source series is a disclosed proxy for requested 80%. Tests 167 and 168 are distinct contact arrangements. Their exact applicability to this geometry is not established. The author-published transcription is retained at the cited commit; the original experimental report was not independently authenticated.

Spread of selected source rows and declared sensitivity cases; not a confidence interval or demonstrated conservative bound.

The table preserves published reference conditions. The last column divides the reference CHF by the assumed study heat flux solely to illustrate data propagation. **It is not study DNBR and cannot establish a 5% penalty.**

Closure %	Test	P MPa	Inlet degC	G kg/m2s	CHF MW/m2	Index
0	166-9	16.547	295	2759.9	1.1704	1.3972
0	166-8	16.547	291.33	3349.9	1.3786	1.6457
0	166-7	14.479	294.61	3356.7	1.1987	1.4311
50	170-4	16.651	292.83	2713.8	1.1357	1.3557
50	170-5	16.513	293.83	3374.3	1.3249	1.5817
50	170-6	14.479	296.17	3359.4	1.2114	1.4461
80	169-6	16.547	292.33	2991.8	1.1546	1.3783
80	169-8	14.582	293.72	3382.4	1.2019	1.4348
80	169-7	16.582	295.28	3397.4	1.306	1.5591
100	167-5	16.547	291.39	2750.4	0.96215	1.1486
100	167-6	16.547	288	3465.2	1.101	1.3143
100	167-7	14.479	297.61	3378.4	1.1451	1.367
100	168-5	16.582	295.06	2753.1	0.95584	1.1411
100	168-8	14.479	293.11	3383.8	1.2334	1.4725
100	168-6	16.547	293.78	3401.4	1.0915	1.303

Source: HTRF author-published data at the retained commit.

7. End-of-life support estimate

Retained X-750 plate aged 977 K for 24 h; NRU reference around 570–573 K, fluence 6e24 n/m2.

Transferred reference retention 0.50216 gives 2.5108 N from an assumed fresh preload of 5 N. The retained slope sensitivity is an assumed scenario envelope, not a confidence interval.

This retained material/history-specific transfer estimate is reported separately; it is not the 20/50 stiffness ratio and is not included as a preload in the zero-preload incremental beam model.

The source fit is $R(F) = 0.915 \exp(-1e-25 F)$, with F in n/m^2 . Its non-unity intercept is retained; it is not interpreted as instantaneous preload loss. At $6e24 n/m^2$, the retained ratio is 0.50216. The stated +/-25% slope scenario gives a ratio range 0.43222 to 0.58343, corresponding to 2.161 to 2.917 N for the assumed 5 N preload. This range is not a confidence interval. The unity-anchored alternative ratio is 0.54881.

Source: Griffiths and colleagues, 2008, X-750 stress relaxation, retained pages 6 and 8. The NRU flux range is $1.5e17$ to $1.8e17 n/(m^2 s)$, above 1 MeV. A material/history-specific reference transfer is provided; an operating PWR assembly life prediction is not.

8. Requirements disposition

Requirement	Evidence	Disposition
Eight closure/stiffness cases	Exact native case outputs and matching baselines	Demonstrated under the stated reduced model
Grid force	Native effective-spring reaction	Provisional aggregate estimate; individual contacts unresolved
Added cladding bending stress	Paired native axial integration-point stress	Provisional beam estimate; local contact stress unresolved
Material/history-specific EOL force	Documented X-750 reference and stated preload transfer	Unvalidated transferred estimate
Thermal-hydraulic redistribution	Conditional bulk balance and published experimental analogues	Study local flow and temperatures not established
Maximum 5% DNBR penalty	No applicable validated study CHF calculation	Not established

9. Reviews, evidence and limitations

Checkpoint A and the failed pilot assessment are retained in the original run; B/C belong to its linked continuation. This report does not assert public-release approval or physical acceptance. Inputs, native outputs, source conditions, hashes, numerical checks and the process swimlane accompany the report. Changes to those inputs invalidate dependent comparisons and reviews.

No solver, physical correlation, material library or MCP provider was developed or patched for this demonstration.

10. Original verification requirements and current evidence

The original requirements below remain unchanged. Evidence for the reduced demonstration is distinguished from full engineering compliance.

V01 Requirements and units

Original criterion: All supplied quantities and both stiffness states preserved; explicit SI conversion; no silent defaults

Evidence and disposition: Supplied values retained; additional choices explicitly proposed and reviewed. This does not resolve every original physical input.

V02 Case coverage

Original criterion: Unbowed, 50%, 80%, 100% closures for both states, or an explicit accepted nonapplicability rationale

Evidence and disposition: All eight requested closure/stiffness combinations now have native results, including both unbowed baselines.

V03 Independent geometry

Original criterion: OD 9.5 mm, pitch 12.6 mm; target minimum gaps 3.1, 1.55, 0.62, 0 mm measured on exported geometry

Evidence and disposition: Check nodal centerline approach against an undeformed neighbor. This is not independent exported 3D surface-gap measurement for all cases.

V04 Full closure

Original criterion: Real contact topology and contact formulation; no artificial finite flow slit

Evidence and disposition: The 100% case denotes nominal touching; no rod-contact topology or pressure solution.

V05 Linear spring unit case

Original criterion: Incremental force matches declared k times measured relative spring displacement, with preload accounted for separately

Evidence and disposition: Effective-spring force checks passed at all eight cases, with a separately declared zero-load normalization; individual contact forces remain outside scope.

V06 Analytical beam limit

Original criterion: Simple independent straight-beam benchmark matches its exact support/load assumptions

Evidence and disposition: Earlier beam-limit evidence is retained. It does not automatically validate the new pipe-beam case or its physical applicability.

V07 Mechanical equilibrium

Original criterion: Residual vector force and moment each $\leq 1\%$ of the corresponding total applied/reaction scale

Evidence and disposition: Not established. The pilot RF-sum screening failed in all three meshes. The B exception permits demonstration reporting only; full force and moment equilibrium remains unresolved.

V08 Structural refinement

Original criterion: At least three systematically refined discretizations; lateral force and nonsingular section bending stress change $\leq 2\%$ between two finest, with trend inspected

Evidence and disposition: Three meshes completed. The 100-to-200 axial integration-point stress change is 0.164%, below 2% and 5%. This is partial evidence for the original requirement, not contact-stress convergence.

V09 Contact consistency

Original criterion: No tensile normal contact force in unilateral contact; action/reaction balance; penetration within an explicitly chosen geometric tolerance

Evidence and disposition: No unilateral rod or individual spring/dimple contact model is executed.

V10 Stress interpretation

Original criterion: Separate added bending stress, pressure/membrane stress if modeled, local contact stress and total equivalent stress

Evidence and disposition: Report actual global axial integration-point stresses and matching-baseline subtraction. Local contact and pressure stresses are unavailable; no allowable/failure verdict.

V11 Relaxation implementation

Original criterion: Zero exposure retains post-immediate-relaxation force; nonnegative parameters give nonnegative, monotone retention; units invariant

Evidence and disposition: Reuse the documented reference arithmetic and sensitivity evidence. Do not substitute the stiffness ratio for relaxation.

V12 Relaxation applicability

Original criterion: Spring alloy, condition, temperature, exposure, preload and constraint history agree with accepted model or explicit uncertainty treatment

Evidence and disposition: Documented X-750 reference material/history; transfer to the study is explicit and unvalidated.

V13 Hydraulic conservation

Original criterion: Integrated steady mass imbalance $\leq 0.1\%$ and energy imbalance $\leq 1\%$, using defined inlet/outlet/source terms

Evidence and disposition: Reuse the conditional bulk energy calculation and native property observations. No spatial inlet/outlet flux integration or local redistribution result.

V14 Thermal-hydraulic refinement

Original criterion: At least three spatial resolutions and a time-step study where relevant; key local temperatures, pressure drop and minimum DNBR change $\leq 2\%$ between finest runs

Evidence and disposition: No spatial thermal-hydraulic refinement or time-step convergence campaign for this study.

V15 Experimental benchmark

Original criterion: Compare measured and calculated DNB power/location and other relevant measurements using source-specific uncertainties

Evidence and disposition: Retain published source conditions and measured CHF. No matched study-solver prediction is validated against those measurements.

V16 CHF/DNBR implementation

Original criterion: Correct table units, interpolation at nodes and interior points, explicit out-of-range handling; q'' and CHF evaluated on compatible physical locations

Evidence and disposition: No qualified study CHF calculation. A reference CHF/study-heat-flux scaling index is not DNBR.

V17 Bow-method applicability

Original criterion: Demonstrate relevance of benchmark to bow, grid, flow regime, contact and local heat transfer; quantify model discrepancy

Evidence and disposition: Source geometry, grids, bow and operating-condition differences remain explicit; applicability is not demonstrated.

V18 DNBR penalty assessment

Original criterion: Matched reference and bowed minima use the same accepted domain and operating conditions; assess supplied 5% limit with uncertainty

Evidence and disposition: The original 5% DNBR penalty requirement stays visible without an invented compliance value.

V19 Evidence and reviews

Original criterion: Every result uses accepted upstream revisions; changed dependencies invalidate affected results/reviews

Evidence and disposition: Exact saved inputs, native attempts and review subjects retained. A was explicitly approved for both the original basis and corrected encoding. B approved the disclosed force-check exception. C remains pending for these final report bytes.

V20 Report and public package

Original criterion: Editable/PDF/web report share accepted study revision; public bytes match checkpoint C manifest; no restricted material or execution authority

Evidence and disposition: Editable, PDF and HTML report files are produced from the same source. Final public-content approval and hosting remain pending; their verification is recorded separately.

11. Reproducibility and evidence identities

- Pilot run: f54961438ce44220b2645b32b9951b8e
- Linked continuation: eb65943f1886437c86705b421853f776
- Failed assessment: assessment-2e5afb6903de40a38e35fd242e1fcb6e
- Approved-scope assessment: assessment-15152e60a34a4575a356d2b8e3a7cfca

The accompanying evidence preserves source conditions, exact decks, native observations and hashes. This revision changes presentation and evidence explanation only; it reruns no analysis. Public-content approval is pending.