Non-Linear Mechanical Modeling in Materials Subject to Property Changes due to Neutron Irradiation

NRC 2019 Materials Workshop

Paul Kirchman
Principal Structural Analyst

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Background

- Nuclear reactor reflector blocks undergo significant changes in their physical properties due to radiation damage over time.
- The conditions that induce material property changes in NBG (Nuclear Block Graphite) are dependent on the cumulative radiation exposure and the temperature at which the exposure occurs
- The temperature and fluence vary throughout any given component leading to complex stress/strain fields
- Radiation induced changes in component size are significant and need to be accounted for in tolerance stacking for mechanical analysis and bypass flows for CFD analysis

Assumptions

- Uniform radiation induced dimensional change creates strain without stress in the manner of thermal expansion. Stress in this scenario results from non-linear gradients of temperature, dimension change, and external forces.
- The stress relief effect of mechanical creep is critical to the calculation of stresses to be evaluated for failure probability
- The blocks in a typical design are otherwise lightly stressed due to their own weight, pressure due to fuel pebbles and seismic loading.

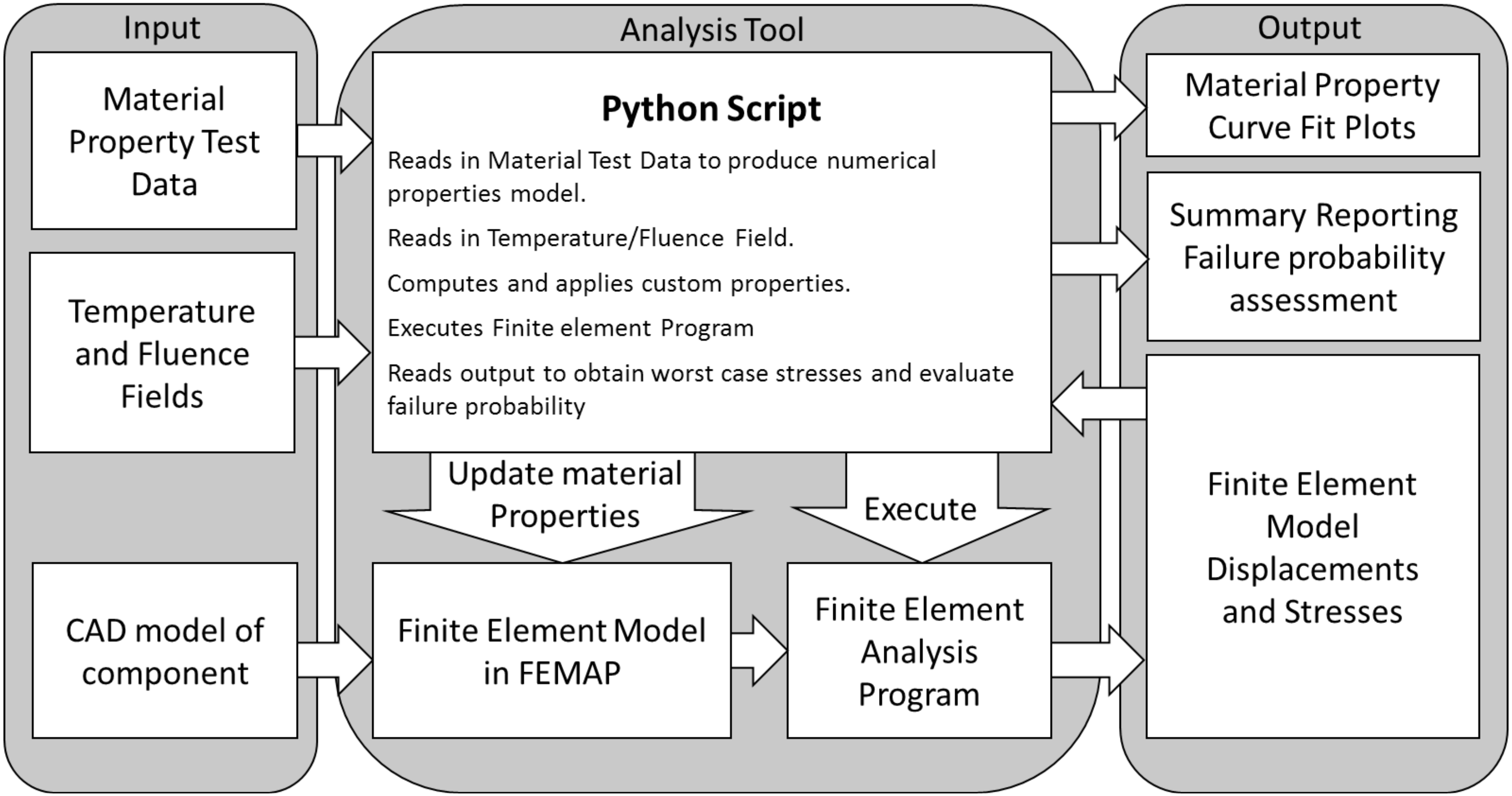
Assumptions (continued)

- The temperature and rate of radiation dosing remains constant at each location allowing for a linear solution at each cumulative dose level as the properties undergo non-linear variation.
- The available property data represents cumulative change so that time integration is entrained in the input curves.
- The reactor is anticipated to operate in the nominal predicted condition for the majority of it's active life with only transitory variations making it possible to sum full power equivalent time for analytical evaluation.

Approach

- From material test data, create a continuous numerical model of the changing properties using standard math libraries.
- Interface numerical model to any FEM solver through object oriented programming interface, in this case FEMAP.
  - Calculate unique material properties for each analysis element based on input temperature and fluence fields
  - Apply new properties to elements and execute FEM solver
- Automate this process for use on multiple load cases, candidate materials and model geometries.
- Include iterative capability to step through sequential cases making a time history – note that maximum stresses occur during maximum gradient conditions which are not necessarily at end of life

Numerical Properties Model Application Flow



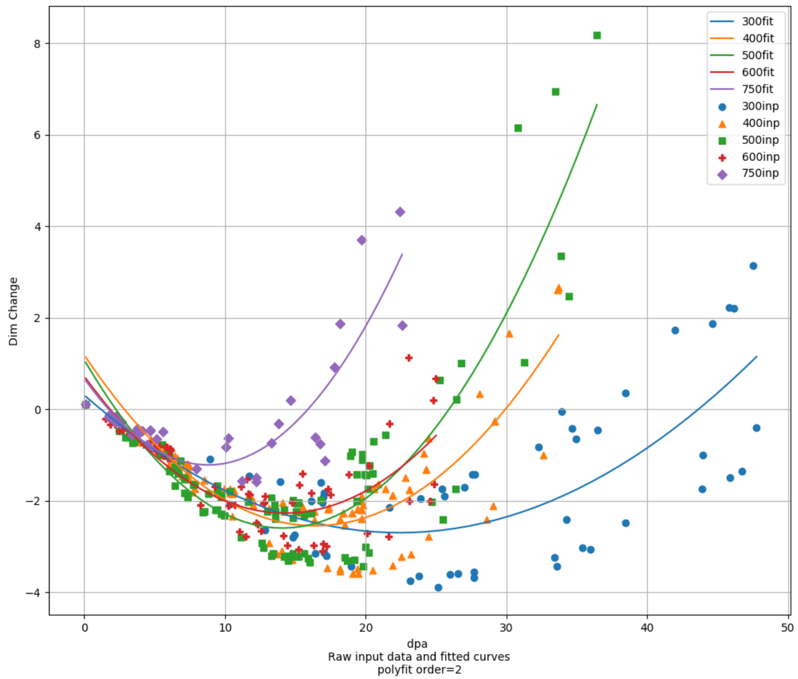
Material Property Raw Input

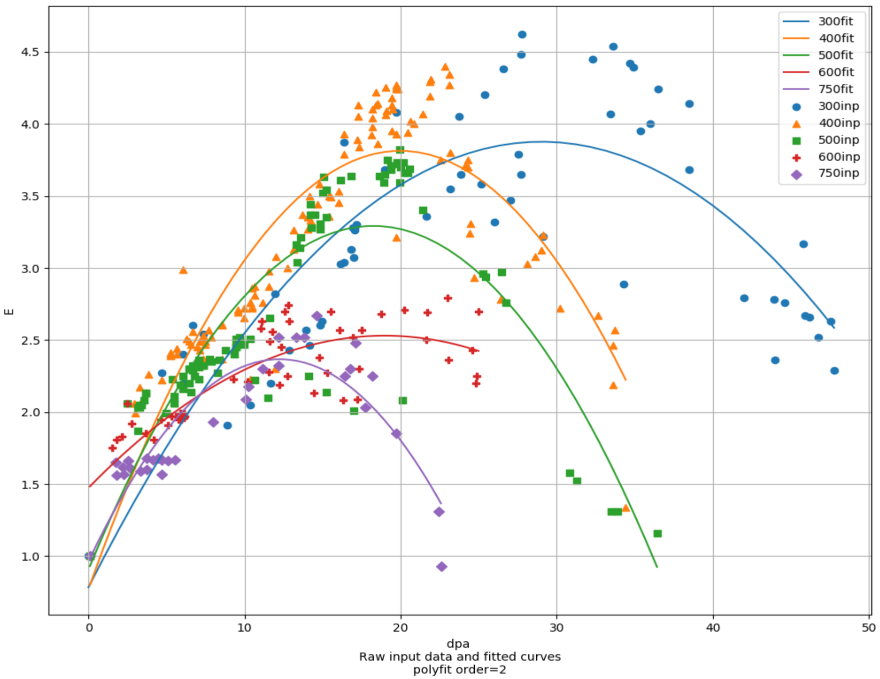
Material Property test data input as xy pairs with no restrictions on order or number of pairs

Params	Values	300C	Dim wg	400C	Dim wg	500C	Dim wg	750C	Dim wg	300C	Dim ag	400C	Dim ag	500C	Dim ag	750C	Dim ag
# properties	6	0	0.01	0	0.01	0.01	0	0.01	0	0.01	0	0.01	0	0.01	0	0.01	0
# temps	4	8.9	-1.1	6.5	-1	3.7	-0.6	1.8	-0.2	10.4	-2.1	6.1	-1.2	2.5	-0.5	1.8	-0.1
# extrap	4	17	-1.9	14.1	-2.1	13.5	-2.1	2.2	-0.3	19	-3.4	13.1	-2.9	3.5	-0.7	2.3	-0.2
iterations	1	25.4	-1.8	19.7	-1.9	20	-1.4	2.5	-0.3	26.6	-3.6	18.2	-3.5	13.4	-3.2	2.7	-0.3
dpa Begin	60	33.9	-0.1	20.9	-1.6	25.3	0.6	3.4	-0.6	34.3	-2.4	19.4	-3.5	19.8	-3.4	3.8	-0.4
dpa End	61	16.8	-1.6	30.2	1.7	36.4	8.2	3.8	-0.6	17.1	-3.1	29	-2.1	25.5	-2.4	4.1	-0.5
Prop 1	Dim wg	27.6	-1.4	7.4	-1.2	3.3	-0.5	4.5	-0.8	27.7	-3.6	7.5	-1.5	3.4	-0.7	4.7	-0.5
Prop 1 p	Dim ag	38.5	0.4	15.5	-2.1	7.9	-1.6	4.7	-0.9	38.5	-2.5	14.7	-3.2	11.2	-2.8	4.7	-0.5
Prop 2	E wg	47.5	3.1	22.8	-1.5	15.2	-2	8	-1.3	47.8	-0.4	21.9	-3.4	18.5	-3.2	5.1	-0.7
Prop 2 p	E ag	17.1	-1.8	24.1	-1	10.4	-1.8	11.2	-1.6	17.2	-3.2	23.2	-3.2	24.7	-2	5.6	-0.5
Prop 3	CTE wg	27.8	-1.4	33.7	2.7	16.8	-2	12.2	-1.5	27.7	-3.7	32.6	-1	34.4	2.5	10.1	-0.8
Prop 3 p	CTE ag	13.9	-1.6	3.3	-0.5	3.7	-0.6	12.2	-1.6	14.8	-2.8	3.9	-0.7	8.5	-2.2	10.3	-0.6
Order P1	3	23.9	-2	6.3	-1.2	13	-2.2	16.4	-0.6	25.1	-3.9	7.7	-1.8	16	-3.4	13.3	-0.7
Order P1p	3	34.7	-0.4	12	-2.1	20.5	-1.4	16.8	-0.8	35.4	-3	13.7	-3.2	3.7	-0.7	13.8	-0.3
Order P2	3	45.8	2.2	13.2	-2.2	26.8	1	17.1	-1.1	45.9	-1.5	14.8	-3.3	3.4	-0.7	14.6	0.2
Order P2p	3	16.9	-2	21.4	-1.7	3.3	-0.6	22.6	1.8	16.4	-3.2	22.5	-3.2	12.7	-3	17.8	0.9
Order P3	5	27	-1.7	10.4	-1.7	3.2	-0.6	22.4	4.3	26	-3.6	10.5	-2.3	20.2	-3.1	18.2	1.9
Order P3p	5	36.5	-0.5	19.7	-2	5.4	-1			36	-3.1	19.5	-3.6	26.4	-1.8	19.7	3.7
Ezero	9.00E+10	46.2	2.2	20.6	-1.7	11.6	-2			46.7	-1.4	20.5	-3.5	3	-0.6		
CTEzero	4.43E-06	11.7	-1.5	28.1	0.3	6.7	-1.4			12.9	-2.6	28.6	-2.4	3	-0.6		
Temp 1	300	21.7	-2.2	7.4	-1.2	13.6	-2.4			23.2	-3.8	7.9	-1.7	10	-2.3		
Temp 2	400	32.3	-0.8	16.4	-2.2	26.4	0.2			33.4	-3.3	17.2	-3.5	15.9	-3.3		
Temp 3	500	42	1.7	17.4	-2.2	6.7	-1.4			43.9	-1	18.1	-3.5	6	-1.4		
Temp 4	751	16.1	-2	24.5	-0.6	13.6	-2.2			15	-2.8	24.4	-2.8	12.6	-2.9		
ExTemp1	300	25.6	-1.9	6.6	-1.1	9.7	-1.9			23.8	-3.6	6.9	-1.5	7.4	-1.9		
ExTemp2	400	34.9	-0.7	14.2	-2.2	15.6	-2.3			33.6	-3.4	14	-3.1	14.5	-3.2		
ExTemp3	500	44.6	1.9	19.8	-2.1	20.2	-1.7			43.9	-1.8	19.1	-3.6	7.4	-1.9		
ExTemp4	750			5.3	-0.9	9.5	-1.8					5.8	-1.2	14.5	-3.3		
				10.6	-1.8	14.8	-2.4					11.8	-2.5	9.7	-2.3		
				17.3	-2.2	19.4	-2					18.7	-3.3	15.6	-3.2		
				5.7	-0.9	9.7	-1.9					6.2	-1.3	20.5	-0.7		
				11.6	-1.9	16.1	-2.3					12.7	-2.8	9.5	-2.2		
				18.4	-2.3	7.7	-1.7					19.7	-3.6	14.8	-3.2		

Material Property Curve Fit

Data points fitted to polynomial curves and plotted as a diagnostic





Scripts Developed in Python

- Object oriented, powerful, compact, and simple coding.
  - Analysis speed bound by program interface
- Open source with straightforward syntax and extensive specialty libraries.
- Naturally interfaces with an object oriented FEM pre and post processing toolkit like FEMAP.
- Has libraries available with the numerical analysis capability of MATLAB
- Provides a single language for:
  - the development of the numerical model
  - Application to FEM
  - Post processing
  - Results evaluation and report generation.

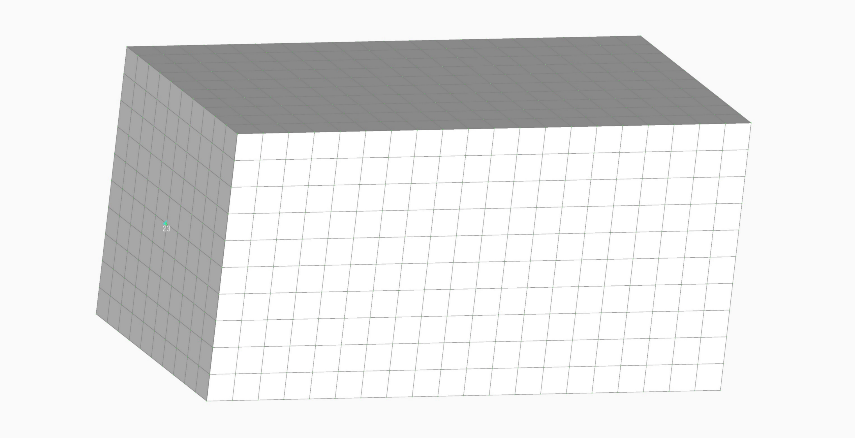
FEMAP Interface

- Object oriented programming interface with access to every aspect of FEM model creation, load application, solver execution, and results evaluation.
- Accepts geometry from any CAD program through STEP files.
- Solver independent since it maintains FEM models in a generic object space.
- Creates input files compatible with dozens of commercial FEM solvers.
- Extensive post-processing capabilities once FEM results are imported into the FEMAP database.
- Results are accessible by the Python script making automated failure probability reporting possible.

Simplified Test Model

This allows both a fast turnaround for example runs as well as checks against textbook cases.

- A ten by ten by 20 cm model supported kinematically along the 20 cm axis passed checks for no stresses generated by a uniform free expansion as well as expansion with a linear gradient.
- Free expansion displacements of a uniformly applied dimensional change are also zero
- Free expansion of a linear expansion gradient result in zero stresses in this simplified case
- Stresses from a high thermal gradient (shock) match results from Roark's "Formulas for Stress and Strain"

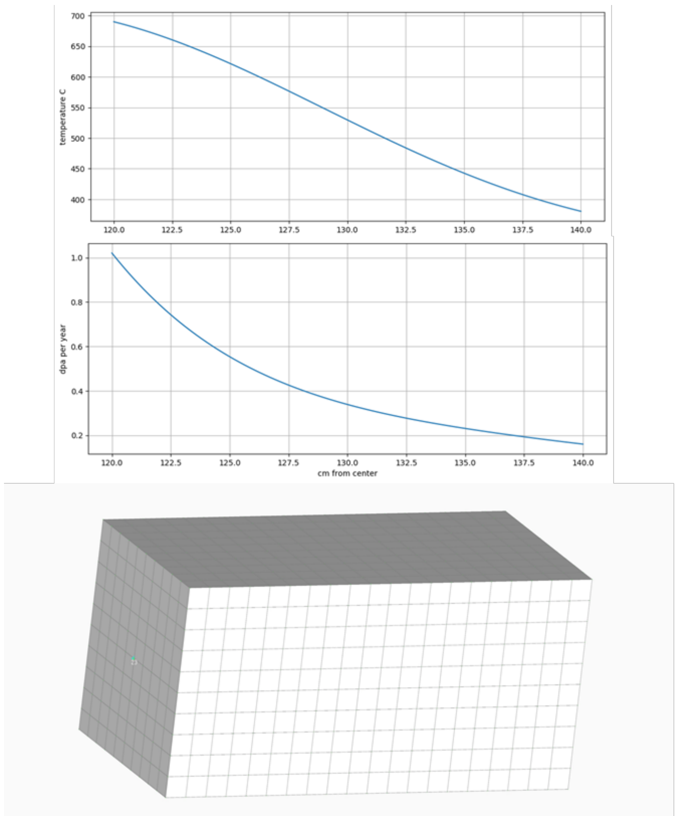


Load Application

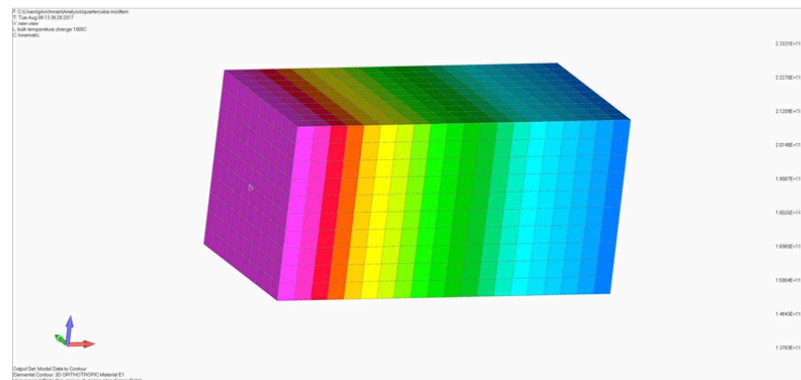
- Temperature and radiation dose loads are presently accepted in table form in cylindrical coordinates centered along the axis of the reactor vessel.
- These loads have rotational symmetry and reduce to a function of the radial distance from the center and the vertical station.
- Input values for the region being evaluated are fitted to a polynomial and applied by location to the model

Calculation and Application

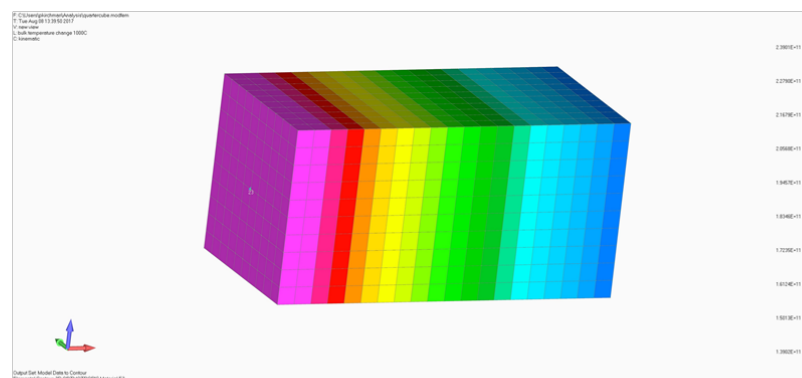
Material properties are adjusted based on conditions unique to the location of each element.



Against Grain Young's Modulus

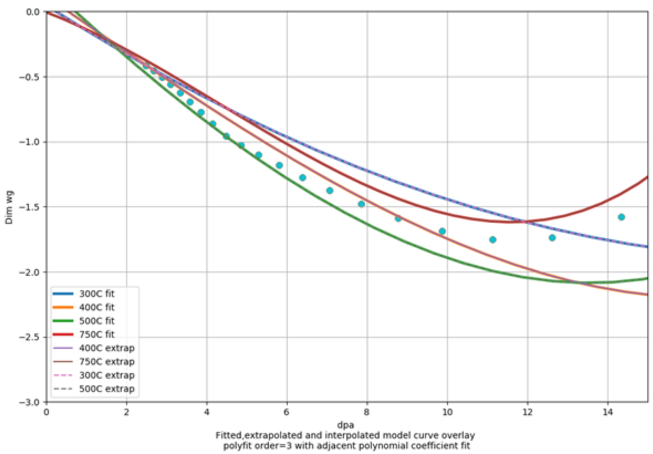


With Grain Young's Modulus

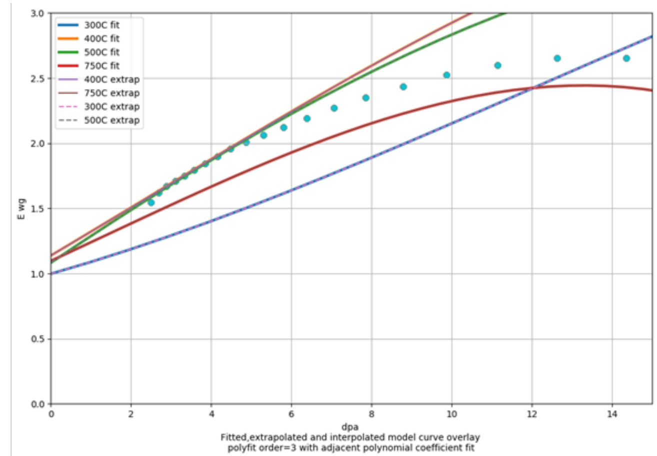


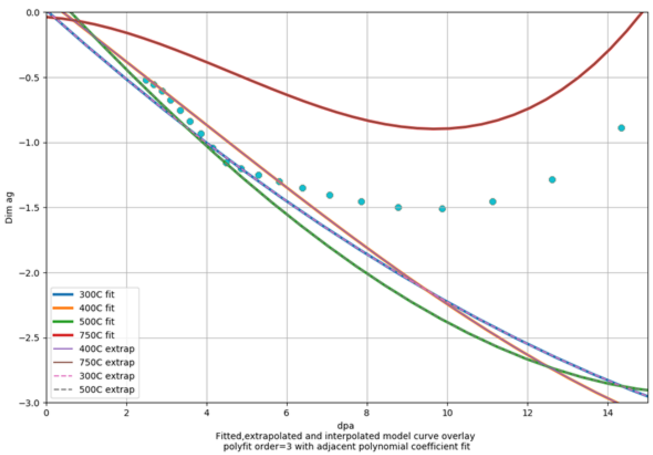
Calculation of Intermediate Property Values

The dots overlaid on the property model curves represent individually computed solutions based on input conditions. Values to the far right represent the core facing side grading to the outward facing side on the left.

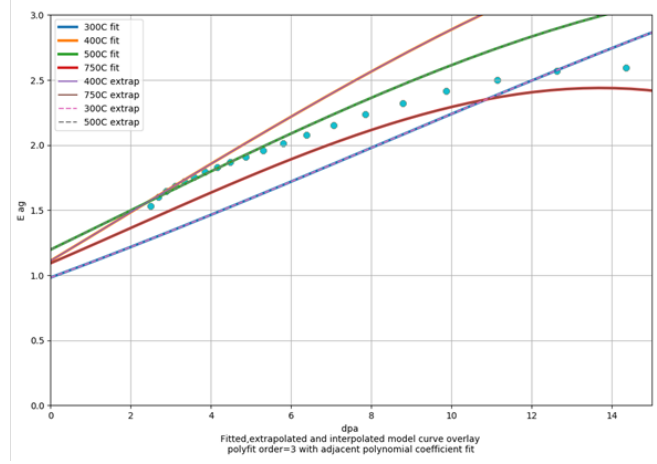


With Grain



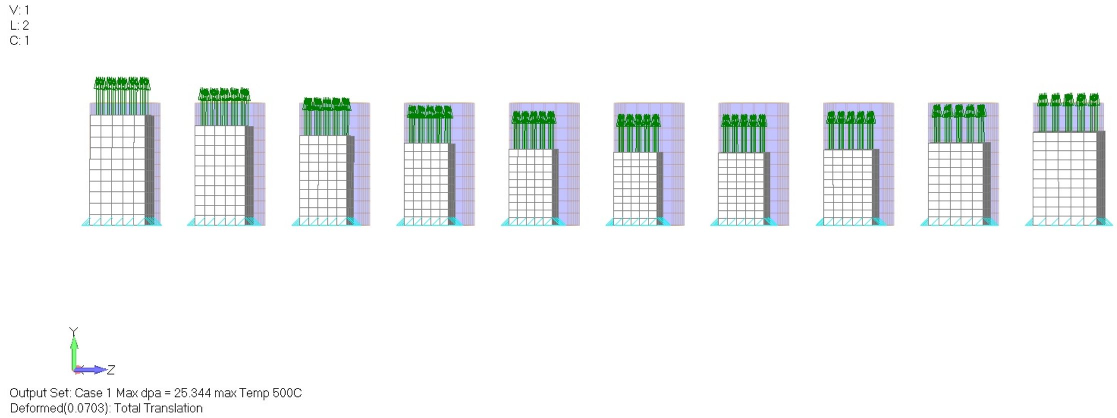


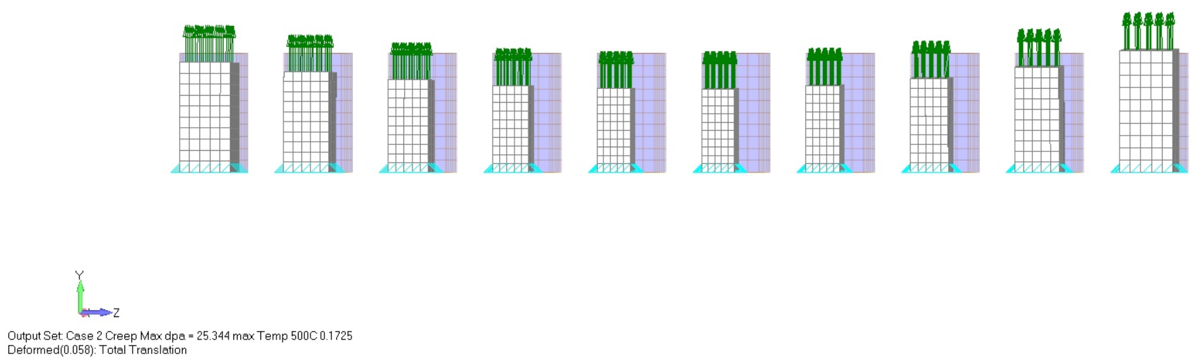
Against Grain



Verification of creep model

Coupon from creep testing described in Reference 2, Section 6





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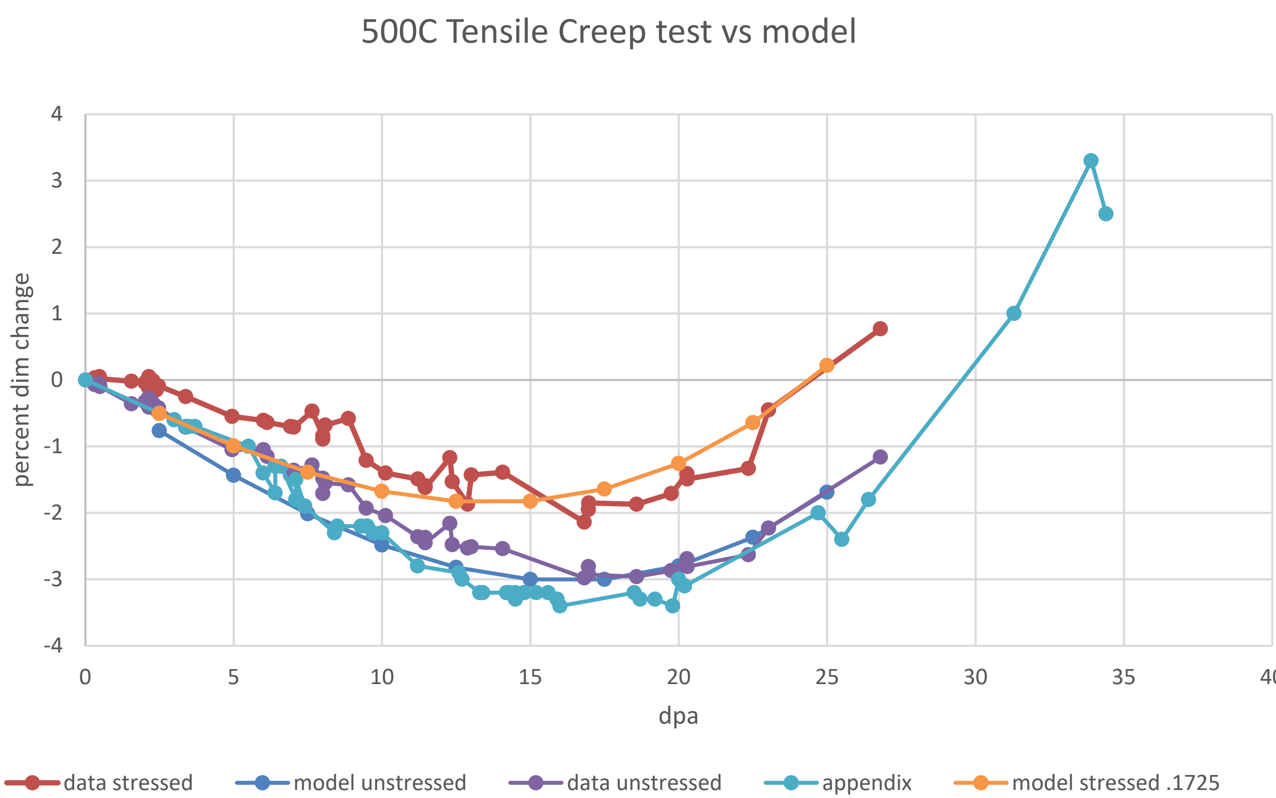
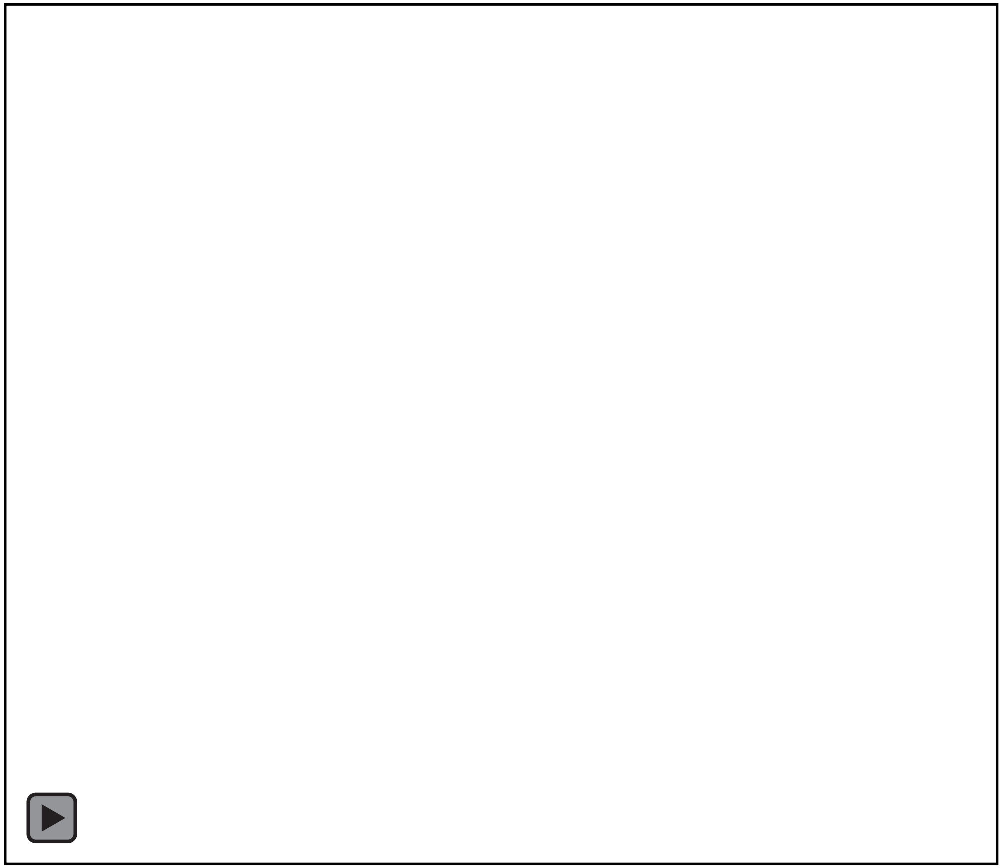


Test Case FEM Results

Progressive material change as radiation dose increases at approximately one year per frame. Displacements exaggerated to highlight dimensional change over time and show turnaround.

Block Interaction

Block interaction is complex and requires non-linear contact effects



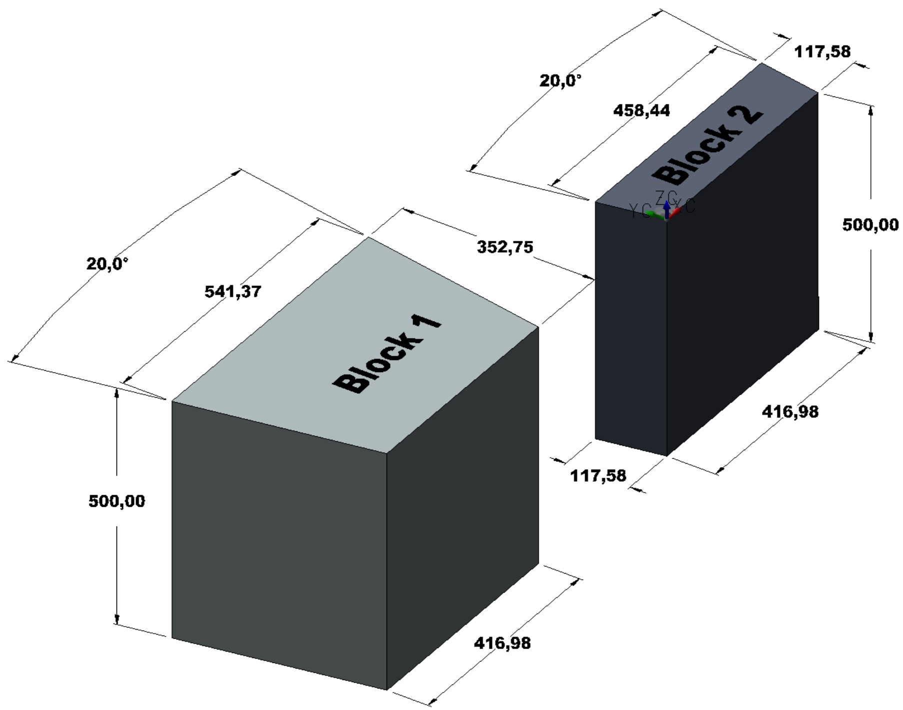
Reference Blocks

Generic Reference Blocks for Independent Review

- A set of generic graphite blocks using ATR2-E properties was generated and solved for displacements and stresses using notional HTGR fluence and temperature loading fields.
- To be exchanged with an external entity for validation and documented in Reference 3

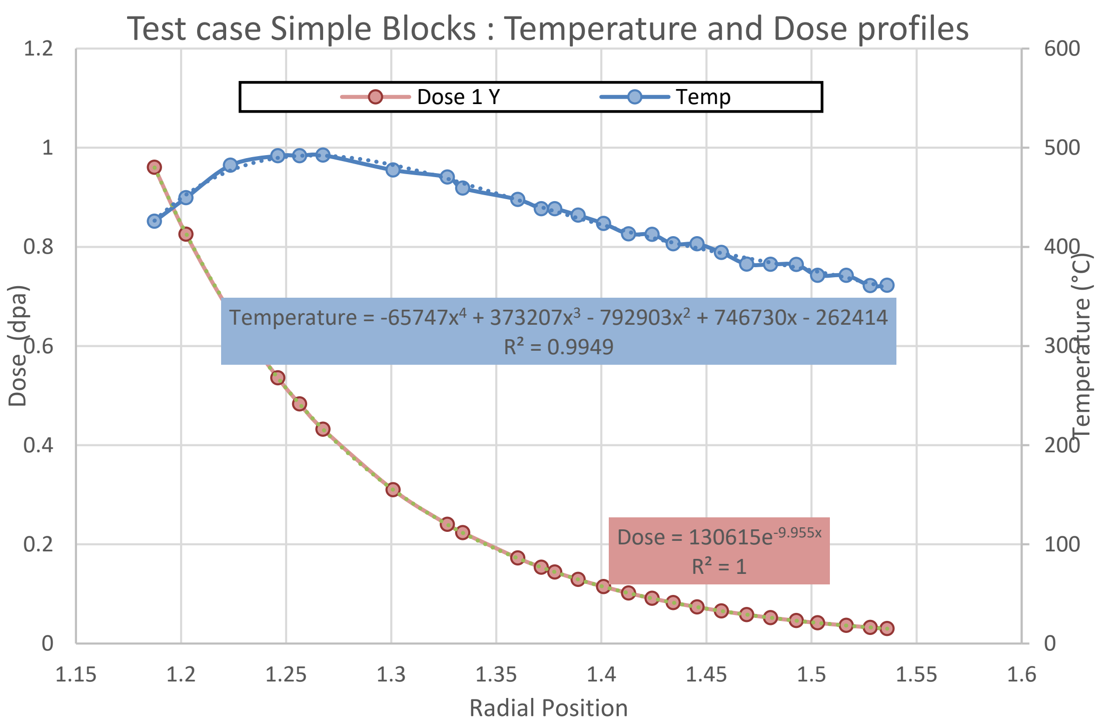
Reference Blocks

Generic Reference Blocks for Independent Review



Reference Blocks

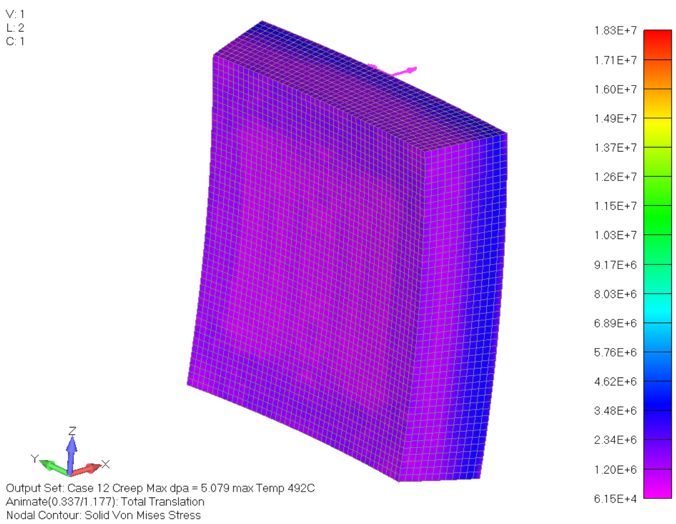
Example Temperature and Fluence

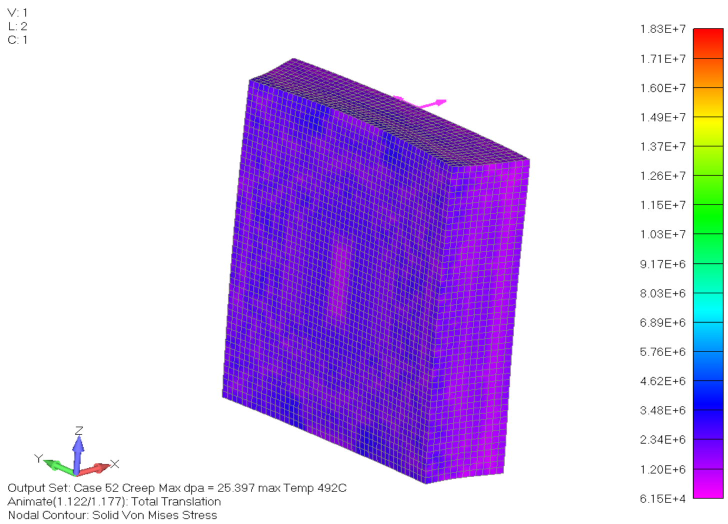


Nuclear Energy. Reimagined.

Reference Blocks

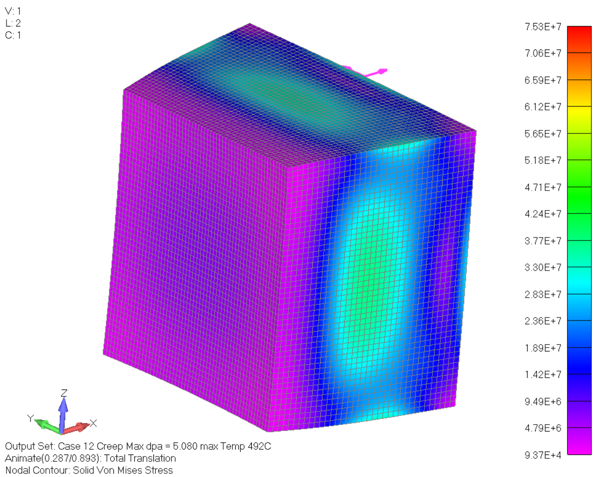
Example Results

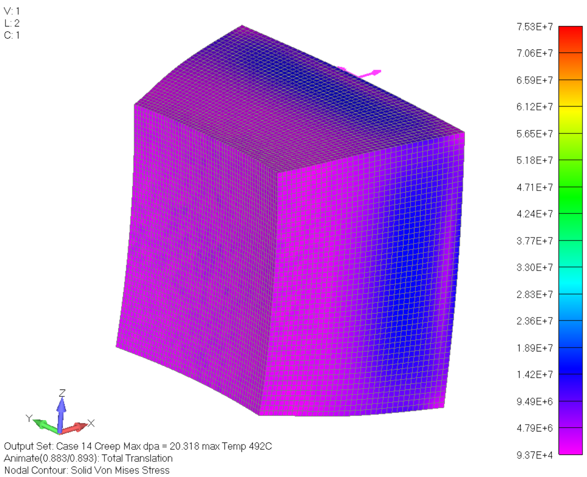




Reference Blocks

Example Results





References

- Reference 1 – “Properties of ATR-2E Graphite and Changes due to Fast Neutron Irradiation” Gerd Haag, Berichte des Forschungszentrums Jülich ; 4183, ISSN 0944-2952, Institut für Sicherheitsforschung und Reaktortechnik Jül-4183
- Reference 2 “Reactor System Coupon Model Reference Analysis Report” X-Energy XE01-TS3-Sw-D 000105 Jun 2018
- Reference 3 “Graphite Reference Block Analysis Benchmark Report” X-Energy XE01-N-R-Z-D 000110 Aug 2018

End of Presentation

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