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TRIGA Type U-ZrH Cladding Steady State Mechanical Limitations

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In operation for 30+ years providing a wide range of radiation environments in pulse or steady-state operating modes.

Examples of experiments and research programs:

- Weapon component vulnerability
- Electronic component hardening
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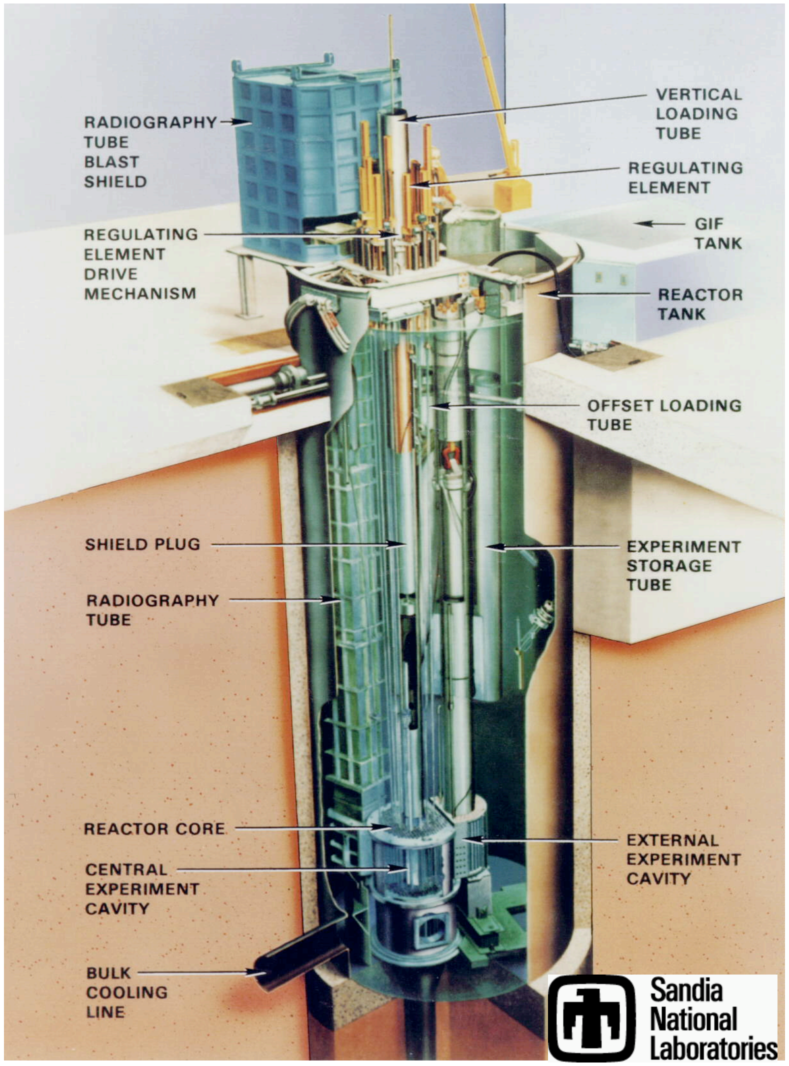
- Space reactor fuels development
- Medical isotope research and production
- In-pile experiments to examine commercial reactor fuel accidents (fuel swelling, fuel failure and extreme accident conditions)
- Pulse reactor kinetics
- Research reactor heat transfer and fluid flow
- Neutron radiography of reactor fuels, classified materials and explosive devices, and education service and training programs.



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REACTOR CONFIGURATION

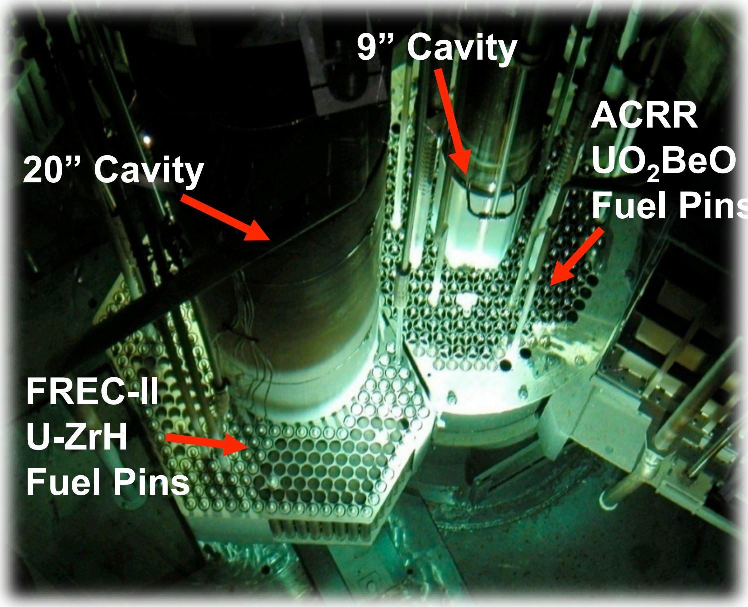
Annular Core Research Reactor (ACRR)

- UO_2BeO fuel elements surrounding a central dry irradiation cavity (9” diameter)

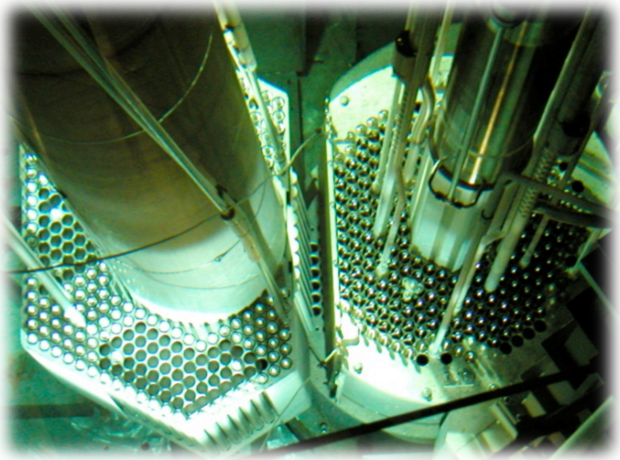
FREC-II Core

- Fuel Ringed External Cavity V-II, a 20” dry cavity adjacent to the ACRR, partially surrounded by **U-ZrH TRIGA** fuel elements
- The FREC-II is a subcritical neutron multiplier that is neutronically driven by the ACRR core
- Master/slave relationship between the ACRR and FREC-II results in significantly less (~1/3) power levels in the FREC-II as compared to the ACRR

COUPLED CONFIGURATION



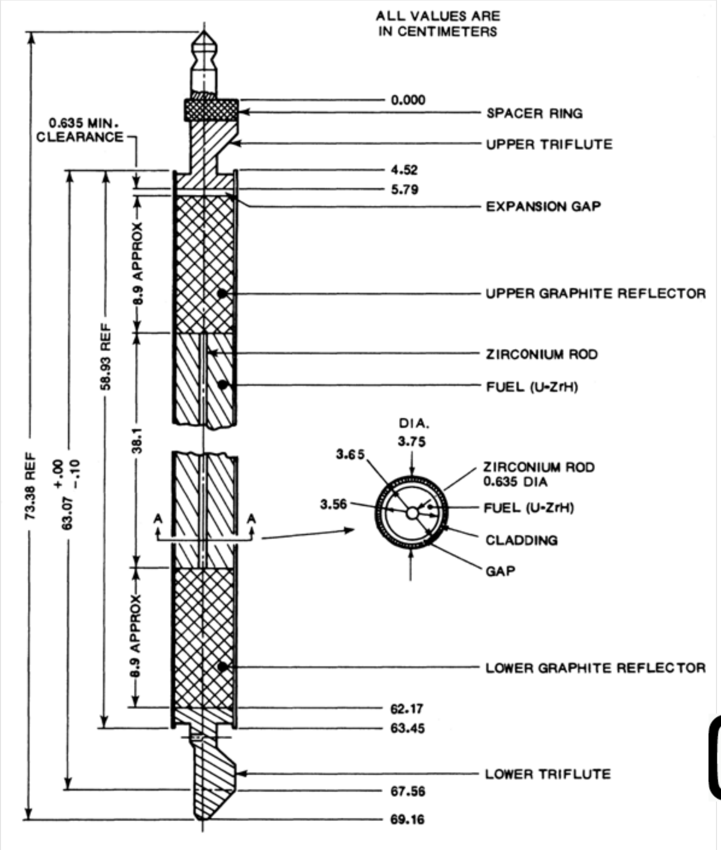
NORMALLY UNCOUPLED



FREC-II FUEL ELEMENT

U-ZrH TRIGA Fuel

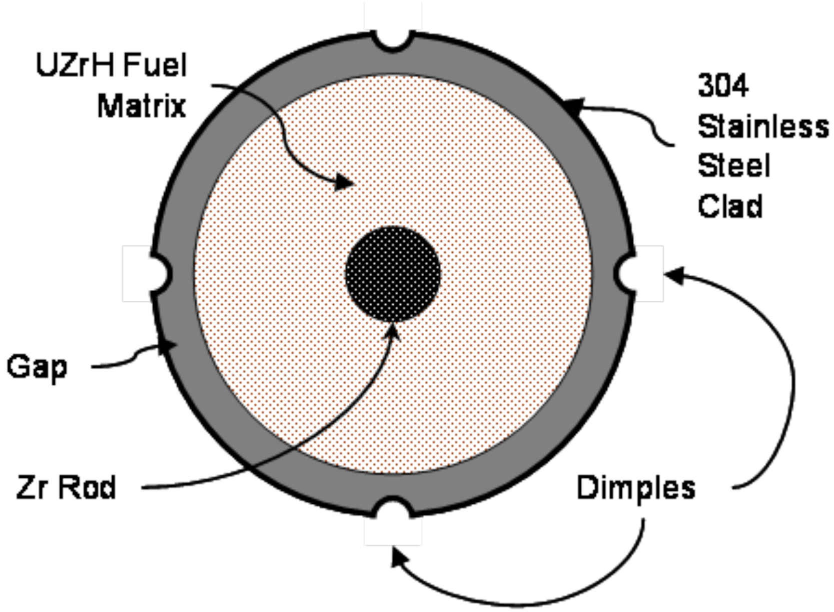
- Traditional TRIGA type fuel uses a combined fuel/moderator matrix of Uranium and Zirconium Hydride and Stainless Steel 304 cladding
- This fuel was designed in the 1960s by General Atomics (GA), who were/are designers and suppliers of TRIGA reactors



FREC-II FUEL DIMPLES

<u>High Power Pulse Design Features</u>

- Dimples were designed into the clad to assure proper alignment (centering) of the fuel pellets after a high power pulse
- These dimples are necessary because of the rapid energy deposition during a pulse, when mechanical and thermal shock waves travel through the fuel pellets



ANALYTICAL PURPOSE

- Create an FEA model that shows the mechanical interaction between the fuel and the cladding dimples
  - Thermohydraulics and other phenomena are not considered
- Develop a conservative analytical model that supports the facilities Documented Safety Analysis (DSA)
  - 34 kW element power
  - 1000ºC average fuel temperature
- Determine if mechanical failure of cladding precedes the design limit established by the safety analysis

MODELING CONSIDERATIONS

Cladding mechanical stresses are due to the following loading mechanisms

1. Mechanical contact
2. Gas pressure buildup

Gas pressure increases due to the following phenomena

1. Hydrogen evolution from the U-ZrH fuel
2. Reduction in free volume
3. Increased gas temperature

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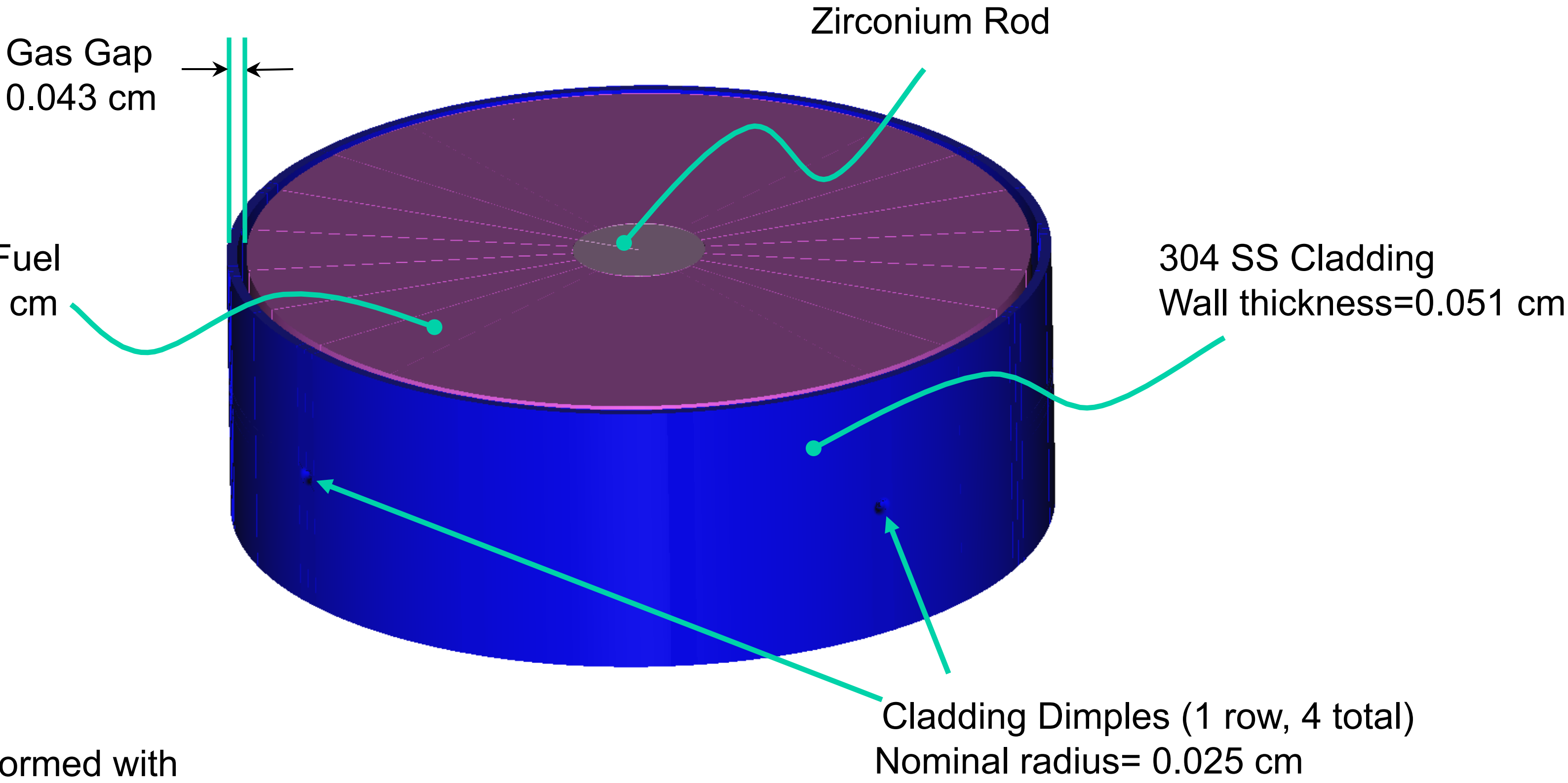
MODEL GEOMETRY



FEA performed with
ABAQUS V 6.7-1

ASSUMPTIONS / GIVENS

1. The U-ZrH fuel can be operated up to steady-state ***design*** limits.
2. U-ZrH fuel temperature is uniform at 1000ºC
3. The clad temperature is uniform at 154ºC, and heat flux remains constant.
4. Total Gas Pressure is calculated to be 2.44×10^6 Pa at the 1000ºC limit and according to:

$$P_T = P_B + P_{Heq}$$

$$\log P_{Heq} = K_1 + (K_2 \times 10^3)/T$$

Where:
$K_1 = -3.8415 + 38.6433\,X - 34.2639\,X^2 + 9.2821\,X^3$,
$K_2 = -31.2982 + 23.5741\,X - 6.0280\,X^2$,
P = pressure in atmospheres (atm),
T = temperature (ºK),
X = hydrogen to zirconium atom ratio (1.6).

Physical properties of U-ZrH fuel

PROPERTY	VALUE
Thermal expansion coefficient (α_l)	4.52E-6 + 19.25E-9 T/(ºC)
Density (ρ)	5940 kg/m^3
Elastic modulus (E)	6.1×10^{10} Pa
Poisson's ratio (ν)	0.32

Physical properties of SS 304 cladding

PROPERTY	VALUE
Density (ρ)	8000 kg/m^3
Elastic modulus (E)	1.9×10^{11} Pa
Poisson's ratio (ν)	0.3

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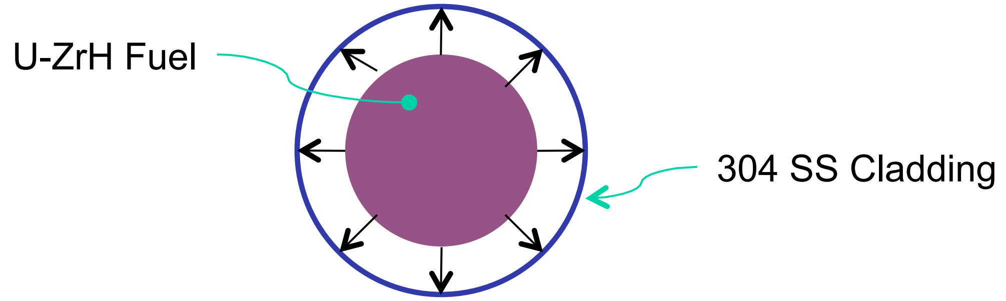
LOADS AND BOUNDARY CONDITIONS

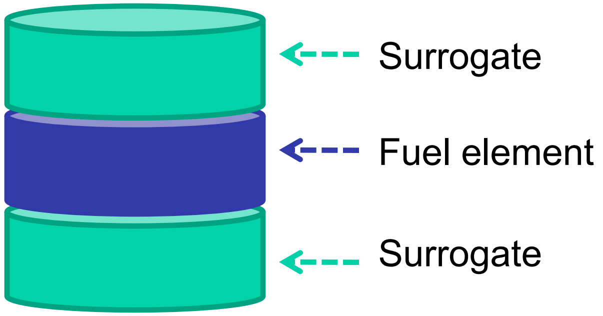
- **Pressure Load:** Static outward loading on cladding uses ideal gas law for the backfill/fission product gases (for given temperature and free volume) summed with the H_2 equilibrium pressure.

Top View

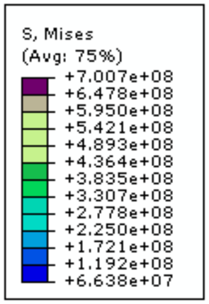


- **Thermal Loads:** From ambient temperature of 20ºC, fuel temperature increases to 1000ºC, and cladding temperature increases to 154ºC.
- **Physical Constraint:** Axial expansion is bounded by surrogate material. No restraint on radial expansion (i.e. vacuum conditions).

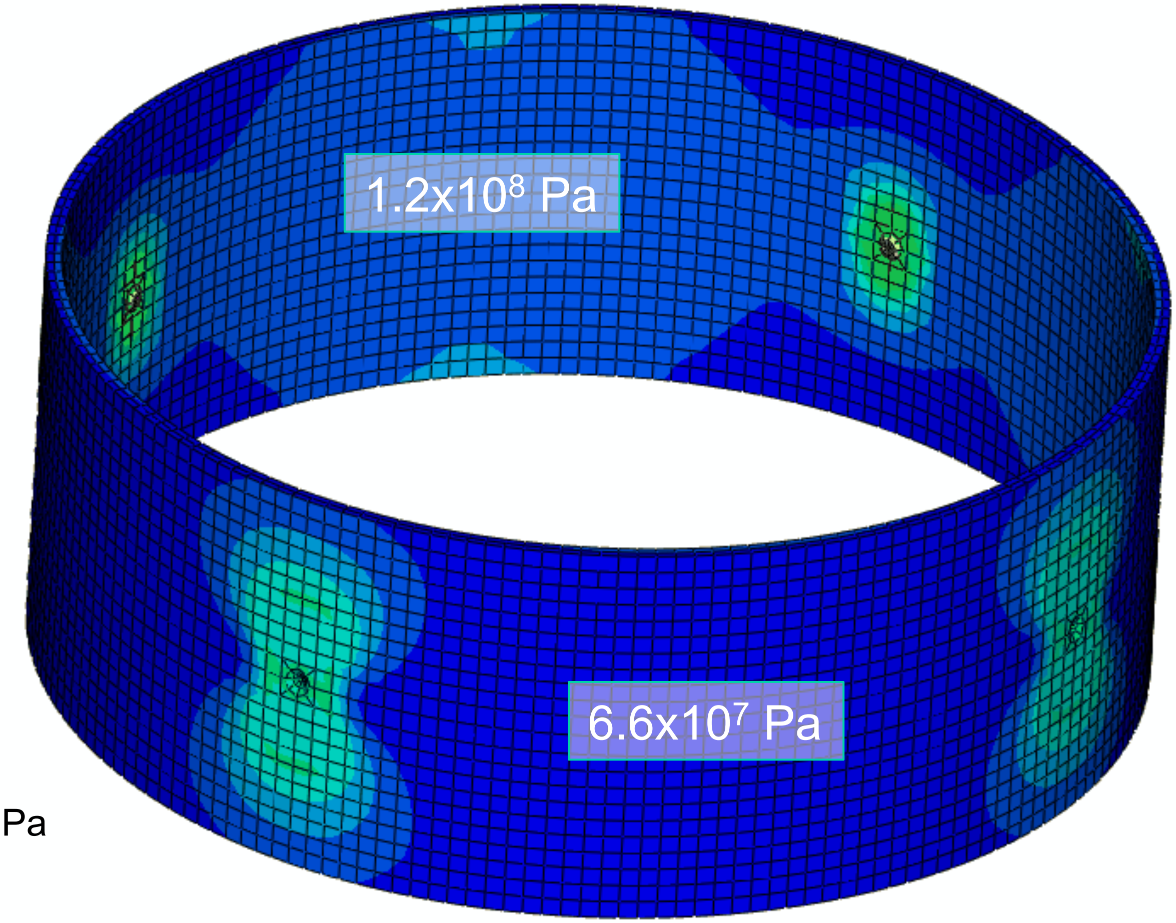
Side View



STRUCTURAL ANALYSIS RESULTS



Mises Stress on cladding material for 1000ºC U-ZrH fuel temperature



$1.2\text{x}10^8$ Pa

$6.6\text{x}10^7$ Pa

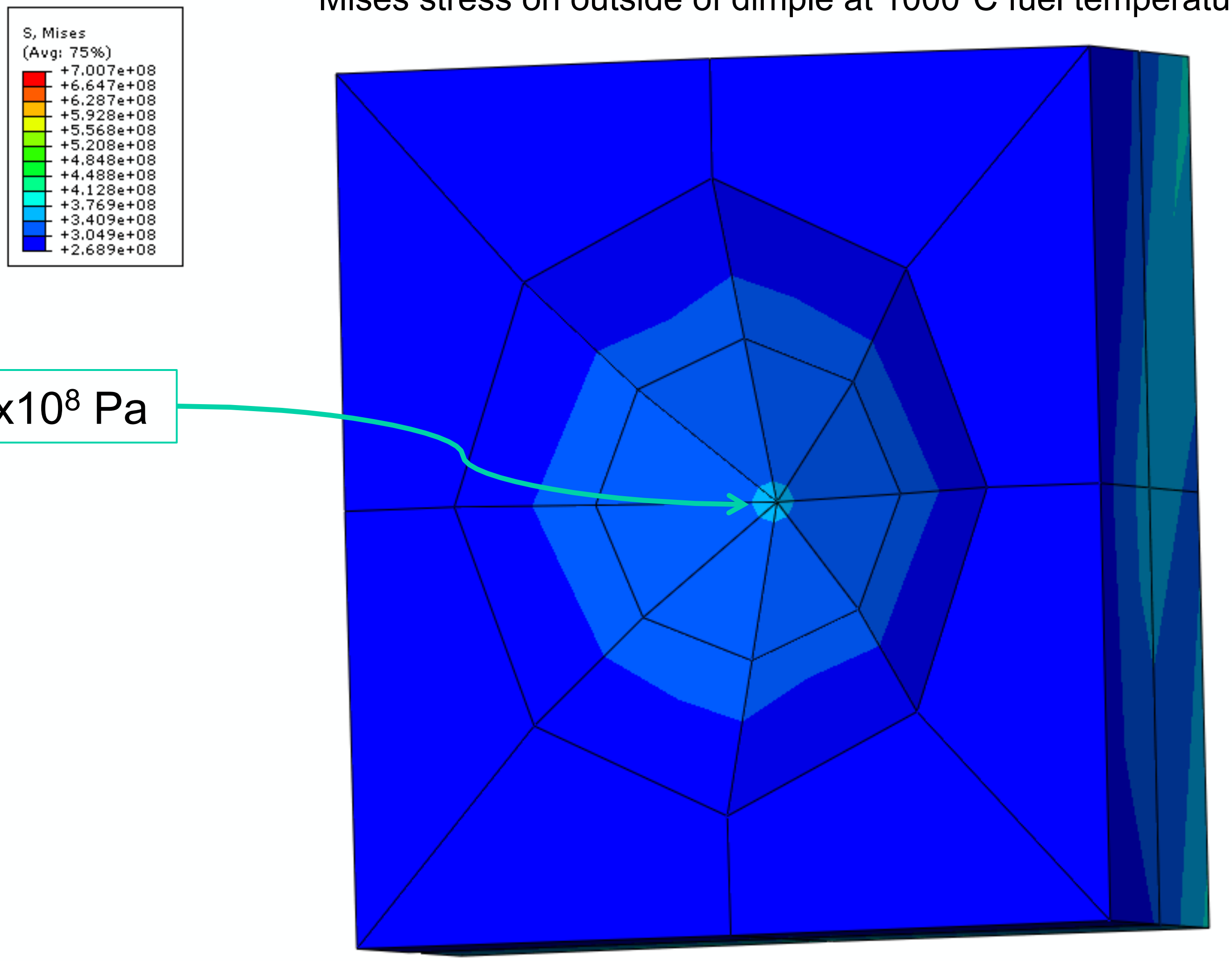
SS 304 Cladding

Yield strength = $2.0\text{x}10^8$ Pa

UTS = $5.1\text{x}10^8$ Pa

STRUCTURAL ANALYSIS RESULTS

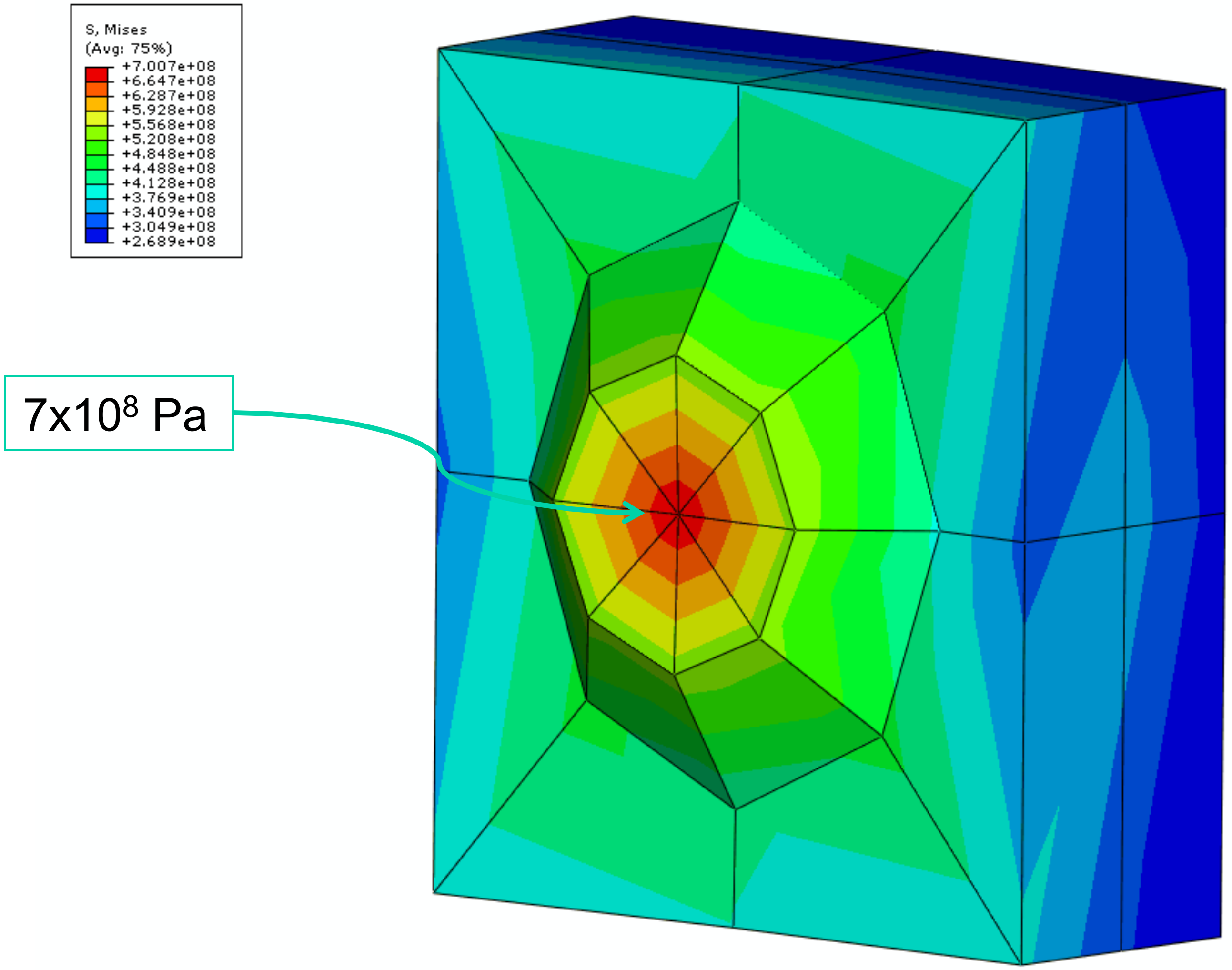
Mises stress on outside of dimple at 1000ºC fuel temperature



3.4×10^8 Pa

STRUCTURAL ANALYSIS RESULTS

Mises stress on inside of dimple at 1000ºC fuel temperature

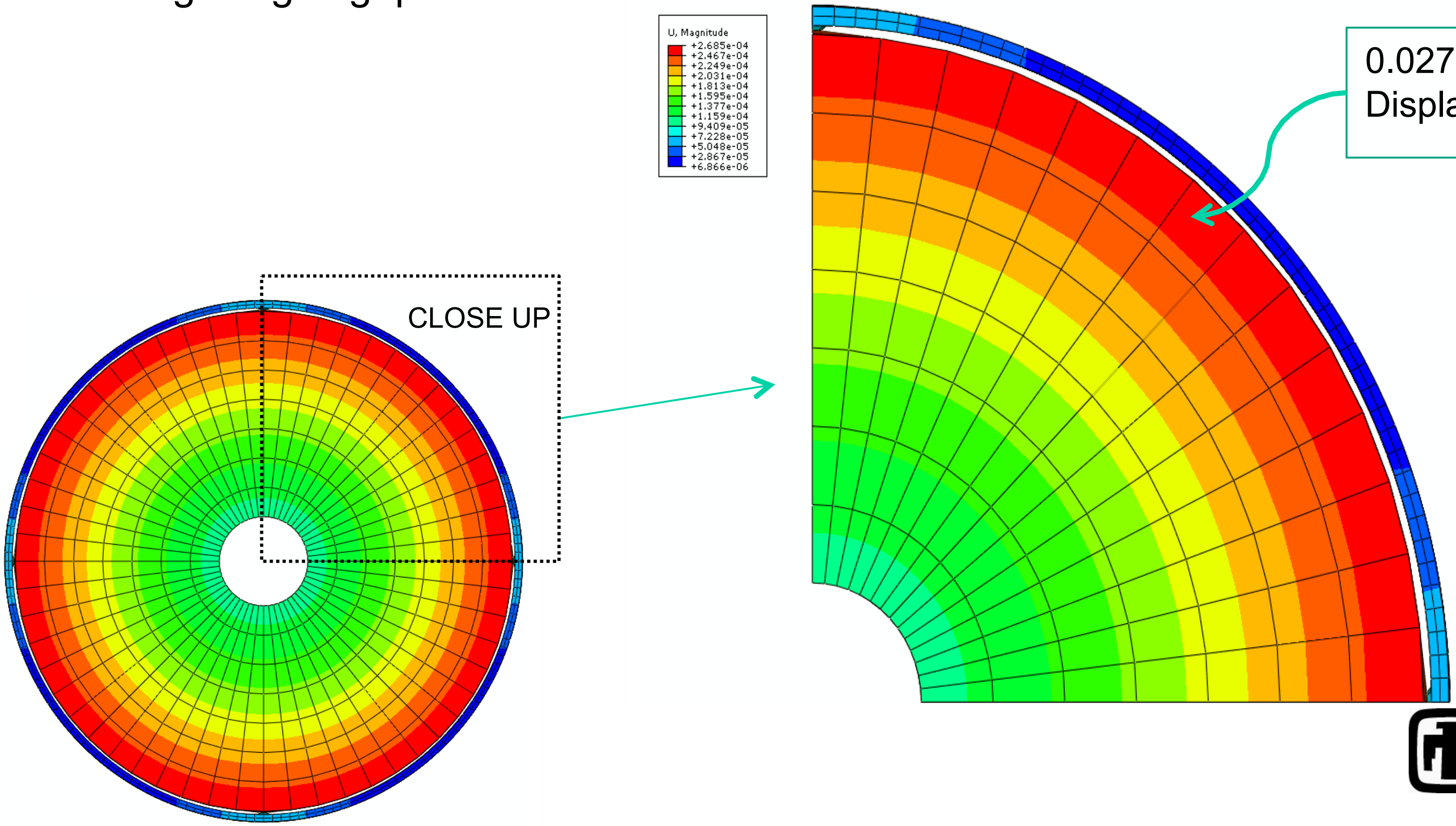


$7x10^8$ Pa

STRUCTURAL ANALYSIS RESULTS

- The fuel only contacts the cladding at the dimple locations at 1000ºC fuel temperature.

- The original gas gap was 0.043 cm



0.027 cm Displacement

CONCLUSIONS

- Mechanical interaction between fuel and cladding is the dominating effect.
  - Evident from the localized stress concentrated on the dimples.
- Permanent deformation of cladding dimples without failure.
  - Verification by radiography.
- Bulk cladding deformation is elastic and fully recovered upon removal of loads.
  - U-ZrH fuel elements have passed all physical inspections.

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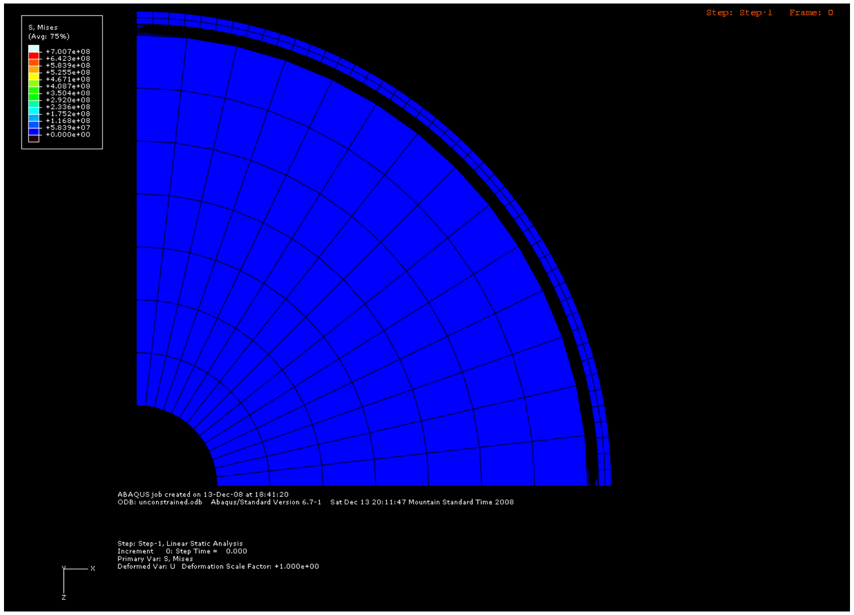
STRUCTURAL ANALYSIS RESULTS



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ABAQUS job created on 13-Dec-08 at 18:41:20
ODB: unconstrained.odb    Abaqus/Standard Version 6.7-1    Sat Dec 13 20:11:47 Mountain Standard Time 2008

Step: Step-1, Linear Static Analysis
Increment     0: Step Time =    0.000
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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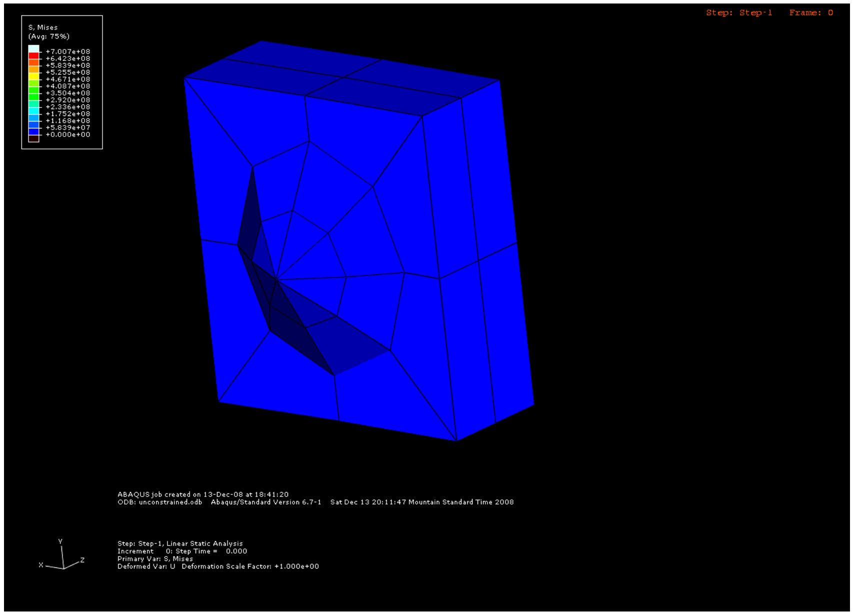

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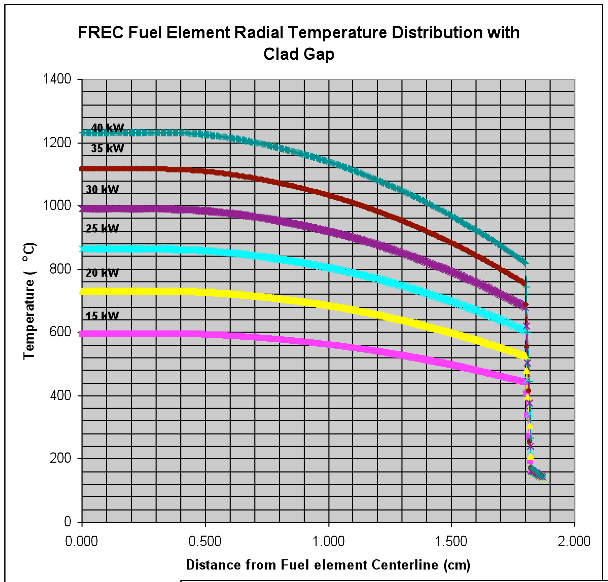
HOOP STRESS CONSIDERATION

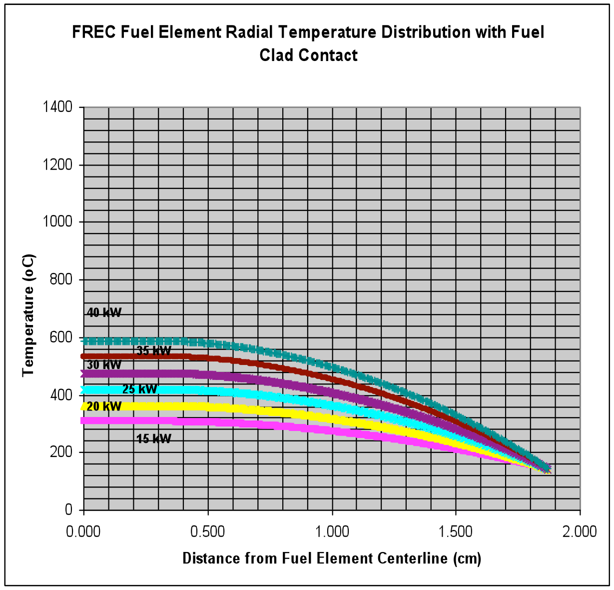
- Hoop Stress: $$\sigma = P\left(\frac{R}{t}\right)$$

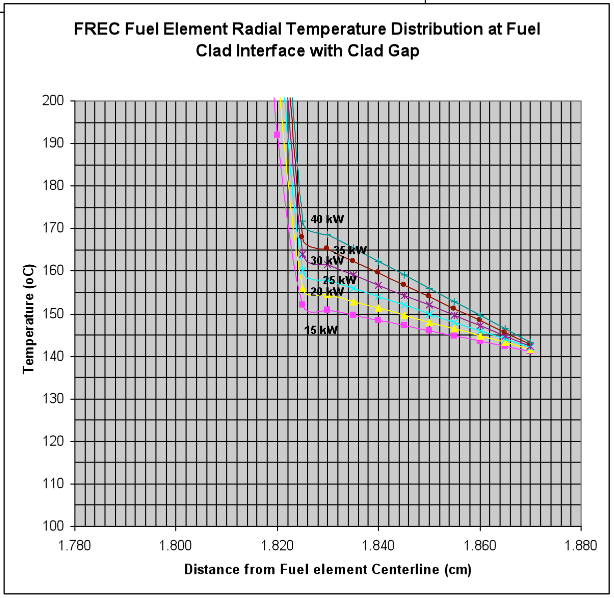
σ=stress
P=pressure
R=pressure vessel radius
t=wall thickness

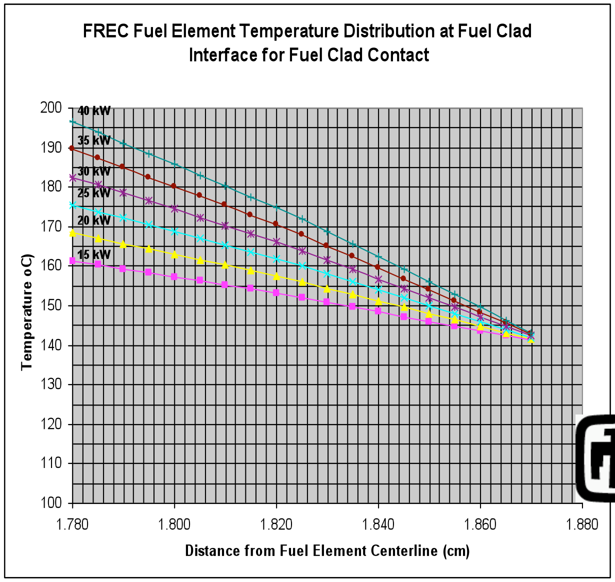
- At 154ºC: the pressure to exceed hoop stress at yield strength is 6.5×10^6 Pa, and the pressure to exceed at tensile strength is 14×10^6 Pa. Remember the calculated internal pressure is 2.44×10^6 Pa.

FUEL/CLADDING CONTACT


FREC Fuel Element Radial Temperature Distribution with Clad Gap


FREC Fuel Element Radial Temperature Distribution with Fuel Clad Contact


FREC Fuel Element Radial Temperature Distribution at Fuel Clad Interface with Clad Gap


FREC Fuel Element Temperature Distribution at Fuel Clad Interface for Fuel Clad Contact

SS 304 CLADDING PROPERTY