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Title: Neutron Imaging at LANSCE: Characterizing Nuclear Materials for Next Generation Reactor Designs

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Neutron Imaging at LANSCE: Characterizing Nuclear Materials for Next Generation Reactor Designs

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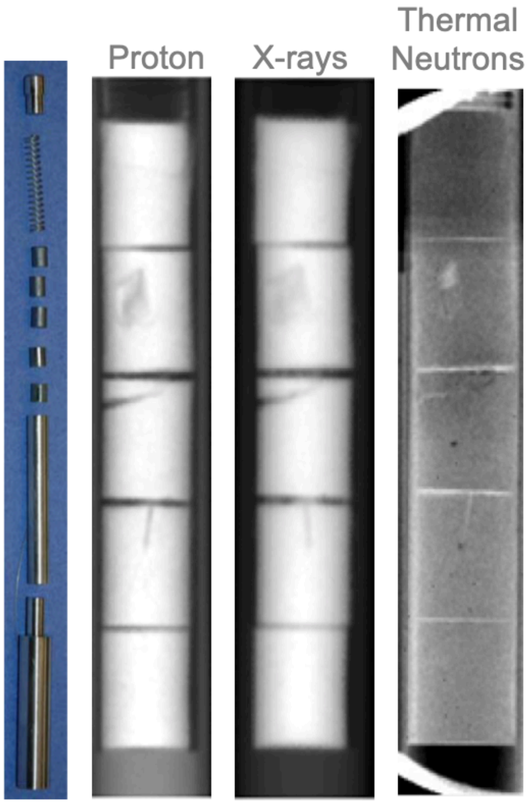
Neutron Radiography as a NDTE Technique

Similar to other radiography probes

A Set of UO_2 Fuel Pellets



Interactions with electron shells

Attenuation Coefficients (cm^{-1}) for 150 keV X-rays

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H																	He
0.02																	0.02
Li	Be											B	C	N	O	F	Ne
0.06	0.22											0.28	0.27	0.11	0.16	0.14	0.17
Na	Mg											Al	Si	P	S	Cl	Ar
0.13	0.24											0.38	0.33	0.25	0.30	0.23	0.20
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
0.14	0.26	0.48	0.73	1.04	1.29	1.32	1.57	1.78	1.96	1.97	1.64	1.42	1.33	1.50	1.23	0.90	0.73
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
0.47	0.86	1.61	2.47	3.43	4.29	5.06	5.71	6.08	6.13	5.67	4.84	4.31	3.98	4.28	4.06	3.45	2.53
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
1.42	2.73	5.04	19.70	25.47	30.49	34.47	37.92	39.01	38.61	35.94	25.88	23.23	22.81	20.28	20.22		9.77
Fr	Ra	Ac	Rf	Ha													
	11.80	24.47															
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
*Lanthanides	5.79	6.23	6.46	7.33	7.68	5.66	8.69	9.46	10.17	10.91	11.70	12.49	9.32	14.07			
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr			
**Actinides	28.95	39.65	49.08														

Relatively simplistic relationship between attenuation and material density

Interactions with nucleus

Attenuation Coefficients (cm^{-1}) for thermal neutrons (0.025 eV)

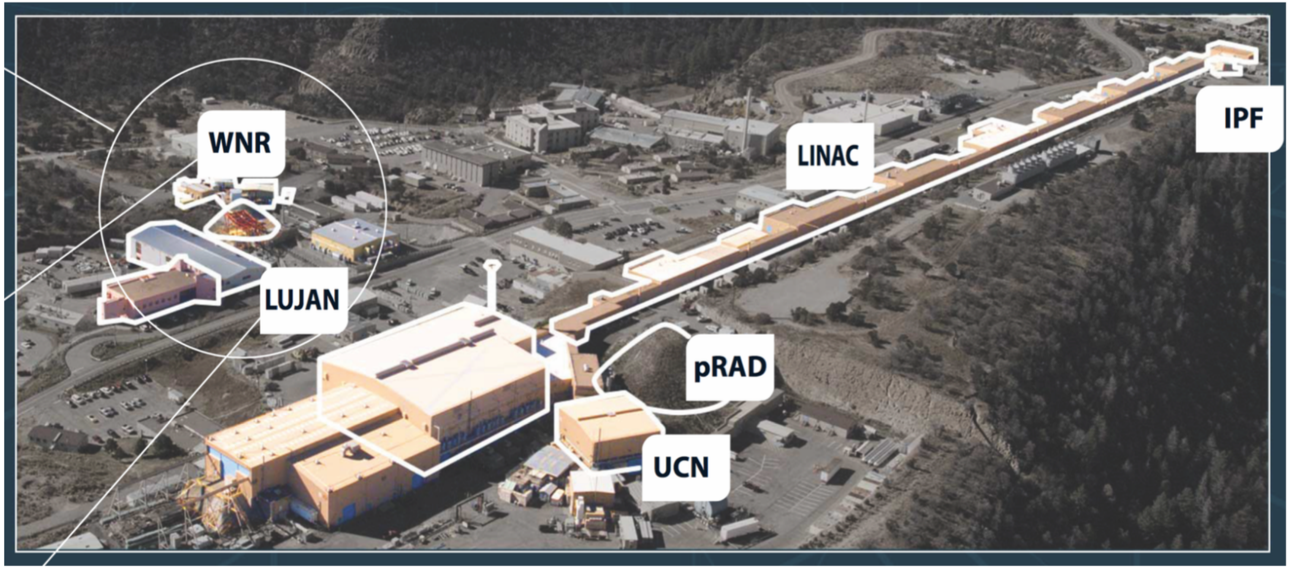
1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H																	He
3.44																	0.02
Li	Be											B	C	N	O	F	Ne
3.30	0.79											101.60	0.56	0.43	0.17	0.20	0.10
Na	Mg											Al	Si	P	S	Cl	Ar
0.09	0.15											0.10	0.11	0.12	0.06	1.33	0.03
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
0.06	0.08	2.00	0.60	0.72	0.54	1.21	1.19	3.92	2.05	1.07	0.35	0.49	0.47	0.67	0.73	0.24	0.61
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
0.08	0.14	0.27	0.29	0.40	0.52	1.76	0.58	10.88	0.78	4.04	115.11	7.58	0.21	0.30	0.25	0.23	0.43
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
0.29	0.07	0.52	4.99	1.49	1.47	6.85	2.24	30.46	1.46	6.23	16.21	0.47	0.38	0.27			
Fr	Ra	Ac	Rf	Ha													
	0.34																
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
*Lanthanides	0.14	0.41	1.87	5.72	171.47	94.58	1479.04	0.93	32.42	2.25	5.48	3.53	1.40	2.75			
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr			
**Actinides	0.59	8.46	0.82	9.80	50.20	2.86											

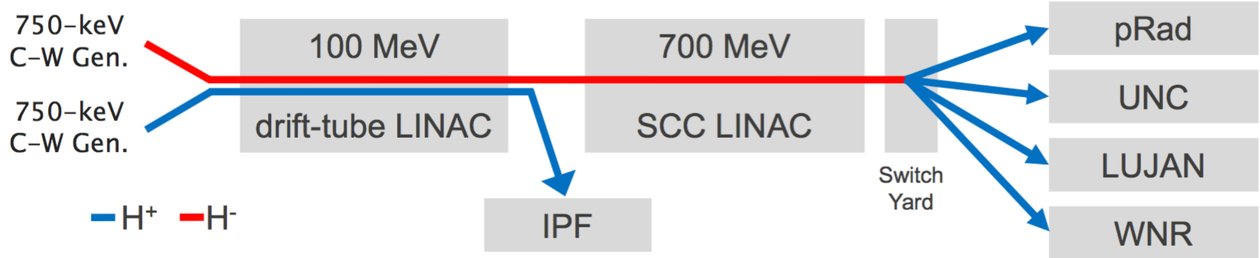
Complex relationship between attenuation and material compositi

Morris *et. al.* Review of Scientific Instruments 84 (2013)
Tremsin *et. al.* Neutron News 24 (2013)

https://www.psi.ch/en/niag/comparison-to-x-ray

Los Alamos Neutron Science Center (LANSCE)





Neutron Imaging Flight Paths at Lujan

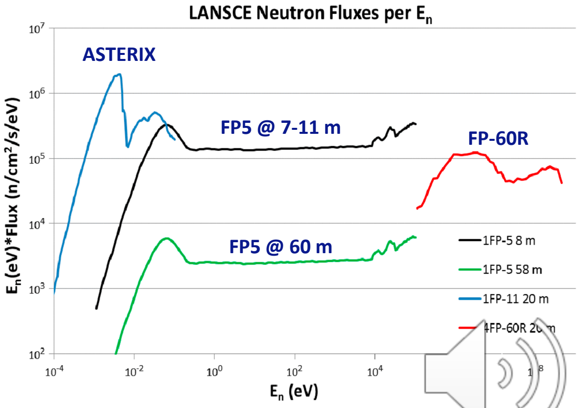
Flight Path 5:
- Thermal and epi-thermal neutron radiography and energy resolved neutron imaging.

Flight Path 11 (ASTERIX):
- Cold neutron imaging and neutron grating interferometry.

Neutron Imaging Flight Paths at WNR

Flight Path 60-R:
- Fast neutron radiography.

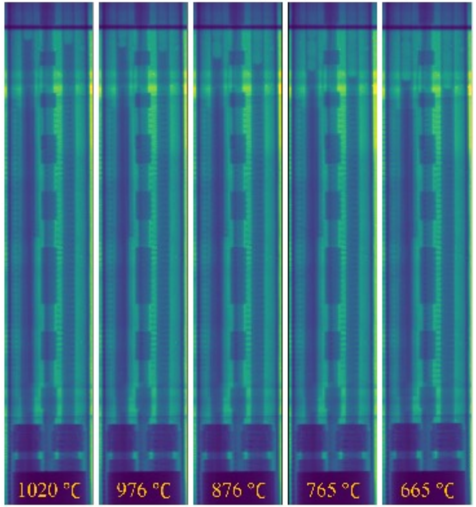
See talk by Danielle Schaper for more!



Some Neutron Imaging Projects in Nuclear Energy

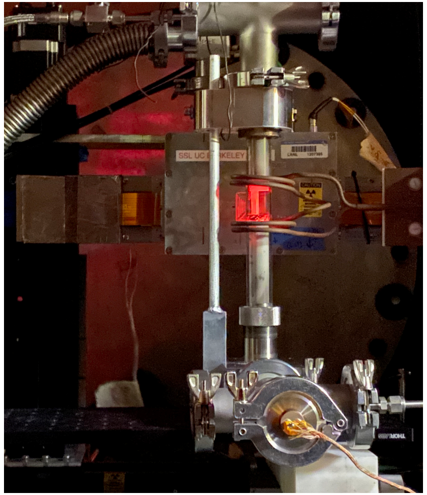
Thermophysical measurements of molten salts

Measuring densities in chloride based molten salts to evaluate MSR designs and performance



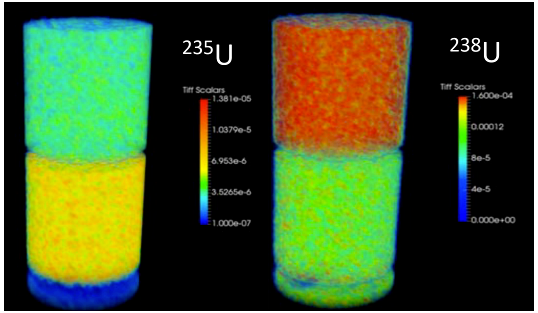
Quantifying hydrogen concentrations in YH_{2-x}

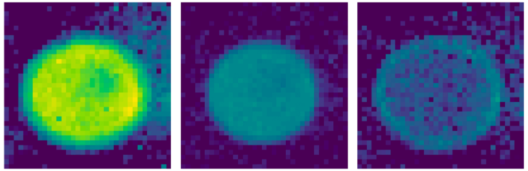
Mapping hydrogen in YH_{2-x} for potential use as high density moderators in microreactors



Energy resolved neutron imaging on nuclear fuels

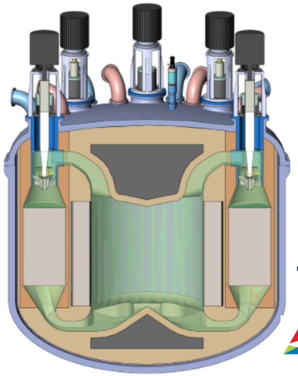
Utilizing ERNI techniques to map out isotopic distributions in fresh and irradiated fuels





Traditional — Imaging Techniques — Advanced

Remote Density Measurements of Molten Salts



Next Gen. molten chloride fast reactors

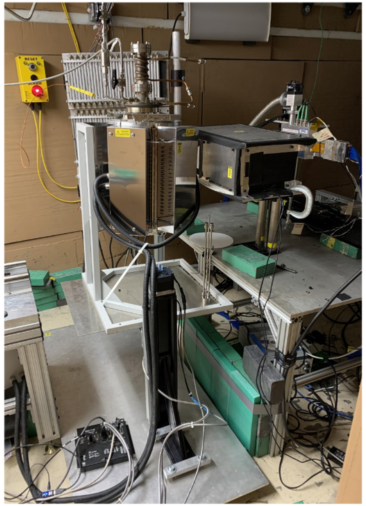
TerraPower

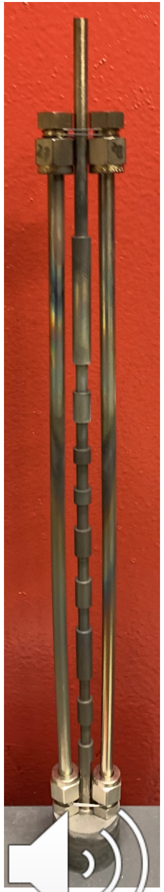
Southern Company

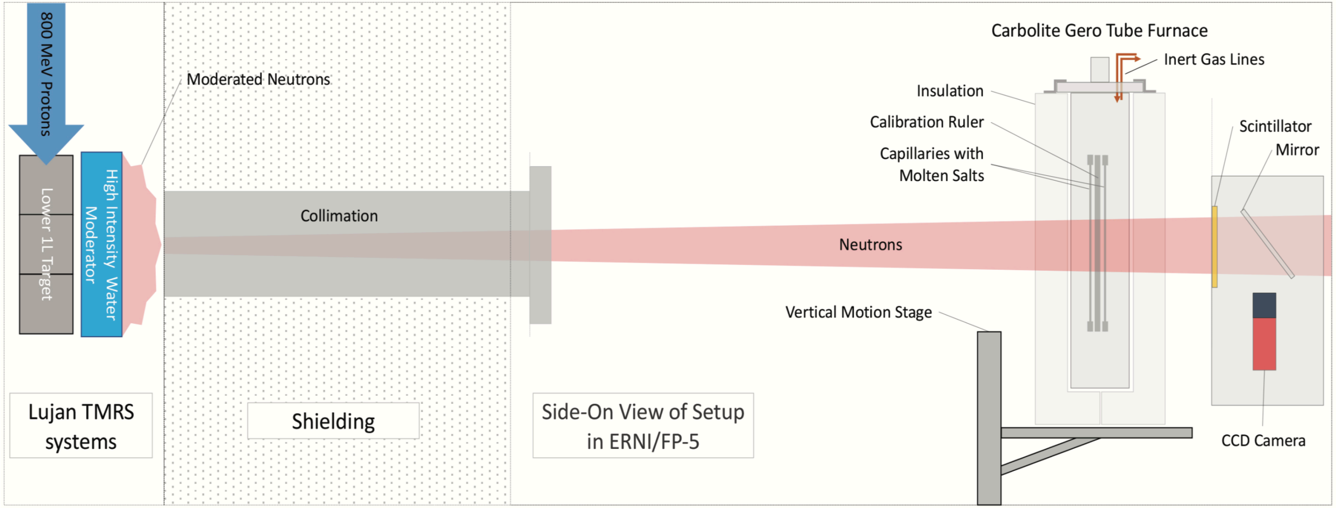
Many chloride-based salts currently lack much needed thermophysical data at the relevant temperatures to confidently assess and evaluate new reactor designs.

Measuring density as a function of temperature and chemical composition is critical to predicting salt behavior and performance.

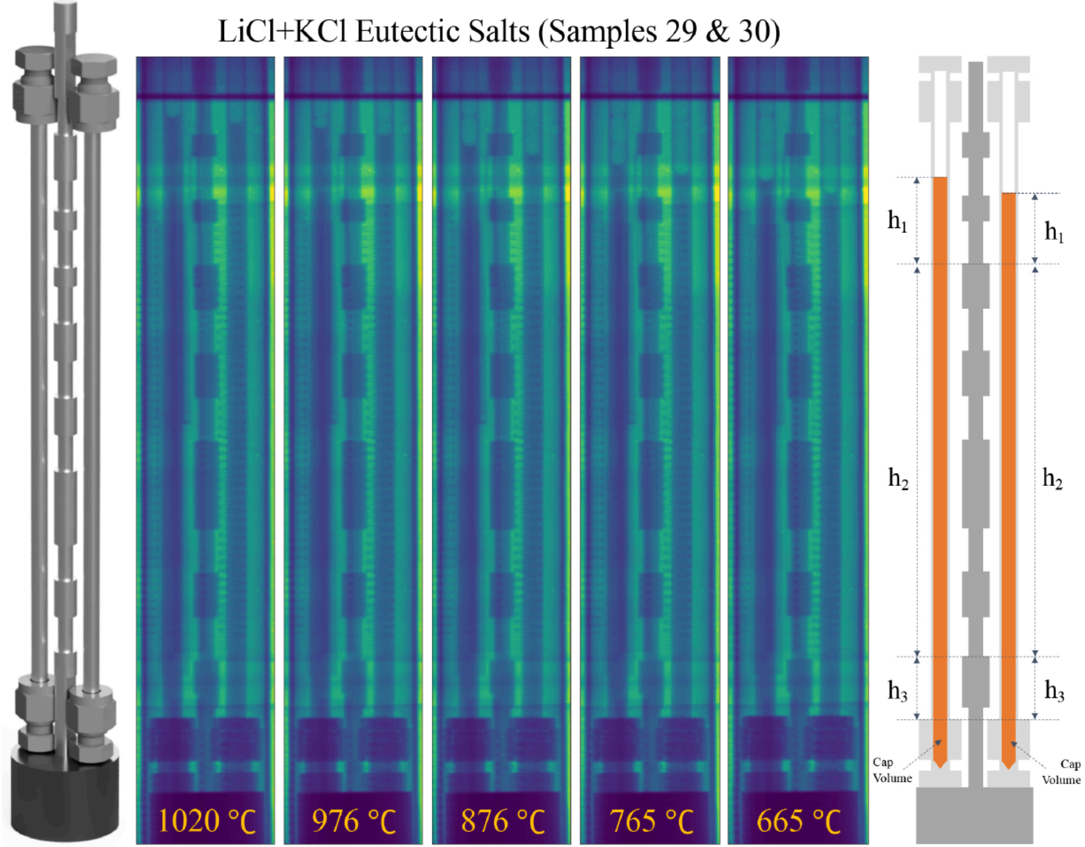
Density measurements via neutron radiography on FP5 (Oct 2020)



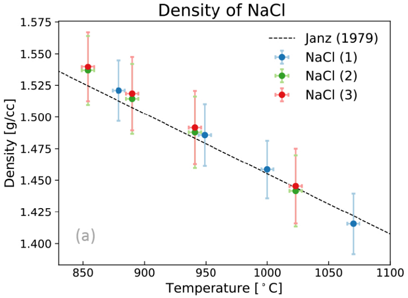


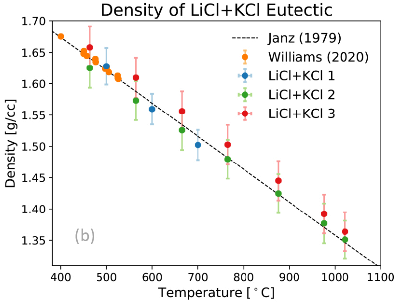


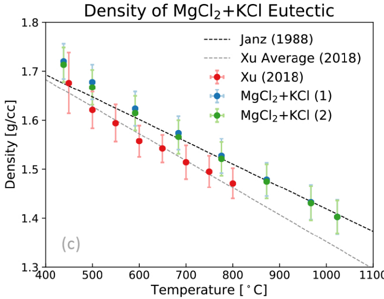
Remote Density Measurements of Molten Salts



Final uncertainties in density ~ 1-2%







Additional density measurements were performed on UCl_3-based eutectic and off-eutectic mixtures with NaCl, KCl, LiCl, $MgCl_2$, and $CaCl_2$

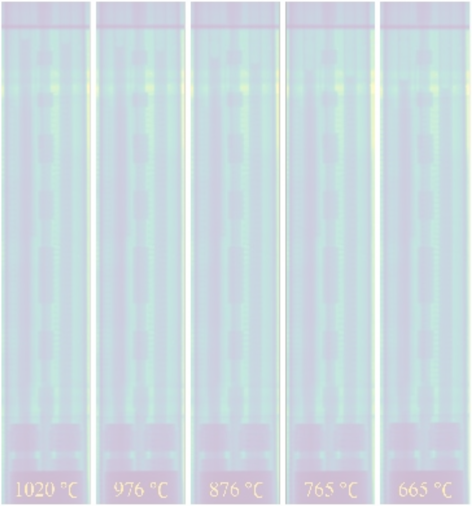
Advantages over other methods:

- Compact designs = very little sample material
- Measure multiple samples at a time.
- Able to see the material through out the measurement.

Some Neutron Imaging Projects in Nuclear Energy

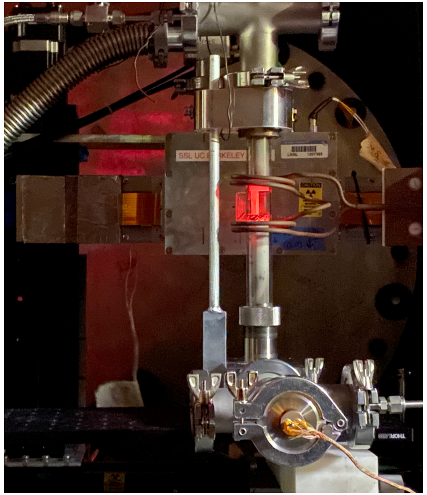
Thermophysical measurements of molten salts

Measuring densities in chloride based molten salts to evaluate MSR designs and performance



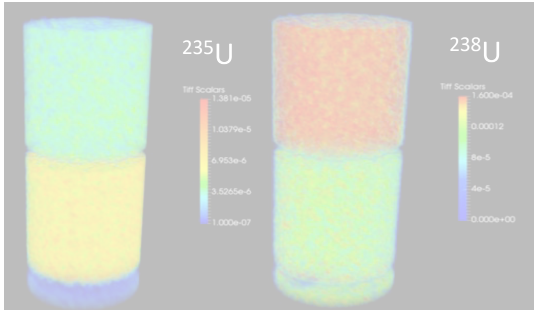
Quantifying hydrogen concentrations in YH_{2-x}

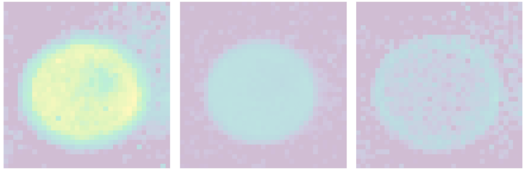
Mapping hydrogen in YH_{2-x} for potential use as high density moderators in microreactors



Energy resolved neutron imaging on nuclear fuels

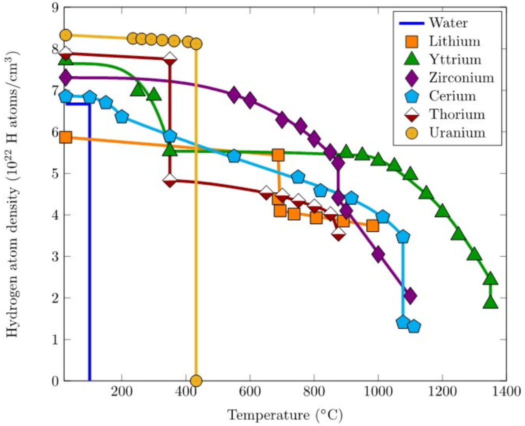
Utilizing ERNI techniques to map out isotopic distributions in fresh and irradiated fuels



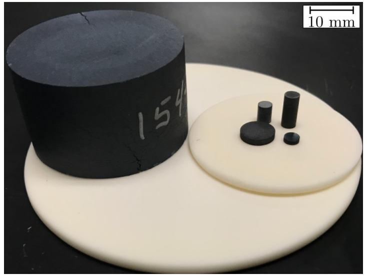


Traditional ← Imaging Techniques → Advanced

Measurements Hydrogen in High Temp. Compact Moderator Materials

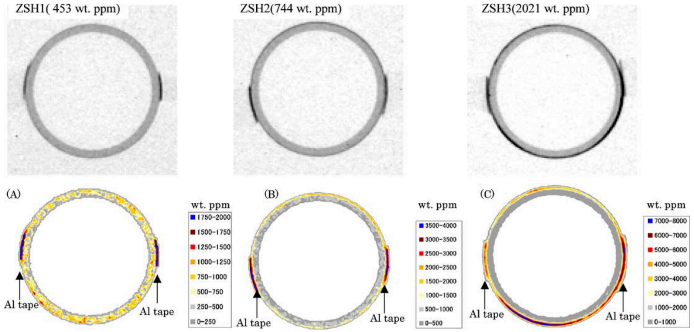


YH_{2-x} is a promising candidate for compact high temperature moderator materials.



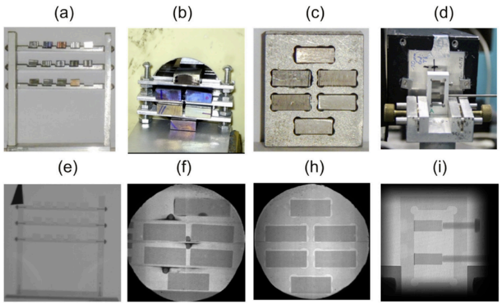
Accurate spatially resolved measurements via neutron attenuation

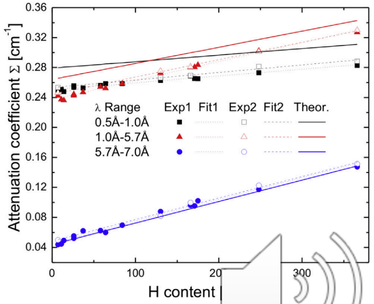
Previous measurements of H-distributions in Zircaloy materials.



Measure — Determine — Calibrate/Model

$$T(x,y,E_n) = exp(-z_H(x,y)\ \Sigma(x,y,E_n))$$





One of the main Questions:

- ***Hydrogen is highly mobile in YH_{2-x}. What is the H-distribution response to large high temperature gradients across the moderator?***

Shivprasad et. al. Advanced Moderator Material Handbook (2020)

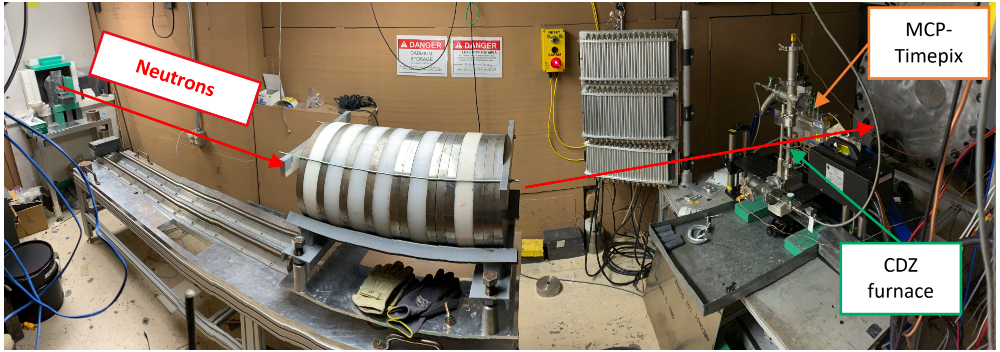
R. Yasuda et al. Journal of Nuclear Materials 320 (2003) 223–230
N.L. Buitrago et al. Journal of Nuclear Materials 503 (2018) 98-109

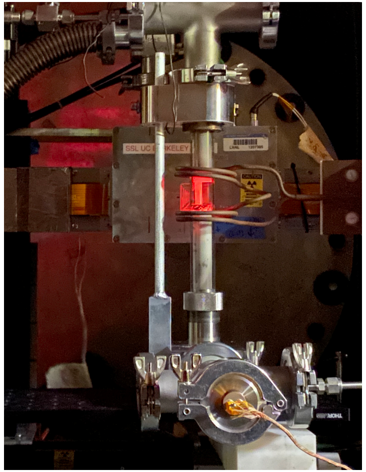
Quantifying Hydrogen in YH_{2-x} at FP5

Main Goal: To observe H-distribution response to uniform elevated temperatures and temperature gradients.

- Commissioned new compact dual zone (CDZ) furnace*.
- Performed mid Dec. 2020
- Samples: Two YH pellets ($YH_{1.15}$ & $YH_{1.6}$) placed inside TZM can.
- Took long (~9 hours) exposure at room temp.
- Heated up to ~900 °C

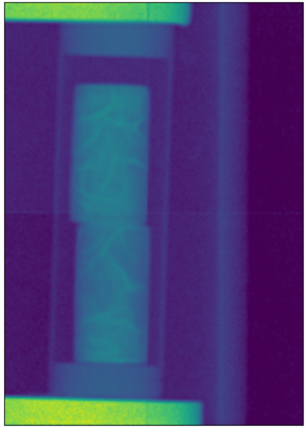
* One of the heating elements in the CDZ furnace malfunctioned, so RF heating was employed to continue the measurements. With RF only elevated uniform heating on TMZ samples could be performed.





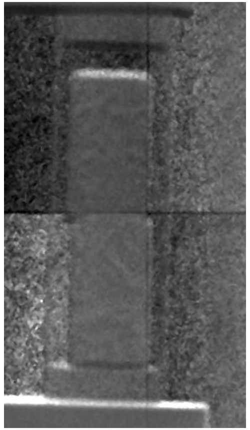
CDZ furnace with RF

Mass attenuation



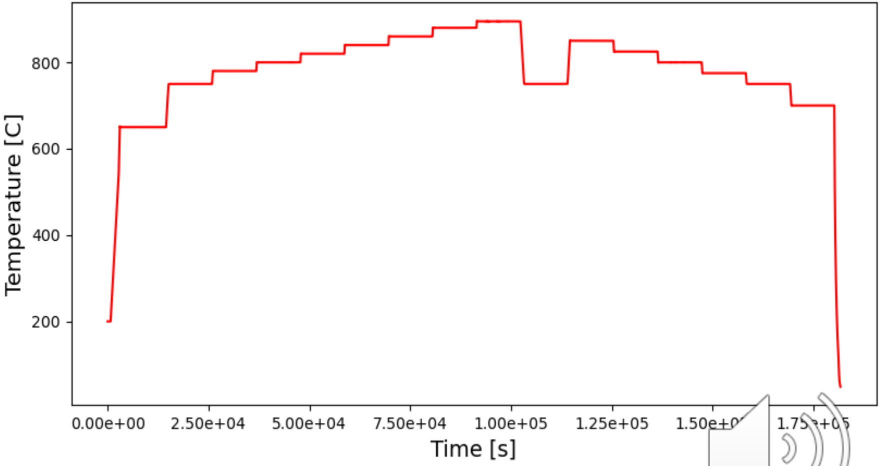
@ room temp

Attenuation ratio



@Temp/RT

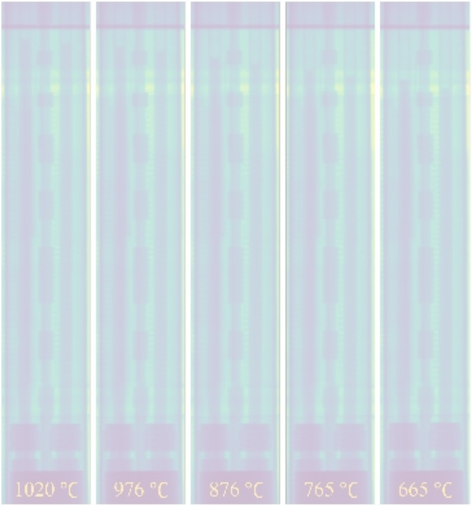
Temperature profile over two days of uniform heating



Some Neutron Imaging Projects in Nuclear Energy

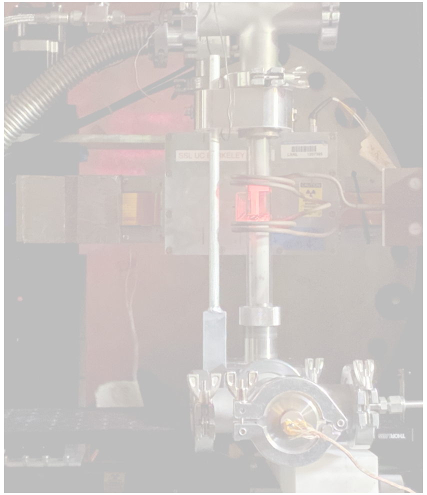
Thermophysical measurements of molten salts

Measuring densities in chloride based molten salts to evaluate MSR designs and performance



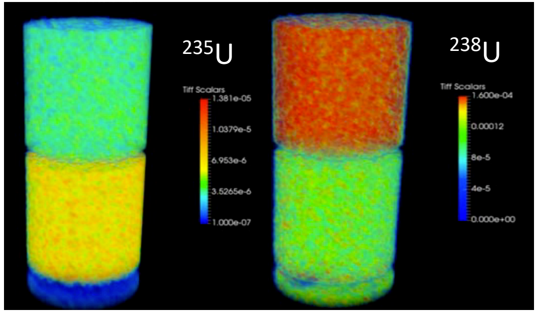
Quantifying hydrogen concentrations in YH_{2-x}

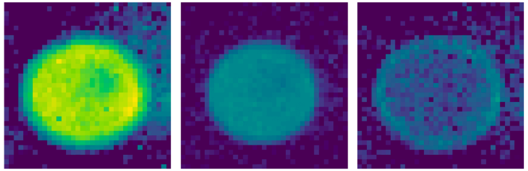
Mapping hydrogen in YH_{2-x} for potential use as high density moderators in microreactors



Energy resolved neutron imaging on nuclear fuels

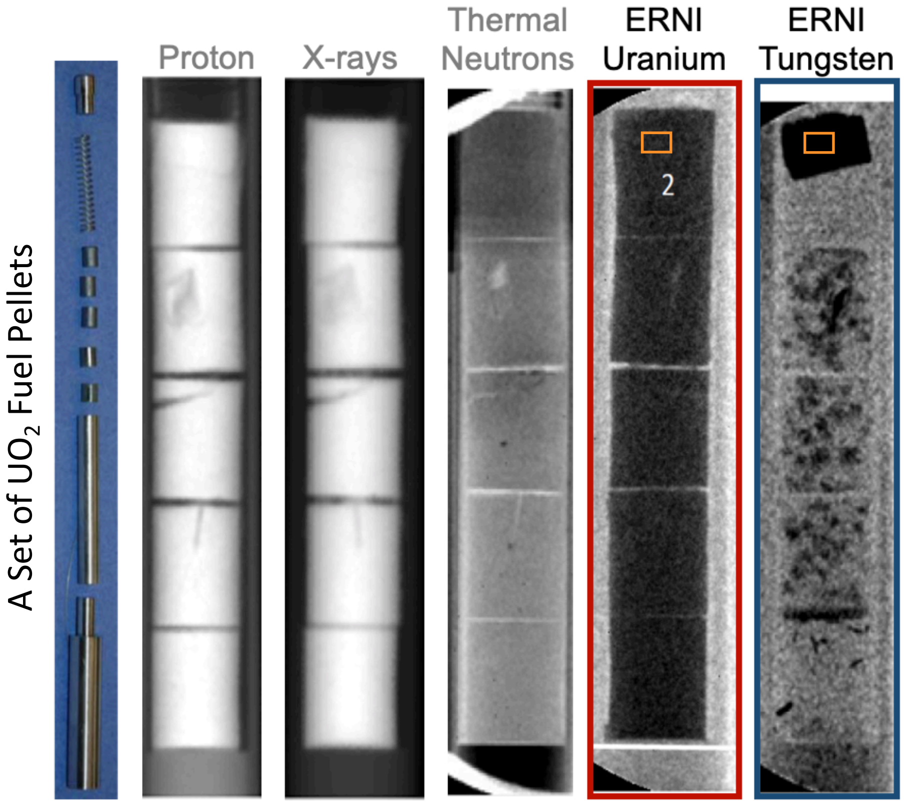
Utilizing ERNI techniques to map out isotopic distributions in fresh and irradiated fuels





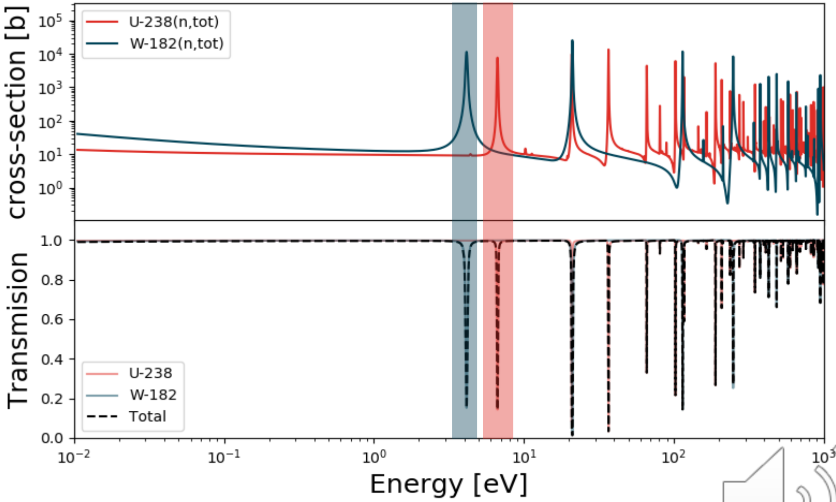
Traditional ← Imaging Techniques → Advanced

Energy Resolved Neutron Imaging (ERNI)



- Advanced neutron radiography technique
- Neutrons have complex cross-sections
- If neutron energy is known, transmissions can be further resolved based on incoming neutron time of flight

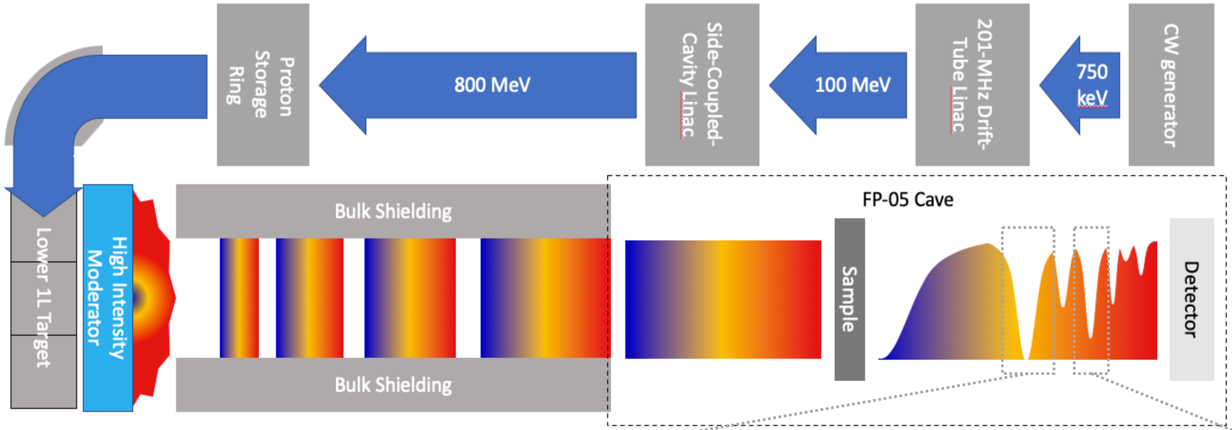
Each pixel has additional energy information in the form of a transmission spectra

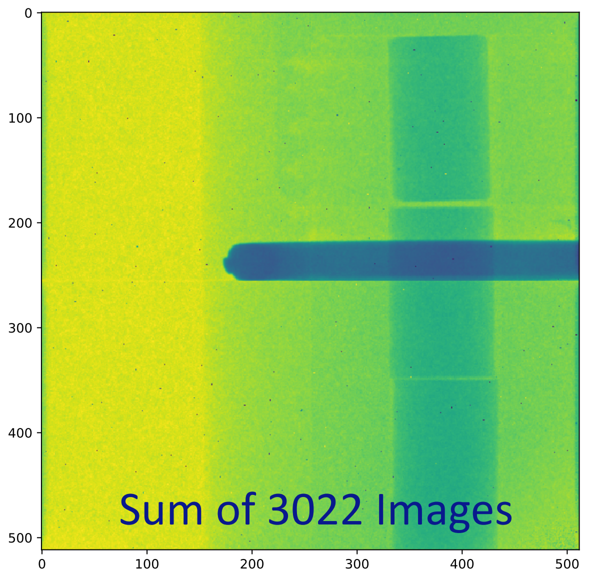


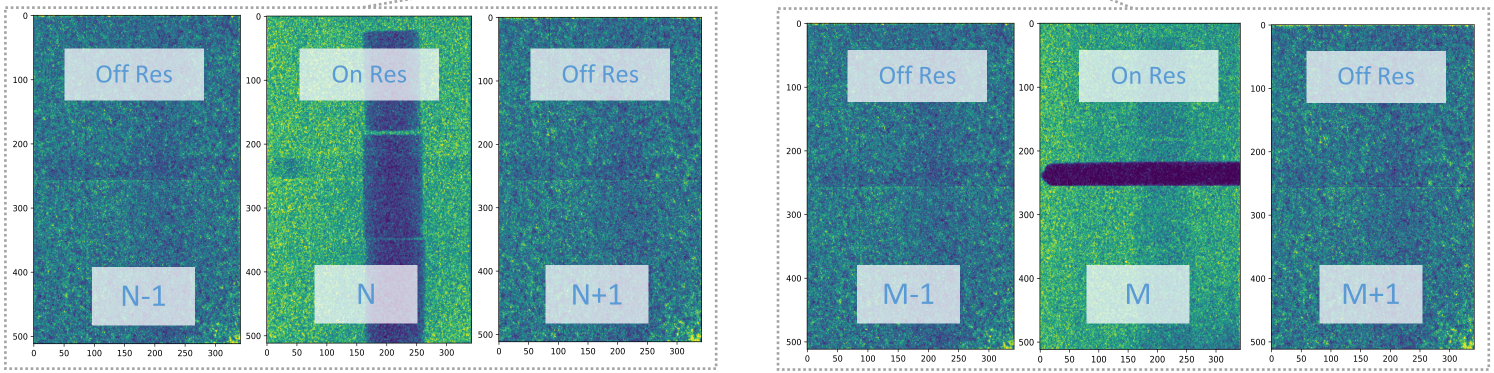
Morris *et. al.* Review of Scientific Instruments 84 (2013)
Tremsin *et. al.* Neutron News 24 (2013)

Energy Resolved Neutron Imaging on FP5

Using epi-thermal neutrons and absorption resonances to create contrast

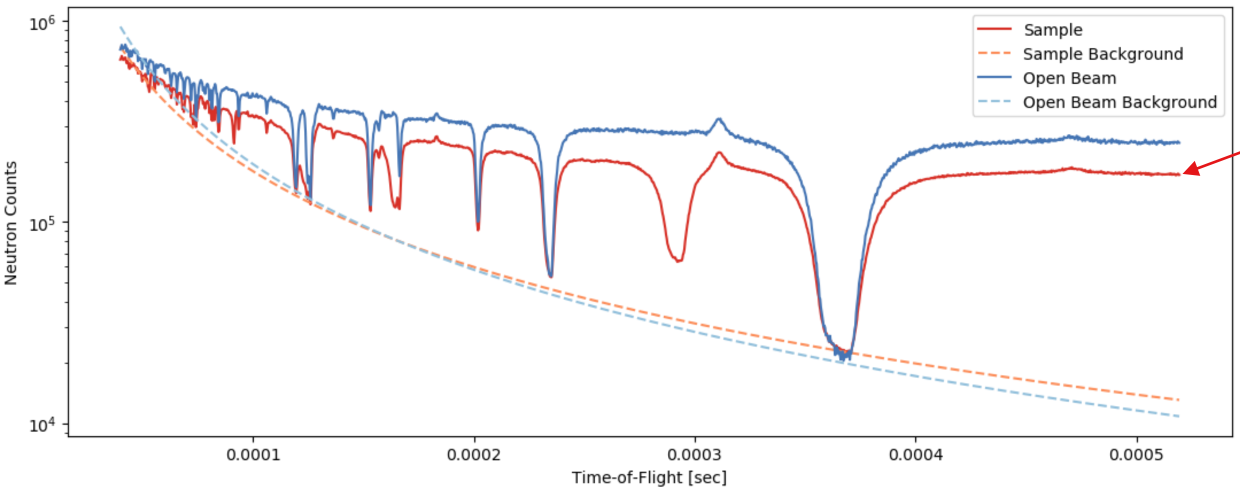


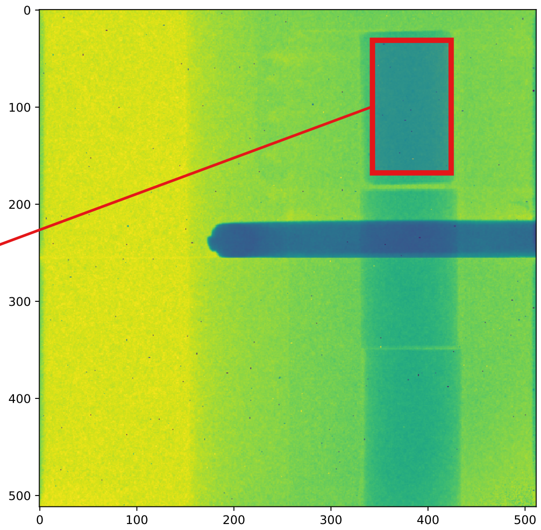


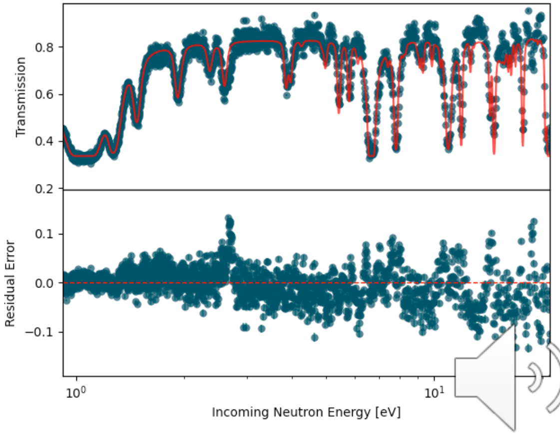


Extracting Isotopic Densities with ERNI

Average Number of Neutrons in Regions of Interests







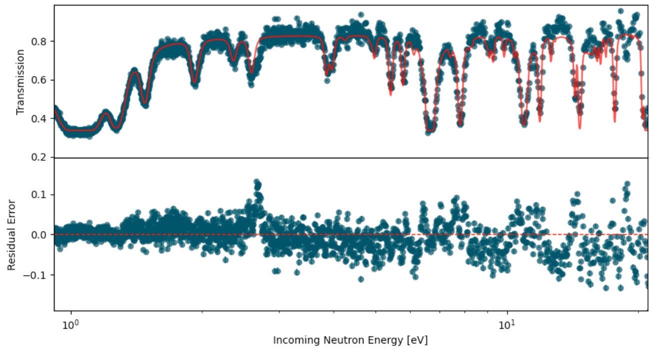
$$T(E_n) = N_b \frac{I_{obj}(E_n) - B_{obj}(E_n)}{I_{blk}(E_n) - B_{blk}(E_n)} = e^{-\sum_k n_k \sigma_{tot,k}(E_n)}$$

With a transmission spectrum, we can now use R-matrix codes like SAMMY, *or new material decomposition codes**, to extract areal densities (n_k) of specific isotopes.

** See talk by Thilo Balke*

ERNI-CT on FP5 @ LANSCE

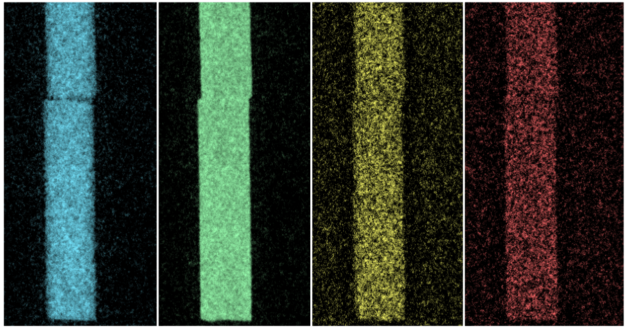
Fitting transmission spectra from each pixel



512 x 512 Trans. fits

Obtain 2D heat maps of each isotope

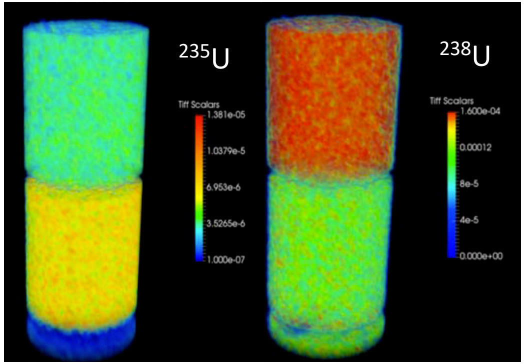
Isotopic areal densities in g/cm^2



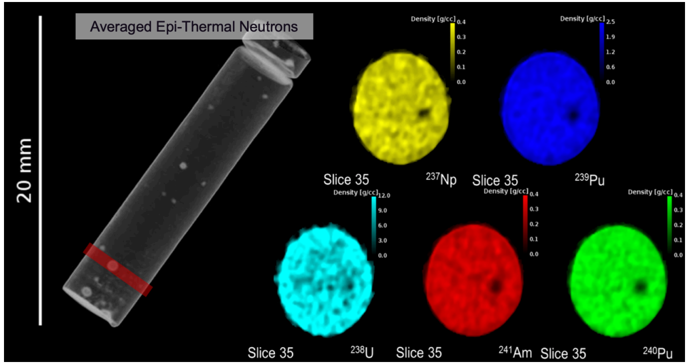
Perform over many rotations

Perform CT reconstruction on each isotope

Enrichment levels in U_3Si_5 and UN AT fuels



Transmutation U-20Pu-10Zr fuels



ERNI-CT reconstructions could be computationally intensive using current R-matrix code SAMMY. Sometimes taking weeks-months for a single reconstruction.

New codes are much faster

(See talk by Thilo Bal

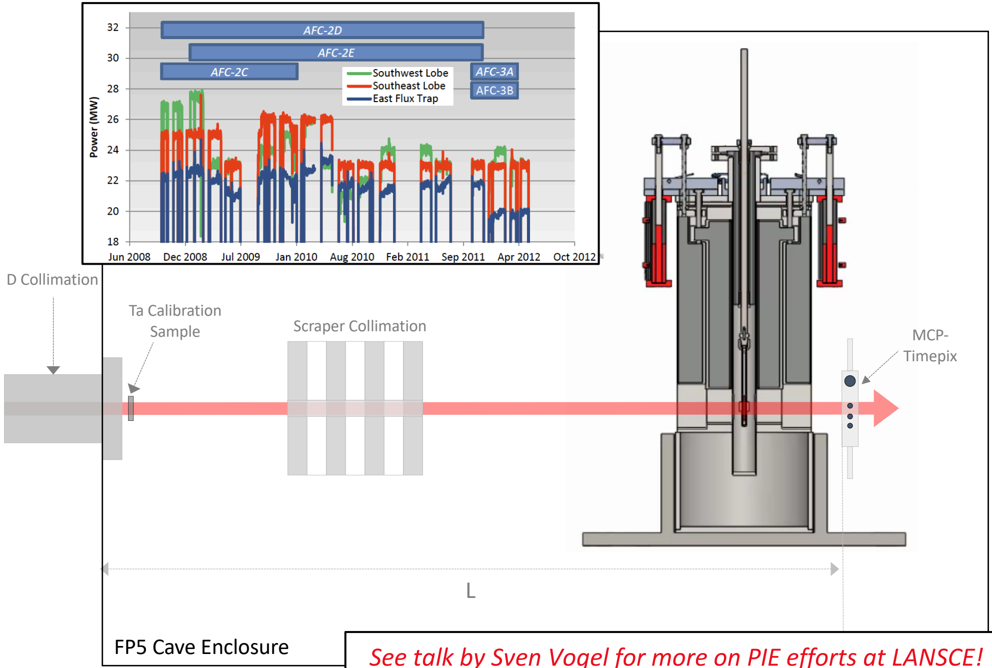
ERNI-CT reconstructions by Adrian Losko using SAMMY 8.1

ERNI-PIE on irradiated fuels at FP5

Post irradiation examination is critical to understanding fuel performance.

ERNI-PIE can be extremely useful:

- **Remote** ➞ Able to measure highly radioactive samples.
- **Non-destructive** ➞ Can guide further, more direct, PIE measurements.
- **Probe Internal structure** ➞ Help identify any "off-normal" conditions due to irradiation condition.
- **Spatial isotopic info** ➞ Spatially measurements of fuel and fission product distributions can help solve certain questions surrounding FCCI, fuel redistribution, and uniformity of burnup.

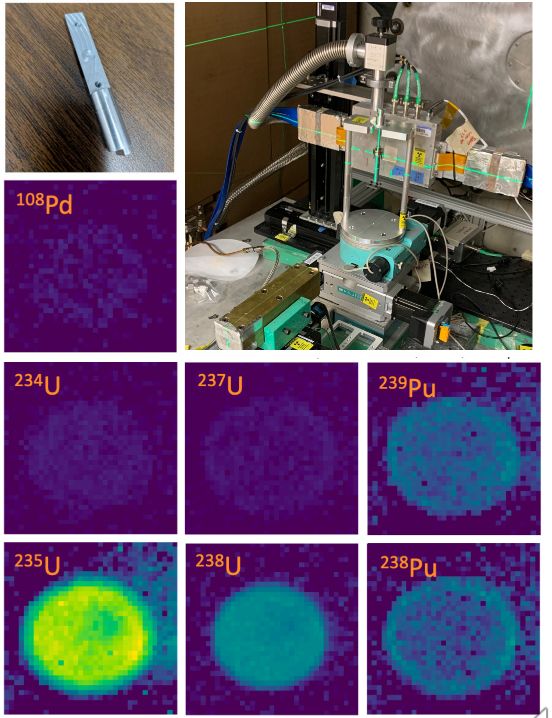


See talk by Sven Vogel for more on PIE efforts at LANSCE!

Preliminary ERNI measurements on U-1Pd-10Zr sample irradiated at the ATR @ INL (2020 LANSCE run cycle)

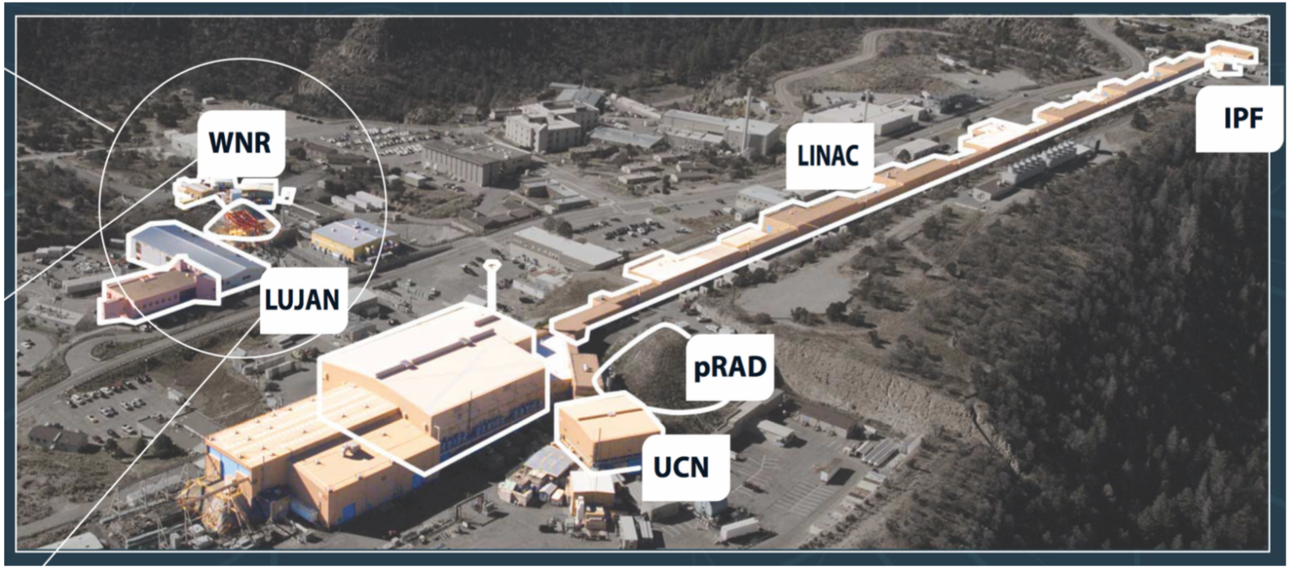
~1.5 mm thick disk prepared from AFC-3A-R5A

Dose rate on contact: ~3R/hr

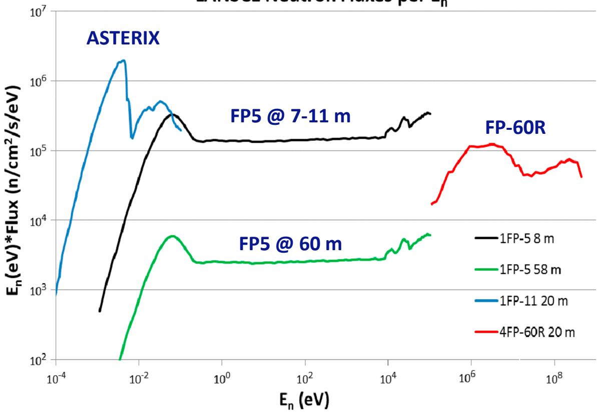


Used MAD-neutron code for decomposition

Take Away Message…

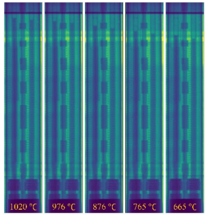


LANSCE is a unique facility that offers a wide range of neutron energies that are available for neutron imaging experiments!



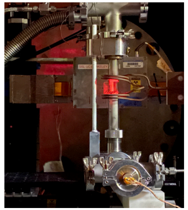
Thermophysical measurements of molten salts

Measuring densities in chloride based molten salts to evaluate MSR designs and performance



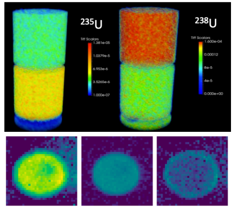
Quantifying hydrogen concentrations in YH_{2-x}

Mapping hydrogen in YH_{2-x} for potential use as high density moderators in microreactors



Energy resolved neutron imaging on nuclear fuels

Utilizing ERNI techniques to map out isotopic distributions in fresh and irradiated fuels



NSUF Nuclear Science User Facilities

Lujan Center is a NSUF partner facility!

Proposals for 2021 LANSCE run cycle due March 29th

LANSCE 2021 Call for Proposals

Calls for proposals are issued **once a year**, for each run cycle of the accelerator.
To submit a fast access proposal please directly contact the LANSCE User Program Coordinator.

Please contact Alex Long (*alexlong@lanl.gov*) or Sven Vogel (*sven@lanl.gov*) if you have any questions.

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Advanced Fuels Campaign

NTRD Nuclear Technology Research & Development

Nuclear Science User Facilities

Los Alamos NATIONAL LABORATORY

Density measurements of molten salts:

Team: A.M. Long, S.S. Parker, M. Monreal, M. Jackson, D.T. Carver, and S.C. Vogel.

Funding: LANL LDRD Office (20210113DR & 20190650DI)

Hydrogen measurements in YH_{2-x}:

Team: A.M. Long, H. Trellue, A. Shivprasad, E. Luther, D.T. Carver, and S.C. Vogel.

Funding: LANL LDRD Office (20190649DI)

ERNI measurements on fresh and irradiated fuels:

Team: S.C. Vogel, A.M. Long, K.J. McClellan, J.R. Angell, T. Balke, L. Capriotti, A.E. Craft, J. Harp, P. Hosemann, J. Lin, E.J. Larson, D.C. Schaper, B. Wolhberg

Funding: LANL LDRD Office (20200061DR)
DOE-NE Advanced Fuels Campaign
Nuclear Science User Facilities
Nuclear Technology Research & Development.

Thank you!

Please feel free to contact us if you have any additional questions!

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