INL/CON-23-71585-Revision-0

Annular Metallic Nuclear Fuel Informatics at 50 nm Resolution

March 2023

Fei Xu, Daniele Salvato, Lu Cai, Fidelma Dilemma, Luca Capriotti, Tiankai Yao

Changing the World's Energy Future

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Annular Metallic Nuclear Fuel Informatics at 50 nm Resolution

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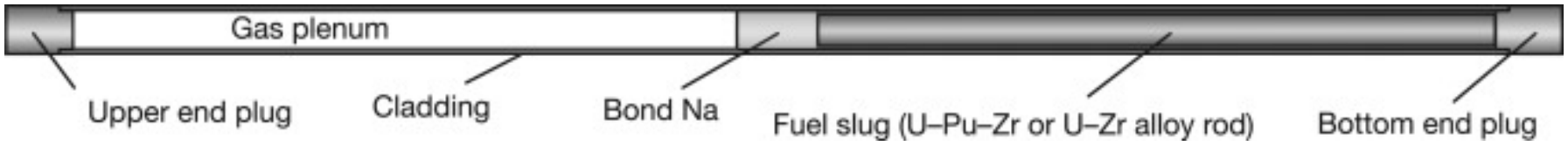
Outline

- Metal fuel development challenges
  - Background and motivation
- Our approach – workflow
  - Fission gas bubble segmentation
  - Fission gas bubble classification (Decision Tree)
- A showcase study on two U-10Zr annular fuel
  - Porosity analysis
  - Phase identification
- Conclusion and Future Work

Nuclear Test Reactors

Background – Cladding Integrity

➔ Fuel bundle

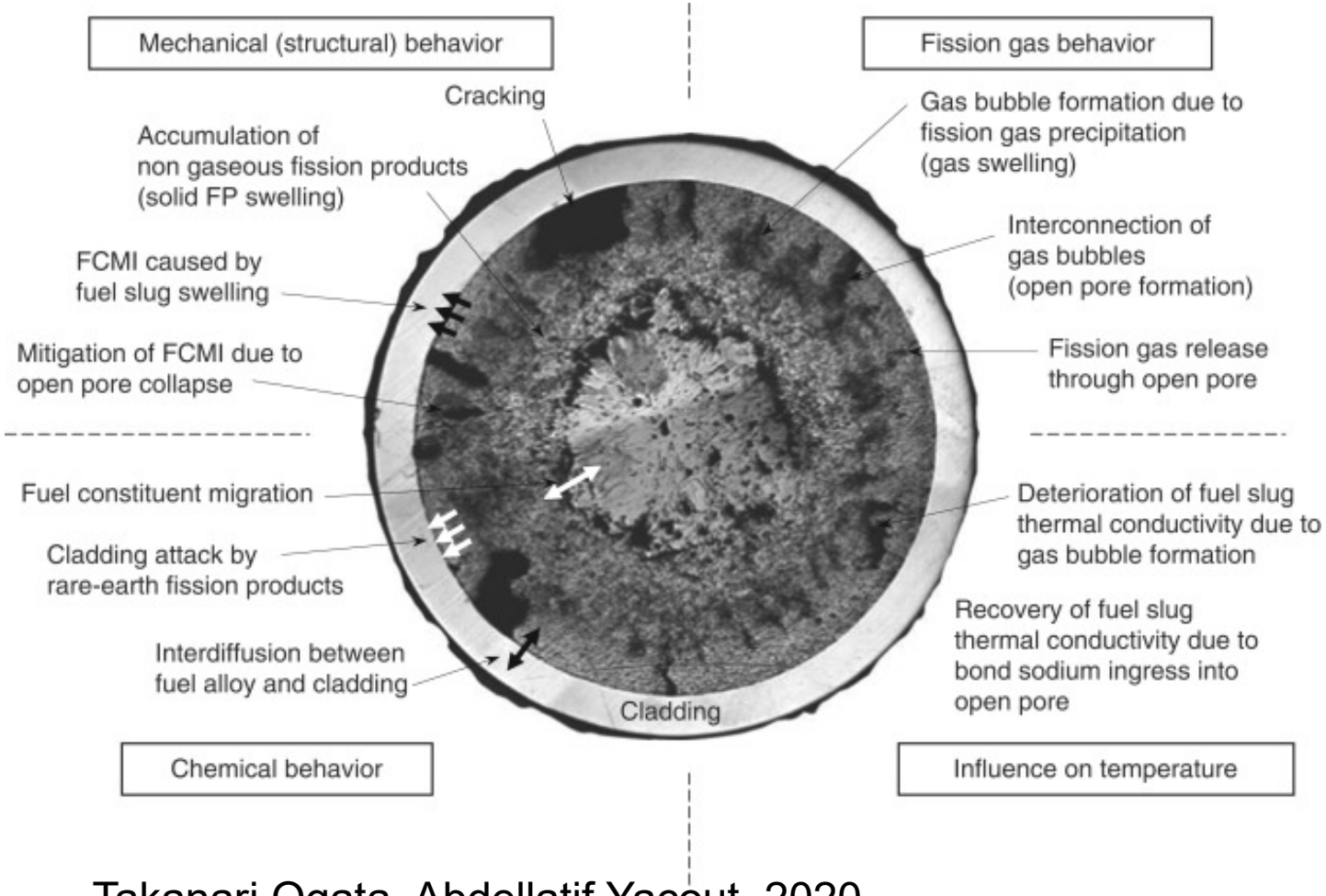


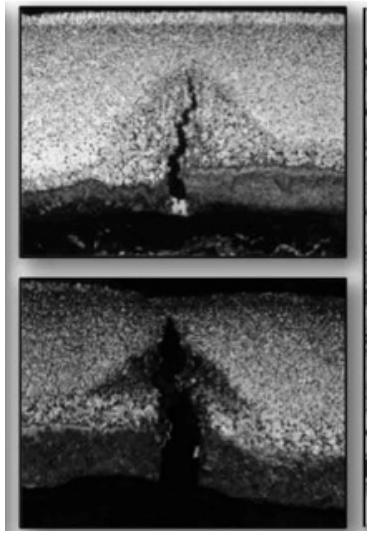
Fuel rod

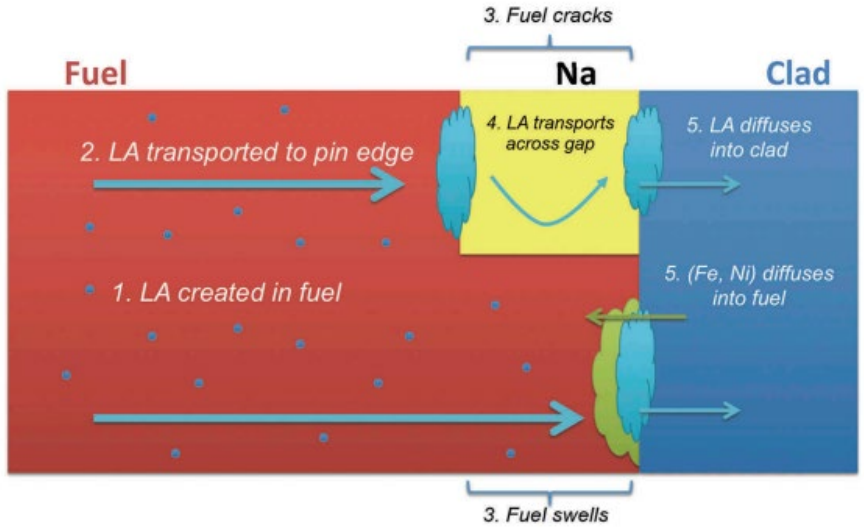
Cladding is the thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. It prevents corrosion of the fuel by the coolant and the release of fission products into the coolant. It is a **first barrier** for retention of fission products.

Source: Tanju et al, Nuclear Sci. Tech. 2015; W.J. Williams et al. / Annals of Nuclear Energy 136 (2020) 107016; Olander, 1976; Takanari Ogata, Abdellatif Yacout, 2020

Background - Metal fuel irradiated microstructure







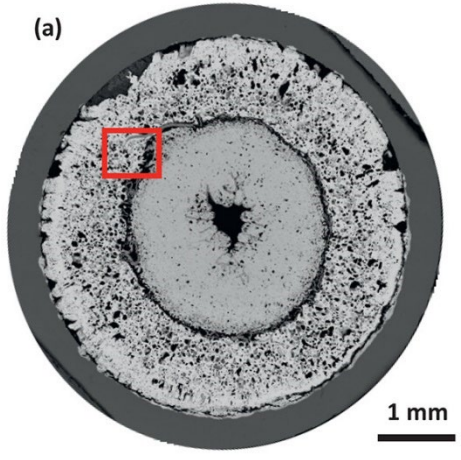
Takanari Ogata, Abdellatif Yacout, 2020
Mattews C. et al, Nuc. Tech. 2017

Motivation – A big picture

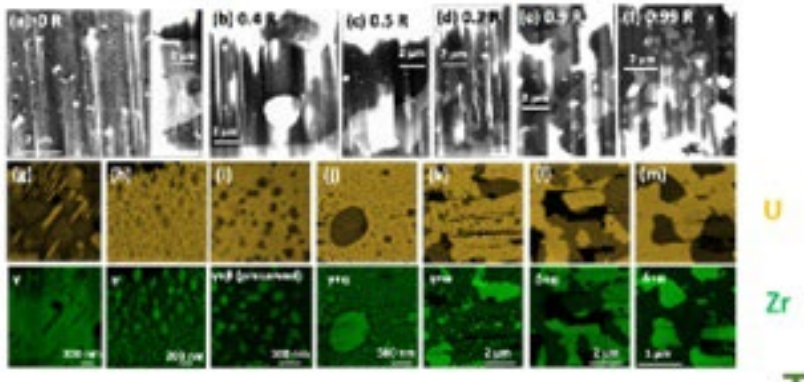
Huge microstructure data

Metallography

SEM

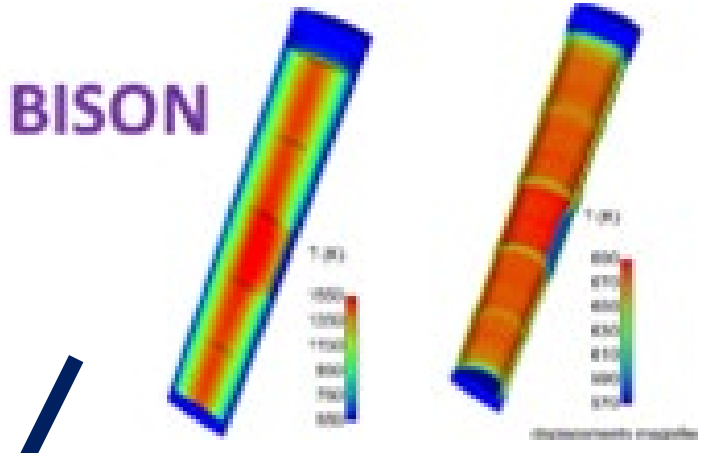


TEM, phase and composition



Machine learning to aid mechanistic understanding

Fuel modeling code to better predict fuel performance



Fuel qualification and licensing

Outline

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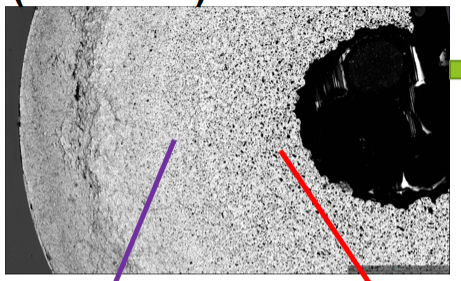
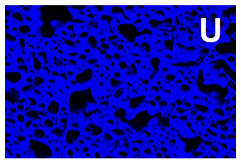
Nuclear Test Reactors

Approach - Workflow

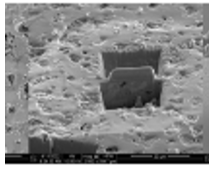
Irradiated fuel microstructure (SEM/FIB)



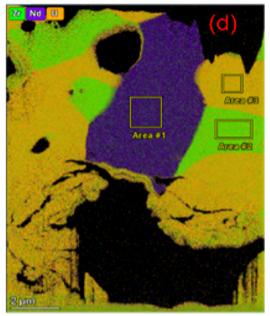
Phase determination through advanced characterization



SEM/ EDS

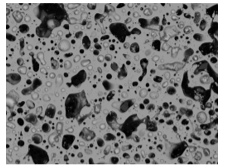


FIB

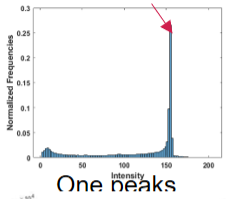


STEM/EDS

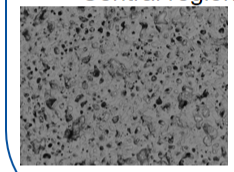
phase determination through image processing



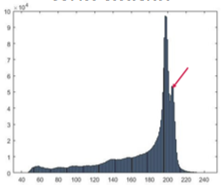
Central region



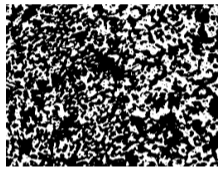
One peaks



Edge region

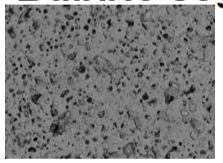


Two peaks

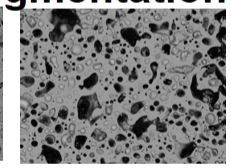


UZr_2 phase

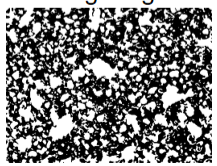
Bubble segmentation



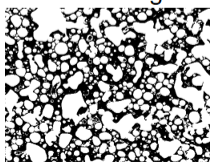
Edge region



Central region

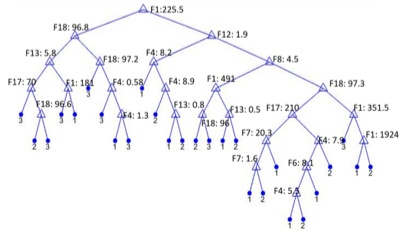


Bubble detection



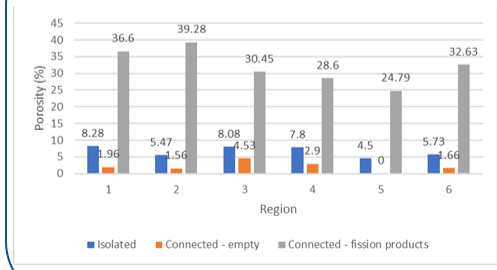
Bubbles detection

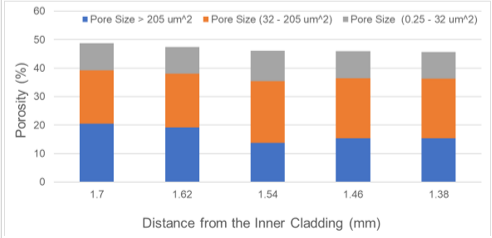
Bubble Classification



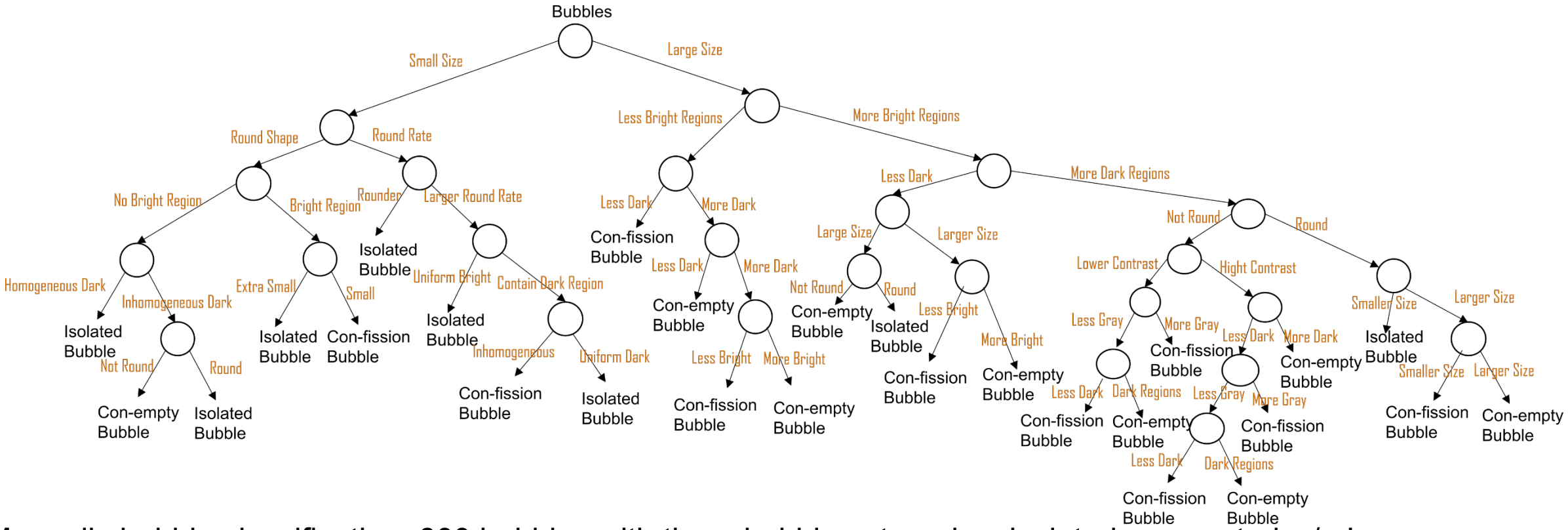
Applying the trained decision tree model

Quantitative results





Decision Tree Classifier



- Manually bubble classification: 800 bubbles with three bubble categories: isolated, connected w/o Ln, connected with Ln
- Training and testing: 80% training, 20% testing
- 18 features including bubble's mean intensity, size, standard deviation of intensity, intensity histogram, intensity range and the shape convexity
- Challenges: unbalanced and limited data

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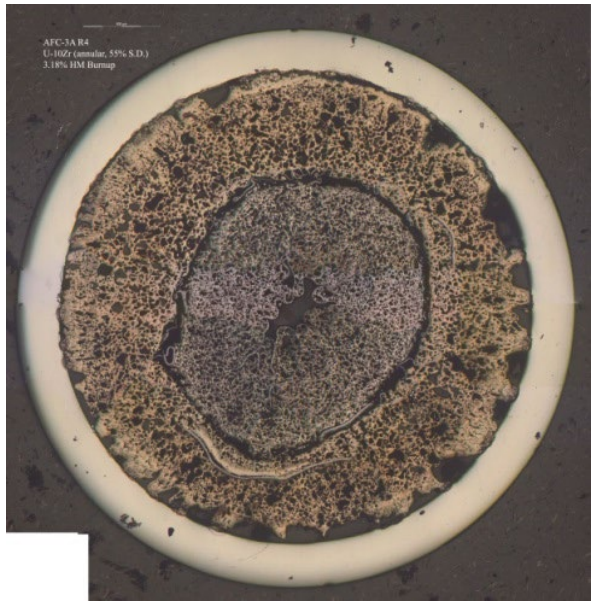
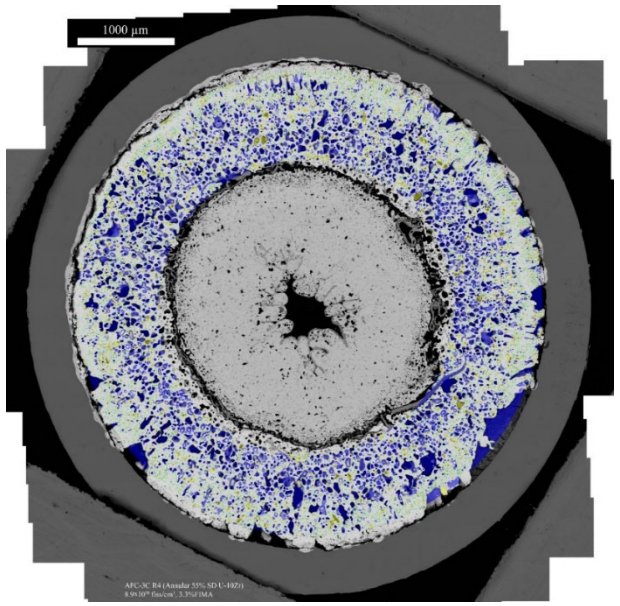
Nuclear Test Reactors

A showcase - Two metallic fuel cross-sections

21 X





83 B

Cast into annular molds

U-10Zr, 55% SD, annular, He, 3.3%FIMA, 540-600+ C

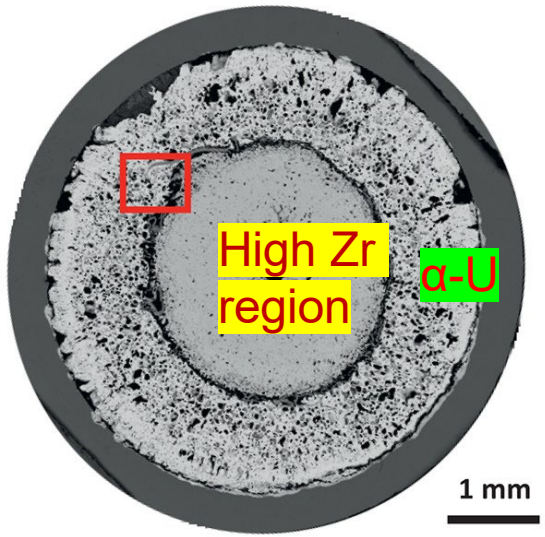
83 B better fuel performance, low FCCI

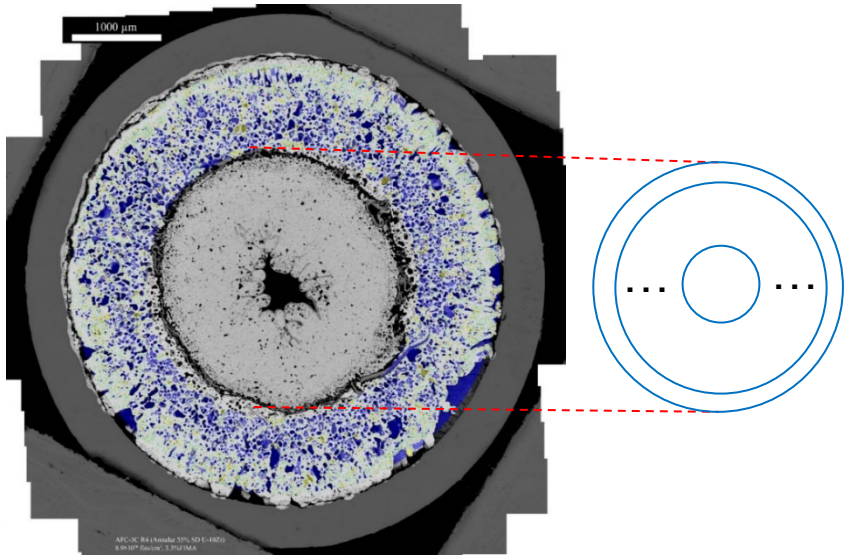
Machined holes after cast

U-10Zr, 55% SD, annular, He, 4.3% FIMA, 600°C

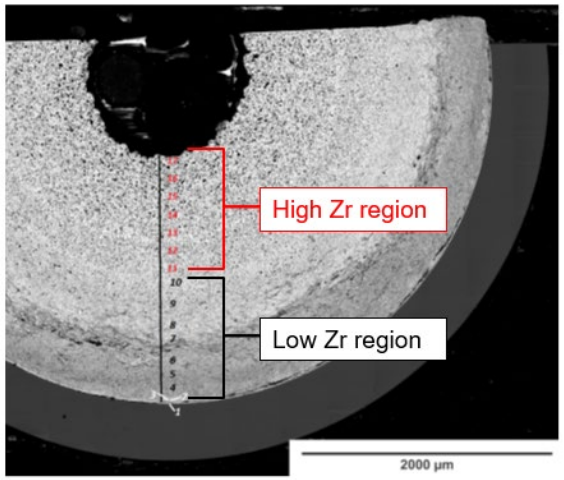
Microstructure Comparison

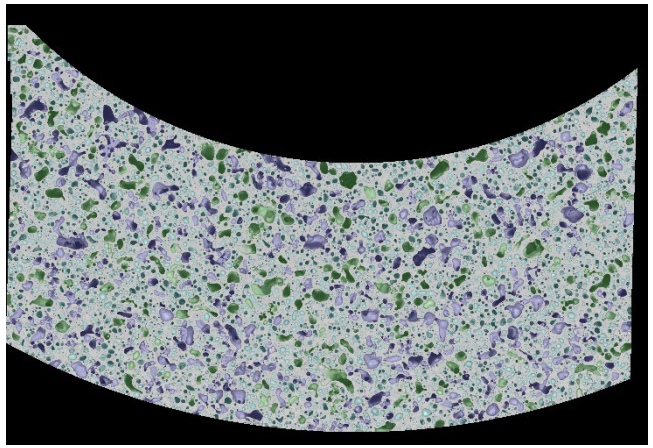
High Zr region





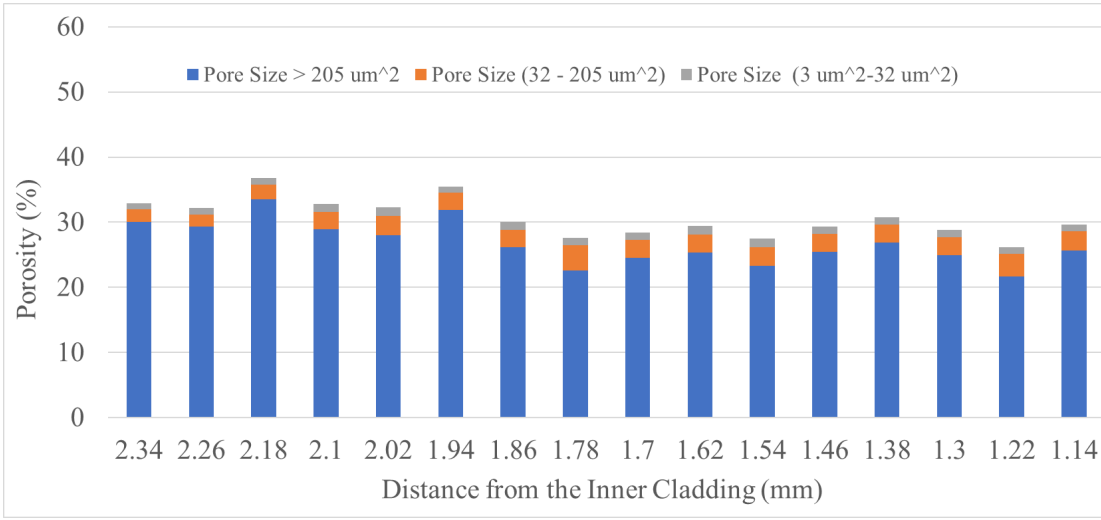
21X

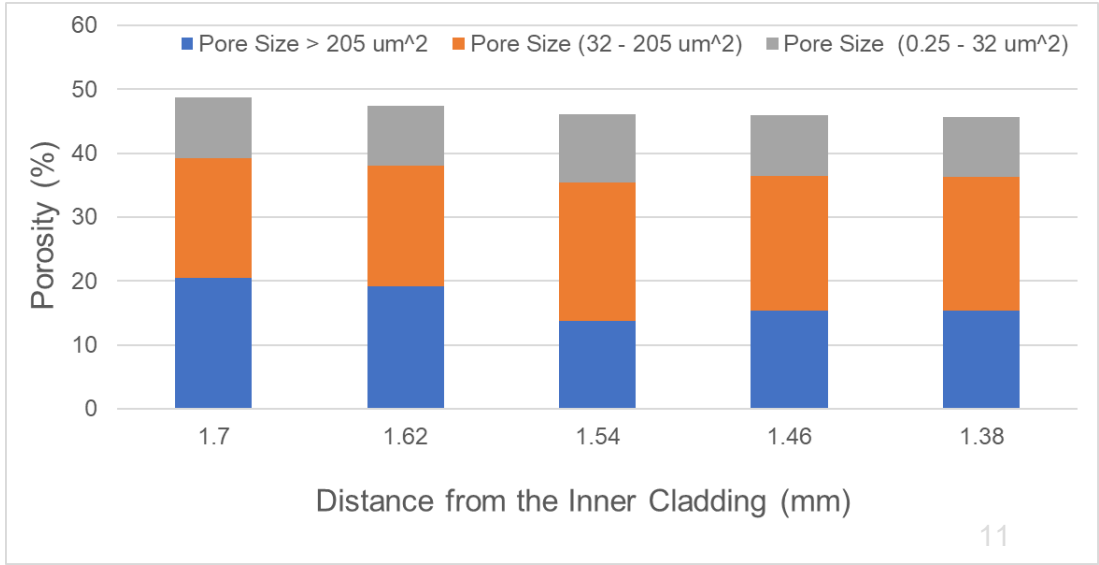




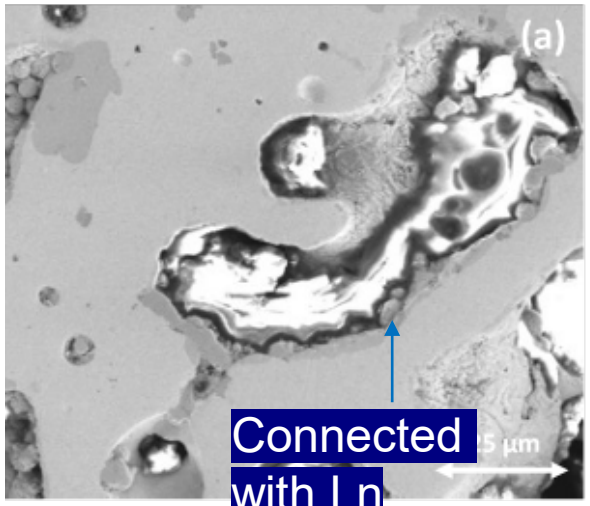
AFC-3D R1 (U-10Zr, 55% SD, annular, He, 4.3%FIMA, 600 C)

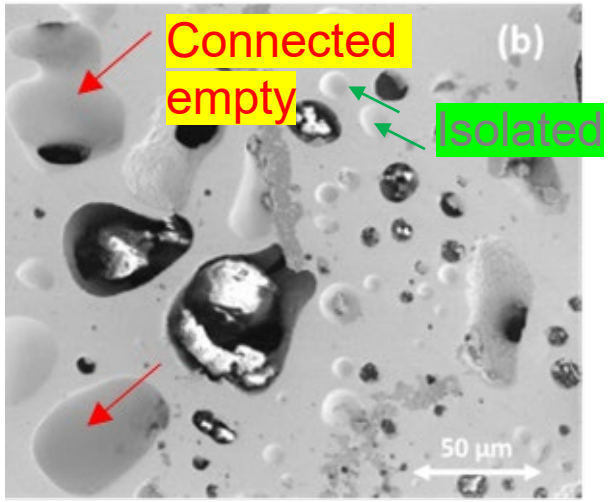
83B

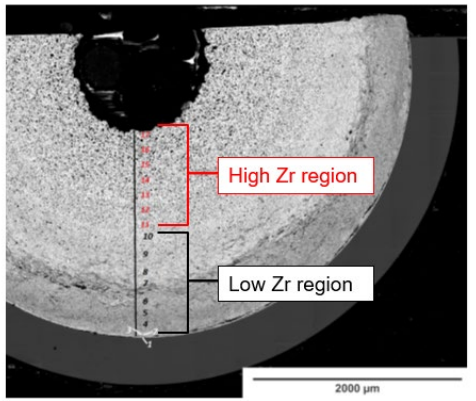




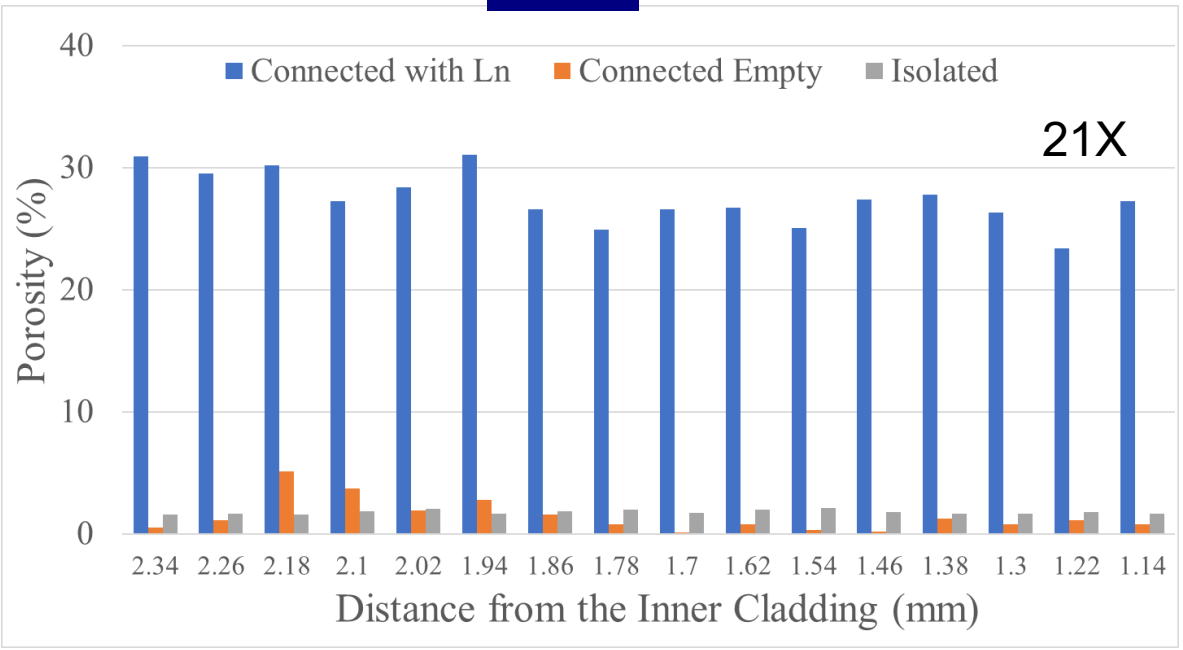
Microstructure – bubble classification



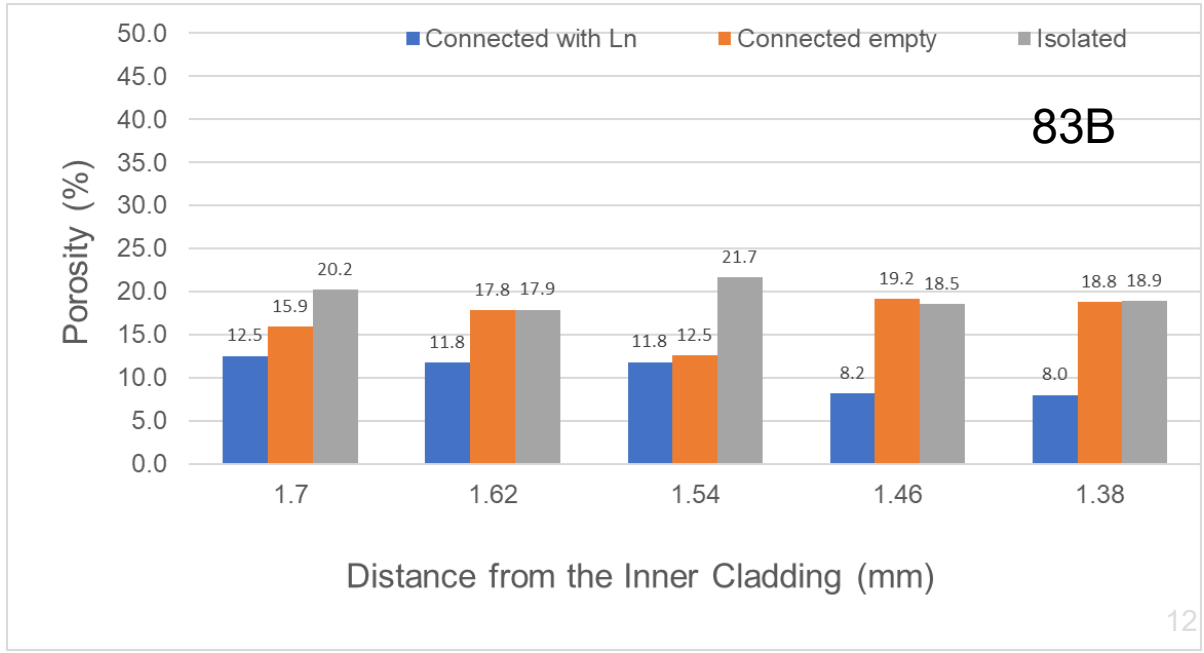




AFC-3D R1 (U-10Zr, 55% SD, annular, He, 4.3%FIMA, 600 C)



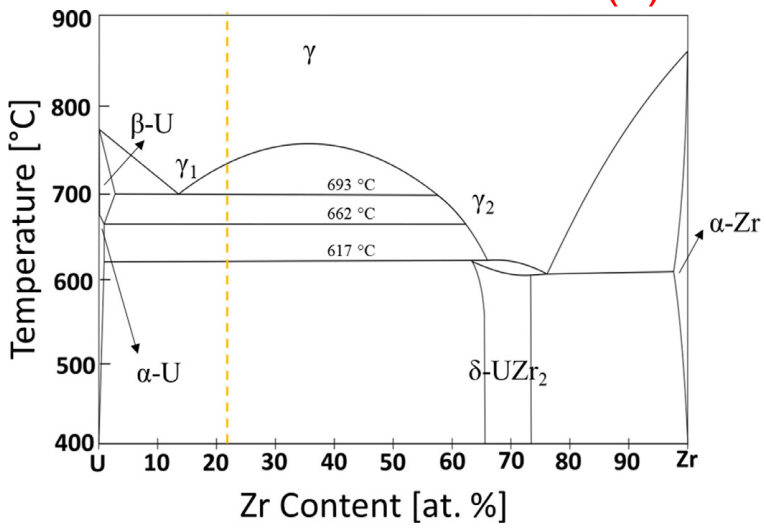
High Zr region



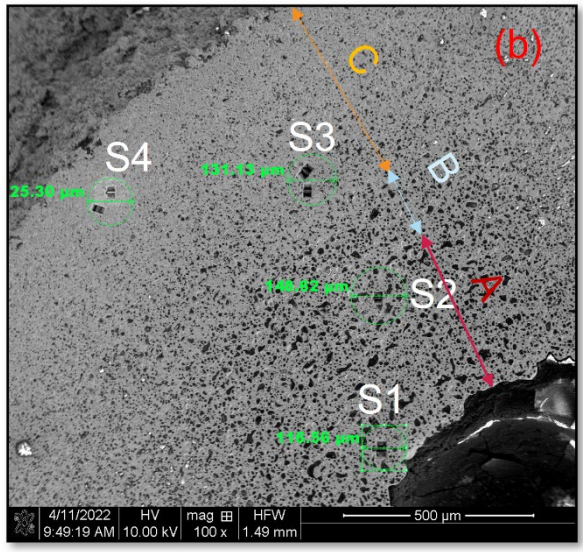
Phase Identification on 83B - Zr redistributions

Phase Diagram

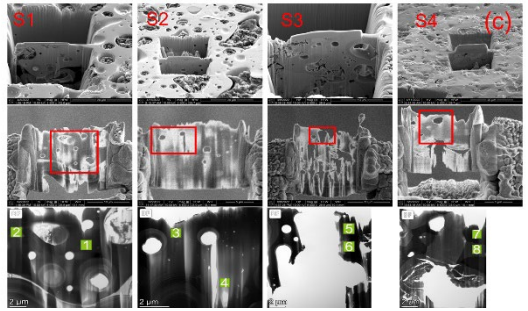
(a)



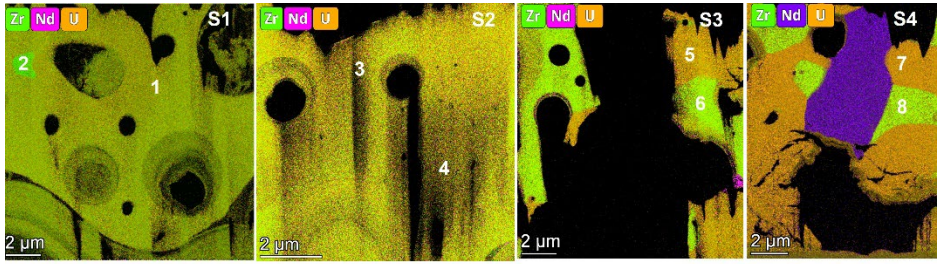
SEM



FIB



STEM/EDS

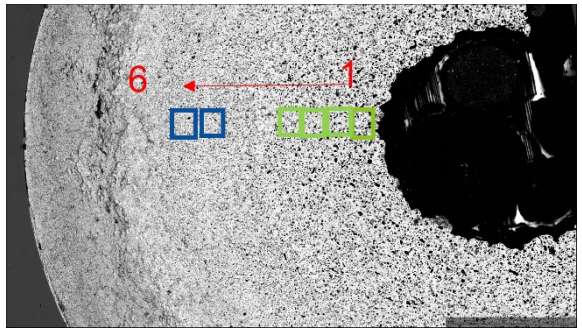


Region	Sample#	U [at.%]	Zr	Phases (d)
S1	1	59	41	(U, Zr) matrix
	2	2	98	Pure Zr
S2	3	67	33	(U, Zr) matrix
	4	55	45	(U, Zr) matrix
S3	5	92	8	α-U
	6	43	57	UZr_2
S4	7	90	10	α-U
	8	37	63	UZr_2

Salvato et al, JNM, 2022
Yao et al, Materialia, 2021
Xu et al. Scientific Report, submitted

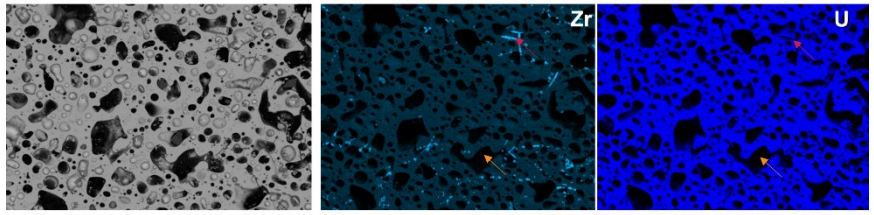
Phase Identification on 83B - Zr redistributions

SEM - fuel cross-section

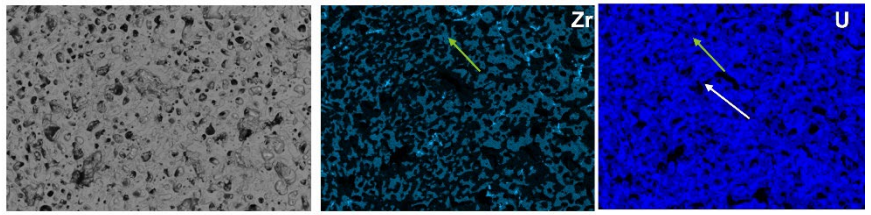


6 sample regions

SEM/EDS – element mapping

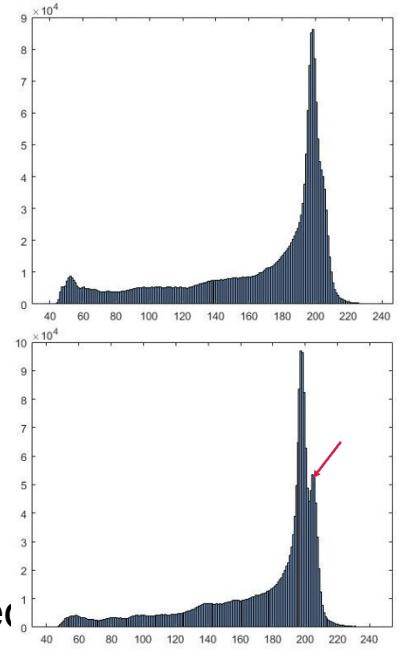


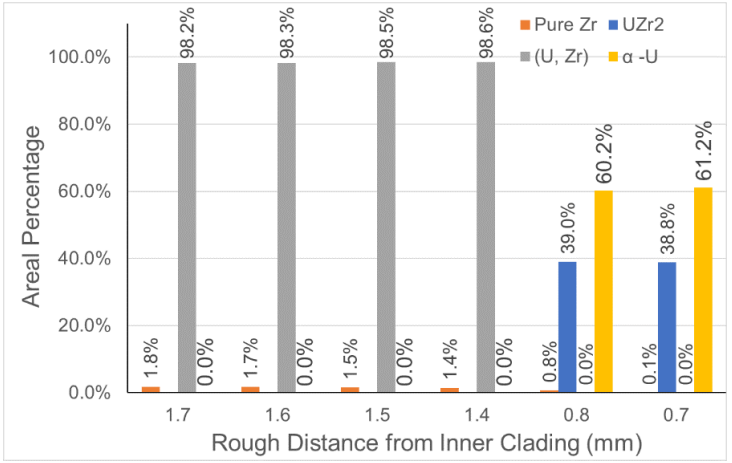
Close to **center** region

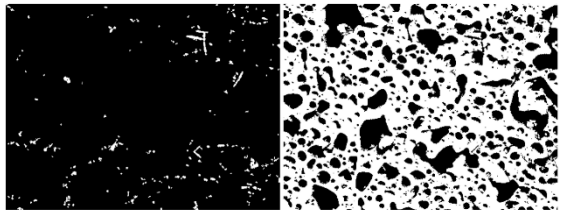


Region 6

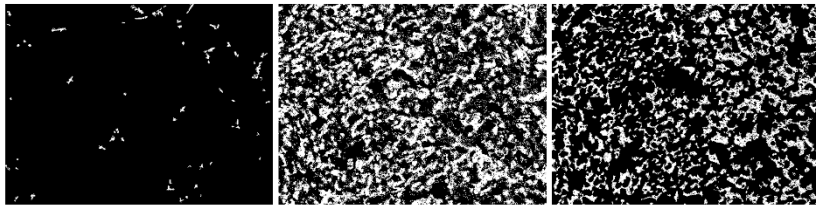
multi-thresh method







Pure Zr (U, Zr) matrix



Pure Zr $(\alpha - U)$ matrix UZr_2

Xu et al. Scientific Report, submitte

Phase Identification

Conclusion

Why machine learning

Complex problem
Huge dataset
Avoid human preference
Quantitative data for analysis

- Porosity distribution
- Bubble types/distribution
- Phase identification/distribution

Better understanding and prediction of fuel performance

Accelerate fuel qualification and licensing

Thank you for your attention

Backup - slides

$$Accuracy = \frac{\sum_j answer_j == predict_j}{\sum_j 1}$$

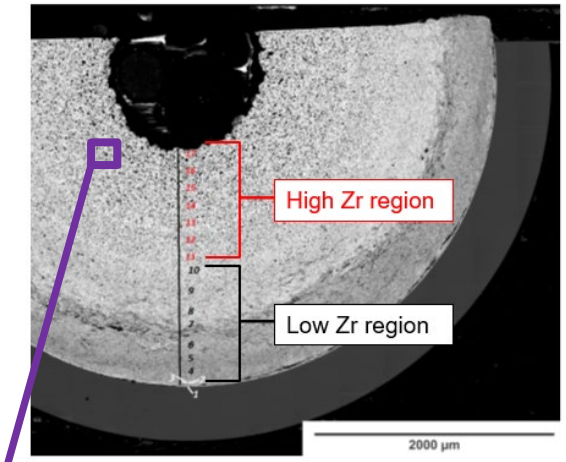
$$Precision = \frac{\sum_j answer_j == predict_j}{\sum_j predict_j == 1}$$

$$Recall = \frac{\sum_j answer_j == predict_j}{\sum_j answer_j == 1}$$

$$F\_measure = \frac{2 * Precision * Recall}{(Precision + Recall\ )}$$

	Bubble types	Accuracy	Precision	Recall	F_measure
Test dataset	Connected with fission product bubbles	0.85	0.47	0.29	0.36
	Connected empty bubbles	0.86	0.32	0.32	0.32
	Isolated bubbles	0.89	0.96	0.90	0.93
Entire dataset	Connected with fission product bubbles	0.94	0.69	0.84	0.76
	Connected empty bubbles	0.94	0.75	0.74	0.74
	Isolated bubbles	0.95	0.98	0.96	0.97

Manual Verification – Bubble Segmentation

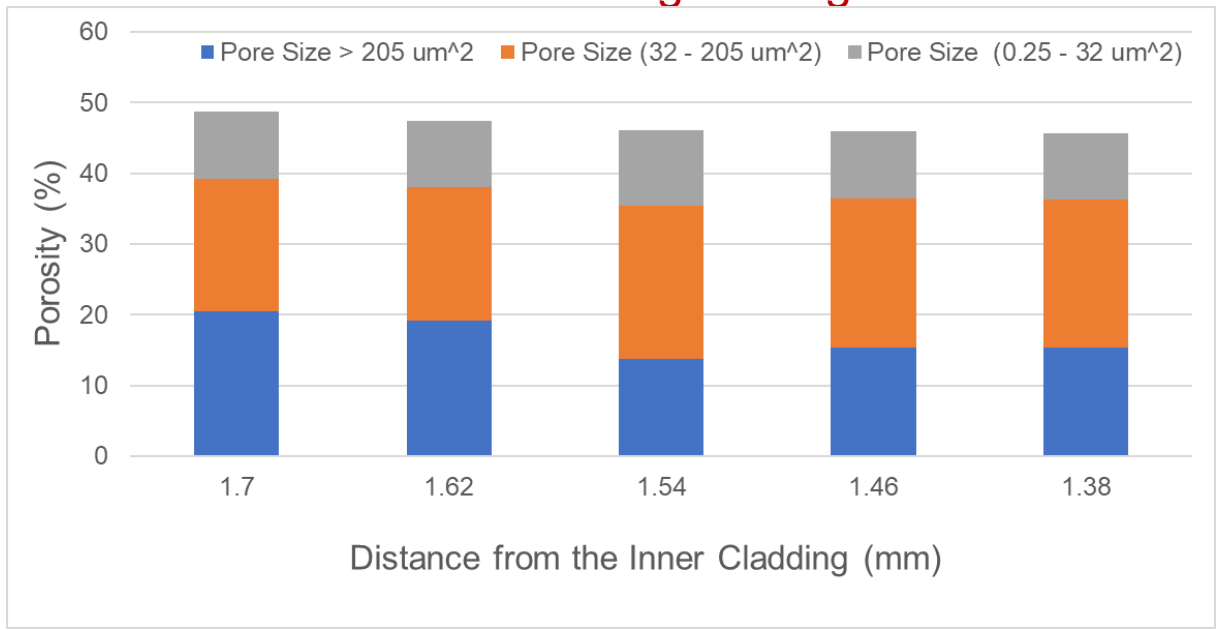


AFC-3D R1 (U-10Zr, 55% SD, annular, He, 4.3%FIMA, 600 C)

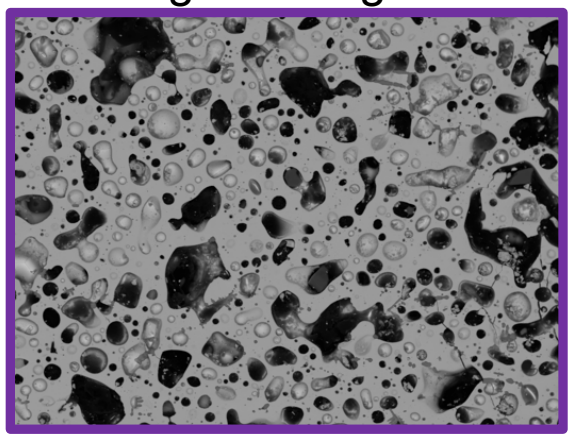
Automatic bubble segmentation

Machine learning

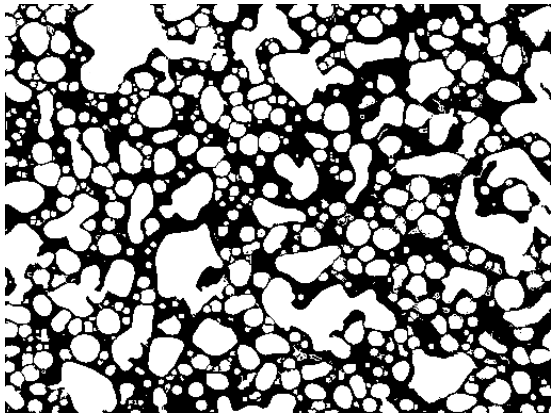
High Zr region



Original image



Manual bubble label



Porosity: 50.3%

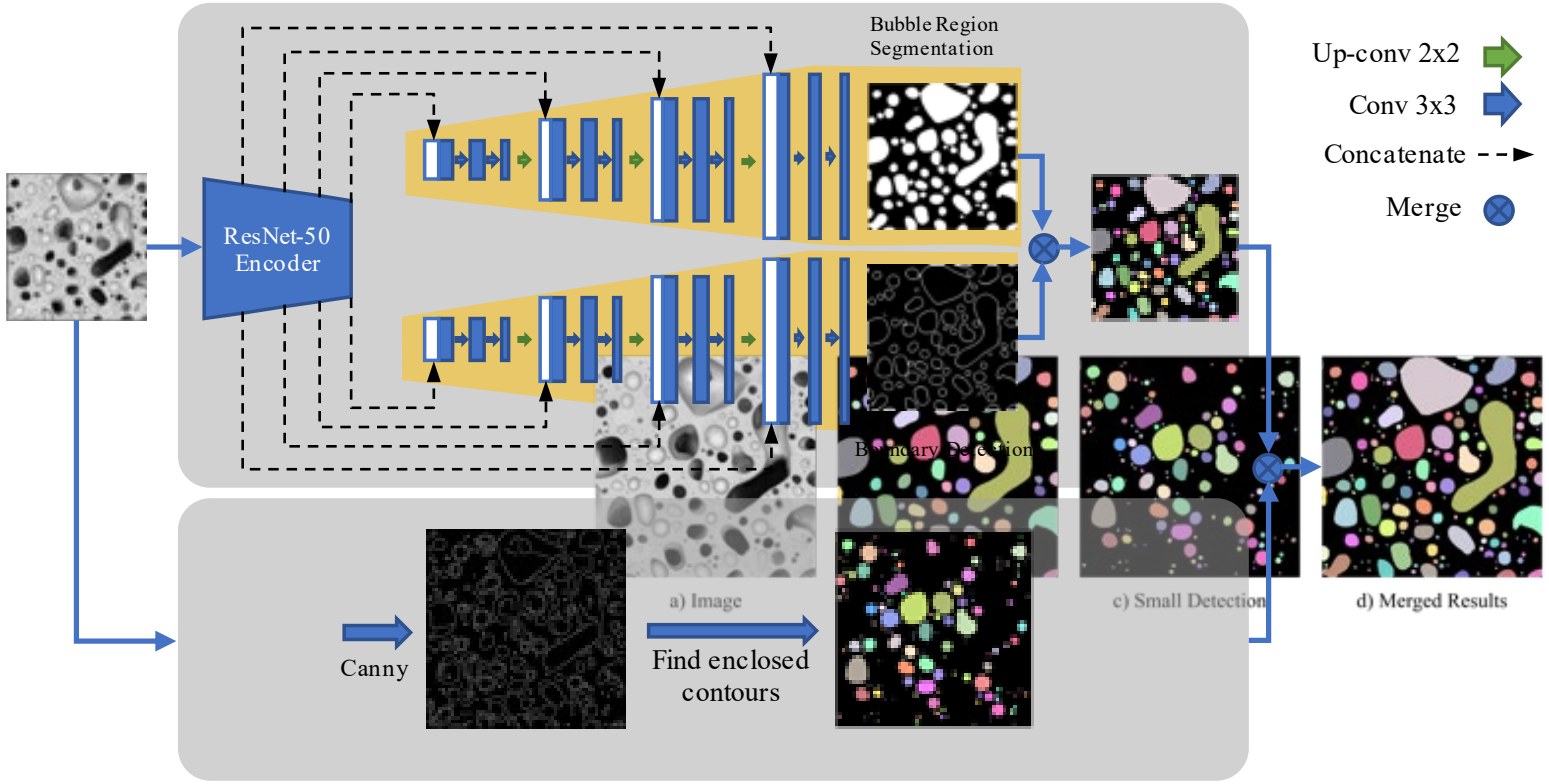


Image Processing

https://arxiv.org/ftp/arxiv/papers/2302/2302.12833.pdf