Engineered *Zircaloy Cladding Modifications* for Improved Accident Tolerance of LWR Fuel

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ENGINEERING AT ILLINOIS

US DOE NEUP ATF-IRP—UIUC Prime

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Objectives and Background

- Response to large amounts of H generation due to high temperature oxidation of Zr-base cladding
- A major concern both Post-Three Mile Island and Post-Fukushima
- Several US and International Programs

Issues: Extensive experience with Zr-based cladding

- Irradiation performance, processing experience, …
- Qualification issues, …
- Very difficult to move to a new cladding material

Approach: Examine Zr-based cladding with improved high temperature oxidation resistance

Participants

Project Director:	Brent J. Heuser/University of Illinois	
Partner Institutions:	University of Illinois:	Brent J. Heuser, Thomasz Kozlowski, Rizwan Uddin, James F. Stubbins, Dallas R. Trinkle, Robert. S. Averback
	University of Michigan:	Thomas J. Downar, Gary S. Was
	University of Florida:	Yong Yang, Simon R. Phillpot
	Idaho National Laboratory:	Piyush Sabharwall, Michael V. Glazoff, Jason D. Hales
	University of Manchester	Michael Preuss, Simon M. Pimblott, M.G. Burke, E. Jimenex-Melero, Fabio Scenini, Philip J. Withers
	ATI Wah Chang:	Melissa Martinez, Greg Vignoul

UIUC AFT-IRP Philosophical Approach

U.S. LWR assets are safe, well-maintained, and well-operated.

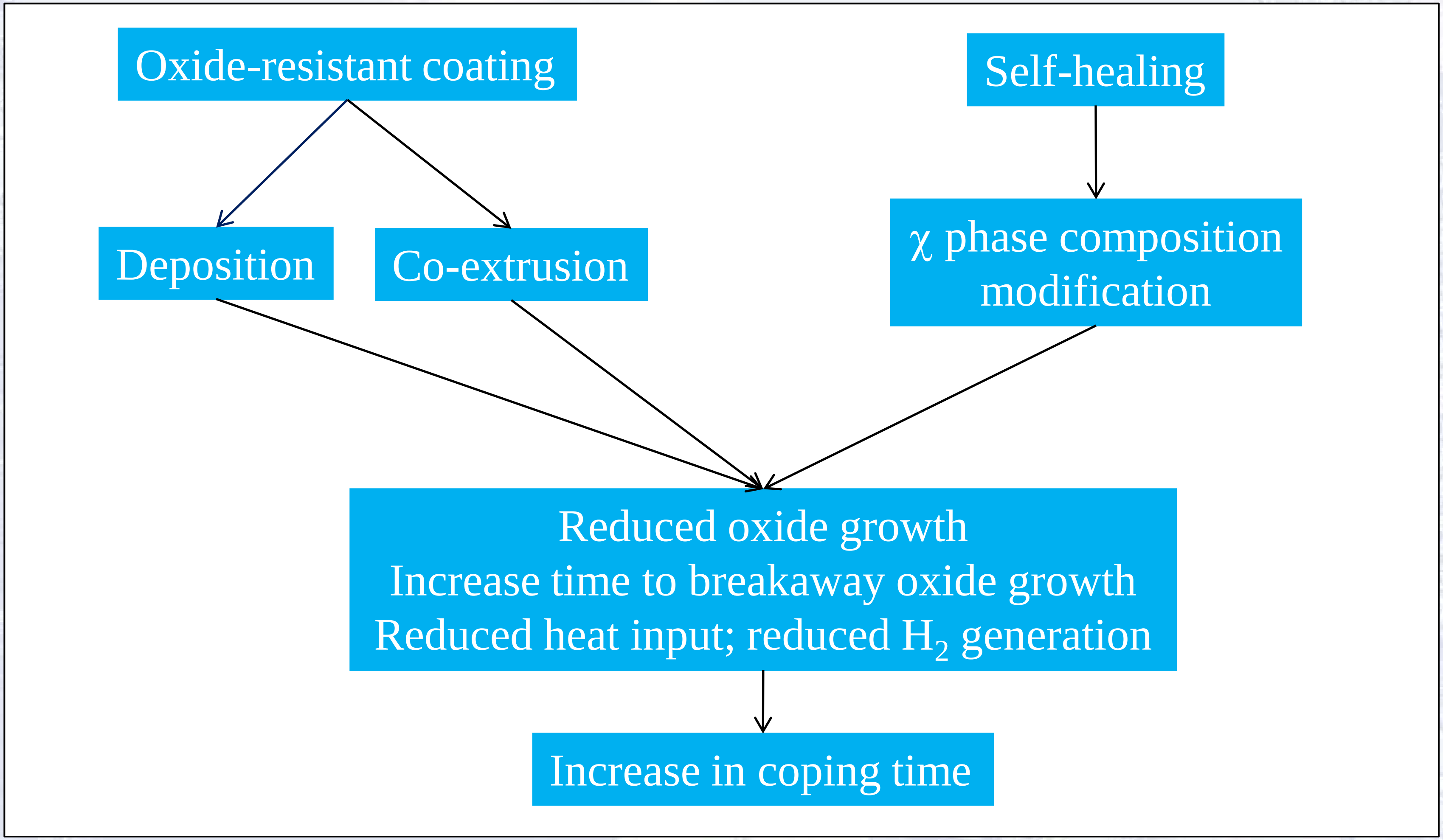
Zr-based cladding performs well in LWRs under normal operational conditions.

Extensive performance data base with respect to normal and transient conditions.

Regulatory approval/industry acceptance for modified Zr-based cladding path of least resistance.

Modifications of Zr-based cladding can lead to ATF without significant impact on performance under normal operational conditions.

Two Solution Pathways to Mitigate Accelerated Oxidation and H_2(g) Production



Self-healing pathway

ATI Wah Chang
(intermediate stock supplier)

χ phases with additives:
Si, Al, Mo, Cr

Zircaloy

Composition[a] (weight %) of various zirconium alloys.

Alloys	Tin	Iron	Chromium	Nickel	Niobium
Zircaloy-1	2.50	–	–	–	–
Zircaloy-2	1.50	0.12	0.10	0.05	–
Zircaloy-3A	0.25	0.25	–	–	–
Zircaloy-3B	0.50	0.40	–	–	–
Zircaloy-3C	0.50	0.20	–	0.20	–
Zircaloy-4	1.50	0.20	0.10	–	–
ZIRLO	1.02	0.10	–	–	1.01
M5®	–	0.05	0.015	–	1.0
É110	–	–	–	–	0.95–1.05
É125	–	–	–	–	2.20–2.60
É635	1.1–1.3	0.3–0.4	–	–	0.95–1.05
OPT ZIRLO	0.66	0.11	–	–	1.04
X5A (AXIOM)	0.5	0.35	0.25		0.3

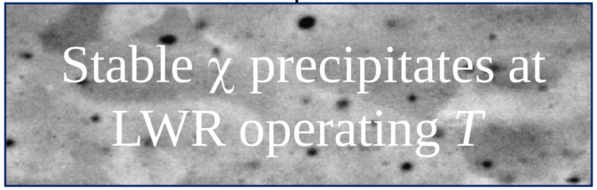
[a] Remainder zirconium.

χ phases

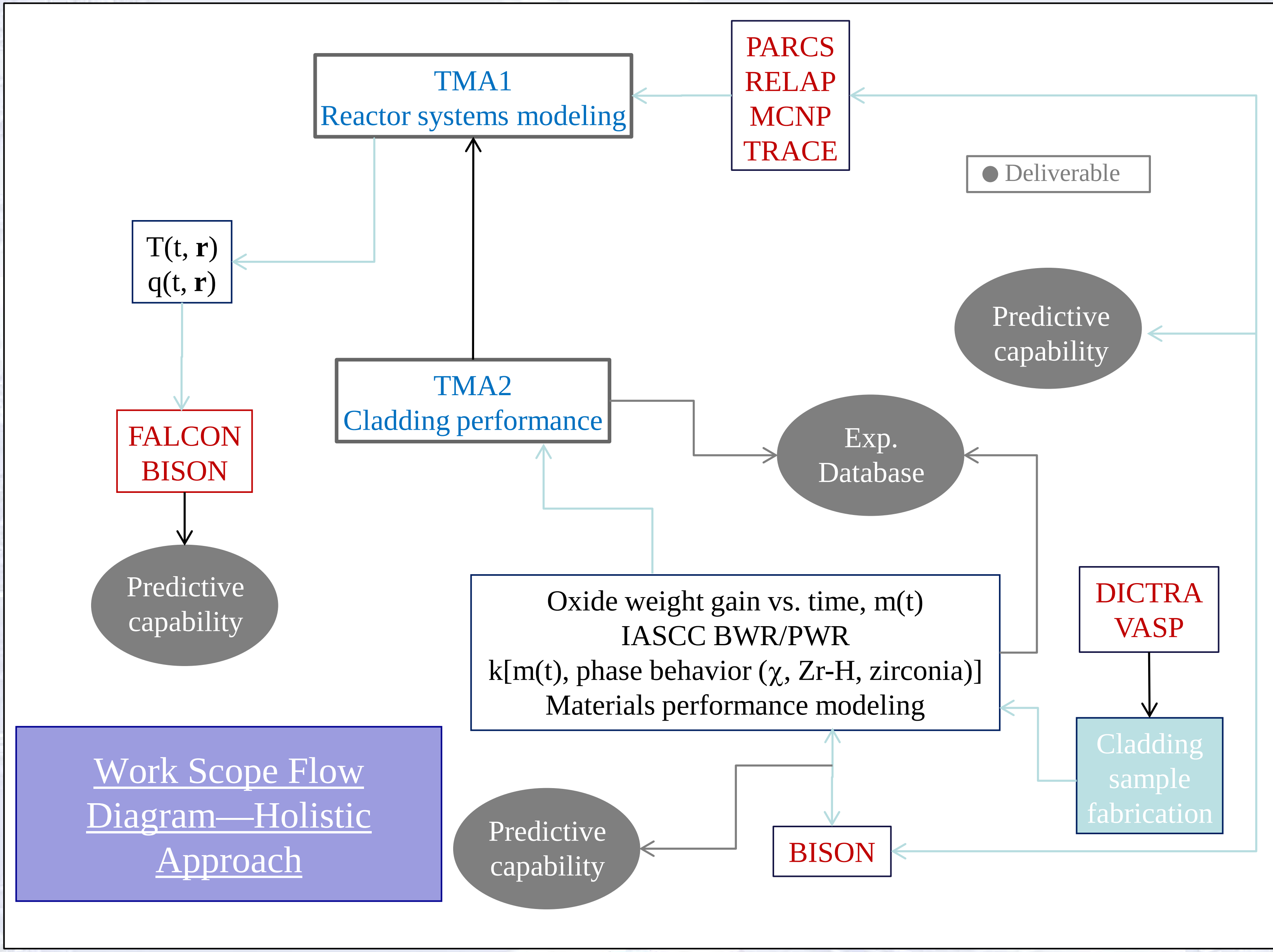
Additives segregate to free surface;
incorporated into oxide;
lower growth kinetics;
longer onset to accelerated
oxide growth.

χ precipitates dissolve
~900 C

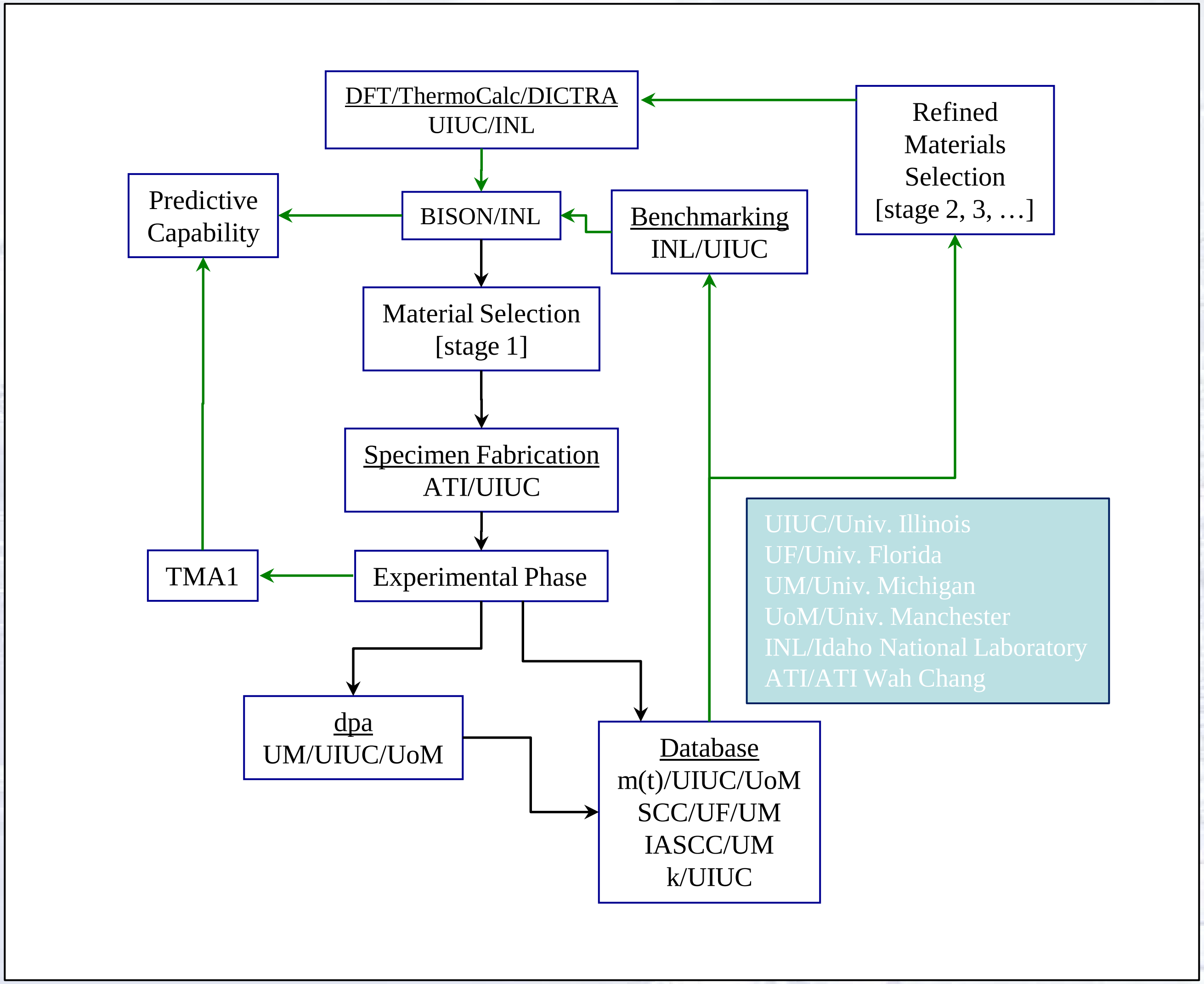
T



Work Scope Flow Diagram—Holistic Approach

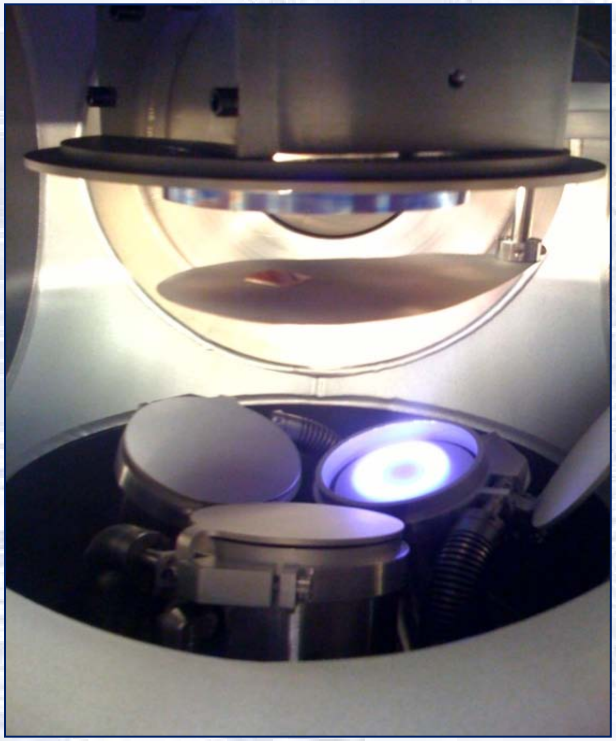


Participation Interconnections



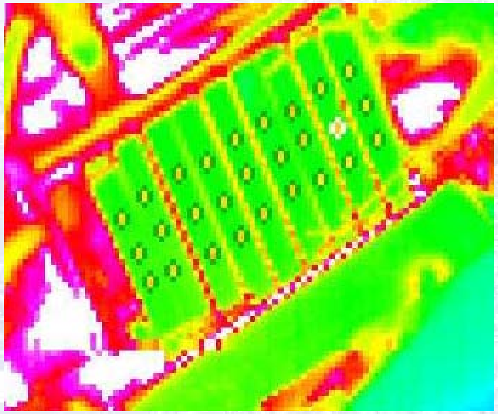
Experimental Capabilities—Sample Fabrication

Sputter deposition: U. Illinois
Cladding fabrication: ATI Wah Chang



Experimental Capabilities—In-service corrosion

Autoclave capability: U. Michigan, U. Florida, U. Manchester
Ion accelerator capability: U. Illinois, U. Michigan, U. Manchester

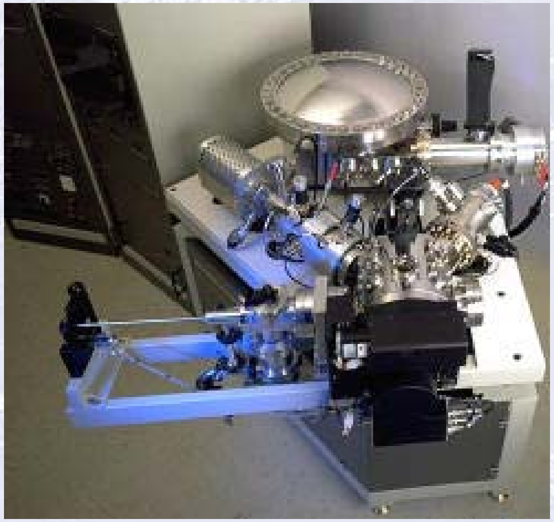


Experimental Capabilities—Off-normal oxidation

TGA: U. Illinois, U. Manchester

Experimental Capabilities—Microanalytical Characterization

Microanalytical: U. Illinois (FS-MRL), U. Michigan, U. Florida, U. Manchester
AES, TOF-SIMS, XPS, FIB, X-ray based techniques, TEM, SEM, AFM,…
ANL: IVEM, APS

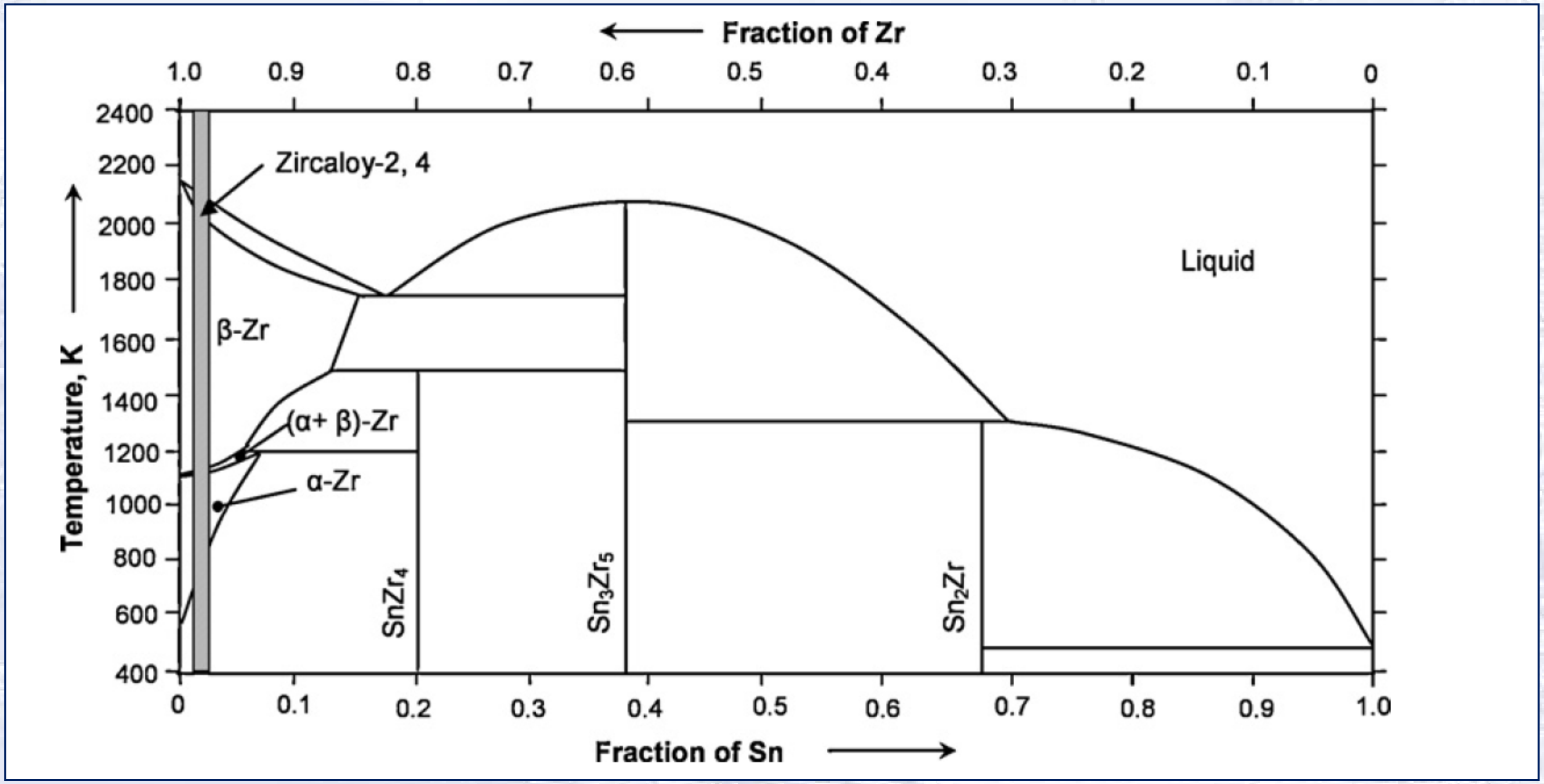


U.S. DOE NEUP/U.K. RCEP Investment

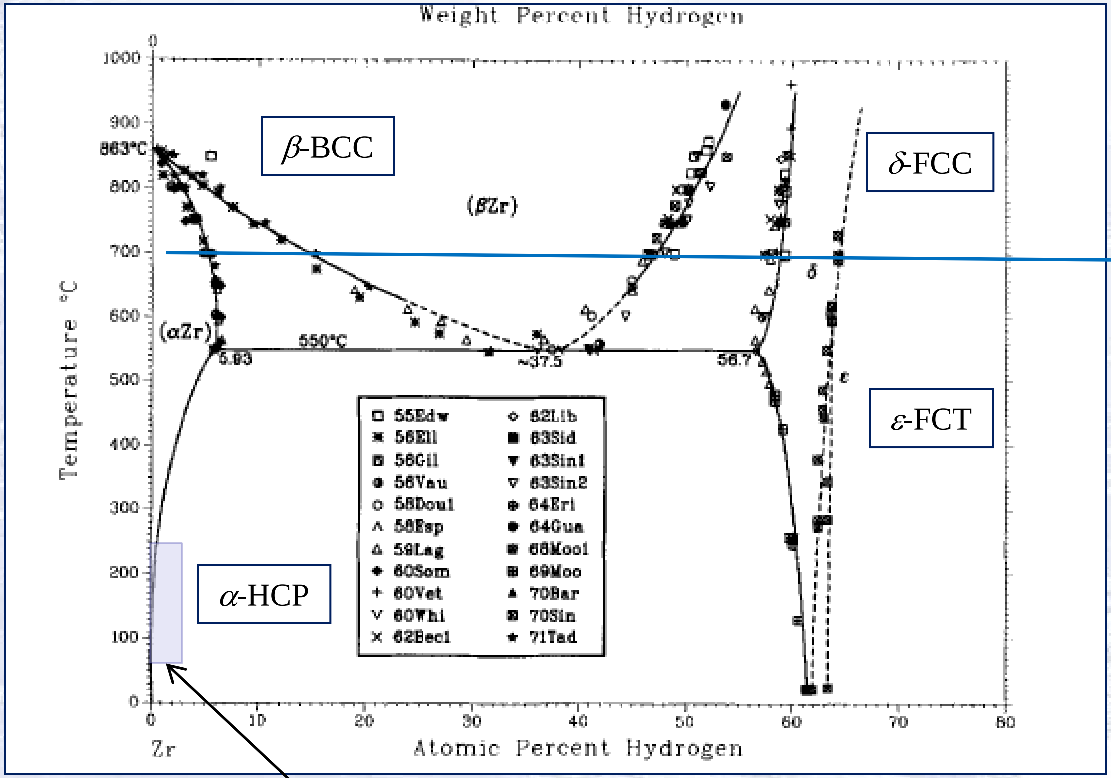
Table 5. Summary of budget allocation for IRP partners.

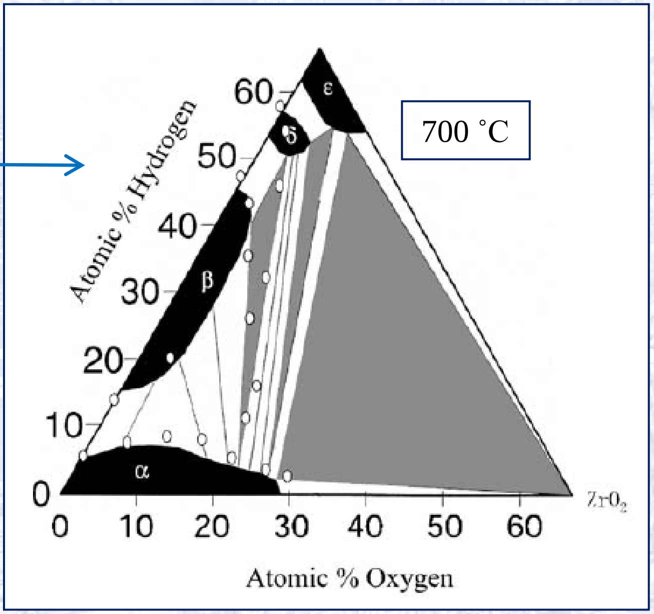
Partner	Year 1	Year 2	Year 3	Total
U. Illinois	$538,764	$543,416	$557,768	$1,639,945
U. Michigan	$230,000	$230,000	$230,000	$690,000
U. Florida	$213,180	$165,492	$161,329	$540,000
INL	$150,000	$150,000	$150,000	$450,000
ATI Wah Chang	$60,000	$60,000	$60,000	$180,000
U. Manchester (funded via the U.K. Research Council Energy Programme)				£984,270*
TOTALS	$1,191,944	$1,148,908	$1,159,097	$3,499,945*

Zr-Sn phase diagram



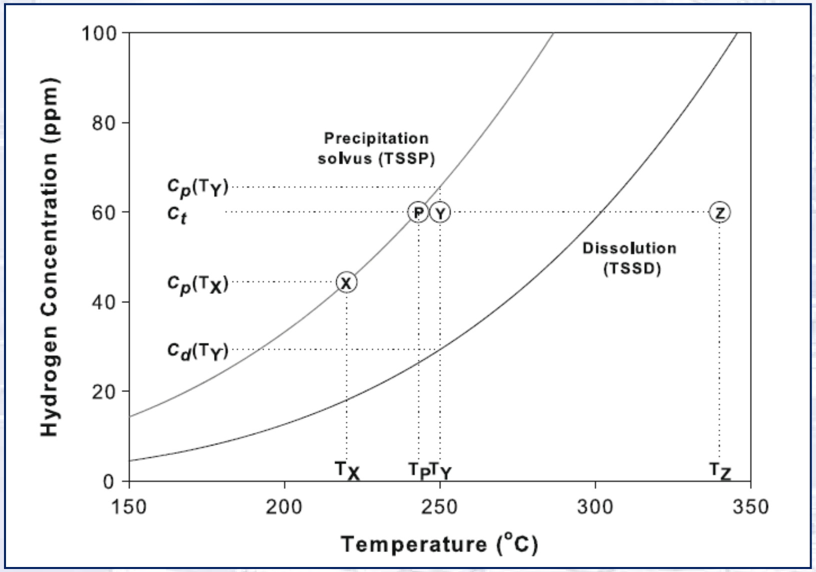
Zr-H and Zr-H-O Phase Diagrams





Relevant region for in-service and UFS

Zr-H phase behavior at low H concentration



G.A. McRae et al. / Journal of Nuclear Materials 396 (2010) 130–143

Conclusions

- Multidisciplinary Approach to Accident Tolerant Fuel Cladding – materials, neutronics, irradiation performance, processing, corrosion, …
- Response to large amounts of H generation due to high temperature oxidation of Zr-base cladding
- A major concern both Post-Three Mile Island and Post-Fukushima
- International Collaborations