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

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E N G I N E E R I N G A T I L L I N O I S

US DOE NEUP ATF-IRP—UIUC Prime

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Participants

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UIUC AFT-IRP Philosophical Approach

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

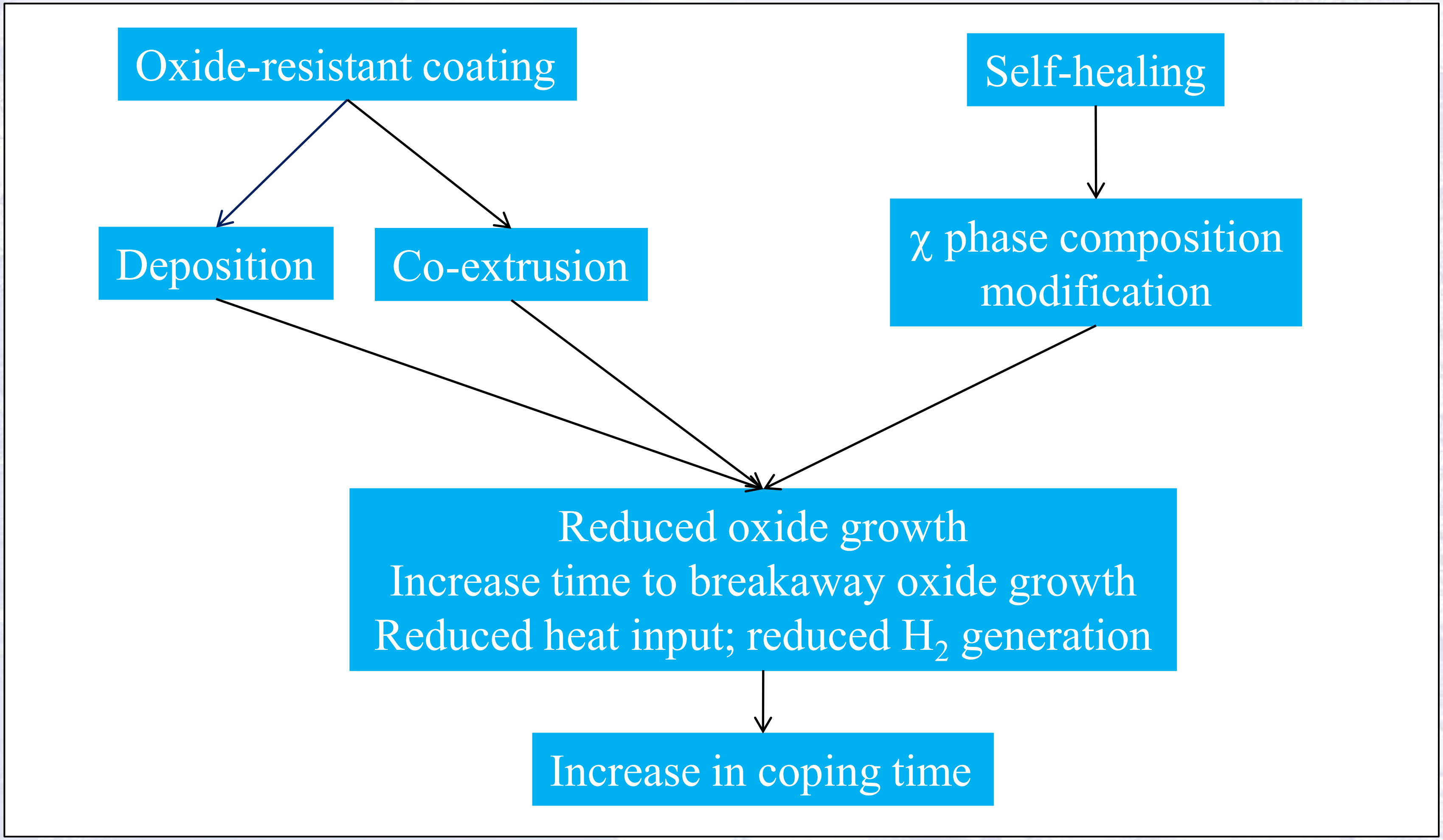
Zr-based cladding performs well in LWRs under normal operational conditions.

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



Possible Coating Materials

Table 3. Listing of potential candidate materials Zr-based cladding modification.

Candidate Material	Current Applications	Advantages	Disadvantages	Reference
ZrO_2 (Al_2O_3)	Micro-plasma oxidation in electrolyte solution in AC conditions	Exceptionally hard, pore-less coating structure, tried for Zr-4	Possibly prone to brittle fracture under shock loading	[45]
Fe-Cr-Al	Boiler tank applications	Best for sulfur envir.	Not tried for Zr-alloys	[46]
Al-Mn	Steam corrosion applications, e.g., for ferritic steel like P-92	Uniform coating, excellent adhesion to P-92	Not tried for Zr alloys	[47]
Al_2O_3	Metal cutting coatings	Inert, high temperature, tried for Zr-2 and Zr-4	Porous structure	[48]
Fe-Cr-Mo	Suitable for coatings of mild steel	HVOF and APS processes	Works as amorphous material, not tried for Zr	[49]
Al_2MnO_4	Works for P92 ferritic steel	Aggressive environment , overheated steam	Careful control of CVD deposition process is required	[50]
$ZrSiO_4$	Exceptional stability to water vapor, high temperature stability	Potential coating materials for Zr-alloys	Not studied as coating	[51]

Self-healing pathway

ATI Wah Chang
(intermediate stock supplier)

χ phases with additives:
Si, Al, Mo

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

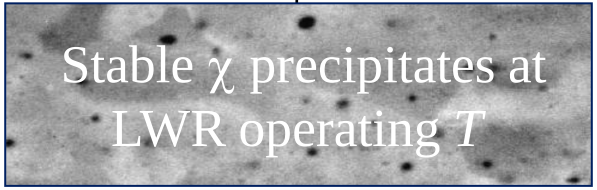
[a] Remainder zirconium.

χ phases

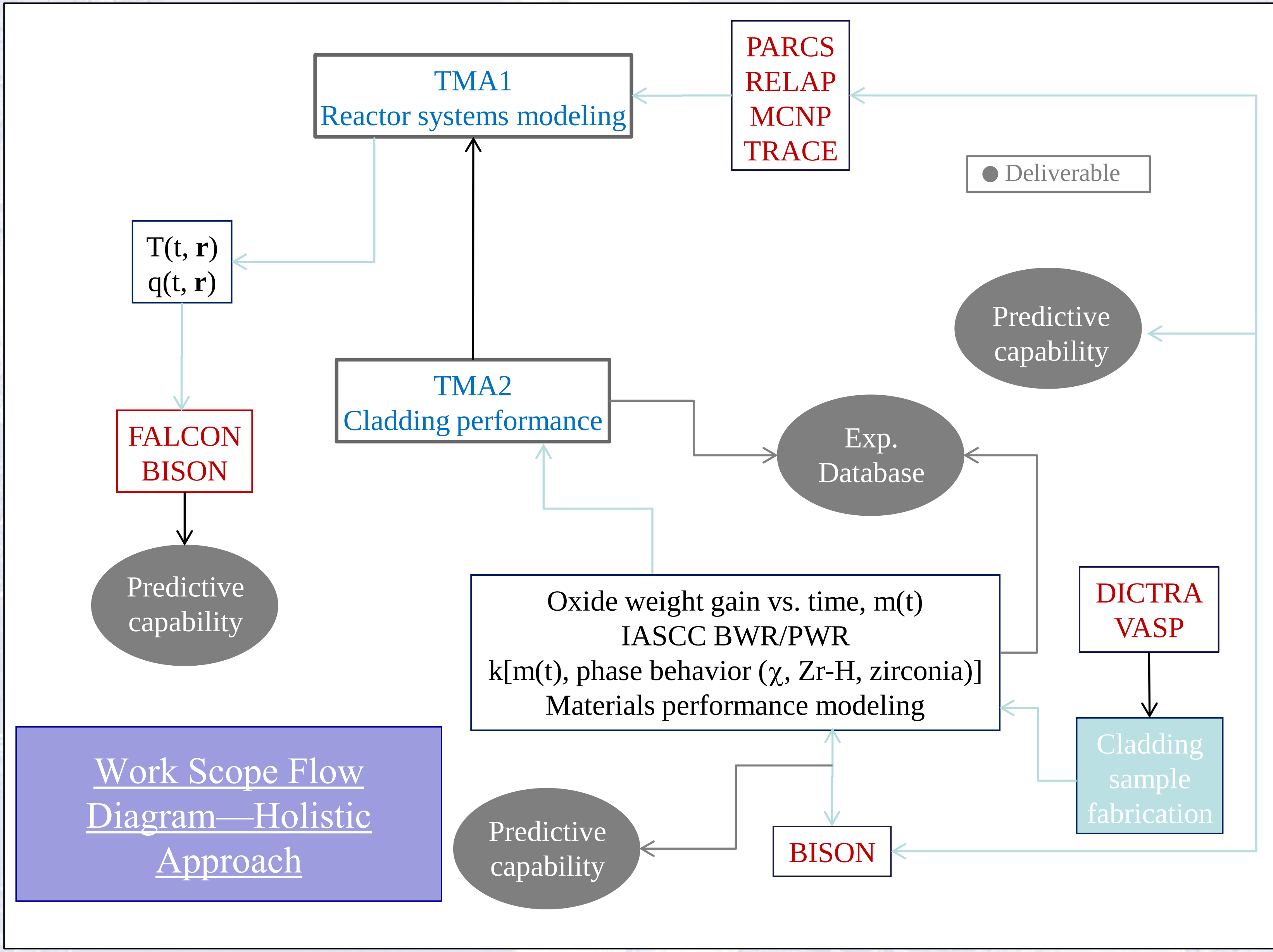
Additives segregate to free surface;
incorporated into oxide;
lower growth kinetics;
longer onset to accelerated
oxide growth.

χ precipitates dissolve
~900 C

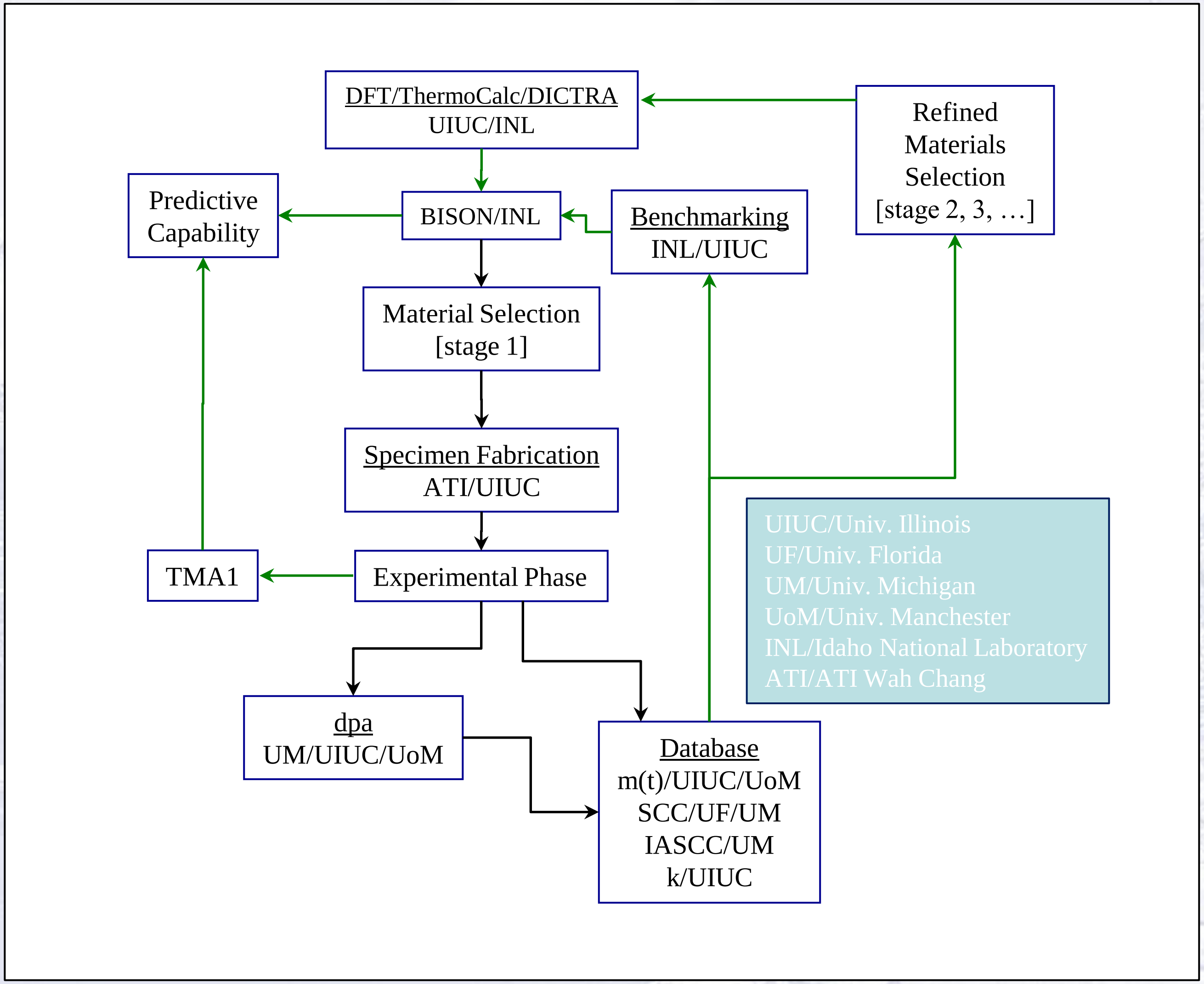
T



Work Scope Flow Diagram—Holistic Approach



Participation Interconnections



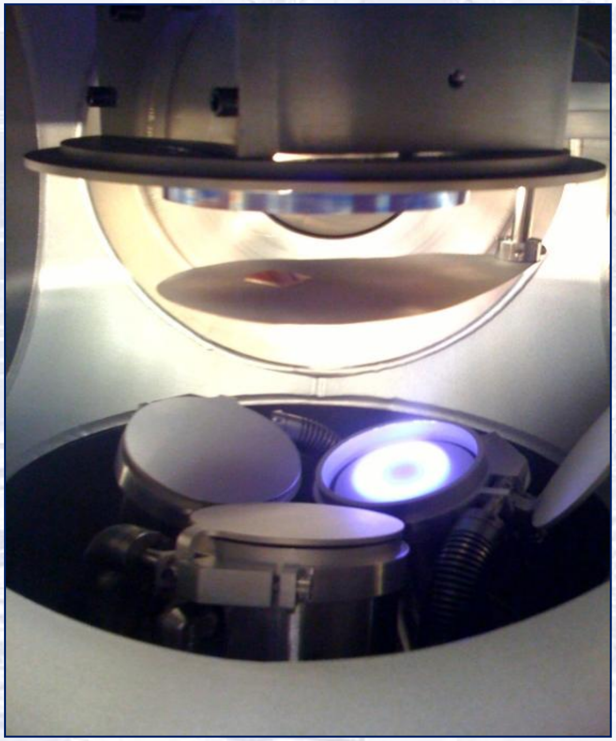
U.S. DOE NEUP/U.K. RCEP Investment

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*

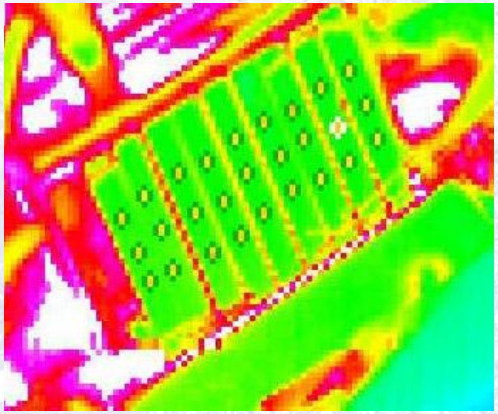
Experimental Capabilities—Sample Fabrication

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