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PROtect Cr: The leading E-ATF solution by Framatome

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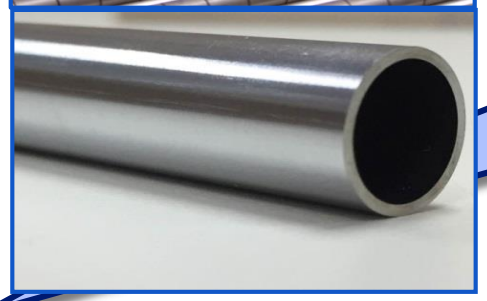
PROtect: Framatome's E-ATF Concepts

PROtect Cr
An evolutionary solution
Cr-coated $M5_{Framatome}$
- Incremental easy-to-license solution
- LFR irradiations since early 2019



PROtect SiC
A revolutionary solution
SiC_f/SiC Cladding
- Disruptive BDBA capabilities
- High challenges: product design, manufacturing, licensing

Benefits

Technological challenge

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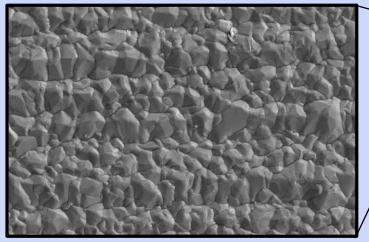
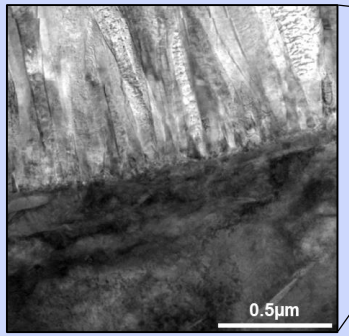
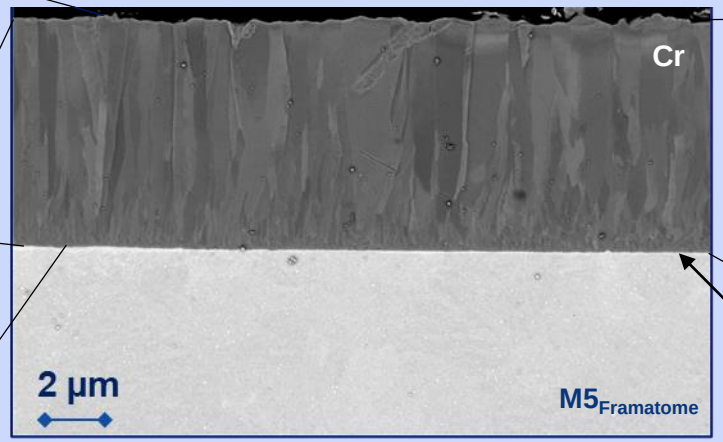
PROtect-Cr: Our Evolutionary E-ATF Solution

Roughness equivalent to uncoated cladding



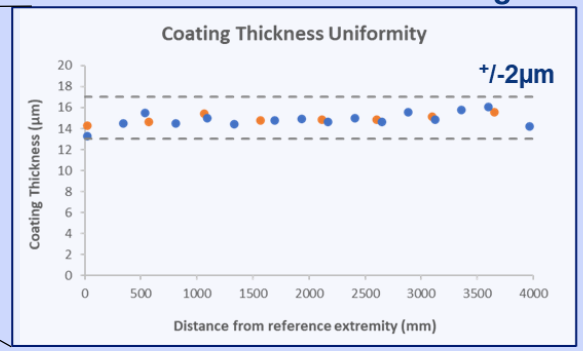


No significant modification of cladding microstructure

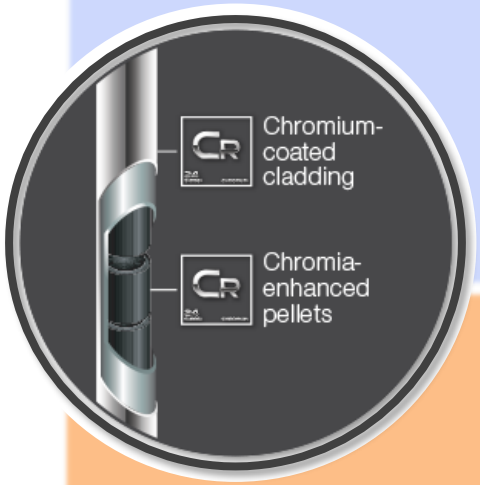


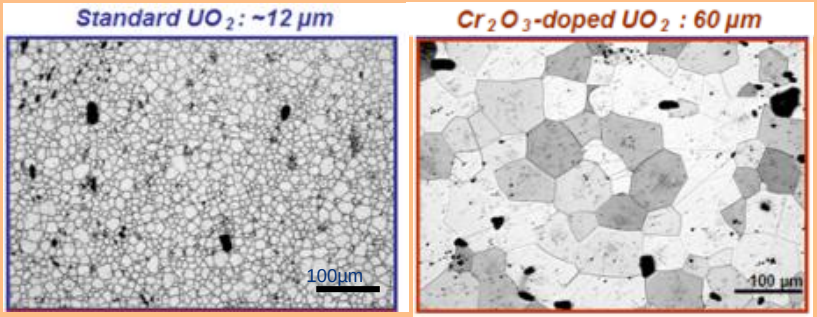
PVD produces a highly protective and adherent coating while retaining key $M5_{Framatome}$ cladding properties

Dense & uniform coating

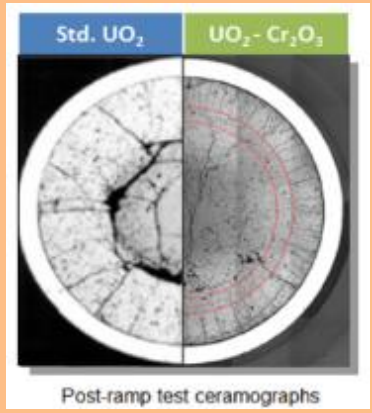


Excellent adherence





Large grain microstructure for improved fission gas retention

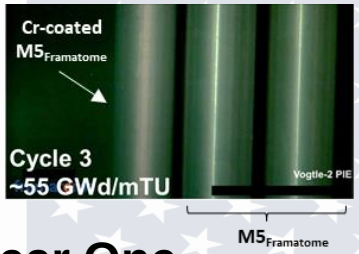


Enhanced viscoplasticity for improved PCI performance

PROtect-Cr: Worldwide Irradiation Program

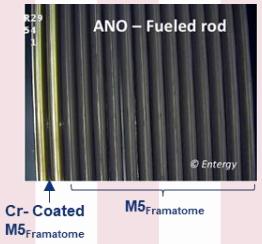
Vogtle

Program completed after 3 cycles of irradiation (18 month cycles)



Arkansas Nuclear One

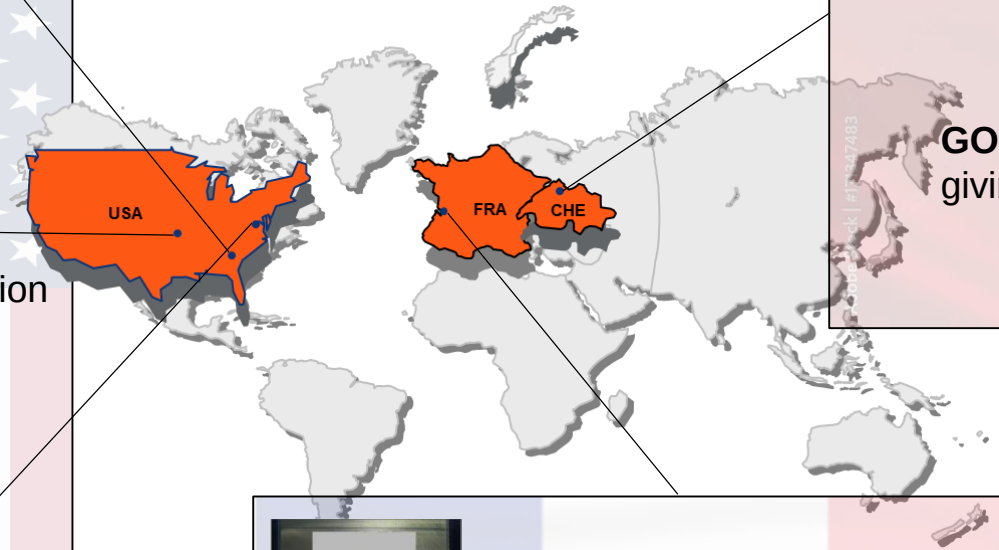
Program completed after 3 cycles of irradiation (18 month cycles)



Calvert Cliffs 2

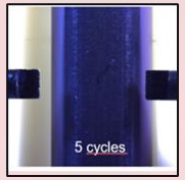
First fully-coated fuel completed its 2nd 24 month cycle

→ 3rd cycle in progress!

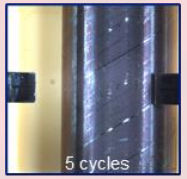


Gösgen → highest fluence/burnup reached for Cr-coated cladding

IMAGO – Six 12-month cycles giving an equivalent burnup of **~90GWD/tU**



GOCHROM – Five 12-month cycles giving a burnup of **~73GWD/tU**



→ Fuel rods reinserted for 6th cycle!

Blayais

First cycle in an EDF reactor completed

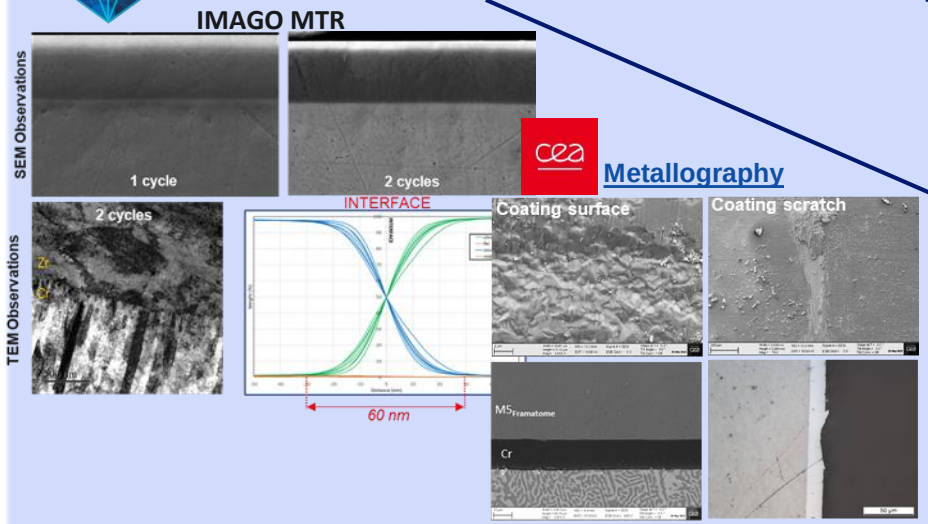
→ Second cycle in progress!

Records reached in qualifying Framatome's PROtect-Cr solution

PROtect-Cr: Demonstrated Performance

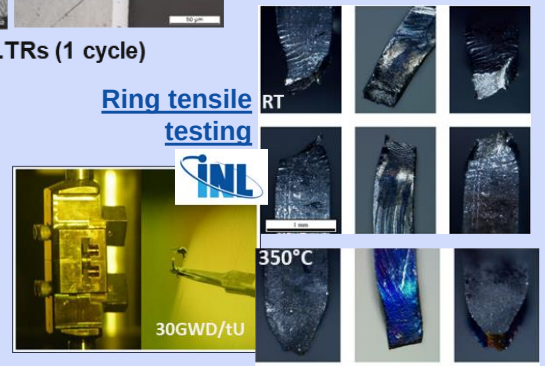
Excellent performance confirmed by PIE observations

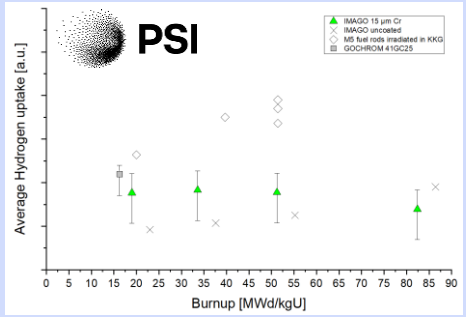
- Post-irradiation examinations ongoing with our global network of collaborators (CEA, PSI, INL, ORNL…)
- Excellent Cr-coating adherence confirmed. Mechanical properties of irradiated Cr-coated $M5_{Framatome}$ similar to irradiated $M5_{Framatome}$ cladding



Metallography

Burst testing





Hydrogen uptake
(IMAGO & GOCHROM)

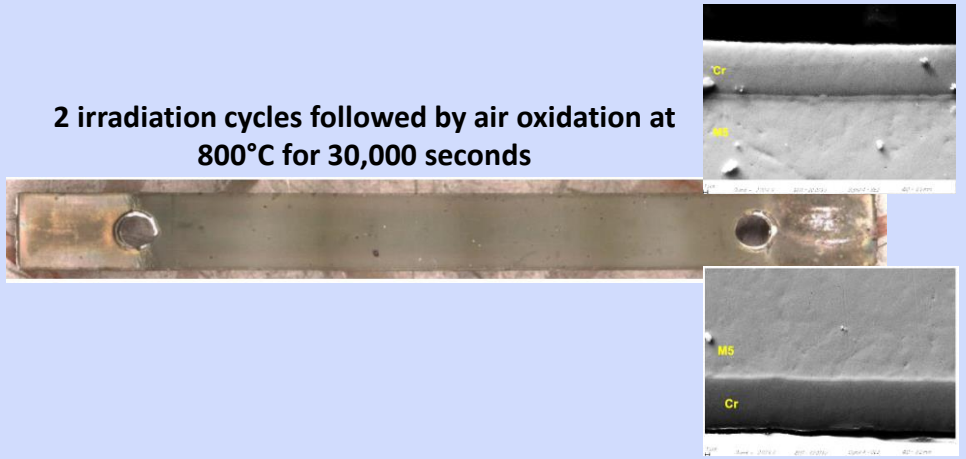
Key data setting the platform for US and EU licensing

PROtect-Cr: Resistant at High Temperatures

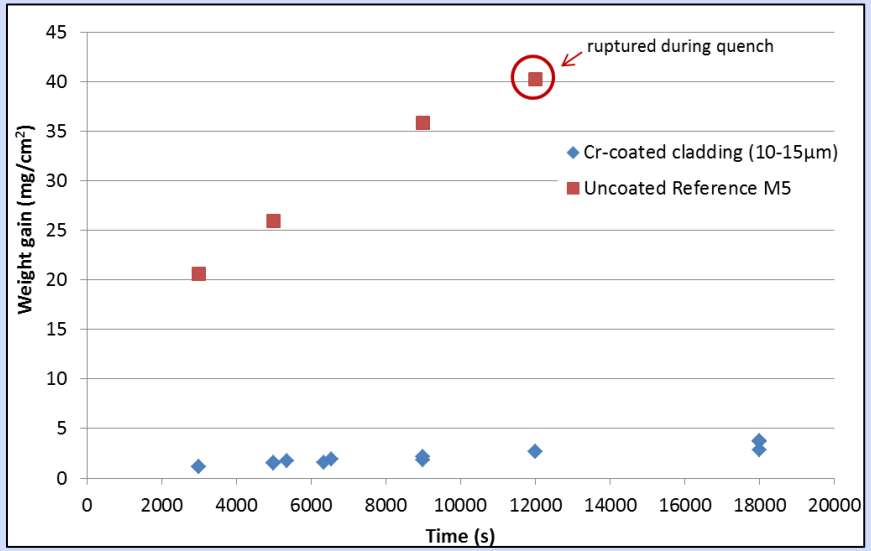
Added performance in accidental conditions

- Significantly reduced oxidation kinetics and hydrogen pick-up
- Reduced peak cladding temperature
- Reduced cladding strain at burst

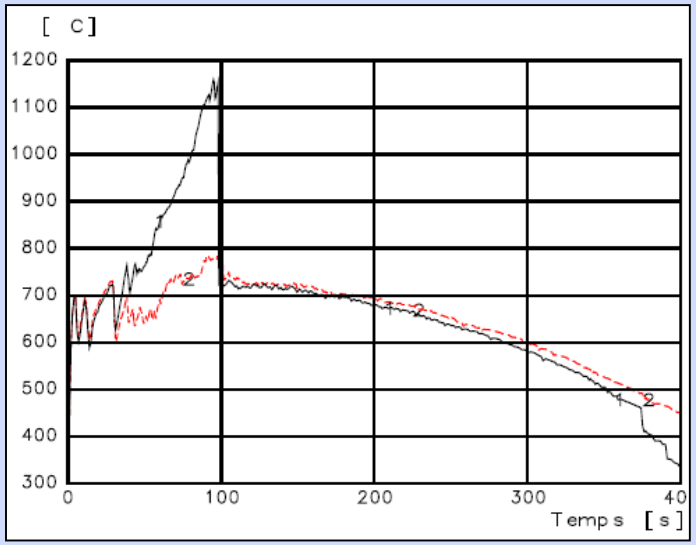
2 irradiation cycles followed by air oxidation at 800°C for 30,000 seconds



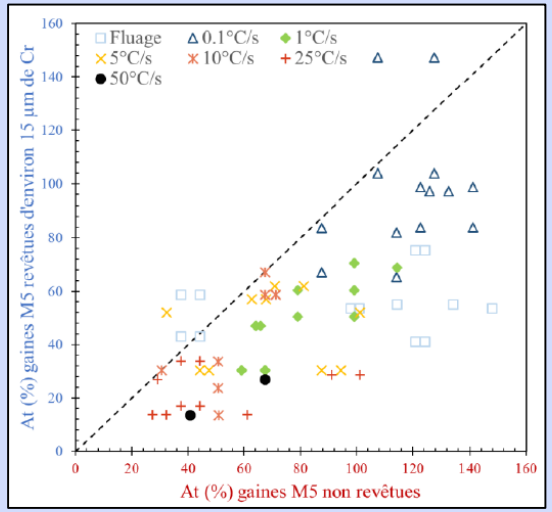
Oxidation kinetics at 1100°C

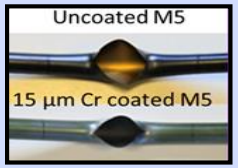


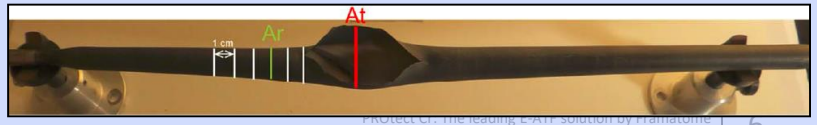
Large-break LOCA cladding temperature



Cladding strain at burst







PROtect-Cr: VVER Materials Qualification

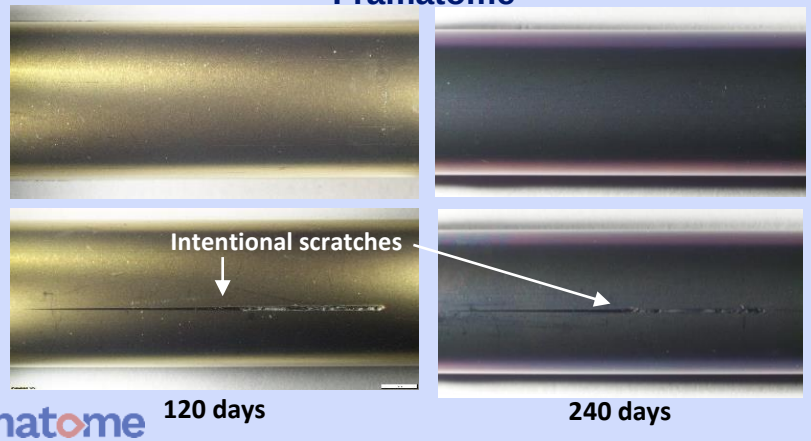
VVER 440 Fuel materials qualification program

- Autoclave exposure and high temperature oxidation of Framatome's fuel materials (including E-ATF) performed at UJP Praha under the Safe an Alternative VVER Europe Fuel (SAVE) project

Cr-coated $M5_{Framatome}$ cladding irradiation in the Temelin NPP

- Planned irradiation of Cr-coated $M5_{Framatome}$ cladding sections within the FIDES-II MCA-ATF JEEP irradiation program

Cr-coated $M5_{Framatome}$ – VVER1000 conditions



- ✓ Excellent corrosion performance consistent with PWR experience
- ✓ Adherent coating & excellent performance in the presence of pre-existing damage

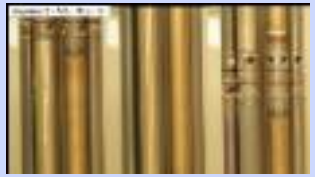
Important collaborations bringing Framatome Fuel to VVER reactors

PROtect-Cr: Towards Industrial-Scale Production

2026
Reload production readiness

OSIRIS 2015

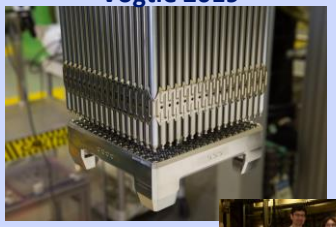
Halden 2017



IMAGO 2016

ATR 2018

Vogtle 2019



Gösgen 2019

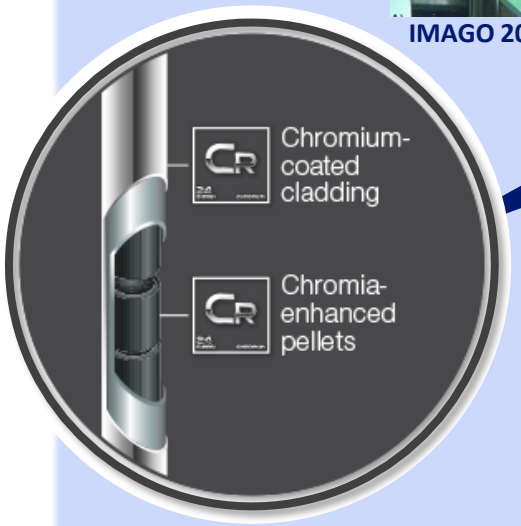
ANO 2019

Calvert Cliffs 2021

Hermès-P/Seismic test assemblies 2021

Blayais 2023

ATR 2025



2016: Cr-coating of small samples mastered

Lab-scale coater

2018: Cr-coating of full-length cladding begins

Full-length Prototype (FLP) Machine

2020: Full-length Cr-coating begins at Framatome Paimboeuf

Coating PROtect Prototype (CPP) Machines

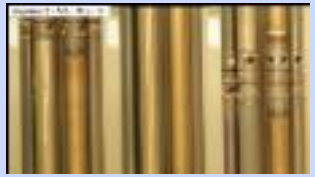
2025: Installation of industrial pilot line at Framatome Paimboeuf **(100,000 tubes/year)**

PROtect Industrial Pilot Facility

PROtect-Cr: Towards Industrial-Scale Production

OSIRIS 2015

Halden 2017



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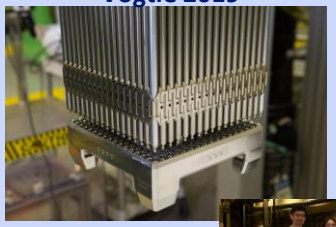

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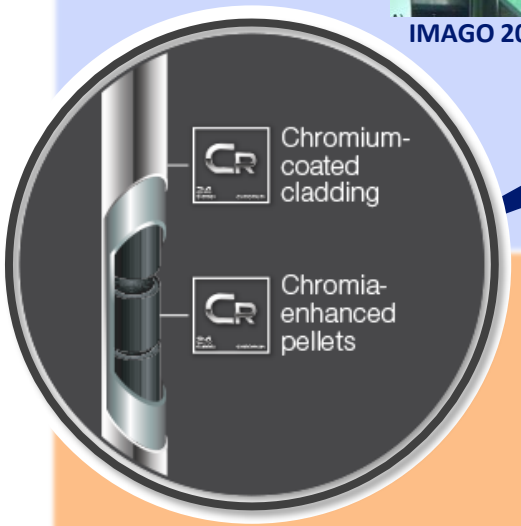
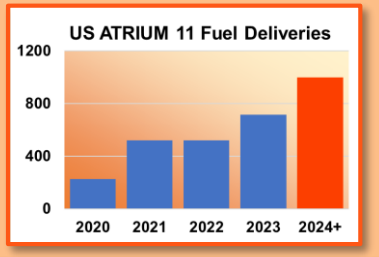


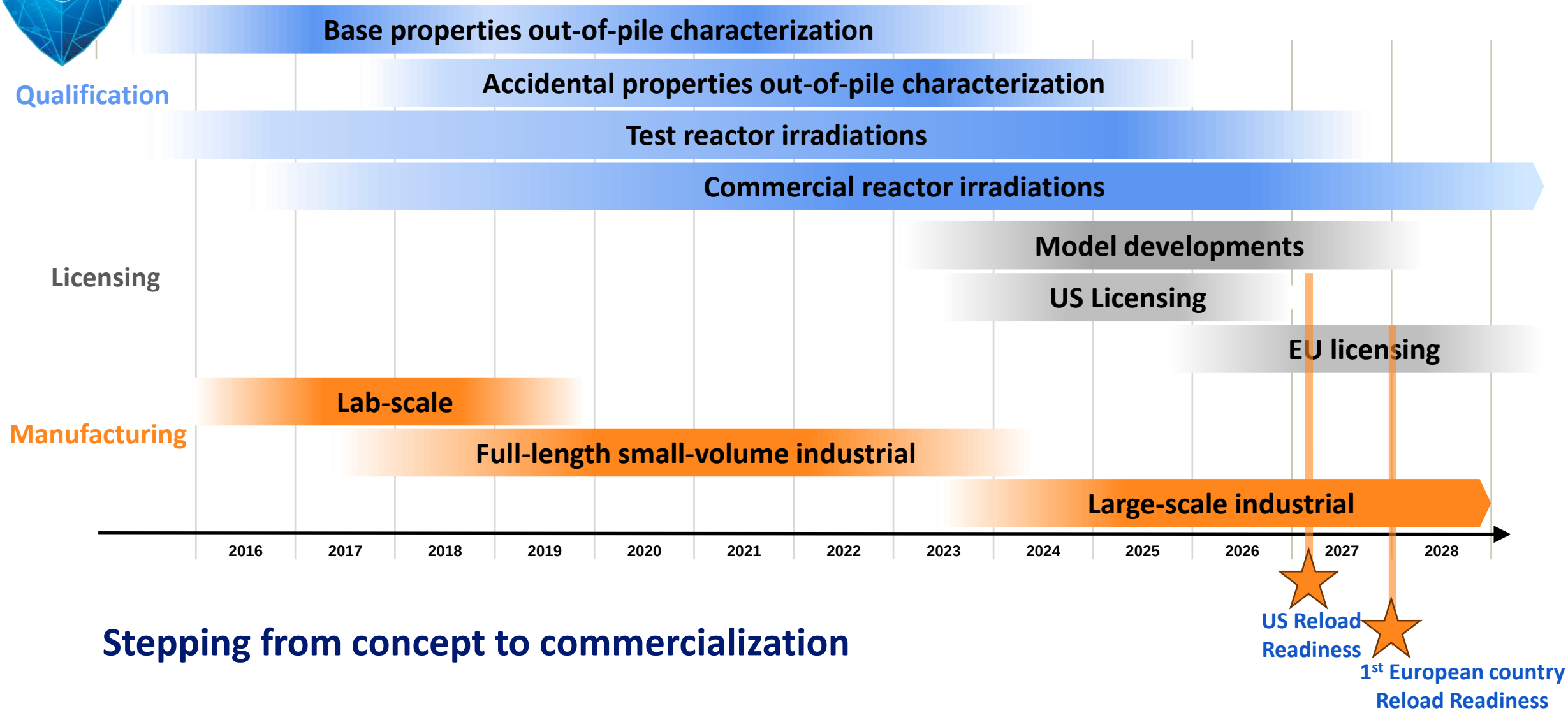
PWR reloads commercialized since 2018



BWR ATRIUM 11 reloads use Cr-enhanced pellets for PCI-resistance benefits

Commercialized & available at reload scale

PROtect-Cr: Step-by-Step approach



Stepping from concept to commercialization

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Making History

PROtect
Enhanced accident tolerant fuel program milestones are **taking fuel to the next level.**

120 million
chromia-enhanced fuel pellets manufactured

~500
chromium-coated full-length rods in operation

PROtect solutions have been implemented in

6 different reactor types

B&W, CE, KWU15, W17, and BWRs

2 in Europe

4 in the U.S.

2016 **Gösgen**
1st use in a reactor

2019 **Vogtle U2**
1st use in a U.S. reactor

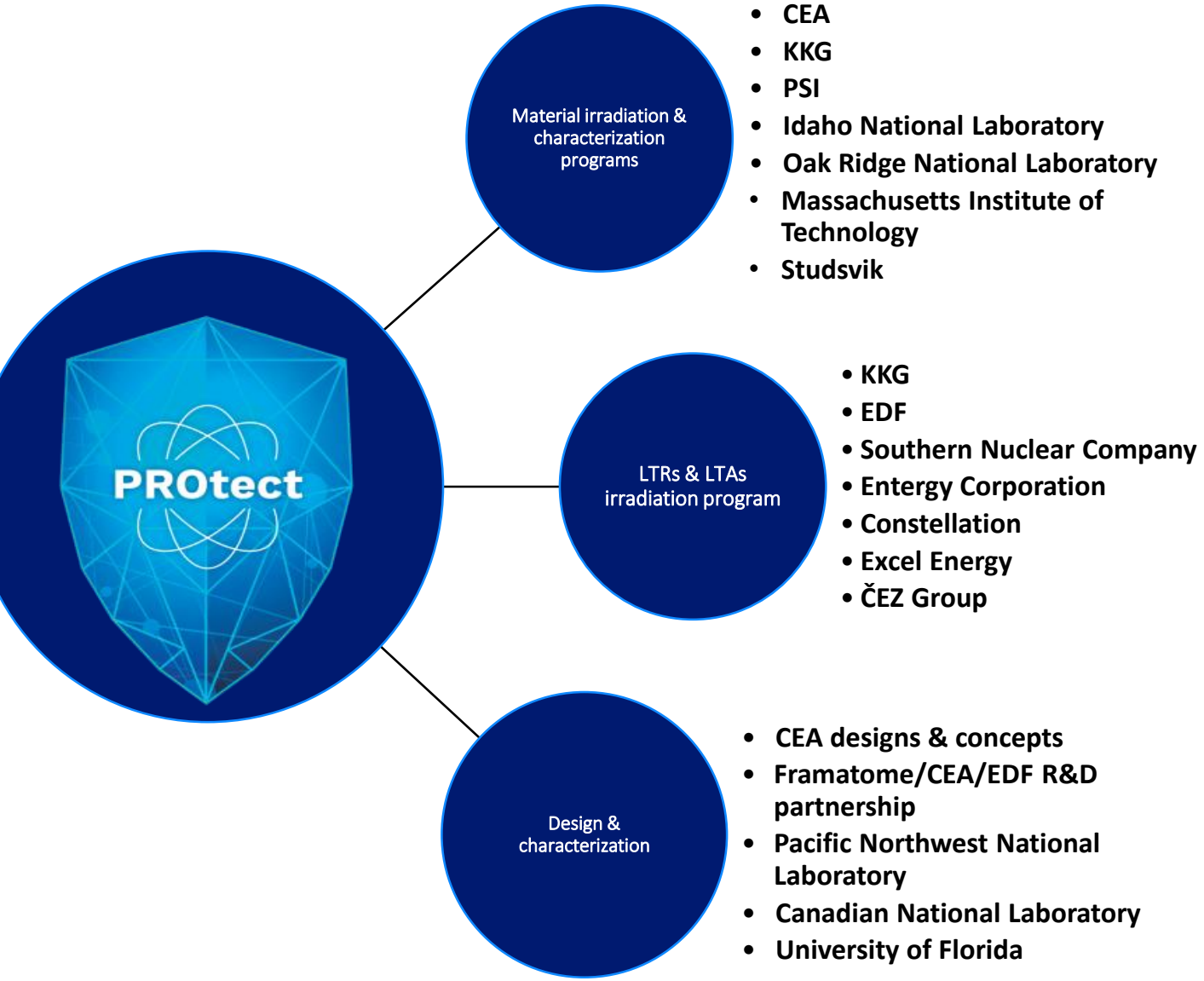
2020 **BWR Unit**
1st commerical reload using PROtect chromia-enhanced fuel pellets

March 2021 **Calvert Cliffs**
1st complete PROtect fuel assembly in operation

June 2021 **Gösgen**
1st complete lifecycle

Future technologies and expansion include: increased uranium enrichments and silicon carbide.

Acknowledgements



- CEA
- KKG
- PSI
- Idaho National Laboratory
- Oak Ridge National Laboratory
- Massachusetts Institute of Technology
- Studsvik

- KKG
- EDF
- Southern Nuclear Company
- Entergy Corporation
- Constellation
- Excel Energy
- ČEZ Group

- CEA designs & concepts
- Framatome/CEA/EDF R&D partnership
- Pacific Northwest National Laboratory
- Canadian National Laboratory
- University of Florida

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- The **I3P collaboration** for contributing to the initial development of Cr-coated cladding

PROtect

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