A Coordinated Framework for Proactive Materials Aging Management in Nuclear Power Plants



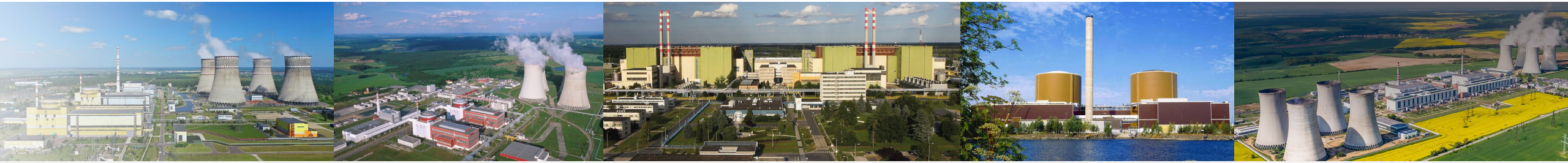
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PWR Prague 2026
Grand Hotel International Prague, October 21, 2026

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Outline

- EPRI Nuclear Materials R&D
- Materials Degradation Matrix (MDM) & Issue Management Tables (IMT)
- Case: SCC in Primary Water
- Future Outlook



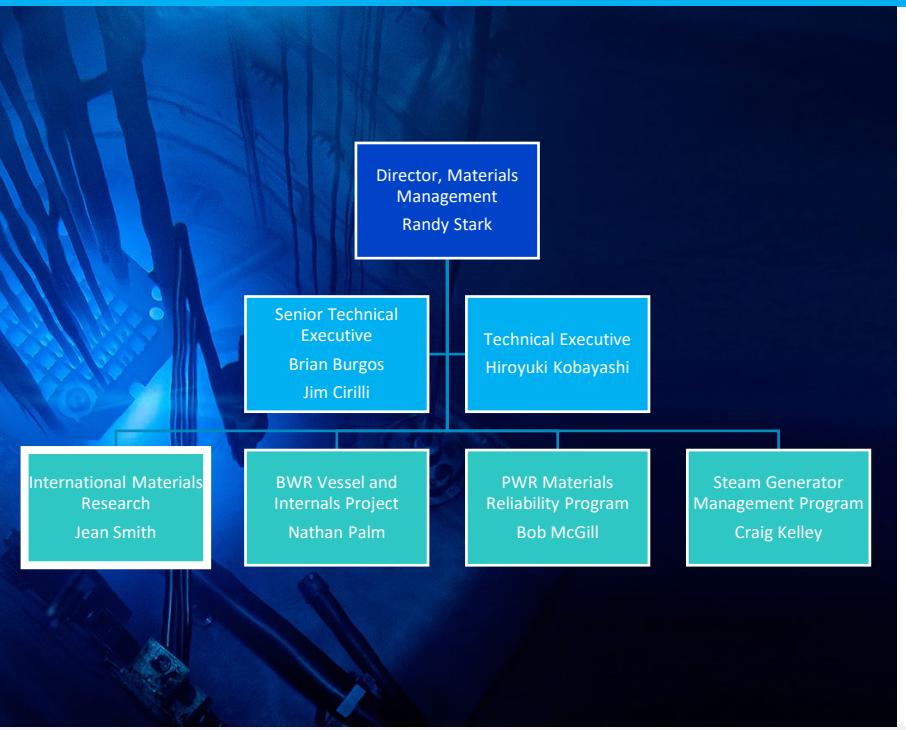
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IMR and the EPRI Nuclear Materials Department

International Materials Research conducts research to enhance the understanding of the damage mechanisms in materials used in water-cooled reactors

- International Materials Research (IMR) is an EPRI Nuclear Sector Base Program under the Materials Management Executive Committee
- IMR Members come from across the world and operate all reactor types (PWR, BWR, VVER, and CANDU) and are developing water-cooled SMRs

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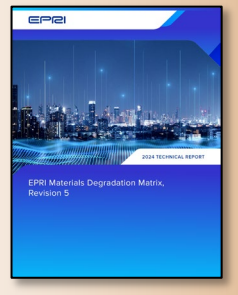
EPRI Materials Aging Management Process

Collect Operating Experience

EPRI SMEs collect data from field reports and inspection results and assess the efficacy of corrective actions (mitigation, repair, replacement).

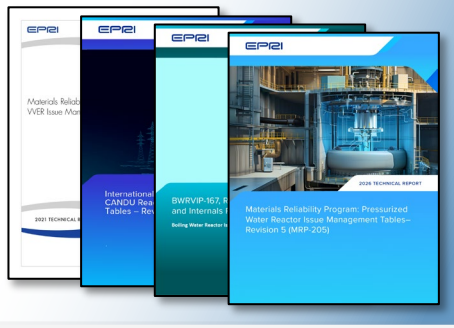
Review Research Results

Updated research results from EPRI programs, technical literature, and conferences are reviewed by EPRI SMEs.



Evaluate Technical Gaps

Gaps are reviewed from previous IMTs (close, keep open, re-rank). Define new gaps based on OE, prioritize gaps with utility members.



Address High-Priority Gaps

Conduct research on representative materials, perform simulations, develop new models to address high-priority assessment and degradation mechanism gaps.

Calibrate Models

Improve accuracy and technical robustness of databases that provide inputs to materials models. Calibrate conservatism applied to aging management strategies.

Optimize Inspections

Increased confidence in aging management strategies leads to optimized inspection requirements with respect to scope and frequency.

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EPRI Nuclear Materials R&D

Industry State-of-Knowledge



Reactor Types
↳ **Systems**
↳ **Materials/Environments**
↳ **Degradation Modes**

Utility Member Inputs



R&D Gaps
↳ **Categories**
↳ **Member Priority**

EPRI Materials R&D



Strategic Plans
↳ **Budget Allocations**
↳ **Project Portfolios**

Close R&D Gaps

Improve the State-of-Knowledge

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Historical Background of MDM and IMTs



A need to summarize the degradation mechanisms observed in primary system components led to the development of the Materials Degradation Matrix (MDM)

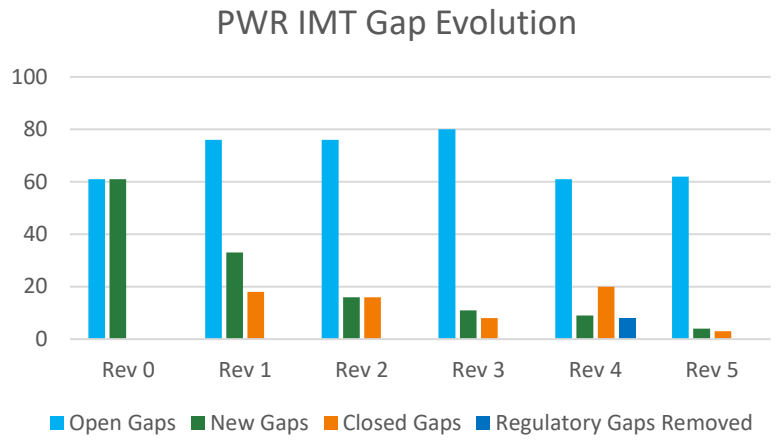


To address the degradation issues, Issue Management Tables (IMT) were developed as a tool to assist in identifying, describing, and prioritizing knowledge gaps requiring R&D

In the US, the MDM and IMTs are strongly linked to the industry policy in the Guideline for the Management of Materials Issues (NEI 03-08)

- Nuclear industry committed to follow the guideline
- EPRI materials programs (and other industry programs) have the primary responsibility for managing materials issues within their scope





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EPRI Materials Degradation Matrix (MDM)

- The EPRI Materials Degradation Matrix (MDM) summarizes the state of industry knowledge regarding degradation mechanisms and related research activities
- Rev. 4 (2018) the first one to introduce VVER-related materials and degradation mechanisms
- Latest revision (Rev. 5) published in November 2024



Table 6-4
VVER reactor vessel internals

MATERIAL	DEGRADATION MODE														
	Corrosion					Wear	SCC		Fatigue		Reduction in Frac. Properties		Irradiation Effects		
	Wstg.	Pitting	FAC	Foul	IGA		IG/TG	IA	HCF	EAF	Th	Env	Emb	VS	IC/SR
SS: Ti-Stabilized[1]	N	Y v4-2a	N	N	Y v4-5a	Y v4-6a	Y v4-7a	Y v4-8a	Y v4-9a	Y v4-10a	N	Y v4-12a	Y v4-13a	Y v4-14a	Y v4-15a
SS: Welds	N	N	N	N	Y v4-5b	Y v4-6b	N	Y v4-8b	Y v4-9b	Y v4-10b	Y v4-11b	Y v4-12b	Y v4-13b	Y v4-14b	Y v4-15b
SS: Martensitic[2] (VVER 440 only)	N	Y v4-2c	N	N	N	Y v4-6c	Y v4-7c	Y v4-8c	Y v4-9c	Y v4-10c	Y v4-11c	Y v4-12c	Y v4-13c	Y v4-14c	Y v4-15c
PH High Ni Stainless Steel[2]	N	N	N	N	N	Y v4-6d	N	Y v4-8d	Y v4-9d	Y v4-10d	Y v4-11d	Y v4-12d	Y v4-13d	N	N

1. Includes both internal structures (base metal and HAZ material) as well as baffle bolts.
2. Material associated with internal fasteners/hardware.

v4-8d	IASCC initiation in components fabricated from high-strength ChN35VT-VD high-Ni stainless steel is possible at doses as low as 1 dpa (experimentally proven), but not confirmed on operational components. Bolts made from high-Ni stainless steel could be replaced if any failure is detected. [R&D Status = GREEN]

Color coding:

- Green fill indicates that the degradation mechanism is sufficiently well understood.
- Yellow fill indicates R&D is in progress to address gaps associated with the degradation mechanism in a reasonable time frame.
- Orange fill indicates insufficient R&D is ongoing or planned to address gaps associated with the degradation mechanism in a reasonable time frame.
- Blue fill indicates insufficient data exist to establish degradation mechanism applicability.

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EPRI Issue Management Tables (IMTs)

The MDM and IMTs are publicly available on the EPRI website

- The EPRI IMTs proactively identify, categorize, and prioritize the R&D gaps based on member feedback
- Primary tool to manage EPRI Materials R&D
- 4–5-year update cycle

Gap Type
Design Type (V = VVER) — Sequential ID Number
V – AS – 01

Degradation Mechanism (DM) Gaps		
Gap ID	**Gap Description/Title**	**Priority (R0)**
V-DM-01	**Environmental Effects on Fracture**	High
V-DM-03	**Long Term SCC Susceptibility**	Medium
V-DM-04	**Steam Generator ODSCC at Extremely Highly Alkaline pH**	Medium
V-DM-02	**SCC of Thermally Aged CASS Pressure Boundary Components**	Low
V-DM-05	**Increased Fastener SCC Susceptibility due to Long Term Aging**	Low
V-DM-07	**Hydrogen Embrittlement of Piping between Pressurizer and Safety Valve**	Low
V-DM-06	**Thermal Embrittlement of Low alloy Pressure Vessel Steels**	Not Relevant/ Closed

V-DM-04 – Steam Generator ODSCC at Extremely Highly Alkaline pH

Status: Open

Priority: R0 - Medium

Issue:

Both VVER440 and VVER 1000 steam generators use titanium stabilized stainless steel tubes. This material is known to be susceptible to SCC initiated from secondary side (outer diameter) in acidic environment, but according to chromium oxide solubility curves the steel is susceptible to degradation in (highly) alkaline pH as well. (Note that there is no corresponding gap in the PWR IMT for this situation.)

Description:

The titanium stabilized stainless steel is extensively used in VVER design and it is also a material of steam generator. Although the material has an outstanding performance record for using in nuclear plants, it is known to be susceptible to SCC in acidic environment. As a result, the secondary chemistry focuses on minimizing the chloride and sulfide ingress to mitigate ODSCC. Also, micro-dosing of alkali hydroxide is used at some plants to shift crevice pH(T) to higher values. To date only the acidic crevice pH(T) was a concern, but extensive retubing of VVER fleet condensers for stainless steel improved secondary chemistry and highly alkalic crevices (according to Hide Out Return calculations) are observed in some plants.

There is a need for developing scientifically strong basis for crevice pH control specifying both acidic and alkalic limit to prevent corrosion issues of the steam generator tubes.

References:

EPRI Materials Degradation Matrix, Revision 4. (Notes v5-7a, v5-7b) EPRI, Palo Alto, CA: 2018. 3002013781.

Steam Generator Reference Book, Volume 1, Revision 1. (Table 24-31), EPRI, Palo Alto, CA: 1994. TR103824-V1R1



3002032174 3002034451 3002021033 3002031002

Degradation Mechanism (DM) Gaps → R&D needed to understand mechanism
Assessment (AS) Gaps → Mechanism understood, R&D needed to address impact and/or to characterize and manage
Mitigation (MT) Gaps → R&D needed to towards mitigation technology
Inspection & Evaluation (I&E) Gaps → Inspection guidance, NDE development, improvement, qualification
Repair / Replacement (RR) Gaps → Development of repair techniques

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VVER IMT Revision

Initial Review

1

- ☑ Kick-off meeting held on January 20-22, 2026
- ☑ Review of knowledge gaps by external contractors (SMEs)

Q1/2026

Draft revision

2

- ☑ EPRI/SMEs
- ☑ Add/Open/Close gaps
- ☑ Review/write technical descriptions
- ☑ Review gap priorities

Q2/2026

Gap Prioritization

3

- ☑ Virtual Workshop held on October 13-15, 2026
- ❑ Review the suggested revisions and priorities
- ❑ Update draft revision based on the workshop

Q3–Q4/2026

Publication

4

- ❑ Finalize report
- ❑ EPRI internal technical review process
- ❑ Publication

Q4/2026–Q1/2027



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MDM Revision 5 – Primary System Piping Updates

PWR

MATERIAL	DEGRADATION MODE: Corrosion – Wstg.	Pitting	FAC	Foul	Wear	SCC – IG	TG	IA	Fatigue – HCF	EAF	Reduction in Fract Properties – Th	Env
C&LAS: Base Metal & HAZ	Y p1-1a	N	N	N	N	Y p1-6a		Y p1-7a	N	Y p1-9a	Y p1-10a	Y p1-11a
C&LAS: Welds	Y p1-1b	N	N	N	N	Y p1-6b		Y p1-7b	N	Y p1-9b	Y p1-10b	Y p1-11b
SS: 300 Series SS Base Metal & HAZ	N	Y p1-2c	N	N	N	Y p1-6c		N	Y p1-8c	Y p1-9c	N	Y p1-11c
SS: 300 Series SS Welds & Clad	N	Y p1-2d	N	N	N	Y p1-6d		N	Y p1-8d	Y p1-9d	Y p1-10d	Y p1-11d
Cast Austenitic Stainless Steel	N	N	N	N	N	Y p1-6e		N	Y p1-8e	Y p1-9e	Y p1-10e	Y p1-11e

VVER

MATERIAL	DEGRADATION MODE: Corrosion – Wstg.	Pitting	FAC	Foul	IGA	Wear	SCC – IG	TG	IA	Fatigue – HCF	EAF	Reduction in Fract Properties – Th	Env	Irradiation Effects – Emb	VS	IC / SR
VVER 440 (All Piping Components[1]) & VVER 1000 (Branch Lines Only[2])																
SS: Ti-Stabilized (08Ch18N10T, 08Ch18N12T)	N	Y v3-2a	N	N	Y v3-5a	N	Y v3-7a	N	Y v3-9a	Y v3-10a	N	N	N	N	N	
CASS and SS: Welds (UONI 13/55)	N	N	N	N	Y v3-5b	N	Y v3-7b	N	Y v3-9b	Y v3-10b	N	N	N	N	N	
VVER 1000 (Large Bore Piping Components[2]) & Pressurizer[3]																
C&LAS (10GN2MFA) C&LAS Welds	N	N	N	N	N	N	N	N	N	N	Y v3-11c	N	N	N	N	
SS: Cladding (08Ch18N10T)	N	N	N	N	Y v3-5d	N	Y v3-7d	N	N	Y v3-10d	N	N	N	N	N	
CASS and SS: Welds (PT-30)	N	N	N	N	Y v3-5e	N	Y v3-7e	N	N	Y v3-10e	Y v3-11e	N	N	N	N	

The status was conservatively set to yellow to reflect potential gaps in knowledge with respect to the identification of susceptible components based on the recent OE with SCC of non-isolable branch piping in the safety injection system of some plants.

Y ⇨ Y

According to recent OE with SCC indications in the safety system piping in some Western-style PWR plants as well as the current knowledge of the root causes and influencing parameters, additional R&D is deemed necessary. Specifically, the role of dissolved oxygen and its effect on electrochemical potential in stagnant systems is not clear. This applies to piping made from both Ti-stabilized stainless steel and carbon steel piping with stainless steel cladding.

Y ⇨ Y

A national research project was initiated in the Czech Republic to better understand the mechanism of EAF and, if possible, to remove conservatism from the present methodologies for fatigue life calculations. Material testing under this project is done for the base metal of the primary piping 08Ch18N10T. Welding materials require further investigation.

Y ⇨ Y

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Issue Management Tables – SCC in Primary Water

MRP-236R1 (2017) | French OE (since 2021)

Reactor Type	Gap ID	Gap Title	Priority History						
			R1 (2008)	R2 (2010)	R3 (2013)	R4 (2020)	R0 (2021)	R5 (2026)	R1 (2027)
PWR	P-AS-09	SCC of Stainless Steels Exposed to Primary Water	High	High	High	Medium ↓	-	High ↑	-
VVER	V-AS-03	SCC of Stainless Steels Exposed to Primary Water	-	-	-	-	Medium	-	High ↑

DRAFT

PWR

Issue:

Field experience with austenitic stainless steel in operating PWRs has, in general, been good, with a relatively small number of failures attributed to SCC. Nevertheless, the number and nature of these failures are not insignificant and could potentially become more important as the PWR fleet ages. As a result, there is a need to better understand the factors controlling the potential for SCC occurrences so that proactive mitigation or management can be implemented.

Key questions remaining:

- Effects of chemical and material variables on crack initiation and growth. In particular, cold work, dissolved oxygen and temperature.
- Threshold conditions for initiation.
- Heat-to-heat variability (martensite, ferrite, sulfide inclusions, etc.).
- LTO and late life SCC initiation.

VVER

Issue:

VVER units use almost exclusively Ti-stabilized austenitic stainless steel (Type 321) in the primary circuit. Field experience with these steels in operating VVER reactors has been good, with a relatively small number of failures attributed to SCC (all occurrences under off-normal chemistry conditions). There is a need to better understand the factors controlling the potential for SCC occurrences so that proactive mitigation or management can be implemented.

Key questions remaining:

- Stabilized stainless steel has been shown to be particularly susceptible to SCC (initiation and crack growth) in highly caustic environments (e.g., crevices).
- Effects of transient, off-normal chemistry (e.g., chloride) and countermeasures (peening, electropolishing).

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EPRI Activities Related to SCC of Stainless Steel (PWRs)

- Revision of MRP-236R1 *"Stress Corrosion Cracking of Stainless Steel Components in Primary Water Circuit Environments of Pressurized Water Reactors"* to capture the knowledge and operating experience since 2017.
- Participation in industry focus groups: Auxiliary Piping SCC OE FG and Core Barrel FG.

Aux Piping SCC OE FG

- Coordinates efforts between PWROG and EPRI in evaluating OE
- Focus:
  - Understanding causal factors associated with recent aux. piping SCC operating experience
  - Understand relevance to the rest of the industry
  - Development of industry positions and/or guidance, as needed
  - Regulatory interactions

Core Barrel FG

- Coordinates efforts between PWROG, EPRI, NSSS vendors and utility personnel
- Focus:
  - Understanding technical issues associated with recent core barrel cracking
  - Coordinate an agreed upon industry approach to resolving issues
  - Goal is generic applicability and overarching recommendations

High-level updates from both FGs are publicly available via the NRC-Industry Tech Exchange Meeting

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EPRI Activities Related to SCC of Stainless Steel (VVERs)

SCC Initiation of Type 321 Stainless Steel in VVER Primary Water Environments under Off-Normal Conditions *(ongoing)*

01 R&D Gaps

- Understanding SCC susceptibility for primary circuit under off-normal conditions
- Off-normal material: sensitized or weld repaired stainless steel
- Off-normal chemistry: unintentional O_2 ingress and AL3 level contamination

02 Objectives

- Acquisition of time-to-initiation data for Type 321 stainless steel as a function of [O_2]
- Acquisition of time-to-initiation data for Type 321 stainless steel as a function of anionic impurities

03 Material

- Type 321 Ti-stabilized stainless steel (08Cr18Ni10Ti)
- Base metal, base metal sensitized, welded, welded and then repaired
- U-bend test specimen as per ASTM G-30

TEST ENVIRONMENTS

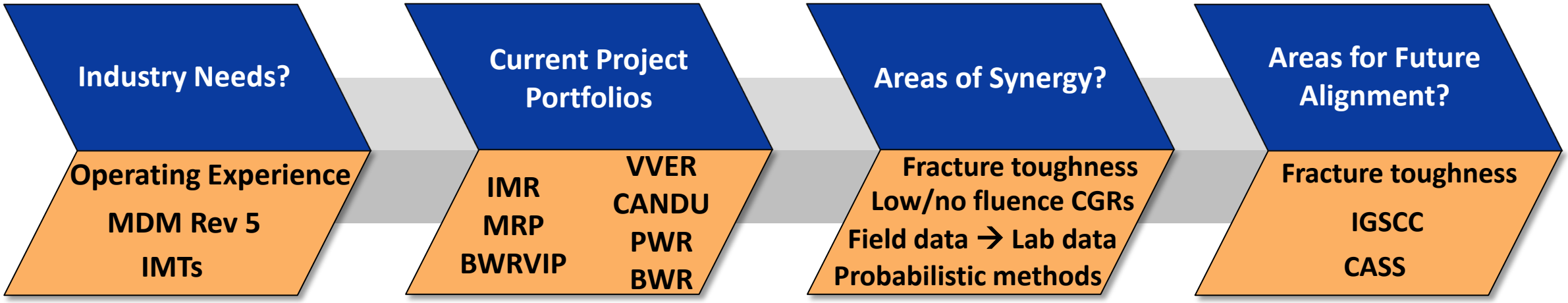
Parameter	Unit	Env. 1	Env. 2	Env. 3	Env. 4	Env. 5
$pH_{300°C}$	-	6.9-7.2	6.9-7.2	6.5-6.9	7.5-8.0	6.5-6.9
H_3BO_3	g/kg	5±0.5	5±0.5	6±0.5	2±0.5	6±0.5
KOH	ppm	21±2	21±2	18±2	27±2	18±2
NH_3	ppm	15.5±2.0	15.5±2.0	11.0±2.0	20.0±2.0	11.0±2.0
dO_2	ppb	200-250	200-250	200-250	200-250	200-250
Cl^-	ppb	-	150±25	150±25	150±25	150±25
SO_4^{2-}	ppb	-	150±25	150±25	150±25	150±25
F^-	ppb	-	150±25	150±25	150±25	150±25
Cu^{2+}	ppb	-	10±2	10±2	10±2	10±2



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Future Outlook

- Alignment between EPRI materials programs and plant types
- Identification of cross-cutting topics
- Maintaining the IMTs current and ensuring project and resource coverage of high-priority gaps



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QUESTIONS?

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