ELECTRIC POWER RESEARCH INSTITUTE

International Materials Research (IMR) Update

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Date: Add submission date and/or revision date & #

Topics

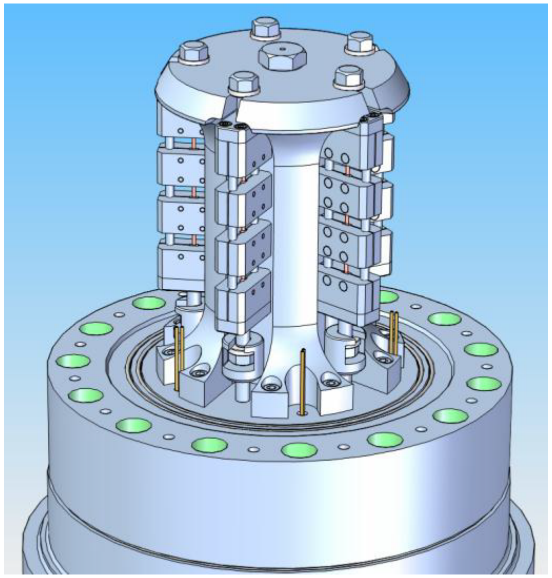
- 2019 Deliverables
- 2019-2020 Research Focus Areas and Projects
- Government Proposals and Awards
- KOH Qualification Project
- Trainings Accessible via EPRI U
- Conclusion

Top Technical Topics

- **Irradiated Materials Testing and Modeling of Stainless Steels**
  - Participate in global research efforts to better understand the role of key parameters associated with IASCC and void swelling of reactor materials and develop improved materials for reactor vessel internals components for replacement in existing plants or for new plants

- **Potassium Hydroxide Materials Testing**
  - Perform materials testing to qualify potassium hydroxide to potentially replace lithium hydroxide in certain PWR designs

- **Environmentally Assisted Fatigue Testing and Modeling**
  - Perform testing and develop models to more accurately predict EAF in light water reactor environments for existing and new plants



IASCC Initiation Test Set-up

2019 Deliverables Update

Product ID	Product Title	Actual or Planned Completion Date
3002014740	IASCC Susceptibility and Evolution of Microstructure in Commercial-Grade and Advanced Alloys for Core Internals	03/08/2019
3002015011	Materials Handbook for Nuclear Plant Pressure Boundary Applications Module 1: Introduction to The Materials Handbook for Nuclear Plant Pressure Boundary Applications	03/05/2019
3002015012	Materials Handbook for Nuclear Plant Pressure Boundary Applications Module 2: Section I Chapter 3 Stainless Steel for Piping, Components	03/05/2019
3002015013	Materials Handbook for Nuclear Plant Pressure Boundary Applications Module 3: Section I Chapter 4 Nickel-Base Alloys for Pressure Vessels, Components and Piping	03/05/2019
3002015936	Microstructure Characterization of Alloy 600TT Steam Generator Tubing, Revision 1	08/21/2019
3002016000	Materials Handbook for Nuclear Plant Pressure Boundary Applications (2019)	12/20/2019
3002016002	Introduction to EPRI Materials Degradation Matrix	12/20/2019
3002016003	Characterization of the Dilution Zone of Alloy 690/52/Carbon Steel Welds of CANDU Feeder Pipe Flow Elements, Revision 1	04/29/2019
3002016005	PWR Primary Chemistry KOH Qualification: Material Testing: Alloy 600 Crack Initiation and Crack Growth	10/30/2019
3002016007	Measurement of Strengths of Oxidized Grain Boundaries of Alloy 600 Exposed to PWR Environments	Delayed to 2020

2019-2020 Research Focus Areas and Projects (1/2)

Materials RFA Number	Materials RFA Title	Project Title
1	**Internals Management**	No current projects.
2	**Stainless Steel Alloys**	
	2.1	Development of IASCC Data and Models for Ti Containing Stainless Steels in VVER
	2.2	Mechanistic Understanding of IASCC Failures in BWR Shroud
	2.3	Development of a Microstructural Database of Irradiated Stainless Steels and of Models that Link Microstructure and Materials Performance
	2.4	Alloy Variability and IASCC Susceptibility in Stainless Steels
	2.5	Rapid Quantification of Irradiation Induced Microstructures by Deep Learning
	2.6	Critical Stress for IASCC Initiation at Grain Boundaries
	2.7	Irradiation Effects on Stabilized Stainless Steels (IASCC, Void Swelling)
	2.8	Rapid Simulation of Void Swelling in Stainless Steels at High Fluence via Ion Irradiation of LWR Irradiated Steels
	2.9	Planning of Plant Materials Extraction
3	**Nickel-base Alloys**	
	3.1	Grain Boundary Oxidation and Cohesive Strength of Oxidized Grain Boundaries of Alloy 600/600TT in PWR Environment
	3.2	Characterization of the Dilution Zone of Alloy 690/52/Carbon-Steel Welds of CANDU Feeder Pipes
	3.3	Investigate Applicability of LRO of Alloy A690 to LWR Components
4	**Low Alloy Steels**	
	4.1	Impact of Carbon on Mechanical Properties of Low Alloy Steels
	4.2	Containment Liner Plate Corrosion Modeling

2019-2020 Research Focus Areas and Projects (2/2)

Materials RFA Number	Materials RFA Title	Project Title
5	**Fatigue**	
	5.1	Investigate Short Crack Behavior in EAF of Stainless Steel
	5.2	EAF Prototypical Full Component Test (Co-funded)
6	**Wear**	No current projects.
7	**Flow Phenomena**	No current projects.
8	**Water Chemistry and Mitigation**	
	8.1	Testing of Irradiated Materials in Support of a Plant Demonstration of KOH for PWR Primary pH
	8.2	Testing of Unirradiated Materials in Support of a Plant Demonstration of KOH for PWR Primary pH
	8.3	Development of More Rugged ECP Probe for BWRs
9	**Repair and Fabrication**	
	9.1	Technical Concepts and Viability Assessment of Direct Additive Manufacturing for Chemically Uniform Large Wrought Components of NPPs
10	**New Alloy Development**	
	10.1	Advanced Radiation Resistant Materials (ARRM) Phase 1 -- Completion
	10.2	Advanced Radiation Resistant Materials (ARRM) Phase 2 -- Neutron Irradiation
11	**Inspection**	No current projects.
12	**Database, Training and Tech Transfer**	
	12.1	Update the Materials Handbook for Nuclear Plant Pressure Boundary Applications
	12.2	Update the Materials Information portal with the revised MDM and Materials handbook
	12.3	Generate CBT Trainings on PSCR Related Subjects

Government Proposals and Awards (1/2)

- DOE National Scientific User Facility (NSUF) award received on 8/16/2018 for *Rapid Simulation of Void Swelling* at Michigan Ion Beam Laboratory, which is a Partner Facility of the NSUF providing access to the capabilities of the laboratory.

- DOE NEUP (Nuclear Energy University Programs) award received on 6/18/2018 for *Development of Corrosion Resistant Coatings and Liners for Structural Materials for Liquid Fueled Molten Salts Reactors* which aims to expand the application of EPRI-developed Moly-related technology to the next generation nuclear concepts.

- Application to DOE NE CINR RC-9: "Elucidating how water chemistry affects the corrosion sensitivity of pristine stainless steel in Nuclear power plants" with North Carolina State University, U.C. Berkeley and PNNL for *Corrosion Sensitivity of Stainless Steels in Pressurized Water Reactor Water Chemistry: Can KOH Replace LiOH in PWRs?* was awarded in 2020.

- EPRI proposal to DOD for National Defense Stockpile Research Defense Logistics Agency (DLA) Strategic Materials BAA No.: BAA-DLASM-2018-01 Titled *Qualification of Potassium Hydroxide for Primary Coolant pH Control in Western-Design Pressurized Water Reactors.* Resubmission in Dec. 2019 has been accepted for funding – revised scope is in review by DoD and start date of 9/01/2020 is expected. Follow on phase is also anticipated for 2021.

Government Proposals and Awards (2/2)

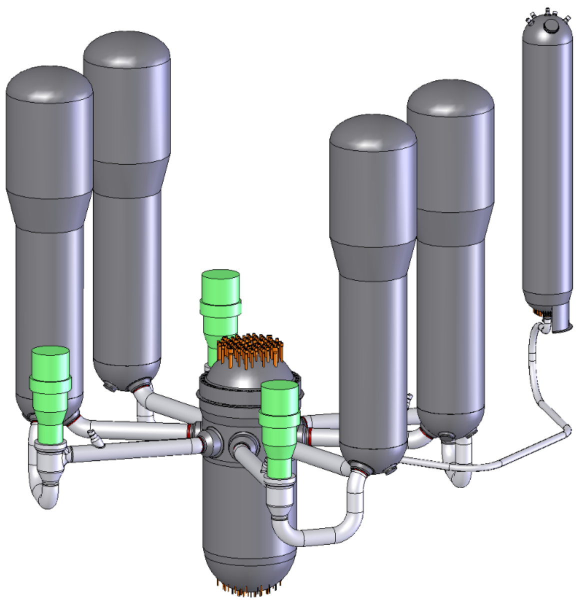
- Application to "DOE NE CINR FC-2.3 HIGH-THROUGHPUT AND/OR MICRO-SCALE POST-IRRADIATION EXAMINATION TECHNIQUES TO SUPPORT ACCELERATED FUEL TESTING" with U. C. Berkeley, LANL, and LLNL for *Femtosecond Laser Ablation Machining & Examination - Center for Active Materials Processing (FLAME-CAMP)* was awarded.

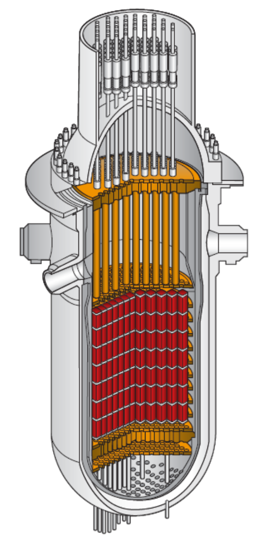
- Application to NSUF for the *Advanced Radiation Resistant Materials (ARRM) Phase 2* was rejected. The team is reevaluating the strategy, scope, and associated cost.

- EPRI Cross Sector (Nuclear + Generation) proposal to DOE for "'Beyond Code' Requirements: Development and Validation of Materials Properties for High Temperature Advanced Reactor Applications" submitted June 30, 2020 to DOE Advanced Reactor FOA (DE-FOA-0001817).

PWR Primary Chemistry and KOH Qualification Project

- EPRI's PWR Primary Chemistry Guidelines are required by NEI 03-08 (Materials Initiative)
- Optimize chemistry to:
  - Mitigate materials degradation
  - Enhance fuel performance and reliability
  - Minimize radiation fields
- Three key chemistry controls:
  - **pH control (required)**
  - Dissolved hydrogen (required)
  - Zinc injection (recommended)
- **Potassium hydroxide** may likely be a better choice than Lithium hydroxide for pH control





Why Potassium Hydroxide?

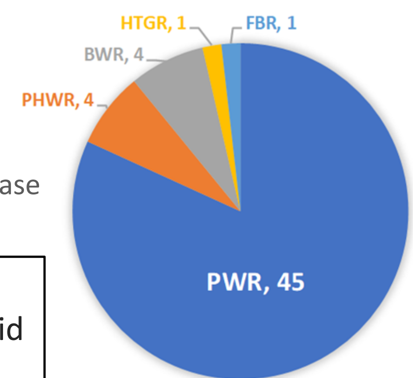
- **Successfully used for decades in VVER plants**
- **<u>Eliminate</u> vulnerability to enriched Li-7 supply**
  - Limited production in China and Russia
  - Increased demand from flexible operations
  - New PWRs under construction globally
  - Molten salt reactor(s)
- **Significantly reduced operational cost**
  - Estimated savings per year of ~$100k/unit (2016 estimate)
- **May have a beneficial effect on IASCC initiation**
  - Much lower lithium concentrations possible with KOH
- **May be more beneficial for Fuel**
  - Data indicate lower corrosion risk
  - Mitigation strategy for Crud Induced Power Shift (CIPS)

GAO-13-716, "Managing Critical Isotopes: Stewardship of Lithium-7 Is Needed to Ensure a Stable Supply", Sep. 2013.

Press Release, House Committee on Science, Space, & Technology, "GAO Raises Questions about Adequate Supply of Lithium-7 for Nuclear Power Reactors", Oct 9, 2013.

Reactors Under Construction by Type

Source: IAEA PRIS Database
Updated 05 Jan 2019



<u>In 2018</u>
9 new PWRs connected to Grid
4 PWRs re-connected (Japan)

Significant value with KOH

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Overall EPRI Plan to Qualify KOH for pH Balance in Western Style PWRs

Program	Area	Testing Projects 2016 -2020	Plant Demonstration: Planning 2019 -2021	Plant Demonstration: Demonstration 2022-2026/2027
IMR & MRP	Materials Testing	• Initiation & Crack Growth Rate Testing – Non-irradiated testing • Stainless Steels (304, 316), Ni-alloys (Alloy 600), + Alloy (A-286) – Irradiated testing • Stainless Steels (304, 316)	• Plant consideration and selection • Confirmation of feasibility per lab results • Plan for 3-Cycle demonstration • Plan for in-demonstration examinations etc. • Plant specific analyses – additional equipment, fuel loads etc. • Schedule and plan for demonstration • Plant "Go" decision	• Equipment installation • Coordination of plant materials and component inspections • Fuel exams over the course of the demonstration, collaboratively with fuel vendor • Radiation fields monitoring and rad safety assurance • Water chemistry monitoring • Decision on generic acceptability of KOH for Western style PWRs
FRP	Fuels Testing and Exams	• Fuel Vendor Assessments • Experimental Loop Testing		
RS	Radiation Fields and Radwaste	• Activation species and dose pathways • Effect on plant radiation fields • Effluent and radioactive waste handling		
Chem	Chemistry/pH Control	• System review and impacts • High temperature chemistry (MULTEQ) • Purity specifications • Modeling multiple alkali control		

Structural Materials Testing to Support KOH Qualification

Prior to a decision on a plant demonstration…

- **Extensive laboratory testing program measures key properties of plant structural materials in comparable LiOH- and KOH-balanced PWR coolant chemistries**
- **Objective is to determine that alkali ion substitution induces no deleterious effects on plant component materials**

Initiation Testing

Material	Nominal Chemistry (BOC, EOC)	Crevice Chemistry
Nickel-base Alloys	YES	YES
Non-Irradiated SS	YES BOC for A-286 OFF NORMAL oxygenated BOC for 304	YES (crevice water chemistry with No oxygen)
Irradiated SS	YES	NO
Low alloy steel	NO	NO

Crack Growth Rate Testing

Material	Nominal Chemistry (BOC, EOC)	Crevice Chemistry
Nickel-base Alloys	YES	NO
Non-Irradiated SS	Yes BOC for A-286 only.	NO
Irradiated SS	YES	NO
Low alloy steel	NO	NO

"No" - due to either sufficient data available for VVERs or data are not needed to disposition materials usage

Nickel Base Alloy (Alloy-600) Testing

- **Material**: Alloy 600 MA [representing Ni-base alloys]
  - Wrought material with 15% cold-forging in all testing
  - Weld metal (Alloy 182) included in crack growth testing
- **Nominal Water chemistry (BOC, EOC) Testing**
  - **Crack Initiation Testing**
    - BOC B-K chemistry shows somewhat longer time to initiation than the B-Li chemistry, (not a concern)
    - EOC B-K data show somewhat shorter mean time to initiation than the B-Li data (difference does not have statistical significance)

➡ **No clear difference of B/Li vs. B/K solutions**

  - **Crack Growth Rate Testing**
    - Water chemistry changeout method
    - Direct comparison of crack length vs time before, during and after changeouts

➡ **No significant change in rates among LiOH and KOH (BOC and EOC)**
No significant effects of midcycle, mixed B/K/Li water chemistries.

- **Crevice Water Chemistry Testing**

➡ Test runs completed
Analysis and reporting in progress

Non-Irradiated Stainless Steels Testing

<u>Material</u>: 300 Series Austenitic stainless steel

- SCC of Stainless Steels in well controlled water chemistry is not expected
- Focus on high oxygen and elevated pH (crevice) conditions
- Widely employed **304 grades** identified for testing of water chemistry LioH vs KOH effects
- **Crevice chemistry (non-oxygenated) crack initiation testing**
  - Non-sensitized 304L + 15% cold-forged
  - Separate test series in KOH and LiOH - Monitor and compare time to initiate crack at constant imposed stress

  → Testing in KOH completed
  Testing in LiOH in progress
- **Highly oxygenated nominal PWR primary water: sensitized 304 + 15% cold-forged**
  - Sensitized 304 + 15% cold-forged
  - Separate test series in KOH and LiOH - Monitor and compare time to initiate crack at constant imposed stress

  → Testing in LiOH completed
  Testing in KOH in preparation, to begin mid-July

<u>Material</u>: Precipitation Strengthened Austenitic stainless steel

- Behavior of **Alloy A286** Precipitation Strengthened stainless steel identified during the project as being potentially different to that of non-precipitation hardened stainless steels
- A286 included into test matrix
- **SCC initiation testing**
  - 2 parallel autoclaves running BOC water chemistries (LiOH vs. KOH)
  - 10 Specimens at 105% YS, 10 Specimens at 120% YS in each autoclave
  - Looking for differences in statistical distribution of crack initiation times

  → Testing completed
  Analysis and reporting in progress
- **SCC Growth Testing by "Water Chemistry Changeout Method"**
  - BOC water chemistries (LiOH vs. KOH)
  - Monitor crack growth over time and at water chemistry changeouts

  → Testing completed
  No discernable difference between LiOH and KOH water chemistries

Irradiated Stainless Steels Testing

- Irradiated materials extracted from service reactor exposed components
  - 316 Flux Thimble Tube for initiation testing ~100dpa material
  - 304 SS Baffle Plate for Crack Growth Testing ~10-15 dpa materials

- SCC Crack Growth
  - Testing by "Water Changeout Method"
  - BOC and EOC Conditions
  - Monitor crack growth over time and at water changeouts
  - Test under controlled K   K = 11, 14, 18, MPa√m

All testing completed
No discernable difference between LiOH and KOH balanced waters

- SCC crack initiation testing
  - "Applied Stress" vs Time to crack initiation data
  - Constant load "O-ring" Specimen testing
  - Selected stress levels - 30% to 70% of Yield Strength,5 duplicate samples per stress level
  - Water Chemistry 2000 ppm B balanced by 19.8 ppm K enables comparison to previously developed EPRI data in equivalent 3.5 ppm Li water

Tests runs completed (1500 hour test duration)
Fractography, data analysis and reporting are in progress

KOH Qualification Project Summary

- **Alternative to Li-7 is sought for flexibility of PWR operations**
- **KOH is an obvious alternative to Li-7**
  - VVER usage
  - Potential benefits to fuels, etc.
- **Broad-based EPRI program including Water Chemistry, Radiation Fields and Rad. Waste, Fuels and Structural Materials is being conducted**
- **Comprehensive test plan has been executed by EPRI to address any gaps between VVERs and Western-style PWRs**
  - Included PWR OEMs reviews
  - Extensive testing program to assess behavior of structural materials in KOH balanced PWR coolant is being conducted and is almost complete
  - Parallel work on fuel materials in KOH has also been conducted
- **Proceeding to a plant demonstration**
  - Risk to structural materials is assessed to be low based on results from the testing programs
  - Demonstration plant discussions are ongoing
  - Comprehensive monitoring plan will be used during demonstration…
    - ➢ Fuel exams, material inspections, monitoring of radiation fields and effluents, etc.
  - Detailed plan with plant and fuel vendor for fuel exams that preserve outage schedules will be developed

Trainings on IMR Related Subjects Available via EPRI U

Approach:

Interactive and user-oriented computer-based training (CBT) modules have been developed for Materials Handbook (MHB), Materials Degradation Matrix (MDM), and other topics.

Value:

MHB and MDM trainings provide the necessary guidance to access:

- Materials information that is often required for failure analyses or replacement materials selection.
- The state of industry knowledge regarding degradation mechanisms and related research and development activities.

Trainings on IMR Related Subjects

Objectives of the Materials Handbook and Materials Degradation Matrix Trainings are:

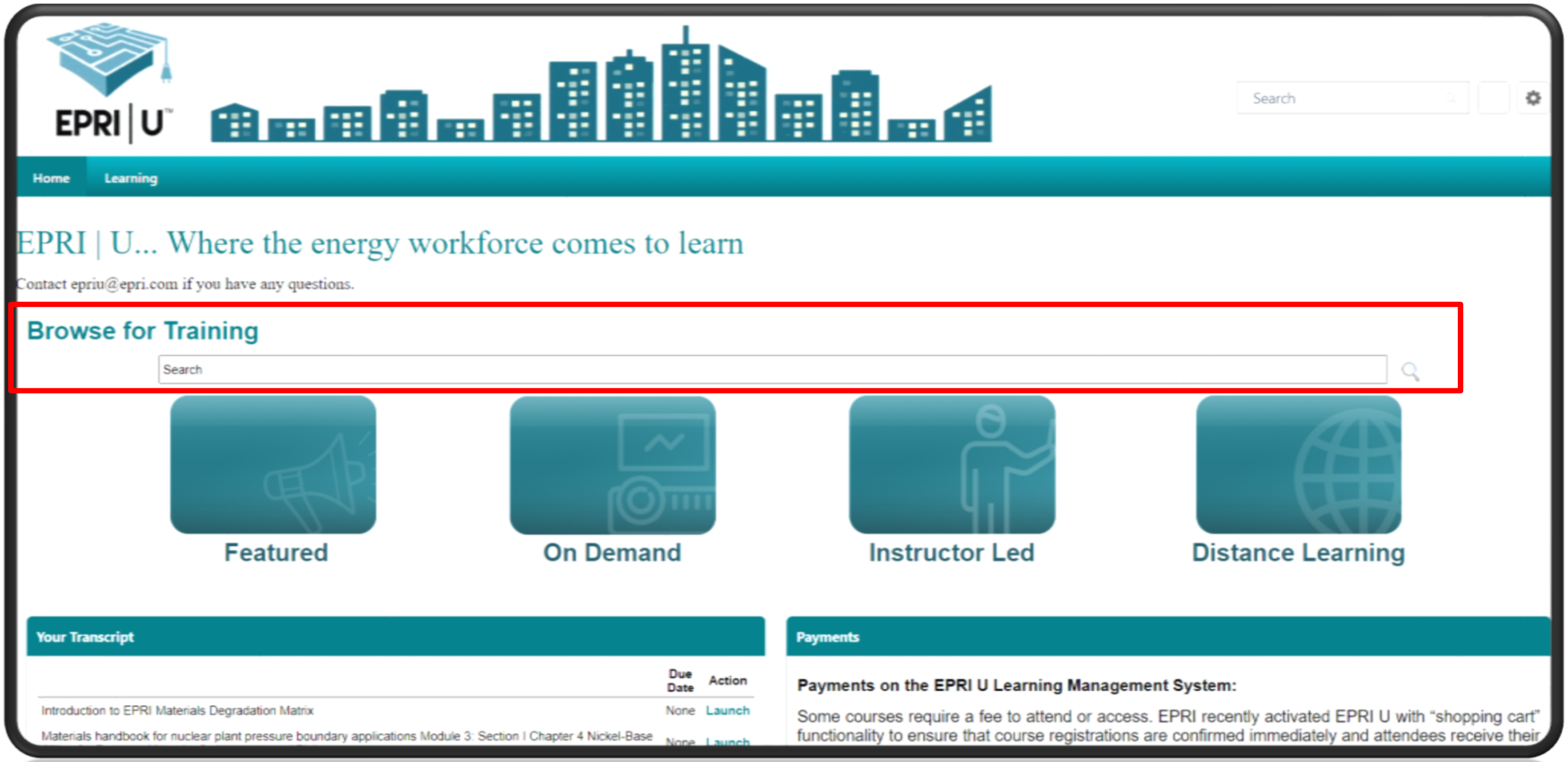
- To help utilities and other stakeholders increase their familiarity with the revised EPRI Materials Handbook and Materials Degradation Matrix.
- To provide an overview of the Materials Handbook and Degradation Matrix.
- To cover specific sections from the Materials Handbook and Degradation Matrix in detail, and illustrate key points with examples.

Trainings on IMR Related Subjects Available via EPRI U

Three CBTs on the **"EPRI *Materials Handbook for Nuclear Plant Pressure Boundary Applications*"** and one CBT on the **"EPRI Materials Degradation Matrix"** are online at EPRI U**.**

- **Training Module 1: Introduction to the Materials Handbook** (Product ID: 3002015011)
  - Outlines the contents of the materials handbook
  - Summarizes the materials covered with the emphasis on the operating experience
- **Materials Handbook Chapter-based training modules that provide more in-depth and material specific information:**
  - **Training Module 2:** Stainless Steels for Piping, Components, and Pressure Vessels (Product ID: 3002015012)
  - **Training Module 3:** Nickel-Base Alloys for Pressure Vessels, Components, and Piping (Product ID: 3002015013)
- **Introduction to EPRI Materials Degradation Matrix Training** (Product ID: 3002013781)
  - **Training Module 4:** This computer-based training provides a detailed introduction to the publicly available 4th Revision of the EPRI's Materials Degradation Matrix.

Computer-Based Training Modules at EPRI U



CBTs are available at EPRI U (https://www.epri.com/#/epri-u/)

Questions about EPRI's Training offerings or requests for custom training can be sent to EPRIU@epri.com

Introduction to EPRI Materials Degradation Matrix Training

- This computer-based training is based on the publicly available 4th Revision of the EPRI's **Materials Degradation Matrix (Product ID: 3002013781)** that was published in 2018.

Introduction to EPRI Materials Degradation Matrix Training (Product ID: 3002016002) is available at EPRI U

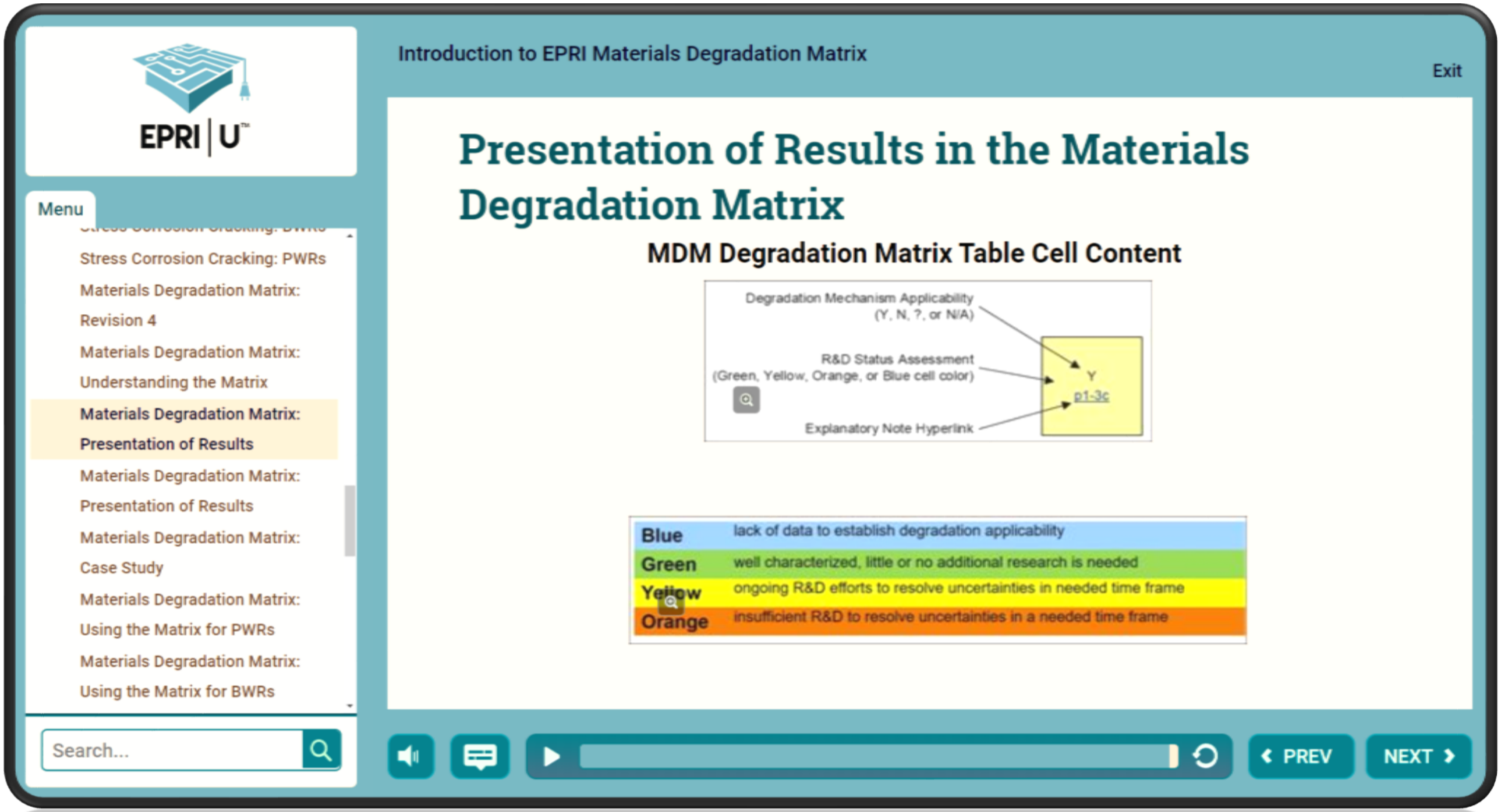
Introduction to EPRI Materials Degradation Matrix Training

This computer-based training contains information on:

- Nuclear Energy Institute Materials Initiative (NEI 03-08) and the development of EPRI's MDM.
- Objectives of the 4th Revision of the EPRI's MDM.
- Materials and degradation modes listed in the MDM.
- The matrix format and the nomenclature used to describe the results.
- The state of industry knowledge regarding degradation mechanisms and related R&D activities on various materials.
- The Strategic Issues described in the MDM for Western LWRs, VVERs and CANDU.

Upon completion of this Module, the trainee should be able to use the EPRI MDM to characterize degradation phenomena and identify associated knowledge gaps & the status of R&D needed to resolve the knowledge gaps.

Introduction to EPRI Materials Degradation Matrix Training



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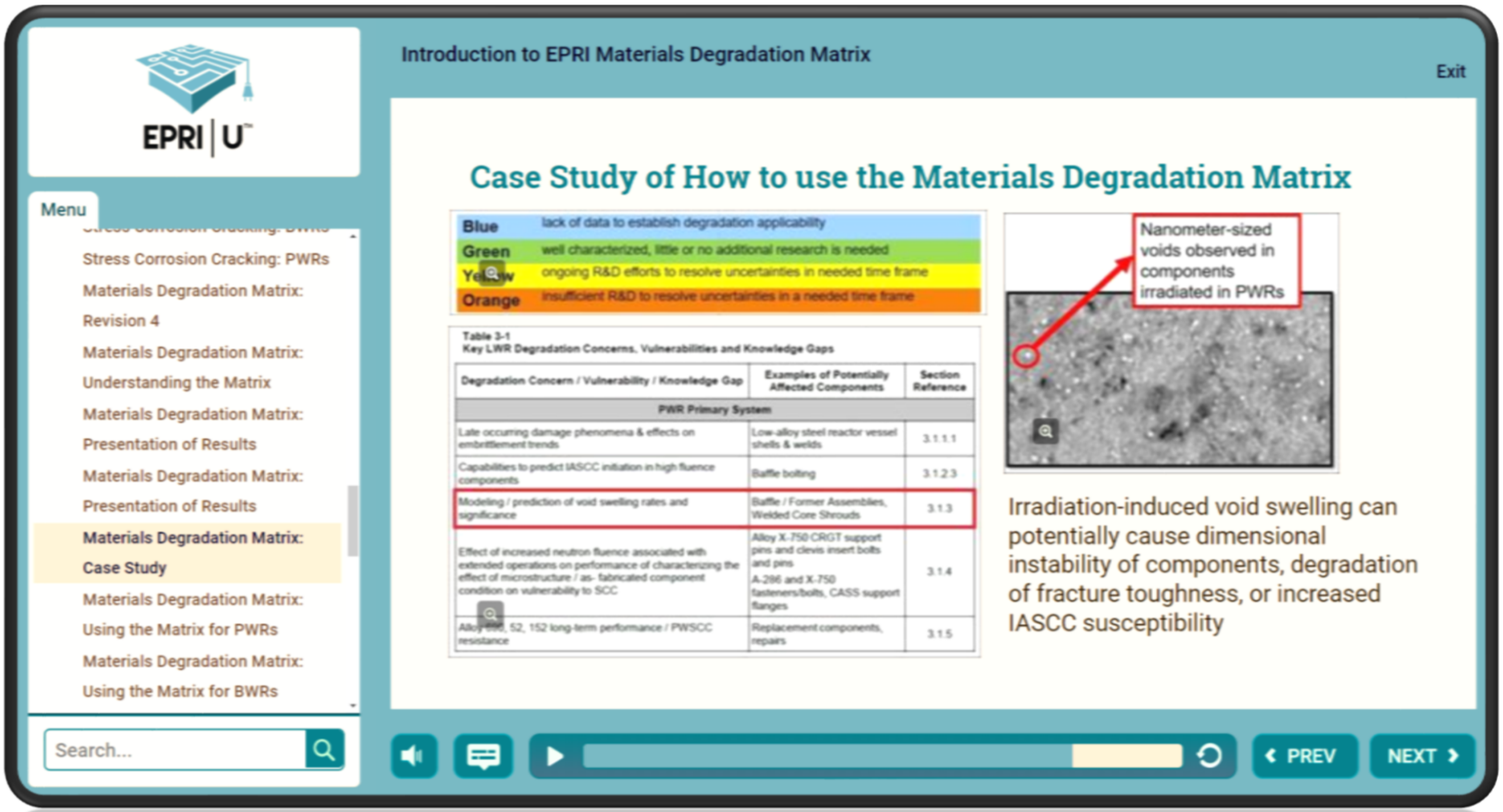

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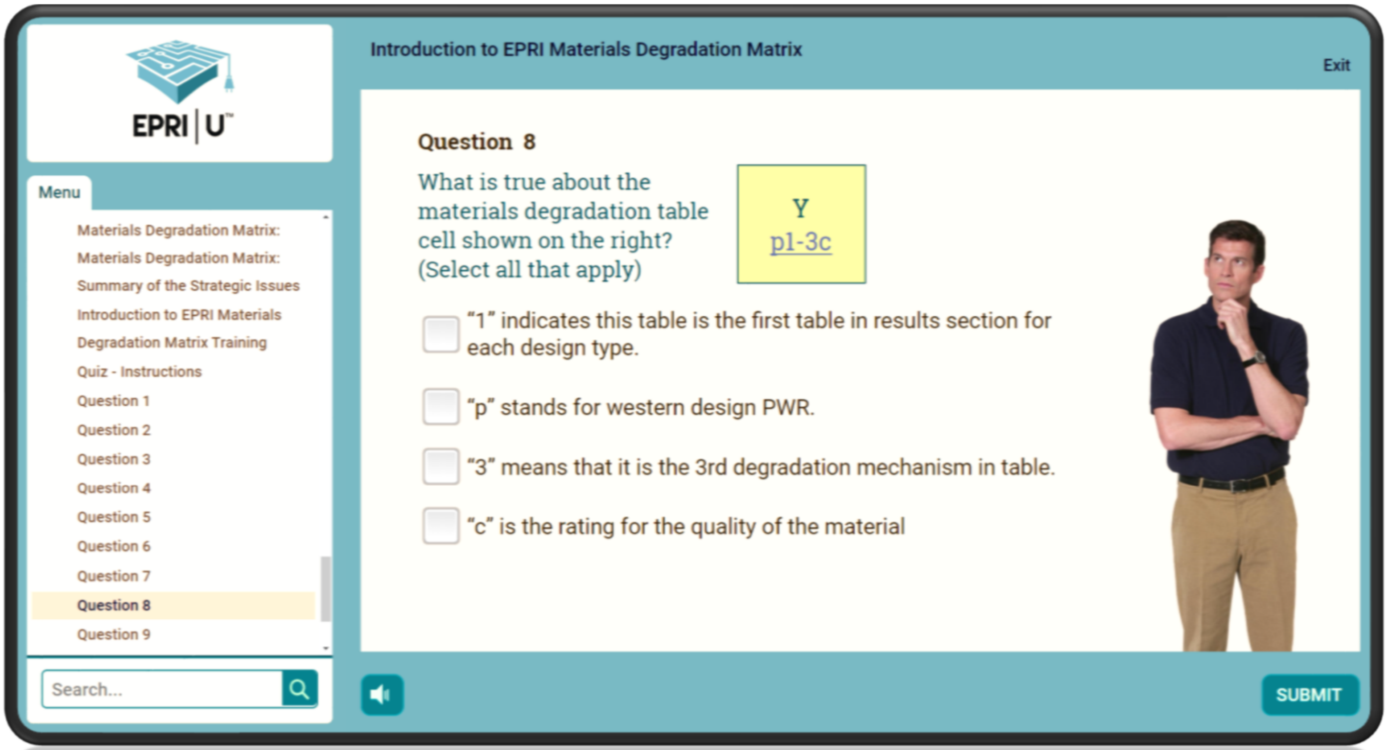

Materials Handbook for Nuclear Plant Pressure Boundary Applications Module 1: Introduction to The Materials Handbook for Nuclear Plant Pressure Boundary Applications

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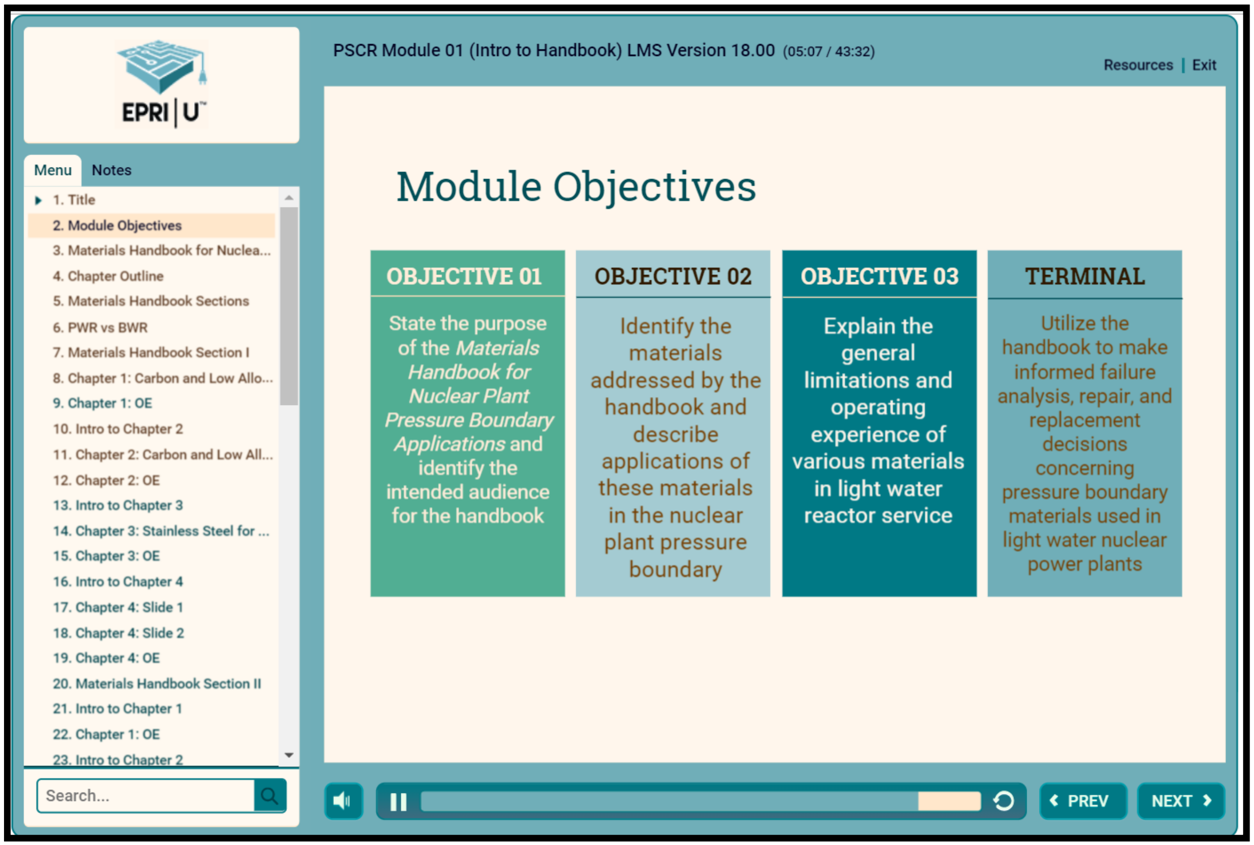

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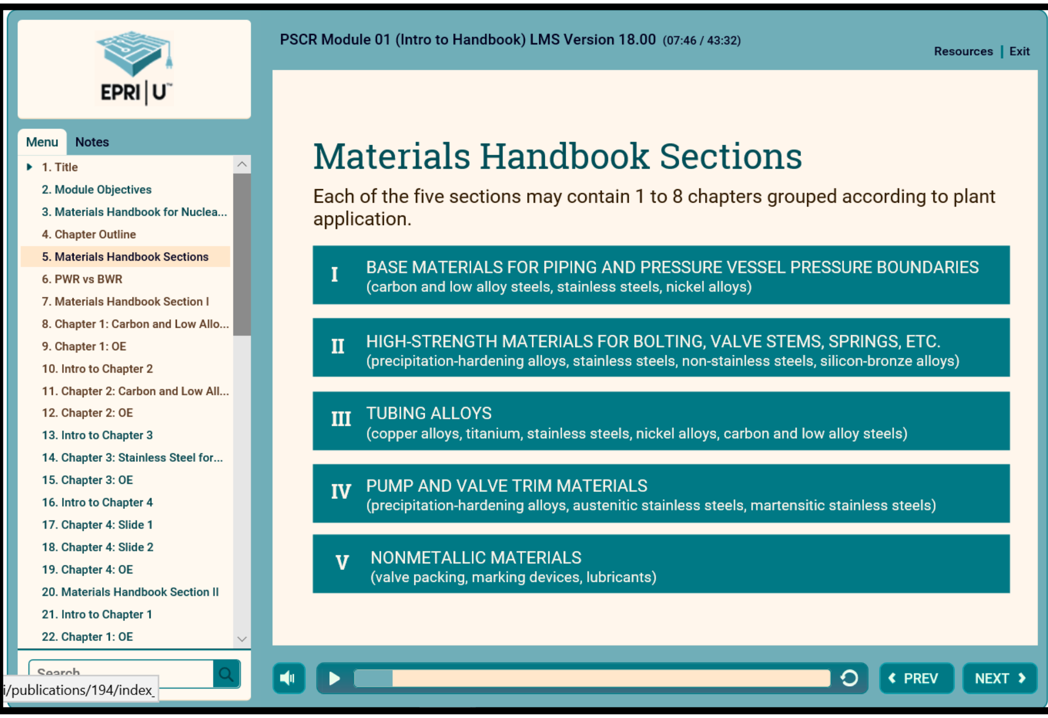

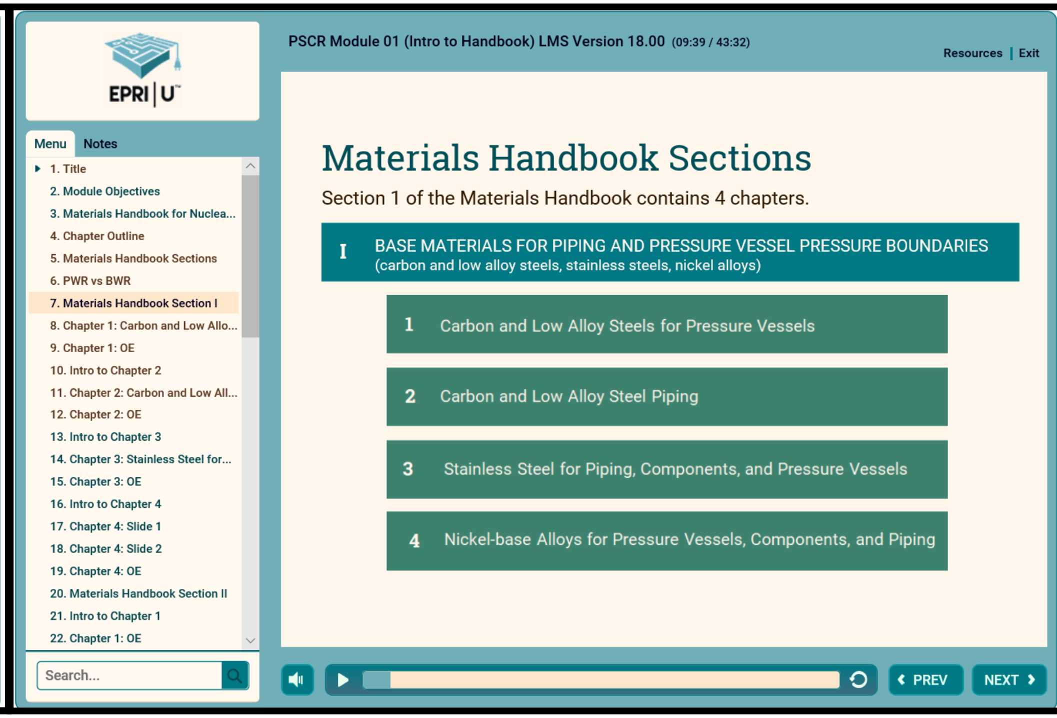

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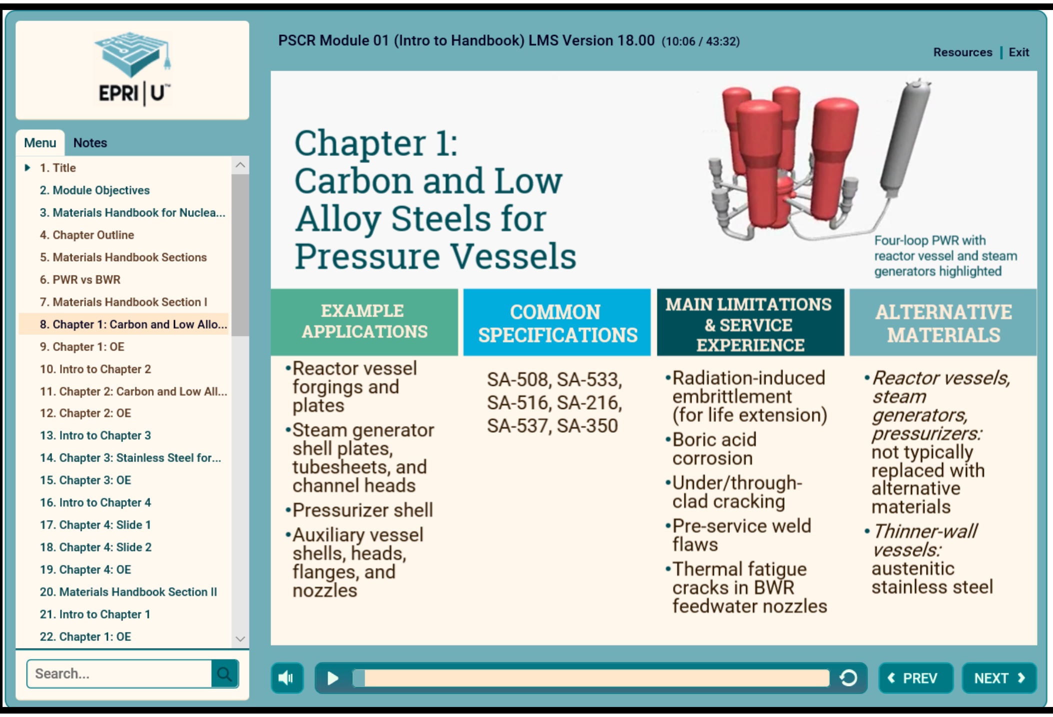

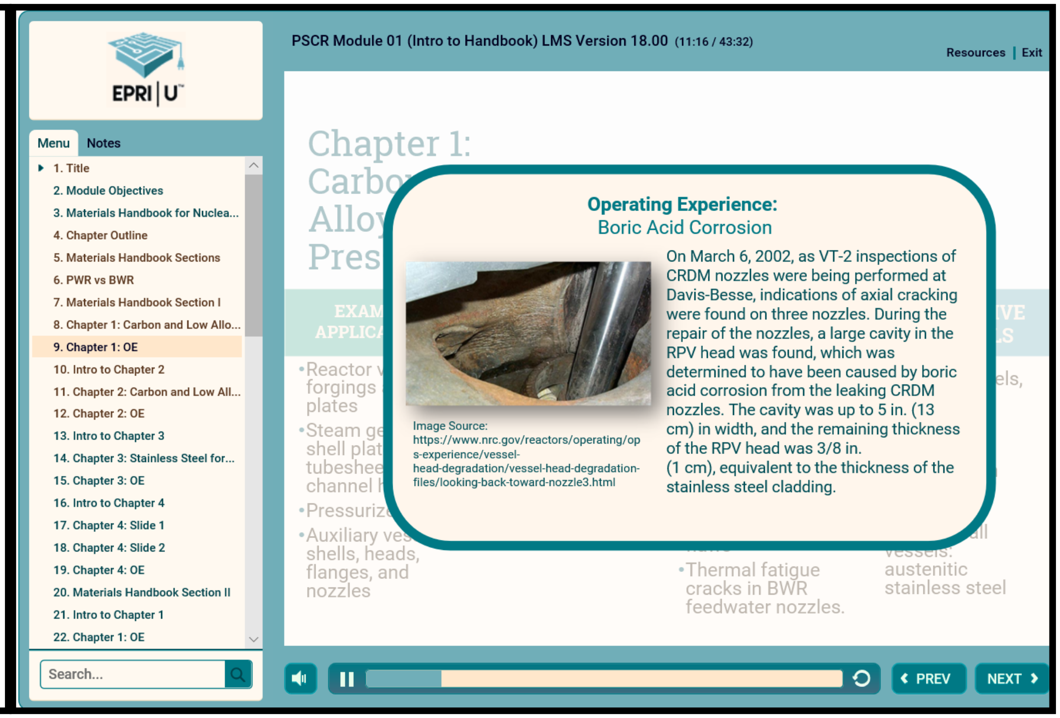

Conclusion

- International Materials Research (IMR) will
  - Continue existing projects and identify new projects to resolve research gaps for our members
  - Continue to collaborate with U.S. government research organizations, international laboratories, and universities

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