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ACRS Subcommittee – ANP-10358 Increased Burnup for PWRs

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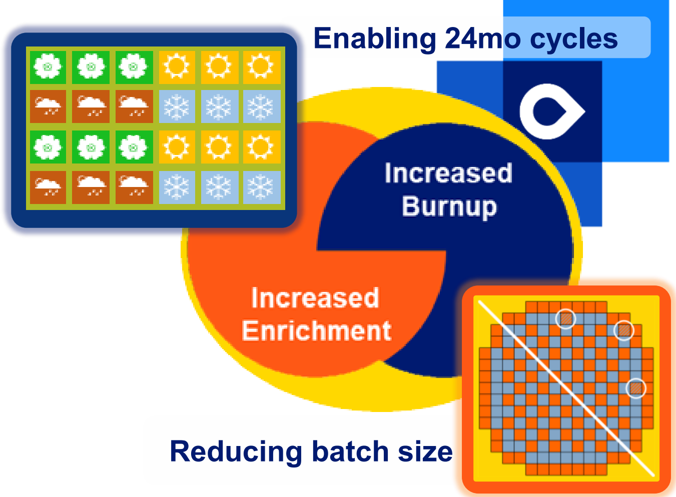
Open Meeting

Agenda

- Open meeting - overview
  - Motivation for increased burnup
  - Scope of topical report
- Closed meeting
  - Extension of methods
    - ARCADIA
    - Fuel assembly growth
  - Updates to current methods
    - Fuel rod internal pressure criteria
    - LOCA
    - Fuel dispersal

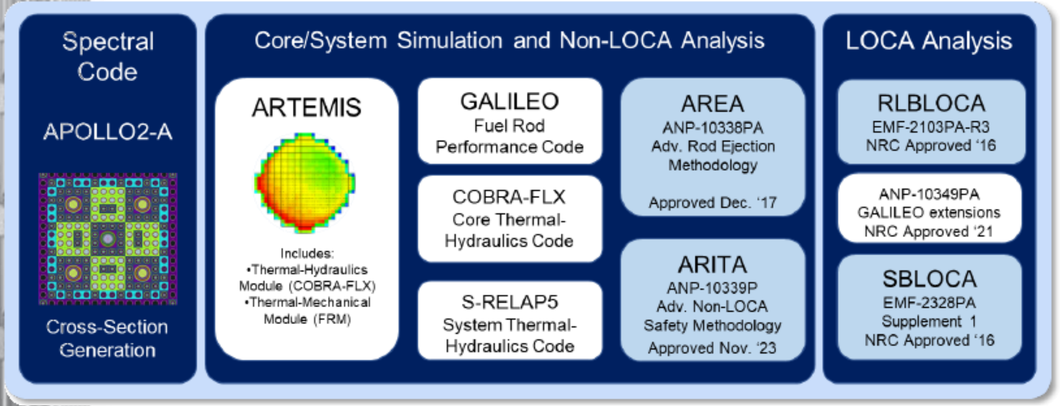
1. Overview

Advanced Fuel Management



Industry need

- Market demand and government incentives for increased power production
- Increased enrichment and burnup → efficient core designs, longer operating cycles
- 24-month cycles for W17-4L PWRs → significant cost and operational benefits



Framatome Approach to AFM

- Employ fuel components with a service record of robust performance
- Use focused subject topical reports to build up foundation of code and methods enabling advanced features and flexibility to support AFM core designs

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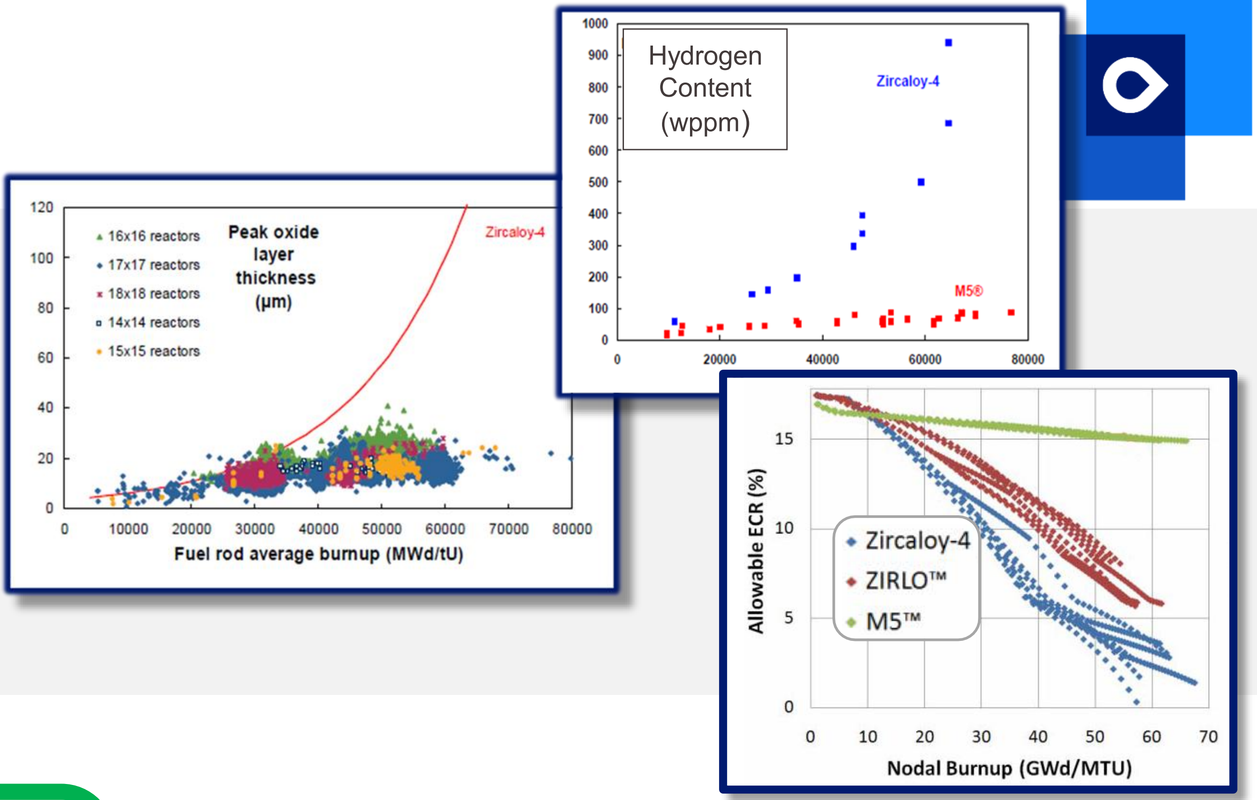
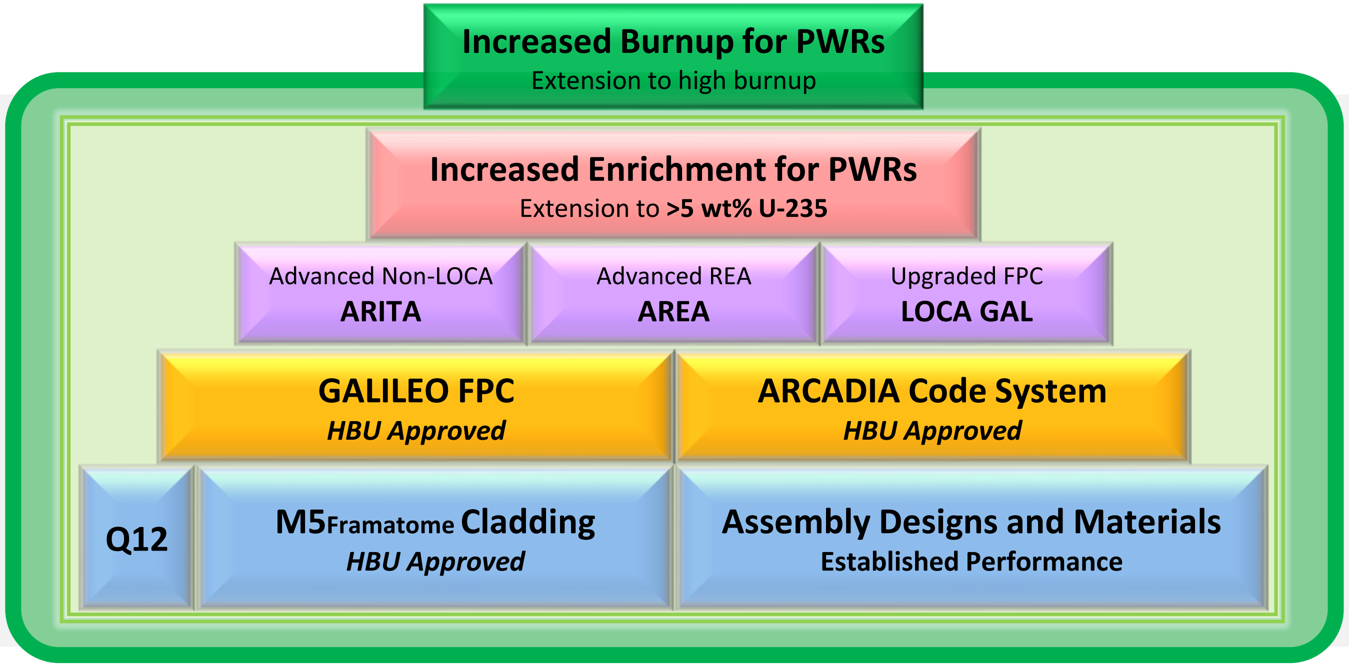
Increased Burnup



Proven fuel designs that maintain their performance through irradiation are essential

- With over 20 years of operation, $M5_{Framatome}$ cladding remains the gold standard
  - Deployed in over 7 million fuel rods worldwide
  - Recognized for its mechanical properties, superior corrosion resistance, and very low hydrogen pickup



Advanced codes and methods suite is fully compliant with NRC regulations and guidance

- The cladding and fuel performance code are the key elements for high burnup licensing and are fully approved to target burnup
- Increased enrichment topical validated suite for target enrichment
- Increased burnup topical report is the last piece to licensing PWR AFM operation

ANP-10358 Topical Report

1. Introduction
2. Fuel Designs
3. Nuclear Design – ARCADIA
4. Thermal Hydraulics
5. Mechanical
6. Non-LOCA
7. LOCA
8. Reactor Pressure Vessel Fluence

- Appendix A – Decay Heat
- Appendix B – Fuel Dispersal
- Appendix C – LOCA Sample Problems

ANP-10358 Topical Report

- Umbrella topical report establishing Framatome's suite of advanced codes and methods
- Extends applicability of codes and methods to target burnup
- Follows the same approach as Increased Enrichment Topical Report that extended applicability to greater than 5 wt% U-235
- Includes:
  - Burnup extension for all methods through disposition, additional justification, or updated models
    - **Today's meeting: ARCADIA extension and fuel assembly growth model**
  - Enrichment extension for select areas not previously addressed
  - Enhancements to provide increased flexibility for AFM operating region
    - **Today's meeting: Rod internal pressure limit, LOCA modifications, fuel dispersal**

Closed Meeting

AFM Range of Applicability

- [ ] GWd/mtU rod average burnup
- [ ] wt% U-235

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2. Extensions

2.1 ARCADIA

ARCADIA

- ARCADIA is used for all reactor core physics calculations
  - Pin-by-pin and subchannel-by-subchannel coolant modeling
  - 3D kinetic modeling captures
- ANP-10297P-A, Rev. 0 (2013) with Supplement 1P-A, Rev. 1 (2020)
  - Burnup limit of 71 GWd/mtU fuel rod average
  - Accurate and reliable prediction of fuel and core behavior for licensing basis event analyses
  - Captures transient changes in reactivity, conductivity, and enthalpy

ARCADIA

- **APOLLO2-A**: Cross-section Generator
- **ARTEMIS**: 3D Core Simulator
- **COBRA-FLX**: Core Thermal-Hydraulics Code

Fundamental element to core design optimization and accident analyses capabilities

ARCADIA Benchmarks

- The ARCADIA TR included benchmarks over a wide variety of core and operation conditions
  - Critical experiments, integral experiments, and spent fuel analyses
  - Startup physics testing and core follow comparisons
  - Burnup limit set by spent fuel analyses

- Additional spent fuel comparisons included in ANP-10358 to extend range
  - Samples taken from various elevations of 3 rods that operated for 5 cycles at Vandellos Unit 2
    - Westinghouse 157 17x17-assembly PWR
    - Rated thermal power = 2711 MW (Cycles 7-10) = 2830 MW (Cycle 11)
  - Sample burnups ranged from 63.8 -78.2 GWd/mtU

ARCADIA Benchmarks Cont.

- Complexities of Modeling and Measurements
  - Operating history – multiple assemblies, locations in core, surrounding assemblies, reconstituted assembly
  - Three different measurement techniques used
  - Measurement uncertainties vary across different measurement techniques and different isotopes
- Benchmarking analysis provides practical validation of the ARCADIA models
  - Qualitative assessment of modeling
  - Results were acceptable, typically within two standard deviations

Results for the Vandellos samples support the extension of the ARCADIA code package to a rod average burnup limit of [ ] GWd/mtU

2.2 Fuel Assembly Growth

Q12 Fuel Assembly Growth Model

Q12 Fuel Assembly Growth Model

3. Updates

3.1 Rod Internal Pressure Limit

Rod Internal Pressure Limit

- Limit is tied to three phenomena
  - No reorientation of the hydrides in the radial direction in the cladding
  - No clad liftoff during normal operation
  - Consideration for additional fuel failures from DNB propagation in postulated accidents
    - Framatome's DNB Propagation methodology is **independent** of fuel rod overpressure magnitude
      - Simple, conservative methodology
      - Documented in Section 9.1.4.5 of ANP-10339PA-00 (ARITA), Section 6.8.4 of ANP-10338PA-00 (AREA)

ANP-10358 Overpressure Limit: [ ]

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Radial Hydride Reorientation

- Radial hydride reorientation in M5Framatome clad does not occur for overpressure of [ ]
  - Documented in ANP-10323PA-01, Appendix B (GALILEO)
    - Corresponding US NRC Safety Evaluation: Section 3.7.5

[ ]

[ ]

ANP-10358 limit is [ ]

Cladding Liftoff

- ROPE-II, IFA-610 (series), and IFA-683 experiments
  - Devised to study fuel rod behavior in overpressure conditions
    - Range of rod overpressure: 5 ~ 28 MPa
    - Range of burnup: 40 ~ 90 GWd/mtU
  - Clear evidence of radial hydride reorientation below the threshold of cladding liftoff
  - Overpressure liftoff threshold
    - Framatome evaluation: [ ]
    - Independent evaluation: 13.8 +/- 0.9 MPa (*)
- Analytical studies with GALILEO concluded:

[ ]

(*) Wolfgang WIESENACK, Terje TVERBERG, Margaret MCGRATH, Erik KOLSTAD & Stephan BÉGUIN (2006), "Rod Overpressure/Lift-off Testing at Halden In-pile Data and Analysis," Journal of Nuclear Science and Technology, 43:9, 1037-1044, DOI:10.1080/18811248.2006.9711193.

Conclusion

- DNB propagation methodology approved in ARITA and AREA TR is not impacted by overpressure magnitude
- [ ] overpressure precludes radial hydride reorientation in M5 cladding
- [ ] overpressure precludes clad liftoff in M5 cladding
  - ANP-10358 provides conclusive evidence from both experimental results and GALILEO analyses
  - [ ]

Fuel rod overpressure limit for M5 cladding with ANP-10358 is [ ]

3.2 LOCA

LOCA Evaluation Models

- Framatome conservatively reduces the 10 CFR 50.46 space into two sub-regions with a separate NRC-approved evaluation model (EM) for each
  - SBLOCA EM: EMF-2328, Rev. 0 & Supplement 1
  - RLBLOCA EM: EMF-2103, Rev. 3

- ANP-10358 Modifications
  - [ ]
    - [ ]
    - Implementation of Alternative Compliance Criteria

[ ]

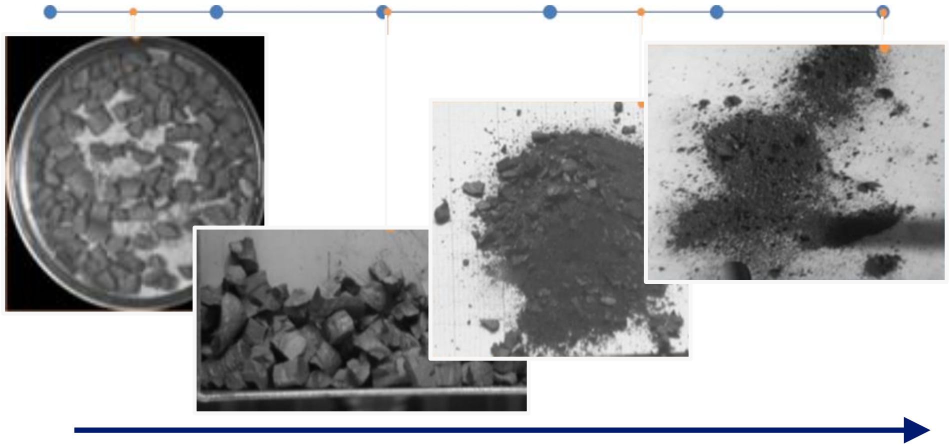
Today's meeting: Alternative Compliance and Dispersal Validation

3.3 Fuel Dispersal

FFRD: Fuel Fragmentation, Relocation, and Dispersal

Economical 24-month core designs with increased enrichment and burnup

Once-burned fuel has higher rod internal pressure and burnup



Increasing fragmentation with burnup

<u>Increased likelihood</u> of fuel dispersal during accident with cladding breach

ANP-10358 addressed these changes <u>within the existing regulatory framework</u>

Fuel Dispersal Summary

4. Summary

ANP-10358 Topical Report Summary

- Umbrella topical report establishing Framatome's suite of advanced codes and methods
- Extends applicability of codes and methods to [ ] GWd/mtU rod average burnup
- The last building block to license PWR AFM operation

Framatome's advanced codes and methods support safe operation of the fuel and reactor system in the AFM operating region

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Thank you

Acronyms

AFM	Advanced Fuel Management
BJ-ECR	Baker Just – Equivalent Cladding Reacted
CDF	Cumulative Distribution Frequency
CHF	Critical Heat Flux
CLD	Cold Leg Discharge
CP-ECR	Cathcart Pawel - Equivalent Cladding Reacted
DNB	Departure from Nucleate Boiling
ECC	Emergency Core Cooling
ECCS	Emergency Core Cooling Systems
EM	Evaluation Model
FGR	Fission Gas Release
FFRD	Fuel Fragmentation, Relocation, and Dispersal
FOM	Figure of Merit
FPC	Fuel Performance Code
FRM	Fuel Rod Model
GDC	General Design Criterion
HBU	High Burnup
LB	Large Break
LBLOCA	Large Break Loss of Coolant Accident
LTOM	Least Transient Oxidation margin
LOCA	Loss of Coolant Accident
LOOP	Loss of Offsite Power
NRC	Nuclear Regulatory Commission
PCT	Peak Cladding Temperature
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RLBLOCA	Realistic Large Break Loss of Coolant Accident
SBLOCA	Small Break Loss of Coolant Accident
SF	Single Failure
TOM	Transient Oxidation Margin
TR	Topical Report

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