Topical Report on Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance

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May 8, 2019
NRC Topical Report Pre-submittal Meeting

Key Partners and Stakeholders

The High Temperature Reactor Technology Working Group

HTR

Simple Safe Secure

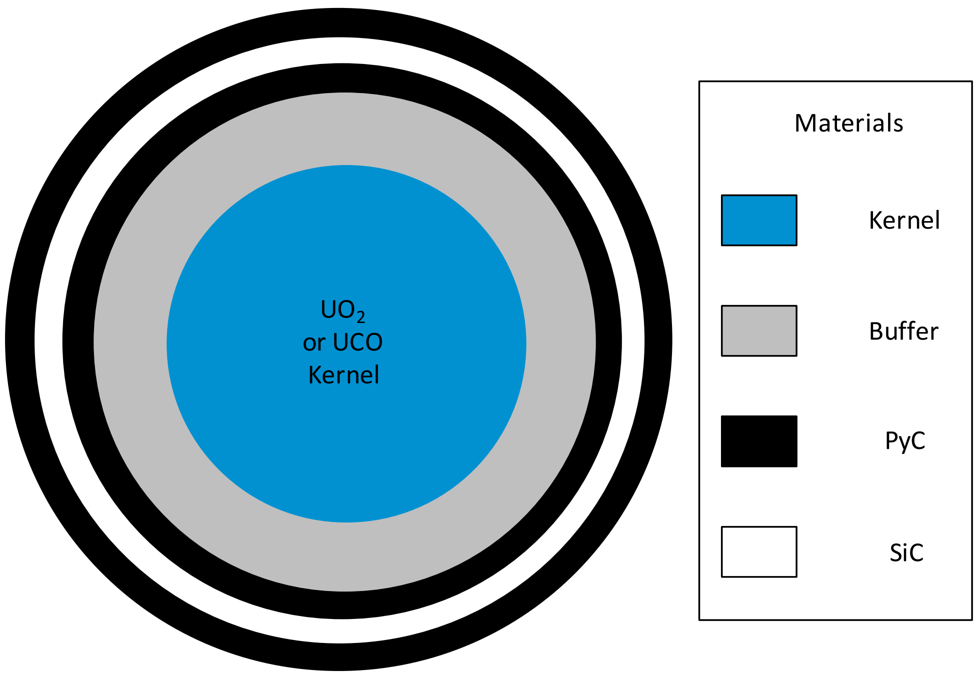
TRISO Topical Report Review: Request to NRC

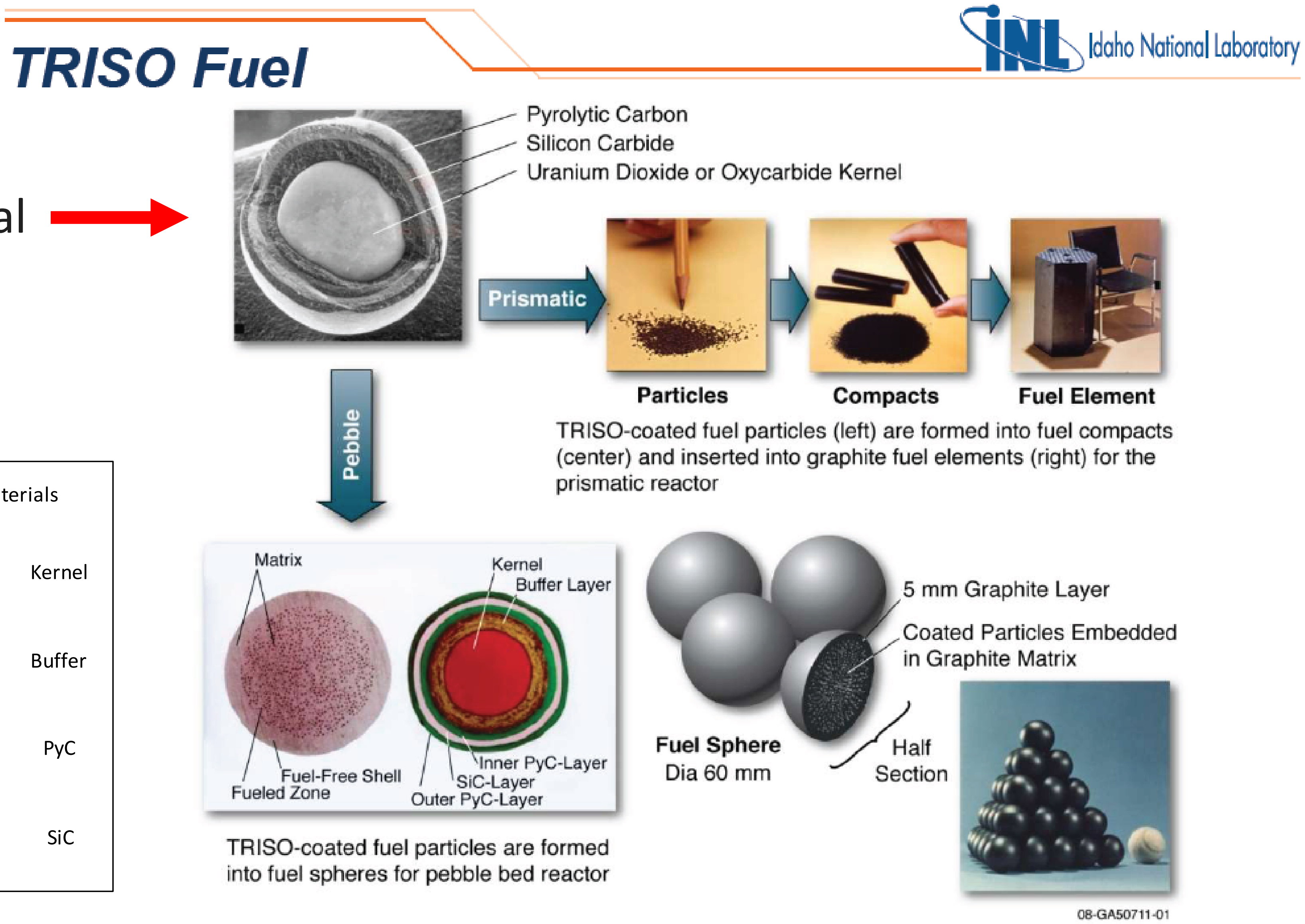
- Sections 1 – 4 provide historical background and context
  - NOTE: historical pre-AGR data are NOT relied on for U.S. TRISO fuel qualification program or the conclusions in the Topical Report
- Sections 5 – 7 present the AGR program content and represent the core scope of Topical Report for review
- Approval requested for Conclusions (in Section 8) with issuance of a Safety Evaluation Report

TRISO Fuel and U.S. DOE Advanced Gas Reactor Fuel Development and Qualification (AGR) Program

Tristructural Isotropic (TRISO) Coated Particle Fuel

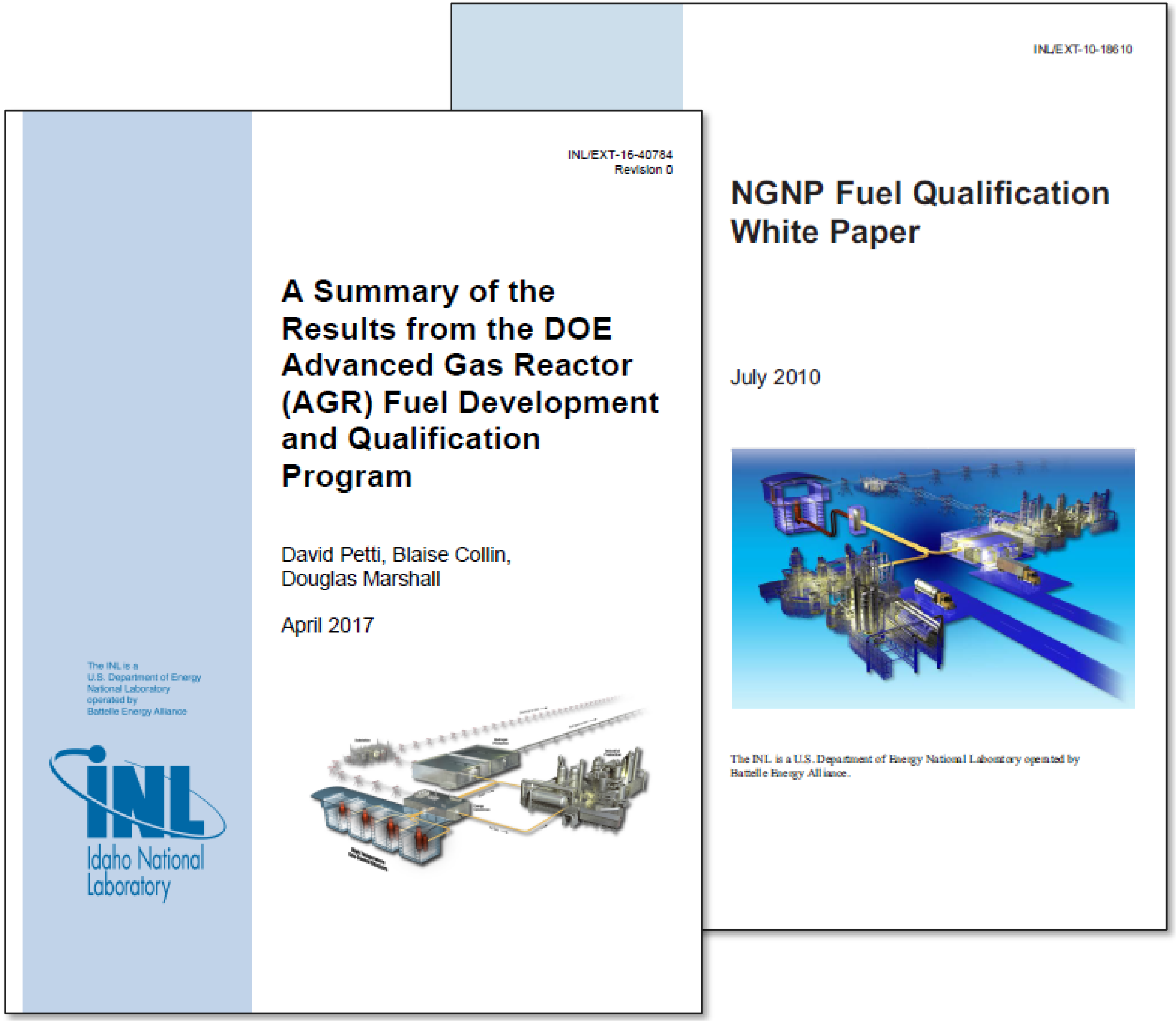
TRISO particle = Scope of Topical





U.S. and International Experience

- International experience:
  - high-quality TRISO fuel can be fabricated in a repeatable, consistent manner
  - fuel performance with very low in-service failures is achievable under anticipated modular HTGR conditions
  - historical international experience is relevant to prismatic and pebble fuel forms
- U.S. DOE AGR program:
  - fabrication of high-quality low-defect fuel is achievable at industrial scale via stable, repeatable processes
  - demonstration of excellent irradiation performance of a large statistical population of UCO TRISO fuel particles under high-burnup, high-temperature modular HTGR conditions



AGR Program Goals

- Provide data for fuel qualification in support of reactor licensing

- Establish a U.S. commercial TRISO fuel fabrication capability

AGR Approach: Developing and Testing UCO TRISO Fuel

- **Develop fuel fabrication and QC measurement methods**, first at lab scale and then at industrial scale
- **Perform irradiation testing** over a range of conditions (burnup, temperature, fast neutron fluence)
- **Perform post-irradiation examination and safety testing** to demonstrate and understand performance during irradiation and during accident conditions
- **Develop fuel performance models** to better predict fuel behavior
- **Perform fission product transport experiments** to improve understanding and refine models of fission product transport
- **10 CFR 50 Appendix B compliant data acquisition** using NQA-1 2008, 2009

Key Parameters for Fuel Performance

- **Temperature**: Many of the potential failure mechanisms and fission product transport mechanisms are dependent on both time at temperature during power operation and time at temperature under postulated accident condition.

- **Burnup**: Determines the quantity of fission products in the kernel and thus the gas pressure and fission product concentration in the particles that can interact with the coating layers.

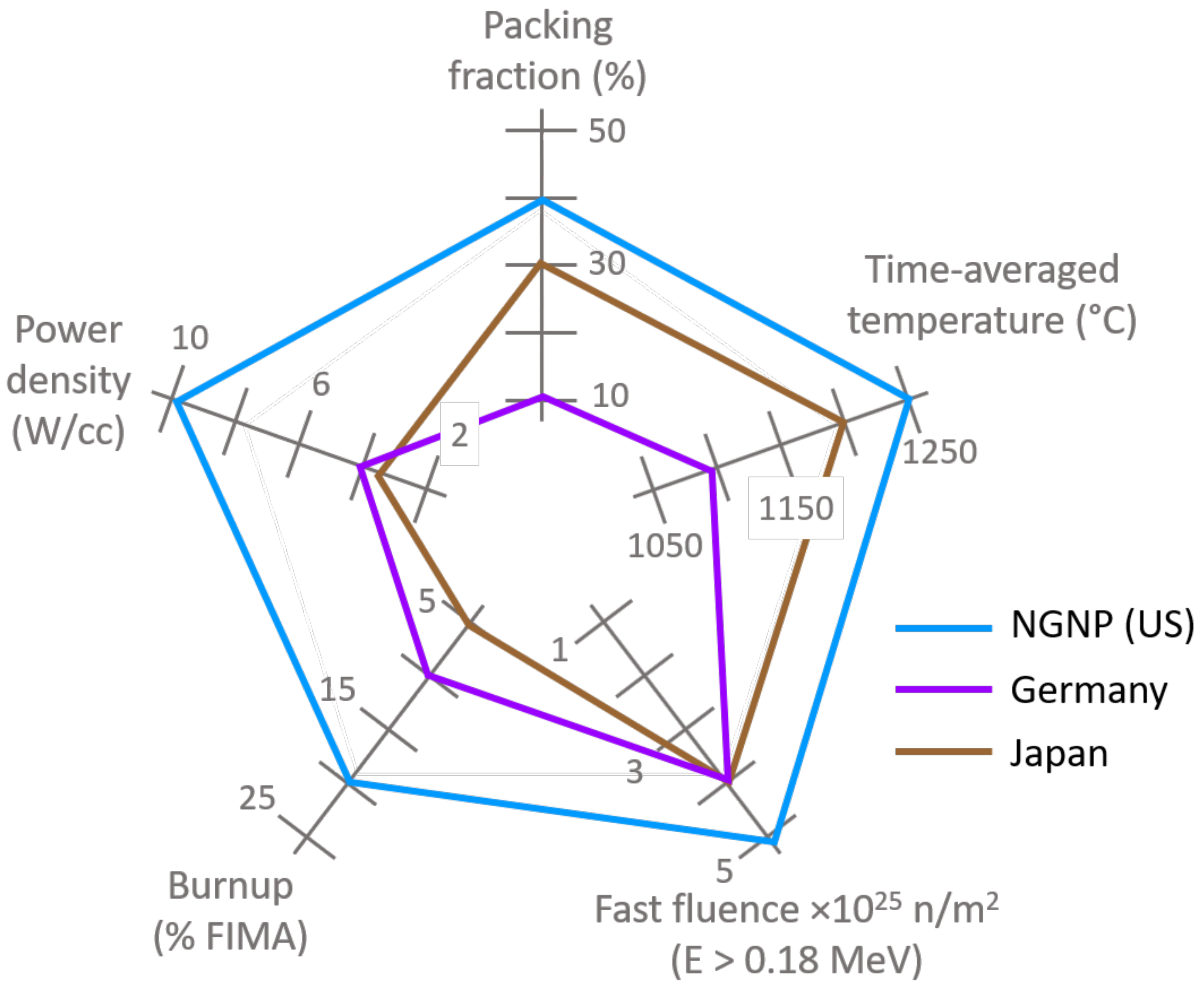
- **Fast fluence**: Determines the level of radiation damage in the particles and the potential changes in properties and dimensions in the layers.

- **Power density**: Together with the thermal conductivity and the geometry of the fuel (e.g., compact, pebble) determines the temperature gradient across the fuel specimen as some potential failure mechanisms depend on this temperature gradient.

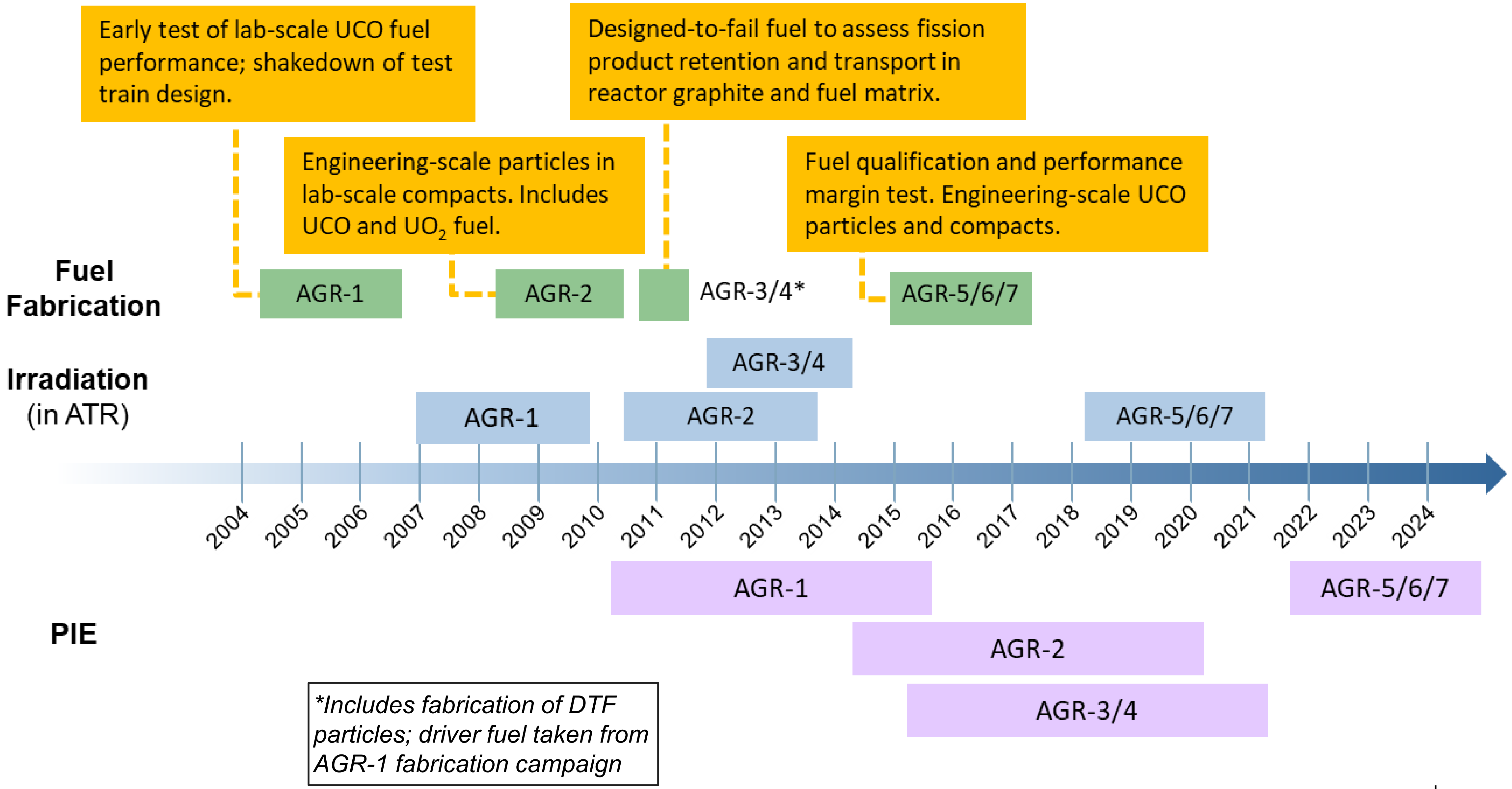
- **Particle packing fraction**: Packing fraction together with the global power density can be used to establish the power per particle, which establishes the temperature inside the particle.

TRISO Fuel Performance Parameter Envelopes

- Germany and Japan plots = historic values
- NGNP = **anticipated** performance envelope for U.S. HTGR designs
- AGR irradiation testing plan informed by the expanded NGNP envelope



AGR Program Overview and Timeline



HTGRs and Other Designs Rely on TRISO Fuel

- Framatome
  - SC-HTGR: prismatic core modular HTGR
- StarCore Nuclear
  - StarCore: small modular prismatic core HTGR
- X-energy
  - X-100: pebble bed modular HTGR
  - TRISO coated particle fuel
- Kairos Power
  - KP-FHR: pebble bed fluoride salt cooled high temperature reactor (FHR)
- BWX Technologies (BWXT)
  - TRISO coated particle fuel

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TRISO-coated particle fuel is basis for ALL thermal HTGRs…and other designs.

Need and Opportunity

- TRISO fuel performance is fundamental to reactor safety and a major source of regulatory uncertainty

- Progress toward fuel safety qualification is important for reactor developers with designs that depend on TRISO for performance

- AGR program has generated (and continues generating) information essential to TRISO fuel safety evaluations

- While applicants are responsible for demonstrating performance of their respective fuel forms, results to date from AGR support this process.

Need and Opportunity (cont'd)

- *"Fuel qualification for advanced reactors is the long pole in the tent"*
  NRC/NRO Director, 2016 DOE-NRC Workshop

- Data and analyses are of limited value unless consolidated and made more accessible
  - What happens if time passes and institutional memory fades?
  - Greatest value would come from formal NRC review and approval

- Opportunity: Assemble data and analyses of greatest design-independent relevance and importance and submit to NRC as a topical report for review
  - EPRI is willing and able to package and submit a generic TRISO topical report on behalf of stakeholders
  - NRC has allocated resources for review

Topical Report

UCO TRISO Particle Fuel Performance Topical Report

- Objective: Demonstrate excellent and predictable performance of UCO TRISO fuel particles manufactured to AGR specifications when tested within the specified performance envelope

- Scope:
  - provide regulatory frame and message
  - provide global context, history, and experience
  - describe the AGR-1 and AGR-2 campaigns
  - focus on UCO fuel performance demonstration
  - capture available AGR-1 and AGR-2 irradiation, PIE, and safety testing data
  - include enough fuel fabrication information to interpret results

AGR-1 Campaign Objectives

- Shakedown test lab-scale coated fuel particles and compacts
- Establish methods for irradiation, post-irradiation examination, and safety testing
- Explore effect of coating variations on fuel performance
- Confirm performance of the AGR UCO particle design
- Support selection of reference particle design for the AGR-2 irradiation
- Test performance of fuel at expected accident temperatures and beyond
- Improve understanding of TRISO fuel behavior

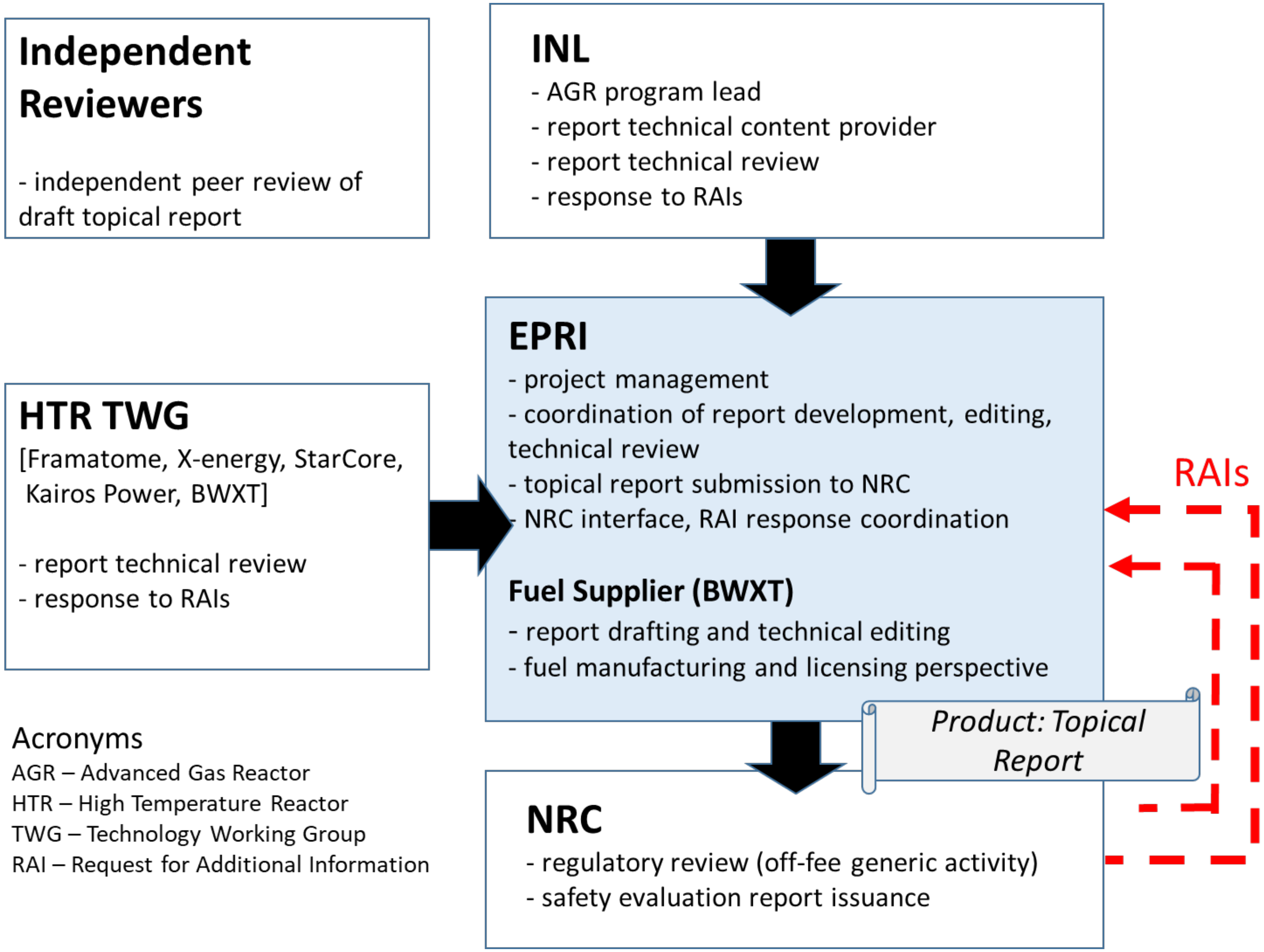
AGR-2 Campaign Objectives

- Demonstrate performance of particles produced at the production scale (compacts still produced at lab-scale)
- Compare UCO and UO2 fuel types
- Test fuel at in-pile temperatures beyond normal services conditions (up to 1360°C time-average peak temperatures)
- Test fuel performance at and above expected accident temperatures
- Further advance understanding of fuel behavior

Value Proposition

- **EPRI**
  - provides tangible contribution to advanced reactor community through a collaborative, broadly applicable project
  - extends EPRI expertise and focus beyond LWRs
- **U.S. DOE and national labs**
  - leverages substantial R&D investment and global experience
  - provides model for proactive and productive industry partnership
- **Developers and vendors**
  - supports fuel qualification for HTGR and FHR design community
  - provides an incremental step forward on long road to design certification and/or licensing path
- **U.S. NRC**
  - provides opportunity for early engagement and staff training ahead of design-specific applications
  - supports demonstration of staged licensing review process using existing regulatory framework

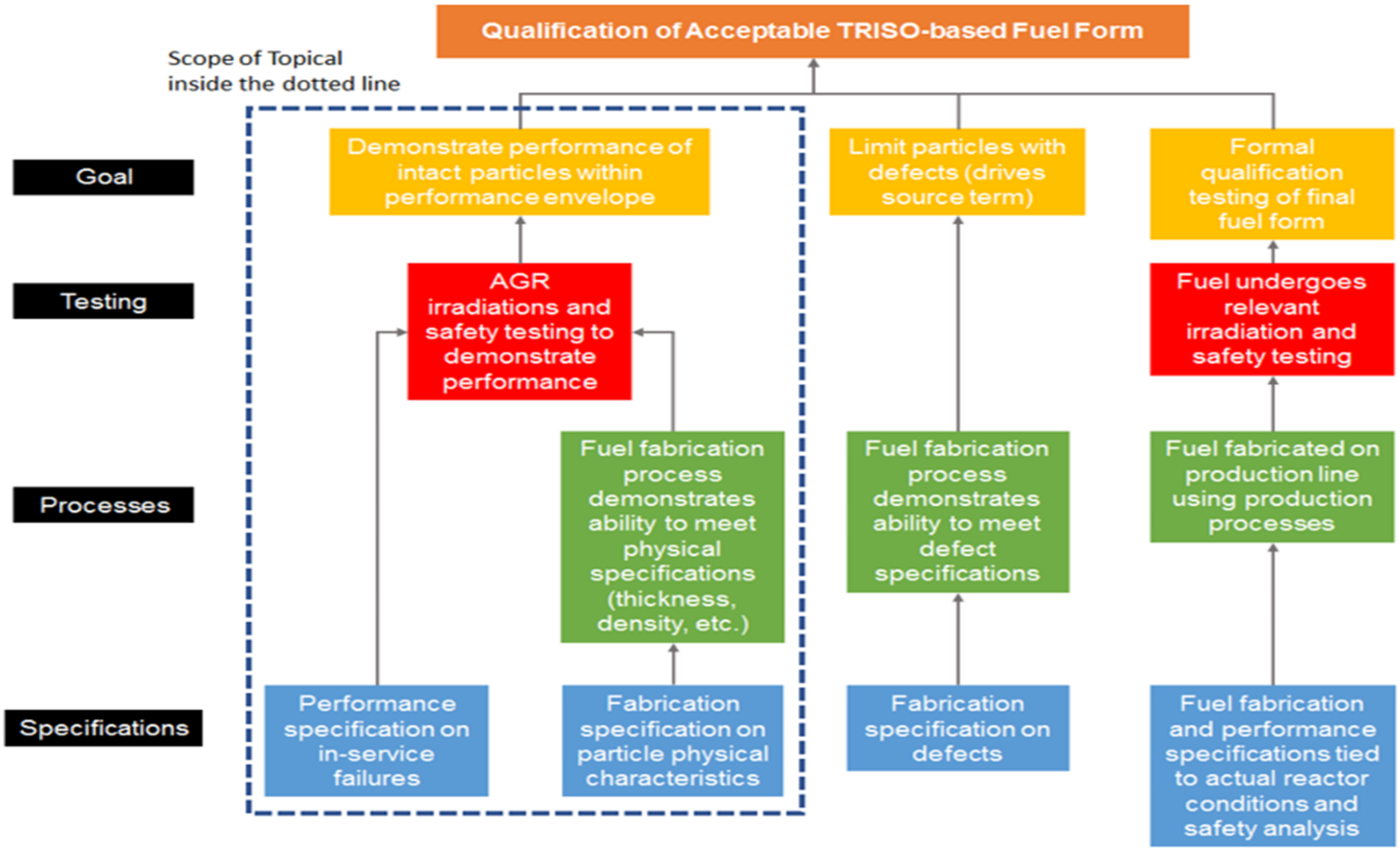
Roles and Responsibilities



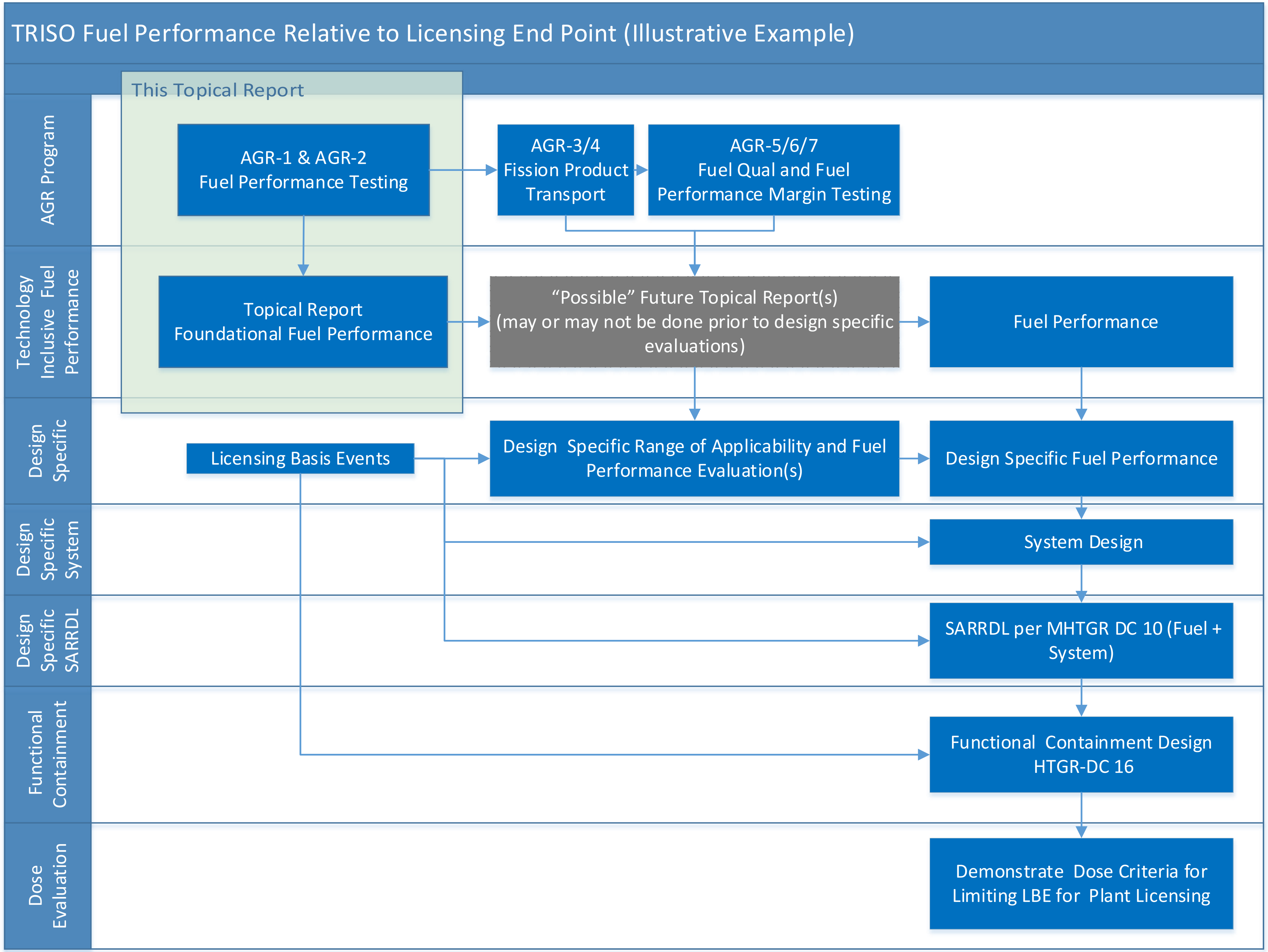
Acronyms
AGR – Advanced Gas Reactor
HTR – High Temperature Reactor
TWG – Technology Working Group
RAI – Request for Additional Information

- Public-private partnership
  - DOE and EPRI co-funding
  - Industry in-kind support
  - NRC off-fee review

Scope Definition



Licensing Context



Report Structure and Content

Content (1 of 3): Background

- Section 2 provides an overview of the TRISO-related NRC Regulatory Bases, including a description of how this topical report fits conceptually into the overall TRISO-fueled plant licensing strategies.

- Section 3 summarizes the background information for the basis of TRISO-coated particle fuel technology resulting from decades of development in the United States and internationally.

- Section 4 introduces the concept of fission product retention for reactor systems that use TRISO-coated particle fuel and presents the basis for the particle design and performance used in the AGR program, and provides representative levels of fuel performance requirements necessary to implement such an approach.

Content (2 of 3): AGR Program

- Section 5 provides a brief overview of the AGR program, including the different program elements and the four fuel irradiation campaigns around which the program is structured.
  - Fabrication of the AGR fuel described in Section 5.3

- Section 6 provides the irradiation response of fuel particles in the AGR-1 and AGR-2 campaigns.

- Section 7 presents follow-on safety test performance and post-irradiation examination (PIE) data for AGR-1 and AGR-2.

- Section 8 provides a summary of the report, including the key conclusions drawn from this work in regard to U.S. UCO TRISO fuel performance.

Content (3 of 3): References and Appendices

- Section 9: provides references for main body of report.

- Appendix A: provides more detail on regulatory history for the U.S. related to TRISO fuel.

- Appendix B: provides more detail on international TRISO-coated particle fuel experience base.

Logistics and Schedule

Important Aspects of Topical Report Review Process

- Continuity of review, e.g., via a consistent core team of NRC staff
- Limited subject matter expertise available to support review
- RAI response timeframe for industry team: 60-days
- Targeted timeframe for safety evaluation report: one-year from submission

Notional Schedule for Topical Submission and Review

- May 31, 2019: Topical report submission
- June 30, 2019: Completion of acceptance review by NRC
- July – December 2019: RAI response and resolution
- January 30, 2020: NRC issues draft safety evaluation report
- *February – April 2020: possible ACRS review*
- May 31, 2020: NRC issues final safety evaluation report

Addressing Requests for Additional Information (RAIs)

- EPRI will coordinate NRC engagement and RAI response process with HTR TWG stakeholders and INL
- HTR TWG members to provide technical support from developer and fuel supplier perspectives
- INL to provide in-depth technical support on AGR data and analyses

Conclusions and Request for Approval

Conclusion 1

The testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitute a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions and thus serves as a foundational basis for use of these particle designs in the fuel elements of a variety of TRISO-fueled HTR designs (i.e., designs with pebble or prismatic fuel and helium or salt coolant).

Conclusion 2

The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited some degree of property variation and were fabricated under different conditions and at different scales with remarkably similar excellent irradiation and accident safety performance. Thus, there is some allowance in terms of the actual values for key critical characteristics of the kernels and coatings necessary to impart satisfactory performance.

Conclusion 3

- Aggregate AGR-1 and AGR-2 fission product release data, AGR-1 fuel failure fractions, and estimated AGR-2 fuel failure fractions, as summarized in this report, and provided in more detail in the literature referenced in the corresponding sections where the data are presented, can be used for licensing of reactors employing UCO TRISO-coated fuel particles.

Request to NRC

- Consider Sections 1 – 4 as historical background and context
  - NOTE: historical pre-AGR data are NOT relied on for US TRISO fuel qualification program or the conclusions in the Topical Report

- Review Sections 5 – 7 as the AGR program content and core scope of Topical Report

- Approve Conclusions in Section 8 with issuance of Safety Evaluation Report

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