TerraPower

NATRIUM

Radiological Source Term Methodology Development

a TerraPower & GE-Hitachi technology

SUBJECT TO DOE COOPERATIVE AGREEMENT NO. DE-NE0009054

Objectives

- Natrium™ reactor overview
- Mechanistic source term methods development

Natrium Reactor Licensing Overview

- Regulatory Engagement Plan submitted 6/8/2021
- 10 CFR 50 licensing process will be followed
  - Construction Permit Application 8/2023
  - Operating License Application 3/2026
- Numerous pre-application interactions are planned to reduce regulatory uncertainty and facilitate the NRC's understanding of Natrium technology and its safety case
- LMP (NEI 18-04), as endorsed by Regulatory Guide 1.233, will support this application

Natrium Reactor Licensing Overview

- Each pre-application interaction will build upon risk insights from prior interactions to demonstrate the Natrium reactor's safety case.

- Future Meetings and Presentations include:
  - Testing Plan and Methodology
  - Functional Containment Strategy
  - Codes and Standards Review

Advanced Reactor Demonstration Program

- Demonstrate the ability to design, license, construct, startup and operate the Natrium reactor within the Congressionally mandated seven-year timeframe
- Include improvements in safety, security, economics, and environmental impacts
- Utilize a simple, robust, reliable, and proven safety profile
- Lower emissions by initiating the deployment of a fleet of Natrium reactors – Demonstrate that the plants can be built economically and that they will be attractive for future owner/operators

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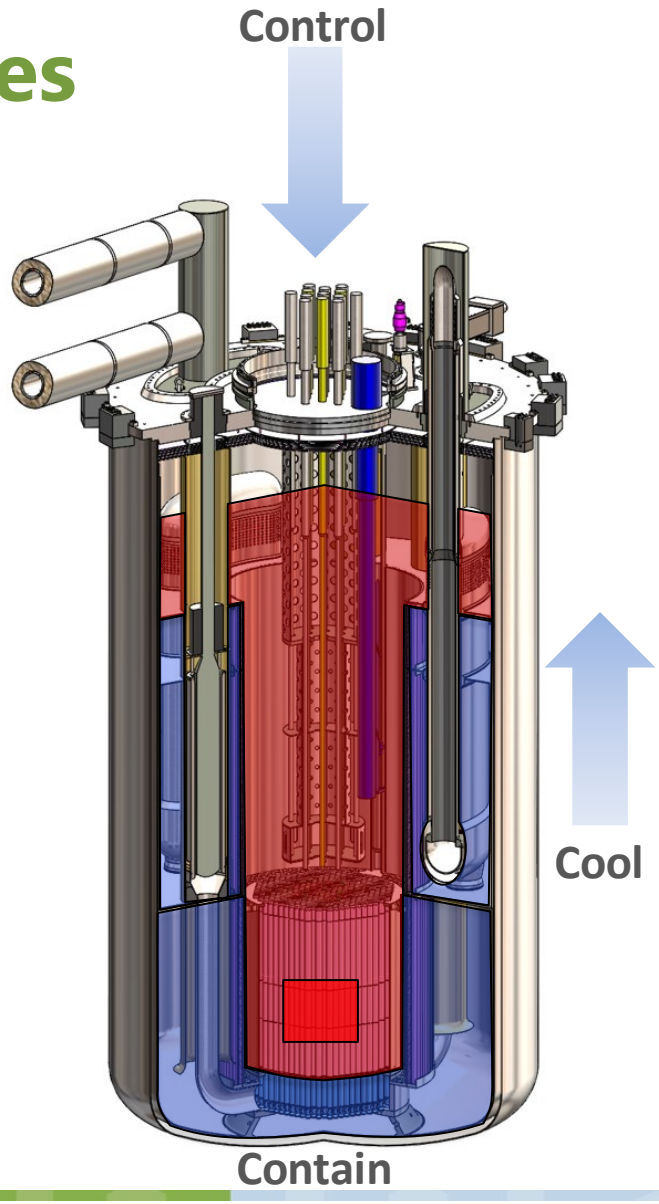
Natrium Safety Features

- Pool-type Metal Fuel SFR with Molten Salt Energy Island
  - Metallic fuel and sodium have high compatibility
  - No sodium-water reaction in steam generator
  - Large thermal inertia enables simplified response to abnormal events
- Simplified Response to Abnormal Events
  - Reliable reactor shutdown
  - Transition to coolant natural circulation
  - Indefinite passive emergency decay heat removal
  - Low pressure functional containment
  - No reliance on Energy Island for safety functions
- No Safety-Related Operator Actions or AC power
- Technology Based on U.S. SFR Experience
  - EBR-I, EBR-II, FFTF, TREAT
  - SFR inherent safety characteristics demonstrated through testing in EBR-II and FFTF



Control

- Motor-driven control rod runback
- Gravity-driven control rod scram
- Inherently stable with increased power or temperature

Cool

- In-vessel primary sodium heat transport (limited penetrations)
- Intermediate air cooling natural draft flow
- Reactor air cooling natural draft flow – always on

Contain

- Low primary and secondary pressure
- Sodium affinity for radionuclides
- Multiple radionuclides retention boundaries

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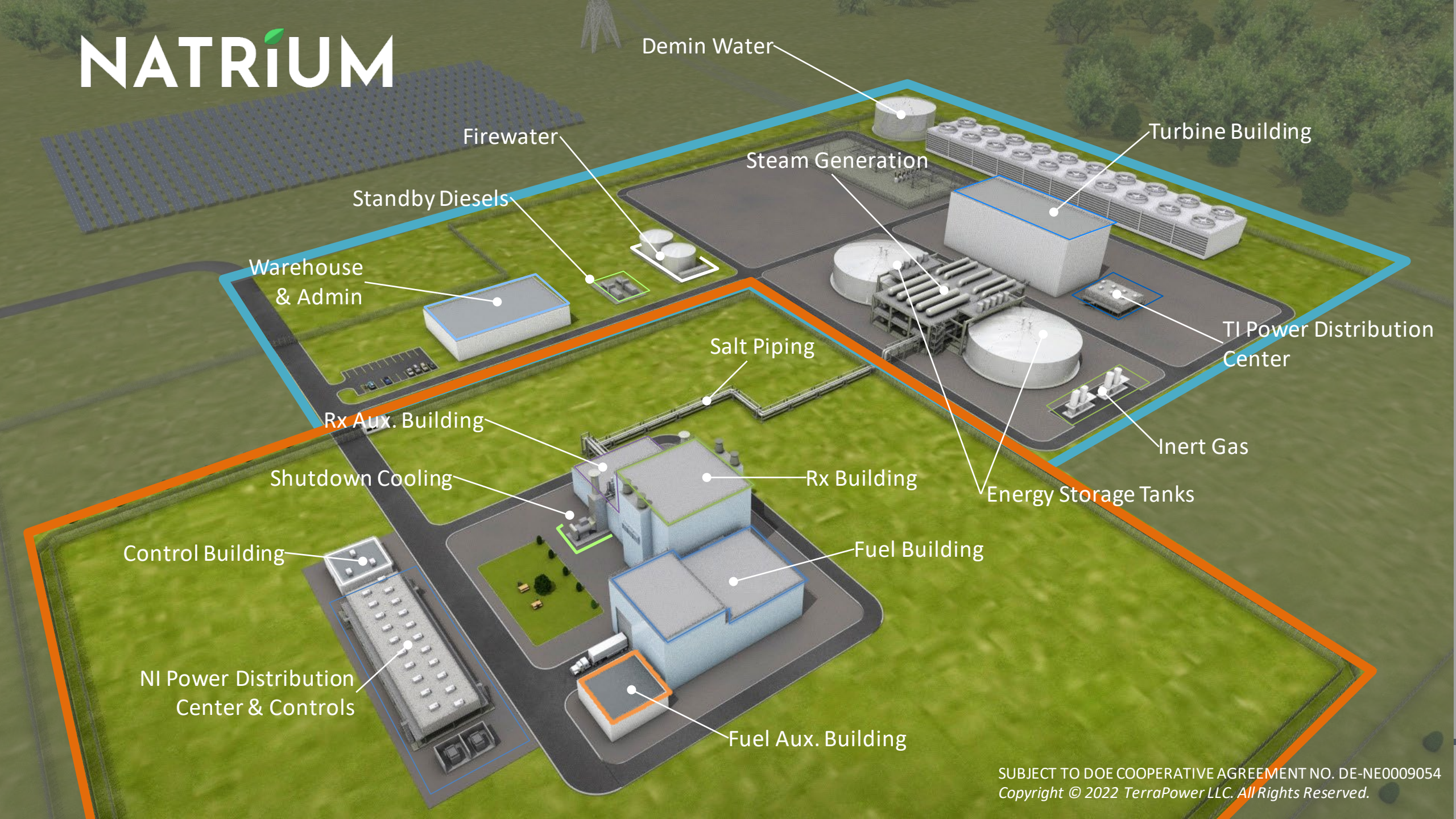

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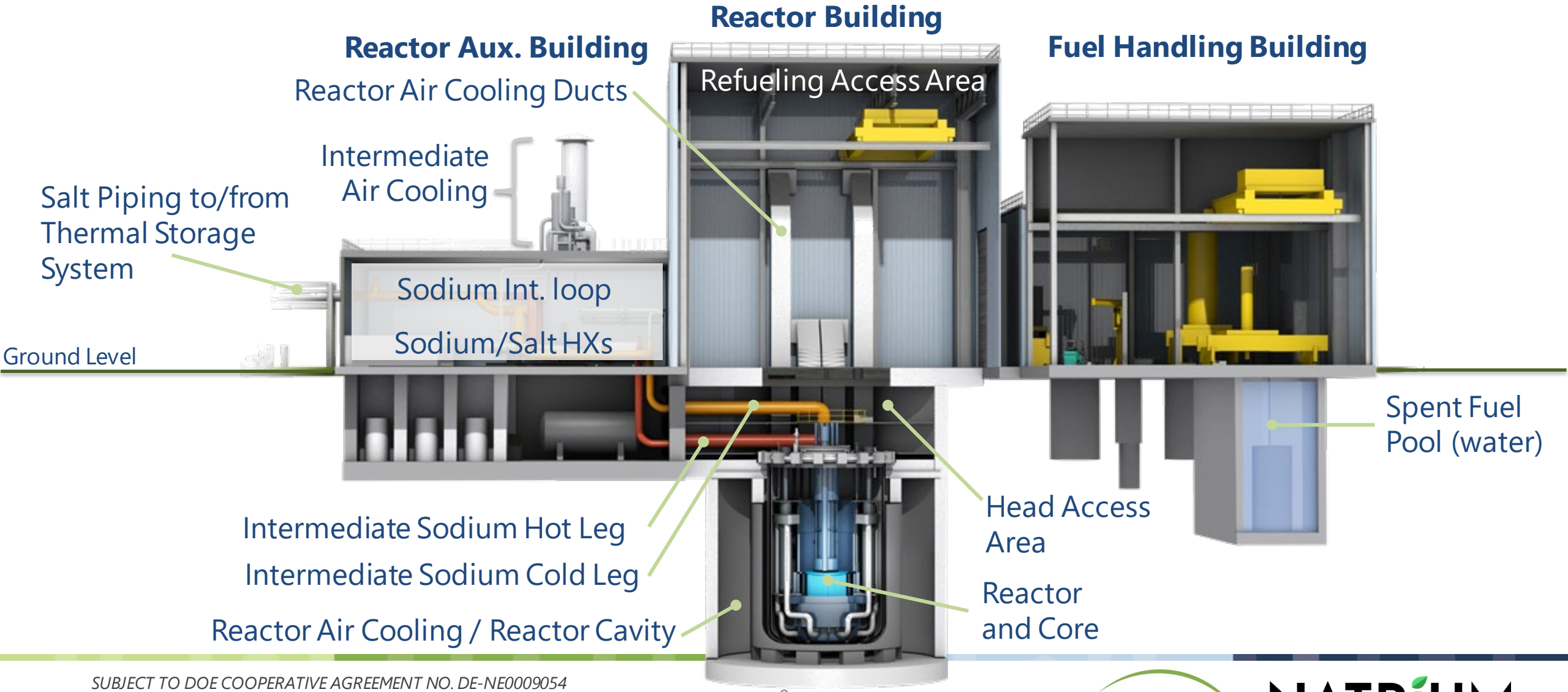
Plant Overview



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SOURCE TERM DEVELOPMENT PROCESS

Toward mechanistic source term

Radiological Source Term

"The fission product release from the reactor core into containment is referred to as the source term…" [64 FR 71991]

- Normal Radiological Source Terms (i.e., contained source terms)
  - Fuel defect
  - Activation: tritium, Na-24, Ar-41, Co-60

- Accident Radiological Source Terms (i.e., released source terms)
  - LBEs with fuel failure
  - Flow blockage
  - Fuel handling accidents

Accident Source Terms

- Conservative accident source term for LWRs
  - TID-14844 (1962)
  - Regulatory Guides 1.3*, 1.4*, 1.5*, 1.25*, 1.77*, and 1.195
- Alternative accident source term for LWRs
  - NUREG-1465 (1995)
  - Regulatory Guides 1.183, 1.194, and 1.236
- Mechanistic accident source term for SFRs
  - Near future …
  - SRM-SECY-93-092, Regulatory Guide 1.233, ANSI/ASME/ANS RA-S-1.4-2021

** withdrawn*

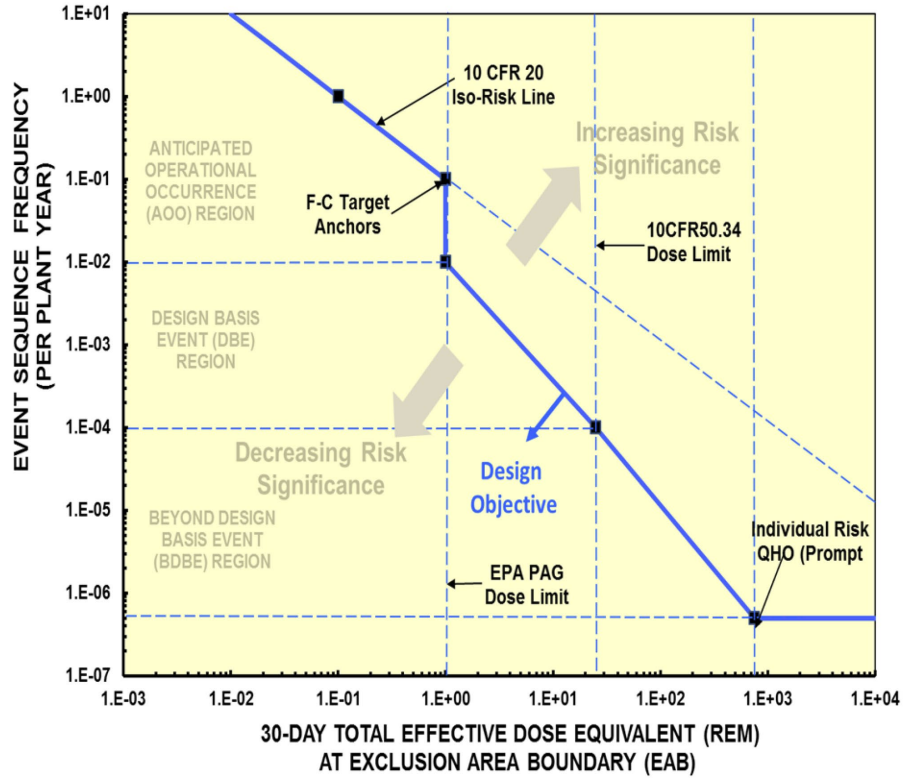
Mechanistic Source Term

- *"A mechanistic source term is the result of an analysis of fission product release based on the amount of cladding damage, fuel damage, and core damage resulting from the specific accident sequences being evaluated. It is developed using best-estimate phenomenological models of the transport of the fission products from the fuel through the reactor coolant system, through all holdup volumes and barriers, taking into account mitigation features, and finally, into the environs."* [SECY-93-092]

- *"The characteristics of a radionuclide release… that are calculated using models and supporting scientific data that simulate the physical and chemical processes that describe the radionuclide inventories and the time-dependent radionuclide transport mechanisms that are necessary and sufficient to predict the source term"* [ANSI/ASME/ANS-RA-S-1.4-2021]

Risk-Informed Performance-Based Licensing

- LMP requires more realistic radiological consequence analysis, based on mechanistic source terms
- The mechanistic source terms provide margin to F-C target
- SARRDL is derived from the margin to F-C target [*presented during the TerraPower PDC & LMP public meeting on 12/09/2021, ML21340A107*]



Taken from NEI 18-04

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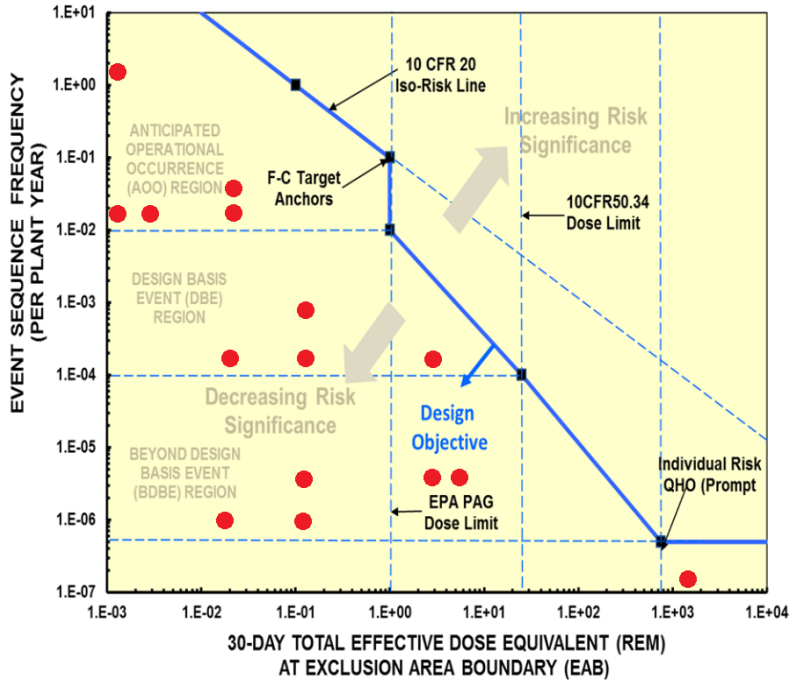
Risk-Informed Performance-Based Licensing (cont.)

- "*The evaluation of the consequences of all LBEs are supported by mechanistic source terms.*" [NEI 18-04, Rev. 1]
- As illustrated, a single system failure may result in very different frequencies and consequences based on event sequences
- LMP departs from the maximum hypothetical accident
- Still need to look at the potential "cliff-edge effects" and to consider uncertainties

For illustrative purposes only



Hypothetical event sequences with release from a specific system

For illustrative purposes only

Adapted from NEI 18-04

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NATRIUM DESIGN AND SOURCE TERMS

Pool-type, sodium-cooled, metal fuel

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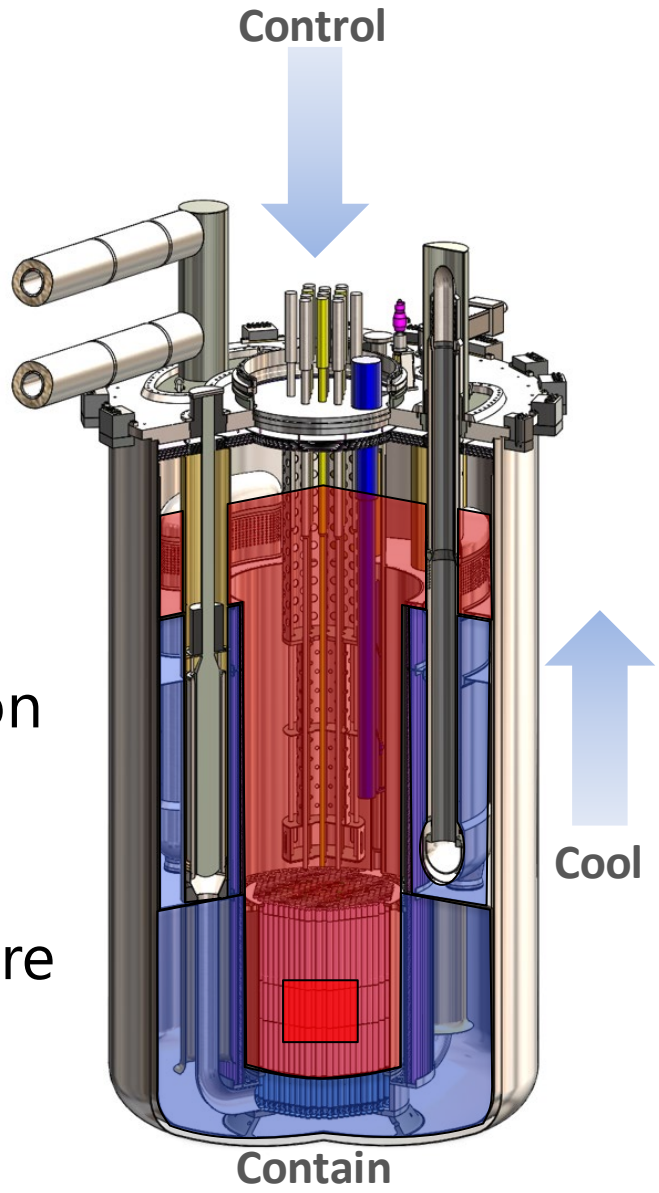
Natrium Safety Features

- Control
  - Robust shutdown
- Cool
  - Reliable decay heat removal: natural circulation
  - Subcooling: large boiling margin & radionuclide retention
- Contain
  - Metal fuel: high thermal conductivity & lower temperature
  - Sodium coolant: affinity for iodine



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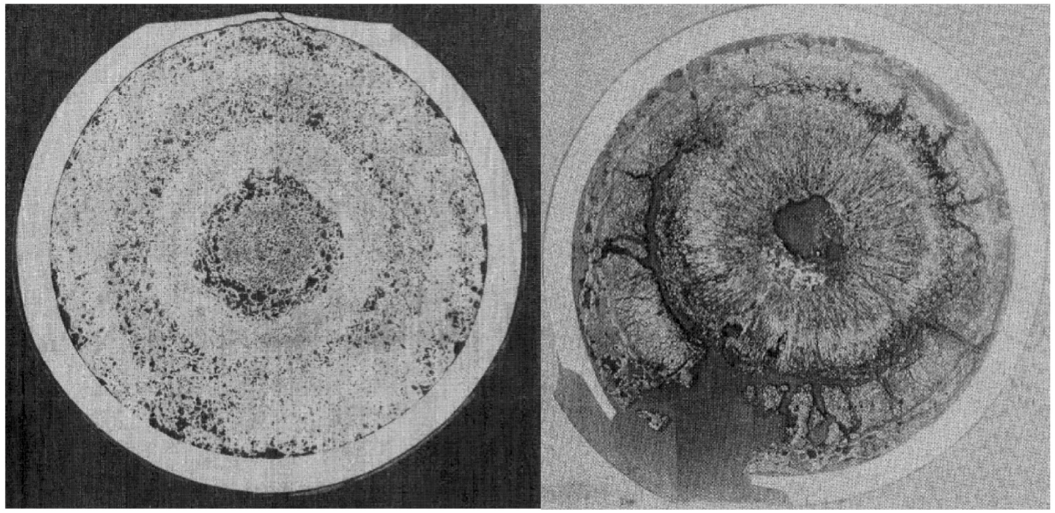
Radionuclide Retention

- Metal fuel
  - High thermal conductivity and lower heat capacity
  - Uranium triiodide (UI_3)
  - Cesium iodide (CsI)
- Sodium coolant
  - Chemically compatible with metal fuel
  - Sodium iodide (NaI)
- Smaller release fractions



Comparison of Breached Cladding for Metal Fuel (left) and Oxide Fuel (Right)

Taken from ANL-ART-3

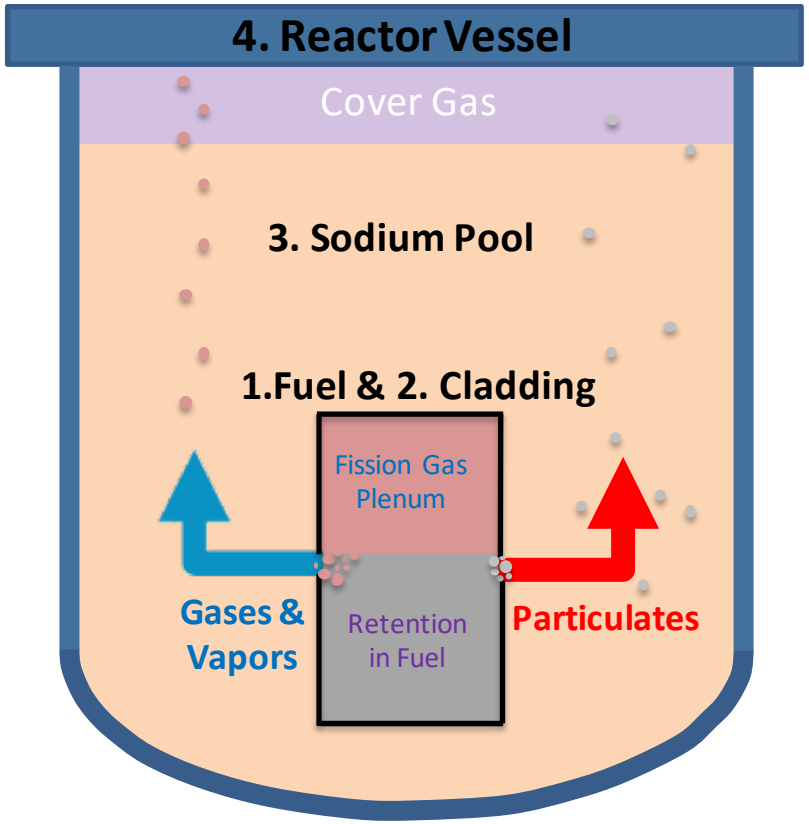
Sodium Pool Scrubbing

- Large volume of sodium pool
  - Reliable decay heat removal
  - No penetration below the reactor vessel head
  - Subcooled with large boiling margin
  - Over 30 feet above the top of the active fuel

- Decontamination factor

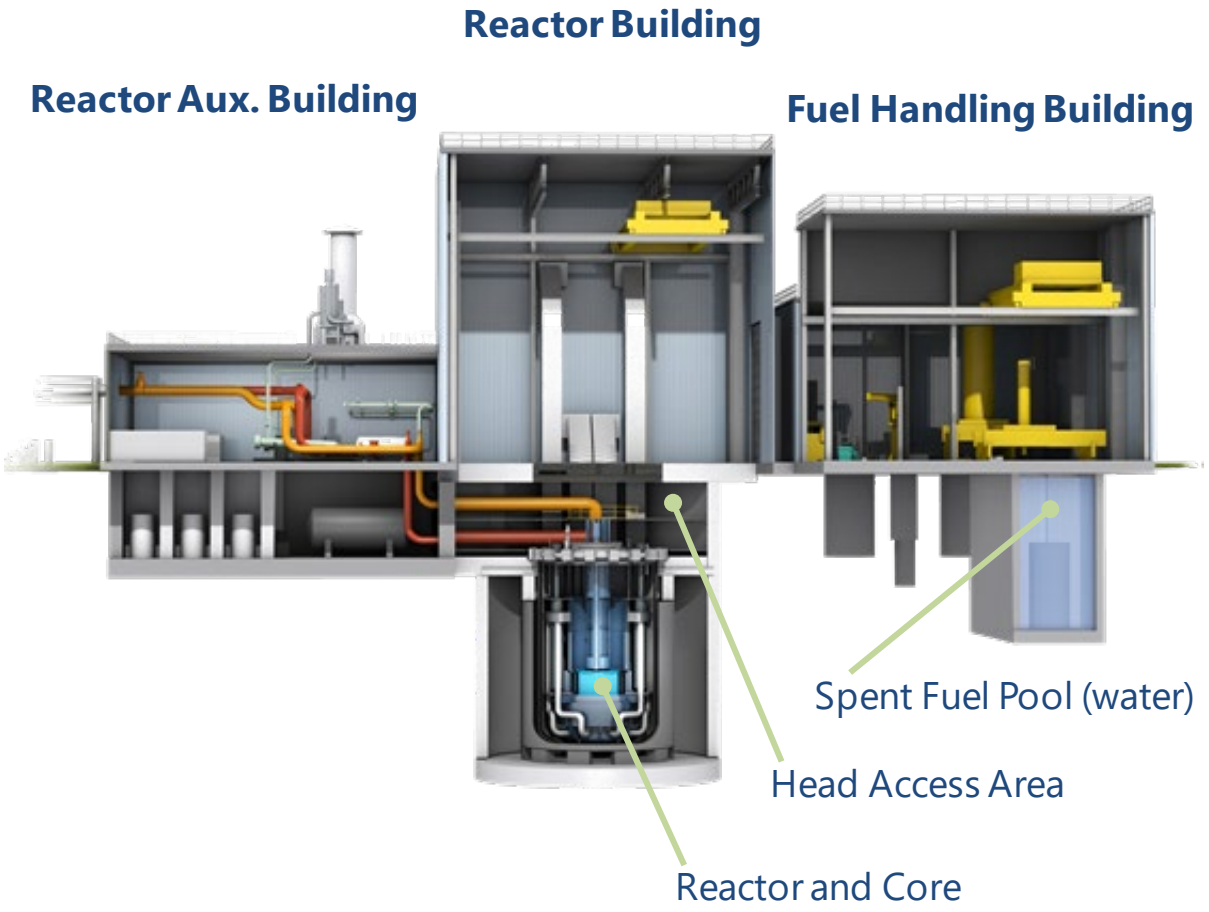
$$DF = \frac{mass\ of\ aerosols\ entering\ sodium\ pool}{mass\ of\ aerosols\ exiting\ soduim\ pool}$$

  - Sodium pool conditions
  - Aerosol density
  - Aerosol size distribution



Aerosol Dynamics and Natural Deposition

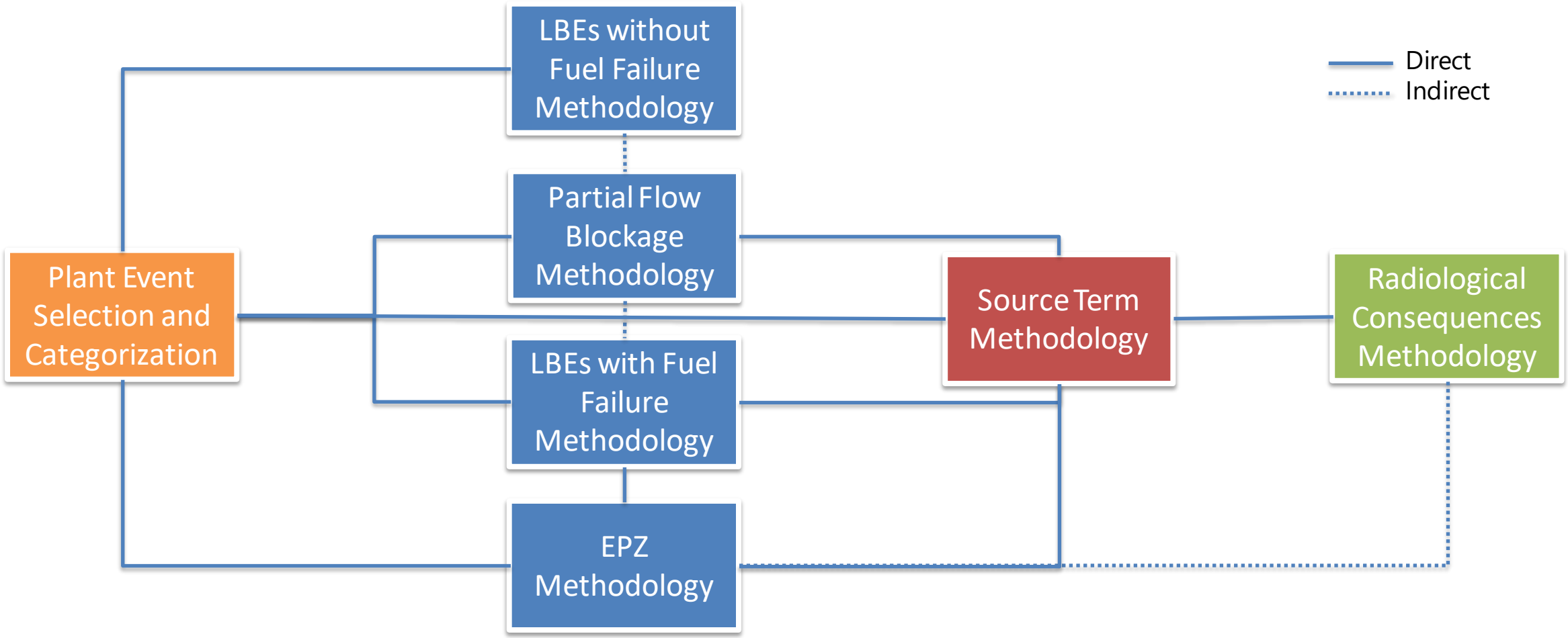
- Cover gas region
  - Argon cover gas
  - Reactor vessel head
  - Low primary system pressure
- Confinements
  - Reactor head access area
  - Reactor building
  - Fuel handling building



DEVELOPMENT OF NATRIUM SOURCE TERM METHODS

Closing gaps on mechanistic source terms

Source Term within Safety Analysis Methodologies



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Phenomena Important to Natrium Source Term

- Key phenomena associated with fission product release and transport have been identified in previous SFR designs and are applicable to the Natrium design (e.g., pool-type, sodium coolant, and metal fuel)

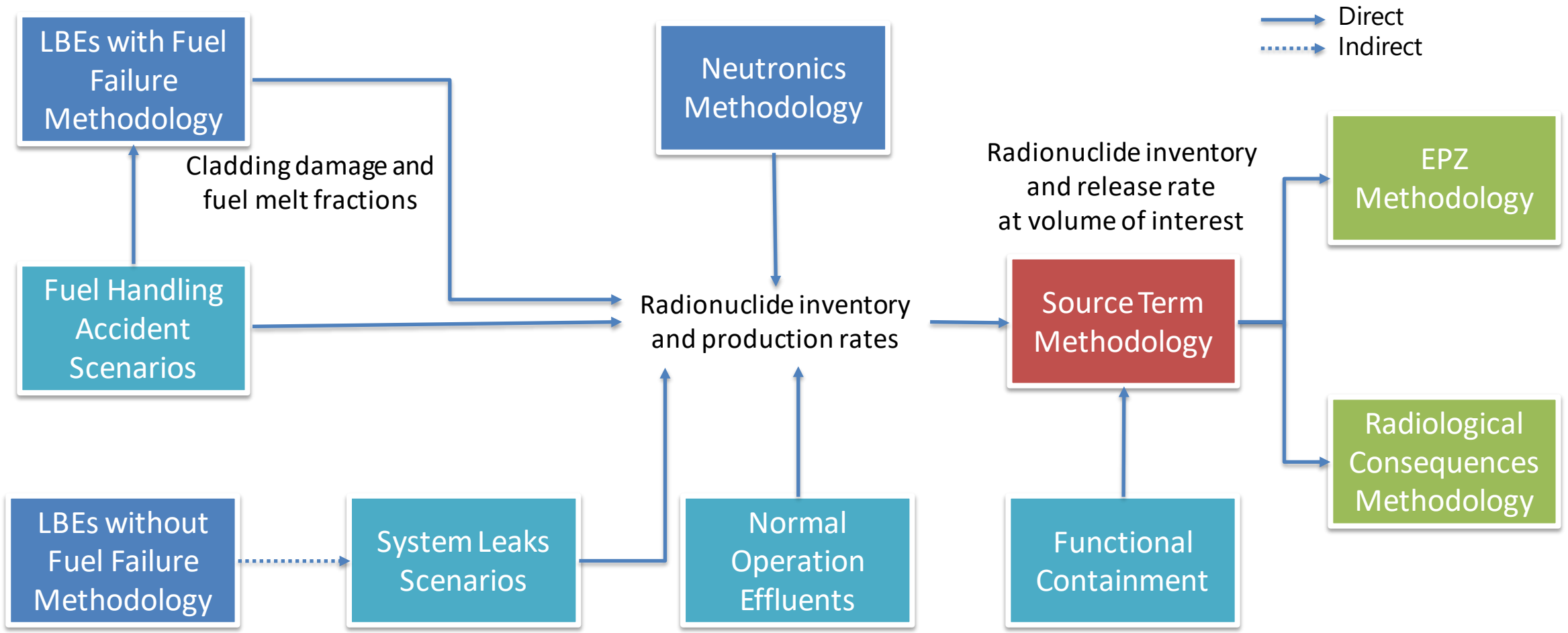
- TerraPower has performed preliminary assessments and scoping studies and developed trial mechanistic source term tools with Argonne National Laboratory [ANL-ART-49]

- Three key areas are important to address uncertainties:
  - Sodium pool scrubbing
  - In-pin radionuclide migration and release
  - Aerosol dynamics including sodium chemical reactions

Potential Testing Relevant to Source Term

- Sodium pool scrubbing
  - University of Wisconsin – Madison
- In-pin migration & release
  - Metal fuel post-irradiation examination
  - Metal fuel qualification
- Aerosol dynamics
  - Sodium chemical reactions
  - Natural deposition
- Holdup & leakage
  - Reactor vessel head seal leak
  - Equipment qualification
  - Functional containment barrier performance

Key Interfaces to Source Term



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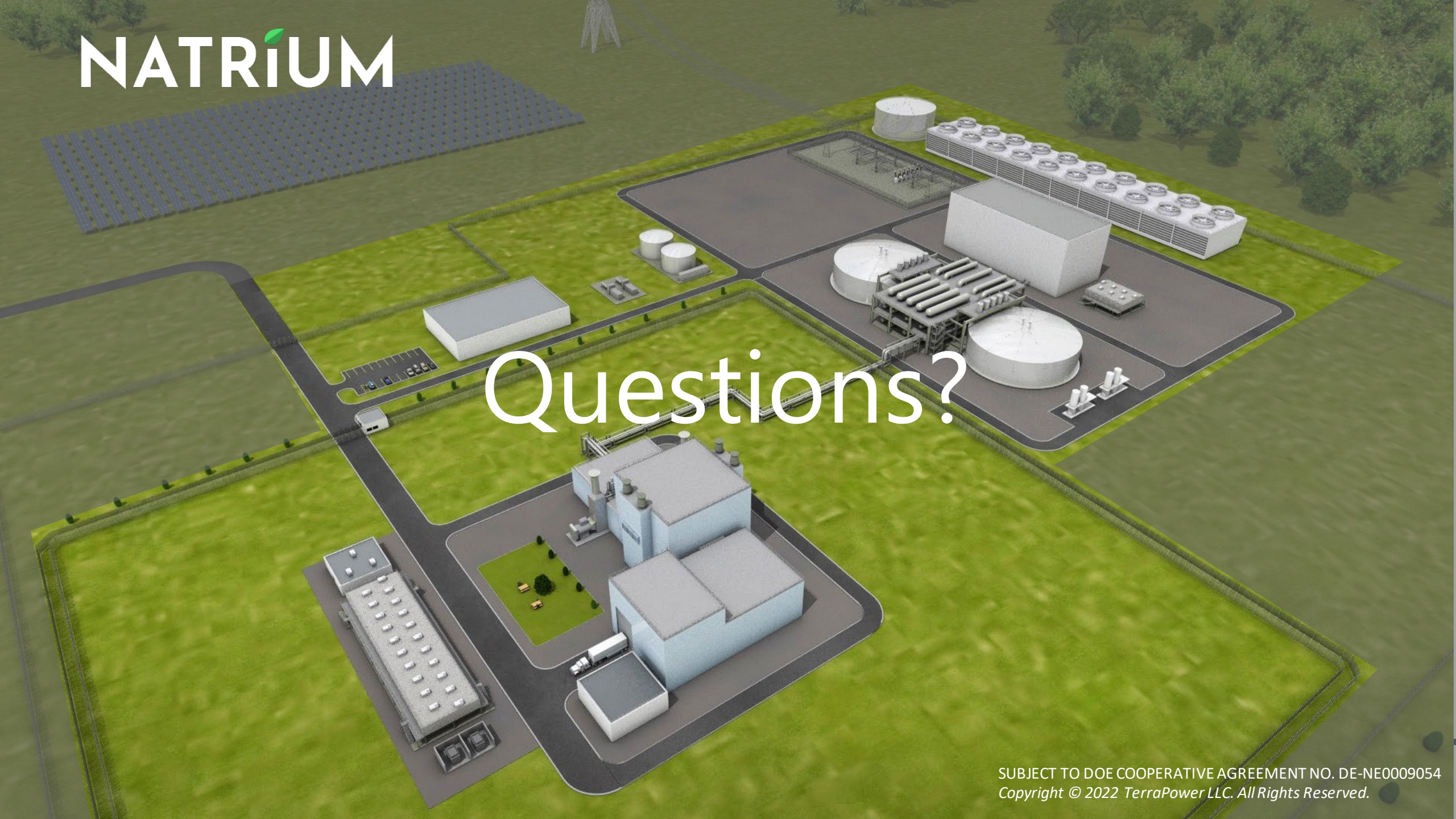
Other Areas Related to Source Terms

- Effluent release including tritium
- Radioactive waste management
- Neutron and gamma-ray shielding

- Metal fuel qualification
- Functional containment strategy
- Sodium chemical reactions
- On-site and off-site radiological consequence analysis
- Emergency Planning Zone scaling methodology
- Energy Island decoupling strategy

Natrium Mechanistic Source Term Methods

- The enhanced safety features of the Natrium reactor are based on the past U.S. SFR experiences (i.e., a pool-type, sodium-cooled fast reactor with metal fuel)
- The mechanistic source term is a key to the risk-informed performance-based licensing framework and supports the Natrium plant design and licensing
- The mechanistic source term methods development interfaces with all the safety analysis methodologies
- Next steps:
  - Source term topical report (planned for April 2023)
  - Functional containment strategy presentation (planned for March 2022)
  - Emergency planning methodology presentation (planned for July 2022)



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Abbreviation and Acronym List

AC – Alternating Current
CFR – Code of Federal Regulations
DF – Decontamination Factor
EBR – Experimental Breeder Reactor
EPZ – Emergency Planning Zone
F-C – Frequency-Consequence
FFTF – Fast Flux Test Facility
HX – Heat Exchanger
LBE – Licensing Basis Event
LMP – Licensing Modernization Project
LWR – Light Water Reactor
NEI – Nuclear Energy Institute
PDC – Principal Design Criteria
SARRDL – Specified Acceptable System Radionuclide Release Design Limit
SFR – Sodium Fast Reactor
TREAT – Transient Reactor Test