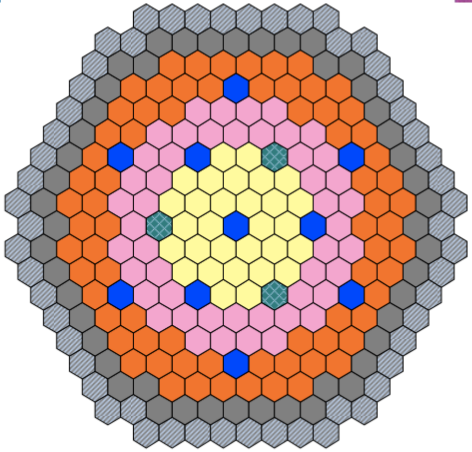
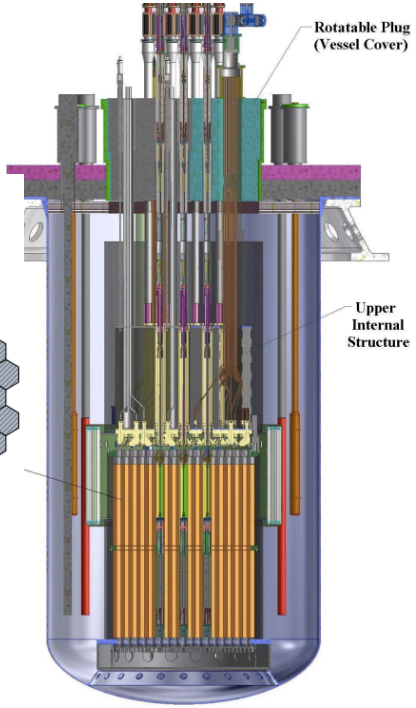
# INTRODUCTION






**TANJU SOFU**
**ARGONNE NATIONAL LABORATORY**

March 26, 2019
Fast Reactor Technology Training
U.S. Nuclear Regulatory Commission

# OUTLINE

- Training agenda
  - Day 1
  - Day 2
- Motivations for fast reactors
- Fast spectrum design options
- High-level design approach
- High-level safety approach

# TRAINING COURSE OUTLINE

## Day 1

- Introduction: Motivation and applications, high level design and safety approach
- Historical perspective for fast reactors
- Fast reactor physics
- Fast reactor fuels
- SFR technology overview
- Sodium technology, test facilities, and materials research
- Considerations for operational states
- Overview of past U.S. SFR operations experience and safety testing program

# TRAINING COURSE OUTLINE

## Day 2

- Fast reactor safety design approach
- Safety analyses
- Mechanistic source term calculations
- Fast reactor modeling and simulation tools and methods
- Probabilistic risk assessments
- Overview of LFR technology
- Overview of heat-pipe based micro-reactor technology
- Summary and concluding remarks
- Q&A

# MOTIVATIONS FOR FAST REACTORS

- Fast reactors aim for significant advances in sustainability, safety, reliability, economics, and non-proliferation
- Importance for closed fuel cycle systems to support sustainability goals
  - Efficient resource utilization
  - Reduced repository space needed for waste isolation
- Potential for significant design simplifications for improved reliability and enhanced safety
  - Unique properties for SFR/LFR (very-low Pr#) and MSFR (very high Pr#) coolants allow unpressurized operations
  - Inherent safety for reactivity control, and passive safety for decay heat removal
- Fast reactors can be designed to have a long core life, some even without refueling, via use of “breed-and-burn” concept
  - Alternatively, they can be designed for actinide burning

# FAST SPECTRUM DESIGN OPTIONS

- Full range of coolant alternatives
  - Sodium- and lead-cooled fast reactors (SFR and LFR)
  - Heat-pipe cooled fast spectrum micro-reactors
  - Gas-cooled Fast Reactors (GFR)
  - Molten-Salt-fueled Fast Reactors (MSFR)

Focal concepts for this training

- Each concept uses different fuel forms
  - SFR with metallic alloys or oxide fuels
  - Micro-reactors with metallic alloys
  - LFR with oxide or nitride ceramic fuels
  - GFR with carbide fuel in SiC-composite cladding
  - MSFR with uranium dissolved in chloride-salt
- SFR, LFR and MSFR systems can employ either a pool- or loop-type plant configuration
  - Each with unique reliability and safety implications for design of the core, reactor/guard vessels, primary and intermediate coolant systems, decay heat removal systems, pumps, refueling and storage systems

# HIGH-LEVEL DESIGN APPROACH

## Characteristics of SFR and LFR designs with liquid metal coolants

- High core power density (~up to 5X in comparison to an LWR)
  - Compact lattice with triangular pitch
- Large margin to boiling
  - Boiling can only be expected only during highly unlikely accidents with large-scale fuel failures
- Unpressurized heat transport systems
  - No LOCA or need for high-pressure injection system
- High temperature operation (>500$^{o}$C core outlet temperature)
  - Material challenges due to thermal creep and fast fluence
- Large thermal inertia with long grace period
- Natural circulation potential
  - ΔT is ~150$^{o}$C during normal operation (>300$^{o}$C during accidents) leading to significant sodium inlet/outlet density difference and large buoyancy force

# HIGH-LEVEL DESIGN APPROACH

## Characteristics of SFR and LFR designs with liquid metal coolants

- Interdependent design factors:
  - Fuel type
  - Material compatibilities and corrosion concerns
  - Core configuration and core flow distribution
  - Pumping power
  - Burnup considerations
  - Thermal and mechanical limits
  - Steady-state and transient liquid-metal coolant flow and heat transfer
  - Thermal inertia of coolant inventory
  - Pump coast-down profiles
  - Coolant stratification
  - Decay heat profile
  - Reactivity feedback mechanisms
- Major thermal-fluid design parameters
  - Peak fuel centerline temperature, margin to fuel melting
  - Peak cladding temperature, margin to cladding failure
  - Peak coolant temperature, margin to coolant boiling

# HIGH LEVEL SAFETY APPROACH

- Fast reactor safety and reliability goals are:
  - Improvements in operational safety and reliability
  - Low likelihood and degree of core damage
  - Smaller emergency planning zone
- Defense-in-depth is the key concept on which all fast reactor safety is based:
  - Level 1: Prevention of operational failures
  - Level 2: Control of abnormal operation and detection of failures
  - Level 3: Control of accidents within the design basis
  - Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences
  - Level 5: Mitigation of radiological consequences should significant releases of radioactive materials occur

# PLANT STATES AND DID LEVELS

High probability, low consequence

Low probability, high consequence

| Defense-in-Depth Levels | | | | |
|---|---|---|---|---|
| Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
| Operational states | | Accident conditions | | EP&R |
| Normal Operation | Anticipated Operational Occurrences | Design Basis Accidents | Beyond Design Basis Accidents | Residual risk and practically eliminated accidents |

Severe accidents

Plant states considered in fast reactor design
(safety analyses)

Out of the design
(source term assessments)

# CLASSIFICATION OF EVENTS

| Events | Frequency | Expected Consequences |
|---|---|---|
| Anticipated Operational Occurrences (AOOs) | Expected during the lifetime of the plant (>$10^{-2}$ per reactor year) | None. Maintain large margin to fuel failure |
| Design Basis Accidents (DBAs): Typically failure of one safety-grade system | Not expected to occur during the lifetime of the plant but anticipated in the design (>$10^{-4}$ per reactor year) | Minor fuel damage permissible for lower probability events (<$10^{-3}$ per reactor year). Individual (offsite) exposure below allowable limit |
| Beyond Design Basis Accidents (BDBAs) : Multiple failures of safety-grade systems, including ATWS and other unprotected events | Highly unlikely accidents not expected to occur during the lifetime of the fleet but considered in the design (>$10^{-6}$ per reactor year) | Substantial fuel damage permissible for lower probability events (<$10^{-5}$ per reactor year). Public exposure below allowable limit |
| Severe Accidents | <$10^{-6}$ per reactor year | Propagation of fuel damage, potentially leading to loss of core integrity and coolable geometry |
| Early or Large Releases | <$10^{-7}$ per reactor year | Emergency response |