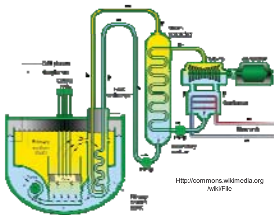
NTech Lehrstuhl für Nukleartechnik

Georgia Tech

Sodium-cooled Fast Reactors

Loss of Intermediate Sodium – Effects of Fuel Type

Project launched at Georgia Institute of Technology to examine the effect of fuel type on the inherent safety characteristics of Liquid Metal Fast Reactors



Background

▪ Increasing world energy demand and decreasing fossil resources → Nuclear energy will still play a role in future power generation. Thermal reactors extract only **<1%** of energy stored in uranium fuel → Development of Gen-IV advanced nuclear systems like LMFRs, with Sodium-cooled reactors most promising type

▪ Wide spectrum of accidents have to be considered for Fast Reactors to comply with U.S NRC Safety Goals and Severe Accident Policies (i.e. Fukushima BWRs). Certainty that all Bounding Events (BE) considered in licensing can be sustained without loss of core coolability

▪ GE's S-PRISM design was chosen as reference reactor. GE included a set of BE to account for uncertainties in PRISM design. S-PRISM can suffer a Double-ended Guillotine Break (DEGB) in the Intermediate Sodium Loop with contemporaneous off-site electricity power loss

Fast Reactor Technology

Nuclear chain reaction sustained by fast rather than thermal neutrons

- Higher neutron fission-to-capture ratio of the actinides → Efficient use of uranium resources leads to a reduced amount of spent fuel and long-lived transuranics
- More neutrons are produced from fast fissions → Breeding of additional fissile fuel from fertile material (e.g. Th-232, U-234, U-238), use of spent LWR fuel and conversion of radioactive long-lived actinides into shorter-lived fission products (Transmutation)

Fast Reactor Fuel Properties

- Low Pu-239 fission to U-238 absorption cross section ratio → FRs require high fissile fuel content. High power density, high fuel burn-up, high melting point and thermal conductivity, negative reactivity feedback
- Study of feasible fuels: fuel type can have a significant impact on consequences arising from accidents, especially for severe accidents

Fast Reactor Fuel Types

- ➢ Metal Alloy Fuel (U, Pu, Zr) – Melting Point: 1350 °K
- ➢ Oxide Fuel (PuO_2, UO_2) – Melting Point: 3035 °K
- ➢ Nitride Fuel (U, Pu, Ni) – Melting Point: 3023 °K

Main Fast Reactor reactivity feedbacks

Fast Reactors also can rely on passive reactivity feedbacks to stabilize power increases.

- ➢ Fuel Doppler Broadening: negative reactivity insertion with increasing fuel temperatures (U-238 atoms neutron capture)
- ➢ Coolant Thermal Expansion: sodium density decrease leads to reduced neutron moderation, increased neutron leakage
- ➢ Core Axial and Radial Thermal Expansion: radial and axial neutron leakage

Simulation in RELAP5-3D Safety analyses with ATHENA version of thermal-hydraulic code

S-PRISM Metal, Nitride and Oxide Core Models

Mesh of single-fuel-pin is divided into 8 axial heat structures and 9 radial mesh points (Fig. 1). S-PRISM core models account for all fuel pins in 5 representative driver and blanket fuel assembly (Fig. 2). Hydrodynamic RELAP5 model is a transient, two-fluid flow model. Complete S-PRISM nodalization comprises the Primary and Intermediate Heat Transport System (PHTS, IHTS) and the Steam Generator (Fig. 6). **Point Reactor Kinetics Model** → At each time step, RELAP5 code calculates immediate fission and decay heat power. Steady-state models are run in transient mode until derivatives of time approach zero. Transient simulations are restarted after 2000s of steady-state calculation.

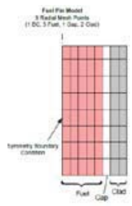


Fig.1: Fuel Pin Mesh

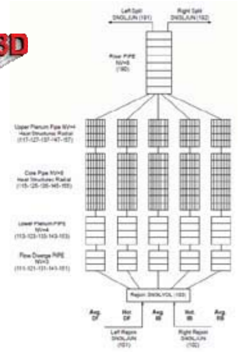


Fig. 2: S-PRISM core nodalization

Break Model in RELAP5

Time-dependent junction 520 defines flow boundary condition in IHTS at steady.state. Trip-valves 950/970 are opened at restart to simulate break junctions in a DEGB. Volumes 610/620 represent broken pipe. PIPE components 505/509 define Intermediate Heat Exchanger (IHX)/SG. Time-dependent volumes 960/980 (with non-condensable gas) simulate the containment into which sodium discharges. Loss of sodium inventory is determined by break size and location. Break is set in IHTS cold leg at the discharge of the electromagnetic pump (Fig. 4). Reactor at full power (1000 MWth) and 100% flow when DEGB in IHTS occurs. Liquid sodium is discharged from both IHTS pipe ends into TMDPVOLs 960/980. Total sodium mass in loop decreases rapidly for about 50s (Fig. 3). No external reactivity assistance from control rods and Gas Expanson Modules (GEM) is accounted. Each core's inherent reactivity feedback is responsible for keeping safe reactor conditions during a transient. **Failure criteria:** coolant boiling, fuel and clad melting.

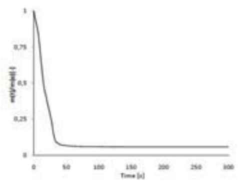


Fig. 3: Initial to transient total mass ratio in IHTS

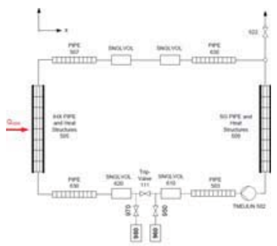


Fig. 4: IHTS Break Model

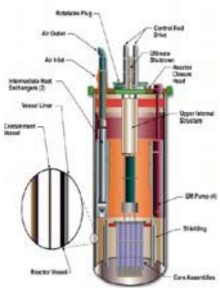


Fig. 5: S-PRISM Reactor core

➢ **Unprotected Loss of all IHTS Sodium cooling with available AC Power**

Diminished core heat removal capability of primary loop via IHX. Overheated primary sodium takes circa 10s to travel through the core and affect it. Increased temperature of the coolant leads to a rise in fuel temperatures from the steady-state value. Transient triggers rapid negative reactivity feedbacks: Nitride core with strongest, metallic fuel with weakest fuel doppler reactivity insertion (Fig. 7). After 30s: average fuel temperatures decrease. All simulated fuels mantained a large margin to fuel melting. Core power is lowered to manageable levels and criticality was reestablished (Fig. 8)

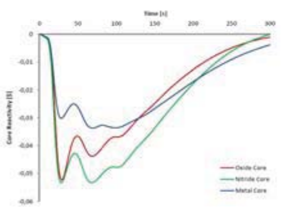


Fig. 7: Reactivity feedbacks during IHTS loss of cooling

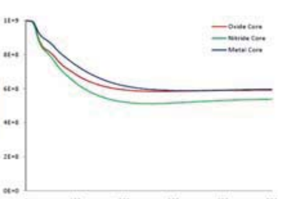


Fig. 8: Total Power during IHTS loss of cooling

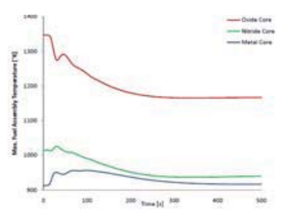


Fig. 9: Peak Fuel Temperature during IHTS loss of cooling

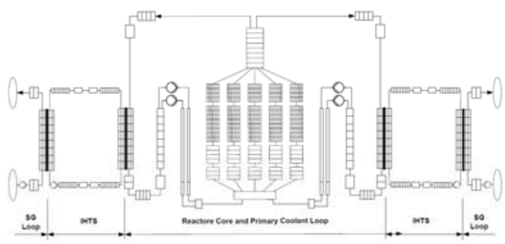


Fig. 6: RELAP5 S-PRISM nodalization

➢ **Unprotected Loss of all IHTS Sodium cooling with Station Blackout**

S-PRISM can suffer a DEGB in IHTS with contemporaneous off-site electricity power loss. To avoid core damages, effective heat removal is crucial in first 120s after the loss of power → PRISM design with primary pump coastdown provided by synchronous machines (Figure 10). Simulation with primary flow coastdown: fuel melting prevented in all fueled core types. Core power decrease to decay power levels. Reactor criticality was never reestablished (Fig. 11). Metal core: largest decrease of margin to fuel melting (95%). Far superior performance of Nitride (7.7%) and Oxide (4.1%) fueled cores (Fig. 12), due to high fuel melting point.

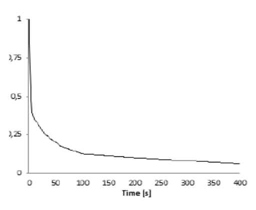


Fig. 10: Primary flow coastdown during loss of power

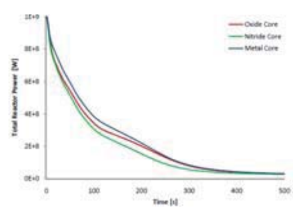


Fig. 11: Reactor power during loss of IHTS cooling with station blackout

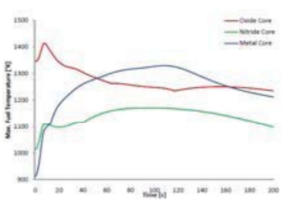


Fig. 12: Peak fuel temperatures during loss of IHTS cooling with station blackout

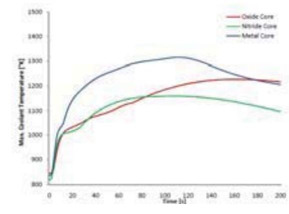


Fig. 13: Peak coolant T. during loss of IHTS cooling with station blackout

Conclusions: In regard to safety, Metal, Nitride and Oxide fuels are all feasible in LMFRs. Differences in thermal and nuclear properties affected the S-PRISM core behavior in the transient simulations. Nitride and Oxide cores showed a remarkable performance in avoiding fuel and clad melting (strong negative reactivity feedbacks, high fuel melting point). Metallic fuel with significantly smaller margins to fuel melting and Core Disruptive Accident. However, the low fuel melting point is a major advantage to promote molten fuel expulsion. In addition, Metal fuels have the highest thermal conductivity (low fuel temperature gradients) and several other operating advantages (transmutation and breeding, fuel recycling and fabrication), that allow an economic closing of the fuel cycle