Review of Application of hafnium hydride control rod to large sodium cooled fast breeder reactor

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I L L I N O I S

Outline

Motivation

Sodium-Cooled Fast Reactor (SFR) is being pursued as Japan's next-generation nuclear reactor.

- Inherent safety features
  - Net negative reactivity feedback with temperature rise
- Better thermal and neutronics properties
  - Larger temperature outlier for liquid sodium (371 - 1156K)
  - Atmospheric operating pressure
  - Low neutron absorption of Na
  - Better heat transfer
  - Higher efficiency
- Breeding of fissile material
- 'Closing' the fuel cycle
- Actinide burning (fueled by TRU-NatU)

Motivation

Need for a control rod with a longer lifetime in Sodium-cooled Fast Reactors

- Current SFR designs use 80% B-10 enriched boron carbide
  - Swelling due to accumulation of He and Li produced by (n,α)
  - He buildup in the gas plenum
  - Degradation of control rod worth with irradiation
  - Lifetime ˜2 years

Hafnium as an absorber - 1/3

Comparable absorption cross section in core with hydrogen moderation

Form of absorber	Nuclides	Absorption cross section (10^{-28} m^2)	Abundance per atoms (%)	Produced nuclides	Capture cross section of products (barn)
80% B-10 enriched B_4C	B-10	2.28	19.9	Li-7	0.00003
	Hf-176	0.38	5.26	Hf-177	1.00
	Hf-177	1.00	18.6	Hf-178	0.21
Hf	Hf-178	0.21	27.28	Hf-179	0.63
	Hf-179	0.63	13.62	Hf-180	0.10
	Hf-180	0.10	35.24	Ta-181	0.49
	Hf-176	1.93	5.26	Hf-177	6.11
	Hf-177	6.11	18.6	Hf-178	0.93
$HfH_{1.3}$	Hf-178	0.93	27.28	Hf-179	3.67
	Hf-179	3.67	13.62	Hf-180	0.21
	Hf-180	0.21	35.24	Ta-181	6.65

Figure 1: Absorption cross section comparison of various forms

Hafnium as an absorber - 2/3

Continued absorption integrity and low induced radioactivity after irradiation.

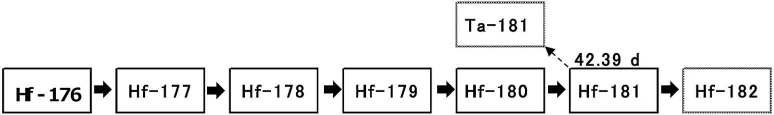


Figure 2: Nuclear transmutation of hafnium nuclides by capture. Ta-181 is stable and Hf-182 has a half life of 8.9e6 years

Hafnium as an absorber - 3/3

Other peripheral beneficial characteristics of hafnium include:

- Malleability, ductility
- Rich reserve of raw materials
- Resistance to chemical activity
- Corrosion resistance
- High melting temperature
- Stable at high temperature and pressure

Objectives

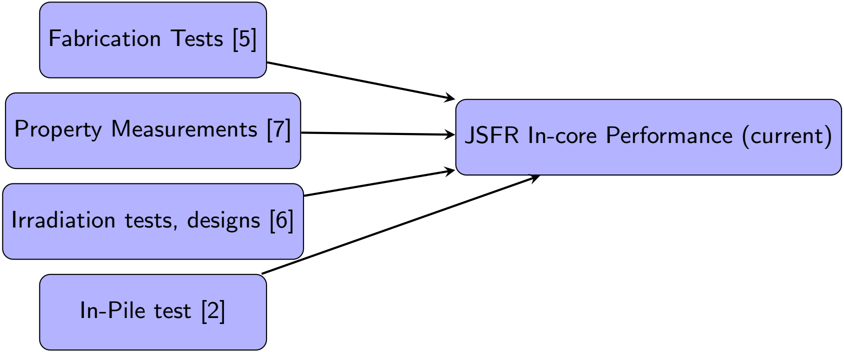
Demonstrate the feasibility and benefits of using a HfH_x control rod over a B_4C control rod in a Japanese Sodium-cooled Fast Reactor (JSFR) by comparing various metrics. Metrics include:

- Reactor nuclear characteristic (Enrichment, Na void reactivity, etc.)
- Coolant flow rate
- Hydrogen desorption
- Control rod performance over time (irradiation)
- Linear heat rate
- Reactivity
- Temperature distribution

Outline

Previous Work

6-year study of HfH_x control rod feasibility



Deterministic Method for reactor design

- Unified 70-group fast set of group constants (ADJ2000R) [1]
- Diffusion Code (TRISTAN)
  - verified with (CITATION) from Oak Ridge National Laboratory (ORNL).
- Perturbation Code (TRI-PERT)
  - nuclear characteristics
- Depletion (JFS3-J3.3)
- Heating density of hafnium hydride absorber (MCNP-5) [8]
- Nuclear Data (ENDL92 for Hf and ENDF-VI for others)

Monte Carlo Method

- Effects of reactor constants and heterogeneity of control rod structure (MVP, GMVP) [9]
  - Neutron and photon transport
  - Based on continuous energy and multigroup methods

Core simulation with hafnium control rods

Hafnium hydride control rods replaced the boron carbide in the JSFR [10] for comparison, with U-TRU mixed oxide fuel [3].

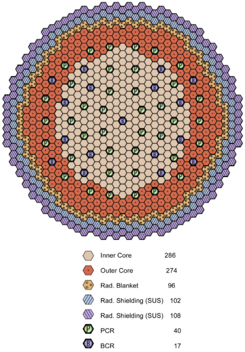


Figure 3: Core diagram of the JSFR.

Assumptions

- Pu enrichments so that excess reactivity ~0.2%
- ratio of H to Hf is constant (no hydrogen desorption)
- Transmutation from Hf-180 to Hf-181, or Ta-181 neglected.
- temperature of cladding limited to 600˙C
- Absorber pellet limited 800˙C for hydrogen desorption
- No swelling of HfH_x control rod

Control Rod Location

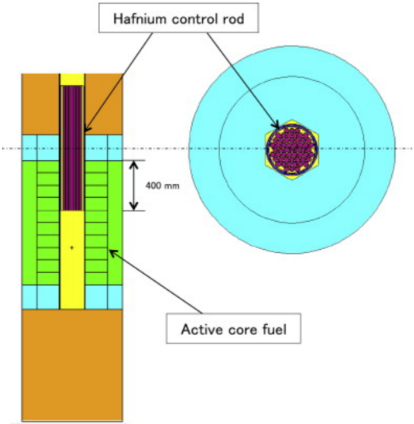


Figure 4: Elevator view of control rod position with respect to active core fuel. Control rod remains static.

Outline

Reactivity of HfH_x control rods

Reactivity similar to 80% B-10 enriched boron carbide rods with enhanced control rod reactivity with hydrogen moderation of neutrons.

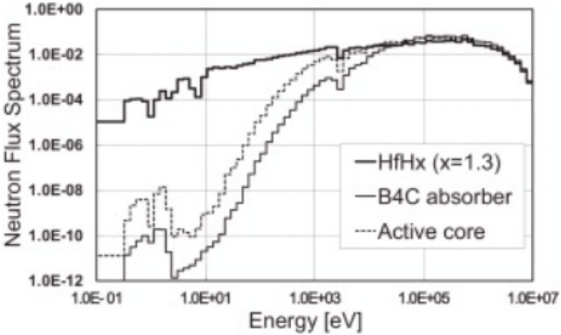


Figure 5: Neutron spectrum of the hafnium hydride control rod

HfH_x control rod depletion calculation results - 1/2

Neutron absorption performance degrades very little with irradiation because the produced isotopes are also absorbers.

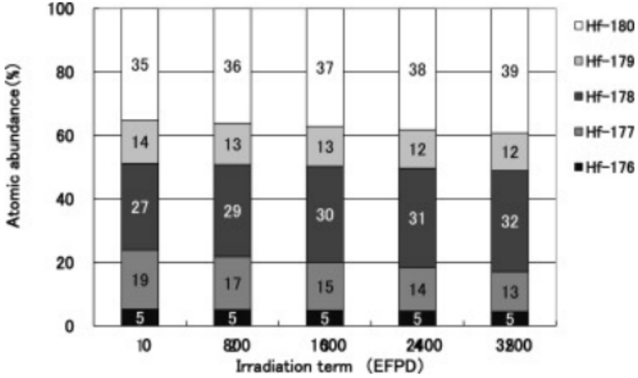


Figure 6: Change of hafnium isotope ratio in the control rod during irradiation.

HfH_x control rod depletion calculation results - 2/2

Reactivity degradation is 4% after 2400 Effective Full Power Day (EFPD) (3 cycles)

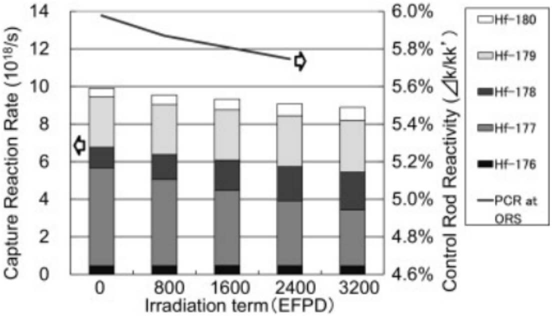


Figure 7: Capture reaction rate and reactivity of hafnium hydride control rod.

Results of nuclear calculation with HfH_x control rods

Nuclear characteristics as good as or better than with B_4C.

	Unit	$HfH_{1.3}$ CR	B_4C CR
Pu enrichment inner/outer	Pu/HM (wt%)	18.1%/20.4%	18.2%/20.5%
Burn-up reactivity	$\Delta k/kk'$	2.3%	2.4%
Maximum linear heat rate	(W/cm)		
Core fuel		391	403
Control rod He/Na		199/313	399 (B_4C)[a]
Fast fluence	(n/cm^2)	5.3E + 23	5.4E + 23
Na void reactivity	$	5.1	5.2
Doppler constant	(Tdk/dT)	−0.00571	−0.00567
Effective delayed neutron fraction	–	0.00334	0.00329
Discharge burn-up	(GWd/t)	145	145
Breeding ratio	–	1.11	1.10

a

The number of pin is assumed to be 37.

Figure 8: Nuclear characteristics of the reactors with the hafnium hydride and the boron carbide absorber.

Heat profile in HfH_x control rod

Neutron-induced energy of the absorber is approximately twice as large as B_4C. Limit of 800°C to prevent hydrogen desorption. Maximum absorber temperature = 718°C

Characteristics	Values
Maximum temperature (°C)	–
Cladding of core fuel	700
Cladding of control rod	600
Pellet of Hafnium hydride He bond/Na bond	718/631
Flow allocation of primary coolant circuit (%)	–
Core fuel and radial blanket	90.5
Control rods	1.6
Sum	92.1

Figure 9: Thermal hydraulic characteristics in the hafnium hydride control rod deployed reactor.

Heat density of HfH_x

Twice the heat generation of B_4C, but peak of heat densities are comparable due to hydrogen moderation and gamma-ray transport.

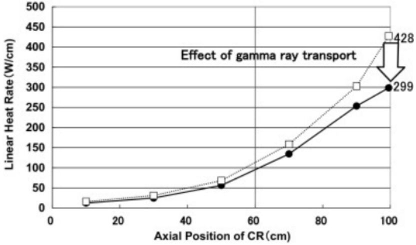


Figure 10: Effect of gamma transport in the linear heat rate of HfH_x absorber.

Local radial power distribution of subassembly adjacent to control rod

B_4C: Less power near the control rod
HfH_x: More power near the control rod due to hydrogen moderation leading to enhanced reaction rate.

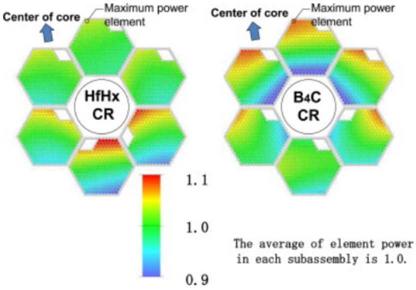


Figure 11: Local radial power distribution of subassembly adjacent to control rod inserted.

Important Results and Conclusion

- Longer lifetime due to hafnium isotopes after neutron absorption
- Hydrogen increase of absorption
- 9 years lifetime (compared with 1-2 year for B_4C)
- Slightly better reactor parameters (flow rate, safety margin, breeding ratio etc.)
- Able to meet absorber temperature below hydrogen desorption temperature

Outline

Relevance and Novelty

- Reactor performance metric change with control rod
- Improvements on SFR design
- Improvements on control rod lifetime and performance
- Reduction in low-level waste
  - Less radiotoxicity from used control rods
  - Longer lifetime = less waste

Technical Detail and Analytic Rigor

- Reactivity and 'nuclear characteristics' of JSFR
- Thermal profile of reactor and control rod
- Lacking in transient scenarios
- Various simplifying assumptions

Verifiability (Reproducibility)

- Codes are well-known and published
- Input files unavailable
- Specifications of simulation (geometry, pellet diameter etc.) well-documented enough to reproduce

Clarity

- Grammatical mistakes
- Confusing noun-verb relationship
- Run-on sentences ("Futhermore the comparison with the B-10 enriched boron carbide rods.")
- Lengthy explanation would be much more concise in tables.
- Abstract represents the conclusion well.
- Axial location of control rod in core simluation unclear

Technical Gaps, missing analyses

- Multiplication factor (assuming critical because it is a control rod experiment)
- Assumed static control rod position for entire cycle
- Non-normal operation scenarios
  - Large temperature shift effect
  - Hydrogen desorption
  - Loss of hydrogen leads to lower control rod worth
- Swelling of hafnium hydride
- Flux profile of reactor
- Static control rod position
  - Axial variation of control rod depletion
- What happens when Hf-180 absorbs a neutron?
- Effect of higher power near control rod

Outline

Future Work suggested by authors

- Hydrogen desorption in operating conditions
- Uncertainty of control rod reactivity
- Swelling of control rod

Potential extension of work

- Accident scenarios leading to higher core temperature → desorption of hydrogen → less control rod worth
- Axial depletion change during operation
  - Position of control rod changes over time with operation
  - Axial variation of irradiation / depletion
- With the allowance of longer life control rods, 'breed and burn' core designs with a much longer cycle time of 800 EFPD
- Swelling of control rod with longer irradiation
- Effect of local moderation on used fuel composition and flux
- Effect of higher power near HfH_x control rod
- Enrichment of Hf (increase composition of lower isotopes) for better performance

Extension 1 - Accident Scenarios

An accident scneario where the temperature of the core increases beyond operating tempearture and the control rods are dropped to high temperature sodium / fuel

- Hydrogen desorption possible at 1,000˙C [4]
- Core temperature higher than 1,000˙C during accident scenarios
- HfH_x can lose up to 65% of reactivity with hydrogen loss

Preliminary study

1. HfH_x in higher temperature than 800˙C and observe hydrogen desorption with temperature
2. Calculate model for hydrogen desorption with temperature
3. Calculate HfH_x control rod reactivity change with temperature / irradiation

In-core Simulation

1. Run accident scenario core simulation with implemented hydrogen desorption model
2. Modify cross section of control rod with temperature / irradiation using model obtained
3. Track core nuclear and thermal metrics with time
4. Identify reactor shutdown problems

Extension 2 - Axial variation of control rod

In normal operation control rod position moves within cycle.

- This paper remains control rod static at half way pulled out
- In reality control rod would be irradiated more if starting from bottom
- Axial variation of control rod depletion

Methods to measure control rod movement in cycle

Simplified to more elaborate:

- Linear control rod position from bottom to top throughout cycle ($y = \frac{h}{800}t$)
- Past historical control rod movement throughout cycle
- Use code to figure out critical rod position in t

Axial power distribution change with control rod depletion

Run core simulation with control rod movement.

- Core axial power distribution with axially-varying control rod
- Linear heat rate with axially-varying control rod
- Better insight into control rod depletion

Outline

Conclusion

- This paper claims feasibility of HfH_x control rods in SFR reactors
- Performs as good as or better in a JSFR than B_4C control rods using the methodology by the authors
- Multiple issues have not been taken into account
- Hydrogen desorption, criticality and swelling of control rod requires further study

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Coolant Cross section

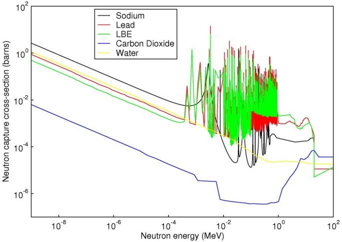

Figure 12: Coolant and cross section [11]

Terms

- Reactor Shutdown System - passively released due to curie point effect by abnormal rising of coolant temperature.
- Passive safety $\rightarrow$ thermal expansion of absorbing liquid
- Edge - Na expansion leads to more neutron leakage (negative reactivity coeff)
- Center - Na expansion leads to less absorption (positive reactivity coeff)
- Doppler coefficient : "Fuel temperature coefficient of reactivity" how reactivity changes per temperature in fuel
- Gamma Ray transport: Gamma ray has a long mfp that the decay energy to leave the zone of origin
- Fuel Slumping: Fuel melts to the bottom of the pin, increasing fuel density
- Peaking Factor: $\frac{HighestLocalPowerDensity}{AvgPowerDensity}$

Codes

Predictor - corrector method
Current flux, deplete the fuel, if it is critical.
ENDF JEFF 252 groups 'continuous'
SERPENT 2 and SCALE are for doing depletion calculation and generates homogenized cross section - collapses to 7 group for fast
Homogenized cross sections to characterize the core

- criticality values
- critcial control rod position / ppm for boron
- fuel depletion

Thermal hydraulics that work with PARCS

- internal to PARCS
- coupled to TRACE

Provide reduced number of groups of cross sections to Core simulators like PARCS, set delta t. adjust critical boron concentration and control rod position.