

# 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



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Potential extensions of current work

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Extension 2 - Axial Variation of Control Rod

## 6 Conclusion



# 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  $(n, \alpha)$
  - 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 ( $10^{-28} \text{ m}^2$ )	Abundance per atoms (%)	Produced nuclides	Capture cross section of products (barn)
80% B-10 enriched B <sub>4</sub> C	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-178	0.21	27.28	Hf-179	0.63
	Hf-179	0.63	13.62	Hf-180	0.10
Hf	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
	Hf-178	0.93	27.28	Hf-179	3.67
	Hf-179	3.67	13.62	Hf-180	0.21
HfH <sub>1.3</sub>	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  $8.9 \times 10^6$  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





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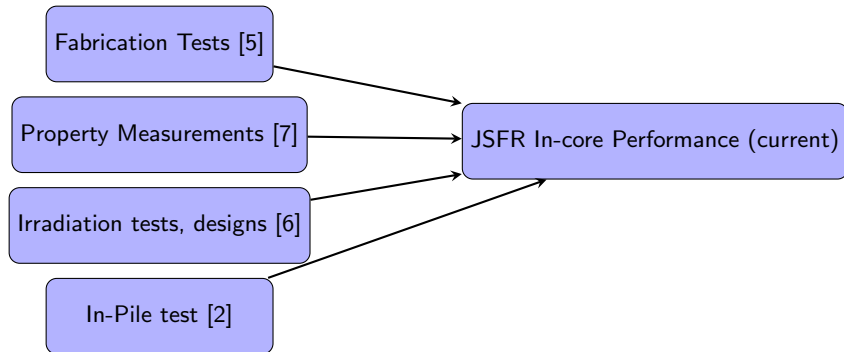
Extension 2 - Axial Variation of Control Rod

⑥ Conclusion



## 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].

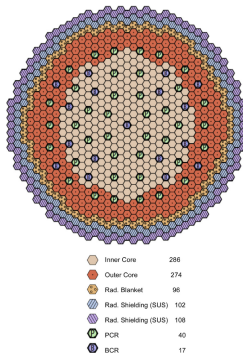


Figure 3: Core diagram of the JSFR.

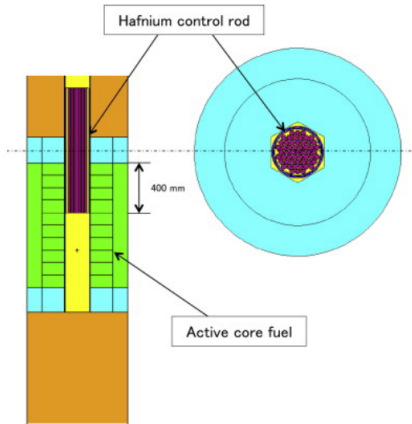


## Assumptions

- Pu enrichments so that excess reactivity  $\sim 0.2\%$
- 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  $600^\circ\text{C}$
- Absorber pellet limited  $800^\circ\text{C}$  for hydrogen desorption
- No swelling of  $\text{HfH}_x$  control rod



## Control Rod Location



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



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## 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.

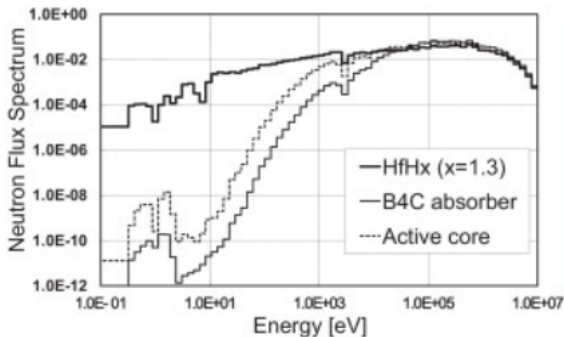


Figure 5: Neutron spectrum of the hafnium hydride control rod



## $HfH_x$ control rod depletion calculation results - 1/2

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

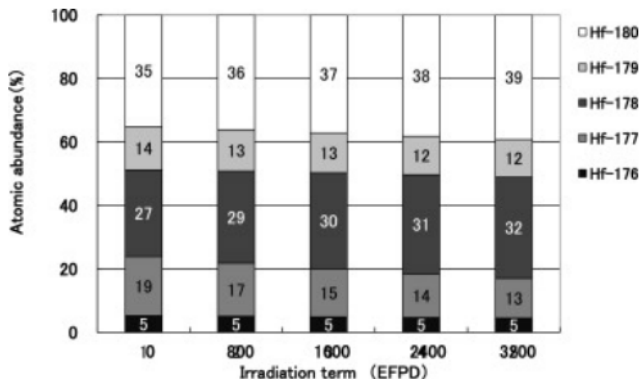


Figure 6: Change of hafnium isotope ratio in the control rod during irradiation.



## $HfH_x$ control rod depletion calculation results - 2/2

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

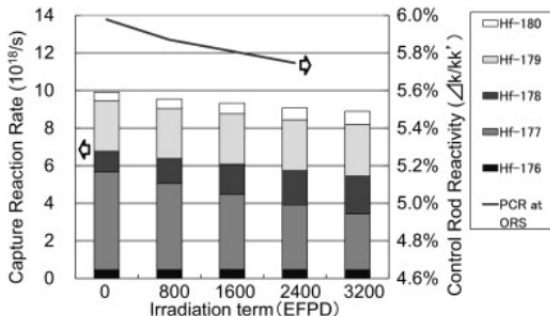


Figure 7: Capture reaction rate and reactivity of hafnium hydride control rod.



## 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 ( $B_4C$ ) <sup>a</sup>
Fast fluence	(n/cm <sup>2</sup> )	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  $800^{\circ}\text{C}$  to prevent hydrogen desorption. Maximum absorber temperature  
=  $718^{\circ}\text{C}$

Characteristics	Values
Maximum temperature ( $^{\circ}\text{C}$ )	—
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.

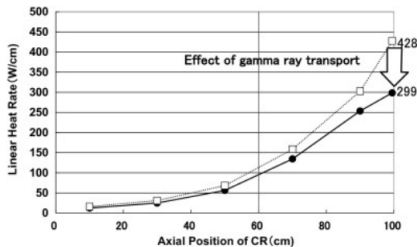
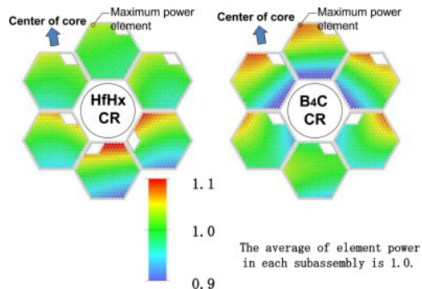


Figure 10: Effect of gamma transport in the linear heat rate of  $HfH_x$  absorber.

## 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





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## 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



## Verifiability (Reproducibility)

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



# 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



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## 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 scenario where the temperature of the core increases beyond operating temperature 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  $800^{\circ}\text{C}$  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
- Control rod depletion



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## 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

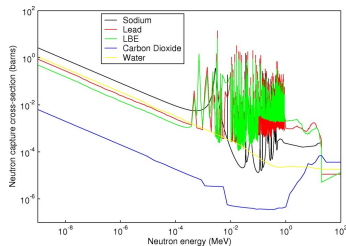


Figure 12: Coolant and cross section [11]



## Cheat Sheet

- Reactor Shutdown System - passively released due to curie point effect by abnormal rising of coolant temperature.
- Passive safety → 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:  $\frac{\text{HighestLocalPowerDensity}}{\text{AvgPowerDensity}}$

Predictor - corrector

Current flux, deplete the fuel, if it is critical Run another calculation to find ENDF JEFF 252 groups 'continuous'

SERPENT 2 and SCALE are for doing depletion calculation generates homogenized cross section collapses to 7 group for fast

homogenized cross sections to characterize the core criticality values critical control rod position / ppm for boron fuel depletion

Thermal-hydraulics code 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.