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Static and transient analysis of a medium-sized sodium cooled fast reactor loaded with oxide, nitride, carbide and metallic fuels

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ABSTRACT

Transient analysis was performed for the BN600 reactor loaded with different types of fuels. In order to obtain core performance parameters and major reactivity coefficients needed for transient analysis, a Serpent model based on geometrical details of the BN600 sodium-cooled fast reactor (SFR) was first created. MOX, (U-Pu) N, (U-Pu) C and (U-Pu) Fs, as representatives of oxide, nitride, carbide and metallic fuels, were loaded into this Serpent model individually. Plutonium contents were adjusted to 16.3, 14.3, 14.5 and 12.6 wt.% for these fuel cases respectively, aiming at the self-sustainability of plutonium. The safety performances of different fuel cases during the unprotected loss of flow (ULOF) and unprotected transient over power (UTOP) transients were then assessed by applying the TRACE code. The point kinetic calculation module in our TRACE model is constructed with safety related parameters obtained from our Serpent calculations.

Based on our transient simulation results, comparing to other fuel cases, our nitride fuel case was proved to be able to provide the biggest margin to the working limits defined in this paper, concerning fuel melting, cladding rupture and coolant boiling. This enables the nitride fuel to be a competitive candidate for the BN600 type sodium cooled fast reactor usage.

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1. Introduction

As the most mature fast neutron reactor technology, not only prototype but also half commercial sodium-cooled fast reactors (SFR) have been commissioned. Actually, except several experimental facilities operated in 1940s and 1950s, e.g. CLEMENTINE (US), BR-I(USSR) and EBR-I (US), liquid Na has been chosen as the primary coolant for all fast neutron reactors, especially for the ones with breeding ratio higher than unity. Liquid Na was preferred mainly because: first, the maximum allowable velocity of liquid Na through pin bundles concerning the flow-induced vibration, was reported to be 8.0 m/s (Konomur and Ichimiya, 2007). The product of the maximum allowable velocity, the density and the heat capacity of liquid Na is higher than those of other coolants proposed for fast reactor usage, such as inert gases or heavy liquid metals. Thus, a smaller pitch-to-diameter ratio of fuel pin bundles is required when cooled by liquid Na, in order to provide sufficient cooling. This permits a smaller neutron leakage, a harder neutron spectrum and therefore a better neutron economy. Second, comparing to heavy liquid metals, liquid Na has approximately one order of magnitude lower capture cross sections in the fast neutron region, which leads to less neutron loss in the primary coolant inventory. Third, the thermal conductivity of liquid Na is much higher than those of the other fast reactor coolants, which enables a higher heat transfer coefficient and therefore a lower temperature difference between pin cladding and coolant for a specific linear power rating.

Since the first prototype sodium cooled reactor was commissioned, several types of fuels, including oxide, nitride, carbide and metallic fuels, have been considered for the SFR usage. For each type of fuel, one or several reactor designs were proposed concerning factors like: the core breeding capability, the working limit of the structural material, the thermal efficiency of reactor systems and so on. Therefore, it will be valuable to evaluate the impacts on core safety performances from loading different types of fuels, based on which the most competitive fuel type for the SFR usage can be preliminarily determined.

As a commercialized SFR that has been commissioned since 1980, the BN600 reactor has been reported to have excellent operational performances for more than 30 years. Besides, after improving the reliability of primary pump impellers and applying the 20%CW ChS68 stainless steel (Porollo, 2009) as the cladding material, the lifetime of primary pumps was extended to 35,000–50,000 h and the maximum irradiation damage that can be

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withstand by pin cladding was raised up to 94 dpa (Buksha et al., 1997). Therefore, in this paper's study, design details of the fully UOX loaded BN600 core were used for our TRACE model creation.

In this paper, core performances of the oxide, nitride, carbide and metallic fuel cases during the postulated ULOF and UTOP transients were simulated with the TRACE code. The point kinetic module in our TRACE model was constructed with the core performance parameters and safety related reactivity coefficients calculated with the Serpent Monte Carlo code.

2. 3-D Serpent model of BN600

BN600 is a 600 MW_e (1500 MW_{th}) sodium-cooled fast reactor, which has been operated in Beloyarsk since 1980 (FRdatabase, 1996). As a representative for the medium sized SFR, the fully UOX fueled BN600 reactor was chosen as the reference design in current study (Cherny, 2000).

As a fast reactor with the breeding ratio of ≈1.3, BN600 is loaded with both fuel assemblies and blanket assemblies (Waltar and Reynolds, 1980). In order to meet the self-sustainability requirement of the Gen-IV reactor systems, depleted UO_2 in blanket assemblies was replaced by stainless steel in our Serpent model. Besides, Pu contents of different fuel cases also need to be adjusted individually. The self-sustainability is considered to be achieved when the change of the plutonium inventory from BOL to EOC is less than 2 wt.%.

For hosting metallic fuel bonded by liquid sodium, fission gas plenum designed to be below the active section of fuel pin in the reference BN600 design was moved above.

In the fully MOX fueled BN600 design, annular pellets with 1.7 mm diameter central hole were loaded (Abe and Asakura, 2012), in order to reduce the maximum temperature in fuel column and also stress on clad inner surface. For fuel materials with much higher thermal conductivities, such as (U-Pu) C, (U-Pu) N and (U-Pu) Fs, central hole is not considered in this paper's study.

Due to different thermal and irradiation swelling rates of fuel materials, volumetric fractions of fuel in fuel pins in the reference designs are significantly different as listed in Table 1. In current study, assembly and pin dimensions were kept the same for all fuel cases, in order to minimize the influence from structural configurations on neutronic calculations. Outer diameters of the fuel column were then needed to be re-calculated, in line with the fuel volumetric fractions proposed for the BN1200, FBTR and EBR-II designs. Porosities of MOX, (U-Pu) N, (U-Pu) C and (U-Pu) Fs fuel materials discussed in this paper were set at 5%, 15%, 10% and 0% respectively. These values were recommended for the commercial MOX fuel (Massih, 2006), the (U-Pu) N sample sintered at 2023 K (Arai, 2012), the $(U_{0.3}Pu_{0.7})$ C loaded in the FBTR reactor (Venkiteswaran et al., 2011) and the U-5Fs alloy used in the EBR-II reactor (Sumner and Fei, 2012).

Table 1
Dimensions of fuel pins in reference reactor designs (Zhang et al., 2013; Ganguly et al., 1988; Boltax et al., 1993).

Fuel type	Oxide	Nitride	Carbide	Metallic
Representative reactor	BN600	BN1200	FBTR	EBR-II
Fuel type	(U-Pu) O_2	(U-Pu) N	(U-Pu) C	(U-Pu) Fs
Fuel porosity, %	5	15	10	0
Fuel inner diameter, mm	1.70	0.00	0.00	0.00
Fuel outer diameter, mm	5.90	7.70	4.18	3.37
Bond material	He	He	He	Na
Cladding inner diameter, mm	6.10	8.10	4.36	3.81
Cladding outer diameter, mm	6.90	9.30	5.10	4.42
Gap volume/fuel volume at BOL, %	7	11	9	28

Table 2
Design details for the Serpent modeling (Waltar and Reynolds, 1980; FRdatabase, 1996; Abe and Asakura, 2012).

Fuel type	Oxide	Nitride	Carbide	Metallic
Fuel inner diameter, mm	1.7	0.0	0.0	0.0
Fuel porosity, %	5	15	10	0
Fuel outer diameter, mm	5.9	5.8	5.6	5.4
Bond material	He	He	He	Na
Cladding inner diameter, mm	6.1			
Cladding outer diameter, mm	6.9			
Pin lattice geometry	Hexagonal			
Pin pitch, mm	8.0			
Fuel column length, mm	1030			
Gas plenum length, mm	800			
Gas plenum position	Lower	Lower	Lower	Upper
Lower/upper reflector length, mm	300/200			
Lower/upper blanket length, mm	300/400			
Number of fuel rods per assembly	127			
Number of fuel assemblies in core	369			
Flat-to-flat distance in SA, mm	90			
Duct thickness, mm	2			
Inter-assembly gap width, mm	1			

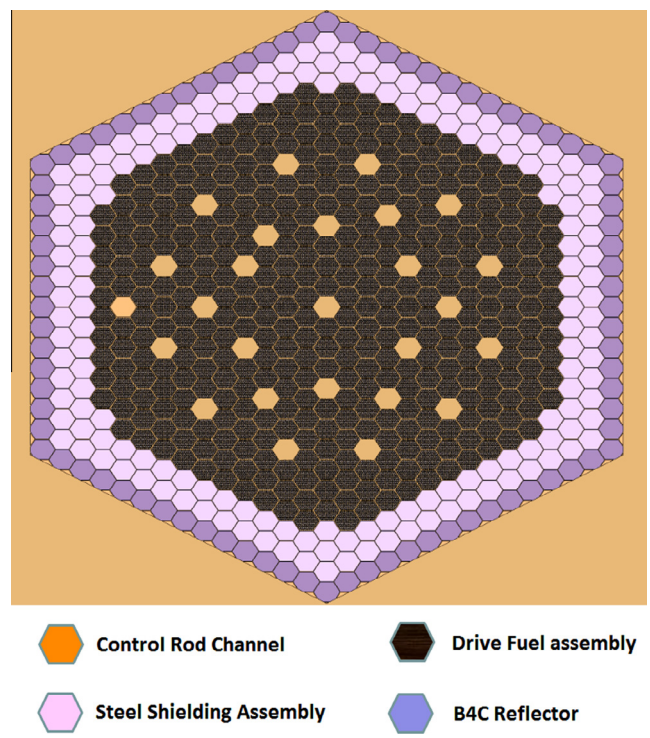

Fig. 1. General core layout of BN600 (Zhang et al., 2010).

Based on the geometrical details listed in Table 2, a Serpent model was created as shown in Fig. 1. The fuel zone consists of 12 hexagonal rings and is loaded with 369 fuel assemblies. Fuel assemblies located at the six corners of the outermost ring were substituted by stainless steel (SST) assemblies. The 27 sodium blocks were left for control rods. The reflector zone is loaded with 300 steel shielding assemblies (SSA) and 102 boron assemblies (BSA). Inner structures, such as core diagrids (steel plates on which fuel assemblies were installed) and wire spacers between fuel pins, were neglected from our Serpent model.

The isotopic vector of plutonium in our Serpent model, as listed in Table 3, is obtained from the spent fuel discharged from LWRs with 50 MWd/kgHM burnup and then 5 years' cooling (Zhang et al., 2010). Medium-sized fast reactor cores normally are subdivided into several fuel zones with different enrichments to achieve

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