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An investigation on Unprotected Loss of Flow Accident in Th–Pu metal fuelled 500 MWe fast reactor

Neethu Hanna Stephen [a,*], T. Sathiyasheela [a], Debanwita Paul [a], K. Devan [a], R.S. Keshavamurthy [a], C.P. Reddy [b]

[a] Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu 603102, India
[b] Bharatiya Nabhikiya Vidyut Nigam Limited, Kalpakkam, Tamilnadu 603102, India

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ABSTRACT

This study focuses on computing static reactivity coefficients and analyzing Unprotected Loss of Flow Accident in a Th–Pu fuelled metal reactor. An attempt is also done to compare the static and dynamic performance of the fresh core with characteristics of U–Pu–6Zr fuelled 500 MWe metal reactor. Isothermal temperature coefficient and power coefficients are evaluated in the steady state and found to be negative. The excess reactivity and control rod worth requirements of Th–Pu metal core are assumed similar to that of U–Pu–6Zr metal core. In the Unprotected Loss of Flow Accident (ULOFA) analysis, with flow coast down initiated by station black out, it is found that power to flow ratio is increasing initially up to 53 s and then starts to reduce continuously. Power to flow ratio is found to be less than 2 at all times thus ensuring the absence of coolant boiling in the entire core. Sodium voiding starts around 886 s in the upper axial blanket and provide negative reactivity. Also it will not propagate to the core center ensuring the probability for core disruptive accident a remote one. Net reactivity feedback is negative and the major contribution is from core radial expansion. Within 12 min, the power drops to 32 MWt, making it possible for Safety Grade Decay Heat Removal (SGDHR) system to start heat removal from core ensuring safe shutdown of reactor. Sensitivity analysis by considering an uncertainty margin of ±10% in thermo physical properties of fuel composition shows that feedback reactivity of the Th–Pu system is insensitive and the conclusion on the safe shutdown remains unaltered. From this study it is found that inherent safety of Th–Pu metal fuel core is better than that of reactor core fuelled with U–Pu–6Zr metal type under ULOFA condition.

1. Introduction

The increase in global energy demand has led to the release of over 1100 GTe of CO_2 (carbon dioxide, a green house gas that is contributing mainly to global warming) into atmosphere which is mainly from the combustion of fossil fuels (Sims et al., 2007). In order to reduce the CO_2 emission, one has to look for more realistic options such as increased use of renewable sources of energy and nuclear power (Peter Fairley, 2013). There are regional variations in the demand for energy and according to the fourth Intergovernmental Panel on Climate Change (IPCC) report, the highest per capita demand for energy is coming from developing countries (Sims et al., 2007). In a developing country like India where reserves of fossil fuels are scarce, to meet the energy requirements, a three stage nuclear program was formulated by Dr. Homi Bhabha in 1950 with a focus on utilizing its vast thorium reserves (Majumdar, 1999). India's fast reactor program which comes in the second stage focuses on increasing the fissile material base, mainly the fissile isotope ^{233}U produced from thorium along with ^{239}Pu, so that ^{233}U/Th can be better utilized in the third stage. Future of the expanded nuclear power industry of Fast Breeder Reactors (FBRs) depends critically on the choice of fuel cycle, especially a fuel type which has the potential for high breeding so that doubling time is shorter. Therefore the development of metal fuel reactors has been recognized (Baldev Raj et al., 2005; Chetal, 2009) and metal FBR cores having various sizes have been designed to study their neutronics characteristics (Devan et al., 2011; Riyas and Mohanakrishnan, 2008). Harder neutron spectrum due to the absence of lighter atoms in metal reactors increases breeding ratio. Breeding ratio is also increased due to the fact that η value of ^{239}Pu as well as fast fission of ^{238}U and ^{232}Th are large in harder neutron spectrum. Metal fuels also have some favorable thermo-physical

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[*] Corresponding author at: Room No: C 229, Building No: 200, Reactor Physics Section, Reactor Operation and Maintenance Group., Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu 603102, India. Tel.: +91 44 27480500x26356; fax: +91 44 27480336.

E-mail addresses: neethu83@igcar.gov.in, neethu.stephen@gmail.com (N.H. Stephen).

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properties such as high density and thermal conductivity. High thermal conductivity results in smaller temperature gradient (i.e., between fuel center and fuel surface) which reduces the thermal stresses on the fuel pellet and hence the life span of fuel pin is increased. If liquid sodium is used as the bonding material in fuel-clad gap, the gap conductance is increased which reduces thermal time constant (time required for the temperature difference across fuel pin to change by a factor of e). High thermal conductivity and associated shorter thermal time constant reduces temperature swing in metal fuel between zero and nominal power.

In addition to its higher breeding capability, metal FBRs have better core safety characteristics during both normal and accidental conditions. The passive safety of U–Pu–6Zr metal fuel in small reactors such as EBR II has been demonstrated during the experiments such as Loss of Flow Accident (LOFA) and Loss of Heat sink Accident (LOHA) under Integral Fast Reactor (IFR) program (Chang, 2007). Even though sodium has excellent coolant properties, the major safety concern in medium and large sized metal reactors are regarding coolant loss and its associated positive reactivity contribution (Vladimir et al., 1985). The initiation of transient in a FBR is due to many internal and external disturbances. The imbalance in heat generation to heat removal can come from either Unprotected Transient Over Power Condition (UTOPA) in which uncontrolled reactivity insertion causes the rise of power or from the Unprotected Loss of Flow Accident (ULOFA) in the core where primary coolant flow is lost and as a result system can go to super critical state. Even though the frequency of such accidents are very low (less than 1.0×10^{-6} per reactor year), analysis of such events will provide useful inputs for design measures and also to obtain source term necessary for planning emergency preparedness.

For UTOPA accidents the assumed initiator is an uncontrolled withdrawal of a single, maximum-worth control rod. For metal reactors, since control rod worth requirements are low, UTOPA accidents are less severe (Cahalan et al., 1990). But in medium and large sized metal reactors, especially with U–Pu–6Zr fuel type, the principal concern is its large sodium void coefficient and reduced Doppler effect (Yokoyama et al., 2005; Riyas and Mohanakrishnan, 2008; Stephen and Reddy, 2013). In a situation where there is an uncontrolled insertion of positive reactivity, fast reactors rely on temperature related negative reactivity feedbacks to attain another steady state. Therefore an alternative fissile/fertile combination of metal fuel which has a good breeding ratio along with negative Doppler coefficient and low positive sodium void coefficient is desirable. The comparison study of breeding potential and safety related parameters of a wide range of advanced fuels showed that Th–Pu metal fuel has breeding ratio 1.22 and better performance in safety related parameters such as Doppler feedback (−1.46 pcm/°C) and sodium void reactivity (2.87 $) (Stephen and Reddy, 2013). These neutronic parameters by themselves do not suffice to explain the safety and reliability of the Th–Pu fuel type, especially during unprotected transients which translates to inherent safety characteristics of the system. It is of interest to know how the system will behave in a transient scenario especially in ULOFA which is a scenario of primary importance to study the passive safety character of the reactor. ULOFA analysis provides a glimpse on the possibility to initiate coolant boiling in the central part of the core which leads to the voiding of whole reactor.

The present paper focuses on computation of static reactivity coefficients as well as ULOFA analysis of Th–Pu fuelled 500 MWe fresh metal reactor to gain an insight about excess reactivity requirements, starting and propagation of sodium void, initiation of melting of fuel, time availability for corrective actions such as opening the damper to initiate SGHDR system ensuring the passive shutdown capability of the reactor. A comparative study is also carried out with 500 MWe metal core fuelled core with U–Pu–6Zr to understand the differences in the static and dynamic responses of these two systems.

2. Design input

The analysis is carried out for a fresh reactor core with Th–Pu metal fuel composition and sodium as coolant. The same core design is used in the study of Stephen and Reddy (2013). Top view and sectional view of the reactor core is given in Figs. 1 and 2. There are 85 subassemblies in core 1 region, 96 subassemblies in core 2 region and 120 subassemblies in the blanket region. Core design parameters are given in Table 1. Thermo physical properties of the fuel with the enrichments used in the study is not available in the literature other than solidus temperature (Peterson, 1990). Physical and mechanical properties of the alloy in most cases are expected to lie between those of the pure components fabricated similarly (Sigfred et al., 1965).Wherever thermo physical data of an alloy is not available, the estimates are made by linear weighting the data of pure components. This method is often used in the literature (where the alloys form solid solution), (Carbajo et al., 2001) for computation of alloy densities. Since the temperature profile starts from 740 °C, the Th–Pu alloy forms solid solution (for the enrichments considered in the study). The thermo physical property of thorium and plutonium are taken from literature IAEA-THPH, 2008 and is given in Table 2. However transport properties such as thermal conductivity are found to be lower in the alloy form, when compared to the thermal conductivity of pure elements (Kingery, 1959). Therefore sensitivity analysis also has been carried out to understand the dependence of uncertainty in the data of thermo physical parameters on the reactivity feedback and is given in Section 5. Since the previous study (Stephen and Reddy, 2013) considered wide range of fuel types, the excess reactivity limit was 4700 pcm, i.e., $k_{eff} \sim 1.047$. For the sake of comparison with U–Pu–6Zr metal fuel core of 500 MWe capacity, the excess reactivity in the present study is taken as 5000 pcm with Monte Carlo simulations (cold critical condition), which also happens to be the excess reactivity of the reference core (Riyas and Mohanakrishnan, 2008; Sathiyasheela et al., 2011). Therefore enrichment of the core 1 region is increased from 18.8% (Stephen and Reddy, 2013) to 19.3%. Linear power at the core center is found to be 470 W/cm. Delayed neutron fraction is computed with the code PERT (ABBN) that is based on first order perturbation theory, which is a modified version of NEWPERT (John, 1984) and is given in Table 3. The reactivity worth distribution and power densities prior to the start of transient calculation are available from the two dimensional diffusion theory calculations performed with cross sections in the energy group structure of ABBN (Devan, 2003; Manturov, 1997). Reactor core is divided into number of meshes and the removal worth is evaluated by noticing the reactivity change when fuel, steel and sodium are removed from each mesh. Even though sodium bonded pins are used in the study, voiding of bonded sodium is not considered. Doppler worth in each mesh is the reactivity change arising due to the temperature change going from zero power to nominal power (473–1100 K). Integral value of Doppler worth along with voiding worth of fuel, steel and sodium is given in Table 4. When compared to U–Pu–6Zr system there is a large difference in the sodium voiding and Doppler worth. For fuel types containing thorium, spectral hardening does not play an important role as thorium has higher energy threshold for fast fission than ^{238}U. Therefore sodium void worth is smaller in Th–Pu system than U–Pu–6Zr metal core. Doppler feedback is mainly from neutron captures in fertile isotopes occurring below 100 keV. The lower Doppler worth in Th–Pu system when compared to U–Pu–6Zr system is due to the difference in the extent of resonances in fertile isotopes. In the case of thorium,