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Comparative study of unprotected loss of flow accident analysis of 1000 MWe and 500 MWe Fast Breeder Reactor Metal (FBR-M) cores and their inherent safety

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ABSTRACT

Unprotected loss of flow (ULOF) analysis of metal (U–Pu–6% Zr) fuelled 500 MWe and 1000 MWe pool type FBR are studied to verify the passive shutdown capability and its inherent safety parameters. Study is also made with uncertainties (typically 20%) on the sensitive feedback parameters such as core radial expansion feedback and sodium void reactivity effect. Inference of the study is, nominal transient behavior of both 500 MWe and 1000 MWe core are benign under unprotected loss of flow accident (ULOFA) and the transient power reduces to natural circulation based Safety Grade Decay Heat Removal (SGDHR) system capacity before the initiation of boiling. Sensitivity analysis of 500 MWe shows that the reactor goes to sub-critical and the transient power reduces to SGDHR system capacity before the boiling initiation. In the sensitivity analysis of 1000 MWe core, initiation of voiding and fuel melting occurs. But, with 80% core radial expansion reactivity feedback and nominal sodium expansion reactivity feedback, the reactor was maintained substantially sub-critical even beyond when net power crosses the SGDHR system capacity. From the study, it is concluded that if the sodium void reactivity is limited (4.6 $) then the inherent safety of 1000 MWe design is assured, even with 20% uncertainty on the sensitive parameters.

1. Introduction

From the available vast experience with oxide fuel in thermal nuclear reactors, mixed oxide fuel was chosen by many countries in designing Liquid Metal Fast Breeder Reactors (LMFBR). On the other hand, better neutronic and thermal hydraulic properties of metal fuel can not be ignored. In metal fuels, due to the absence of low mass moderating atoms, spectrum is hard which increases the neutron production per neutron absorption. This is mainly due to the higher η (number of neutrons produced per neutron absorption) value of Pu^{239} and the enhanced fast fission of U^{238} (Walter and Reynolds, 1981) which results in better breeding. With better breeding, it is possible to achieve lower doubling time (Riyas and Mohanakrishnan, 2008).

Metal fuel has better thermo-physical properties such as high density and high thermal conductivity. Compatibility of metal fuel is found be good with liquid metal which allows the reactor designer to use liquid metal in the fuel-clad gap, which in turn increases the gap conductance. Thus the thermal time constant (Hummel and Okrent, 1970), *i.e.* the time taken for the temperature difference across the fuel pin to decrease by a factor of 1/e is very small as compared to oxide fuel which uses helium as a fuel-clad gap material. Temperature gradient between the centerline fuel pin and the fuel surface is considerably small due to high thermal conductivity of the metal fuel and better heat transfer properties of the sodium bond gap. Because of the small temperature gradient across the fuel pin and the low thermal time constant, the temperature swing between zero power and nominal power is relatively small. So the temperature dependent Doppler reactivity does not swing much between the zero power and nominal power. Consequently the reactivity loss during start up is reduced and the positive reactivity insertion during power decay is also reduced. Higher breeding ratio and low burn up loss brings down excess reactivity and lowers control requirements. Required control rod worth in metal core is almost half of oxide core, thus making uncontrolled withdrawal accident significantly less severe.

Analysis of Anticipated Transient without scram (ATWS) such as loss of coolant flow, loss of heat sink and transient over power are available in the literature (Cahalan et al., 1990; Royl et al., 1990; Yokoo and Ohta, 2002) for metal fuel. From the results it is confirmed that due to lower excess reactivity and control rod worth, unprotected transient over power (UTOP) incidents are less severe in metal cores as compared to oxide cores and also larger temperature margin is available to coolant boiling.

The EBR-II inherent safety test program with metal fuel has demonstrated: (i) passive removal of decay heat by natural circulation, (ii) passive reactor shutdown for loss of flow without scram and (iii) passive reactor shutdown for loss of heat sink without scram-ULOHS (Planchon et al., 1986, 1987; Golden et al., 1987).

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Not only under cooling incident, but also over cooling incident is found to be benign in EBR-II test (Lehto et al., 1988). However, EBR-II was a relatively small 62.5 MWt sodium cooled, pool type fast reactor with negative coolant void reactivity effect. But the larger positive coolant sodium void reactivity effect in medium and large sized metal fuel FBR raises doubt about the safety in loss of flow incidents such as ULOF and ULOHS.

The important drawback of metal fuel harder neutron spectrum is higher positive sodium density coefficient and a possible reduction in Doppler effect. When fuel changes from oxide to U–Pu–Zr 6% for 1250 MWt reactor (Harish et al., 2009) the positive sodium worth increases from 1.7 $ to 5.1 $ and the negative Doppler worth decreases from −2.1 $ to −1.17 $. Sodium void reactivity effect depends on the chosen core design, it can be made zero or negative by lowering height to diameter ratio, where the sodium void leakage component is more than the spectral component. For example, the design of BN-800 uses a sodium plenum to replace top axial blanket and reduce sodium void reactivity effect (Yu et al., 1986). Large leakage of neutrons reduces breeding and increases burnup reactivity loss resulting in substantial increase in control rod worth, which may lead to more severe transient over power accidents (Wade et al., 1997).

The important design parameters to achieve inherent safety in large LMFBR are (Coffield et al., 1986) extended flow coast down, reduced linear power rating, and decreased coolant inlet temperature. Reduced linear power rating results in economic penalty and decrease of inlet coolant temperature is difficult to implement. Extended flow coast down is a possible way of achieving inherent safety. Flow coast down transients in the metal core results in decreasing power because the magnitude of the negative reactivity feedback from the radial expansion is more than the magnitude of positive reactivity feedback of sodium expansion (Mueller, 1986). Ott (1988) has compared unprotected loss of flow (LOF) and loss of heat sink (LOHS) analyses of both oxide and metal core. In case of oxide fuel, power decreases slowly and reactor finally goes to a low power critical state. In case of metal fuel, total reactivity feedback brings the reactor considerably sub-critical, and considerable negative reactivity is maintained for hours leading to die away fission power. The natural asymptotic state for the metal fuel is subcritical core with extinguished chain reaction, power generated only by decay heat.

A comparative study (Singh and Harish, 2002) of ULOFA analysis was carried out on a medium size 500 MWe liquid metal fast breeder reactor with oxide, carbide and metal fuels. Sodium voiding starts early in oxide core as compared to carbide and metal-fueled cores. Voiding propagation is fastest for oxide core and slowest for metal core. Thus, time is available for corrective action such as manual operation of safety grade heat removal systems (SGDHRS). Similarly it is also found that initiation of fuel melting takes longer time in metal fuel as compared to carbide and oxide fuels. Though the sodium void reactivity effect for metal fuel is highest among the three fuels the initiating (pre-disassembly) phase lasts longest for metal fuel. ULOFA analyses of 500 MWe metal core reactor was carried out (Harish et al., 2009) and concluded that sodium boiling is delayed even after considering uncertainties in feedback reactivity effects. If SGDHRS is able to remove decay heat after 20 min, further increase in sodium voiding or coolant temperature increase can be prevented. It is possible to design natural circulation based SGDHRS with capacity >2.5% of thermal power (Chetal et al., 2006). Thus the SGDHRS capacity of 500 MWe and 1000 MWe case is taken as 32 MWt and 67 MWt respectively in the present study at the nominal temperature of hot pool at full power. It may be noted that SGDHRS capacity during transient increases when reactor outlet and hot pool temperatures rise.

In the present work, ULOF analysis are carried out for FBR-M (U–Pu–6% Zr) 500 MWe (1250 MWt) and 1000 MWe (2632 MWt) reactors to verify and compare the passive shutdown capability of the reactors. U–Pu–Zr alloys prevent the U–Pu interaction with clad. Addition of Zr increases fuel melting point and slightly reduces conductivity. While both 10% Zr and 6% Zr content have been tested in the past, metal fuel with 6% Zr is chosen here, because of its higher breeding capacity. The present study is also to check the passive shutdown capability of the reactor with the inclusion of uncertainties on sensitive feedback parameters such as core radial expansion reactivity feedbacks and sodium void reactivity effect. Typical uncertainty in reactivity coefficients are about 20% (Mueller, 1986 and Lehto et al., 1987). The cross-section set (Devan, 2003; Manturov, 1997) and the computer codes of IGCAR were used recently in BN-600 benchmark core analysis where experimental data on sodium void reactivity effect in BFS62–3A experimental set up was also compared with predictions (IAEA-TECDOC-1623). An uncertainty of 16% was found. Still, we have assumed 20% uncertainty in sodium void reactivity effect along with 20% uncertainty of radial expansion reactivity feedback. Presently analysis has been done with data for fresh core. With core burnup reactivity feedback coefficients can change. For example, sodium void reactivity effect tends to increase. It is expected that, due to swelling of hex-can with irradiation, free expansion of core with temperature gets restricted, resulting in possible reduction of radial expansion reactivity feedback. Thus we considered a case of higher uncertainty of 50% in radial expansion reactivity feed back also.

2. Reactor description

The 500 MWe FBR core design consists of 181 fuel sub-assemblies, 85 in the inner core and 96 in the outer core of a slightly higher enrichment. There are 12 control rods out of which nine rods are called the control and safety rods (CSR) and three rods are called the diverse safety rods (DSR). The cross sectional view is given in Fig. 1. Geometrical details of the core are given in earlier papers (Harish et al., 2009; Riyas and Mohanakrishnan, 2008). For the 500 MWe metal core, the fuel pin diameter is 6.6 mm. Small diameter is favorable to reduce the fuel inventory, but leads to a reduction in breeding ratio due to the smaller fuel volume fraction. In 1000 MWe case, pin diameter is chosen to be 8 mm to get higher breeding ratio. Correspondingly fuel volume fraction is higher and Na volume fraction is lower. Breeding ratio computed is 1.49.

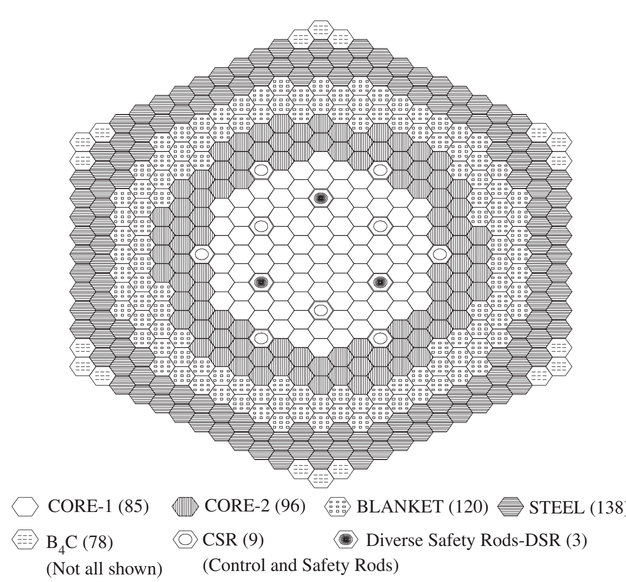

Fig. 1. Core configuration of 500 MWe FBR.