Severe Accident Assessment for PFBR: Designer's Perspective

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General Safety Features of PFBR

A 500 MWe Prototype Fast Breeder Reactor (PFBR) designed and developed by Indira Gandhi Centre for Atomic Research (Chetal 2006). PFBR is under advanced stage of construction at Kalpakkam. PFBR possesses all the intrinsic and engineered safety features viz. two independent, fast acting, reliable shutdown systems, decay heat removal capability by natural circulation through dedicated heat exchangers, warm roof concept to minimize the risk of sodium aerosol deposits, application of leak before break justification for the main vessel, sodium piping & steam generators, provision of robotic device for the main vessel in-service inspection, etc. The core is monitored by functionally diverse sensors. Two diverse parameters as far as possible are provided for every design based event, which have the potential to cross design safety limits. The pump discharge head and speed are measured and used as trip parameters for the protection against primary pipe rupture and pump seizure respectively. Failure of fuel is detected by monitoring the cover gas fission product activity and delayed neutron detection in the primary coolant. Design Basis Events (DBE) as well as Beyond Design Basis Events (BDBE) have been systematically identified and analyzed using validated computer codes. With the chosen reactor core parameters viz. lower height/diameter ratio (0.5), smaller pin diameter (6.6 mm), annular pellets and lower fuel volume fraction at the mid-level of fuel assembly (0.32), sodium void co-efficient under postulated core disruptive accident (CDA) is limited to 2.4 $, when both fuel melting and sodium boiling occur together and consequent energy release is insignificant (< 1 MJ) (Sathiyasheela and Srinivasan 2008). This void co-efficient is smaller compared to other international values: 4 $ for 600 MWe Japanese DFBR (Endo 1994) and 5.9 $ for the French SPX-1 (Stark 1991).

In order to accommodate the design basis mechanical energy release, a containment system has been conceived as two portions: the upper and lower portions divided by the top shield of reactor assembly. The upper portion is Reactor Containment Building (RCB) and the lower portion is termed as primary containment. The primary containment consists of main vessel welded to top shield, which is supported on the outer reactor vault. Surrounding the main vessel, there is a ‘safety vessel’ supported independently from the inner reactor vault. The inter-vessel space between main and safety vessels is a leak tight boundary, filled with nitrogen. RCB, top shield, main vessel along with safety vessel are designed to meet the specified safety criteria relevant to structural integrity of containment system and post accident heat removal capability under CDA (Bhoje 1990). To facilitate the post accident heat removal capability for a long term, an in-vessel core catcher structure has been incorporated below grid plate (Chellapandi 2011).

It is a general feeling that a heterogeneous core would be the best choice for the sodium void considerations. This has to be seen comprehensively by taking into all the aspects. An organization, while studying the various design concepts, selects an option that can be designed and operated with confidence and also considering the world over operating experience and trend. This is the justification for the choice of homogenous core instead of heterogeneous one in PFBR.

CDA Scenario and Energy Release in PFBR

The main parameter in the energy release is reactivity insertion rate, which mainly comes from sodium void effects. The studies performed by Ompal Singh and Harish (2002) have brought out the effect of reactivity insertion rate on the mechanical energy release and indicated that the energy release gets stabilized to 1000 MJ beyond 100 $/s. This implies that there is no need of assessing critically the energy release mechanisms, once it is assumed to be >1000 MJ. In fact, this is the approach followed for the reactors of 1980’s. However, the authors in the same paper indicated clearly that the realistic estimate for oxide fuel is limited to 50 $/s, which would result in an energy release of 23 MJ. Subsequently, motivation to understand the realistic scenarios supported by tests data: TREAT (Wright 1990), CABRI (Nissen 1986) and SEFOR (Caldarola 1972) could have led to choose the value even lower than 50 $/s for PFBR (Sathiyasheela and Srinivasan 2008). This comes from the improved understanding on the in-pin motion of molten fuel during pre-disassembly phase, swept out effects of the core due to shearing forces of the coolant and clad vapors. The reactor physics analysis carried out with such improved understandings indicates that the whole core sodium void coefficient is 2.4 $. A few fundamental experiments, carried out at IGCAR to quantify the mechanical energy release due to molten fuel coolant interaction effects have indicated that the transient pressure due to Molten Fuel Coolant Interaction effects is insignificant. In spite of these data, an energy release of 100 MJ is pessimistically considered, for which the RCB is designed. It has been assessed though backward computations that the 100 MJ of energy release corresponds to reactivity insertion rate of 66 $ /s. This is possible only through melting of almost entire whole core and subsequent gravitational fall of the molten core coherently, thereby increasing the effective density and reactivity. No other initiating events such as gas and oil entries, sodium voiding or uncontrolled withdrawal of all the control rods can add such reactivity insertion rate. This clearly demonstrates that 100 MJ is pessimistic energy release postulated for PFBR just to raise the confidence among designers and regulators.

Containment Design Aspects

Under normal operation, the pressure acting on containment structures is insignificant. However, under a CDA, the main vessel and top shield would be subjected to a static equivalent pressure of about 2 bar (cumulative effect of short duration high peak pressure) (Chellapandi 2002). The RCB would be pressurized due to temperature rise consequent to chemical fire of sodium ejected during CDA from the narrow penetrations provided in the top shield for facilitating the rotation of plugs during fuel handling operations. Thus, the extent of temperature and pressure rise in the RCB depends on the quantity of sodium released to RCB from sodium pool contained in the main vessel. The phenomenon of sodium release is explained briefly below. More details can be found in (Chellapandi 2010)

CDA results in the formation of a core bubble constituted by vaporized sodium, metal and fuel materials, having high thermal energy. The process of rapid expansion manifests as mechanical energy release. The maximum work potential of the bubble is the energy release when it expands from its initial pressure till it attains 1 atmosphere.

As far as mechanical energy release is concerned, the primary containment is subjected to transient forces in two consequent phases: direct impact pressure on the radial and bottom portions causing radial expansions of the reactor internals (first phase) and impact of accelerated sodium at the bottom of the top shield causing sodium leak through top shield penetrations as well as local bulging of the upper portion of the main vessel (second phase). In these phases, the reactor internals absorb the maximum energy released through core bubble expansion (~ 80 %). Remaining energy is associated with the sodium release phenomenon through top shield penetrations: since the top shield is rigid structure, energy imposed on the top shield is absorbed by the above core structures (control plug consisting of many long and slender structures) to the large extent) and further by a number of long ductile tie rods incorporated at the periphery of the top shield support embedment, developing minimum strains on the bolts in the top shield. Consequently, the lifting of rotatable plugs is insignificant due to sodium slug impact. These apart, the gaps in the penetrations through which sodium can leak out are kept as minimum as achievable by the manufacturing process. Hence, the sodium release to RCB through top shield penetrations is found to be less than 350 kg and associated sodium fire above top shield provides the basis for defining the design pressure of 25 kPa for RCB introducing adequate conservatisms in the fluid flow and sodium fire simulations (Chellapandi 2002).

Energy Absorbing Potential of PFBR Primary Containment

A parametric study was performed on mechanical release without linking to the design basis value (100 MJ). The analysis indicated that higher the energy release, larger is the vessel deformation. This allows the liquid sodium free level to fall down in the first phase, thereby limiting the magnitude and duration of sodium slug impact force on the roof slab. This has been demonstrated in our simulated tests involving many scaled down models employing low density chemical explosive. This has also been demonstrated experimentally and numerically that the main vessel alone can absorb more than 1200 MJ of energy before failure, thanks to the high ductility of austenitic stainless steels used as structural material in PFBR (TBRL Report 2002).

The core bubble in the reactor environment can release a mechanical energy of 70 to 80 MJ, due to the constraints imposed by the reactor internals that do not allow the bubble to attain 1 atmosphere. However, in the simulated tests to assess the mechanical consequences (structural integrity and sodium release), the mass of low density chemical explosive is such that, it released an energy of 110 MJ. This implies that the applied mechanical energy for assessment of mechanical consequences is about 30 % higher (TBRL Report 2002).

In view of the above, it is concluded that the main vessel has potential to absorb more than 1200 MJ of energy and the sodium release to RCB would not exceed design basis leak (350 kg), even if the mechanical energy release exceeds beyond the design basis value (100 MJ). This substantiates the perceptions of designers that there may not be any need of RCB for PFBR; instead a simple confinement would suffice (Paranjpe 1992) (Paranjpe1991).

Economy without Sacrifice of Safety: A Major Challenge to the Designers

While designing the experimental reactors or small size reactors, the 'hell for strong' concepts are generally adopted without giving high emphasis on economy. The economics with due concern for safety forms the fundamental basis for any engineering activity or industry to succeed and providing adequate conservatism is the essence of design. To achieve targeted commercial exploitation, particularly for the large size reactors, precise assessment of design basis loads is essential for the designers worldwide and adequate experimental knowledge needs to be incorporated in the safety evaluation. In this respect, it is worth to comment on the conservatism embedded in SNR-300 or SPX-1 in the definition of CDA energy release. During the design phase, high conservative energy release values were defined for these reactors (370 MJ (Hennies1989) and 800 MJ respectively (Guezence). Subsequently, the reassessment of CDA for SNR 300 with experimental findings showed that design basis of 370 MJ is far conservative and mechanical energy release of more than 100 to 150 MJ still could not be substantiated by any physically conclusive line of arguments (Hennies1989). In the case of SPX-1, subsequent to its construction, it was shown that even with very permissible assumptions, CDA energy overestimate is by a factor of 2 or 3 for SPX-1 (Guezence). Hence, the design values adopted for SNR-300 and SPX-1 should not be the basis for new reactors. In fact, they are not the basis for new reactor in Western Europe. For the next fast reactor in France (SPX-2), such conservative approach that was adopted for SPX-1 was not followed: the energy release for SPX-2 was estimated only 150 MJ (Dell Beccaro 1989).

Accordingly, the design of PFBR conceived in 1992 was reviewed critically including the issues related to reactor safety based on accumulated numerical and experimental data from in-house and international resources (Bhoje 2001). Revision of design basis loads is based on the comments received from extensive multitier review mechanisms (about 100 Project Design Safety Committee Meetings and numerous review input from seventeen specialist groups). Among them, the RCB design pressure is one important parameter. The design pressure of 25 kPa approved by the safety committee has undergone investigations by multi-disciplinary experts backed up with numerous high quality data. In this exercise, we have established a few international benchmark data particularly in the domain of the mechanical consequences of CDA (Chellapandi 2010).

International Perspective on Severe Accident Assessment Methodology

The design–experience shows that a larger safety margin to the conservative limits is possible. This, in turn is reflected also in the practical experience with the prototype plants: over 1,00,000 FBR fuel – pins up to a burn-up of about 1,00,000 MWd/t were irradiated world wide (Von Heinz Vossebrecker 1999), in which the failure rate was generally lower than by an order of magnitude, below the limit of 1%, depending upon the design. Regarding reactivity insertion rate due to sodium voiding for the large core, results of analysis carried out by Hummel et al. (Hummel 1976a) using a more recent version of the SAS code can be referred, where it is noted that a maximum ramp rate of \$30/s results from sodium voiding even for a 4000 MWt reactor design with a \$ 7 sodium void contribution. Hummel et al. (1976a & 1976b) performed similar calculations for CRBRP and found a maximum voiding rate of \$ 25/s; they suggested that a loss-of-flow accident would not lead to prompt critical conditions with a possibility of subsequent large energy releases. It was shown by theory and experiments at SEFOR between 1969 and 1972 that large mixed – oxide fueled cores always have a strong negative power coefficient and a good control stability against reactivity or coolant–flow oscillations (Caldarola 1972). In addition, it was concluded that the strong negative Doppler coefficient together with the negative structural and fuel expansion coefficients predominate over the positive sodium void coefficient in central parts of LMFBR cores. Further it is confirmed that the oxide fuel is favorable (some in-pile demonstration exists) by clad vaporization. The cladding boiling point is roughly equal to the melting point of the fuel (uranium plutonium) suggesting that steel vapor from clad boiling can provided an effective dispersal mechanism. Explosive sodium vapor formation is not likely to be involved for oxide- fuel/sodium systems. (Fauske 1976) summarized the technology status during CRBRP licensing. In contrast to FFTF (~0 $), CRBRP had a significantly positive coolant void reactivity worth (~3 $). Regulators agreed with the applicant that CDA energetics would be excluded from the plant design basis (Strawbridge1985). Ultimately, a construction permit was issued for CRBRP, but after its construction was abandoned for reasons not related to safety (Cahalan 2005).

With reference to mechanical energy release, it is worth to look at the FRAX calculations performed for EFR (Bernard 2005), which indicates that the mechanical energy release is 1000 MJ with the assumption of coherent core and it is insignificant for the realistic core. The most likely estimate was lower than 150 MJ for this 1500 MWe MOX reactor. It is also worth to note the conclusions of (Richard 1977), where it is stated that the mechanical energy itself is not the number of interest for any given reactor, rather it is instantaneous forces and pressures which could raise the reactor vessel head and / or violate the containment. The energy available to raise the vessel head is about one-tenth to one-fifth of the energy of expansion to one atmosphere. This justifies that sodium release is not strongly linked to mechanical energy in CDA.

The above few extracts raise the confidence on the CDA analysis and design provisions adopted for PFBR, which are all of course based on widely accepted practices followed by designers of sodium cooled fast reactors worldwide.

Epilogue

Sodium cooled fast reactors have several inherent and engineered safety features. Further for PFBR, robust safety features have been incorporated and qualified based on extensive theoretical and experimental testing and evaluations, which have been reviewed elaborately through multi-tier review process under Atomic Energy Regulatory Board. With these justifications, it can be stated with high confidence that there is no concern on core melt down accident and associated mechanical consequences such as failure of containment system in PFBR.

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