Safety Adequacy of Indian Fast Breeder Reactor

Baldev Raj[1] and Prabhat Kumar[2]

[1] Director, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102
2 Project Director, Bharatiya Nabhikiya Vidyut Nigam Limited, Kalpakkam.

it is the firm conviction of the energy policy makers of India that the Fast Breeder Programme is essential for the utilization of huge thorium reserves and limited sources of natural uranium I the country. Nevertheless, from the global perspective, it is appropriate to highlight the generic motivation for the development of fast breeder reactors (FBRs). These are the most efficient energy systems for the effective utilisation of uranium resources: at least 70 times more energy extraction is possible as compared to the energy extracted in water reactors, due to the possibility of using the uranium stored in spent fuel by multiple recycling while producing energy. Further, in view of high energy neutron spectrum prevailing in the core, the Fast Spectrum Reactors have unique features to burn high level radioactive wastes containing long lived minor actinides and fission products. The FBRs with closed fuel cycle give us clear possibilities for the minimisation of mining efforts in the fuel cycle and waste management burdens. These facts have been brought out clearly by OECD NEA, 9th IEM on Actinides …, France, 25-29 Sep 2006, where it is stated as *"In a sustainable development perspective, full FBR schemes are by far the most efficient due to (1) environmental dimension: reduction of the uranium mining requirements by a factor of 50 or more and (2) social dimension: reduction of waste volume by a factor of 30"*. The statements *"…….. the only certain conclusion is that a new nuclear era could be fuelled comfortably for many generations to come either by developing various breeder designs or by exploiting thorium whose resources are much more plentiful and also more accessible than those of uranium"* are from Vaclav Smil, "Energy at the Cross Roads – global perspectives and uncertainties" MIT press, Cambridge, UK, 2003. We would also like to underline the statements of Enrico Fermi, in a meeting with Wigner, held on April 26, 1944, *"The country that learns to build breeder reactor would have solved its energy problems for ever.., The country which first develops a breeder reactor will have a great competitive advantage in Atomic Energy"*. These are the basis for considering the FBRs as the most promising options for delivery of mega energy in near future, by the international initiatives, such as GEN-IV international forum and IAEA Joint Assessment Study on closed nuclear fuel cycle with fast reactors (CNFC-FR). Among various FBR concepts, the sodium cooled fast reactors (SFRs) have obtained sufficient technological maturity and demonstrated safety. The SFRs have gained more than 400 reactor-years of operation till date through operation of prototype, test and experimental reactors, apart from numerous sodium test loops. The technologies of sodium coolant and mixed oxide fuels, in particular, are largely mastered. These have demonstrated robust safety characteristics and inherent safety features are the basis of such safety assurance.

In the Indian context, with the limited energy resources available, the realization of energy projection to increase four times the current level in 20 years and ten times within 50 years demand a major share from the nuclear. The coal, oil and hydro options are becoming more and more expensive systems and even their availability would be of concern for the deployment on a mega scale production. Under this scenario, FBRs would play a major role, thanks to abundant thorium available in the country (second largest in the world). So, the energy option should be viewed as a 'country specific' strategy and FBRs should be acceptable as most preferred solution for India. Based on this premise, FBR programme has been pursued vigorously since 1970's, by setting up a dedicated scientific organization 'Indira Gandhi Centre for Atomic Research (IGCAR)' under the Department of Atomic Energy (DAE). The centre has established indigenous capability to design and develop SFRs through *'science based approach'*. With the successful operation of Fast Breeder Test Reactor (FBTR) over 25 years, a 500 MWe Prototype Fast Breeder Reactor (PFBR) was designed and developed with the objective of techno-economic demonstration for building a series of commercial reactors to follow. Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI), a Government Company was incorporated for executing the FBR projects in the country. IGCAR, BHAVINI and as well as several leading industries are working with high synergism in constructing PFBR project, which is now under advanced stage of construction at Kalpakkam. Beyond PFBR, DAE is planning to construct six more FBRs of 500 MWe with improved economy in the commercial domain.

Safety has been given highest attention in the design of PFBR. The design complies with robust, nationally as well as internationally acceptable safety criteria. The safety has been well demonstrated through analytical and numerical analyses as well as through extensive experimental investigations under environments such as sodium and high temperatures as prevailing in the reactor. These were executed through in-house expertise/ facilities and extensive collaborations (more than two hundred in number) over three decades. The design and safety aspects have been reviewed thoroughly at all the stages starting from design to component erection stage by well qualified experts in the country, under Atomic Energy Regulatory Board (AERB).

On the PFBR Containment Design

The containment design basis for water reactors (PHWR for example) is quite different from SFR (PFBR in the present case). PHWR containment is designed for pressure that would develop in containment, resulting from loss of coolant accident (LOCA) caused by a rupture of primary heat transport piping as well as steam line break. On the contrary, for the PFBR, there is no such loading in view of sodium remaining in liquid state at low pressure even at high temperatures. However, its containment is designed for withstanding the pressure generated due to sodium fire as a consequence of sodium expulsion under a postulated core disruptive accident. The quantity of sodium expelled through the rigid top cover of the reactor vessel and consequent pressure rise is very insignificant for the huge containment volume. In brief, there is no one-to-one relationship between the containment pressure of PFBR and PHWRs. It is pertinent to note that containment function for PFBR is needed only in case of the beyond design basis core disruptive accident. For PFBR, the event has been analysed as a design extension on conservative basis and radiological limits of design basis accident have been specified and met with adequate margins.

On Sodium Void Co-efficient:

PFBR has been designed with enhanced safety features compared to reactors of past era: two independent fast acting shut down systems; dedicated decay heat removal systems and provision of in-service inspection of the main vessel are typical examples. Like other fast reactors, the temperature and power coefficients of reactivity are negative in PFBR in all operating regimes thus making it safe. The effect of sodium voids formed due to local boiling of coolant under any design basis events would also cause negative reactivity, especially in the medium size reactors like PFBR. However, under extreme conditions (categorized under design extension conditions), the sodium void co-efficient per se could be positive. In spite of this, it is not a safety concern in PFBR, due to the presence of other prompt negative reactivity feed backs like Doppler and fuel expansion coefficients. Under a postulated core disruptive accident scenario, when both fuel melting and sodium boiling occur together in the core, the coolant void positive reactivity addition is about 2 times the delayed neutron fraction, which is much less than the reactivity addition due to fuel melting.

On Decay Heat Removal Capability

The author is right in stating that the use of water would be impossible in any accident at an FBR to cool the reactor core. However, his simplified interpretation that the real lesson of Fukushima is that FBRs are inherently risky is not correct. The author may take note of the fact that that ultimate heat sink in SFR during decay heat removal condition is air in PFBR and not water. In this respect, it is prudent to understand the unique advantages of sodium in the pool type design adopted for PFBR. During the reactor shutdown state, even under extreme condition of off-site power failure, the decay heat generated in the core will be removed comfortably by a set of dedicated heat exchangers, called safety grade decay heat exchangers (SGDHR). These heat exchangers, immersed in sodium pool, will ultimately reject the heat to atmospheric air by natural convection (refer the attached figure). Once the temperature is raised in the core, the sodium in the hot pool would be heated up, thereby developing high driving force for the coolant flow through natural circulation without calling any power supply. Sufficient heat removal is feasible in view of: (1) high heat transfer properties of sodium, (2) availability of a large margin between the operating temperature (820 K) and its boiling point (1200 K) that can accommodate significant temperature rise without vaporization, and (3) large difference between the temperature of hot sodium at 820 K and ambient air at 310 K, coupled with significant variation of sodium density with temperature. Hence, there is no need of any additional emergency core cooling system.

On Chemical Reaction Effects of Sodium

The violent chemical reaction with air and water in case of a coolant leak is truly the challenging issue with sodium. The operating experience has indicated that there have been minor sodium leaks in various reactors. Large leaks are prevented since the occurrences of sodium leaks have been detected precisely with diversified leak detection systems. Designers are very conscious of this and robust design provisions are made, so that the problems related to sodium do not affect the reactor safety: the result is that there have been no serious fires not affecting the other components. Author may refer our joint publication with French experts on the operating experience with sodium (J. Guidez and L. Martin, S. C. Chetal, P. Chellapandi and Baldev Raj, 'Lessons Learned from Sodium-Cooled Fast Reactor Operation and Their Ramifications for Future Reactors with Respect to enhanced Safety and Reliability', Nuclear Technology, Vol. 164, Feb 13, 2008).

For PFBR, various measures, such as reduction of welds in piping by adopting two (minimum possible number) primary and secondary sodium loops, use of improved materials (SS 316/304 type instead of stabilized grade SS 321), state-of-art non-destructive examination techniques with innovative sensors and instruments for detecting the defects, etc., are incorporated to reduce possibility of sodium leaks. The direct contact of radioactive sodium with air is prevented by: (1) the primary sodium pipings are surrounded by guard pipes filled with inert gas or the piping is kept in an inert atmosphere and (2) the main vessel containing the entire radioactive sodium (1150 t) is also surrounded by the safety vessel with its inter-space filled with nitrogen. This apart, innovative self-extinguishing materials / techniques have been deployed to mitigate the effects of sodium leaks from the pipings. With these robust features, it can be stated that issues related to sodium leaks and fires can be managed in a comprehensive manner.

With reference to the effects of Tsunami attack on the nuclear power plant recently in Japan: the major consequence of Tsunami is the raise of flood level. The design flood level for Kalpakkam site is governed by severe cyclone of low probability (return period is 10000 years), rather than the flood level due to Tsunami, because Kalpakkam is at low seismic zone. It is worth mentioning that the flood level caused by 2004 tsunami is only 4.4 m, against the design flood level governed by cyclone is 4.8 m. From the design point of view, the finished floor level of the nuclear island building of PFBR site is 9.6 m above the mean sea level, clearly indicating the margin of about 5 m above the 2004 tsunami water level. Hence, there is no possibility of water entry in to the building housing the sodium systems.

On the International Experience with Sodium

In response to the comments raised on Russian FBRs, we wish to highlight the current status. The sodium leaks had occurred in BN-350 steam generators (SGs) during the first two years (1973-75), because of inadequate quality in manufacturing of heat exchangers. In spite of these leaks, its operation on the whole has shown correctness of principal solutions accepted in its design, demonstrated stability and easiness of SFR control, their sufficient reliability and safety. These leaks in fact provided important experience to improve the design of BOR-60, BN-600 and BN-800 reactors towards further upgrading SFR technology. BN-600 has operated practically for its full design lifetime equal to 30 years: the last outside sodium leak being more than fifteen years ago (May 1994). As for leaks in SG, during last 25 years of BN-600 operation there was only one small leak in SG in January 1991. In fact, Russian reactors have demonstrated high safety and reliability indices during its commercial operation including sodium coolant technology.

We would like to clarify to the author that the SGs in BN 600 are located in SG building and not in bunkers as stated by the author. Further, a spare generator is provided to replace the SG with leaked tubes towards ensuring plant availability, not from the point of view of need for replacing the ‘fire damaged SG’. The philosophy of providing a spare part or spare component is well established maintenance approach.

The reason for the long delay in restarting of MONJU, the Japanese SFR, is more political rather than scientific. It is similar in some way to the closure of German nuclear reactors after Fukushima accident in Japan on March 11, 2011. Many of the reactors world over (for example EBR-II, PFR, JOYO, Phenix, BoR 60, BN 600) have completed their targeted mission and as well as their design life. PFR in UK, has completed design life of 20 calendar years and by no means was shutdown for long periods by sodium fire, as stated by author. In fact, French reactor Phenix had operated for six years from the year 2003-2009 as part of radioactive waste management demonstration during its extended life. BN 600, the highest rated fast reactor, after 30 years of successful operation, would be in operation for another 10 years. Decision on permanent closure of SPX is a consequence of political compulsion of coalitions of government prevailing at that time.

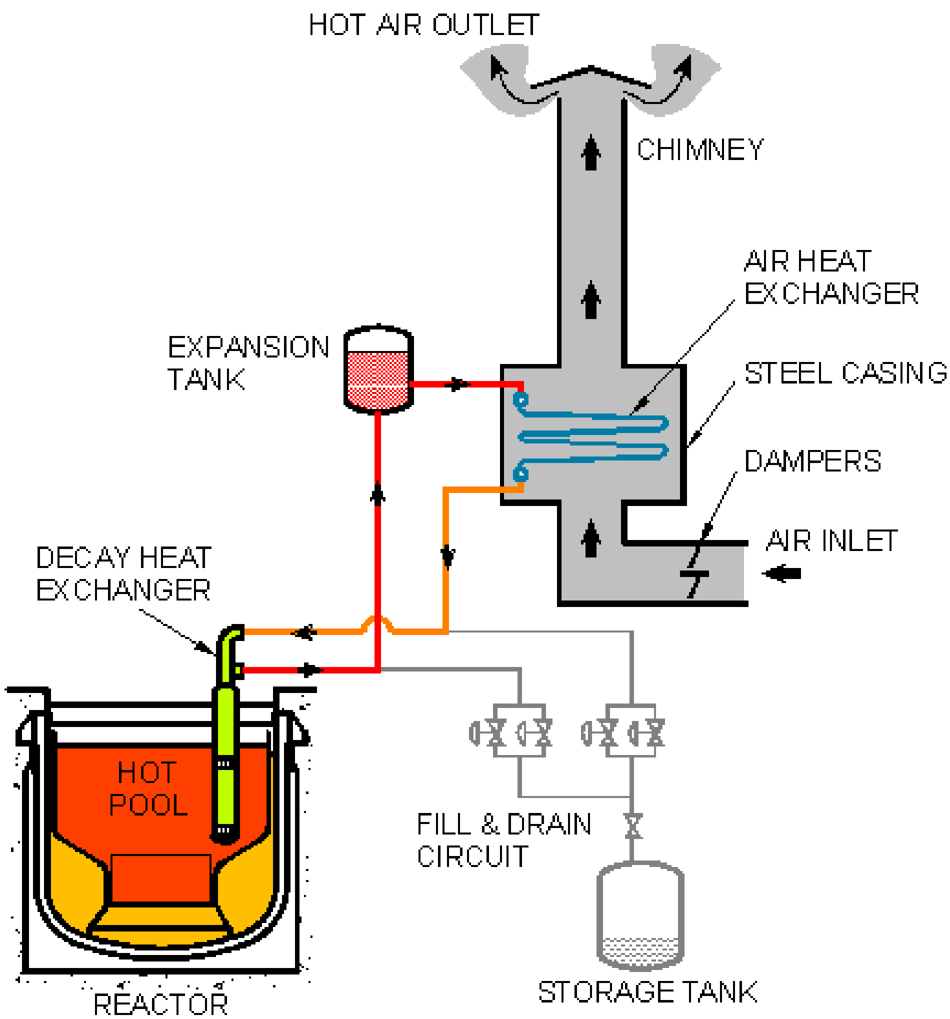
Our experience with sodium, both in FBTR and various sodium loops over 40 years is benign. There was one significant primary sodium leak (~75 kg) in FBTR, which has not resulted in any fire or safety concern and reactor was brought back to operation within two months. Even in PFBR, more than 1600 tonnes of sodium from tankers has been transferred to various storage tanks successfully without any single incident.

We would like to admit that adverse posturing of a few countries against fast reactors or for that matter nuclear power itself is, in fact unavoidable. Even, those countries appear to be walking away from their rigid stance and planning to pursue the SFR programme. Countries like China, France, Japan, Russia and South Korea, are expanding their programmes and in fact they are in the race towards attaining the global leadership status in FBR technology, like us. It is a fact that the most learned world community salutes us for our track record and safety approaches enumerated in several hundreds of publications of high relevance and merit.

Summary:

The fast reactors have demonstrated robust safety characteristics, inherent safety features and possibility of introduction of passive safety functions with less uncertainty and with high confidence. These have been thoroughly validated with tests covering fundamental aspects to large scale demonstration. We strongly hope that the article provide clarifications on concerns on PFBR safety, which may raise in the minds of certain people.

* * *



There are four safety grade decay heat removal systems incorporated in PFBR and one typical system is shown in the figure. Four dedicated diverse sodium to sodium heat exchangers immersed in the sodium pool can transfer the heat to sodium to air heat exchanger by natural circulation itself. The heat from sodium to air heat exchangers placed at elevated locations will be dissipated to ambient air, again by natural circulation. These systems do not call for any power supply and the air is the ultimate heat sink