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Ravi Kumar Bansal
Nuclear Power Corporation of India, ravibansal@npcil.co.in

H. S. Sharma Dr
Amity Institute of Nuclear Science and Technology, Amity University, Noida, hssharma1@amity.edu

R. K. Singh Dr
Raja Ramana Fellow and Amity Institute of Nuclear Science and Technology, Amity University, Noida

P. N. Prasad
Nuclear Power Corporation of India

See next page for additional authors

Presenter Information

Ravi Kumar Bansal, H. S. Sharma Dr, R. K. Singh Dr, and P. N. Prasad

Review of Fuel Management Practices at Various stages of Nuclear Fuel Cycle in PHWRs in view of Environmental Effects

Ravi K Bansal*, H.S. Sharma†, Tejram†, Ram Kumar Singh‡ and P. N. Prasad

*, *Nuclear Power Corporation of India Limited, Anushakti Nagar, Mumbai.* ravibansal@npcil.co.in

†*Amity Institute of Nuclear Science and Technology, Amity University, Noida, Uttar Pradesh,* hssharma1@amity.edu, tram@amity.edu

1.0 INTRODUCTION

Electricity is the key element for human development on earth. Therefore, to meet the demand of increasing electricity generation, it is essential to enhance the capacity of pollution free nuclear energy along with other available energy sources. India has the total installed capacity of 6780 MWe of Nuclear Power as as on date and around 15700 MWe is being planned to installed in future by 2031 with commissioning more nuclear reactors which including the ones under construction/planning stage.

Currently about 454 nuclear reactors are operating all over the world and the nuclear power contributes to over 11% of total electricity produced globally.[1] In view of the fast depleting fossil fuels (coal, oil etc.) reserves and need of clean and green source of energy, nuclear power looks to be highly attractive option, which is free from SO_x, NO_x, CO_x gases that is released in conventional fossil fuel based power plants. The nuclear power technology has developed and matured as a safe, clean and efficient means of electricity generation for meeting the global expanding energy needs. However, the public understanding and acceptability of nuclear power earlier remained shrouded in myths and fears quite disproportionate to the scientific facts for the last four decades following Three miles, Chernobyl and Fukushima severe accidents. Following the demonstration of the safe nuclear power technology severe accident management and the understanding of the hazards emanating from the natural events, the public is now accepting the nuclear energy generation for societal benefits and is now aware that the risk associated with radiation from Nuclear Power Plants is minimal due to the restricted and acceptable releases, which at present are extremely low and comparable to the natural background radiation levels. However, it is recognized that excess exposure to radiation could lead to clinical damage in tissues of human body and has potential for delayed induction of malignancies. It is therefore very essential that radiation exposure are strictly controlled during the complete fuel cycle right from the transportation of radioactive material including nuclear fuel to nuclear reactors for power generation, in-core fuel management, including online refueling, to run the nuclear power station, disposal of generated radioactive waste so as to limit the exposure for occupational workers as well as to the public. All these activities are performed as per guidelines and safety standards set by International Atomic Energy Agency (IAEA) as recorded in various IAEA guides.

Looking into the large years of experience of nuclear power across the world vis a vis the overall fuel management in the complete nuclear fuel cycle, it is important to review the Linear-No-Threshold (LNT) principle in a scientific manner. LNT principle based on linear interpolation from data collected at very high radiation levels of radiation exposure resulted into the myth that that any insignificant amount of radiation exposure howsoever small can affect the human body is cause for the deeply rooted fear of radiation in public mind. This has enormous political, economic, social and psychological impact on nuclear industry and the scientific measures have been initiated to address this problem. Meanwhile it is prudent that a systematic study be undertaken to examine the impact associated with the generation of nuclear power resulting from a number of processes and operations involved in the complete nuclear fuel cycle, which has been addressed in the paper. [1]

2.0 MINING, MILLING and FUEL FABRICATION

Uranium ores are found in many parts of the world but with different varying percentage of uranium up to 2% mainly in form of oxide minerals. Since medium grade ores contain large amount of inert material, a concentration operation is needed in a mill located close to the mining area. Typical operations utilize either chemical leaching or solvent extraction process. The product is known as yellow cake which contains around 80% U_3O_8. This yellow cake is then transported to a central purification facility where further chemical operations are carried out to remove impurities and produce nuclear grade uranium dioxide or uranium hexafluoride for subsequent use in fuel fabrication.

Waste from mining and milling activities contain very low concentrations of radioactive material. The long-lived radionuclides include Ra-226 and Rn-222 and this has important implications for its management. Rainfall and snowmelt runoff and seepage from stockpiles and areas of uranium process plants are well managed and the releases are extremely below the acceptable levels. The waste rocks produced in mining are used for backfill of mines and the construction of embankments on the mine site etc. Mine-water is as far as possible usually recycled back in the mine and the mill.

The operators of the mine and mill have a comprehensive radiological protection program. The design of tailings pile has a feature that incorporate multilevel barrier for minimizing the migration of contaminants. To achieve optimization in radiological protection, principle of As Low as Reasonably Achievable (ALARA) is used with social and economic factors being taken into account. [2]

During fuel fabrication especially with enriched uranium accidental aggregation of fuel may lead to chain reaction though very improbable but great care in material handling is taken to avoid any such possibility. The presence of toxic Fluorine in fabrication requires a greater care and procedures at this stage. However, the production of UO_2 elements is now a well-established and almost free from hazards. [3]

With all the controls in place the annual effective annual dose has been less than 5.5mSv in a five year study whereas the AERB limits is 20mSv per year. The annual exposure is estimated to be 1.7 to 3.1 mSv with a mean of 2.49mSv per annum to the members of public and around 65% of the world population receive an annual dose of 1-3mSv p.a. All these doses have been very small as compare the doses of very high natural background in many parts of the world like Ramsar in Iran reach >400mSv/year and Brazil up to 700mSv/year. No harmful effects has been observed in high natural background areas [1], which again calls for a detailed scientific evaluation of LNT principle.

3.0 NUCLEAR FUEL MANAGEMENT in OPERATION of NUCLEAR POWER PLANTS and ENVIRONMENTAL ASPECTS

The most important contaminants from fossil-fueled power plant operation are carbon dioxide, sulfur dioxide, nitrogen oxides and particulate matter. The combustion process contributes about 10 % of the carbon dioxide emitted to the atmosphere, the remainder being primarily the result of natural decay. Increasing Carbon dioxide levels in atmosphere can affect the earth's climate as a result of the greenhouse effect. Other gases act as pollutants to the ecosystem and lead to acid rain.

Power generation from nuclear fission of Uranium, which is a nuclear reaction and does not involve any combustion process and therefore CO_2 and other pollutants unlike a fossil power plant, are not generated. However, due to operation of a Nuclear reactor a large number of radioactive fission and activation products are produced which if not contained and managed may pose threat to the environment. In order to contain and restrict the emissions of radiation and radiation sources, a Defense-In-Depth approach is used by Nuclear Power operators both philosophically and its implementation physically. This means that if there is one barrier to control radiation release is breached; it is backed up by second barrier and so on; for example in PHWRs – First barrier is UO_2 fuel matrix itself, second barrier is Zircaloy cladding of fuel; third barrier is Pressure tube, Fourth barrier is Primary containment, Fifth barrier is Secondary containment and sixth barrier is exclusion boundary of the reactor. The approach encompasses accident prevention, control of abnormal operation, detection of fuel failures and the mitigation in exigencies. Prevention is achieved philosophically by employing various technical and administrative controls and the target is to prevent any incident initiation for prevention of accident and provision of mitigation measures in case of an accident. The next layer involves various countermeasures in sequential manner to control the incident of radioactive release. In this defense-in-depth approach, various physical barriers mentioned above for confinement of radiation and fission products, are enforced.

The fuel has operating power limits beyond which higher amount of volatile fission products especially noble gases(Xe133, halogens etc. may be produced and this can lead to fuel pellet clad interaction under pressure/temperature condition and may damage the cladding. Iodine-131, one of the fission products, is monitored in coolant heavy water routinely every day to check such a breach. With the online refueling, it is possible to remove the defective fuel from the core by refueling individual channel while the reactor is in operation.

In Indian PHWRs, the fuel is loaded in the core in the form of Natural Uranium dioxide in fuel bundles, which has either 19 element pencils or 37 element pencils, depending on the rating of the reactor. Uranium dioxide pellets are stacked in each pencil and encapsulated in zircalloy-4 tube. To replenish the fuel material inside the reactor core, online refueling system on both sides of the reactor exists. During the operation of reactor and during refueling the integrity of various systems is ensured like fuel pencils, cladding, pressure tubes, Calandria vessel housing of the reactor core etc. The fuel has operating power limits (483KW for 220MWe, beyond which higher amount of volatile fission products may be produced and this could lead to fuel pellet clad interaction under pressure/temperature and may damage the cladding. If this situation arises, the breach in Zircaloy cladding can occur and the fission product may come out of fuel to heavy water coolant in the pressure tubes.Iodine-131, one of the fission products, is monitored in coolant heavy water routinely every day to check such a breach. With online refueling is possible it is possible to remove the defective fuel from the core by refueling individual channel while the reactor is operating. So the main job remains is to identify the channel containing the defective fuel. This is done by trending I-131 in coolant. Normally this Iodine-131 concentration is less than 2µCi/l and if this concentration increases beyond 10 µCi/lit it becomes imperative that there is a presence of defective/failed fuel inside the core and it should be removed. Apart from fission neutrons there are delayed neutrons present in the core and their concentration ranges up to 0.65% of total neutrons. These neutrons are emitted from fission product precursors like Br-87 and I-137 with half lives of 55 sec and 22 sec respectively. These neutrons are being measured for Delayed neutron counts in BF_3 filled detector with sensitivity of around 4cps/nv (count per second per unit flux) to estimate the change in their population. Whenever there is a defective fuel the corresponding detector reads higher than normal and out of large number of channels in the operating reactor core, the defective bundle/channel is identified using Delayed Neutron (DN) monitoring technique to pin point the location of failure. In this, the variation in the delayed neutron counts from different channels is observed and the data is analyzed for 99% confidence level. Fuel channels showing DN ratios beyond $1\pm 3\sigma$ are trended to ascertain the fact of existence of cladding breach. Individual channel is monitored during refueling and when the failed fuel passes through various neutron flux locations while travelling through the core gives an idea of the individual bundle pair having the failed fuel. This ensures to restrict any radiation release beyond the closed loop of Primary Heat Transport system at all times. If the I-131 increases without removal of defective fuel inside core, the reactor is shut-down till defective fuel is removed to restrict any possible environmental effects.

Improvements based on lessons learnt in fuel design, such as graphite coating, use of split spacer design etc., has been incorporated. Further before transporting fuel to reactor site, 100 % fuel bundles undergo quality assurance check for Helium leak test. After receiving the bundles at the reactor site, fuel bundles are rechecked with helium leak test on statistical basis for any manufacturing, visual defect etc., well before loading in the reactor core. After loading the fuel in the core, In-Core fuel management is done in such a way that the regulatory safety limits on bundle power(limiting conditions for operation at around 46 W/cm) do not exceed and fuel integrity is maintained. Channels for refueling are selected based on the average burn-up (consumption) of the fuel. The channels showing design limit of the burn-up are refueled, employing online bidirectional process. The discharge Spent fuel bundles are kept under Spent Fuel Storage Bay(SFSB) in a large pool of water for cooling for a satisfactory short term storage but it cannot be a permanent disposal facility. I^{131} is also monitored routinely or health risks like child thyroid and maintained under limits by purification system in SFSB

The spent fuel in SFSB after cooling and decay of short lived fission products are removed for reprocessing in closed fuel cycle and this takes couple of months. At reprocessing plant the fuel is chemically treated by solvent extraction process and a portion of residual fuel is recovered. The gaseous and volatile fission products Kr^{85}, I^{129}, tritium are released during reprocessing. To maintain the emission standards the release of these materials and the liquid and generated solid waste is controlled by standard methods.

The discharge Spent fuel bundles are kept under pool of water known as spent fuel bay for cooling. I131 is also monitored routinely and maintained under limits by purification system in spent fuel bay and normally SFSB iodine is maintained below 1 µCi/lt. The purification is through Ion exchange columns which has both Cation and anion resins to remove iodine radioactivity. Further, the PH of spent fuel bay is maintained basic at around 8.5 by adding chemicals like LiOH and hydrazine, which further help in trapping Iodine. Air ventilation recirculation of spent fuel bay is maintained through activated charcoal filter to ensure the discharges at Below Detectable Level (BDL). Whenever a defective fuel is refueled, the bundle is kept in the fueling machine magazine under purification flow through IX columns till iodine discharges from the fuel bundle comes down to acceptable level wherein it can be safely discharged to spent fuel storage bay. The used exhausted resins from IX- columns are radioactive waste and are stored in waste management facility in concrete canisters after vitrification.

During this route, there is no chance of any radiation release to the environment. Now this spent fuel after cooling for six months by which the short half- life radioactive elements decay completely, the fuel is transported for reprocessing. After reprocessing the long-lived radioactive element remain in the radioactive waste and the waste is disposed in repositories in concrete canisters after vitrification. Thus, the entire in-core nuclear fuel cycle till reprocessing ensures minimal release of radiation to environment and is well below within the acceptable limits.

It may be observed that compared to the average background radiation level of 2400µSv/yr and further the limit set by Indian Atomic Energy Regulatory Board (AERB) at 1000 µSv/yr is very conservative because the actual releases from Indian Nuclear sites is less than 5% of the dose limit with all the above measures during the nuclear power plant operation in India. [4 &Fig1]

In Case there are inadvertent deviations in operation of nuclear reactor either natural or induced, various Engineered Safety Features(ESFs) are installed in nuclear power plant to manage design basis accident and response for bringing reactor under safe shut-down condition while maintaining the desired safe status of reactor. For situations like Design Extension Conditions that are very improbable, Severe Accident Guidelines are issued to mitigate the situation and limit the radiation releases in public domain.

Further, as a part of nuclear industry safety culture the lessons learnt from any of the events in a nuclear power plant are being shared globally and appropriate measures are implemented for both forward fit and retrofit. This has tremendous effect on the sturdiness of nuclear power reactor throughout the world for maintaining an accident free/limited manageable accidents track record of nuclear power industry.

4.0 SPENT FUEL TRANSPORTATION

Security and safety is maintained while transporting the spent fuel bundles for reprocessing. The bundles are kept in air cooled Lead Flask to ensure that radiation limits outside the flasks are maintained within acceptable regulatory guidelines. This flask is transported on a long trailer escorted with proper security cover and procedures and under the leadership of a Radiation Safety officer in an emergency vehicle fitted with radiation monitors. The speed of the convoy is limited and travels only in day time. During night time the convoy is halted under police cover and concerned state authorities and regulatory bodies are well informed.

If there is any accidental fall of the flask on the road due to any exigency, the area around the flask is cordoned with display radiation symbol around for alert and traffic is diverted till problem is rectified

Spent fuel from Indian PHWRs are kept in air-cooled Lead flask to ensure that radiation limits outside the flasks remain within acceptable regulatory guidelines. . It is ensured in design of the flask that no inadvertent criticality would occur during transportation. Packaging and Transport of radioactive materials are regulated by international as well as National transport regulations published by IAEA for the safe transport of radioactive materials

5.0 ROLE of NUCLEAR SAFEGUARDS in ENVIRONMENTAL PROTECTION

In the entire fuel cycle whether front end or back end strict vigilance and care is required both at the national and international levels to ensure that nuclear material remains with the authorized agencies. To achieve this Nuclear Material Accounting (NUMAC) and Nuclear Security Procedures like Physical Protection systems etc. have to be placed in the correct perspective. In India, it is ensured by IAEA safeguarded system for the facilities covered under International IAEA Safeguards as per the agreement with IAEA and rest nuclear facilities are ensured by Domestic Safeguarded system.

6.0 THE CASE OF ACCIDENTS

The three accidents in Nuclear History viz Three mile island(1979-USA),Chernobyl-1986(Former USSR), Fukushima(2011-Japan) have been widely studied and analyzed and led to large improvements in operations and safety culture of a nuclear power plants worldwide as both forward fitting and backward fitting of the lessons learnt has taken place. These improvements have helped to bring back confidence in nuclear power as safe source of energy. However the Fukushima event which occurred in recent history due to multiple units of nuclear reactor getting affected resulting from natural events of earthquake and tsunami external to the plant and occurred as beyond design basis. This escalated to a level, which inducted severe damage sequences, and consequently a large-scale evacuation of people living in the vicinity was required. One of the experiences gained is that there is a need to review the impact of radiological event in public domain from the psychological trauma on public due to large-scale pre-emptive evacuation due to limitations in the policies because of the foundation on Linear-No-Threshold (LNT) [5, 6]

7.0 CONCLUDING REMARKS

7.1 With a large number of technical and administrative controls with Defense in Depth philosophy in design, operation, maintenance and accident management, the prescribed dose limits set by the regulatory authorities are followed in a very conservative manner. Nuclear power in upcoming years has to play a global role in reducing GHGs emissions and meeting the targets of COP conferences to limit the average rise of earth's temperature beyond 1.5 ^{0}C.

7.2 It is noted that during reactor operation and complete nuclear fuel cycle there is a large margin available between the dose limits set by regulatory mechanism for public domain and the actual releases and therefore all the concurrent safety principles should be continued in practice. Further, in case of an extreme event occurs in a nuclear power plant, implementation of severe management guidelines should limit its consequences. The target should be to avoid large-scale relocation of people has been done as has been done in the case of Fukushima (2011) accident that caused lot of public trauma. In view of this it is imperative that the present deficient policies based on inherently limited Linear No Threshold (LNT) principle that "No Radiation is safe" should be reviewed on a scientific basis rather than heuristically for management of an accident in public domain and exposure limits should be accordingly quantified which may be further reviewed with the available data.

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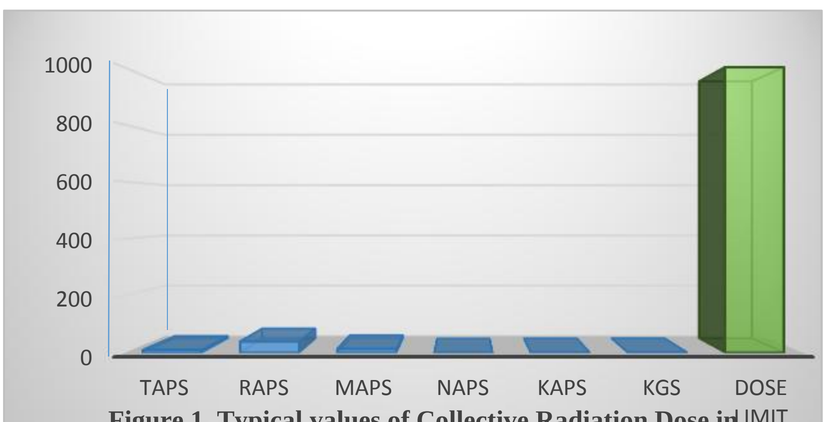

Figure 1. Typical values of Collective Radiation Dose in Public Domain due to Indian Nuclear Power Plants (µSv/yr). Average World Background is 2400µSv/yr (Source: BARC Website)