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Radiation Exposure Minimisation by Smart Reactor Design and Intelligent Plant Layout for Bountiful Harnessing of Clean Nuclear Energy

B. Narayana Karkera[1] and Lewlyn L. Raj Rodrigues[2]
[1,2]Manipal Institute of Technology, Manipal University, INDIA
[1]Formarly Bhabha Atomic Research Centre, Mumbai, INDIA

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Abstract

Presently, each year 26 billion tons of CO_2 emission is avoided by the 385 nuclear power reactors world over. 4.6 billion Years young earth, born within the 13.7±0.3 billion year old 'Big Bang Universe' is surviving as a living planet; proving the nuclear phenomenon to be a creator, a savior and clean. If anything is faulty, it is the way we harness the nuclear energy. Major accidents are few in ~15,000 reactor-year-operations; but cannot be ignored. Very little has been done to circumvent the problem of reducing the exposure to nuclear radiation from the control rod drive mechanisms (CRDM). We propose a telescopic design of CRDM, with its massive portion integrated with the reactor body to be free from maintenance and reducing the overall height of the reactor – a paradigm shift.

Keywords: RCDM, Radiation, Exposure, Nuclear.

Introduction

Nuclear Power Reactors Around: Since the mid fifties 385 nuclear power reactors are operating and 83 are under constructions, totaling to 468 around the globe. In India, the number of nuclear power reactors in operation are 20; under construction are six; and planned up for future are 12; totaling 38 with capacities 4.78 GWe, 4.8 GWe, and 12.6 GWe respectively[1]. It is estimated that if the electricity produced by nuclear reactors worldwide are replaced by coal reactors the additional contributions of CO_2 worldwide would be 26000 million tons each year. The worldwide distribution of Nuclear Reactors and the net installed capacity of them and the relative percentages are given in the table-1.

This paper limits the discussion to minimize the radiation exposure to the technicians operating the reactors. Nuclear power stations are built to operate continuously as base stations, over long periods of time for many decades, controlled by neutron absorbing rods. These rods are heavy and moved vertically in and out of the reactor vessel calendria using a range of heavy duty RCDMs to start (*Karkera, 1976), operate (*Karkera, 1977), control (*Karkera, 1972), shutdown (*Karkera, 1972), trip (*Karkera, 1974) the reactor; as well as override built-up xenon poison (*Karkera, 1980, 1981). Each RCDM is designed specifically for certain functions. For one particular RCDM vertical orientation is a must and it is for Shut-Off-Rod (SOR) (*Karkera, 1974). Rest of the RCDMs are oriented parallel to SOR for engineering conveniences.

Design Trend In Practice – A Compromise: Technicians do wide ranging handling of RCDMs for reactor operation, servicing, preventive maintenance, unforeseen breakdown maintenance, health testing, timely replacements before predicted life and disposal as nuclear waste and for nuclear medicine. A sound logical philosophy for deriving design specifications of an ideal RCDM is the first basic step for protecting the service personnel from nuclear radiation. The literature is rich in various forms of solutions[2-5]. But very little has been done to circumvent the problem of reducing the exposure to nuclear radiation by reducing the mass of driver mechanism itself[6-10]. This shortcoming is generally true in few hundreds of journal papers studied, including the six papers listed above. It is true even in the case of about 35 years of project work undertaken by the author for the few nuclear research reactors of Bhabha Atomic Research Centre (BARC) at Trombay and Indira Gandhi Centre for Atomic Research (IGCAR) at Kalpakkam and also the nuclear power reactors of Nuclear Power Corporation of India Ltd. (NPCIL), India. However during this period, the numerous innovative design features recorded in 18 of his "Personal Communications" have encouraged him in undertaking ongoing research work. They are as briefed ahead.

PURNIMA-1 is India's first fast research test reactor, commissioned on 18 May 1972 in the premises of BARC. The Reactor Drive Mechanisms (RDMs) for three control rods and a reactor core; with scram provision for the later, (*Karkera, 1972) were fabricated, deployed and commissioned, all within just 10 months and the site manager was rewarded by IAEA fellowship. Work on subcritical multiplying system was undertaken in PURNIMA-4 later (*Karkera, 2001, 2003), generally in line with the Physics of Subcritical Multiplying Systems and beyond[6].

Tarapur Atomic Power Plant (TAPP) Units 1 and 2 BWRs are India's very first nuclear power reactors operating since May 1969. During 1972-'73 the sharp dipping of power output in one of them was doubted as a result of uncontrolled unnoticed discharge of secondary steam due to emergency-discharge valve remaining stuck open[9,7]. The author avoided this by instrumentation of the Secondary Steam Generators of both the reactor units using a set of thermo-wells (*Karkera, 1973). The work zone was highly radioactive, needing planning, briefing, drilling, welding and inspection. Radiation exposure of individuals was limited by distributing the work to 70 strong workforces. These thermo-wells provided the valve status to the reactor operate, who repeated the closure operations till all the valves are found closed well.

The indigenous 100 MWt DHRUVA Research Reactor is India's largest nuclear research reactor functioning since August 1985. The drive mechanism of the neutron absorbing shutoff rod (*Karkera, 1974) is used for emergency scram shutting down and it uses electromagnetic cum spring holder, unlike a Movable Coil Electromagnet Drive Mechanism[3,5]. This mechanism is contained within the stand pipe, ensuring free deck plate top face for fuelling machine operations and is the seed for the present ongoing research work. This feature was adapted to its Adjuster Rod Drive mechanism as well (*Karkera, 1980)[2,4].

The smooth zero power startup control of TAPP Units 1 and 2 need compact highly enriched uranium neutron sensors of m/s General Electric (GE) make for Source Range Monitors (SRM) and Intermediate Range Monitors (IRM). They get burnt and consumed with usage and there was no possibility of their replacement by GE and such sensors from French source are larger in size, forcing closure of these reactors. Over dimensioned French neutron sensors were management by innovative and smart design of the SRM (*Karkera, 1976) and IRM (*Karkera, 1977) Drive Mechanisms. The extra space needed for these over dimensioned sensors were swapped from the drive components, which reduced the drive mass significantly. On hinds view, this is the methodology for reducing the radiation exposure to the reactor operators, as specified in the current research work.

Experience of designing components to work inside the reactor vessel calendria was gained with CIRUS Adjuster Rod (*Karkera, 1981), PHWR Garter Spring relocation (*Karkera, 1984, 2005), mapping of FBTR Guide Tube (*Karkera, 1988) and DHRUVA Cold Neutron Facility (*Karkera, 1990)[8,10].

Industrial usage (*Karkera, 1995, 1996, 1999), medical benefits (*Karkera, 2002) and research tools (*Karkera, 2001, 2003) of nuclear radiation are many[6].

Radiation Exposure - Nuclear Accidents in Power Reactors: Since the mid-fifties of the last century, 385 nuclear power reactors have been operating around the globe producing 335 Giga Watts of electrical power table-1. Another 83 reactor are under constructions which are expected to add additional 92 Gigawatts of electrical power. What certainly is commendable and goes to the credit of the designers and operators of the power reactors, is the fact that, despite the large number of reactors operating for such long periods, (~15,000 reactor years) the number of major accidents are few. Nevertheless some minor and major accidents have taken place which cannot be ignored[1].

Radioactive Gas Leakage in the Three Mile Island Accident: A nuclear accident of INES level 5 occurred at the Three Mile Island in Pennsylvania, USA on 28th March 1979. Investigations revealed that the accident was due to operator error and failure of monitoring instrumentation. A small valve in the plumbing system opened to relieve the pressure in the reactor but failed to close. This caused the cooling water to drain off which led to the overheating of the core. The monitoring instruments provided false information which made the plant operator shut down the emergency water supply that would have cooled the reactor. The core temperature rose to 4300^{o}F. The plant designers who were contacted stepped in at this stage and controlled further damage. There was a small release of radioactive gas. No one died.

Full-blown nuclear meltdown in the Chernobyl Nuclear Accident: During a routine test, the plant's safety systems were turned off to prevent any interruptions of power to the reactor. The reactor was supposed to be powered down to 25 percent of its capacity, and this is when the problems began. The reactor's power fell to less than one percent, and so the power had to be slowly increased to 25 percent. Just a few seconds after facility operators began the test, however, the power surged unexpectedly and the reactor's emergency shutdown failed. What followed was a full-blown nuclear meltdown. The reactor's fuel elements ruptured and there was a violent explosion. The fuel rods melted after reaching a temperature over 3,600 degrees Fahrenheit. The graphite covering the reactor then ignited and burned for over a week, spewing huge amounts of radiation into the environment.

Reactors Full Melt Down In Fukushima Daiichi: The Fukushima Nuclear Disaster happened on 11th March 2011 following a major earthquake that triggered a Tsunami in the Pacific Ocean. Reactors 1, 2 and 3 suffered full melt down since the Tsunami had resulted in tripping the grid, flooding of emergency generators, and consequential failure of the coolant water circulation. Further, the efforts to use sea water to cool the reactors resulted in completely ruining the reactors. No immediate deaths, but six workers had been exposed to very high levels of radiation.

Smart Reactor Design For Radiation Exposure Minimisation: On exposure to neutron radiation, material mass gets transmuted into nuclear waste in proportion and the transmuted mass starts radiating Gamma rays. The material mass discussed here is of drive components such as gear boxes.

There are reactor personnel operating, providing preventive maintenance, repairing and servicing, and also attending after-life-disposal of these drive components. With sophistication and massiveness of these components, on approaching these drive mechanisms, the operators get exposed to Gamma radiation and the amount of Gamma dose received by them increase on successive visits. In India alone, such personnel may number at around 1Lakhs with projected 650 GWe Nuclear Reactors, by 2050. We propose a simpler lighter telescopic design of CRDM, with a longer life, with its major massive portion to be integrated with the reactor body such that they are not to be handled by the operators throughout the design-life of the reactor, reducing the Gamma radiation risk – a paradigm shift in reactor engineering. This major massive portion of the telescopic CRDM is hollow cylindrical with internal threading of either (i) a dual Worm Wheel segments of infinite radius; or (ii) a dual Rack segments. The balance portion of this telescopic CRDM is either (i) a Worm; or (ii) an array of Pinions respectively; both functioning as a rabbit. These rabbits are having the Outer Rotor Submersible Induction Motors; linked through an umbilical cord to a Variable Frequency Control unit. Through this umbilical cord the also supplies pressurized coolant; which is reactor moderator itself.

Intelligent Plant Layout - Underground Siting: The following statements by two top nuclear scientists Andrei Sakharov from Russia and Edward Teller from USA, made immediately after the Chernobyl reactor accident in April 1986.

Andrei Sakharov (Memoris, P. 612): "Plainly, mankind cannot renounce nuclear power, so we must find technical means to guarantee its absolute safety and exclude the possibility of another Chernobyl. The solution I favor would be to build reactors underground, deep enough so that even a worst case accident would not discharge radioactive substances into the atmosphere"

Edward Teller (Memoris, P. 565): My suggestion in regard to [the containment of nuclear material in case of an accident] is to place nuclear reactors 300 to 1000 feet underground …" I think the public misapprehension of risk can be corrected only by such a clear-cut measures as underground siting.

The first set of three underground reactors was set up in Russia in 1958, 1961 and 1964 in Central Siberia. Out of them, the first two were for production of Plutonium and the third one was to provide electricity and hot water to the city of Zheleznogorsk. These were water cooled uranium-graphite reactors. The turbine and the Yenisey River which supplied the water for cooling are also shown in the photographs. The next set of underground reactors came up in Europe and some details regarding these are given in the table-2. None of them have leaked any radio activity and radiation to cause any hazard to the public, even under worst accidents.

The underground reactor at Lucerne, Switzerland generated 30 Megawatts of heat and 8.5 Megawatts of electricity with heavy water as the moderator. In 1969 the loss of coolant resulted in partial core melt down and there was heavy radioactive contamination of the cavern which was immediately sealed and not opened for a few years. There was no effect of any radioactive leak that affected the workers or the population in the surrounding areas. Later, the cavern was opened, and decontaminated.

The experiences of the European Laboratories in operating for several years Nuclear Reactors of various types underground not only confirmed the main advantage of effective shielding against radioactive fallout in case of an accident, as it did happen in one cases and the cavern effectively shielded radioactive leaks but also brought to focus how such installations can provide safety against several other features like terror attacks, air craft crashes, sabotage, vandalism etc., which are becoming more serious now a days. Such locations also provide better protection against natural disasters like Tsunamis, Volcanoes, and Earthquakes etc. There have been several large scale studies on all aspects relating to the siting of nuclear power stations underground particularly by US groups. These ideas have been discussed in several International Conferences on Nuclear Engineering; several symposia have been held exclusively to discuss the underground siting of nuclear reactors.

Bountiful Harnessing Of Clean Nuclear Energy: The power projections are discussed in "Strategy for Growth of Electrical Energy in India Document 10, August 2004, DAE", and also in the article by Dr Srikumar Banerjee, Former Chairman of DAE. There is also an excellent review article by Prof. Sukhatme, Former Chairman, Atomic Energy Regulatory, in which he has discussed the relative merits and demerits of the energy options before us. There are many who are optimistic about breakthroughs in Solar Energy. Prof. B.N. Karkera himself is promoting 90% efficient 'Solar Bio Electricity' for domestic lighting by peddling dynamo for health, free of tariff and with nominal investment by Electricity Boards for the benefit of remote isolated population for whom it is impractical to reach electrical supply for decades and for the benefit of poor labor class for diverting the saved electricity to small scale industry.

Results and Discussion

The results of the above review is generally reflected in the Indian three stage strategy for achieving large scale increase of Nuclear Power production. Incidentally, it was spelled out by the farsighted Dr. Homi Bhabha, based on India's strengths and weaknesses, spelt out below.

Facts Dictating Stage-1: India has limited U and is used in this stage, in which U^{235} generates fission power while a tiny fraction of the balance fertile U^{238} transmutes into a new fissile material Pu^{239}. U^{235} is natural fissile material and the rest 99.3% is fertile material U^{238}. India uses this process in Pressurised Heavy Reactors (PHWRs) for best possible thermal neutron economy. This is Thermal Reactor using Heavy Water (HW) as moderator to thermalise the fission neutrons and as coolant to transport the thermal energy from the fuel elements. With the perfection of HW technology, India has mastered Stage-1 by using well its strengths; which will wind-up with U. The limited quantity of transmuted Pu^{239} and large quantity of depleted U are essential for the next stage-2.

Facts Dictating Stage-2: India has started building Fast Breeder Reactors (FBRs) using limited quantity of transmuted Pu^{239} for (i) highest yield of fission neutrons; (ii) fast neutron economy; (iii) consequential breading of its own fuel Pu^{239} from depleted U; and (iv) later breading another fissile material U^{233} from fertile Th^{232}; while generating fission power from fissile Pu^{239}. FBRs use difficult liquid sodium technology to transport the thermal energy from the fuel elements, now mastered in India. This stage will be wound-up eventually with the depletion of the supply of depleted U as a consequence of closing of Stage-1. The bread U^{233} is the fuel for the next Stage-3.

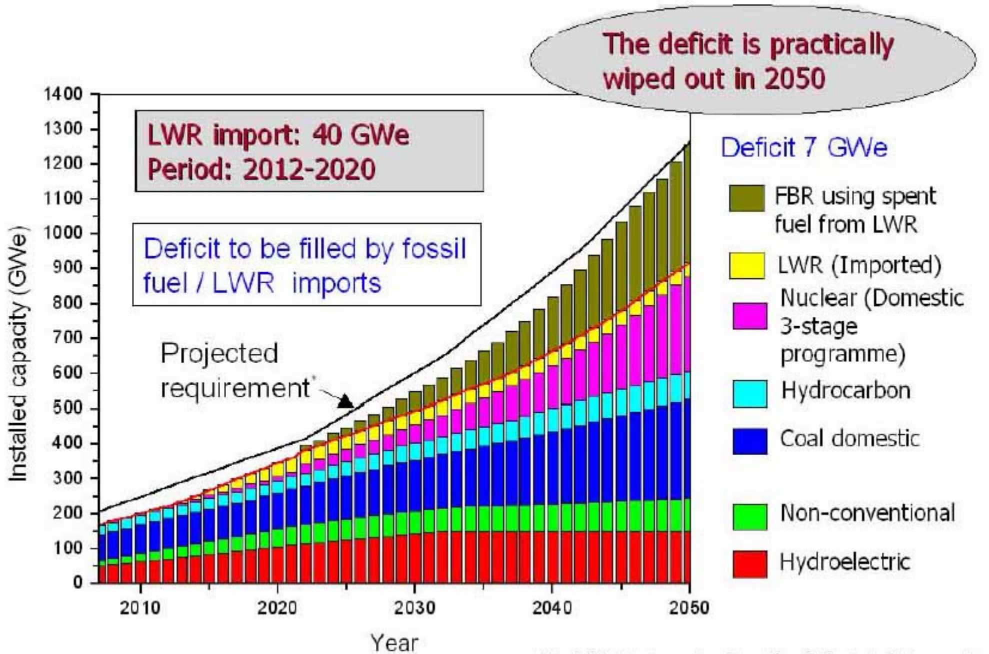
Facts Dictating Stage-3: India has designed AHWR, a prototype of Stage-3 thermal breeder reactors (TBR). U^{233} is bread from fertile Th^{232}, initially in FBR (Stage-2) and continued in TBR (Stage-3). TBR is simpler and bread their own fuel U^{233}. They will be further safer as ADS reactors to follow.

Table-1
Nuclear Reactors Operating in the World (*Sreekantan, Karkera, 2012)

Country	No. of Reactors	Net Installed Capacity (MWe)	Percentage of Nuclear Power
Spain	8	7,450	22.9
Sweden	10	8,958	51.8
China	11	8,438	2.2
Ukraine	15	13,107	51.1
Germany	17	20,470	32.1
India	20	4,780	2.9
Canada	18	12,577	15.0
United Kingdom	19	10,097	19.4
Korea, Republic	20	17,647	37.9
Russian Federation	31	21,743	15.6
Japan	53	45,957	29.3
France	59	63,260	78.1
USA	104	1,00,683	19.9

Table-2
Underground Nuclear Reactors outside Russia (*Sreekantan, Karkera, 2012)

Name and location	Size	Purpose	Configuration/Location		Status	Reactor Chamber Dimensions (feet)
			Turbine Generator	Reactor		
Halden Norway (BHWR)	25 MWt	Experimental	None	Rock Cavern	Operational (1959-2020)	98’ long 85’ high 33’wide
Agesta Stockholm, Sweden (PHWR)	80 MWt/ 20MWe	Heat Production	Above ground at grade level	Rock Cavern	Operated from 1964-1974. Shutdown since 1974.	88’ long 66’ high 54’wide
Chooz Ardennes, France (PWR)	266 MWe	Power	Above ground	Rock Cavern	Operated from 1967-1991. Shutdown since 1991.	138’ long 146’ high 69’wide
Lucerne, Switzerland	30 MWt/ 8.5 MWe	Test Reactor	Rock Cavern	Rock Cavern	Operated from 1968 to 1969. Shutdown since 1969.	--



* - Assuming 4200 kcal/kg

*Ref: "A Strategy for Growth of Electrical Energy in India", document 10, August 2004, DAE

Figure-1
Strategies for Long-Term Energy Security (*Sreekantan, Karkera, 2012)

Conclusion

However, dark clouds have appeared in recent years, which, if not satisfactorily dispelled, may impede the progress of nuclear power generation in the whole world for a reason beyond the nuclear accidents. This reason is addressed by the first author B. Narayana Karkera, on a social front to create public demand to house nuclear power stations in their own backyard on economy front.

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