Development of innovative proposals for improving the environmental situation in the Novovoronezh NPP region using the comparative analysis of waste management at Kudankulam NPP in India and Bruce NPP in Canada

M G Dobrosotskikh¹, D I Emelyanov, V R Kuznetsov, E V Rodina
Department of technology, construction organization and realty’s expertise, Voronezh State Technical University, 20 let Oktjabrja, 84, Voronezh, 394006, Russia
E-mail: dobrmax@yandex.ru

Abstract. Paper provides a comparative analysis of three nuclear power plants: Novovoronezh NPP in Russia, Kudankulam NPP in India, and Bruce NPP in Canada. The basic parameters (site plan, biosphere diversity, types and capacity of reactors, amount of electricity generated and its cost) are compared. Types of waste generated at all three nuclear power plants and methods of their treatment are analyzed. Brief overview of some of the security systems used at these power plants is conducted. On the basis of comparative analysis, proposals for improving the environmental situation in the Novovoronezh NPP region (e.g. improvement of the wastes management) are made, with the proposal of nuclear fuel cycle scheme enhancement.

1. Introduction
In the today’s world the use of atomic energy is an integral part of any developed country’s lifestyle, but generation of electric power this way has a damaging impact on the environment and human health. In this regard, each country has developed its own policy to minimize the adverse effects of atomic radiation on the biosphere. In this context one of the important measures is assigned to waste management.

The comparative analysis of waste management presented in this paper is based on the data from three nuclear power plants, namely: Novovoronezh NPP in Russia (Concern Rosenergoatom), Kudankulam NPP in India and Bruce NPP in Canada. The main sources of information for the comparative analysis are [6,5,23]. The choice of these particular NPPs is justified by the fact that the Novovoronezh NPP (here and after NV NPP) is one of the oldest nuclear power enterprises in the Russian Federation (the largest producer of electrical energy in the Voronezh Region) became the first power plant in contemporary Russia with the rector of the new generation VVER-1200 [32]. The Indian Kudankulam NPP was chosen because at the moment it is named to be the largest Russian-Indian economic cooperation facility. Since October 2002, the leading Russian design organizations and research centers are taking part in construction of Kudankulam NPP (e.g. the chief designer is Moscow Institute Atomenergoproekt, the general designer is Gidropress office, the scientific head is Kurchatov Institute [19]). In total, more than 100 Russian enterprises are involved in the Kudankulam project (including Voronezh architectural and construction offices). The Canadian Bruce NPP was
chosen due to the fact that numerous Internet resources name it to be the one of the most powerful power plants in the world. Moreover, Canadian legislation has strict regulations and guidelines for ensuring the safety of its nuclear power plants, enforcing continuous environmental monitoring and ecological improvement in NPPs regions.

The main objective of the comparative analysis of the three above-mentioned NPPs is the methods of their waste management with the aim of identification of the positive and negative components of the technological processes applied, which affects the safety of strategic atomic infrastructure and the surrounding biosphere respectively.

The site of NV NPP (Fig. 1) is located on the left bank of the River Don, 40 km south of Voronezh and 5 km south of Novovoronezh – the city with the estimated population of 31.5 thousand people (in 2018), most of which works and lives in close proximity to the nuclear power plant.

![Topographical view of the Novovoronezh NPP](image)

**Figure 1.** Topographical view of the Novovoronezh NPP [11]

NV NPP (one of the oldest power plants in Russia) has been built in three phases, namely NPP-1, power units: 1 (VVER-210 in 1964), 2 (VVER-365 in 1969); at the NPP-2, power units 3 and 4 (VVER-440 in 1971 and 1972), at the NPP-3, power unit 5 (VVER-1000 - in 1980). In 1984, after 20 years of operation, the power unit 1 was decommissioned, following by the decommission of power unit 2 in 1990 and power unit 3 in 2016. Since 1995, NV NPP has been gradually upgrading its power units to bring them in line with modern security standards. From 2007 to March 22, 2019, two power units (6 and 7) of the new generation “3+”, with the most powerful reactor facility in today’s world (VVER-1200) were built at the site of the NV NPP [32]. This epoch-making event allowed Russia to take the leading role in the atomic high-tech industry.

At the moment, the NV NPP has three power units (4, 5 and 6 (in commercial operation since 2017), with the reactor of the 7th unit being brought to the minimum controlled power level on March 22, 2019 (Fig. 2). The VVER-1200 reactor is an evolutionary project that emerged from the VVER-1000 options, which were built for foreign customers in the 1990s and 2000s (e.g. Bushehr NPP, Kundankulam NPP, Tianwan NPP).

To construct the VVER-1200, each reactor parameter of VVER-1000 has been slightly improved with many modern technological safety systems introduced to reduce the likelihood of radiation leak beyond the hermetic dome reactor compartment (containment) in any possible accidents. The reactor uses a passive heat removal system from the reactor, a passive system for the catalytic removal of hydrogen and a core melt trap. The double containment shell, in which the inner shell prevents the leakage of radioactive substances in case of accidents and the outer shell resists natural and man-made influences (such as tornadoes or the fall of an aircraft) became another innovative feature of the new reactor. VVER-1200 is distinguished by increased power (by 20%) with approximately the same
equipment size, a service life of 60 years, the ability to maneuver power in the interests of the power system, high capacity factor (installed capacity utilization factor), the ability to work for 18 months without fuel overload and other improved specific indicators.

The Kudankulam NPP (located in the south of the Indian state of Tamil Nadu, whose capital (and the fourth largest city in India) is Chennai (formerly Madras) is being built as part of the Russian-Indian agreement from November 20, 1988 and its addendum dated June 21, 1998 year [19]. The customer is the Indian Atomic Energy Corporation. In the period from 2002 to 2013, 1 and 2 power units with VVER-1000 reactors with a total capacity of 2000 MW has been built (Fig. 3). The 3rd and 4th power units of the Kudankulam nuclear power plant are scheduled for launch in 2020 and 2021, respectively [28].

Figure 2. Actual view of Novovoronezh NPP [20]

Figure 3. Actual view of Kudankulam NPP [17]

For construction of the Kudankulam NPP dry and barren land has been acquired, however, its location on the very shore of the oceanic waters (Fig.4) possess a certain threat to the marine life. The size of the nearby resident population is 12 thousand people. In 2004, in the immediate vicinity of the power plant (1500 m), a small seaport has been built with the purpose to eliminate the risk of damage during transportation of components coming from Russia and nuclear fuel [8].
Figure 4. Topographical view of Kudankulam NPP from above [15].

The Bruce nuclear power plant is located on the eastern shore of Lake Huron, about 18 km north of Kincardine and 17 km southwest of Port Elgin in Bruce County, Ontario, and covers an area of 932 hectares (2,300 acres) (Fig. 5).

Figure 5. Topographical view of NPP "Bruce" from above [12].

In close proximity to the station the agricultural, recreational and rural residential areas are located. The population size is 65 thousand people. Recreational land use includes Inverhuron Park with residential cottages in the village of Inverhuron (south of Bruce Power) and in the Baie du Doré / Scott Point area (north of Bruce Power). It should be noted that over the past 50 years the nuclear energy was safely generated at the plant site, first through the Douglas Point NPP (1968-1982), and then through the Bruce A and B NPPs, which were introduced into operation from 1977 to 1979 and from 1984 to 1987, respectively.

At the Bruce power plant, there are 8 reactors of the CANDU type (Canada Deuterium Uranium) (Fig. 6) - a heavy-water nuclear water reactor produced in Canada. CANDU uses heavy water as a moderator, which makes it possible to use ordinary natural uranium as a fuel. Unlike most water-cooled reactors (for example, VVER), the CANDU is a channel-type reactor, which allows replacing the used fuel with fresh fuel without stopping the reactor. The primary coolant can be both heavy and ordinary water.
Table 1 presents the site plan summary of three power selected plants (e.g. comparison by terrain type, number of inhabitants and diversity of flora and fauna). From the comparison presented it is clear that all the power plants are located close enough to the residential areas. A wide range of biological diversity both on land and in water presented around the NV NPP and “Bruce” power plants. “Kudankulam” in India is located on a comparatively deserted and biologically poor land area, but it has a direct impact on the biosphere of the ocean, located directly in its water basin. In 2011, Tamil Nadu residents have massively protested against the construction of NPP, among them were the local fishermen, who expressed the concern that the water temperature would rise due to the power plant’s operation and the fish would leave these places [27]. This once again confirms the need for the careful monitoring and control and waste management.

Table 2 presents the comparative power capacity characteristics of the three NPPs.

**Table 1.** Site plan summary of the three selected NPPs.

| Terrain type          | NV NPP Field/Forest/City | Kudankulam NPP Wasteland | Bruce NPP Forest/City |
|-----------------------|--------------------------|--------------------------|-----------------------|
| Waters around         | River                    | Ocean                    | Lake                  |
| Distance to the settlement, km | 5                     | 8                        | 0                     |
| Population size, thousand pers. | 31                    | 12                       | 65                    |
| Variety of flora      | average                  | low                      | high                  |
| Variety of fauna      | average                  | low                      | high                  |
| Variety in waters     | average                  | low                      | high                  |

**Table 2.** Comparative power capacity characteristics of the three NPPs.

|                     | NV NPP          | Kudankulam NPP | Bruce NPP |       |
|---------------------|-----------------|----------------|-----------|
| Number of active power units | 3               | 2              | 8         |
| Reactor type        | VVER-1200       | VVER-1000      | CANDU 750, 791 |
| Most powerful reactor (Net power), MWt | 1114            | 917            | 817       |
| Total capacity, MWt | 2449            | 1834           | 6258      |
2. Methods of waste management and emissions.

2.1. Waste management methods at Novovoronezh NPP

Waste at nuclear power plants are divided into radioactive (RW) and non-radioactive waste (NRW). RW is divided into solid (SRW) and gaseous (GRW). During the operation of the plant, as well as the decommissioning of old power units, the generated solid RAW is collected, reprocessed and stored in temporary storage facilities before being transferred to specialized organizations for disposal. For the primary collection of SRW, tripods and supports are used in which plastic or kraft bags are inserted, along with plastic or kraft bags being used in the in the form of self-packing, which after filling are loaded into collection containers. The drainage collection system of organized and unorganized leaks from technological systems and the reactor compartment equipment, and special water treatment, is designed to receive and pre-clean the collected water from mechanical impurities for subsequent processing in evaporation plants.

For dealing with GRW, the existing ventilation system of the NV NPP units provides:
- means to ensure fire and explosion safety, including means for prevention of flame spread and combustion products through air ducts and ducts;
- means for regulating the performance of the blower devices (gas blowers, ventilation units, fans, compressors, etc.);
- redundancy of filtering and absorbing elements of equipment with a chain to ensure the replacement or regeneration of filters without stopping cleaning;
- local air cleaning, removed from the places of possible formation and accumulation of GRW (e.g. from repair or dismantling jobs).

Technical characteristics of fans in the supply and exhaust systems are chosen in a way so that during the normal operation of ventilation systems, the total flow of exhaust air exceeds the air flow. Air intake by air supply ventilation systems is carried out from the roof of the machine room through air supply shafts. The air is cleaned of dust by fabric filters. The air that is removed from controlled access zone premises by the exhaust ventilation systems is emitted into the atmosphere through a ventilation pipe with a height of 120 m and a mouth diameter of 3 m.

NRW at the NV NPP are divided into 5 hazard categories, which are:

Hazard Category 1 includes: used mercury-containing fluorescent lamps, metallic mercury (drained from mercury-containing devices), mercury thermometers (which are not reused, but transferred to enterprises have the appropriate disposal license).

Hazard Category 2 includes: waste batteries with non-drained electrolyte, spent battery fluid (which is transferred to specialized waste treatment plants or other organizations have the appropriate license for this type of activity).

Hazard Category 3 includes: waste oil, wiping oily rags and greasy gloves, oily soil, ferrous metal (copper); Waste oil products are sent for processing and use in organizations that have a license to carry out activities in the field of hazardous waste management. Used oil filters are placed in special metal containers in open areas and transferred to enterprises that have the appropriate license for the right to handle this type of waste. Non-ferrous and black scrap metal is collected in containers or piles in designated areas (ferrous scrap is stored separately from non-ferrous scrap metal) and subjected to radiation monitoring.

Hazard Category 4 includes: used car tires, slag wool, and household garbage. Spent car tires are accumulated at a special site, then transported to a company that has a license to collect and process car tires.

Hazard Category 5 includes: small fractions of ionexchange resins and iron oxides (sludge after neutralization unit and chemical water treatment plants), black scrap metal, non-ferrous scrap metal (aluminum), sediment from vehicle washing, cost estimation paper documentation from industrial areas, rubber hoses, abrasive dust from grinding and grinding tools and equipment, stubs of electrodes, construction waste (broken brick, plaster, concrete pieces, glass, etc.), glass wool, coastal pumping sludge, hay, wood waste from the cutting of tree branches, food waste of canteens. All this waste is
accumulated at the designated locations in the NPP units, and then disposed to municipal dump (within its stated disposal limits) on enterprise that have the appropriate disposal license.

During waste loading and transporting, conditions are provided to exclude their loss and dusting (the filled body is covered with tarp).

All RW and NRW exported from the territory of the NV NPP are monitored for radiation control. Material passes must be made for each waste removal carry out from the territory of the NV NPP, with indication of waste type and its total quantity in cubic meters.

2.2. Waste management methods at Kudankulam NPP

RW management at Kudankulam NPP focuses on the effective reduction of radioactivity (decontamination) and minimization of secondary waste, where the promising new technologies introduced include the synthesis and use of specific sorbents (inorganic, magnetic and biological technologies), the use of electro-oxidative methods for organic waste, cryogenic distillation to separate radionuclides from waste gases, liquid-based membranes, etc. [5]. Facilities for the treatment of solid radioactive waste (SRW) are equipped with equipment for separation, repackaging, compacting, incineration and embedding of radiation sources.

To eliminate GAO (volatile radionuclides such as iodine, ruthenium, etc.) adsorbers are used. All waste gases pass through highly efficient particulate filters, which are designed to be more than 99.9% efficient for submicron-sized particles. Leakage of radiation waste at this Indian NPP is minimized, due to the fact that the main cooling water circuit at the NPP is a closed loop, any radioactivity resulting from the fuel enters the filters and ion exchangers, thus does not pose any danger to the facility or its personnel (without any chance of entering into surrounding biosphere). Other liquid waste from the technological processes evaporates with a mildly condensate remaining, which is recyclable at the plant and safe for disposal. If any SRW is contaminated with radioactivity, it is collected and incinerated or compressed to reduce its size; then the waste is conditioned by fixing it in cement concrete. In a few years they will be considered for burial in a near-surface repository (if enough time passes for the decay of short-term radioactivity) [5].

2.3. Waste management methods at Bruce NPP

The following types of RW and NRW are identified at the Bruce NPP [6]:

- Hazardous RW (oils, chemical lighting lamps and ballasts (some of them are recycled)
- Recycled NRW (glass, plastic, metal, cardboard, paper, wood, batteries and electronics)
- Organic NRW (compost)
- Radiological RW
- Waste for NRW landfills (for those items that are neither hazardous, nor recyclable, neither organic nor radiological).

To minimize the amount of waste sent to landfills every day, the Bruce NPP has implemented a number of waste management methods, such as:

1) Sending to recycling and then recycling of hazardous waste (chemicals, oils, batteries and fluorescent lamps). Pick up is conducted by a number of contractors with whom the NPP cooperates and who are responsible for the environmentally safe transportation, recycling, waste disposal, etc.

2) Minimization of recyclable waste by applying the principles of reduction, reuse, recovery and recycling.

3) Composting of organic waste, including food, paper towels and biodegradable containers.

4) Managing and minimizing the amount of radiological waste through effective materials management, decontamination and separation, with the use of the reduction, reuse, recycling and recovery principles where possible. RW is handled in a safe, environmentally responsible manner that takes into account the ALARA principle (As Low As Reasonably Achievable), which provides for maintaining as low as possible and attainable levels of both individual (below the limits set by current standards) and collective doses of radiation, taking into account social and economic factors.

Table 3 provides comparative data on waste disposal and treatment at three NPPs.
Table 3. Comparative data on waste disposal and treatment at three NPPs.

|                        | NV NPP | Kudankulam NPP | Bruce NPP |
|------------------------|--------|-----------------|-----------|
| Total amount of waste treated % | 5.4%   | Data is inaccessible | 62.2%     |
| Independent waste recycling | Low level | Low level | High level |
| Reuse/recycling of waste by other organizations | Yes | Yes | Yes |
| Reuse of recycled materials | Low level | Low level | High level |
| Total amount of waste, tones | 6830   | Data is inaccessible | 1967      |

Table 4 provides comparative data on the radiation situation and the quantity / cost of electricity in the regions of NPPs.

Table 4. Data on the radiation situation and quantity / cost of electricity in the regions of power plants

|                        | NV NPP | Kudankulam NPP | Bruce NPP |
|------------------------|--------|-----------------|-----------|
| Maximum radiation background, mSv/year | 0.78   | 0.042           | 0.00167   |
| Presence of reactor safety systems that do not require operator intervention in an accident | Yes | No | No |
| Presence of modern monitoring systems | Yes | Yes | Yes |
| Population size of the region receiving electricity from NPP, mil. persons | 2.34 | 72.1 | 14.3 |
| Total capacity of reactor, MVt (see Tab..2) | 2449   | 1834           | 6258      |
| The amount of electricity per person, KW/hour per person | 1.05   | 0.25           | 0.44      |
| Average cost of KW/hour, USA cents | 5      | 5              | 13        |

3. Conclusions
From the results of the comparative analysis, it is clear that in all countries, security issues are taken seriously, however, despite the many similarities in the waste treatment methods, there are also some differences.

Unfortunately, all measures for the protection of the environment and safety at NVNPP and Kudankulam NPP are only mandatory, indicated by the regulatory documentation and legislation of the countries, but not proactive.

The particular difference between the Canadian Bruce NPP and the other two is the highest priority in ensuring safety in the first place (this applies to both employees and the environment). This NPP constantly seeks to reduce its emissions by upgrading the equipment for radiological monitoring of wastewater. The transition has been made to the use of NuclearIQ, a laboratory information management system that will provide maximum quality assurance and quality control when recording data obtained as a result of sampling and analysis. Furthermore, annual testing of monitoring capabilities is being carried out, along with the Canadian Nuclear Safety Commission (CNSB) conducting its independent environmental monitoring that analyzes samples near the Bruce power plant to confirm the safety of the power plant. Also, due to the increased attention to the issues of reducing the amount of materials used and efforts to separate materials, Bruce NPP managed to significantly increase the amount of material sent for recycling, rather than throwing it away as waste, which is another cardinal advantage over the other NV NPP and Kudankulam NPP.
Table 3 clearly shows that the total waste at the Bruce NPP is more than 3 times less (3.47 times) than the total waste of the NV NPP, while the capacity of the Canadian nuclear power plant is almost 2.5 times more. Most importantly - more than 62% of the total amount of waste at NPP Brus is recycled, which is 11.5 times more than at NV NPP. The reduction of radioactive background data at three NPP to one unit of measurement (the readings of the background radiation at the Russian NPP presented in Micro X-rays / hour, at the Indian NPP in mSv/year, and at Canadian NPP in Millierv / year (which is 1000 times less than 1 MicroSiev er ) allowed to find out that the radiation background at NV NPP is 18.5 times higher than at Kudankulam NPP and 467 times higher than at Bruce NPP. However, Russian legislation states that these figures do not exceed the allowable values and natural background.

At present, the NV NPP uses an open nuclear fuel cycle scheme and waste disposal methods (Scheme 1).

![Figure 7. The existing fuel cycle and waste management at the NV NPP](image)

Considering the comparative analysis conducted the more efficient scheme is proposed for improving waste management at NVNPP (Scheme 2).
Effective proposals for improving waste management at NV NPPs can be:

1) Reduction to waste-free production, i.e. sending all non-radioactive waste for processing for possible subsequent use in various fields (agriculture, medicine, manufacturing, etc.).

2) Reprocess of RW for possible subsequent re-use (stages of closed NFC include exposure of spent nuclear fuel on the NPP territory for 3–10 years; temporary controlled storage of SNF in autonomous storage facilities at the radiochemical plant, processing of SNF with separate (or total) fissionable nuclides from it and fission products of commercial interest, solidification and disposal of waste).

Reprocessing of the nuclear fuel spent provides certain economic benefits, restoring unused uranium and drawing into the power industry the accumulated plutonium. This reduces the amount of highly radioactive and hazardous waste that must be properly stored, which also has a certain economic and environmental feasibility. The spent nuclear fuel, containing about 1% plutonium, considered to be a very good nuclear fuel, which does not need any enrichment process, it can be mixed with depleted uranium and supplied as fresh fuel assemblies for loading into the reactors. It can be used for loading and in breeder reactors (covertors and breeders).

Other NRW generated at NPP should be send to storage facilities, using decontamination measures, and then recycled (instead of many years of burial). Moreover, to minimize the amount of stored waste at NV NPP it is recommended to exclude the disposal of radioactive waste, increase the types and volumes of recyclable materials, and apply the waste treatment, using third parties services only for the disposal of residual waste (to minimize waste transportation), respectively, thereby improving the ecological situation in the region.
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