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Research Article

Site Related Factors and Design Criteria Considered in the Architectural Design of Nuclear Power Plants

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Abstract This paper aims to study the site related factors and design criteria considered in the architectural design of nuclear power plants. It is focusing on the architectural design and components of nuclear power plants. This paper aims also to study the architectural principles and standards used in designing and planning and of nuclear power plants**.** In drawing up a master plan ofa nuclear power plant, the methods used in town planning should be used. These methods are centralized, linear, radial, clustered and grid. This paper aims also to study the special features of the master plan of a nuclear power plant. The buildings in a nuclear power plant should be segregated according to the levels of radioactivity in each one of them. There are cold areas, warm areas and hot areas. Kaiga nuclear power plant in India and Angra nuclear power plant in Brazil have been chosen as examples. This paper presents design analyses for these nuclear power plants that include design theory (linear design and radial design) and positive & negative aspects of these designs .The paper proved that the radial design concept is the best among all the design concepts.

Keywords Site related factors, design criteria, architectural design, nuclear power plants.

1. Introduction

A nuclear power plant is a thermal power station in which the heat source is a nuclear reactor. As is typical in all conventional thermal power stations the heat is used to generate steam which drives a steam turbine connected to an electric generator which produces electricity [1]. Electricity was generated by a nuclear reactor for the first time ever on September 3, 1948 at the X-10 Graphite Reactor in Oak Ridge, Tennessee in the United States, and was the first nuclear power station to power a light bulb [2-4]. The second, larger experiment occurred on December 20, 1951 at the EBR-I experimental station near Arco, Idaho in the United States. On June 27, 1954, the world's first nuclear power station to generate electricity for a power grid started operations at the Soviet city of Obninsk [5]. The world's first full scale power station, Calder Hall in England opened on October 17, 1956 [6].As of 23 April 2014, the IAEA report there are 435 nuclear power reactors in operation [7] operating in 31 countries [8]. Nuclear power stations are usually considered to be base load stations, since fuel is a small part of the cost of production [9].

2. Components of a Nuclear Power Plant

The conversion to electrical energy takes place indirectly, as in conventional thermal power stations. The fission in a nuclear reactor heats the reactor coolant. The coolant may be water or gas or even liquid metal depending on the type of reactor. The reactor coolant then goes to a steam generator and heats water to produce steam. The pressurized steam is then usually fed to a multi-stage steam turbine. After the steam turbine has expanded and partially condensed the steam, the remaining vapor is condensed in a condenser. The condenser is a heat exchanger which is connected to a secondary side such as a river or a cooling tower. The water is then pumped back into the steam generator and the cycle begins again [10].

The nuclear power plant consists of:
(1) Nuclear Reactor
(2) Control Building
(3) Turbines Building
(4) Cooling Towers
(5) Services Buildings
- Office Building
- Medical Research Center

(6) Nuclear and Radiological Waste Storage Building
The activities and facilities included in a nuclear power plant put constrain on the design aspects which should assure the safety for people and environment. In these plants protection against hazards of ionizing radiations, is one of the basic duties of the administrations and the workers. The nuclear safety is an objective to protect the public and the environment from the radiological consequences of radioactive releases due to accidents or due to normal operation.

3. Site Related Factors and Design Criteria Considered in the Architectural Design of Nuclear Power Plants

(1) Topography and levels.
(2) Climatic factors.
(3) Water sources.
(4) Main function of the nuclear power plant.
(5) Visual concept.
(6) Positive impact effects.
(7) Negative impact effects.
(8) Natural environmental systems and preservation of the environment.
(9) Flexibility and ease of movement in accordance with the requirements of IAEA.
(10) Radiation protection.
(11) Dominant thought.
(12) Reactor space site.
(13) Idea of design.
(14) Design concept.
(15) Positive aspects of the design.
(16) Negative aspects of the design.
(17) Dominant character.

4. Architectural Principles and standards used in planning and designing of nuclear power plants

The architectural principles and standards of nuclear facilities differ from other facilities. The nature of the radioactive material to be handled and the type of work to be carried out in the facility will determine the planning and designing of the facility.

4.1 General Planning of nuclear power plants

The main problem when considering the master plan for a nuclear power plant is to provide effectively for future expansion. The nuclear power plant site should not be located in or near a heavily built-area. Ideally, a nuclear power plant is best situated in rural or semi-rural districts in which a certain degree of isolation may be achieved. In these districts extra free space around the plant should be available for future expansions.

In drawing up a master plan the methods used in town planning must be used. These methods are [11]:

(1) Centralized:
It consists of a central dominant space about which a number of secondary spaces are grouped.
(2) Linear:
It consists of a linear sequence of repetitive spaces.
(3) Radial:
It consists of a central space from which linear organization of space extends in a radial manner.
(4) Clustered:

It consists of spaces grouped by sharing of a common visual relationship.

(5) Grid:

It consists of spaces organized within the field of a structural or other three dimensional grid.

Different aspects should be considered in the master plan of nuclear power plants. Traffic routes have to be established. Areas must be set aside for each of the buildings of the plant, large enough to provide for growth. The central focus is the nuclear reactor building.

4.2 Special features of a nuclear power plant master plan

The buildings in a nuclear power plant should be segregated according to the levels of radioactivity in each of them. The radioactive buildings designed on the system of segregation should be planned from Cold to Hot areas. The types of buildings to be contained in each area are [11]:

(1) Cold areas should contain Control Building, Services Buildings (office building and Medical Research Center), Turbines Building, Cooling Towers and Fire Station.

(2) Warm areas should contain buildings for experimentation at low or warm level of radioactivity and should contain low level laboratories and mechanical workshops. Physics and chemistry laboratories should also be in these areas.

(3) Hot areas are for experimentation at high level of radioactivity. Nuclear Reactor and Nuclear & Radiological Waste Storage Building are always placed in the hot areas. These areas should also contain Hot Laboratories, Isotope Production Facilities and Decontamination Facilities.

5. Comparative Architectural Study on Two Nuclear Power Plants

5.1. Analytical Architectural Study on Kaiga Nuclear Power Plant in India

Kaiga is a city in India. The research studies Kaiga nuclear power plant. It has been established for the purpose of energy production, nuclear researches and desalination of sea water.

5.1.1. History of Kaiga nuclear power plant

In 1947, India began the nuclear program. In 1950, India began the construction of the first Indian reactor. India needs high levels of energy. India cooperated with Canada. India used the Canadian experiences. The first Indian reactor was Canadian reactor (CANDU). It is expected in 2020, Indian production of electrical energy by nuclear technology will reach 20 GW. India occupies globally the ninth position in the field of nuclear energy production. India has achieved a great success in the field of nuclear energy development. In 1974, India cooperated with China. In 2006, India cooperated with the United States of America. India has many nuclear scientists who are capable to develop its nuclear program. Until1974, India got the enriched uranium under the supervision of the International Atomic Energy Agency (IAEA). Many uranium mines have been discovered in the southern and eastern of India. So, India relied on itself in the operation of the reactors. There are more than 9 Indian reactors for energy production [12].

5.1.2 Historical overview of Kaiga city in Karnataka province [12]

(1) The nuclear power plant is located in Kaiga city in Karnataka state in the southern of India (Fig. 1). It consists of four units. In 1989, India began the construction of two units. In 1999, they were opened. In 2000, India began the construction of another two units. They were heavy water developed reactors. In 2007, they were opened. Each unit produces 220 megawatts;

(2) Kaiga nuclear power plant is located on the Indian Ocean in southwest of Bangalore city which is the capital of Karnataka state. It is one of the most important states in India;

(3) The population of Karnataka state is 55 million people;

(4) The area of the plant is 192 square kilometers;

(5) The reactor is a pressurized heavy water reactor (PHWR);

(6) Kaiga city is an industrial city with a variety of investments;

(7)This plant was designed to provide Karnataka state with high electrical energy for the development of industrial projects in the provinces;

(8) The plant was opened in 1999 and it produces 1,200 megawatts.

Figure 1: Karnataka province in India [13].

Figure 2: Layout of Kaiga Indian nuclear power plant [14].

Figure 3: The use of landscape to separate the elements [14].

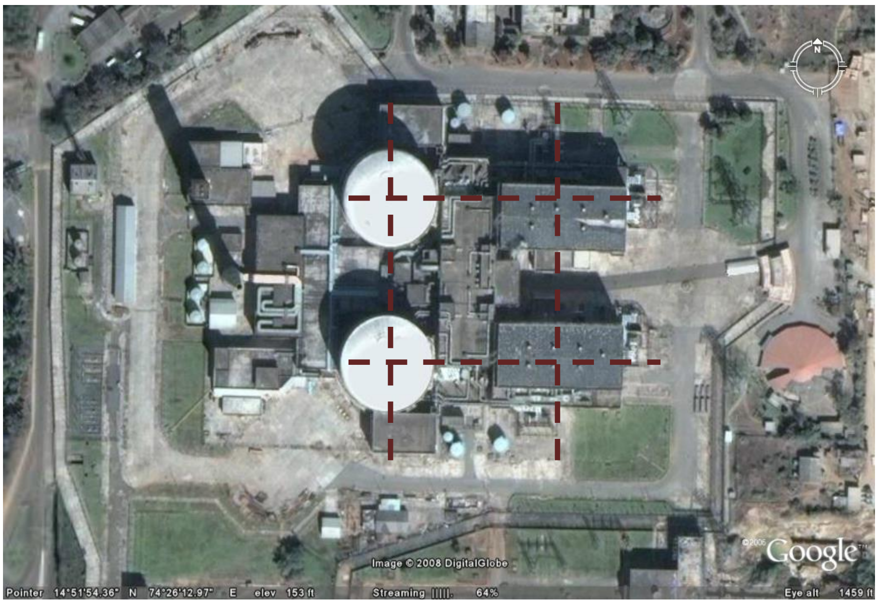


Figure 4: Linear design of Kaiganuclear power plant [14].

Figure 5: Linking between the two cylindersof the two reactors [15].

Figure 6: Perspective snapshot of Kaiga nuclear power plant, India [15].

5.1.3 Analysis of KaigaNuclear Power Plant, India

5.1.3.1 Site characteristics

(1) Topography and levels

Highly efficient in dealing with the natural contours of the site and good exploitation of the mountains.(Figs. 2 and 3).

(2) Climatic factors

Deal with climatic element in a traditional way.

(3) Water sources

The nuclear power plant depends on the Indian Ocean waters.

5.1.3.2 Main Function of the Nuclear Power Plant

This nuclear power plant is used for electrical energy production, nuclear researches and desalination of sea water.

5.1.3.3 Planning and Design Theories

(1) Layout

Linear design (Fig. 4).

(2) Visual concept

Good and distinctive visual experience characterized by the richness of elements and vocabularies (Figs. 5 and 6).

5.1.3.4 Analysis of the Urban

(1) Positive impact effects

- Site viewing the Indian Ocean (provides a water source for cooling operations);
- Site is an extension of several urban industrial and governmental projects;
- The project is a nucleus for many industrial and urban projects;
- There is a station in the plant for desalination of sea water and to provide safe drinking water for the province.
- The site is far from the residential areas.The site is surrounded by natural mountains.
- The use of trees to separate the buildings from the surrounding area.

(2) Negative impact effects

- The site is isolated from many important industrial activities in the province.
- The workers of the nuclear power plant are isolated fromany neighboring residential areas.It may leave a negative impact among the workers.

5.1.3.5 Design Standards (Fig. 7)

(1) Natural environmental systems and preservation of the environment

- Ignore the environmental aspects, and not to exploit the well featured site of the reactor, with the greatest emphasis on the functional aspects.
- Good exploitation of environmental aspects,especially the use of green elements and the seafront.
- Good exploitation of the site of the plant which is located in a low sitebetween groups of mountains.

(2) Flexibility and ease of movement in accordance with the requirements of IAEA

Obtain the flexibility factor and the ease of movement, according to the reports of International Atomic Energy Agency.

(3) Radiation protection

Achieve the protection factor from radiation, according to the reports of the International Atomic Energy Agency.

5.1.3.6 Design Criteria (Fig. 8)

(1) Dominant thought

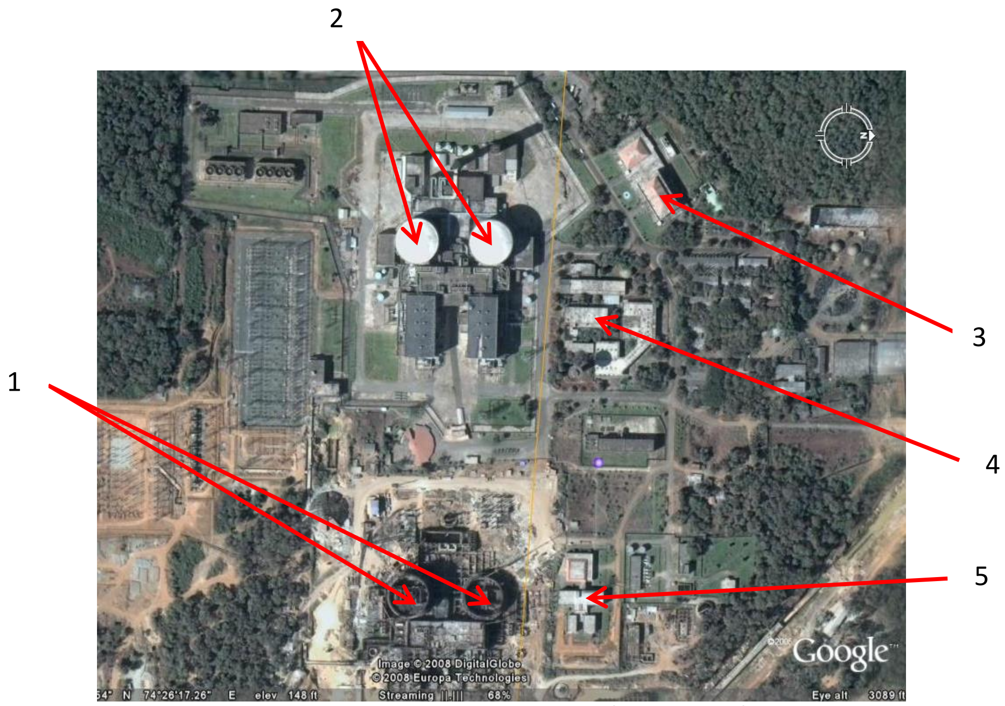
Economic-functional thought.

(2) Reactor space site

Linear relationship between the two centers of the two reactors contributes to connect the reactor buildings(Fig. 5). The buildings appear as one unit.

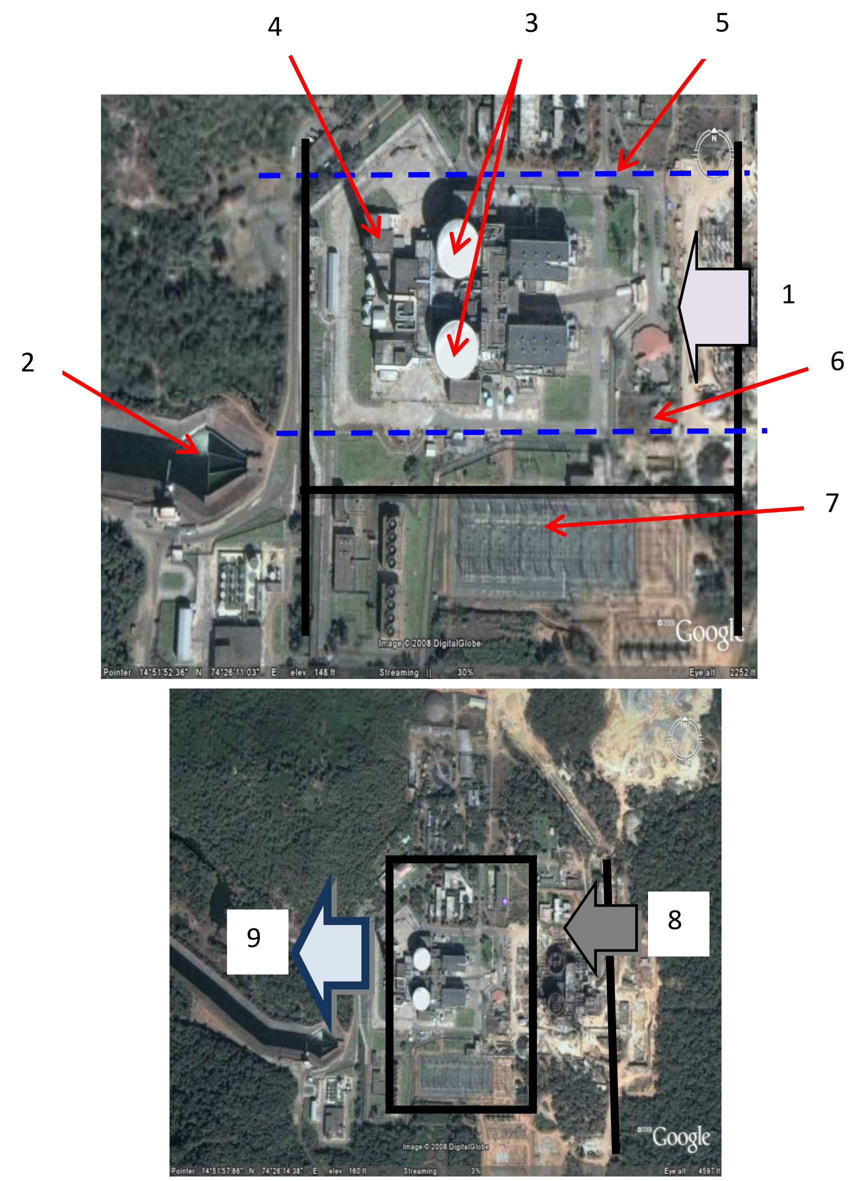
(3) Idea of design

It (linear design) is based on a main axis linking the two main cylinders of the two buildings which contain the two reactors. From the middle of this axis a main axis has been designed to connect all auxiliary buildings of the two reactors.The services and activities have been distributed by this axis on both sides.



1. The old reactor (It has been decommissioned because the work life span had finished).
2. The new reactor.
3. The waste stores.
4. The main laboratories, medical laboratories and research center.
5. The main control building for security operations.

Figure 7: Analysis of layout of Kaiga nuclear power plant, India [14].



1. The plant's main entrance.
2. The water source from the Indian Ocean.
3. The reactor buildings includea building for control and energy conversion.
4. The control building.
5. The road leading to the first reactor.
6. The road leading to the second reactor.
7. The waste storage buildings.
8. The main road leading to the reactor.
9. The Indian Ocean.

Figure 8: Linear design of Kaiga nuclear power plant, linking the centers of two cylinders to link the design of two reactors [14].

(4) Analysis of design concept

- Clarity and simplicity;
- Ease of perception;
- Spreading;

- Pheasant;
- Ease of distribution;
- Relay.

(5) Positive aspects of the design

- Good employment of the elements and components in an integrated framework;
- Interest with the insurance operations of the reactor by changing the tracks. Confirmation of the overall shape of the design by using a distinctive cylinder.
- The separation of the functional elements for each reactor, with the possibility of the complete separation.
- The interest of the use of natural elements [trees, green areas and industrial elements (tiles)] in the buildingsseparation, which contributes in the secure operations.

(6) Negative aspects of the design

- The extreme adjacency between the two reactors.

(7) Dominant character

The typical design of this type of reactors. The distinctive cylinder contributed to the uniqueness of the design.Especially, it is the only reactor in Africa.

5.2 Analytical Architectural Study on Angra Nuclear Power Plant in Brazil

Angrais a city in Brazil. This research studies Angra nuclear power plant. It has been established for the purpose of energy production, nuclear researches, medical researches and desalination of sea water.

5.2.1History of Angra Nuclear Power Plant

In 1970, Brazil decided to build two reactors (Angra 1 and 2) to provide it with its needs of electricity and the development of researchs in the nuclear field. Brazil began to develop an advanced nuclear program and launched an international tender. In 1971, the company (Westinghouse) had got a license to build the first reactor (Angra 1). The region had been selected between Rio de Janeiro city and Sao Paulo city. In 1975, Brazil decided to become self-sufficient in the field of nuclear technology. There was a cooperation protocol between Brazil and West Germany to supply Brazil with three units of energy production. Their capacity was 1,300 megawatts. In 1982, the first reactor had been opened. It produced 626 megawatts. In 2000, the second reactor (Angra 2) had been opened. It produced 1,270 megawatts(Fig. 10) [16].

5.2.2 Historical Overview of Angra City[16]

(1) The nuclear power plant is located in Angra city. It faces the Atlantic Ocean. It was located between the two largest cities in Brazil: Rio de Janeiro and Sao Paulo. Rio de Janeiro is the ancient capital of the country (Figs. 9). It is the economic capital and the second most important city after Brasilia;

(2) The type of the reactor is pressurized heavy water reactor;

(3) The nuclear power plant serves 13 millions;

(4) The nuclear power plant had been designed to supply the main cities with the electrical needs, as well as, the development of the country's nuclear ability in research, medical and technical fields;

(5) In 1975 the nuclear power plant was started. In 1982 it was inaugurated;

(6) The first unit produces 626 megawatts.

5.2.3.1 Site characteristics

(1) Topography and levels

Highly efficient in dealing with the natural contours of the site and good exploitation of the green mountains.

(2) Climatic factors

Deal with climatic element in a good way.

(3) Water sources

The reactor depends on the Atlantic Ocean waters.

Figure 9: Rio de Janeiro province in Brazil [17].

Figure 10: Layout of Angranuclear power plant, Brazil

Figure 11: The external formation of Angra nuclear power plant [18].

Figure 12: Special dome of (Angra 2) reactor and the control building [18].

Figure 13: Brazilian Angra nuclear power plant. Two snapshots from the ocean illustrate the excellent exploitation of the surrounding natural elements [18].

5.2.3 Analysis of Angra Nuclear Power Plant, Brazil

5.2.3.2 Main Function of the Nuclear Power Plant

This nuclear power plant is used for energy production, nuclear researches, medical researches and desalination of sea water.

5.2.3.3 Planning and Design Theories

(1) Layout

Radial design

(2) Visual concept

Rich and distinctive visual experience characterized by the richness of elements and vocabularies (Figs. 11 and 12).

5.2.3.4 Analysis of the Urban

(1) Positive impact effects (Fig. 13)

- Site viewing the Atlantic Ocean. It is located in an isolated area from residential areas;
- The region is characterized by distinctive landscapes;
- The site is surrounded by a mountainous region which contributes in securing the site;
- The site is surrounded by an agricultural area. The site is equipped for the establishment of several industrial areas;
- Good planning of the site, in terms of movement corridors and the coordination of the site;
- The site is located in a peninsula. It is filled with a natural landscape. This gives the site distinctive views.

(2) Negative impact effects

- Site is isolated. It is surrounded by mountains from all sides. It may leave a negative impact among the workers of the nuclear power plant;
- Lack of clarity of the main corridors in the nuclear power plant planning. It may be due to the desire to secure the nuclear power plant.

5.2.3.5 Design standards (Fig. 14)

(1) Natural environmental systems and preservation of the environment

Good exploitation of environmental aspects, as well as the permanent periodic detection on the surrounding environmental vocabularies. Lasting contribution from the reactor in the development of the surrounding environmental protection operations.

(2) Flexibility and ease of movement in accordance with the requirements of IAEA

Obtain the flexibility factor and the ease of movement, according to the reports of International Atomic Energy Agency.

(3) Radiation protection

Achieve the protection factor from radiation, according to the reports of the International Atomic Energy Agency.

5.2.3.6 Design Criteria (Fig. 15)

(1) Dominant thought

Philosophical-creative-functional thought

(2) Reactor space site

Uniqueappearance of the reactor space, the reactor space is located below its distinctive dome (Fig. 12).

(3) Idea of design

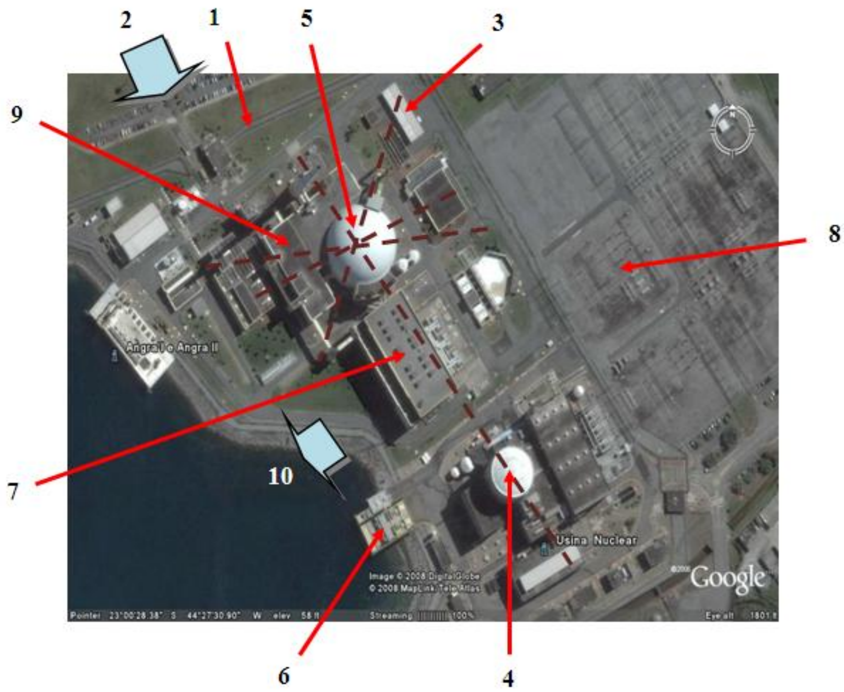
It (radial design) is based on an imaginary main center which is considered a radial center for the plant. The centers of the project spaces came from this center.There is proximity between the service buildings and the reactor core. The use is more suitable shape for the design of the reactor. In spite of the implementation of the reactor (Angra 2) after many years of the reactor (Angra 1), the centrality of the design has made the design balance is linked to the center of the larger reactor (Angra 2). The design of reactor (Angra 2) is different from the design of reactor (Angra 1). The dome was used to cover the reactor (Angra 2) core, while the cylindrical shape was used to cover the reactor (Angra 1) core.

(4) Analysis of design concept

- Proliferation;
- Ease of perception;
- Equilibrium;
- Pheasant;
- The control of the main mass and an easily realization.

(5) Positive aspects of the design

- Good employment of the elements and components in an integrated framework;
- Interest with the insurance operations of the reactor by changing the tracks. Confirmation of the overall shape of the design by using a distinctive dome that covers the reactor core to give a special uniqueness;
- Proximity of the service units from the reactor core did not decrease the strength of the design. The reactor building became a one unit;
- Change the shape of the second reactor from the first reactor, characterized the second reactor and make it visible and unique;
- Accuracy of the design, clarity of the passages, good employment of the services and the exploitation of the natural landscapes have contributed in the beauty of the design.



1. The main road leading to the plant.
2. The plant’s main entrance.
3. The main entrance building, the nuclear exhibition and the parking garages.
4. The old reactor (Angra 1) as a cylindrical shape.
5. The new reactor (Angra 2) is surrounded by its own services.
6. The station that supply the two reactors with sea water.
7. The turbines building.
8. The conversion of the electrical output to high power.
9. The nuclear research building.
10. The Atlantic Ocean direction.

Figure 14: Analysis of layout of Angra nuclear power plant, Brazil [14].

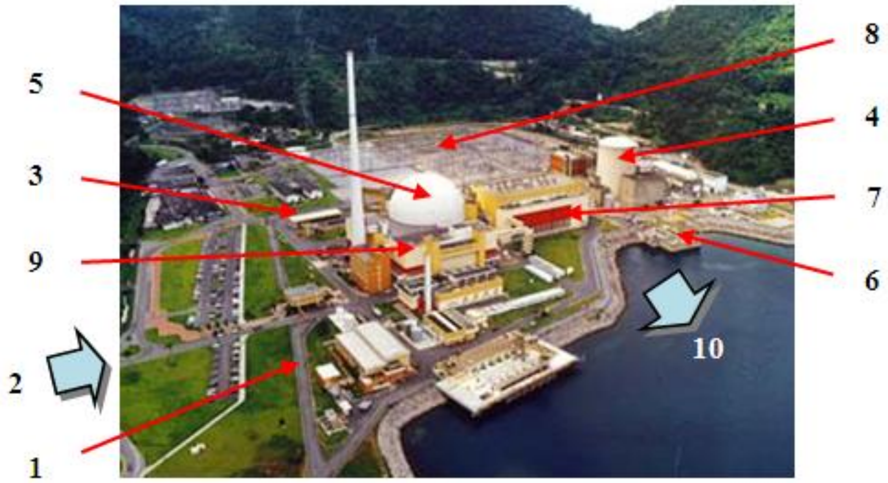


Figure 15: Analysis of perspective of Angranuclear power plant, it is completely surrounded by mountains except for the direction of the sea [18].

(6) Negative aspects of the design

- Change the shape of the second reactor from the first reactor, caused the obliteration for the design of the first reactor. It is not appearing due to the strength of the design of the second reactor (Angra 2);

No distribution of the services away from the reactor core. No exploitation of the available spaces.

(7) Dominant character

The use of a distinctive dome is to cover the center of the second reactor. The use of a cylindrical shape is to cover the first reactor. The company which implemented the first reactor is different from the second company. The site has contributed in the uniqueness and excellence of the design.

Table 1: Evaluation of site characteristics, main function, planning theory,urban factors, design standards and design criteria for the two nuclear power plants which have different design concept.

No.	**Site characteristics, main function, planning theory, urban factors, design standards and design criteria**	**Proposed Rate % Grade**	**Kaiga NPP Linear C. Grade**	**Angra NPP Radial C. Grade**
1	Topography and levels	5	3	4
2	Climatic factors	5	3	4
3	Water sources	5	4	4
4	Main function of the nuclear power plant	5	4	4
5	Visual concept	5	3	4
6	Positive impact effects	5	3	4
7	Negative impact effects	5	2	3
8	Natural environmental systems and preservation of the environment	10	4	8
9	Flexibility and ease of movement in accordance with the requirements of IAEA	5	3	4
10	Radiation protection	10	8	8
11	Dominant thought	5	3	4
12	Reactor space site	5	3	4
13	Idea of design	5	2	4
14	Design concept	10	7	9
15	Positive aspects of the design	5	3	4
16	Negative aspects of the design	5	3	4
17	Dominant character	5	3	4
	Total	100	61	80

6. Results

The nuclear power plants sites should not be located in or near a heavily built-area and are best situated in rural or semi-rural districts. Radiation safety is an important aspect in the design of NPPs. The architectural design of a nuclear power plant is a very important subject. Many factors should be taken into consideration:

- Site related factors such as topography and levels, climatic factors, water sources, natural environmental systems and preservation of the environment, etc.
- Design criteria such as visual concept, positive impact effects, negative impact effects, flexibility and ease of movement in accordance with the requirements of IAEA, radiation protection, dominant thought, reactor space site, idea of design, design concept, positive aspects of the design, negative aspects of the design, dominant character, etc.

Kaiga NPP well utilized with the surrounding area to serve the design and the general layout of the plant. Kaiga NPP has been established in good agreement with the climactic aspects according to the site nature and conditions. Functionally, the design of Kaiga NPP focused on achieving reasonable rates of spaces and dimensions.

Angra NPP has dealt well with the surrounding urban which has been exploited to serve the design. The impact of surrounding urban has been reflected on the overall shape of the plant, its vocabulary and its interaction with the surrounding area. Angra NPP has shown keen interest with proportions of the spaces, good distribution of the services and good employment of the elements and components in an integrated manner. The addition of a new reactor which has a new shape to the plant gives a spirit of excitement for the plant. Also, there is clarity, ease of movement between the activities and the buildings and keen interest with insurance operations .Angra NPP tried to be environmental friendly by establishing an environmental studies and research center inside the plant and by establishing an exhibition which explains to the visitors how the plant works for the development of the region. The treatments, the materials and the colors have been selected in Angra NPP. The compatible materials with the surrounding area have been used which give a good impression to the plant customers.

The design of Kaiga NPP and Angra NPP is innovative. The two plants have dealt accurately and carefully with the climatic elements depending on the circumstances and the nature of the site. The linear design of nuclear power plants is distinctive for its clarity, simplicity, realization, gradualism and easy distribution. The radial design of nuclear power plants is distinctive for its clarity, simplicity, realization, equilibrium and clarity of the main space as a center for the buildings. It could be observed in Table 1 that Angra Nuclear Power Plant in Brazil (radial concept) is better than Kaiga Nuclear Power Plant in India (linear concept) in terms of design and planning, taking into account the site related factors and design criteria.

7. Recommendations

It is recommended that the architectural design for nuclear power plants should be supervised by an architectural engineer experienced in architectural design of nuclear facilities. The electricity problem in Egypt can be solved by nuclear power generation from the plants to be established.

The architects are recommended to design and plan the NPPs taking into consideration the radial planning concept because it is the best with regard to radiation safety requirements. They are recommended to follow a scientific approach in designing NPPs and present ideas that achieve the desired requirement of a good design that takes all aspects into consideration. They are recommended to leave an area in the master plan of the nuclear power plant for future expansion.

The architects who design NPPs should be aware of the standards approved by the International Atomic Energy Agency. They are recommended to be able to work in close co-operation with other engineers from different departments. They are recommended to clarify the feasibility of establishing NPPs from urban, architectural and environmental terms. They are recommended to identify the suitable sites for constructing the NPPs.

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