CONCEPT DESIGN OF THE TLP-TYPE OCEAN NUCLEAR POWER PLANT

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ABSTRACT

In this study, we present a concept design of a Tension Leg Platform (TLP)-type Ocean Nuclear Power Plant (ONPP) using System-integrated Modular Advanced ReacTor (SMART), which is the most recent Small Modular Reactor (SMR) in the Republic of Korea. In order to mount SMART on the TLP platform effectively, we define design requirements and design variables, and perform a modularization and rearrangement of the SMART and other facilities. We focus on maximizing the advantages of TLP and SMART. Finally, we introduce a construction plan that covers from fabrication to installation and a new total General Arrangement (GA) of a TLP-type ONPP.

I. INTRODUCTION

The concept of an Ocean Nuclear Power Plant (ONPP) has emerged as an alternative to land-based Nuclear Power Plants (NPPs). The ONPP has some advantages including the following: (1) an infinite heat sink,[1] (2) safety from tsunamis,[1] (3) easy site selection, and (4) ample installation space. However, it is difficult to cope with sudden accidents due to low accessibility.

Various types of ONPPs recently have been proposed. In 2011, a submerged type ONPP, named Flexblue, was proposed by DCNS (a state-owned defense group) from France (Ref. 2), as shown in Fig. 1. In addition, a Gravity Based Structure (GBS)-type ONPP led by Korea Advanced Institute of Science and Technology (KAIST) in the Republic of Korea, as shown in Fig. 2, was proposed (Ref. 3).

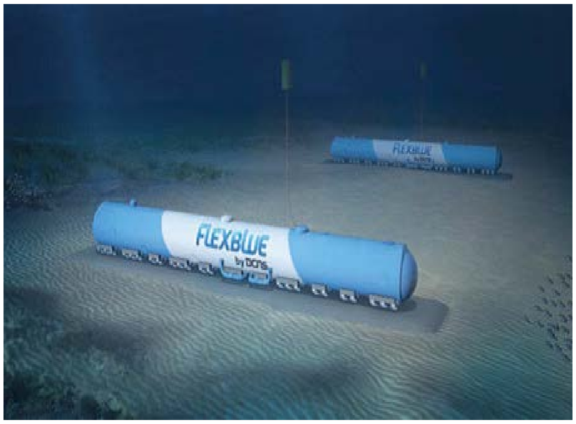

Fig. 1. Flexblue (Ref. 2)

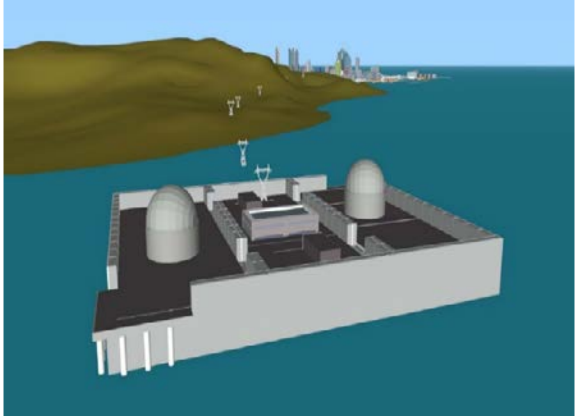

Fig. 2. GBS-type ONPP (Ref. 3)

Floating type ONPPs also have been developed. A Russian project to develop barge type floating nuclear power stations (see Fig. 3), named Akademik Lomonosov, also started in the early 2000s and it will be deployed at Vilyuchinsk in the Kamchatka region in Russia in 2016 (Ref. 4). More recently, a team led by Jacopo Buongiorno at Massachusetts Institute of Technology (MIT) has been developing a new concept for an offshore floating nuclear plant (OFNP) on a spar type floating platform (Ref. 5), as shown in Fig. 4. The features of these ONPPs are well summarized in a recent paper.[6]

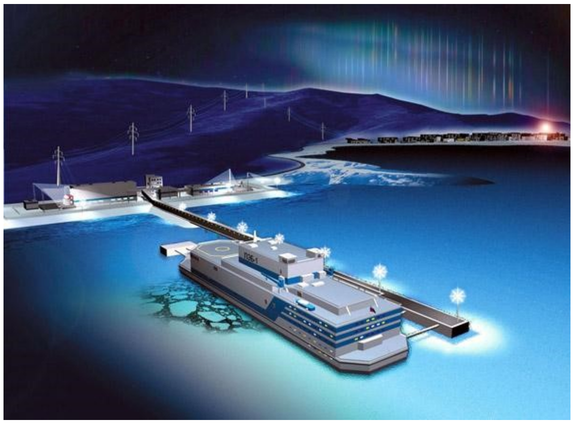

Fig. 3. Akademik Lomonosov (Ref. 4)

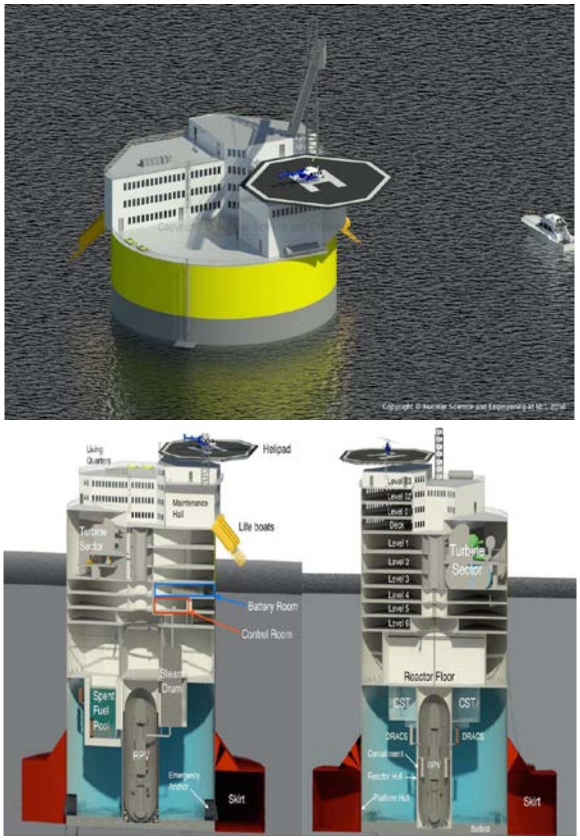

Fig. 4. OFNP (Ref. 5)

In this paper, we propose a new floating type ONPP using a Tension Leg Platform (TLP). TLP is one of the floating structures, and is known for its good motion response, especially in vertical motion. We name this concept a TLP-type ONPP. A System-integrated Modular Advanced ReacTor (SMART) is used as a reference reactor for implementing the proposed concept.

In order to mount SMART on the TLP platform, the facilities and buildings are modularized and rearranged based on the proposed design requirements and variables. Finally, we introduce a construction plan and new total GA of the TLP-type ONPP.

II. DESIGN CONCEPT

We utilize TLP and SMART. The properties of TLP and SMART are explained in Sec. II.A, II.B.

To mount SMART on the TLP platform, the facilities and buildings should be modularized and rearranged because SMART is originally designed for land-based NPPs. We minimized the modifications of the original features of SMART such as physical connectivity, safety systems, and building arrangement to simplify the entire iterative design process and make our concept feasible.

Concrete is chosen as the material for the structure due to its features of impact resistance, fire resistance, and durability.[7]

II.A. SMART

The System-integrated Modular Advanced ReacTor (SMART) is a recent Small Modular Reactor (SMR) developed by Korea. It is an integral reactor that includes steam generators in Reactor Pressure Vessel (RPV). This integrality provides SMART with enhanced safety and reliability.[8] Key parameters of SMART are listed in Table Ⅰ.

TABLE Ⅰ. SMART Information[8]

Parameters	Value
Electrical/thermal capacity	100MWe/300MWt
Primary coolant	Light water
Primary circulation	Forced
Fuel (enrichment)	UO_2 (4.8%)
Refueling cycle	36 months
Design life	60 years

II.B. TLP

The Tension Leg Platform (TLP) is defined as a buoyant unit connected to a fixed foundation by pre-tensioned tendons.[9] The principle of TLP is outlined below.

All the normal floating structures are in an equilibrium state where the buoyancy is equal to the weight. However, in the case of TLP, the buoyancy is greater than its weight, as shown in Fig. 5. The difference between buoyancy and weight is loaded to tendons. In this manner, TLP has a good motion response, especially in vertical motion such as heave, roll, and pitch.

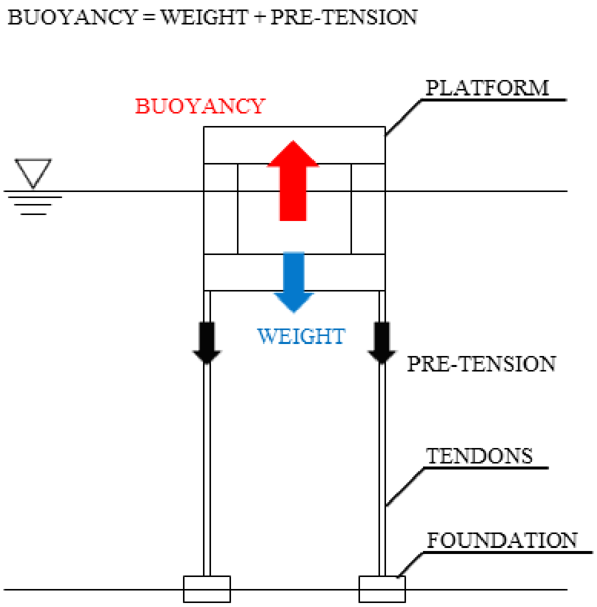

Fig. 5. Schematic Design[9] and Principle of TLP

The typical weakness of TLP is that it requires sensitive weight control. The failure of weight control results in a change of pre-tension loaded in tendons. This will worsen the entire system.

TLP has been widely used for offshore production in the oil and gas industry. In 2010, Offshore Magazine published a worldwide survey of TLPs. [10] 25 models were introduced, and the largest model was Heidrun TLP, which is shown in Fig. 6. Heidrun TLP's displacement is 285,000 tons, and it is also the world's first concrete TLP.[11] Heidrun TLP shows that our design concept is quite feasible.

Fig. 6. Heidrun TLP

II.C. Construction plan

TLP-type ONPP decouples the site of fabrication and operation for elaborate fabrication of nuclear facilities.

It is difficult to fabricate the TLP-type ONPP at a dry dock because the TLP-type ONPP is designed to have a deep draft. Alternatively, it is fabricated at the construction yard. Launch rails and heavy-lift vessel are used for launching and installation. Detailed construction procedures are explained in Table II and Fig. 7.

TABLE II. Construction Procedures of TLP-type ONPP

Step1	The structure is fabricated at a construction yard. At the same time, construction work of the tendon system is conducted at the installation site.
Step2	The structure is shifted to a heavy-lift vessel by using launch rails, and transported to the installation site.
Step3	The heavy-lift vessel submerges by using its ballasting system and the structure floats alone.
Step4	Once the heavy-lift vessel is gone, the structure fills its ballast tank for the installation. After the structure is hooked up to tendons, the ballast tank will be drained for loading pre-tension to the tendons.

During the construction procedures, elaborate ballast control is required. A temporary motion keeping system and support vessel are used for assistance.

Once the procedures are completed, inspection of nuclear facilities is conducted. Fuel is then loaded and operation starts.

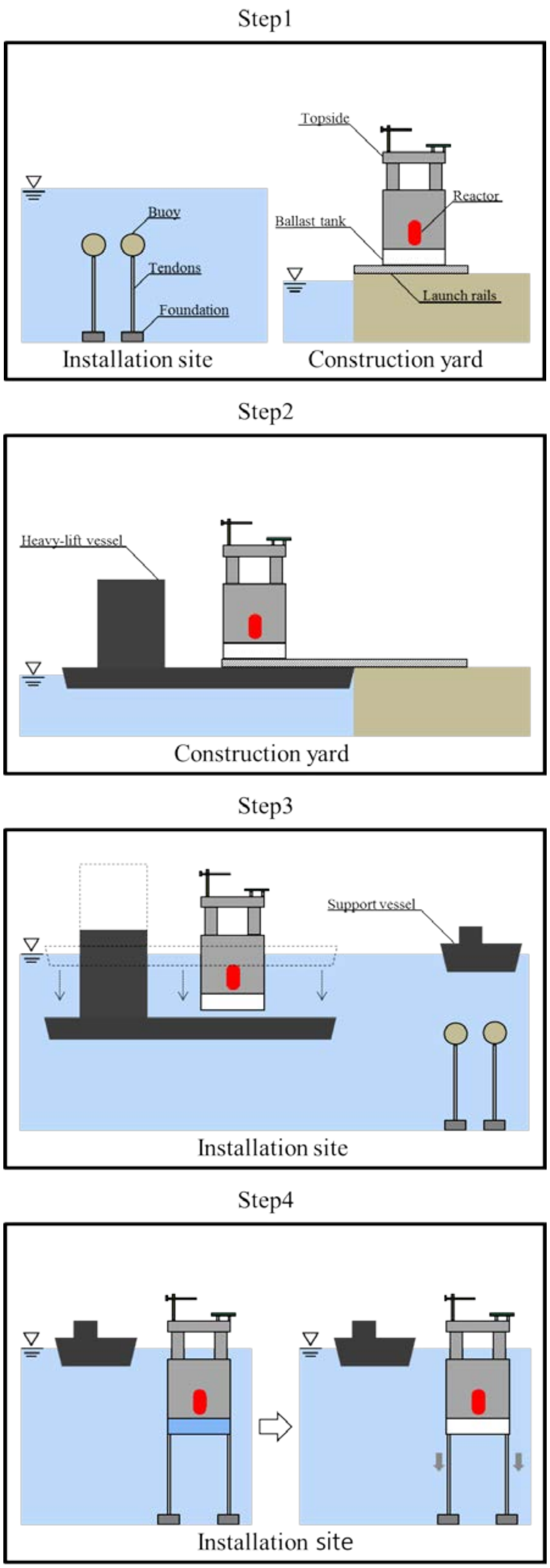

Fig. 7. Construction Procedures

II.D. Modularization and New Total General Arrangement

As shown in Table Ⅲ, design requirements and variables are defined prior to the modularization and rearrangement of SMART and other facilities.

TABLE Ⅲ. Design Requirements and Variables

Design requirements	Design variables
- Compact GA	- Physical connections - Volume and area of facilities - Weight distribution
- Stability & hydrodynamic motion response	- TLP platform design and GA - Tendon system design
- Radiological safety	- Nuclear/non-nuclear area separation - Safety & cooling system
- Nuclear fuel handling	- Nuclear fuel ocean transportation - Motion control
- Safety in extreme conditions	- Storm, extreme waves - Corrosion - Collision, flooding
- Offshore structure construction	- Skid rail, floating dock - Ballasting/de-ballasting system

Stability is a common design requirement for all floating structures. It is defined as an ability to resist overturning moments. If stability is not secured, the structure will be overturned if overturning moments are loaded by environmental forces such as wind loads and wave loads. In our design, the stability is secured by a tendon system. The pretension and stiffness of tendons make the TLP-type ONPP stable.

However, as a countermeasure to an accident where tendons are broken, the platform design to have self-stability is also required. A simplified linear approach[12] is used to calculate the stability.

$$GM = KB + BM - KG$$

KB: Vertical position of the center of buoyancy above the bottom.
KG: Vertical position of the center of gravity above the bottom.
BM: Vertical position of the metacenter above the center of buoyancy. It has the value of moment of inertia for the water plane area divided by submerged volume.
GM: Vertical position of the metacenter above the center of gravity.

When the value of the GM is positive, we can state that the floating structure is stable. Based on this linear approach, we locate heavy facilities and the ballast tank downwards. We expect the TLP-type ONPP will remain stable, even if the tendons are broken by using the platform's self-stability.

This simplified linear approach assumes a small rotation angle. Consideration of a large rotation angle and nonlinear effects is required in order to exactly consider the stability in the stage of detailed design.

The hydrodynamic motion response is also considered. The TLP-type ONPP requires a smaller motion response than the normal offshore structures because nuclear facilities will be operated on it. We design it to avoid resonance with waves. Consequently, we expect vertical motions such as heave, roll, and pitch will be restrained by the tendon system, and horizontal motions such as surge, sway, and yaw are to be restrained by its massive weight.

Separation of nuclear and non-nuclear areas is also considered for radiological safety, as listed in Table Ⅳ.

TABLE Ⅳ. Nuclear/Non-nuclear Area of the Main Buildings

Nuclear area	Non-nuclear area
- Reactor auxiliary building - Reactor containment building - Radwaste building - Fuel handling building	- Turbine generator building - Intake structure & reservoir - Control building - Accommodation & administration building

All the facilities of SMART are summarized in Ref. 9. Based on the design requirements and variables, we modularize all the facilities into eleven groups. The components of each group are listed in TABLE Ⅴ and the new total GA is shown in Fig. 9.

TABLE Ⅴ. Modularized Groups

Group	Facilities and buildings
1	- Ballasting/de-ballasting facility and ballast tank
2	- Reactor containment building - In-containment refueling water storage tank - Hold-up volume tank - Reactor drain tank - Reactor auxiliary building - Volume control tank - Boric acid tank - Chemical addition tank - Other storage tanks - Fuel handling building - Fuel transfer facility - Fuel pools - N_2 and H_2 storage cylinder area - Emergency diesel generator building
3	- Discharge facilities and pond - Wastewater treatment facility - Alternative AC diesel generator building - Aux. boiler and oil storage building - Component cooling water heat exchanger building
4	- Turbine generator building - Main transformer, unit aux. transformer, standby aux. transformer, excitation transformer, and spare transformers
5	- Radwaste building - Fuel transfer facility
6	- Circulating water intake structure - Intake reservoir - ESW intake structure - Fire pump & water building - Sanitary water treatment facility - Chlorination building
7	- Control building
8	- Compound building
9	- Fuel transfer facility
10	- Accommodation building - Administration building - Helideck
11	- Fuel transfer facility

Group 1 is required for the TLP installation, and also functions as a double bottom that protects the reactor from external accidents. In Group 2, the reactor auxiliary building surrounds the reactor containment building for accessibility and protection. In Group 3, the discharge pond and the wastewater treatment facility are located together for easy drainage. In Group 4, breakdown of the turbine over-speed protection system is considered. A turbine missile strike zone is bounded with reinforced concrete walls. This is discussed in our previous work.[3] Group 5 handles all the radioactive waste except spent fuel. In Group 6, intake structures, the sanitary water treatment facility, and the chlorination building are located together for efficiency. The control building is located in Group 7 for convenient access to other facilities. The accommodation building and the administration building are located in Group 10 on the topside for multiple radiation protection.

Fuel transfer facilities for supplying new fuel and disposing of spent fuel are located on every floor, specifically in Groups 2, 5, 9, and 11. These facilities transfer the fuel between the ship and the topside and between the topside and the fuel handling building.

For efficient heat exchange, the turbine generator building and the CCW heat exchanger building are closely located to the reactor containment building and the reactor auxiliary building. The discharge pond is located below the intake reservoir for the natural circulation of circulating water. Electricity generation facilities are dispersed in order to prepare for accidents. The final design of the TLP-type ONPP is shown in Fig. 8.

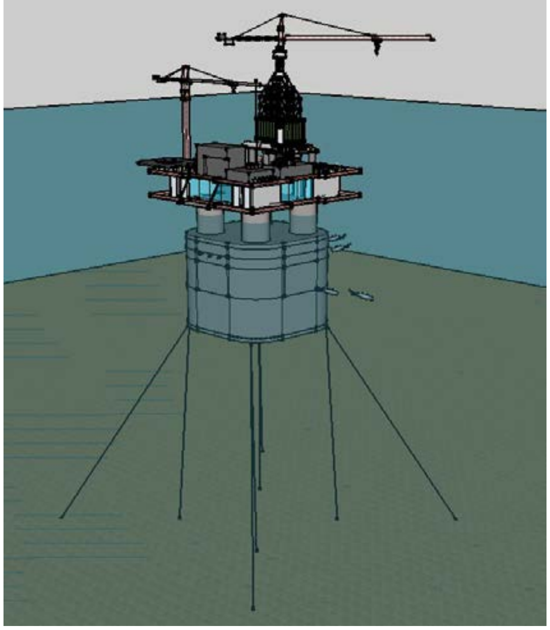

Fig. 8. Final Design of TLP-type ONPP

Ⅲ. CONCLUSION

In this study, we proposed a new concept of a TLP-type ONPP. We exploited the key strength of the TLP, a good motion response. SMART was used as a reference reactor because it has enhanced safety and reliability.

To mount SMART on the TLP platform, modularization and rearrangement of the facilities and buildings were performed based on the defined design requirements and design variables. Our main concerns were to make the TLP-type ONPP safe in terms of radiation safety, stability, and motion response.

We proposed the construction procedure. The TLP-type ONPP is fabricated at an onshore construction yard, towed to the installation site, and moored by tendons for operation.

Finally, we proposed a new total GA for the TLP-type ONPP, as shown in Fig. 9.

In the future, we will perform a hydrodynamic analysis of the TLP-type ONPP numerically, and then calculate the floor response and subsystem response in order to evaluate the safety performance of the TLP-type ONPP.

ACKNOWLEDGMENTS

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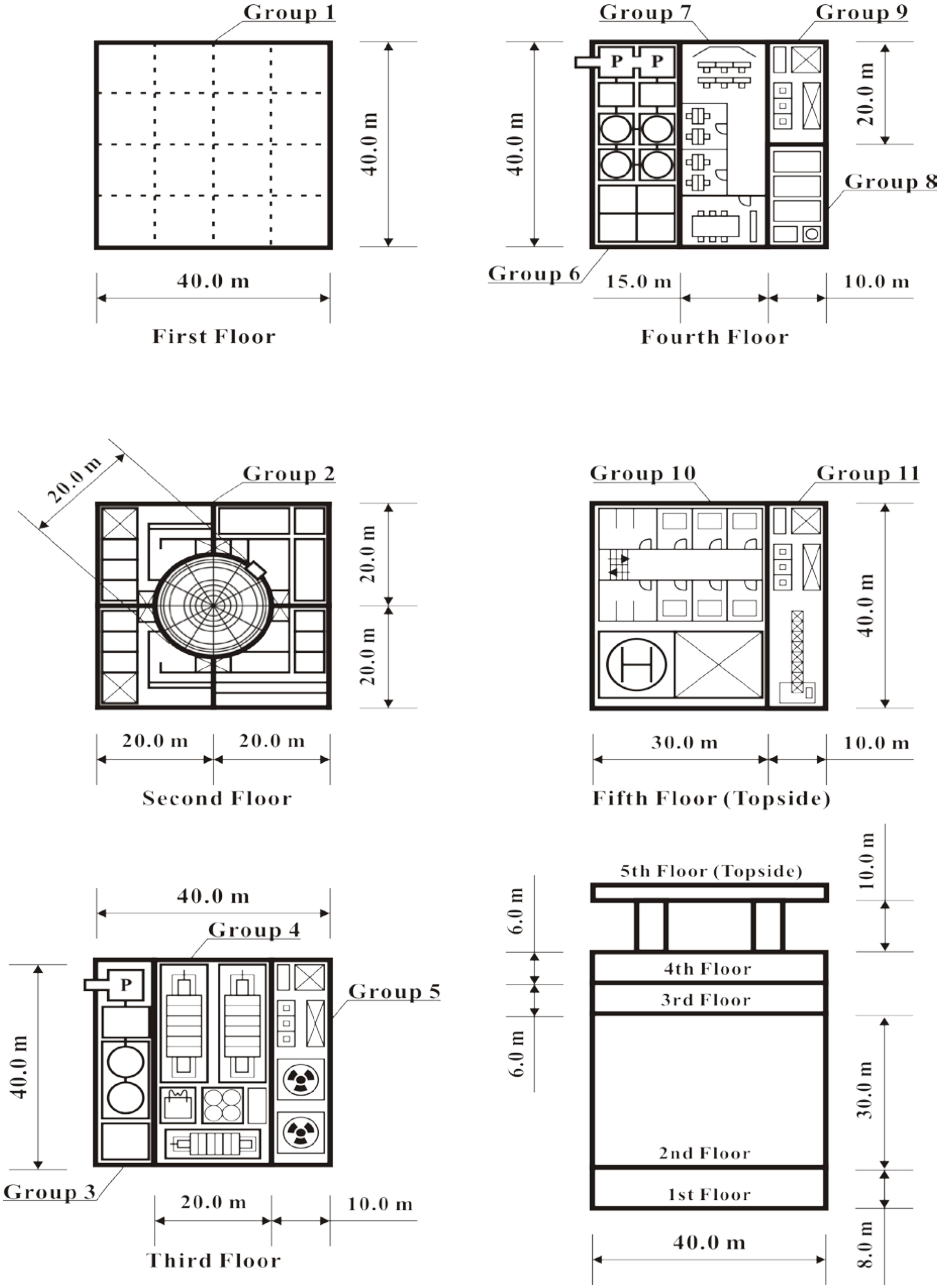

Fig. 9. Total GA of TLP-type ONPP