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A Study of Advanced Construction Technologies for Reduction in Time and Cost of Nuclear Power Plants

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Abstract

Nuclear Power Plants (NPPs) are capital intensive projects. In comparison to the fossil fuel power plants, the NPPs are costlier to build but less expensive to operate and maintain. The higher capital cost of NPPs is a serious setback to the renewed interest in nuclear energy from investors and utilities. Therefore, there is a need to devise strategies for reduction in the total cost of nuclear power while still maintaining high safety and quality standards. Reduction in the project gestation period reduces interest during construction and thus the total cost of NPP. Advanced construction technologies often claim to be reducing project gestation period. This paper reviews literature pertaining to advance technologies that are appropriate for application in NPP construction. Advanced excavation, steel plate reinforced concrete, modularization, open top construction, automatic welding, 3D modelling, and IT systems for construction management etc. are some of the promising technologies that could be instrumental in reducing NPP project gestation period. For effective application, the additional investment required for these technologies should be more that offset by reduction in the total cost of NPP. The agility and rapid development introduced by the advanced technologies may make NPPs more competitive with the fossil fuel power stations.

Introduction

The rise in fossil fuel prices and the increased concern about environmental protection from carbon dioxide emissions have brought the attention to use of nuclear energy as a viable source of power. However, the nuclear energy has to compete with other energy sources. Therefore, it needs to be produced economically.

Many countries rely heavily on nuclear energy for much of their electricity needs. For example, France obtains about 75 percent of its electricity from nuclear energy (IAEA, 2010). Sweden, Finland, South Korea, USA, Japan, Switzerland, and several CIS countries use nuclear electricity in large proportions. In the US, the Nuclear Energy Institute (NEI) published the nuclear energy industry’s “Vision 2020.” This forward-looking document postulates addition of 50,000 MW(e) of new nuclear generating capacity to the US grid by 2020 (NEI, 2001). In China (Dazhong, 2002) and India (Grover, 2006), nuclear power plays a prominent role in their energy strategies for the future, as it does in Japan, South Korea, Taiwan, and many other countries (IAEA, 2004). As environmental awareness grows globally, nuclear power is poised to become an ever more compelling energy option. The world at large would recognize the vital role that nuclear energy must play as the only large-scale energy supply option that does not produce greenhouse gasses or other harmful emissions (USDoE/NPI, 2004).

There are several types of nuclear power reactors operating in the world currently. These include pressurized water reactors (PWRs) and boiling water reactors (BWRs). PWRs and BWRs together are also called light water reactors (LWRs). The other types of reactors are pressurized heavy water reactors (PHWRs), gas cooled reactors (GCRs), fast breeder reactors (FBRs) etc. (Abu-Khader, 2009). These reactors can also be classified by the chronology of their development - and consequently by the type of the safety systems present in different vintages or generations of NPPs - such as Generation I, Generation II, Generation III, Generation III+ and Generation IV reactors (Penner, 2008).

Generation I reactors were early prototypes constructed in 1950s and 1960s. Some of these reactors include Shippingport, Dresden, Fermi I, Magnox etc. Generation II reactors were commercial power reactors designed and constructed in 1970s through 1990s. These were PWR, BWR, PHWR and AGR etc. The Generation III reactors are advanced reactors such as ABWR, System 80+ etc. These are prominent reactor designs from late 1990s to the first decade of the new millennium. Generation III+ reactors refer to evolutionary designs offering improved economics for near term deployment during 2010s and 2020s. It is hoped that Generation IV reactors that are currently under design will be constructed around 2030s. These reactors are expected to be relatively cheaper yet equipped with improved design for enhanced safety performance. Production of waste is expected to be very less in the Generation IV reactors and these will also be proliferation resistant (Penner, 2008). Many new NPP designs have been put forward recently. Some of these NPPs claim to use modular designs with a view to provide safer and more economical electricity.

Nuclear power stations are quite expensive to build but very inexpensive to run, yet the economics of nuclear power look uncertain. That is partly because its green virtues do not show up in its costs, since fossil-fuel power generation does not pay for the environmental damage it does (Economist, 2007). Despite recently revived interest in nuclear power, the prospects for commercial investment in nuclear power plants looks uncertain. The reason is relatively simple: quite apart from overcoming any regulatory and public opinion difficulties, the economic risks of nuclear power have been adversely affected by liberalization. High capital cost, uncertain construction cost, and potential construction and licensing delays are likely to lead private investors to require a substantial risk premium over coal and gas fired power plants to finance at least the new nuclear units. The discussion over economics of nuclear power in terms of the expected levelized cost fails to capture these concerns adequately. Recent cost estimates reveal both the large underlying nuclear cost uncertainties and different interpretations of the impact of liberalization on the cost of finance and, hence, investment choices (Roques, 2007).

The technologies used to design and construct the NPPs may have a dramatic impact on the economics. Minimizing the time between the start of construction and the commissioning date reduces the interest accumulated during construction and thus the total capital cost borne by the owner of the plant. Although, some design and construction techniques may be reactor-specific, there are also generic methods to facilitate delivery of reactor components and to speed up construction. Pre-fabrication, pre-assembly and modularization technologies shift a large part of the construction work from the site to a factory or workshop. These are very efficient means of reducing construction time and costs. Some design features of a nuclear power plant could also shorten construction time. Simplified designs and composite construction, for example, can reduce the amount of on-site work required (IEA, 2002). Other methods, such as the use of 3D design tools, heavy lift cranes, open-top construction, steel plate reinforced concrete, slip and jump forming, advanced welding, all weather construction, advanced information technology systems for project management etc. can also reduce construction time (IAEA, 2004).

Some of the recent NPPs have been constructed using advanced construction technologies in as little as four years. Previously this used to take 8 to 10 years. Therefore, the experience accumulated and lessons learned during the implementation of recent NPP projects have shown that advanced construction technologies can reduce nuclear power's construction costs, mainly by shortening the time needed to build a plant (IAEA, 2007). These technologies are not unique to the nuclear industry, or to any specific nuclear power plant design. Most are also used for other large construction projects such as fossil fuel power plants, large civil construction projects and shipbuilding.

The purpose of this paper is to review the literature pertaining to advance technologies that are appropriate for application in NPP construction. The scope of this paper is limited to the current and proposed technologies for nuclear power plants. This paper is organized in different sections. After introducing the subject of study in the first section, the subsequent sections discuss specific advanced construction technologies for NPPs. The conclusions as well as areas for further study are discussed in the last section.

Advanced Excavation Technologies

Excavation is defined as the removal of material from the plant grade elevation to accommodate the plant's permanent buildings and facilities. The material can be rock or soil or a combination of both (IAEA, 2009). Conventionally, excavation is done manually using backhoes to remove the soil and rock. Blasting is done to loosen rock, if required. This method is relatively inexpensive. However, it requires longer time schedules. Sometimes conventional blasting may remove more rock than required or damage the surface on which foundation is to be based. In such cases, it takes even more time and resources to repair the damage.

Advances in excavation that can be applied to nuclear power plants include precision blasting and chemical foam expansion for excavating rock. In precision blasting technology, several shafts are drilled in a pre-defined pattern in the area to be excavated. These shafts are filled with explosives, which are then detonated. The applicability of precision blasting depends on a site's geology and the NPP's foundation design. Figure 1 shows the excavation done at a site using precision blasting.

Figure1. Precision Blasting

(Source: Khan, 2009)

Chemical foam expansion for breaking rock without blasting can also be used for excavation without causing any damage to the nearby structures and foundation material. This technology utilizes non-detonating chemicals that expand quickly on ignition and produce high volumes of harmless gas, mainly consisting of nitrogen, carbon dioxide and steam. The gas generated by ignition of the chemicals enters into the micro-fractures created by the percussive drilling process and into the natural fractures and planes of weakness of the rock to produce shearing of the rock. Figure 2 shows the excavation done at a site using chemical foam expansion.

Figure2. Excavation Using Chemical Foam Expansion (Source: IAEA, 2009)

Advanced excavation technologies are helpful in reducing excavation time, reducing amount of concrete required for foundation and protecting foundation material from damage. These technologies are also helpful in protecting the operating NPPs if they are located very near the construction site of the new NPP.

Steel Plate Reinforced Concrete

Reinforced cement concrete (RCC) is conventionally used in construction of NPPs. In this technology, steel reinforcement bars (rebars) are surrounded by a temporary external formwork made from wood or steel sheets. In this formwork, the concrete is poured. After the concrete is set, the external formwork is removed. This is a simple technology. However, it takes lot of time in preparation of forms, placement of rebars, and removal of forms after the concrete gains strength. In contrast to this, steel plate reinforced concrete (SC) technology uses permanent steel plate forms that are tied together by welding the steel plate forms with tie-bars and rebars. Concrete is poured in the steel plate forms that are manufactured in factories / workshops and brought to site in almost ready to use condition. The permanent steel plate forms also provide strength to the steel concrete. Accordingly, the requirement of the rebar gets reduced in SC. Figure3 shows a comparison of RCC and SC technologies.

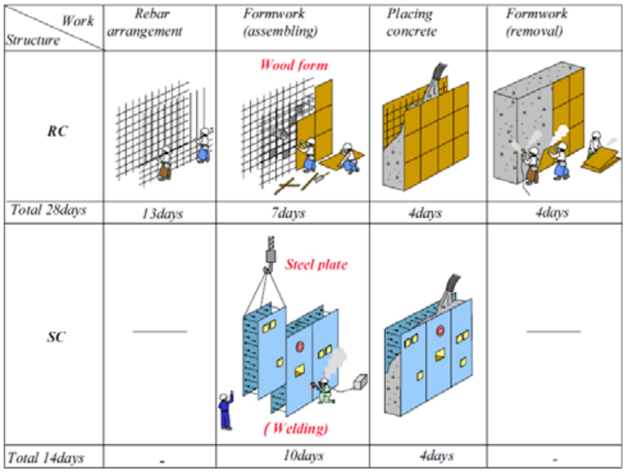

Figure 3. Comparison of RCC and SC Technologies (Source: USDoE, 2004)

SC technology can be used in almost all the walls and floors of the NPP buildings. It offers drastic reduction in construction schedule. SC technology has been used in Japan with 25% reduction in construction schedule (Toshiba, 2009). SC technology can also be used in conjunction with advanced concreting methods. In addition to the automated methods for pouring and installing concrete, there have been recent advances in the composition of concrete to improve strength, workability, and corrosion resistance (Dominion, 2004). Examples are self-levelling concrete, self-compacting concrete, high performance concrete and reactive powder concrete. These can be used in nuclear power plants to reduce construction schedule. Figure 4 shows application of SC design for reactor building.

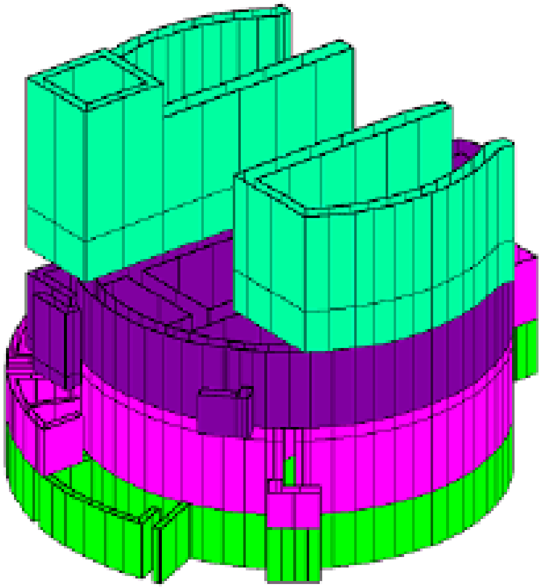

Figure 4. SC Design for Reactor Building
(Source: Kim, 2009)

Slip Forming and Jump Forming

Slip forming involves gradual hydraulic lifting of formwork at a pre-determined rate such that it becomes possible to keep feeding required rebars and pouring concrete from the top. The size of formwork in slip forming technology is usually small. By using slip forming, the vertical walls can be constructed at a significantly higher rate than that is achievable using conventional formwork (Khan, 2009). Therefore, construction schedules can be significantly reduced by slip forming. Figure 5 shows slip forming in NPP stack construction.

Jump forming refers to moving the formwork in steps. This method can be easily used to construct all steel lined walls in NPPs. In this method the wall is formed in stages with the form lifted in steps by jumping up (climbing) to the next stage after the concrete in the lower stage has set (IAEA, 2009).

Open Top Construction

In the past, the walls of the building were constructed with temporary openings to allow the entry of large equipment horizontally. After placing the large equipment in the building, these temporary openings were closed. This used to result in longer construction schedules.

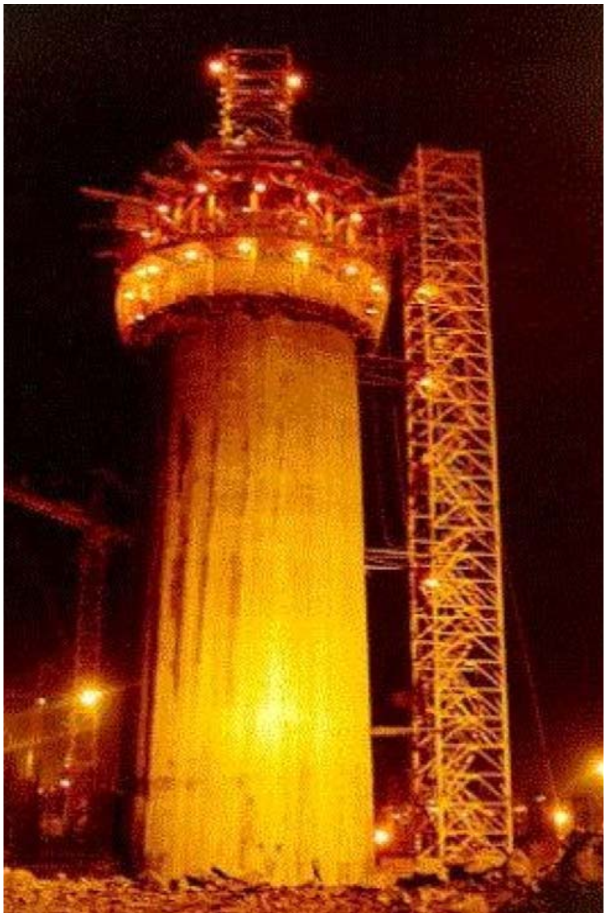

Figure 5. Slip Forming
(Source: Bohra, 2006)

In contrast to this, in the open top construction technique, the buildings are constructed with their top portion open. Through the open top, large equipments such as the reactor vessel and steam generators can be lowered into reactor building at appropriate position using very heavy lift (VHL) cranes. Currently available VHL cranes can lift equipment weighing more than 1000 tonnes with very long reach. As soon as the large equipments are placed inside, the piping electrical and instrumentation systems can be installed while construction of the building progresses further. This saves considerable time in the construction schedule due to parallel working of civil construction along with mechanical, electrical and instrumentation work. Open top installation has been used successfully with modularization, to shorten construction schedules in recently constructed NPPs. Figure 6 shows a super large module being lowered into position using open top construction.

Figure 6. Open Top Construction
(Source: Yahagi, 2009)

The reactor building dome of PHWRs is designed with provisions for openings that can be used for installation of steam generators during NPP construction. The openings are closed after the steam generators are installed. In future, if there is any need to remove the steam generators out of the reactor building for maintenance or replacement etc., this design feature can be used again. Figure 7 shows steam generator being lowered into position through opening in the reactor building dome.

Figure 7. Steam Generator Installation in PHWR (Source: IAEA, 2004)

Modularization

A module is an assembly consisting of multiple components such as structural elements, piping, valves, tubing, conduits, cable trays, reinforcing bar mats, instrument racks, electrical panels, supports, ducting, access platforms, ladders and stairs. Modules may be of different types such as unit module, structure module, system module, component module and composite module. Modularity in the NPPs can be classified as scale, scope and comprehensive modularity (Upadhyay, 2010). Figure 8 shows a rebar module and Figure 9 shows a composite module.

Figure 8. Base Slab Rebar Module
(Source: Khan, 2009

Figure 9. Composite Module
(Source: Toshiba, 2009)

Prefabrication and pre-assembly of modules are construction techniques used in many industries, including nuclear power plants. Modules may be fabricated at a factory or at a workshop near the plant site, while the building construction work is progressing at the site in preparation for receiving the modules. Figure 10 shows a piping module and Figure 11 shows design of a header-feeder module for PHWR.

Figure 10. Piping Module
(Source: Toshiba, 2009)

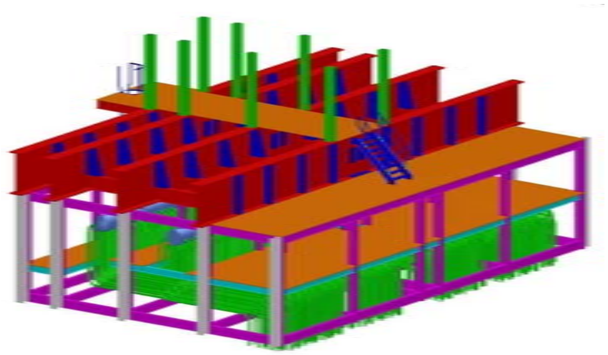

Figure 11. Design of Header Feeder Module
(Source: Byrne, 2009)

Figure12. Reactor Building Dome Module
(Source: IAEA, 2004)

Modularization reduces site congestion, improves quality, improves accessibility for personnel and materials, and can shorten the construction schedule significantly. It can also significantly reduce on-site workforce requirements. Figure 12 shows reactor building dome module and Figure 13 shows a module of submerged discharged tunnel.

Figure13. Discharge Tunnel's Module
(Source: IAEA, 2009)

Modularization also facilitates mass production of modules in the event of several reactors required to be built at the same time. Mass production fosters economies of learning and reduces production times as well as labour requirements (Lapp, 1997).

Advanced Welding Technology

NPPs use welding extensively to join structural elements as well as process equipment and piping. Welding is also used to deposit weld material on surfaces where there is a need for different surface properties than that of the base material. Conventionally, manual welding is used for these requirements. This consumes a lot of time. To reduce the time taken in welding, NPPs can use robotic welding technology. It is electric-arc welding with automatic control of the arc movement along the welding line, the electrode feed, and the arc-gap length. In this technology, welding is performed by a welding machine as per the instructions provided while maintaining high weld quality. Additionally, narrow gap welding and high deposit welding can also be used by NPPs to further speed up the project construction.

Figure 14 shows automatic welding of titanium tubes to condenser tube sheet and Figure 15 shows automatic welding of reactor coolant pipes in NPPs.

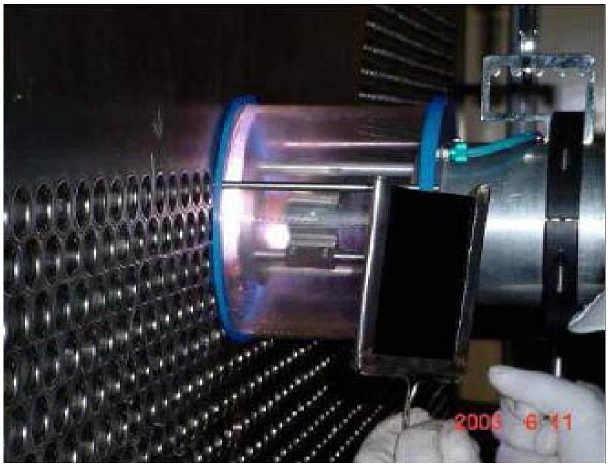

Figure14. Automatic Welding of Condenser Tubes (Source: IAEA, 2009)

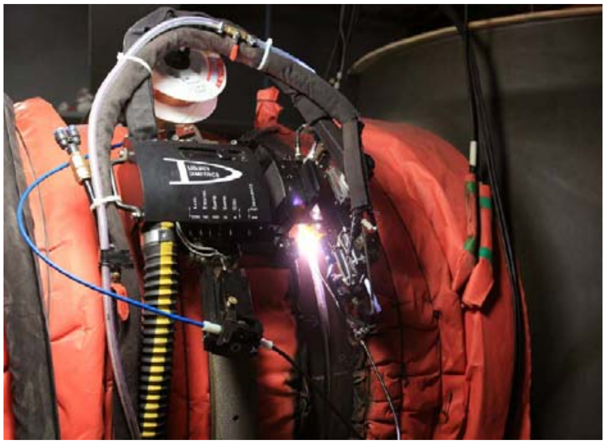

Figure 15. Automatic Welding of Reactor Coolant Pipes (Source: KEPRI, 2009)

All Weather and Round-the-Clock Construction

As NPP construction continues for a period of a few years, the construction activity gets slowed down or stopped during difficult weather conditions such as below freezing point temperatures, snow fall, heavy rains etc. This usually introduces delay in NPP construction. However, techniques have been developed to facilitate work in all weather conditions. These can be used for critical path construction activities to achieve reduction in NPP construction schedule. For example, a temporary all-weather dome can be build over the reactor building during construction. This dome can be opened to allow entry of equipment and material when needed. Figure 16 shows application of this method at Kashiwazaki-Kariwa-6 in Japan.

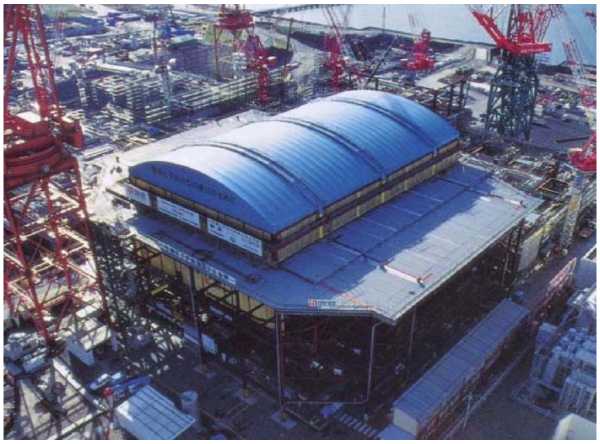

Figure 16. All Weather Construction
(Source: Yahagi, 2009)

With the availability of advanced illumination methods, it has become possible to keep working round the clock at the NPP construction sites. Therefore, the NPPs may adopt round the clock working during construction. This would help in reducing construction schedule significantly. Figure 17 shows night view of activities at NPP construction site.

Figure 17. Night View of Construction Activities (Source: Bohra, 2006)

Use of IT in Design and Construction Management

Currently available computer systems and specialised design applications make it possible to create 3D design of the complete NPP before starting construction. This helps in visualising the plant design with a view to eliminate unintended design errors. This also helps in creating well defined modules that can be manufactured at different factories and joined at site to make the complete NPP. Figure 18 shows 3D model of Quinshan NPP. Specific deliverables at any stage can be extracted from the computer assisted design model, including piping system isometric drawings, general arrangement drawings, and materials quantities etc (Rixin, 2003). The overall installation plan of the NPP structures, systems and components can also be easily visualized using the model.

Such 3D computer models can then be linked to the construction schedule to provide ‘4D modelling’. Further, ‘6D modelling’ that includes 3D models, material quantities, human resources and time can also be used for nuclear power plant construction (Toshiba , 2009).

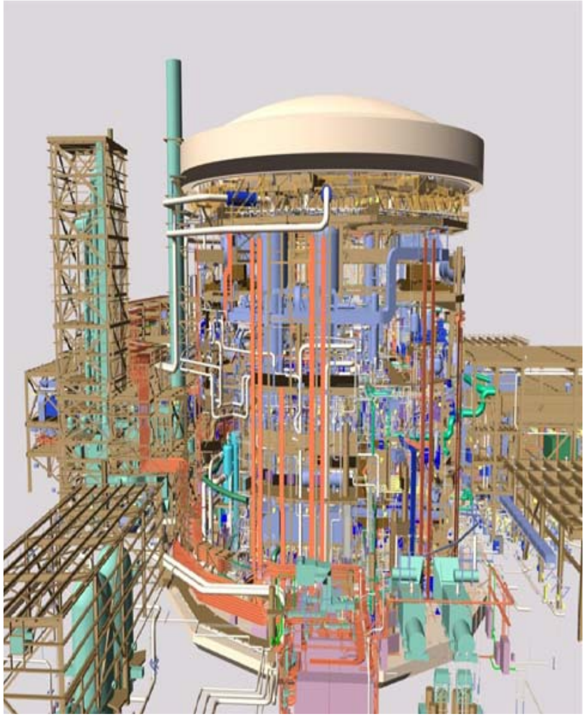

Figure 18. 3D Model of Qinshan NPP (Source: Byrne, 2009)

The benefits of using IT systems for design, procurement, construction, testing and overall project management are that they improve productivity through concurrent engineering, procurement and construction; allow drawings to be revised and accessed electronically; facilitate accurate determination of material quantities; and facilitate efficient procurement and construction management (Exelon, 2009). Figure 19 provides an example of enterprise command centre for project construction.

Conclusion

Construction schedule reduction is very important for new NPPs. It will ensure that they remain commercially viable in the present policy, pricing and regulatory environment. The expected nuclear renaissance would also call for rapid and agile development of new NPPs.

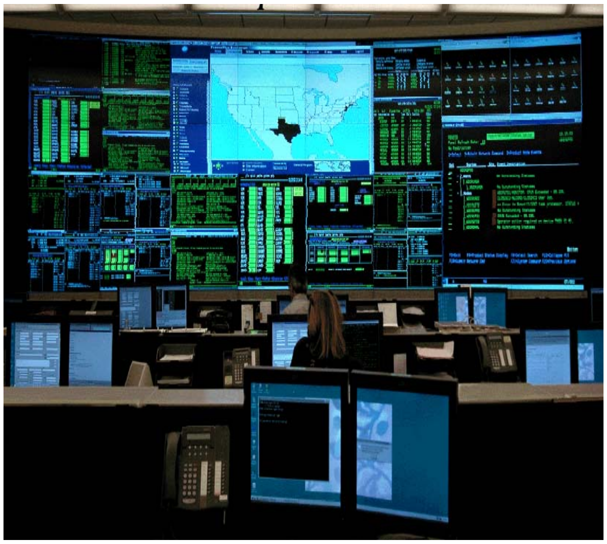

Figure 19. Enterprise Command Centre for Project Construction (Source: Exelon, 2009)

The advanced construction technologies available for new nuclear power plants have made it possible to construct NPPs in just four years. It appears possible to further reduce the construction schedule using these technologies. However, all these technologies may not be either required or feasible for implementation in all the NPPs around the globe. Therefore, there is a need to devise project specific engineering, procurement and construction strategy in advance based on the specific requirements of the NPPs and the available supply chain infrastructure. Once formulated, the strategy needs to be implemented meticulously.

In addition to providing benefit of shorter construction schedule, the advanced construction technologies require additional investments in factories, workshops, VHL cranes etc. So, a cost-benefit-analysis is required for their judicious implementation. Therefore, these technologies may be further studied for evaluation in terms of the net saving in the construction cost.

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