DESIGNING DECOMMISSIONING INTO NEW REACTOR DESIGNS[1]

Dr. J.S. Devgun, Ph.D., CHMM
Nuclear Power Technologies
Sargent & Lundy LLC
55 E. Monroe St
Chicago, IL 60603
U.S.A.

ABSTRACT

One of the lessons learned from decommissioning of existing reactors has been that decommissioning was not given much thought when these reactors were designed some three or four decades ago. Recently, the nuclear power has seen a worldwide resurgence and many new advanced reactor designs are either on the market or nearing design completion. Most of these designs are evolutionary in nature and build on the existing and proven technologies. They also incorporate many improvements and take advantage of the substantial operating experience. Nevertheless, by and large, the main factors driving the design of new reactors are the safety features, safeguards considerations, and the economic factors. With a large decommissioning experience that already exists in the nuclear industry, and with average decommissioning costs at around six hundred million dollars for each reactor in today's dollars, it is necessary that decommissioning factors also be considered as a part of the early design effort. Even though decommissioning may be sixty years down the road from the time they go on line, it is only prudent that new designs be optimized for eventual decommissioning, along with the other major considerations.

INTRODUCTION

With fortunes of the nuclear industry shifting dramatically upwards in the last few years, the industry envisages substantial new nuclear capacity in the next decade and beyond. Several new reactor designs are in various stages of development worldwide. In the United States, four advanced reactor designs have been already certified by the U.S. Nuclear Regulatory Commission (NRC) and several others are in the review process. In fact, consortiums within the U.S. nuclear power industry are planning on submitting combined construction/operating license (COL) applications for advanced reactor designs as early as 2007. In addition to the advanced reactor designs, development work is being carried out on the so-called Generation IV concepts, that envision new reactors designs for commercial power reactors in the longer term (2030 and beyond).

Most of the advanced reactor designs are evolutionary in nature and build on the existing and proven technologies and incorporate many improvements in the reactor safety area and in the construction design to reduce capital costs. Nevertheless, by and large, decommissioning factors are less of a consideration in the design process.

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[1] The views expressed in this paper are those of the author and do not necessarily reflect the views of his employer or the clients.

Substantial decommissioning experience that already exists worldwide can provide valuable input into the design process. With average decommissioning costs at around six hundred million dollars for each reactor in today's dollars, it is necessary that decommissioning factors be considered as an integral part of the early design effort. This paper will discuss what features are being incorporated and what design considerations can be taken into account to further enhance the capability to eventually decommission the new reactors, when they are retired.

GROWTH IN ENERGY DEMAND AND RESURGENCE IN NUCLEAR POWER

Worldwide, the IAEA projections [1] show that by 2020, the nuclear generating capacity will be in the range of 423 to 501 Gigawatts i.e., an increase of approximately 18 % (for the low projection case) over the year 2002 operating capacity of about 359 Gigawatts. Even though there are major variances in the nuclear power growth projections from different sources, nuclear power is expected to provide a significant portion of the future worldwide electricity generating capacity. It is also worth noting that while the energy demand may be increasing at modest rates in the western countries, in Asian countries such as India and China, the high economic growth will continue to drive the energy demand much higher. In Asia, the energy use (from a mix of energy sources) is expected to triple during the same period. The energy projections anticipate that worldwide at least 60 new nuclear plants will be built in the next 15 years and in concert with the energy demands, many of the new reactors are planned in Asia, specifically in China, India, Japan, and South Korea. Other estimates predict [2] that over 130 reactors are being built or planned worldwide. Currently 442 nuclear plants are in operation worldwide.

With respect to the of U.S. nuclear generating capacity, the Energy Information Administration (EIA) estimated in its "Annual Energy Outlook 2006" that 6 Gigawatts of new nuclear generating capacity will be added by 2030. However, the updated estimates released in "Annual Energy Outlook 2007" [3] more than double that estimate to 12.5 Gigawatts. New plant construction that is expected to be stimulated by the provisions in the Energy Policy Act of 2005 are clearly a factor in the predicted increase. However, other industry estimates put the increase in nuclear capacity at much higher levels than the reference case of the EIA. In fact, the EIA's outlook also states that nuclear power is expected to grow relatively slowly; however, if the costs for nuclear power plants decrease, significant quantities of capacity additions could result. According to some industry estimates as many as 20 new plants could be added in the next 20 years. The incentives provided in the Energy Policy Act of 2005 for new reactors include production tax credits, loan guarantees and risk protection for companies building the new nuclear plants. Currently, the 103 operating nuclear reactors (104 have operating licenses) in the country contribute about 20% of the total national electricity generating capacity.

NEW REACTOR DESIGNS & MAIN DRIVING FACTORS

As the reactor technologies continue to evolve, better reactor designs become available. Most of the exiting plants worldwide are so-called second-generation plants that continue to provide safe and reliable operation. However, as far as the new build is concerned (either under construction or planned), the designs that will be used are the advanced reactor designs, the so-called generation III plants. In addition, significant research work is being done on the so-called Generation IV designs that will not be on the market until 2030 or later after the developmental, demonstration and prototype stages are complete.

New Reactor Designs

The advanced reactor designs are generally the evolutionary designs, which means they are based on existing designs and incorporate improvements from the substantial experience from the operation of the existing plants as well as several new technological features. These designs minimize technological risk, maintain proven design features, and can move to construction stage relatively easily after the engineering testing and analyses have been completed and regulatory approvals have been obtained. The innovative designs contain more technological risk, require substantial R&D efforts, and generally go through the development stages involving demonstration of the new design concepts and a prototype operation.

The light water reactors make up approximately 80% of the existing nuclear fleet worldwide and accordingly, several of the advanced reactor designs are in this category, based either on the PWR technology or the BWR technology. In U.S., these designs include General Electric's Advanced Boiling Water Reactor (ABWR) and the Economic Simplified Boiling Water Reactor (ESBWR), Combustion Engineering's System 80+, Westinghouse's AP-600, and Westinghouse's AP-1000. Other designs include, Framatome's European Pressurized Water Reactor (EPR) in Europe, WWER-1000 (V-392) in Russia and in India, ABWR-II in Japan, and the Optimized Power Reactor (OPR) in South Korea.

Among the heavy water reactors (D_2O moderated), Canada's CANDU design has undergone evolutionary developments and the Advanced Candu Reactor (ACR) will use slightly enriched uranium and light water coolant. India, which like Canada has a fleet of operating heavy water reactors, is also developing Advanced Heavy Water reactors. The existing gas cooled reactors (GCRs), primarily in the UK, are graphite moderated and CO_2 cooled. The advances in this area primarily relate to using helium as the coolant. In South Africa, Eskom has completed design of a demonstration reactor, the Pebble Bed Modular Reactor (PBMR) and construction of a demonstration reactor is planned. In the Fast Breeder Reactor (FBR) category, France's liquid sodium cooled Superphenix reactor is the only commercial size unit in the world. Demonstration units have operated in UK, Russia, Japan, and India. After the successful operation of its Indian Fast Breeder Test Reactor, construction of a prototype FBR in India started in 2004. Some discussion of the advanced designs is available in the ANS publications [4].

In the United States, the designs already certified by the NRC include the AP 600 and AP1000 by Westinghouse Electric Company, ABWR by General Electric-Toshiba-Hitachi, and System 80+ by Westinghouse [5]. The ESBWR design by General Electric is nearing final stages of review.

Main Driving Factors

By and large the main factors driving the design of the new reactors are the enhanced safety features, safeguards considerations, and the economic factors.

1. Enhanced Safety Features

The greatest consideration over the existing second-generation designs is what could be termed as enhancing the defense-in-depth (DID) philosophy. Many advanced reactor designs incorporate enhanced safety through increased margins and/or through the addition of passive safety features or the inherent safety design features. The passive safety features require no active controls or operational intervention and ensure that major reactor accidents are avoided in the event of a malfunction. Such designs may rely on gravity, natural convection, or resistance to high temperatures.

2. Safeguards Considerations

The enhanced safeguards in the advanced reactors are generally in the form of advanced instrumentation for materials control, monitoring and protection. In some reactor types mixed oxide fuel could be used that will use plutonium along with the uranium oxide fuels. The Generation IV reactor concepts are looking at proliferation resistant fuel cycles. In February 2006, the Global Nuclear Energy Partnership (GNEP) initiative was announced by the U.S. government and the purpose of this initiative is to develop enhanced safeguard programs and technologies.

3. Economic factors – cost effectiveness

- The advanced reactor designs have to compete with other sources of energy production. Generally, the new designs reduce their capital costs enough to have a generation cost in the range of 3- 5 cents (U.S.) per kWh. Recent industry estimates [6] put the capital costs between $1,600 and $2,000 per kW installed depending on the reactor design. For AP1000, Westinghouse' own estimates have been quoted in the range between $1,500 and $1,800 per kW installed [6].
- Reducing plant components and simplifying plant systems, thus lowering the capital costs
- Shorter construction period leading to lower capital costs

4. Other factors

- Standardization of design to streamline regulatory approvals and construction
- Optimized systems to achieve better capacity factors
- Longer operational lifetime (e.g. 60 years)
- Minimizing environmental effects (less operating waste, decrease in radioactivity etc.)
- Higher burn ups and special fuel capability such as the mixed oxide fuel.

Eventually all reactors, new and old, will be decommissioned even though decommissioning may be postponed for decades given the current industry trends. In the U.S., for example, about three-fourths of the currently operating reactors have already received operating license extensions (for another 20 years over the existing 40 year operating periods) or are in the process of doing so. It is expected that the remaining one-forth will follow the same route. Still, considering that an average commercial nuclear reactor may cost in excess of six hundred million dollars in current dollars, there are significant reasons to ensure that the new reactor designs are optimized for future decommissioning in addition to the optimization for key operational factors, safety factors and the security factors discussed above.

Limited Decommissioning Consideration in New Reactor Design Process

There are several reasons why it appears that decommissioning has not received the same attention in design detail as the other factors during the design process for the new reactors. These include:

1. Given that the life cycle of the new plants, decommissioning is likely 60 years away from the time the new plants come on line. Thus, it is not considered an immediate priority.

2. Given the recent experience with license extensions, the decommissioning of new reactors may be further than even their initial operating license periods.
3. As compared to plant safety and power generation economics, decommissioning is weighted much lower in design efforts.
4. The expectation is that innovative technologies in future may make it much less significant an issue.
5. The high level and spent fuel repositories are national projects on which industry has no control. Even though it impacts the decommissioning costs because of construction of storage facilities (such as ISFSIs in the United States), the industry is more or less resigned to a status quo.

Most of the detailed technical information for the new reactor designs and the design processes is proprietary and a detailed assessment is not possible as to what degree decommissioning factors have been considered. It is also not possible to discuss the design summaries of all advanced reactor designs and their design assessment with respect to decommissioning within the scope of this paper. Instead, we look at only the AP-1000 reactor design as an illustrative example with respect to the theme of this paper.

AP1000 Design and Decommissioning Features

Westinghouse's AP-1000 standard design is a two-loop PWR with an output of approximately 1100 MWe. It is an evolution of the company's AP-600 design that was the first passive, advanced light water reactor design certified by the NRC in December 1999. The AP-1000 final safety evaluation report and final design certification were issued by the NRC in September 2004; however, a supplement to the final safety evaluation report was issued in December 2005. The final design certification rule was published in the Federal Register on January 27, 2006 and a revised final design certification was issued by the NRC in March 2006 [5].

The design life for AP1000 is 60 years without a planned replacement of the reactor vessel. The design does provide for the replacement of other major components, such as the steam generator. Relevant to our decommissioning review, the AP-1000 design minimizes the components and hence, facilitates future decommissioning. It comprises two heat transfer loops, each containing a steam generator, two reactor coolant pumps, one hot leg, and two cold legs as compared to a standard four-loop PWR comprising four steam generators, four hot legs, and four cold legs. The reduction of two steam generators and associated piping alone is a major reduction in the eventual component volumes and disposal cost (at the time of decommissioning). The reduction in equipment and structures is estimated as: 35% fewer pumps, 50% fewer safety valves, 83% less piping, 87% less control cable, and 50% less seismic building volume [7].

Design similarities between the AP-600 and AP-1000 also promote standardization, where medium and large reactors are of the same design family. This has advantages in reduced construction costs, operational system efficiencies, and levels of safety.

Westinghouse AP-1000 design will lead to significantly simpler and cheaper decommissioning because of the following:

1) Modular construction design that will simplify decommissioning,
2) Reduction in components through advanced design as discussed above.

NEW REACTOR DESIGNS AND DECOMMISSIONING FACTORS

Before we look at what decommissioning factors should be considered in the new reactor designs, we need to look at what decommissioning objectives are and what approaches are currently considered in the decommissioning industry.

Decommissioning Process and Approaches

The ultimate purpose of decommissioning is to allow removal of the regulatory controls from the retired reactors and release the nuclear power plant site for other purposes. In some cases, a partial release of the site may be the objective, or depending on the option selected, the site may be maintained under some controls for long periods. The basic deconstruction of a nuclear plant takes place in a multi-step process and under the jurisdiction of national nuclear regulatory agencies. In general, the process consists of developing a decommissioning plan, removing fuel from the reactor, dismantling systems and auxiliary structures, dismantling radioactive systems, removing major components, dismantling the reactor, demolition of bio-shield, demolition of the reactor containment, packaging and disposing waste (at licensed waste disposal sites), performing radiological surveys, and attaining regulatory approval for site license termination.

There is no unique or preferred approach to Decontamination & Decommissioning (D&D) of nuclear reactors but selection of an option may depend on the specific circumstances at the site, specific circumstances of the situation, or specific national policy. Three approaches to decommissioning that are considered at the present are: (1) immediate decontamination and dismantling, (2) safe storage, and (3) entombment. These are the three options that are termed as DECON, SAFSTOR, and ENTOMBMENT in the U.S. regulatory system. In the case of immediate decontamination and dismantling, the plant equipment, plant structures, and the auxiliary buildings are decontaminated to an acceptable regulatory level and dismantled for eventual packaging and disposal. The site is surveyed for residual radioactive contaminants and contaminated soil is removed if necessary. This permits removal of the regulatory control. Generally this option is chosen shortly after cessation of operations. Radioactive waste originating from D&D is treated, packaged and removed to an appropriate waste storage or disposal site. It should be recognized that even in the case of immediate decontamination and dismantling, a decommissioning project may extend over five or more years.

In the case of safe storage option, the nuclear plant is placed in a safe and stable condition for a long period of time, typically decades. It is subsequently dismantled and decontaminated to acceptable levels to permit removal of regulatory controls. In this case, the plant is generally left intact, except that the fuel is removed prior to safe storage, and the systems containing radioactive liquids are drained. Radioactive decay over the safe storage period leads to a reduction in the quantity of radioactive material that must be disposed of during eventual decontamination and decommissioning. In the entombment option, the plant, including structures, systems, and components, is encased in a mothball type concrete structure that is expected to be long-lived, typically hundreds of years. While the entombed structure may be appropriately maintained along with continued surveillance, the expectation is that no further D&D will be carried out until the radioactivity decays to a level that will eventually permit the removal of regulatory controls.

It needs to be noted that of the three options discussed above, the industry preference has been to choose immediate decontamination and dismantling or in some cases the safe storage. In the U.S., four reactors had their licenses terminated earlier and three others (Trojan, Saxton, Main Yankee) in the recent years. Sixteen other commercial reactors are currently undergoing various stages of decommissioning (Note that NRC's listing of power reactor sites undergoing decommissioning also lists Nuclear Ship Savannah, in addition to the sixteen commercial reactors). Of the three alternatives defined above, the shut down power plants have opted for either the DECON alternative or the SAFSTOR alternative; none have opted for the ENTOMB alternative.

Technologies for decontaminating and dismantling nuclear reactors are at a mature level. Nevertheless, there is a continual improvement in the techniques for decontaminating and dismantling based on the decommissioning experience gained and based on the innovations in materials and processes. This would result in better safety, more efficiency, and less cost in the future.

The waste generated during decommissioning is a major component of the overall decommissioning cost. These wastes are different from the operational wastes that the power plants are used to managing and present some new challenges. The major component removal and their disposal (the reactor vessel, the internals, the reactor coolant pumps, the steam generators, the pressurizer, the steam dryers etc.) are major tasks of a decommissioning project. The removal of fuel from the reactor (and its storage) prior to the start of any decontamination or dismantling is a separate step. This is because in most cases the governments are responsible for managing the spent fuel (storage and disposal) for reasons related to security and safeguards and also because disposal of such high level wastes are national projects. It is also worth noting that dealing with the spent nuclear fuel has generally been the Achilles' heel for the nuclear industry. In the U.S. for example, it is uncertain when the Yucca Mountain high level waste repository will actually open to accept the commercial spent nuclear fuel. In the meantime, with spent fool pool storage full or nearly full at most of the reactor sites, the industry has turned to constructing above ground dry storage facilities. For decommissioning projects, facilities such as the as the Independent Spent Fuel Storage Facilities, (ISFSIs) can add 70 to 100 million dollars to the decommissioning cost.

Decommissioning also generates large amounts of low level radioactive waste as well as bulk materials waste (demolition debris, contaminated soils etc.) that have only very small concentrations of radionuclides. Development of guidelines and release of bulk materials with no contamination or very minimal radioactive contamination have been difficult issues for the regulators and the industry for the past several years [8]. For the low level radioactive waste, disposal takes place at commercial disposal sites (for example, Barnwell facility in the U.S. which caters to the U.S. nuclear industry) or at national disposal sites (such as the Drigg site in the UK).

Very substantial experience already exists in decommissioning of nuclear reactors. Worldwide, some 115 power and research reactors have been retired from operation and are either undergoing decommissioning or will soon do so. In the U.S., as mentioned earlier, sixteen power reactors are in various stages of decommissioning; several others have already been decommissioned. Useful summaries of lessons on planning and managing decommissioning of nuclear facilities are available in literature such as the IAEA publications [9].

Incorporating Decommissioning factors into New Reactor Designs

Most of the detailed technical information for the new reactor designs and the design processes is proprietary and a detailed assessment is not possible as to what degree the decommissioning factors have been considered. However, one of the lessons learned from decommissioning of existing reactors has been that decommissioning was not given much thought when these reactors were designed some three or four decades ago. This applies not only in terms of issues related to decommissioning waste arisings, but also the more direct design issues such as the access to bring the large components out of the structures.

Based on the extensive decommissioning experience that is now available, it is possible to summarize some key areas where the new reactor designs could facilitate future decommissioning of these reactors. These considerations include: incorporation of modular concepts, innovations in equipment, materials, and system layout, lessons from decommissioning projects in terms of major component removal, decontamination technologies of today and future, access to highly contaminated components for decontamination, minimization of future waste volume generation during decommissioning, design assessment in terms of decommissioning cost per MWe effectiveness, and design concepts to allow Safstor at site or efficient removal, storage and disposal (Decon). In addition, provisions will need to be made for designs for spent fuel storage on-site, and eventual removal to a repository. Decommissioning factors can be grouped into the "Decommissioning Seven" described below.

Decommissioning Seven

As we have seen in the earlier sections, mature technologies for D&D are already available, and a substantial experience exists in decommissioning the nuclear reactors. It is necessary that this knowledge be one of the important considerations in the development of new reactor designs.

There are seven areas that I would call the "Decommissioning Seven", which need to be considered as important factors during the design development stage for the new reactors. While they may not be all encompassing, they are a good start in any new reactor design process. Clearly, the specific reactor designs may have additional considerations that should be taken into account.

1. Architectural and Structural Design Factors
    - Minimize the foot print of the key structures
    - Modular designs that will facilitate construction as well as deconstruction (during decommissioning)
    - Facilitate large component removal (possibly intact) out of the structures
    - Minimize cracks, crevices, joints that trap radioactive contaminants
    - Smoother surfaces – floors, walls etc.
    - Minimize and seal penetrations
    - Minimize the use of block walls
    - Judicious use of temporary shielding
    - Less is better
2. Site factors
    - Future use of the site and cleanup criteria
    - Recognize that what is rural now (current plant location) may be urban location in 60 years with much larger population density and with associated issues such as transportation, potential releases, cleanup criteria etc.
    - Potential for waste storage on site during decommissioning
    - Minimize the potential for leakage into the environment (one example is the recent tritium releases into underground at some reactor sites)
3. System Design
    - Reduction in the system components as much as feasible
    - Better reliance on passive safety systems

- Contained systems of systems
- Modular design
- Designs that will allow easier segmentation during decommissioning to reduce worker exposure
- Better separation of radioactive and non radioactive systems and areas
- Better designs of piping systems, HVAC systems, and sumps and drains
- Minimize potential traps for radioactive contaminants
- Decommissioning phase power requirements

4. Materials Design
    - Select materials for structures that will minimize activation products (for example, activation products that are of concern in concrete)
    - Select materials for systems that will minimize activation products (for example, issues related to stainless steel vs. carbon steel, use of zircaloy)
    - Optimized bio-shield designs
    - System shielding designs – block walls, lead, steel
    - Potential recycle and reuse of materials
    - Avoid or minimize materials that lead to hazardous waste (for example, asbestos, PCBs etc.)
5. Operational Design
    - Allow for easier maintenance and replacement of systems
    - Allow for decontamination of systems during operational life cycle
    - Allow remote handling capabilities in the design
6. Decommissioning Techniques of Today and Tomorrow
    - Take advantage of substantial decommissioning experience to date – challenges, lessons learned
    - Design based on the techniques of today but also allow for implementation of future techniques
    - Procedures in place to update the decommissioning plan for the reactor annually not only for decommissioning cost estimates but also to include an update of potential decommissioning techniques that can be used
    - Regulatory requirements updates on annual basis
7. Decommissioning Waste
    - Design to include considerations to minimize the volumes of radioactive waste during the decommissioning stage
    - Minimize the volumes of hazardous waste
    - Eliminate or minimize the potential for mixed waste
    - Based on the advanced reactor design, address issues related to specific wastes, such as, beryllium, graphite, sodium etc.
    - Bulk materials recycle, release or disposal
    - Spent fuel storage options either on-site (for example, ISFSI in U.S.) or off-site.

<u>Further Notes and Suggestions</u>

In addition to the Decommissioning Seven, listed below are some notes and suggestions that may be helpful in implementing some of the decommissioning considerations that this paper has listed.

1. It may be a good idea to embed decommissioning engineers on the reactor design team with a specific mission to help optimize the reactor systems and structures with a view

towards eventual decontamination and decommissioning, albeit it may look too distant into the future.

2. Upfront selection of the decommissioning option will be useful. Single unit plants with access to low level waste disposal options will generally choose the immediate dismantlement option. Multiple unit sites where one or more reactors may still remain in operation may choose a deferred dismantlement option. In case of immediate dismantlement option for one reactor at a multi-unit site, consideration must be given to shared auxiliary systems and structures.
3. Over the long operating period of the plant, innovations in technologies that are relevant to decommissioning are bound to occur. Decommissioning plans should be updated annually to include an update of the technologies/techniques that are then available and applicable.
4. The release criteria have also undergone evolution in the past. Criteria for releasing materials and soils with potential residual radioactivity, criteria for the release of bulk materials, as well as the criteria for releasing the site (termination of the license) could change in future. Keeping abreast of such developments will be helpful in the eventual decommissioning.

It is acknowledged that there may be significant technological advances in the future in the methods available for decontaminating and dismantling the nuclear reactors. This is especially relevant given that any of the new reactors will not be up for decommissioning for 60 or more years and breakthroughs in technology are very likely. Nevertheless, the current design development processes must consider the existing decommissioning technology, experience, and know how at the design stage and not simply leave it to the future. It is only prudent that the end of the power plant’s life cycle be a part of the design process from the very outset. Of course, if and when future decommissioning technologies come along they can make the decommissioning process even better, safer and cheaper.

CONCLUSIONS

Decommissioning is what we generally think of at the end of the lifetime of a power reactor. The message from this paper is to think of it from the very outset, at the time of designing and building a new reactor.

While defense in depth (DID) and the generation cost economics primarily drive the reactor design process, designing D&D into the new reactor designs is necessary even though such decommissioning will be several decades down the road. It will ensure that the tail end costs of the nuclear power are manageable. If decommissioning factors such as those discussed in this paper are taken into account at the early design stage, then, when the time comes to retire the reactors, the D&D can be completed in shorter time frames, with minimum generation of radioactive waste, with better radiological safety, and more cost-effectively.

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