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OPTIMIZATION OF COSTS VERSUS RADIATION EXPOSURES IN DECOMMISSIONING**G. J. Konzek****Pacific Northwest Laboratory*****Richland, Washington 99352****INTRODUCTION**

When considering decommissioning activities, it is desirable to achieve a balance between the cost of doing the work and the cost of minimizing the radiation dose to the workers. Ideally, one would like to minimize both of these costs, but, unfortunately, the conditions for achieving these minima rarely coincide in practice. One must make trade-offs to hold both costs and radiation doses to reasonable limits. In this paper I will discuss the opportunities available, during a reference light water reactor's (LWR) lifetime, to optimize its eventual decommissioning. I will present an optimization methodology that could easily be applied to other decommissioning projects, regardless of size. For each specific phase of the reactor's life cycle, different considerations and alternatives are used to formulate an empirical methodology to optimize costs and reduce occupational radiation exposure. This methodology, when fully developed, could be used as the data base for the Master Decommissioning Plan (MDP) of the power plant, which ultimately will guide the actual decommissioning.

As this evolutionary plan unfolds, items that are most likely to influence either external occupational radiation exposure or major expenditures are continually being identified, refined, and updated for future consideration by an optimization planner. When utilized in this manner, this concept represents a dynamic,

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ongoing methodology and constant quest for improvement during the entire lifetime of the reference nuclear project, and not just for the time frame conventionally known as "the decommissioning period."

OPPORTUNITIES FOR DECOMMISSIONING OPTIMIZATION AT THE DESIGN STAGE

Prevention and/or reduction of radiation exposure of operating personnel is an important consideration in the design of a nuclear power station. Cost-benefit evaluations of design features to reduce radiation exposure imply a dollar value for a unit of radiation dose. If the radiation-related duties at the station can be readily performed within the bounds of existing occupational radiation limits (10 CFR, Section 20.101), the economic saving due to further reducing the radiation exposure is nil. However, if the radiation dose for the same duties exceeds that permitted by regulation so that additional staff will have to be employed, then efforts to reduce radiation exposure may produce economic benefits. This logic is as true for the decommissioning phase as it is for the operational phase of a facility's life.

A strong case can be made that optimization of decommissioning cost is most effective when it is imbedded into the design effort from the beginning. However, this is not usually the case. Often, the pressure to adhere to a tight design schedule results in putting maintenance (and certainly decommissioning) considerations on the back burner while a design is being formulated. If optimization of decommissioning costs takes place early in the design phase, as it must if the maximum benefit is to be derived, an optimization planner may be the first person to consider decommissioning factors in detail. On balance, the optimization planner should recognize that since there is lower potential risk to the public during decommissioning, the designs of nuclear power reactor facilities for safe and efficient operation are more important than concerns for decommissioning.

Using as a basis studies conducted at Pacific Northwest Laboratory^{1,2,3} and others reported in the open literature, we have gained insights into plant design characteristics that could expedite and simplify (i.e., optimize) decommissioning. The relative effort that might be applied throughout the life cycle of the reference LWR to anticipate the decommissioning needs is presented in Figure 1. The "level of effort" scale indicates the relative intensity of this effort by the optimization planner in each part of the life cycle. As indicated in Figure 1, the complete optimization cycle for costs and planned reductions of occupational radiation exposures begins at the design stage. It is here that the potential benefits must be gauged against past experience, since the optimum choice may be innovative, involve

Figure 1. Opportunities and Relative Effort for Optimizing Costs and Reducing Radiation Exposure During the Lifetime of a Reference LWR

a process which has not yet been proven in practice, or involve the use of relatively new equipment. For example, with the exception of the reactor pressure vessel, which must meet stringent safety requirements requiring unitized fabrication, components such as pumps, steam generators, and heat exchangers, could be built in sections that would facilitate packaging during decommissioning. This feature is typical of the primary conflict which must be addressed by the owner and designer alike. Sectionalizing a liquid container for ease of packaging and shipping will increase gasketing and sealing requirements, result in the formation of crud traps to aggravate the contamination problems, and provide a higher potential for failure mechanisms during operation. The choice to date has been to minimize operational risks. This procedure aggravates the decommissioning task.

The need for design features to facilitate the decommissioning of nuclear reactors is widely recognized.^{4,5} The proposed changes emphasize in-plant radiation control features, more remotely controlled operations, and increased use of prefabricated parts for concrete structures for later ease of dismantlement. It is stated in a German study on decommissioning⁶ that "no fundamental difficulties with the decommissioning are perceptible which could give a reason for changing the basic design of present nuclear power plants." The authors do, however, consider a number of identified difficulties in detail for the purpose of reducing the decommissioning workload, and hence the costs involved. These include the increased use of the abovementioned prefabricated concrete parts, separation of contaminated systems from "clean" systems, and provision of sufficient room for decontamination operations where needed. These approaches, to a large extent, are already practiced at modern nuclear power stations, particularly with regard to the facilitation of repair work. This effort ultimately aids decommissioning.

A 1977 report by the National Research Council/National Academy of Sciences Committee on Radioactive Waste Management⁷ indicated that more thought must be given to the design of the basic structure of the buildings in commercial power stations "in order that their useful life can be extended even though their internal operational parts are replaced." By designing so that radioactive parts of a system can be replaced, two important goals can be achieved:

- an extension of the useful lifetime of the power generating station, and
- facilitation of the eventual decommissioning of the station.

In addition, since conceptual design is based on large part on estimated levels of the radiation exposure anticipated during

the operating lifetime of the nuclear facility, the level of exposure for that facility is often locked in, or fixed, with the initial design. Since the technology of decommissioning is still evolving, we can be fairly certain that there will be a concomitant evolution of NRC regulatory requirements. For example, if future regulations call for reductions in occupational radiation exposures, the cost of retrofitting could make continued operation of some of the older commercial nuclear power plants prohibitively expensive. With the added impetus of Part 50, Title 10 Code of Federal Regulations, which states: "A design objective shall be to facilitate decontamination and removal of all significant radioactive wastes at the time the facility is permanently decommissioned," an appreciation for the designer's dilemma becomes apparent.

The high costs of past reactor power plant decommissionings relative to nonnuclear facilities are usually attributed to: 1) more massive structures, usually of reinforced concrete; 2) packaging, transporting, and storing or burying radioactive wastes; 3) the need for remote operations, contamination control, and maintenance of radiological surveillance and protection systems; and 4) less cost-efficient manpower use under radiation zone conditions.⁸ Therefore, innovative ideas for improvements in the above four areas could offer considerable potential for developing improved, specialized decommissioning technology, directly leading to reduced costs and occupational radiation exposures.

We often observe that the advances achieved to optimize decommissioning activities can sometimes be currently utilized. It can be seen from Figure 2 that optimization planning should include feedback and subsequent evaluation of the information both from operating plants and from R&D sources. The use of this information can lead to improved design for maintenance. The challenge, however, is to improve maintainability without causing major increases in plant cost and construction schedule.⁹ In general, a design feature that reduces exposure to operating personnel can also be expected to reduce radiation exposure to decommissioning personnel. An example of the concept given in Figure 2 is the recent advance in metal cutting using the arc saw.¹⁰ Widely hailed as a new decommissioning tool, the arc saw obviously has application during the operating years as well. It can be used for various types of maintenance, including equipment removal and replacement activities. Therefore, early consideration given to equipment design, location, accessibility, and shielding requirements also should include consideration for recent advances in decommissioning technology.

The general criteria for selecting design features for consideration should be the beneficial effects such criteria

Figure 2. The Interrelationship of Decommissioning Technology and Initial Optimal Design for the Reference LWR

might have in: 1) decreasing decommissioning cost; 2) reducing total decommissioning time, and 3) creating less volume of radioactive waste. An ideal design feature also would reduce or prevent personnel exposure, and assure an adequate margin of occupational or public safety during inspection, maintenance, operation, safe storage, and/or dismantlement. Early application of radiation dose reduction designs yield benefits extending over the whole operating life of the plant, whereas the cost to achieve the reduction will be incurred initially over a relatively short period.

It should be noted that the time-honored methods used to overcome increased radiation levels during reactor plant life, i.e., remote operations and more shielding, usually translate into increased costs. There is no sure-fire formula to guarantee reductions in occupational radiation exposures in every instance. Presently, the shielding groups of A/E firms are actively involved in developing design methods for providing shield systems that 1) meet the radiological criteria set by the NRC regulations; and 2) facilitate inspection and maintenance for the purpose of increasing overall plant availability during the plant's operating lifetime. A third function must now be considered: i.e., to facilitate and optimize decommissioning.

OPPORTUNITIES FOR DECOMMISSIONING OPTIMIZATION DURING THE OPERATING YEARS

During the operating years, optimization is occasionally forced by external events. For example, the recent closures of several low-level waste burial grounds in the United States left many nuclear plant operators confronted with a choice: either continue the present radwaste cycle of activities and pay the additional transportation costs for the same volume of waste to more distant, rapidly filling burial grounds, or utilize newer equipment and methods to reduce the radwaste volume. In this instance, industry was prepared with new and improved technology and equipment that allowed the second alternative. The plant operator traded increased capital expenditures for lower operating costs. The use of the newer equipment has also resulted in a reduced occupational radiation exposure. This is due, in part, to an increased awareness of this need by the nuclear support industries. The resulting designs and equipment increase the optimization of man-machine interfaces that are an integral part of efficient operation in all nuclear facilities.

Fortunately, the optimization planner should have a somewhat longer time in which to consider the potential problem areas. Thus, he should be better prepared to deal with choices and

decisions. Certain facts are clear at the very onset of his task:

- 1) He can reasonably assess volumes, types, and radionuclide compositions of most of the expected decommissioning radwastes;
- 2) he can study relevant historical records of decommissioning of other nuclear facilities; and 3) he should establish a data bank relating to his own facility. Thus, he develops a keen awareness of most of the potential pitfalls. Once identified, the pitfalls can be dealt with effectively to eliminate or reduce their contributions to cost and/or radiation exposure, both during the operating years and ultimately during decommissioning.

The decommissioning planning field is wide open to new and innovative approaches in the methodology of decommissioning optimization, even though many pieces of such an optimization format would, by necessity, be slanted toward the specific nuclear facility being studied. There are many decommissioning activities common to a broad class of nuclear facilities that are amenable to standardization while still being flexible enough to handle site-specific situations. This flexibility allows the application of innovative thinking (an important human factor) that is so necessary to increase decommissioning productivity.

Accurate record keeping and as-built drawings become increasingly important during this time period, since they provide a major data base for planning the decommissioning of the facility. In addition, modifications and design changes made during the operating years should be examined for both immediate and downstream benefits (i.e., effects on decommissioning). For example, the choice of a simple item such as an epoxy paint might be significant. What is its longevity? Does it penetrate deeply into concrete? A few extra dollars spent now for a paint having specific qualities could mean less radionuclide penetration into the pores of the concrete, making it easier to decontaminate later. It would mean less waste volume of concrete to remove, resulting in lower transportation and burial costs. Considerations like these may not seem very important during the operational period, but they take on increasing importance as decommissioning time approaches.

Each modification and design change represents an opportunity to the optimization planner. He recognizes that these changes have the potential for even greater impact on costs and occupational radiation exposures than the original design. Experience has shown that the following design actions will reduce radiation exposure, both in the operating and in the decommissioning phases. Listed in order of effectiveness, these design actions are:¹¹

- stop adding equipment
- eliminate equipment
- simplify equipment
- relocate equipment in lower radiation field

- provide better chemical control and purification
- extend interval between maintenance periods
- arrange for quick removal for shop maintenance
- reduce in-situ maintenance times
- provide more space around equipment
- provide additional shielding.

In the foregoing examples, the considerations discussed are not new. They are not even novel, for most of us already apply this "best option" type selection process in the solutions to most immediate and pressing problems, but such solutions must be disseminated. Decommissioning optimization methodology is advanced only when the most cost-effective equipment and practices are 1) provided to the whole nuclear community for immediate consideration, utilization, and potential improvement; and 2) the applicable parts thereof are incorporated into a decommissioning data bank for future consideration and use. A continuing effort during the operating years should be directed toward ensuring that knowledge already available is expeditiously evaluated and optimally applied.

COUNTDOWN--THE LAST 5 YEARS OF OPERATION

The objective of a decommissioning is to place the nuclear power plant in a condition which adequately protects public health and safety and which will eventually result in termination of the licensee's responsibilities to the NRC. This objective may not be met in an optimum manner by a decommissioning plan developed early in the facility's life. IN all probability, such a plan would become obsolete. Therefore, the final 5 years of facility operation is an important period for developing practical decommissioning alternatives. By establishing a data bank during the operating years and adding to it as additional experience is gained, the most effective plan from economic, political, and technical viewpoints can be developed by the licensee during this time period using current exposure and contamination limits.

Studies performed to date indicate that radiation doses during decommissioning can be controlled to levels comparable to doses from operating reactors by the use of appropriate work procedures, shielding, and remotely controlled equipment. Therefore, the major effort in this last 5-year time period should be directed toward optimizing costs and reducing radiation exposures through refinements in these general areas. The best utilization of planning time results when an immediate dismantlement mode is the selected decommissioning alternative.

THE DECOMMISSIONING VIA IMMEDIATE DISMANTLEMENT

In establishing initial plans for the actual decommissioning, consideration should be given to cost-benefit analyses that include these important parameters:

- worker radiation exposures
- potential public radiation exposure
- development of realistic decommissioning costs, based on actual experience, when possible
- use of resources
- time and level of surveillance
- the likelihood of various levels of intrusion attempts.

It is preferable that the detailed plans be prepared by those responsible for their implementation. The rigidity required by the operating specifications and procedures during the reactor's life is not necessary in accomplishing the MDP. You will be severely limited if you simply must perform the decommissioning activities within a prescribed framework such as the Critical Path Method. During decommissioning, just as during the preceding planning and preparation period before final shutdown, the plan can and should be flexible. Initial estimates of costs, exposures, and resources should be recognized as just that--engineering estimates to be used for planning the initial work. It is from this base that the optimization planner can set targets and goals for cost and exposure reduction measures. Thus, the OP's professional worth and success will be quite discernible when measured against this yardstick.

In determining and pricing each decommissioning activity, the initial step is to determine possible procedures to follow that will allow decontamination and/or dismantling to proceed safely in a cost-effective manner. This initial procedure and its possible alternatives are then compared and reviewed to arrive at an optimum or "best" procedure for each task. The optimization technical approach for determining the best alternative for a given decommissioning work activity is presented in Figure 3. First, the work activity is clearly defined. Possible alternatives and disposition criteria are considered. Then, plans and techniques are developed to accomplish this task. Cost-benefit and safety analysis are performed. This procedure allows for the comparison of safety, man-rem, and cost from multiple perspectives. The result is the selection of a best procedure for accomplishing

- OPTIMIZATION -
TECHNICAL APPROACH

Figure 3. A Postulated Optimization Technical Approach for Individual Decommissioning Activities

each task based on available information. (One should bear in mind that later discovery of difficulties or alternative possibilities could cause this "best" procedure to be upgraded). This best procedure provides the indispensable function of outlining the series of tasks that must be sequenced and priced to come up with a total cost, a job-time estimate, and an occupational radiation exposure estimate.

A postulated methodology that optimizes the identification, categorization, and prioritization for major and minor classifications of decommissioning activities is shown in Figure 4. Standardized, site-specific criteria are established and then used to categorize each work activity into either the "major" or the "minor" part of the decommissioning program. If a work activity is selected as a major item, concerted efforts to optimize (i.e., further reduce cost and/or radiation exposure from the initial estimate) are made.

Subgroups will emerge in both the major and the minor categories as a result of the selection process illustrated in Figure 4. Thus, even those decommissioning activities relegated to minor status will be automatically prioritized into the MDP as noncritical exposure or expense work items. Continuing computerized follow-up of the minor work activities, based on regular, pertinent information input, is essential. By flagging costs or exposures that exceed preselected limits out-of-tolerance items can be placed in a reclassification status. Thus, if the preselected limit for a specific minor task is exceeded at any time, the task could be reinserted into the optimization program and the classification process begun again, based on the new data.

Application of this methodology should obviate any unpleasant surprises in the decommissioning program. It is possible that a highflyer or two within an optimization subgroup might result in a cost overrun or an occupational radiation exposure greater than anticipated. However, the net cumulative result of each optimization subgroup, in terms of both total cost and exposure, should be smaller than those total amounts would have been had this methodology not been used.

CONCLUSIONS AND RECOMMENDATIONS

The estimated worth of decommissioning optimization planning during each phase of the reactor's life cycle is dependent on many variables. The major variables are tabulated and relatively ranked in Table 1. For each phase, optimization qualitative values (i.e., cost, safety, maintainability, ALARA, and decommissioning considerations) are estimated and ranked according to

Figure 4. A Postulated Optimization Methodology for the Identification, Categorization, and Prioritization of Major and Minor Decommissioning Activities

TABLE 1. Qualitative Values of Optimization Methodology for All Phases of the Reference LWR Lifetime

Life-Cycle Phase ^(a)	Qualitative Value (Potential Benefits)		Other Considerations		
	Short-Term	Long-Term	Cost	Characteristics of Radiation Exposure Reduction	Potential Decommissioning Application
• Design and Construction	High	High	Incurred Initially Only ^(b)	Short-Term and Cumulative	High ^(c)
• The Operating Years					
Data Bank	Low	High	Nominal	Depends on the Program	High
Modifications and Design Changes	High	Medium to	Varies	Varies	Varies
Awareness Program ^(d)	Low to Medium	Low to Medium	Varies	Varies	Medium to High ^(e)
Exposure Reduction Program	High	High	Varies	Potentially Beneficial to Specific Areas of Operation and Ultimately to Decommissioning	High
• The 5-Year Period Before Final Shutdown	Low to Medium	High	Varies	Varies	High
• The Actual Decommissioning	High	Not Applicable	Varies	Varies	Immediate and High (to others)

(a) Immediate dismantlement is the decommissioning mode selected for the end of the life cycle.

(b) Equipment maintainability must be considered for maximum benefit.

(c) In general, a design feature that reduces external radiation exposure to operations staff also can be expected to reduce radiation exposure to decommissioning workers.

(d) Defined as the expeditious dissemination of current decommissioning technology to line management for the purpose of determining economic and operational applicability for its use.

(e) The results from in-the-field utilization of decommissioning-related equipment provides valuable information to the optimization planner.

their short-term and long-term potential benefits. These estimates depend on the quality of the input data, interpretation of that data, and engineering judgment. Once identified and ranked, these considerations form an integral part of the information data base from which estimates, decisions, and alternatives are derived. The optimization of costs and the amount of occupational radiation exposure reductions are strongly interrelated during decommissioning. The greatest benefits in either area are directly related to the amount of effort that is applied to each phase of the facility's life cycle by the optimization planner.

Realizing that building the necessary infrastructure for decommissioning will take time is an important first step in any decommissioning plan. It is because of 1) the contemporary socio-political realities concerning the nuclear industry; 2) the procurement and logistics realities of the marketplace; and 3) our own professional ethics that the planning and preparation for decommissioning must start early in the life of the nuclear facility. In addition, the following conclusions are established to achieve optimization of costs and reduced occupational radiation exposures:

- the assignment of cost versus man-rem is item-specific and sensitive to the expertise of many interrelated disciplines
- a commitment to long-term decommissioning planning by management will provide the conditions needed to achieve optimization
- to be most effective, costs and exposure reduction are sensitive to the nearness of the decommissioning operation.

The main attribute to developing the optimization/life cycle methodology is that it can be utilized starting at any time period in the life cycle of the nuclear facility for decommissioning planning. For a new plant, as we have seen we start at the beginning of the cycle, update continually, consider innovations, and realize full potential and benefits of this concept. For an older plant, the life cycle methodology permits a comprehensive review of the plant history and the formulation of an orderly decommissioning program based on planning, organization, and effort. This program can begin at any time before decommissioning, but the "sooner-the-better" is an essential realization for the optimization/decommissioning planner.

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The estimated worth of decommissioning optimization planning during each phase of the reactor's life cycle is dependent on many variables. The major variables are tabulated and relatively ranked ~~in Table 2.~~ For each phase, optimization qualitative values (i.e., cost, safety, maintainability, ALARA, and decommissioning considerations) are estimated and ranked according to

their short-term and long-term potential benefits. These estimates depend on the quality of the input data, interpretation of that data, and engineering judgment. Once identified and ranked, these considerations form an integral part of the information data base from which estimates, decisions, and alternatives are derived. The optimization of costs and the amount of occupational radiation exposure reductions are strongly interrelated during decommissioning. The greatest benefits in either area are directly related to the amount of effort that is applied to each phase of the facility's life cycle by the optimization planner.

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