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# Radiation-Related Impacts for Nuclear Plant Physical Modifications

Final Report

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## PREVIOUS REPORTS IN SERIES

NUREG/CR-4546	Labor Productivity Adjustment Factors	March 1986
NUREG/CR-5035	Data Base of System-Average Dose Rates	October 1987
NUREG/CR-5138	Validation of Generic Cost Estimates for Construction-Related Activities at Nuclear Power Plants	May 1988
NUREG/CR-5160	Guidelines for the Use of the EEDB at the Subcomponent and Subsystem Level	May 1988
NUREG/CR-4555, Revision 1	Generic Cost Estimates for the Disposal of Radioactive Wastes	September 1988
NUREG/CR-4627, Revision 1	Generic Cost Estimates: Abstracts From Generic Studies for Use in Preparing Regulatory Impact Analyses	February 1989

## ABSTRACT

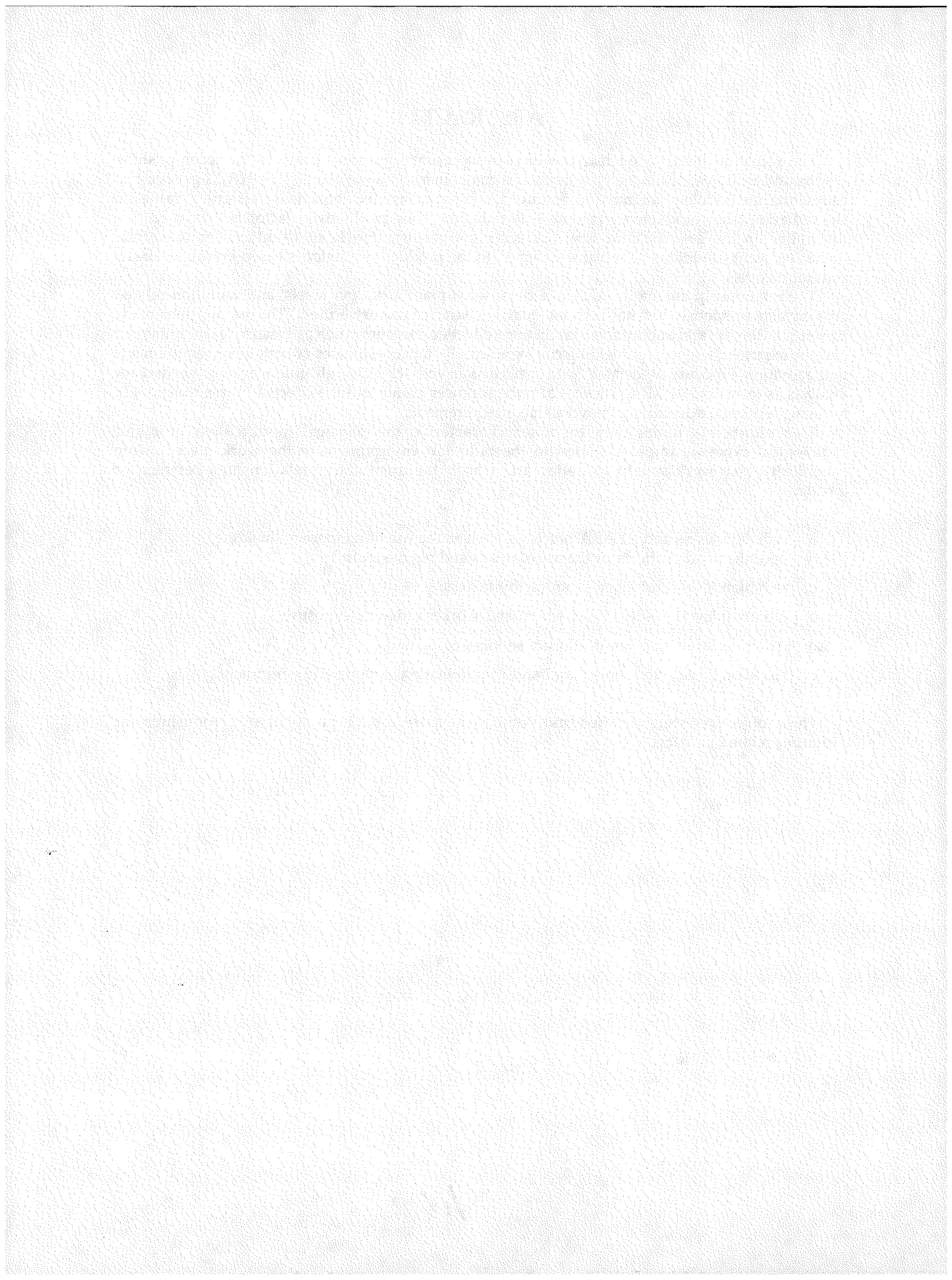
The radiation fields in nuclear power plants present significant obstacles to accomplishing repairs and modifications to many systems and components in these plants. The NRC's generic cost estimating methodology attempts to account for radiation-related impacts by assigning values to the radiation labor productivity factor. This radiation labor productivity factor is then used as a multiplier on the greenfield or new nuclear plant construction labor to adjust for the actual operating plant conditions. The value assigned to the productivity factor is based on the work-site radiation levels.

The relationship among ALARA practices, work-place radiation levels, and radiation-related cost impacts previously had not been adequately characterized or verified. The assumptions made concerning the use and application of radiation-reduction measures such as system decontamination and/or the use of temporary shielding can significantly impact estimates of both labor requirements and radiation exposure associated with a particular activity. Overall guidance was needed for analysts as to typical ALARA practices at nuclear power plants and the effects of these practices in reducing work-site dose rates and overall labor requirements.

This effort was undertaken to better characterize the physical modification cost and radiological exposure impacts related to the radiation environment of the work place. More specifically, this work sought to define and clarify the quantitative relationships between or among:

- a. radiation levels and ALARA practices, such as the use of temporary shielding, decontamination efforts, or the use of robots and remote tools;
- b. radiation levels and labor productivity factors;
- c. radiation levels, in-field labor hours, and worker radiation exposure;
- d. radiation levels and health physics services costs; and
- e. radiation levels, labor hours, and anti-contamination clothing and equipment.

These objectives were satisfied and resulted in more robust quantitative relationships for radiation-related impacts.



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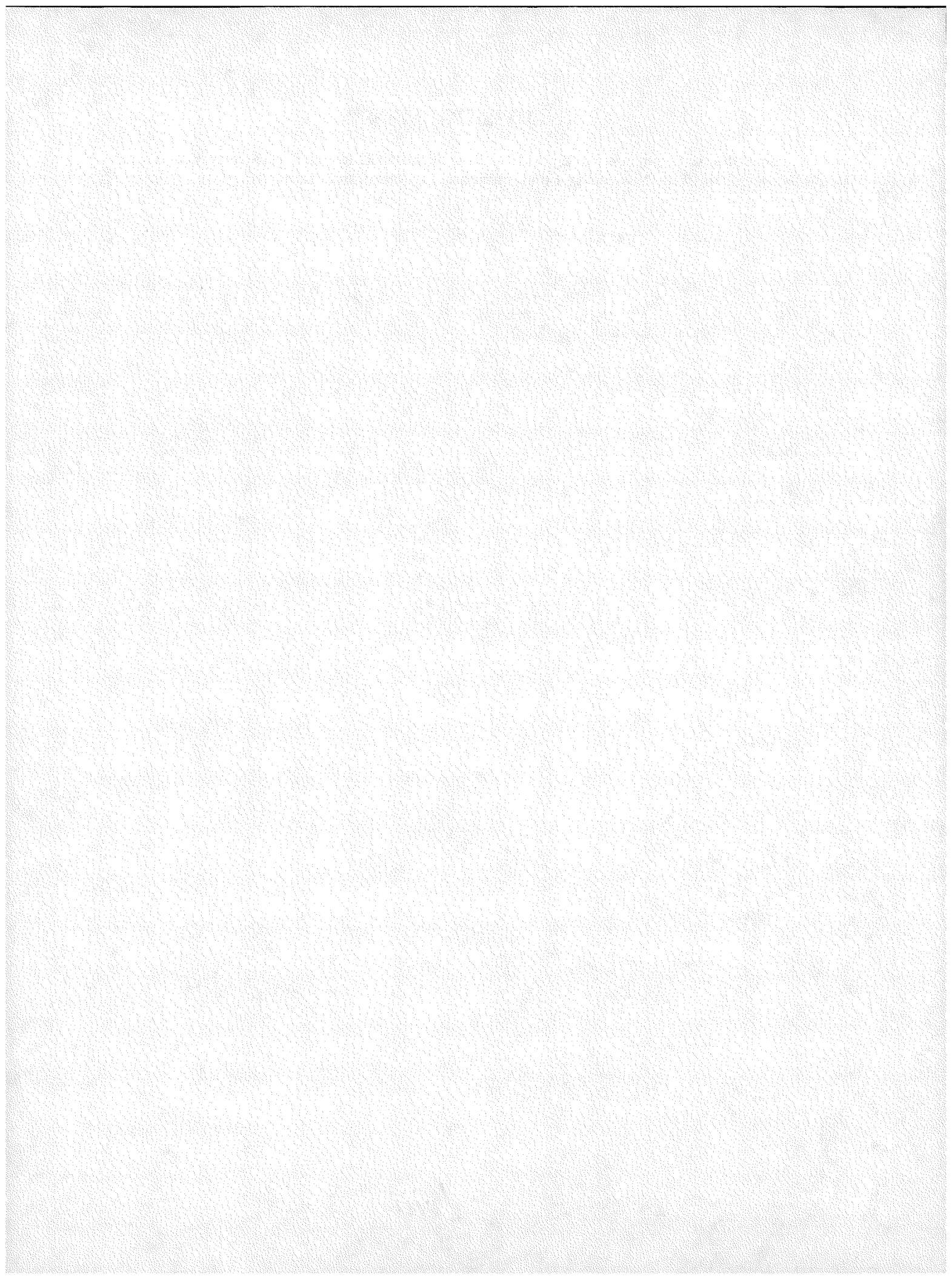
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## NOMENCLATURE

ALARA	As Low As Is Reasonably Achievable
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
DOE	Department of Energy
DPM	Disintegrations per Minute
EEDB	Energy Economic Data Base
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
INPO	Institute for Nuclear Power Operations
LWR	Light Water Reactor
mrem	millirem
NCRP	National Council for Radiation Protection and Measurements
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RCA	Radiological Controlled Area
RWP	Radiation Work Permit

# 1. INTRODUCTION

Over the past several years, the U.S. Nuclear Regulatory Commission (NRC) has developed a generic methodology to estimate the costs and impacts of NRC regulatory requirements. The methodology consists of several components, each of which is abstracted in "Generic Cost Estimates: Abstracts from Generic Studies for Use in Preparing Regulatory Impact Analyses," NUREG/CR-4627 (Ref. 1).

The NRC's generic cost estimation methodology relating to nuclear plant physical modifications is based on the premise that the costs of repairs or replacements in operating plants are related to the original greenfield or new construction costs of the affected systems, components or structures. In using the generic methodology, the first step in estimating costs is to evaluate the greenfield costs for new construction using the Department of Energy's Energy Economic Data Base (EEDB). These cost estimates are modified to take into account the diminished productivity of workers in actual operating nuclear power plants using labor productivity adjustment factors, the original derivation of which is given in "Labor Productivity Adjustment Factors," NUREG/CR-4546 (Ref. 2). The labor productivity adjustment factors are intended to take into account the lack of accessibility, congestion, management complexity, and potential radiation fields in operating plants.

The radiation fields in nuclear plants present significant obstacles to accomplishing repairs and modifications to many systems and components in these plants. The NRC's generic cost estimating methodology accounts for radiation-related impacts in several ways. First, depending on the radiation levels present at the work site, worker stay time may be very limited. This limited stay time decreases labor productivity and increases the number of workers required to perform a task. Second, anti-contamination clothing and equipment are needed to reduce exposure and minimize the spread of radioactive contamination. Third, health physics personnel are needed to police work practices, assist in minimizing worker exposure, and maintain exposure records. Fourth, the exposure actually received by workers is in itself a significant cost impact. Finally, repairs or modifications to radioactive systems invariably produce radioactive wastes, and these must be handled and disposed of in special ways.

The relationship among ALARA practices, work-place radiation levels, and radiation-related cost impacts previously had not been adequately characterized or verified. The assumptions made concerning the use and application of radiation-reduction measures such as system decontamination and/or the use of temporary shielding can significantly impact estimates of both labor requirements and radiation exposure associated with a particular activity. Overall guidance was needed for NRC analysts as to typical ALARA practices at nuclear power plants and the effects of these practices in reducing work-site dose rates and overall labor requirements.

The perceived strong relationship between radiation levels and labor productivity is currently quantified in Abstracts 2.1.7 and 2.1.8 of NUREG/CR-4627, Revision 1. In these abstracts, the radiation labor productivity factors can vary from 0 to 5.6, depending on the radiation levels. The guidance given for selecting the particular value as a function of radiation level has not been verified. This radiation factor potentially has a greater influence than any other labor productivity factor, so it is very important that this relationship be verified. Similarly, present estimates of the time workers actually spend in the radiation environment compared to the total time charged to a job are very approximate. These estimates are presently based on engineering judgement rather than on evaluation of actual data. Because radiation exposure costs can be a significant element in overall modification costs, radiation exposure estimates must be accurate and reliable.

Another cost aspect that is related to the nuclear plant radiation environment, but has not been characterized, is the usage and costs of temporary shielding, decontamination, and the use of robots and/or remote tools. Shielding is often used to reduce exposure and allow greater worker stay time. Then, too, system decontamination, robots and remote tools are used in certain situations and are coming into more wide-spread use. Current practices regarding when temporary shielding, decontamination, robots, and/or remote tools are used, their costs, and their impacts on worker

radiation exposure and labor productivity have not been defined. The impacts of these ALARA options on costs could be significant and should be defined.

## 1.1 PURPOSE

The purpose of this effort was to adequately characterize the physical modification cost and radiological exposure impacts related to the radiation environment of the work place. More specifically, this work sought to define and clarify the quantitative relationships between or among:

- a. radiation levels and ALARA practices, such as the use of temporary shielding, decontamination efforts, or the use of robots and remote tools;
- b. radiation levels and labor productivity factors;
- c. radiation levels, in-field labor hours, and worker radiation exposure;
- d. radiation levels and health physics services costs; and
- e. radiation levels, labor hours, and anti-contamination clothing and equipment.

Clarification of these radiation-related impacts was needed to allow users of NRC's generic cost estimating methods to produce more accurate and more reliable estimates of nuclear plant physical modification impacts.

## 1.2 REVIEW OF EXISTING DATA

A literature search for existing data on radiation-related impacts was performed for this study. In addition to the references cited in Section 7, 40 additional citations of relevant documents are included in the selected bibliography in Section 8. Discussions were also held with knowledgeable government and industry personnel to determine current industry practices.

Existing data sources can be divided into several categories.

### **Trade Magazines, Professional Journals, and Conference Proceedings**

Trade magazines, such as Nuclear News, EPRI Journal, and Nuclear Plant Journal, have periodic issues dedicated to health physics and radiation protection technology and practices. These publications should be reviewed by analysts to determine the latest tools and procedures for minimizing radiation exposure. Professional journals, such as Nuclear Engineering and Design, Nuclear Engineering International, Nuclear Technology, and Transactions of the American Nuclear Society, frequently report conference proceedings and have papers describing new techniques for dose reduction and ALARA. The NRC's annual Water Reactor Safety Research Information Meeting proceedings may have reports of recent research by the NRC in radiation protection issues.

### **Dose Reduction and Optimization Studies**

Most of the citations found describe research into dose reduction and optimization (i.e., ALARA) methodologies. It was hoped that some of these reports might provide some recent cost-benefit analyses that could be applied to this study. However, most of the data found were outdated. Total collective doses at nuclear power plants have decreased significantly since 1980 making cost-benefit analyses of this era obsolete.

The NRC has established an ALARA Center at Brookhaven National Laboratory (BNL) which maintains a data base of information on international projects on dose-reduction research and health physics technology. BNL issues periodic reports describing the new projects added to the data base. The data base is continually updated and can be accessed electronically via computer modem communications.

### **Decontamination**

Several plants use decontamination of systems prior to maintenance as a method for dose reduction. However, this practice is plant specific and difficult to generalize to plant class or the population as a whole.

### **Robotics and Remote Systems**

The use of robotics and remote systems was also inconsistent throughout the industry. Some plants use robots for fuel handling and underwater inspection. There is a trend toward greater use of these systems in the future. Cost-benefit analyses have been performed to justify the use of these systems over the plant lifetimes, but their use is sporadic in the industry, and rare during plant modifications. Remote tools are used frequently during plant maintenance in radiation fields, but their cost is judged insignificant.

### **Occupational Radiation Exposure Statistics**

The NRC issues an annual compilation of occupational radiation exposure at nuclear power plants and other NRC licensees. Radiation exposure at individual plants can swing from 150 person-rem to 1000 person-rem over a two-year period depending on the timing of refueling outages and major maintenance or repair activities, such as BWR recirculatory pipe replacement. The average for all plants is about 500 person-rem per year, but the available information does not allocate exposures to specific plant modifications.

## **1.3 REPORT ORGANIZATION**

This report has been organized into eight sections. Section 2 discusses the concept of ALARA and its impact on dose reduction and health physics support costs. Section 3 presents our methodology for estimating the radiation-related cost and exposure impacts that are incurred during nuclear power plant physical modifications. Section 4 provides a comparison of our estimates to actual data. Section 5 provides an example so that the analyst can see how the methodology is applied to a real problem. Finally, Section 6 summarizes the methodology and discusses the applications and limitations of the methodology in impacts estimation.



## 2. ALARA: ITS IMPACT ON DOSE REDUCTION AND HEALTH PHYSICS SUPPORT COSTS

The principle of maintaining radiation exposure as low as practicable has long been the goal of radiation protection programs. The first regulatory requirements were introduced in Title 10 of the Code of Federal Regulations, Part 20, in January 1971. This regulatory basis evolved from recommendations of the National Council on Radiation Protection and Measurements (NCRP), who first stated the basic principle as early as 1954. In the 1976 revision of 10 CFR Part 20, the term "as low as is reasonably achievable" (ALARA) was coined and defined to incorporate "...the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations..."

### 2.1 PHILOSOPHY

Since the early 1940s, it has been a recognized principle of radiation protection that the prescribed limits were, indeed, limits for planned exposure, and that every reasonable effort should be made to keep exposures below the limit and avoid unnecessary exposure to radiation. Therefore, the "as low as reasonably achievable" (ALARA) philosophy has long been the basic doctrine among radiation protection programs. This philosophy is based on the premise that all exposure should be considered to involve risk of somatic or genetic consequences.

"Reasonably achievable" is judged by considering the state of technology and the economics of improvements in relation to the benefit from the improvement. This philosophy leads to one objective: reduce personnel and environmental radiation exposure to the lowest level commensurate with sound economics, societal considerations and operating practices.

### 2.2 PROGRAMMATIC ELEMENTS OF ALARA

Although ALARA programs vary among utilities, common and fundamental elements prevail in all. The basic ALARA objective, to ensure that radiation exposures are kept to the lowest levels, requires a unified and utility-wide effort. Although the radiological controls staff is generally viewed as the principal executor of the ALARA program, all individuals affecting management, design or modifications, operation, and maintenance of a facility in which radiation exposure is received are directly or indirectly involved in the execution of the radiation protection and ALARA program. Therefore, management's policy and commitment to ALARA, training of personnel in ALARA and radiation protection principles, incorporating ALARA into initial design and procedures, establishing dose goals and auditing for effectiveness are all essential components of a successful ALARA program.

For the sake of brevity, however, only those elements of ALARA directly applicable to dose reduction techniques which can be applied to existing operating power plant environments will be discussed. The following is a list of ALARA elements:

#### ALARA Techniques During Work Planning

- Plan in advance
- Delete unnecessary work
- Determine expected radiation levels
- Determine protective clothing and equipment requirements
- Plan access to and exit from work area
- Ensure proper lighting
- Ensure proper lay-down space for tools and equipment

- Provide service lines (air, ventilation, etc.)
- Provide portable ventilation system
- Provide appropriate communications
- Consider potential accident situations or unusual events
- Perform as much work as practicable outside radiation area
- Minimize discomfort to worker
- Use mock-up duplicating work conditions
- Rehearse
- Brief workers

#### **Dose Reduction Considerations**

- Install temporary shielding between source and occupied area
- Flush or drain systems to eliminate radiation source
- Use decontamination techniques (e.g., chemical, mechanical, and electrochemical processes)
- Use remote handling tools in order to increase distance from source (e.g., reach rods)
- Use robots and remotely-operated tools to perform work and inspections in high radiation areas
- Use containment devices (e.g., glove boxes and tents)
- Flush and shield floor drains

#### **Exposure Control During Work Performance**

- Keep excess personnel out of radiation area
- Clearly post radiation levels
- Work in lowest radiation levels
- Evaluate use of fewer workers
- Track individual's radiation exposure
- Reevaluate reducing radiation exposure
- Perform routine surveys to keep abreast of radiation, contamination, and airborne radioactivity status

#### **ALARA Considerations Subsequent to Performance of Work**

- Evaluate effectiveness of dose reduction techniques
- Monitor dose estimates against goal
- Identify "lessons learned"
- Perform post-operation debriefing

A detailed check list of radiological control considerations for design modifications in nuclear power plants is provided in Appendix A.

## **2.3 COST-BENEFIT ANALYSIS**

In theory, a properly implemented ALARA technique results in benefits which are at least equal to or greater than its implementation costs. The benefits of ALARA programs are reductions in occupational and public radiation exposures. Reduced exposures reduce the risk of adverse radiation-related health effects. The monetary value of exposure reductions has not been rigorously quantified, and, indeed, may not be quantifiable in any precise way. Nevertheless, there is value in keeping exposure levels low.

The ALARA concept as it appears in the federal regulations does not provide guidance on what is considered "reasonably achievable" in the area of radiation exposure minimization. Naturally, the more aggressive the dose reduction techniques, the more expensive it becomes. Each employer faced with ALARA requirements must make a decision as to what is a reasonable expenditure for dose reduction and at what point further reductions are no longer justified due to costs.

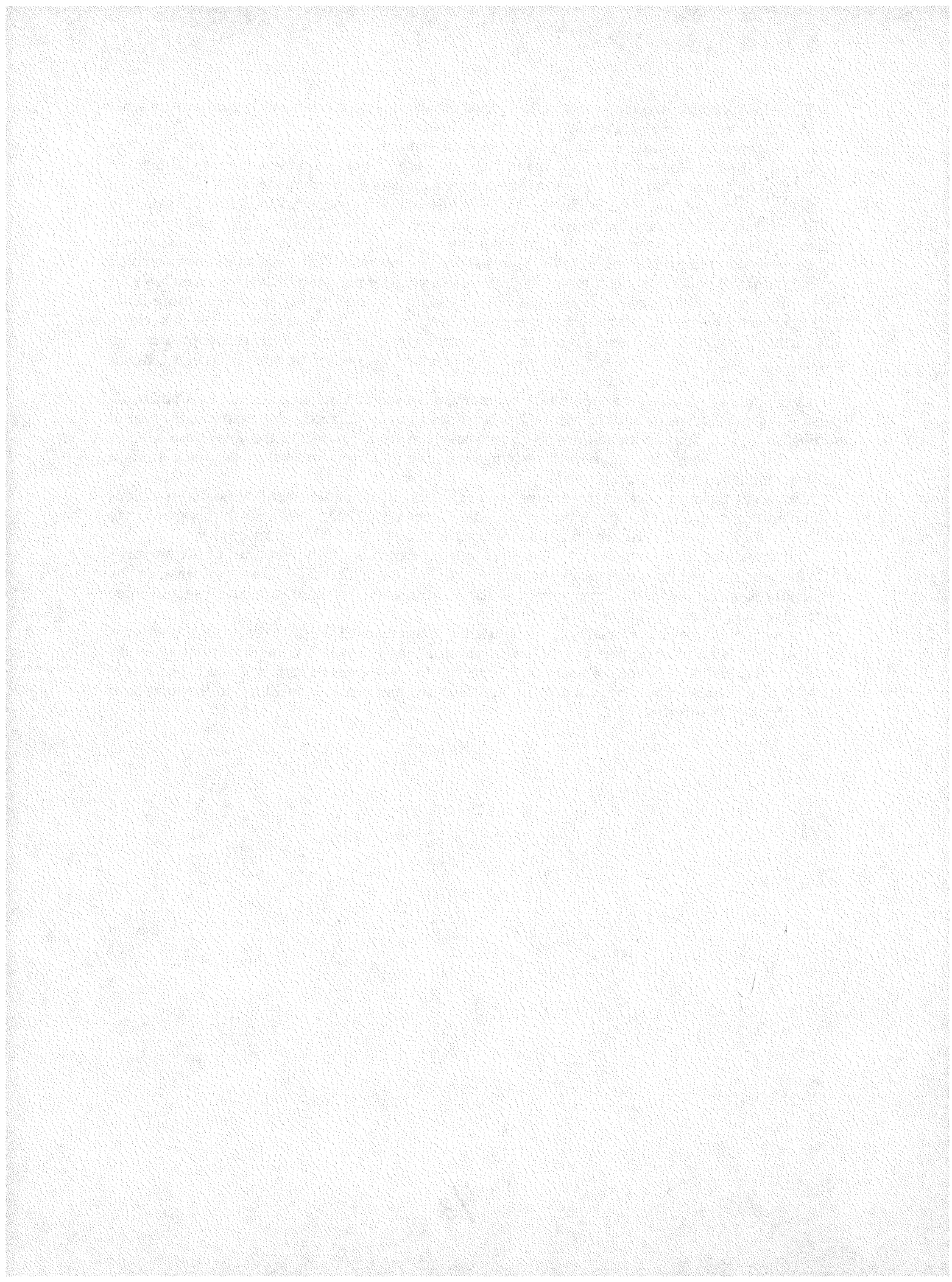
Several years ago, the NRC published a value of \$1,000 per person-rem to define the extent to which controls were to be used in reducing exposures to the general public from environmental releases. As nuclear power plants began to develop more aggressive ALARA programs, higher values were adopted for use in controlling occupational exposures. Most companies have accepted several thousand dollars per person-rem as a reasonable value of person-rem averted. One basis for such values has typically been the average worker's salary divided by his annual exposure limit. This approach assumes that if a worker is exposed up to his limit, he would be unable to perform any further productive work and a replacement would have to be hired. While this approach is an oversimplification, it nevertheless does provide a practical means for utilities to assign a dollar value to dose reduction activities.

Once a numerical value is adopted by a company, it is used as a management tool. A dollar per person-rem value allows standard cost-benefit analyses to be performed. For example, the cost of adding additional dose reduction processes to a task can be compared to the total dose savings expected multiplied by the value of this savings (i.e., the \$/person-rem value) so that a straight dollar to dollar comparison can be made.

The ALARA groups also use these values as a vehicle to affect management decisions on various plant modifications. For example, a project designed to net a \$200,000 savings for the company may be abandoned if 50 person-rem would be accumulated at a "cost" of \$5,000/person-rem.

The actual degree to which this concept is utilized depends on the strength of a company's ALARA program and its acceptance by management. Emphasis placed on "dose performance" by regulatory agencies and industry groups will also tend to result in more extensive use and more aggressive (higher) values placed on a person-rem.

For most NRC regulatory analyses, a quantitative assignment of ALARA costs is not necessary, since ALARA is an integral part of any health physics program which is implemented when the highest individual dose or the collective dose for a specific task exceeds certain values. The cost of ALARA as it relates to NRC-required plant modifications and repair is included in the total costs of health physics services.



### 3. IMPACTS ESTIMATION METHODOLOGY

The NRC's generic cost estimation methodology relies on a factoring approach to relate greenfield construction costs to costs of making repairs/modifications in operating nuclear plants. A key factor in this approach is the radiation labor productivity factor which attempts to characterize the influence of radiation levels on worker productivity. The value of this factor, in turn, is based on the work-site radiation levels. Analysts using this methodology can determine typical system-average dose rates from the information presented in "Data Base of System-Average Dose Rates at Nuclear Power Plants," NUREG/CR-5035 (Ref. 3). If other sources of such data are available (such as plant specific information), this can also be used with the generic methodology.

Several factors need to be quantified and quantitative relationships defined so that analysts can practically account for the impacts of radiological environments on the conduct of work at nuclear facilities. This section discusses this quantification. Factors and/or quantitative relationships are provided for the following:

- ALARA dose reduction factor,
- Radiation labor productivity factor,
- Use of the dose reduction factor and the radiation labor productivity factor in estimating physical modification labor requirements
- Estimation of occupational radiation exposures, and
- Estimation of health physics services costs.

#### 3.1 DERIVATION OF ALARA DOSE REDUCTION FACTOR

Significant dose reductions to individual and collective exposures are achievable with programmatic implementation of ALARA principles and techniques that are consistent with federal ALARA guidelines and regulations.

To ensure effective ALARA programs among the utilities, the NRC has specified certain management oversight responsibilities in Regulatory Guide 8.10 (Ref. 4). Management oversight responsibilities include periodic review and evaluation of the ALARA program in meeting goals and objectives as established by governmental regulations or industry-accepted standards. The ALARA program may be evaluated in context with radiological parameters which define the overall radiation protection program. Some particularly useful parameters for trend analyses include:

- collective doses for routine tasks, operations, maintenance and modifications/repairs
- collective doses for specific categories of plant personnel
- radiation dose readings around key systems/components
- effluent releases by key nuclides.

Although there have been attempts to quantify the effectiveness of ALARA programs in reducing exposure dose rates and personnel exposures to date, most of the data tend to be specific to a utility and limited to a small percentage of plant-related tasks. Moreover, since ALARA is an integral component of a health physics program, any methodology which attempts to evaluate quantitatively the contribution of dose reduction to ALARA techniques is likely to be subjective.

In spite of these inherent limitations with regard to historical data, an attempt was made to assign a generic quantitative dose reduction value to ALARA by polling the lead ALARA coordinators of nine utilities (six PWRs; three BWRs). In addition to telephone interviews, a questionnaire was submitted which included the following questions:

### Questions:

1. What is the collective person-rem criterion for the implementation of a formal documented ALARA review?
2. What is the average net percentage savings in collective radiation exposure that can be attributed to ALARA engineering techniques as prescribed by the ALARA review? (Use actual historical data of tasks for which a formal ALARA review and dose mitigation was performed.)

The responses to these questions were surprisingly consistent and yielded the following average values:

1. Collective person-rem criteria for the implementation of a formal ALARA review: the most frequently cited value was one person-rem.
2. Average net percent reduction in collective radiation dose: 20%

This average net dose reduction of 20% is based on recent utility surveys. It presumably takes into account all methods of dose reduction, including the use of shielding, decontamination, flushing, remote handling, and robots or remotely operated tools.

While most of the respondents cited 20% as the average dose reduction achieved as a result of ALARA activities, the actual dose reduction achieved is highly job-specific. For example, some utilities reported reducing doses by as much as a factor of 10 (a 90% dose reduction) for certain jobs. The 20% reduction should be considered as an average benefit when considering a wide range of activities.

A generic ALARA dose reduction factor of 0.8 is therefore recommended for adjusting system-average dose rates as cited in NUREG/CR-5035 (Ref. 3) when collective exposures exceed a value of one person-rem. By multiplying area dose rates by the ALARA dose reduction factor (0.8), the system-average dose rate will be reduced by 20%.

## 3.2 THE IMPACT OF RADIOLOGICAL ENVIRONMENTS ON LABOR PRODUCTIVITY

### 3.2.1 Radiological Parameters

The operation of a nuclear power plant results in the production of radionuclides which are the source of radiation exposure to individuals performing work within the plant. Radionuclides are produced by neutron activation of impurities in the primary coolant and uranium fission products released to the reactor coolant. The major source of shutdown radiation levels from activation products are the cobalt isotopes, Co-58 and Co-60. The principal fission nuclides contributing to shutdown radiation fields are Cs-134 and Cs-137. All of these radionuclides emit penetrating gamma rays which readily pass through structural materials of the primary reactor system. Contained radioactivity outside the reactor vessel is called crud. Radioactive crud, although physically contained in pipes, valves, tanks and other reactor system components, creates area radiation fields which contribute to whole body radiation exposure to workers. Radiation exposure to contained (sequestered) radioactivity is minimized by (1) shielding techniques, (2) maximizing distance between radiation source and worker, and (3) minimizing a worker's time in the radiation field (stay time).

Although nuclear power plants are designed to contain radioactivity (crud), minute fissures in reactor system components invariably result in small but significant quantities of radioactivity

being released into the work environment. This radioactive material may become airborne or deposit on surfaces and floors. Such deposits are termed radioactive contamination which may become the source of radiation exposure to the skin or to tissues internal to the body if radioactivity is inhaled or ingested. Radioactive contamination, in general, does not significantly add to external whole body radiation exposure. Techniques to eliminate or reduce human exposure to internal radioactive contamination include:

- prior decontamination of work area
- use of containment devices
- ventilation of work area
- wearing of anti-contamination clothing (anti-Cs)
- use of respiratory protection devices.

Since leaked radioactive crud is the principal source of radioactive contamination in the work environment, and since contained crud is the principal source for area radiation fields, there is a generic correlation between area radiation fields (millirem/hour) and surface and airborne contamination levels [expressed in disintegrations per minute per unit area (DPM/100-cm<sup>2</sup>) and maximum permissible levels, respectively].

Based on the results of 60,000 whole body counts at three BWRs and one PWR over a six year period, a 1985 Atomic Industrial Forum study (Ref. 5) calculated that the average radiation worker dose commitment per year from internal emitters was about 10 mrem. This internal dose contribution is small in comparison to the average external whole body dose of more than 600 mrem/year for the same period. Therefore, it is clearly the external whole body radiation exposure which is the limiting radiological parameter in the working environment of an operating nuclear power plant.

### 3.2.2 Radiological Controlled Areas

The purpose of Radiological Controlled Areas (RCAs) is to control access into areas where radiological hazards may exist. An RCA is any area where access is controlled by the radiological controls department. There are three basic criteria which define such areas of the nuclear power plant.

- Area radiation levels. Any area where a major portion of the whole body could be exposed to a dose rate in excess of 2.5 mrem/hour defines the lower limit of a RCA. This lower limit is based on the fact that an individual worker could spend as much as 2000 hours per year in a radiation field of 2.5 mrem/hour or less and not exceed the federal average annual dose of 5 rem (5000 mrem). Incremental radiation areas in excess of 100 mrem/hour are termed high radiation areas and those in excess of 1000 mrem/hour are termed locked high radiation areas requiring locked barricades.
- Contaminated surface areas. Any area in which contamination exceeds specific levels of surface contamination expressed in DPM/100-cm<sup>2</sup>. Varying levels are further defined by the type of emission (beta, gamma, alpha) and whether the contamination is "fixed" to the surface or removeable.
- Airborne radioactivity area. Any area where radioactive material in the ambient breathing air exceeds twenty-five percent (25%) of the limits defined in 10 CFR 20, Appendix B.

A radiological controlled area may be designated as such when any of the above three criteria are exceeded. By controlling personnel access into these areas, exposure to ionizing radiation can be minimized and monitored as required by federal regulations. All entries into a RCA by a worker

requires a radiation work permit (RWP) which, depending on radiological conditions, specifies stringent requirements relative to worker qualifications, protective clothing, respirator use, personnel radiation monitoring devices, and in-field stay times.

It is obvious from the above discussion that radiological conditions in the work environment have a profound effect on labor productivity. The following are the principal reasons for reduced worker productivity in radiation fields.

#### **Access/egress restrictions**

The amount of time required for workers, tools, and materials to be assembled in a radiological controlled work environment increases significantly over greenfield conditions. For radiological work environments, ingress time requires careful donning of anti-Cs, respirator, job briefing, familiarization with RWP requirements, assignments of dosimeters/monitoring instruments, RCA control point log-in time, etc. Exiting or egress time includes the time for protective clothing and respirator removal; personnel, tool, and equipment frisking for contamination; log-out at control point; and job debriefing. For stringent RWP requirements, ingress and egress time can easily consume one hour or more.

#### **Reduced worker efficiency**

Protective clothing, respirators, and electronic personnel radiation monitoring devices when required, represent impediments which handicap the worker physically and physiologically. Layers of anti-Cs restrict physical motion, add weight and induce heat stress. Respirators impair the field of vision, communication and physiologically tax the respiratory system of the worker.

#### **Exposure limits and in-field work time (stay time)**

By far the most significant factor affecting labor productivity is the impact of radiation conditions on the duration of in-field work time (stay time). Stay time is defined as the maximum time a worker is permitted to remain in a given radiological work environment. The considerations which govern stay time are complex. For nearly all nuclear power plants, the limiting variable for in-field stay time is the area radiation dose rate, which determines the external whole body radiation dose to the worker. Federal regulations limit the radiation exposure to 1.25 rem per calendar quarter (without NRC Form 4 data) and to 5 rem per year when averaged over a worker's lifetime. Federal regulations also contain strict limits for exposure of the skin, extremities, and internal organs. As a rule for nuclear power plant environments, the limiting condition for stay time is the external whole body exposure limit. Utilities assure against accidental exposure in excess of federal limits by establishing administrative limits which are lower than federal limits. Most nuclear power plants have adopted an administrative dose limit for whole body exposure of one rem per quarter, which applies equally to in-house employees and contractor personnel.

### **3.2.3 The Radiation Productivity Factor**

Any method for quantifying a generic radiation productivity factor must be consistent with the generic cost database of information available to analysts. The data available to the analyst are the EEDB labor hours/cost and system-average dose rates at nuclear power plants. The radiation productivity factor possess the following specific elements.

- **Simplicity.** The highly complex radiological variables which collectively define a radiological work environment must be reduced to a simple yet representative value.
- **Availability.** The radiation productivity factor must be derived from information which is generic and readily available to the analyst.
- **Quantitative.** It is essential that the radiation productivity factor reflects radiological work conditions quantitatively.

- Defendable. The derivation of the radiation productivity factor must be logical in the sense that it reflects cause and effect relationships between variables which characterize the radiation work environment and their impact on labor productivity.

It is obvious from the above discussion that the key element for the derivation of the radiation productivity factor is the in-field work time which is determined primarily by the radiation dose rate for a given work environment. In other words, the radiation productivity factor must be able to quantitatively reflect the degree by which radiation levels and stay time reduce normal direct work time relative to greenfield construction.

NUREG/CR-4546 (Ref. 2) and NUREG/CR-4627 (Ref. 1) have identified a value for normal direct work time of 37.5% for new nuclear construction. This corresponds to three hours of in-field productive work time of a normal eight-hour shift. For greenfield construction, the average worker would provide a total of 191 hours of direct work time in a three month or calendar quarter (i.e.,

$$\text{total direct work hours} = \left(170 \frac{\text{hours}}{\text{month}}\right) \left(3 \frac{\text{months}}{\text{quarter}}\right) (0.375) = 191 \frac{\text{hours}}{\text{quarter}}$$

Assuming that individuals assigned to do work in radiation environments perform no useful work other than that represented by the time spent within the radiological controlled area(s), one can readily calculate the maximum in-field work time per calendar quarter as a function of area dose rate.

Example #1: Calculate the maximum number of direct work hours per calendar quarter in an environment where the average area radiation level is 5 mrem/hour.

Solution: Since most utilities restrict external whole body exposure of worker to 1000 mrem/quarter, one can calculate that in an ambient radiation field of up to 5 mrem/hour, a worker could spend up to 200 hours per calendar quarter of direct work time without exceeding his quarterly limit of 1000 mrem.

Example #2: Calculate the maximum number of direct work hours per calendar quarter in an environment where the average area radiation level is (a) 20 mrem/hour, (b) 50 mrem/hour, and (c) 100 mrem/hour.

Solutions:

$$(a) \quad \frac{\text{Direct work hours}}{\text{quarter}} = \frac{1000 \frac{\text{mrem}}{\text{quarter}}}{20 \frac{\text{mrem}}{\text{hour}}} = 50 \frac{\text{hours}}{\text{quarter}}$$

$$(b) \quad \frac{\text{Direct work hours}}{\text{quarter}} = \frac{1000 \frac{\text{mrem}}{\text{quarter}}}{50 \frac{\text{mrem}}{\text{hour}}} = 20 \frac{\text{hours}}{\text{quarter}}$$

$$(c) \quad \frac{\text{Direct work hours}}{\text{quarter}} = \frac{1000 \frac{\text{mrem}}{\text{quarter}}}{100 \frac{\text{mrem}}{\text{hour}}} = 10 \frac{\text{hours}}{\text{quarter}}$$

Using this approach for defining the limitations on direct work hours per quarter, a radiation labor productivity factor can also be defined. The radiation labor productivity factor ( $F_r$ ) can be expressed mathematically by the following equation:

$$\begin{aligned}
 F_r &= \frac{\text{Maximum possible quarterly direct work hours}}{\text{Quarterly direct work hours based on radiation exposure limits}} \\
 &= \frac{\text{Greenfield normal direct work} \left[ \frac{\text{hours}}{\text{quarter}} \right]}{\left\{ \frac{\text{Quarterly Whole Body Exposure Limit}}{\text{ALARA adjusted area dose rate}} \right\}} \quad (3-1)
 \end{aligned}$$

Where:

$$\begin{aligned}
 \text{Greenfield normal direct work} \left[ \frac{\text{hours}}{\text{quarter}} \right] &= \left( 3 \frac{\text{months}}{\text{quarter}} \right) \left( 170 \frac{\text{hours}}{\text{month}} \right) (0.375) \\
 &= 191 \frac{\text{hours}}{\text{quarter}}
 \end{aligned}$$

$$\text{Quarterly whole body exposure limit} = 1000 \frac{\text{mrem}}{\text{quarter}}$$

$$\begin{aligned}
 \text{ALARA adjusted area dose rate} &= (\text{system average or area dose rate}^1) \\
 &\cdot (\text{ALARA dose reduction factor})
 \end{aligned}$$

Therefore:

$$\begin{aligned}
 F_r &= \frac{191 \frac{\text{hours}}{\text{quarter}}}{\left\{ \frac{1000 \frac{\text{mrem}}{\text{quarter}}}{\text{ALARA adjusted dose rate} \left[ \frac{\text{mrem}}{\text{hour}} \right]} \right\}} \\
 &= \left( 0.191 \frac{\text{hours}}{\text{mrem}} \right) \cdot \text{Adjusted Dose Rate} \left[ \frac{\text{mrem}}{\text{hour}} \right] \quad (3-2)
 \end{aligned}$$

Example: Calculate the radiation labor productivity factor for 20 mrem/hour work environment.

$$\text{Solution: } F_r = \left( 0.191 \frac{\text{hours}}{\text{mrem}} \right) \left( 0.8 \cdot 20 \frac{\text{mrem}}{\text{hour}} \right) = 3.06$$

This example assumes that the 0.8 ALARA adjustment factor applies.

The foregoing formulation indicates that the value of radiation labor productivity factor is linearly proportional to the prevalent dose rate of the work environment. Theoretically,  $F_r$  can vary from zero to very large values, depending on the area dose rates prevalent at the work location. However, a comparison of estimated labor hours versus actual labor for a number of specific physical modification tasks at operating nuclear plants indicates that the estimated values better match actual labor if a minimum value of 1.0 is assigned to  $F_r$ . The recommended approach, therefore, for quantifying the radiation labor productivity factor is as follows:

<sup>1</sup> Defined in NUREG/CR-5035 (Ref. 3)

For Dose Rates > 5 mrem/hour,

$$F_r = 0.191 \cdot \text{dose rate} \left[ \frac{\text{mrem}}{\text{hour}} \right] \quad (3-3)$$

For Dose Rates  $\leq$  5 mrem/hour,

$$F_r = 1.0$$

Note that since the overall labor productivity factor has the form :

$$F_L = 1 + \text{access factor} + \text{congestion factor} + \text{radiation factor} + \text{management factor}$$

and since the radiation factor has a minimum value of 1.0,  $F_L$  always has a value of at least 2.0.

The radiation labor productivity factor as defined by Equation 3-3 simply provides a numerical indicator of how problematic radiation is in terms of accomplishing work in a radiation environment. This factor should not be interpreted as a strict limitation on the the number of hours a worker can spend in such an environment, nor should it be interpreted as a precise indicator. Rather, Equation 3-3 provides a reasonable means of approaching the quantification of impacts due to radiation. The resulting factor values are judged to provide reasonable approximations of radiation effects on labor productivity.

### 3.2.4 Use of the Radiation Productivity Factor in Labor Cost Estimation

The estimation of labor costs for operating plant conditions involving radiation fields requires that the greenfield labor hours or costs be modified by means of the radiation productivity factor derived above, as well as other labor productivity factors that may apply. The generic cost estimation methodology relies on the EEDB for greenfield labor hours and costs. However, the EEDB labor values represent two different labor elements: (1) the time spent actually performing work and, (2) the time spent preparing for (or peripheral to) the actual work but which is not directly productive. This latter aspect can include time spent in work briefings, job planning, studying drawings and blueprints, worker qualification activities, rework, and rest breaks. It also allows for time spent waiting for instructions, waiting periods while quality checks and inspections are performed, and other necessary but not directly productive time that contribute to total job costs.

The labor productivity factors associated with work in operating nuclear facilities generally further reduce greenfield productive work time. These factors act on the direct work portion of the EEDB labor hours or costs. As stated previously, this greenfield productive work time is estimated to be about 37.5% of the total time. Thus the total adjusted labor hours or labor cost associated with equipment installation activities ( $C'_L$ ) can be represented by the following equation:

$$C'_L = 0.625 C_L + 0.375 C_L \cdot F_L$$

where:

- $C'_L$  = adjusted installation labor hours or labor cost
- $C_L$  = EEDB labor costs or labor hours representing greenfield (new construction) conditions
- $F_L$  = a function of the labor productivity factors

The revised formulation for the radiation labor productivity factor must be used in conjunction with the other labor productivity factors.

$C_L$  must be expanded to account for the individual labor productivity factors and to make the relationship practical. With this expansion, labor associated with the installation of materials, equipment, and structures in operating nuclear power plants is estimated by the following relationship:

$$C'_L = 0.625 C_L + 0.375 C_L (1 + F_a + F_c + F_m + F_r) \quad (3-4)$$

where:

$C'_L$	=	adjusted installation labor cost (or hours)
$C_L$	=	greenfield labor from EEDB or other source
$F_a$	=	access labor productivity factor
$F_c$	=	congestion labor productivity factor
$F_m$	=	management labor productivity factor
$F_r$	=	radiation labor productivity factor as defined by Equation 3-3

Additional factors are applied to account for learning curve effects and engineering and quality assurance costs. The learning curve effects primarily influence the directly-productive component of labor, whereas the engineering and quality assurance costs are determined as a fraction of the total labor, including both the productive and non-productive elements. Including these factors, the total installation labor relationship becomes:

$$C'_L = \{0.625 C_L + 0.375 C_L (1 + F_a + F_c + F_m + F_r)(1 + F_{lc})\} (1 + F_e) \quad (3-5)$$

where:

$F_{lc}$	=	learning curve productivity factor
$F_e$	=	engineering and QA factor <sup>2</sup>

Equations 3-4 and 3-5 deal strictly with the installation of materials and equipment in nuclear power plants. Other relationships are needed to account for labor costs associated with removal activities. Similarly, expressions are also needed for those efforts which encompass both removal and installation activities. The following discussions develop these relationships.

The generic approach for estimating labor associated with the removal of materials, equipment, and structures must also be re-evaluated in light of the revised methods for establishing the radiation labor productivity factor. The generic methodology for estimating removal labor builds on the installation labor estimates. Additional factors are applied to account for specific influences affecting removal labor. The specific removal factors used are as follows:

1. Structural factor (used if item to be removed is structural in nature, i.e., walls, floors, etc.).
2. Ancillary systems and structures factor (used if removal of target items impinges on ancillary systems or structures and requires their removal to accomplish the work).

The prior formulation, as reported in NUREG/CR-4627 (Ref. 1) and NUREG/CR-5138 (Ref. 6), also used a separate, additional radiation removal factor. Its use is no longer recommended. The radiation labor productivity factor as defined by Equation 3-3 adequately accounts for the effects of radiation on both installation and removal labor.

<sup>2</sup> Note that engineering and QA costs are calculated as a certain fraction of total direct costs. Therefore, any other direct costs, such as that for materials and equipment, should be included in the estimation of more comprehensive totals for engineering and QA costs.

The relationship for calculating total labor for jobs that include both installation and removal of items is as follows:

$$C''_L = C'_L + C_{RL} = C'_L (1 + FR_1)(1 + FR_2) \quad (3-6)$$

where:

- $C''_L$  = adjusted total labor (removal plus installation)
- $C'_L$  = adjusted installation labor (Equation 3-5)
- $C_{RL}$  = removal labor
- $FR_1$  = structural removal factor
- $FR_2$  = ancillary systems and structures removal (impingement) factor

Since  $C''_L = C'_L + C_{RL}$ , removal labor can be expressed as a function of the installation labor and the specific removal factors.

$$C_{RL} = C''_L - C'_L = C'_L \{ (1 + FR_1)(1 + FR_2) - 1 \} \quad (3-7)$$

Both the total labor and removal labor can be practically estimated using Equations 3-6 and 3-7 only when  $FR_1 + FR_2 > 0$ . For cases where  $FR_1$  and  $FR_2$  are both 0, Equations 3-6 and 3-7 indicate that removal efforts require no labor, an obviously incorrect result. In these cases, where the item(s) to be removed are not structural in nature, and where there is no impingement on ancillary systems and structures, removal labor can best be estimated as a certain fraction of installation labor. The limited amount of data available on actual nuclear plant physical modification activities indicates that removal labor generally is about 1/3 of installation labor. This applies to those cases where both the structural removal factor and the impingement factor are zero-valued. Therefore, for those cases where  $FR_1 + FR_2 = 0$ ,

$$C_{RL} = 0.33 C'_L \quad (3-8)$$

Since  $C''_L = C'_L + C_{RL}$ , then total labor (removal plus installation) can be estimated using

$$C''_L = 1.33 C'_L \quad (3-9)$$

Similarly, removal labor can be shown to be about 25% of the total labor for these cases, i.e.,

$$C_{RL} = 0.25 C''_L \quad (3-10)$$

The foregoing relationships are summarized below:

Installation labor:

$$C'_L = \{ 0.625 C_L + 0.375 C_L \cdot (1 + F_a + F_c + F_m + F_r) (1 + F_{lc}) \} (1 + F_e) \quad (3-5)$$

Removal labor:

If  $FR_1 + FR_2 > 0$ ,

$$C_{RL} = C'_L \{ (1 + FR_1)(1 + FR_2) - 1 \} \quad (3-7)$$

$$\text{If } F_{R1} + F_{R2} = 0,$$

$$C_{RL} = 0.33 C'_L \quad (3-8)$$

Total labor (installation plus removal):

$$\text{If } F_{R1} + F_{R2} > 0,$$

$$C''_L = C'_L (1 + F_{R1})(1 + F_{R2}) \quad (3-6)$$

$$\text{If } F_{R1} + F_{R2} = 0,$$

$$C''_L = 1.33 C'_L \quad (3-11)$$

### 3.2.5 Special Considerations for Large Piping

NUREG/CR-5138 (Ref. 6) identified that the generic labor estimation methods typically substantially overestimate piping removal and installation labor. This overestimation may be due to the fact that much of the work needed for the original installation may not be needed for piping replacement activities. For example, hangers, snubbers, and other supports need not be replaced along with the piping unless they are defective. The labor associated with the greenfield installation of these items would add to the greenfield installation costs. Since the greenfield costs include labor for installation of these support items, using an unadjusted base could easily result in overestimation of the labor associated with replacement of just the piping.

To correct for this labor overestimation problem associated with large piping, a large piping factor is applied to the generic estimating relationship. Based strictly on empirical observations from a limited number of actual data points, the generic labor estimates must be reduced by about a factor of 10 to reasonably agree with actual costs reported by utilities. For large piping, the labor cost estimation for piping replacement has the form:

$$C''_L = PF \cdot C'_L \cdot (1 + F_{R1})(1 + F_{R2}) \quad \text{for } F_{R1} + F_{R2} > 0$$

and

$$C''_L = PF \cdot 1.33 \cdot C'_L \quad \text{for } F_{R1} + F_{R2} = 0$$

where PF is the large pipe factor.

Reasonable comparisons between generic estimates and actual reported costs are achieved if PF is assigned a value of about 0.1. This factor applies only to piping with diameters of 18 in. or greater. PF is also applied to Equation 3-5 where installation-only is involved, and to Equations 3-7 or 3-8 where separate estimates are needed for removal activities.

### 3.3 ESTIMATES OF OCCUPATIONAL EXPOSURE

Occupational exposure can be estimated by multiplying in-field hours by the average dose rate prevalent at the work site. The dose rate should be determined based on actual conditions if such information is available. Barring this, the dose rates can also be obtained from the tabulations

presented in NUREG/CR-5035 (Ref. 3). An adjustment for ALARA procedures should be made if the cumulative dose for the work performed is expected to be one person-rem or more. As noted in Section 3.1, average dose rates can be reduced by 20% to account for the effects of general ALARA procedures.

The in-radiation-field labor hours are a fraction of the combined productive plus non-productive labor hours as calculated by Equations 3-5 through 3-11. The labor productivity factors which effect in-field hours are those which actually hamper work-place activities. These are the access and congestion factors, and the structural and impingement factors. These considerations or factors restrict the ability of radiation workers to actually perform their work or, in the case of the structural and impingement factors, add to or change the nature of the work to be done in the radiation field. Therefore, these factors influence the in-field time. Based on a comparison of actual exposures and estimated exposures calculated with and without the learning curve and management productivity factors, the use of the management factor is also recommended. A high management factor implies that the work is not well planned or well directed. Poor direction and planning can adversely impact the amount of time spent in the radiation field and the resultant worker exposure. Both the learning curve factor and the radiation factor can influence in-field time to some degree. However, these factors primarily influence the amount of time spent outside the radiation field. If they were used to calculate radiation exposures, the resulting values would considerably overestimate exposures for most activities. This observation is based on a limited comparison of actual versus estimated exposure data points. Therefore, the use of the learning curve and radiation factors is not recommended for calculating in-field time for radiation exposure estimates.

The remaining factor, that for engineering and quality assurance, does not influence in-field time and is not used for calculating exposures.

As with the estimates of labor hours, the estimation of radiation exposures requires the use of several different relationships, depending on the particular work activity of interest. The following relationships are recommended:

Exposure associated with installation activities:

$$E_I = AD \cdot 0.375 \cdot C_L \cdot (1 + F_a + F_c + F_m) \quad (3-12)$$

where:

$$\begin{aligned} E_I &= \text{installation radiation exposure, person-rem,} \\ AD &= \text{ALARA adjusted dose rate, rem/hour} \end{aligned}$$

For removal activities:

$$\text{If } FR_1 + FR_2 > 0,$$

$$E_R = AD \cdot 0.375 \cdot C_L \cdot (1 + F_a + F_c + F_m) [(1 + FR_1)(1 + FR_2) - 1] \quad (3-13)$$

$$\text{If } FR_1 + FR_2 = 0,$$

$$E_R = AD (0.33) (0.375) C_L (1 + F_a + F_c + F_m) \quad (3-14)$$

where  $E_R$  = removal radiation exposure, person-rem.

For combined removal plus installation (total):

If  $FR_1 + FR_2 > 0$ ,

$$E_T = AD (0.375) C_L (1 + F_a + F_c + F_m)(1 + FR_1)(1 + FR_2) \quad (3-15)$$

If  $FR_1 + FR_2 = 0$ ,

$$E_T = AD (1.33)(0.375) C_L (1 + F_a + F_c + F_m) \quad (3-16)$$

where  $E_T$  = combined installation and removal radiation exposure, person-rem.

In Equations 3-12 through 3-16,  $C_L$ , the EEDB labor or greenfield labor obtained from other sources, must be given in hours. Similarly,  $AD$ , the ALARA adjusted dose rate, has the units of rem/hour (not mrem/hour).

Estimates of exposures for repair/replacement of large piping (>18 in. diameter) should use the large pipe factor as previously defined in Section 3.2.5. The recommended value for this factor is 0.1, and it applies to all of the foregoing exposure relationships whenever large piping is the target item for a modification effort.

### 3.4 COST ESTIMATES FOR HEALTH PHYSICS SERVICES

Persons performing work in a commercial nuclear power plant are potentially exposed to radiation in varying amounts. This includes required plant modifications made in response to federal regulatory requirements. The licensee (utility) has the responsibility to ensure the health and safety of its workers and the public.

In a typical nuclear utility organization, the Radiological Controls Department has the responsibility to provide health physics services which ensure that the nuclear station is operated and maintained in a manner which minimizes radiological risks to workers, the public, and the environment, while allowing efficient conduct of operations. External radiation exposure, internal exposure, and releases of radioactivity into the environment must be controlled and maintained "As Low As Reasonably Achievable" and the licensee must abide by NRC regulations, Environmental Protection Agency (EPA) regulations, state regulations, Institute for Nuclear Power Operations (INPO) guidelines, and company policies.

Collectively, compliance is achieved through a highly technical and complex radiation protection program which employs a diverse staff of technical managers, engineers, scientists, first-line supervisors and field technicians. The implementation of the radiological protection program involves a complex array of technical and administrative tasks, which include the following major functions:

- Provide radiological task planning and work supervision to ensure that personnel exposures are minimized
- Assess all radiological environments for their ambient, surface contamination, and airborne levels for radiation/radioactivity
- Provide respiratory protection, bio-assay and whole body counting services
- Minimize all radiation exposure (i.e. ALARA) through engineering controls and other radiological protective techniques
- Control radioactive materials, radioactive contamination, and access to radiological controlled environments
- Provide properly calibrated instrumentation for radiological assessment of the plant, materials, and personnel
- Train and qualify staff personnel
- Maintain all records relating to radiological plant conditions, dosimetry, bio-assay, instrument calibrations, etc.

### 3.4.1 Basis for Cost Estimation

Since the purpose of a radiological controls department is to provide health physics services, it follows that if radiation fields and radioactivity were not an integral component of commercial nuclear power operation, the need for radiological controls and associated health physics services would not exist. The scope of health physics services provided for a given plant is dictated largely by the radiological conditions of the plant and the amount of work conducted in radiological-controlled environments. Work includes those periods of time when the plant is fully operational as well as during outages which include refueling, maintenance, repair, and modifications of plant systems.

NRC Regulatory Guide 8.8 (Ref. 7) points out that annual collective exposure at commercial light water cooled reactors (LWR) has ranged from less than 100 person-rem per plant to over 1000 person-rem per plant, with typical values in the 400 - 1000 person-rem range. It is important to note that average annual values also reflect average capacity factors of 70 - 75%. For a given plant, the annual exposure may obscure the single most important variable, which is the duration of the operating cycle. For example, one plant went from 118 person-rem in 1978 to 1161 person-rem in 1979 due to scheduled maintenance and refueling. Because of inherent design differences, annual collective doses for PWRs tend to be considerably lower than for BWRs. PWR collective doses tend to stabilize at about 400 person-rem between the third and fifth year of commercial operation. BWRs require about five years to stabilize at about 600 to 800 person-rem per year. The weighted average for all LWRs in recent years (1985 and 1986) is about 500 person-rem (Ref. 8).

Cost estimates for health physics services are therefore based on the following interrelationships:

1. As the number of years of plant operation increases, the required scope of radiological control services increases due to increased amount of work hours required for plant maintenance, repair modification of major system components.
2. Also, there is a steady increase in the levels of radiation fields and surface/airborne contamination as the number of years of plant operations increases. These increases are primarily the result of crud build up, failed fuel, and cumulative plant maintenance and repair activities.
3. The combination of increased work activity in RCAs combined with increases in radiation levels throughout the plant result in increased collective dose as well as required health physics support services.

The quantitative interrelationship between the annual station person-rem value and health physics support costs can be illustrated by citing two extreme plant conditions which quantitatively affect required health physics support services.

Steady-state plant operations: During steady-state operations (100% power), cumulative radiation exposures are lowest, reflecting minimal work activities in work environments with low radiation fields.

Plant outages: During plant outages, which include refueling, plant maintenance, repair, and modifications, there is a dramatic increase in the labor force and total RWP work hours. Moreover, work must frequently be conducted in high radiation work environments. The cumulative radiation worker dose increases during outages and reflects increased labor activity and radiation fields. Concurrent with increased work activities in radiological

controlled work environments, there is a proportional increased need for health physics services.

A comprehensive indicator which encompasses all health physics services as they relate to plant activities in radiological environments is the cumulative radiation exposure. Cumulative radiation exposure is expressed in person-rem and therefore represents the cumulative product of labor hours and radiation exposure dose rates in the working environment(s).

$$\text{Total person-rem} = \text{total labor hours} \cdot \text{average exposure dose rate}$$

Based on the proportionality between health physics services and station cumulative exposures (person-rem), it is possible to assess the cost of health physics services per unit person-rem for a specific utility by means of the following formula.

$$\text{Health Physics Service Cost} \left[ \frac{\$}{\text{person-rem}} \right] = \frac{\text{Radiological Controls Annual O\&M Budget} [\$]}{\text{Cumulative Exposure Dose} \left[ \frac{\text{person-rem}}{\text{year}} \right]}$$

### 3.4.2 Applicability

A generic health physics service cost estimator can be established by dividing the average Radiological Controls Department O&M budget for a single station by the average annual cumulative worker exposure. Among utilities polled, the average O&M budget in 1988 was \$4.1 million.

Assuming an average annual station exposure of approximately 500 person-rem, the cost per person-rem is approximately \$8000, as defined by the following equation:

$$\begin{aligned} \text{Average HP Service Cost} \left[ \frac{\$}{\text{person-rem}} \right] &= \frac{\text{Average Rad Con O\&M Budget} [\$]}{\text{Average Cum. Exp. Dose} [\text{person-rem}]} \\ &= \$8000/\text{person-rem} \end{aligned}$$

The generic \$8000/person-rem cost estimator for health physics services is applicable to modifications and repairs at PWRs and BWRs with operating histories. The cost of \$8000/person-rem in 1988 dollars represents total health physics costs associated with ALARA radiation exposure, worker qualification, training, protective clothing, dosimetry, bio-assay, respiratory protection, radiation instrumentation, anti-Cs, radiation surveys, job coverage, maintenance of health physics records, RWPs, etc.

## 4. COMPARISON OF ACTUAL VERSUS ESTIMATED LABOR AND OCCUPATIONAL EXPOSURE

### 4.1 COMPARISON OF LABOR ESTIMATES

Table 4-1 gives a comparison of estimated versus actual labor for a number of specific physical modifications reported by nuclear utilities. These results are presented as the ratio of actual-to-estimated labor. Ratios are shown for total labor (removal plus installation), removal labor, and installation labor. Estimated labor values used in generating Table 4-1 were produced using the revised methodology discussed in Section 3. Ideally, the actual-to-estimated ratio should be 1.0 in all cases. The nearer the values are to 1.0, the better the generic methods accurately model actual labor requirements.

Table 4-1 also shows the ratios of actual-to-estimated total labor for estimates derived using the correlations and factors previously reported in NUREG/CR-5138 (Ref. 6). This old correlation somewhat underestimated the labor requirements, and showed somewhat greater deviation from the actual labor compared to the estimates provided by the revised correlations.

The actual conditions surrounding the physical modifications listed in Table 4-1 are not known to the degree of certainty desired. Labor productivity factors used in the generic methodology labor estimates were selected based on the descriptions of the work environment as provided by utilities. In many cases the descriptions of the work environment were sketchy and did not provide a firm basis for the selection of the various productivity factors. The labor productivity factors in these cases were chosen based on "typical" or expected conditions.

Table 4-2 presents the specific labor productivity factors chosen for each physical modification activity. The dose rates characteristic of the specific work environments and the resultant radiation factor are also shown. Where dose rates were not specifically identified with the data obtained from utilities, they were chosen based on the system-specific dose rates presented in NUREG/CR-5035 (Ref. 3). An exception to this approach was needed for the recirculation piping replacement activities. The total radiation exposure reported for these modifications, together with the actual labor hours needed to accomplish the work, indicates that the average work place radiation levels were considerably less than 100 mrem/hour. The average dose rates cited in NUREG/CR-5035 for BWR recirculation piping systems are about 200 mrem/hour. However, this value reflects conditions a few days after plant shutdown. The 200 mrem/hour also reflects conditions in the absence of any decontamination, shielding, or other ALARA actions. These piping replacement efforts were characterized by extensive decontamination. This, together with other dose reduction activities, lowered doses well below the ~200 mrem/hour levels typical of BWR recirculation piping systems. For these modifications, a dose rate of 50 mrem/hour was used in generating the radiation labor productivity factor.

The radiation labor productivity factor values given in Table 4-2 were calculated using Equation 3-3. In all cases, the assumption was made that ALARA practices had been followed to reduce the typical system dose rates by 20%.

Table 4-2 also displays the total combined labor productivity factor used for estimating the total labor requirement using the generic methodology. This factor multiplies the EEDB labor to produce the generic labor estimates. The values of this total factor range from a low of about 1.8 to a high of more than 50.

A graphical comparison of the estimated versus actual labor requirements for the modification activities listed in Tables 4-1 and 4-2 is presented in Figure 4-1. Total labor hours (i.e., removal plus replacement) are shown. The diagonal line represents an ideal relationship wherein the estimates perfectly match the actual data. The clustering of the data about this line indicates that the generic estimating methods do a reasonably good job of predicting labor requirements for physical modifications.

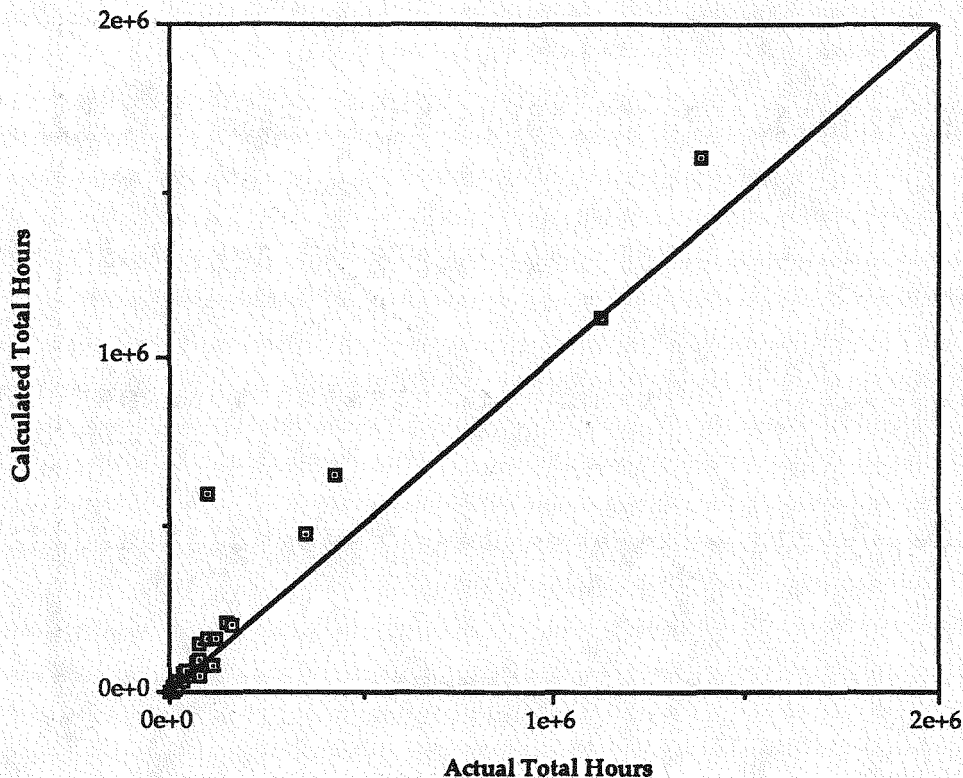
Table 4-1. Comparison of Actual vs. Calculated Labor for Physical Modifications

Modification Activity	Actual/ Estimated Total Costs	Actual/ Estimated Installation Costs	Actual/ Estimated Removal Costs	Old Actual/ Estimated Total Costs
Intake Cooling Pump	1.95	-	-	1.73
#3 Spent Fuel Pool Rerack	0.74	-	-	1.05
#4 Spent Fuel Pool Rerack	0.82	0.85	0.75	1.16
Fire Doors (open area)	0.94	-	-	2.74
Class 1E Station Battery	1.14	-	-	1.18
Reactor Protection System	0.68	0.86	0.13	0.14
Condensate Storage Tank	-	1.89	-	-
2 High Pressure Feedwater Heaters	1.98	1.68	2.71	1.16
2 High Pressure & 4 Low Pressure Feedwater Heaters	1.55	1.33	2.12	0.92
2 Low Pressure Feedwater Heaters	1.58	-	-	0.93
Audiliary Condenser Pump	0.59	-	-	0.48
Condenser Retube	1.19	0.71	2.63	1.02
Radiation Monitoring	1.13	1.38	0.38	0.94
H <sub>2</sub> Recombiner	0.61	0.72	0.28	0.51
Source Range Monitor/ Intermediate Range Monitor (dry tubes) Replace	0.47	-	-	0.94
Make Up Pump	1.57	1.25	2.51	1.58
Fire Doors (containment)	0.97	-	-	1.02
Chillers	0.48	0.43	0.65	0.51
#1 Manipulator Crane	-	-	0.47	-
#2 Manipulator Crane	-	-	0.25	-
#3 Manipulator Crane	-	-	0.12	-
Emergency Cond. Piping	0.66	0.73	0.54	0.59
Resistive Temperature Detector & Pressure Transmitters	0.76	0.88	0.41	1.00
#2 Spent Fuel Pool Rerack	0.55	-	-	0.80
#1 Recirculation Pipe	0.16	0.14	0.22	0.56
#2 Recirculation Pipe	0.61	0.67	0.43	1.30
#3 Recirculation Pipe	0.77	0.87	0.47	0.98
#4 Recirculation Pipe	0.78	0.81	0.69	0.74
#1 Steam Generator Support	-	-	0.62	-
#2 Steam Generator Support	-	-	0.52	-
#1 Main Steam Pipe	2.16	2.40	1.43	1.66
#2 Main Steam Pipe	1.34	1.27	1.55	1.08
Reactor Coolant Pump #1	0.70	0.59	0.88	0.87
Reactor Coolant Pump #2	0.54	0.46	0.68	0.68
Reactor Coolant Pump #3	0.81	0.68	1.01	1.06
Reactor Coolant Pump #4	0.70	0.59	0.88	0.98
#1 Feedwater Pipe	1.01	1.11	0.84	1.36
#2 Feedwater Pipe	0.72	0.25	1.49	1.03
Core Spray Piping	1.32	0.29	3.03	1.80
Steam Generator #1	0.87	1.04	0.57	1.01
Steam Generator #2	1.00	1.23	0.62	1.18
Steam Generator #3	0.66	0.73	0.54	0.80
Steam Generator #4	0.74	0.84	0.57	0.91
#1 Spent Fuel Pool Rerack	0.79	-	-	1.32
Low Power Range Monitor	1.46	-	-	2.39
<b>Average</b>	<b>0.96</b>	<b>0.92</b>	<b>0.94</b>	<b>1.08</b>

Table 4-2. Assigned Labor Productivity Factors

Modification Activity	F <sub>a</sub> (Access and Handling)	F <sub>c</sub> (Congestion)	F <sub>m</sub> (Management)	F <sub>lc</sub> (Learning Curve)	F <sub>e</sub> <sup>*</sup> (Engineering and QA)	FR1 (Structural Removal)	FR2 (Impingement)	Dose Rate [mrem/hour]	F <sub>r</sub> (Radiation)	Total Factor (New Calc/ EEDB)
Intake Cooling Pump	0.3	0.2	0.3	0	0	0	0	0	1	2.23
#3 Spent Fuel Pool Rerack	0.1	0	-0.2	0	0	0	0	0	1	1.78
#4 Spent Fuel Pool Rerack	0.1	0	-0.2	0	0	0	0	0	1	1.78
Fire Doors (open area)	0.1	0	-0.2	0	0	0.5	0	0	1	2.01
Class 1E Station Battery	0.1	0	0.3	0	0	0	0	0	1	2.03
Reactor Protection System	0.1	0	0.3	0	0	0	0	0	1	2.03
Condensate Storage Tank	0.1	0.1	0.3	0	0.25	0	0	0	1	2.6
2 HP Feedwater Heaters	0.3	0.4	0.3	0	0.25	0	0.4	1	1	3.06
2 HP & 4 LP FW Heaters	0.3	0.4	0.3	0	0.25	0	0.4	1	1	3.06
2 LP Feedwater Heaters	0.3	0.4	0.3	0	0	0	0.4	1	1	2.45
Auxiliary Condenser Pump	0.3	0.2	0.3	0	0	0	0	5	1	2.23
Condenser Retube	0.3	0.2	0.3	0	0	0	0	5	1	2.23
Radiation Monitoring	0.3	0.2	0.3	0	0.25	0	0	5	1	2.79
H <sub>2</sub> Recombiner	0.4	0.4	0.4	0	0	0	0	10	1.53	2.7
SRM/IRM (dry tubes) Replace	0.4	0.4	0.4	1.5	0	0	0	20	3.06	7.4
Make Up Pump	0.3	0.2	0.3	0	0	0	0	20	3.06	3.26
Fire Doors (containment)	0.4	0.4	0.4	0	0	0.5	0	20	3.06	3.89
Chillers	0.4	0.4	0.4	0	0	0	0	20	3.06	3.46
#1 Manipulator Crane	0.4	0.4	0.4	2.6	0.25	0	0	20	3.06	12.87
#2 Manipulator Crane	0.4	0.4	0.4	1.5	0.25	0	0	20	3.06	9.25
#3 Manipulator Crane	0.4	0.4	0.4	0	0.25	0	0	20	3.06	4.33
Emergency Cond. Piping	0.4	0.4	0.4	0	0	0	0.6	25	3.82	4.61
RTD & Pressure Transmitters	0.4	0.4	0.4	0	0.25	0	0	40	6.11	6.24
#2 Spent Fuel Pool Rerack	0.3	0.4	0.3	0	0	0	0	40	6.11	4.89
#1 Recirculation Pipe	0.4	0.4	0.4	2.6	0	0	0	50	7.64	18.55
#2 Recirculation Pipe	0.4	0.4	0.4	1.5	0	0	0	50	7.64	13.13
#3 Recirculation Pipe	0.4	0.4	0.4	0.4	0	0	0	50	7.64	7.72
#4 Recirculation Pipe	0.4	0.4	0.4	0	0	0	0	50	7.64	5.75
#1 Steam Generator Support	0.4	0.4	0.4	2.6	0.25	0	0.4	50	7.64	24.34
#2 Steam Generator Support	0.4	0.4	0.4	1.5	0.25	0	0.4	50	7.64	17.24
#1 Main Steam Pipe	0.4	0.4	0.4	0.4	0	0	0	50	7.64	7.72
#2 Main Steam Pipe	0.4	0.4	0.4	0	0	0	0	50	7.64	5.75
Reactor Coolant Pump #1	0.4	0.4	0.4	2.6	0	0	0.6	65	9.93	27.21
Reactor Coolant Pump #2	0.4	0.4	0.4	1.5	0	0	0.6	65	9.93	19.2
Reactor Coolant Pump #3	0.4	0.4	0.4	0.4	0	0	0.6	65	9.93	11.19
Reactor Coolant Pump #4	0.4	0.4	0.4	0	0	0	0.6	65	9.93	8.28
#1 Feedwater Pipe	0.4	0.4	0.4	0.4	0	0	0.6	70	10.7	11.83
#2 Feedwater Pipe	0.4	0.4	0.4	0	0	0	0.6	70	10.7	8.74
Core Spray Piping	0.4	0.4	0.4	0	0.25	0	0.6	100	15.28	14.36
Steam Generator #1	0.4	0.4	0.4	2.6	0.25	0	0.6	110	16.81	52.57
Steam Generator #2	0.4	0.4	0.4	1.5	0.25	0	0.6	110	16.81	36.89
Steam Generator #3	0.4	0.4	0.4	0.4	0.25	0	0.6	110	16.81	21.21
Steam Generator #4	0.4	0.4	0.4	0	0.25	0	0.6	110	16.81	15.51
#1 Spent Fuel Pool Rerack	0.3	0.4	0.3	0	0	0	0	150	22.92	13.29
Low Power Range Monitor	0.4	0.4	0.4	0	0.25	0	0	150	22.92	16.74

\* Engineering and QA costs were included only for those activities where the actual data had included engineering and QA costs.



**Figure 4-1. Comparison Of Calculated Versus Actual Total Labor Hours**

The poorest fit between the estimated and actual labor for any data point is that with an estimated labor of about 600,000 hours and a reported actual labor of only about 100,000 hours. The physical modification involved was the replacement of BWR recirculation piping. Among the factors that could contribute to the poor agreement of the estimates with the actual labor requirements is the lack of definition on both the quantities and sizes of piping replaced. The calculated labor was based on estimated values of these important determinants.

Figure 4-2 also presents a comparison of estimated-vs-actual labor hours. In this case, however, the scales used give greater detail for modifications which required less than 250,000 labor hours to complete.

The generic cost estimating model was not derived using regression techniques. Rather, the overall models were generated based on expert opinion and engineering judgment. Although regression techniques were not used to construct the model, standard regression analysis can be applied to obtain an overall measure of how well the generic methods match the reported actual labor. The parameter  $R^2$  is a common measure of "goodness-of-fit" between sets of data.  $R^2$  can have values between 0 and 1.0. A value of 1.0 would represent perfect agreement between the data sets being compared. The calculated value for  $R^2$ , based on the labor estimates produced using the recommended relationships presented in Section 4 and comparing these to the reported actual labor, is 0.93. This high value of  $R^2$  indicates that the generic model produces results which compare quite favorably with actual labor.

Another comparison of how well the generic models match the actual labor is presented in Figure 4-3. This figure displays the fractional residuals for each of the 39 data points for which total labor hours were reported. The fractional residual is the fractional deviation between the estimated and actual labor for each physical modification, i.e., (actual labor - calculated labor)/actual labor. Ideally, the residuals should be zero. The figure shows that most of the residuals are slightly negative, reflecting the fact that the generic model typically overestimates

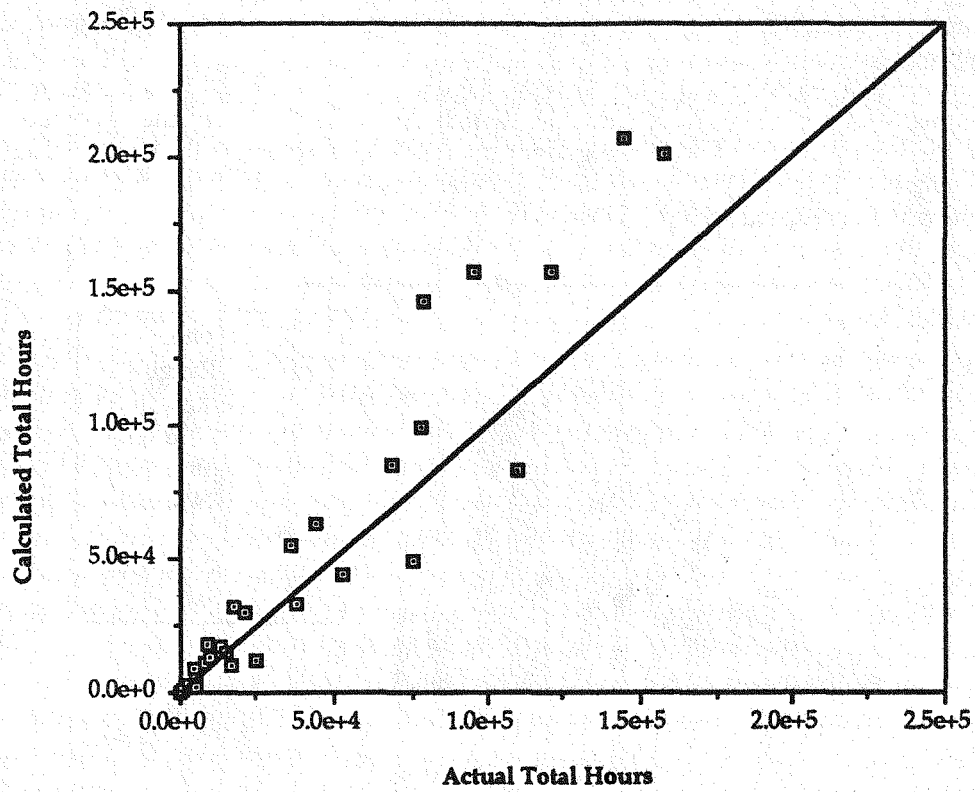


Figure 4-2. Comparison Of Calculated Versus Actual Total Labor Hours (To 2.5e5 Hrs)

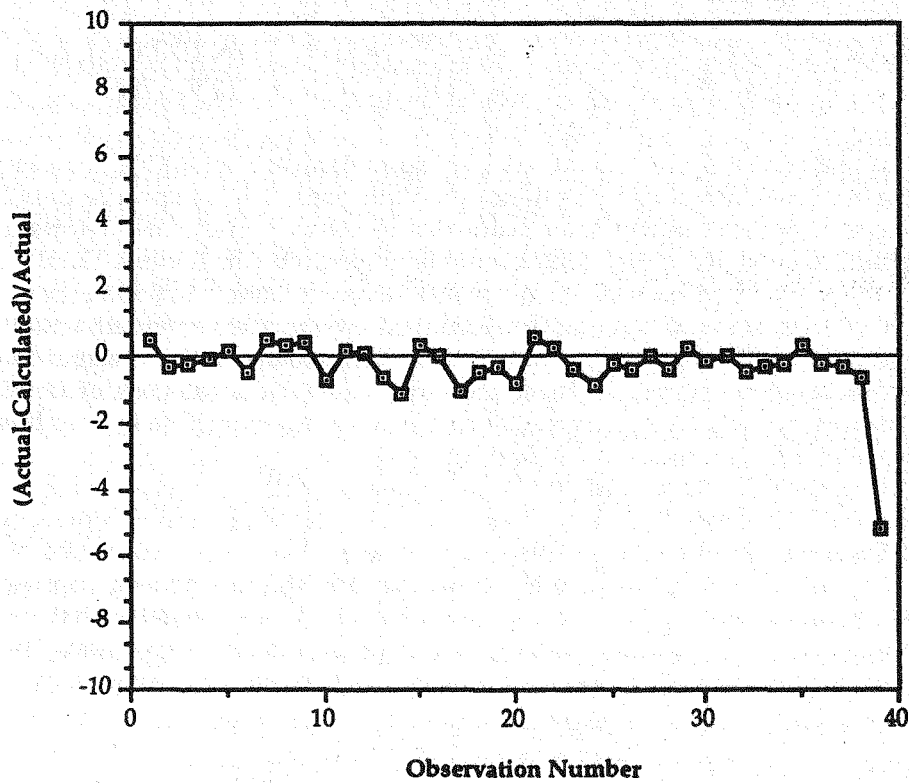


Figure 4-3. Ratio Of Fractional Residuals

the labor requirements slightly. The data point with the largest residual is that for one of the recirculation piping replacement jobs.

The distribution of the residuals is displayed in Figure 4-4. For the 39 data points available for comparison about 60% of them have residuals which are within  $\pm 40\%$  of the reported actual labor. That is, the labor calculated with the generic methodology agrees with the actual labor to within  $\pm 40\%$ . The bell shape of the histogram indicates that the residuals tend to be normally distributed about a mean residual which is close to 0.

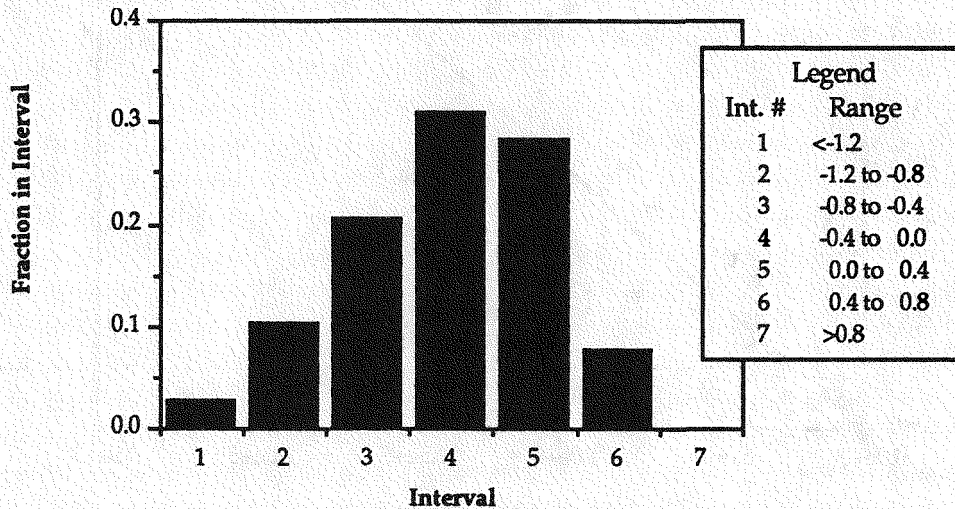


Figure 4-4. Distribution Of Residuals

## 4.2 COMPARISONS OF OCCUPATIONAL RADIATION EXPOSURE ESTIMATES FOR PHYSICAL MODIFICATION ACTIVITIES

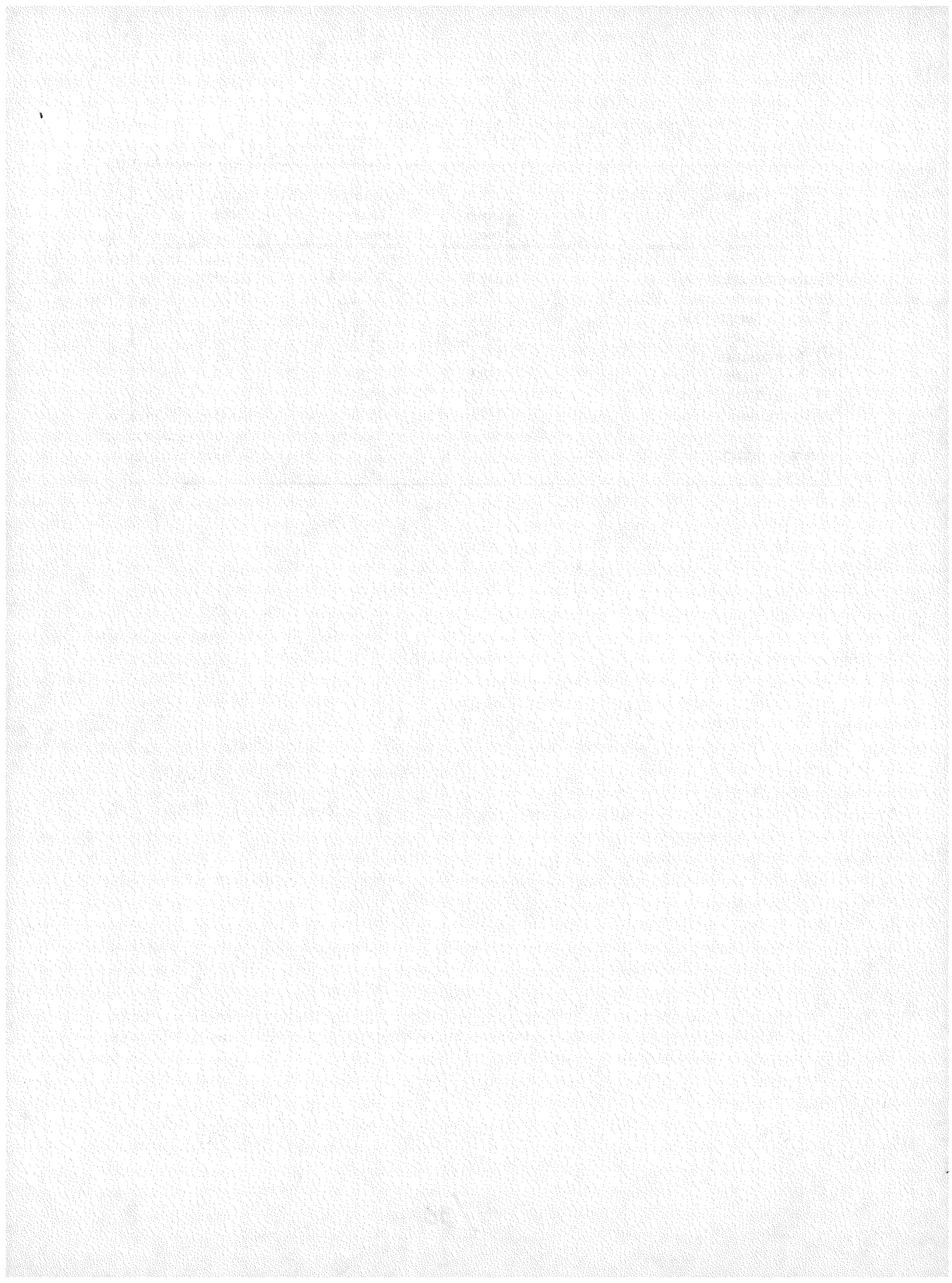
Relatively little job-specific occupational exposure data are available for checking the soundness of the estimates provided by Equations 3-12 through 3-16. Exposure data have been compiled and reported for several very large plant modification efforts. These efforts include the steam generator and recirculation piping replacement activities noted in Tables 4-1 and 4-2.

Table 4-3 presents a comparison of estimated-vs-actual occupational radiation exposures for the eight activities for which exposure data are available. The table gives reported actual exposure, estimated values generated using Equations 3-15 and 3-16, and the ratio of actual-to-estimated values. The recirculation piping replacement activities fall into the category of large diameter piping jobs. Therefore, the 0.1 large piping factor was used in estimating the in-field hours for the four pipe replacement activities shown in Table 4-3.

The exposure values in Table 4-3 indicate that the generic method for estimating occupational exposure generally over-predicted exposures for the steam generator replacements and underestimated them for two of the four piping replacement jobs. The average ratio of actual-to-estimated exposure is about 1.15. This average ratio indicates that the generic approach slightly underestimates personnel doses. However, so few data points are available that only limited conclusions can be drawn regarding the soundness of the exposure estimating method. The approach recommended here does give considerably better results than simply assuming that a certain fraction of the total hours charged to a job are spent in the radiation field.

**Table 4-3. Comparison of Actual Versus Estimated Radiation Exposure**

<b>Replacement Activity</b>	<b>Actual Dose [rem]</b>	<b>Estimated Dose [rem]</b>	<b>Actual/Estimated Dose</b>
Steam Generator #1	2141	3531	0.606
Steam Generator #2	1759	3531	0.498
Steam Generator #3	2151	3531	0.609
Steam Generator #4	1305	3531	0.370
#1 Recirculation Pipe	1464	1397	1.048
#2 Recirculation Pipe	1583	528	3.000
#3 Recirculation Pipe	1895	893	2.122
#4 Recirculation Pipe	1422	1540	0.923
<b>Average Ratio:</b>			<b>1.147</b>



## 5. EXAMPLE APPLICATION

Assume that the safety injection pumps and drives on several PWRs have to be replaced to meet a change in regulatory requirements. There are two pumps per plant. Estimate the labor and equipment costs, the radiation exposure, and the health physics services costs associated with this regulatory change. Assume that 23 plants are affected.

First determine the impacts on a per-plant basis. All baseline information must first be established. Greenfield costs and labor hours are taken from the Energy Economic Data Base (EEDB).

EEDB Acct. No.	223.311
Installation labor	3000 person-hours
Replacement equipment costs	\$50,000 each (assumed)
Assumed Site Material Costs (from EEDB)	\$8,350

These pumps and drives are typically located in the reactor service building, which is generally highly congested. The pump safety function would preclude their replacement during plant operation. Assume the work can be scheduled for the next plant outage. Determine the labor productivity factors from the guidance provided in NUREG/CR-4627 (Ref. 1).

F <sub>a</sub> (access)	=	0.3
F <sub>e</sub> (congestion)	=	0.4
F <sub>m</sub> (management)	=	0.3
FR <sub>1</sub> (structural removal)	=	0.0
FR <sub>2</sub> (implement)	=	0.0

The equipment to be replaced is not considered to be excessively large or unusual. Therefore, learning curve effects do not apply. However, an allowance for engineering and QA should be included.

F <sub>1c</sub>	=	0
F <sub>e</sub>	=	0.25

From NUREG/CR-5035 (Ref. 3), the area dose rate typical of these pumps and drives is 8 mrem/hour. Therefore, the unadjusted radiation labor productivity factor is:

$$F_r = (0.191)(8) = 1.53$$

Roughly estimate the exposure to determine if ALARA dose reduction actions would be implemented:

$$\begin{aligned} \text{Exposure} &= (3000 \text{ hours})(0.375)(1 + 0.3 + 0.4 + 0.3 + 1.53)(0.008 \frac{\text{rem}}{\text{hour}}) \\ &= 31.8 \text{ person-rem} \end{aligned}$$

Since this greatly exceeds 1 person-rem, assume that ALARA dose reduction procedures would be implemented. Therefore, the area dose rate is assumed to be reduced to 80% of the typical value. The radiation productivity factor then becomes:

$$F_r = (0.191)(8)(0.8) = 1.22$$

The total labor for removal and replacement is estimated using Equation 3-11 (since FR<sub>1</sub> + FR<sub>2</sub> = 0).

$$\begin{aligned}
C_L'' &= 1.33 \cdot C_L' \\
C_L' &= C_L [0.625 + (0.375)(1 + F_a + F_c + F_m + F_r)] (1 + F_{lc}) \\
&= 3000 [0.625 + (0.375)(1 + 0.3 + 0.4 + 0.3 + 1.22)] (1 + 0) \\
&= 3000 (1.83) \\
&= 5496 \text{ person-hours (installation only)}
\end{aligned}$$

$$\text{Total labor} = 1.33 (5496) = 7310 \text{ person-hours}$$

Typical labor costs for this account (EEDB labor plus fringe) are \$26.48/hour (1989\$).

$$\text{Direct labor costs} = 7310 (\$26.48) = \$193,569$$

$$\text{Loaded labor costs}^3 = \$193,569 (1.6) = \$309,710$$

Overall direct cost:

Labor	\$193,569
Factory Materials	100,000
Site Materials	<u>8,350</u>
	\$301,919

$$\text{Engineering and QA (@25\%)} = \$75,480$$

Estimate the radiation exposure associated with the removal and replacement of the safety injection pumps:

Since  $FR_1 + FR_2 = 0$ , the appropriate relationship for this estimate is given by Equation 3-16.

$$E_T = (AD)(1.33)(0.375)(C_L)(1 + F_a + F_c + F_m)$$

$$\text{where } AD = \left(8 \frac{\text{mrem}}{\text{hour}}\right) \frac{0.8}{1000 \frac{\text{mrem}}{\text{rem}}} = 0.0064 \frac{\text{rem}}{\text{hour}}$$

$$\begin{aligned}
E_T &= (0.0064)(1.33)(0.375)(3000)(1 + 0.3 + 0.4 + 0.3) \\
&= 19.15 \text{ person-rem}
\end{aligned}$$

Estimate the cost of health physics services:

$$\begin{aligned}
\text{HP costs} &= (\$8,000/\text{person-rem})(E_T) = (\$8,000)(19.15) \\
&= \$153,200
\end{aligned}$$

<sup>3</sup> The multiplier of 1.6 accounts for indirect costs (burden) and reflects the fact that the EEDB labor rates include an allowance for fringe benefits. If direct wages were used as the basis, the indirect cost loading factor would be 2.0 instead of 1.6.

Calculate the total impact for the 23 plants effected by this regulatory change:

Item	Per-Plant Cost/Exposure	Total Impact
Labor (loaded)	\$309,710	$7.12 \cdot 10^6$
Materials & Equipment	108,350	$2.49 \cdot 10^6$
Engineering & Q/A	75,480	$1.74 \cdot 10^6$
HP Services Costs	<u>153,200</u>	<u><math>3.52 \cdot 10^6</math></u>
<b>Total Costs</b>	<b>\$646,740</b>	<b><math>14.87 \cdot 10^6</math></b>
 Radiation Exposure	 19.15 person-rem	 440.5 person-rem



## 6. SUMMARY AND CONCLUSIONS

This report describes the results of research aimed at clarifying radiation-related impacts on costs and radiation exposure of nuclear plant physical modifications. This work has identified a number of improvements in the treatment of radiation-related impacts as they relate to the NRC's generic cost estimation methodology. The major results are summarized below.

### 6.1 ALARA DOSE REDUCTION FACTOR

For radiological exposure conditions for which the collective dose is likely to exceed one person-rem, it is the general practice among utilities to supplement standard radiological practices by means of an ALARA review. ALARA mitigation techniques on the average reduce area radiation levels by 20%. Accordingly, system-average dose rates cited in NUREG/CR-5035 (Ref. 3) should be multiplied by 0.8 when system area dose rates are used to determine (1) the radiation labor productivity factor and (2) the cumulative person-rem value, which defines the total cost of health physics services.

### 6.2 LABOR PRODUCTIVITY FACTORS

It is recommended that factors for (1) access and handling, (2) congestion and interference, and (3) management complexity remain as is. However, since all these labor productivity factors only affect normal direct work time, their application is limited to only 37.5% of the EEDB labor hours.

The radiation labor productivity factor should be derived using Equation 3-3:<sup>4</sup>

$$F_r = 0.191 \cdot \text{Dose Rate} \left[ \frac{\text{mrem}}{\text{hour}} \right] \quad (3-3)$$

The dose rate should be adjusted to reflect ALARA measures whenever the cumulative dose for an activity is expected to exceed one person-rem. To make this adjustment, the dose rate is multiplied by 0.8.

The previous methods included an additional radiation labor productive factor for removal activities. Its use is no longer recommended. The other removal factors and their recommended usage are unchanged.

### 6.3 APPLICATION OF LABOR PRODUCTIVITY FACTORS IN LABOR COST ESTIMATION

The generic methodology formulations for estimating labor costs has been reevaluated to account for the productive and non-productive aspects of the base EEDB labor estimates. Previous work identified that only about 37.5% of the EEDB labor could be assumed to be productive. The reformulation of the generic labor estimation methods recognizes that certain labor productivity factors affect only the productive portion of the greenfield labor, whereas other factors act on both the productive and nonproductive labor base. The revised formulations are as follows:

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<sup>4</sup> Note: This formula replaces the old formula:

$$F_{\text{stay time}} = \frac{\text{Normal direct work time} - \text{stay time}}{\text{stay time}}$$

### Installation labor

$$C'_L = [0.625 C_L + 0.375 C_L (1 + F_a + F_c + F_m + F_r)(1 + F_{lc})](1 + F_e) \quad (3-5)$$

where:

- $C'_L$  = adjusted installation labor cost (or hours)
- $C_L$  = greenfield labor from EEDB or other source
- $F_a$  = access labor productivity factor
- $F_c$  = congestion labor productivity factor
- $F_m$  = management labor productivity factor
- $F_r$  = radiation labor productivity factor as defined by Equation 3-3
- $F_{lc}$  = learning curve factor
- $F_e$  = factor accounting for engineering and quality assurance costs

### Removal labor:

If  $FR_1 + FR_2 > 0$ ,

$$C_{RL} = C'_L [(1 + FR_1)(1 + FR_2) - 1] \quad (3-7)$$

where:

- $C''_L$  = adjusted total labor (removed plus installation)
- $C'_L$  = adjusted installation labor
- $C_{RL}$  = removal labor
- $FR_1$  = structural removal factor
- $FR_2$  = ancillary systems and structures removal (impingement) factors

If  $FR_1 + FR_2 = 0$ ,

$$C_{RL} = 0.33 C'_L \quad (3-8)$$

### Total labor (installation plus removal):

If  $FR_1 + FR_2 > 0$ ,

$$C''_L = C'_L (1 + FR_1)(1 + FR_2) \quad (3-6)$$

If  $FR_1 + FR_2 = 0$ ,

$$C''_L = 1.33 C'_L \quad (3-11)$$

## 6.4 OCCUPATIONAL EXPOSURE

The estimation of radiation exposures requires the use of several different relationships, depending on the particular work activity of interest. The following relationships are recommended:

Exposure associated with installation activities:

$$E_I = AD (0.375) C_L (1 + F_a + F_c + F_m) \quad (3-12)$$

where:

$$\begin{aligned} E_I &= \text{installation radiation exposure [person-rem]} \\ AD &= \text{ALARA adjusted dose rate (0.8 \cdot \text{dose rate})} \left[ \frac{\text{rem}}{\text{hour}} \right] \end{aligned}$$

For removal activities:

$$\text{If } F_{R1} + F_{R2} > 0,$$

$$E_R = AD (0.375) C_L (1 + F_a + F_c + F_m) [(1 + F_{R1})(1 + F_{R2}) - 1] \quad (3-13)$$

$$\text{If } F_{R1} + F_{R2} = 0,$$

$$E_R = AD (0.33) (0.375) (C_L) (1 + F_a + F_c + F_m) \quad (3-14)$$

where  $E_R$  = removal radiation exposure [person-rem].

For combined removal plus installation (total):

$$\text{If } F_{R1} + F_{R2} > 0,$$

$$E_T = AD (0.375) C_L (1 + F_a + F_c + F_m)(1 + F_{R1})(1 + F_{R2}) \quad (3-15)$$

$$\text{If } F_{R1} + F_{R2} = 0,$$

$$E_T = AD (1.33)(0.375) C_L (1 + F_a + F_c + F_m) \quad (3-16)$$

where  $E_T$  = combined installation and removal radiation exposure [person-rem].

In Equations 3-12 through 3-16,  $C_L$ , the EEDB labor or greenfield labor obtained from other sources, must be given in hours. Similarly,  $AD$ , the ALARA adjusted dose rate, has the units of rem/hour (not mrem/hour).

## 6.5 HEALTH PHYSICS SUPPORT COST

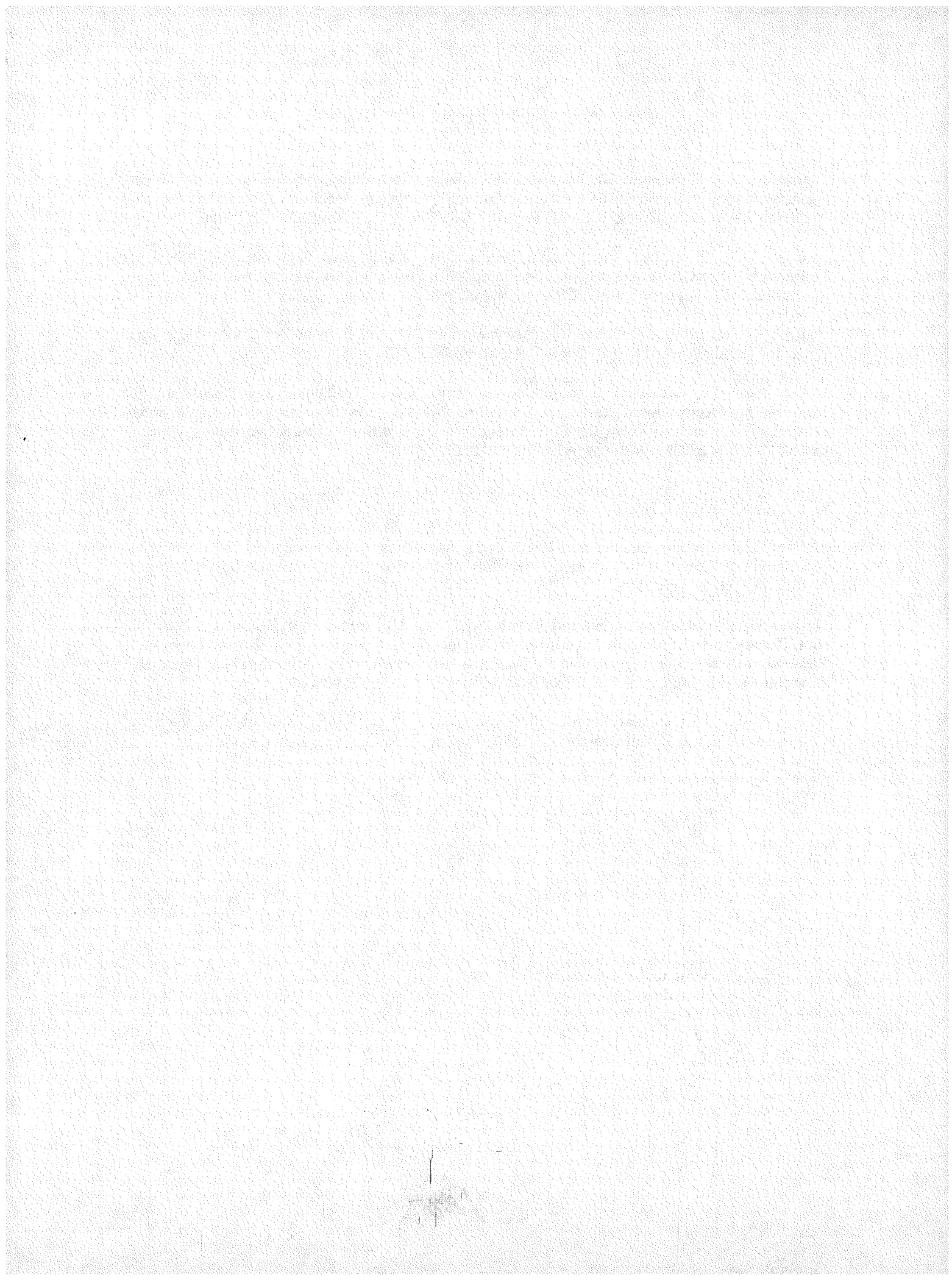
The costs for all health physics services associated with conducting work in a radiological environment can readily be assessed by first determining the cumulative exposure for a task, and multiplying it by \$8000/person-rem. The \$8000/person-rem value was determined by dividing the

average annual O&M budget for a utility radiological controls staff, approximately \$4 million, by the average annual LWR cumulative exposure value, approximately 500 person-rem per year.

Appendix B presents a worksheet designed to aid analysts in quantifying costs and exposure associates with nuclear power plant physical modifications.

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## APPENDIX A

### RADIOLOGICAL REVIEW GUIDELINE CRITERIA

This appendix contains a listing of generic radiological control considerations for various plant applications.

Generically, radiological engineering utilizes a check list such as this in order to ensure that an adequate and thorough review has been conducted for each design/modification. The completed check sheets may be filed to provide documentation for the applicable review.

#### 1. PLANT LOCATION

The reviewer considers the following considerations with regard to the physical plant location(s) of the proposed installation.

1.1 Are existing plant radiation levels, at the sites of intended work activity, sufficiently low such that work may be accomplished in an ALARA manner?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.2 Can work area radiation levels be lowered to acceptable levels by flushing systems?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.3 Can work area radiation levels be lowered to acceptable levels by application of temporary shielding?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.4 Are existing contamination levels, at the sites of intended work activity, sufficiently low such that minimum protective clothing and respiratory protection may be utilized?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.5 Can work area contamination levels be brought to acceptable levels by decontamination activities?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.6 Can work area contamination levels be brought to acceptable levels by utilizing temporary coverings on work surfaces?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.7 Does installation/modification involve removal of components of opening of access pathways which may result in an increase in area radiation levels?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.8 Does installation/modification involve operations which will create an airborne contamination condition due to disturbance of surface contamination accumulations?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.9 Is work area lighting sufficient to adequately illuminate the area during installation/modification and during subsequent operation?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.10 If the proposed design/modification involves system drainage capability, does the design include provisions for directing drainage to a floor drain such that liquids are not caused to flow over floors surfaces?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.11 Is the proposed installation serviced by adequate ventilation capability?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.12 If the proposed design has the potential to create a "locked high radiation area" condition, can the existing location be effectively locked in accordance with the "locked high radiation area" criteria?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.13 Will this installation effect adjacent areas and plant equipment, from a radiological control aspect, during operation?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.14 Will this installation necessitate modification of existing routine and special radiation survey requirements?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.15 Will the new installation affect maintainability of existing equipment?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.16 Will existing alarm systems, instrumentation and operating stations have to be relocated?

YES \_\_\_\_\_ NO \_\_\_\_\_

1.17 If operation of the proposed installation has the potential to produce area contamination during operation and maintenance, are work area structural surfaces properly treated such that they can be easily decontaminated?

YES \_\_\_\_\_ NO \_\_\_\_\_

## 2. PIPING SYSTEM

The reviewer considers the following considerations with regard to any proposed piping runs which will carry radiological controlled materials.

2.1 Are the lengths of proposed piping runs minimized?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.2 Are socket welded joints and flanged joints minimized in order to reduce the number of crud traps in piping runs?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.3 Are horizontal piping runs minimized?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.4 Are drains sloped continuously toward drain collection?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.5 Do equipment and piping drains terminate into a drain collection funnel or a floor drain hub?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.6 Are stagnant piping legs avoided?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.7 Does the system provide a means of periodically flushing piping runs?

YES \_\_\_\_\_ NO \_\_\_\_\_

2.8 Are "field run" joints avoided?

YES \_\_\_\_\_ NO \_\_\_\_\_

### 3. VALVES

The reviewer considers the following considerations with regard to system valving on systems which will contain radiological controlled materials.

3.1 Are check valves included to prevent contaminated fluids from leaking into uncontaminated portions of the system?

YES \_\_\_\_\_ NO \_\_\_\_\_

3.2 Are full ported valves utilized on systems which have the potential to carry fluids containing significant amounts of solids?

YES \_\_\_\_\_ NO \_\_\_\_\_

3.3 Have valve designs with bonnet cavities been avoided?

YES \_\_\_\_\_ NO \_\_\_\_\_

3.4 Are valves installed such that they are accessible for routine maintenance?

YES \_\_\_\_\_ NO \_\_\_\_\_

### 4. INSTRUMENTATION

The reviewer shall consider the following considerations with regard to system instrumentation on contaminated systems?

4.1 Is instrumentation located in what will be a low background radiation area?

YES \_\_\_\_\_ NO \_\_\_\_\_

4.2 Is instrumentation accessible for routine maintenance and calibration?

YES \_\_\_\_\_ NO \_\_\_\_\_

### 5. TANKS

The reviewer considers the following considerations with regard to tanks which will contain radiological controlled materials.

5.1 Are tanks located so as to minimize background radiation effects?

YES \_\_\_\_\_ NO \_\_\_\_\_

- 5.2 Are tank bottoms sloped toward the outlet?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.3 Can the tank be pumped completely dry?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.4 Do tanks contain built-in sparger systems to facilitate cleaning?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.5 Are adequately sized man-ways provided to assist in ultimate tank decontamination?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.6 Do tank outlet pipes have backflush capability?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.7 Are tank vents adequate for both liquid and air?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.8 Are tank overflows directed into a floor drain to avoid liquids from flowing over floor surfaces?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.9 Is the tank interior finish smooth (no lap joints of backing rings) such that it is easily decontaminated?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.10 Does the design provide for curbing around the tank area to minimize problems associated with leakage?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.11 Have filters been included to prevent solids from entering the tank?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.12 Has filter change-out been adequately addressed?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 5.13 Has filter shielding been adequately addressed?  
YES \_\_\_\_\_ NO \_\_\_\_\_

## 6. VENTILATION

The reviewer considers the following considerations with regard to ventilation systems.

- 6.1 If ventilation is required as a part of installation, will existing/proposed ventilation equipment adequately maintain the space under a negative pressure relative to adjacent work areas?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 6.2 Are ventilation duct runs minimized?  
YES \_\_\_\_\_ NO \_\_\_\_\_

6.3 Is ventilation equipment located in a low background area to facilitate maintenance?  
YES \_\_\_\_\_ NO \_\_\_\_\_

## 7. OPERATION OF NEW INSTALLATIONS

The reviewer considers the following considerations with regard to operation of new installation.

7.1 Based upon estimated radiation levels which will be present during system operations, is the installation suitable for routine access?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.2 Should reach rods or remote control devices be considered?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.3 Are instrumentation readouts positioned to minimize exposure during operation?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.4 Are system control valves close to instrumentation?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.5 Should shielding be considered for operators?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.6 Should operating stations be located behind other components to reduce exposure?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.7 If system leakage is expected, are drip pans or other drain collection facilities incorporated?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.8 Should operator and maintenance training be conducted on a clean system, prior to initial start-up?  
YES \_\_\_\_\_ NO \_\_\_\_\_

7.9 Are instruments and controls grouped functionally in order to minimize time at station?  
YES \_\_\_\_\_ NO \_\_\_\_\_

## 8. EXPOSURE REDUCTION

The reviewer considers the following exposure reduction techniques as they apply to installation of equipment.

8.1 Can portions of the intended installation work be accomplished external to radiological controlled areas in order to reduce personnel stay time?  
YES \_\_\_\_\_ NO \_\_\_\_\_

8.2 Does the design document specify all tooling including sizes required to complete installation?  
YES \_\_\_\_\_ NO \_\_\_\_\_

- 8.3 Would system or component flushing operations reduce work area radiation levels?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 8.4 Can properly used temporary shielding materials reduce work area radiation levels?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 8.5 Will sources of radiation be generated, as a result of work performance, which will increase work area radiation levels?  
YES \_\_\_\_\_ NO \_\_\_\_\_

## 9. CONTAMINATION CONTROL

The reviewer considers the following contamination control considerations where applicable.

- 9.1 Is the work area currently contaminated to such an extent that prework decontamination should be considered in order to increase worker efficiency?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 9.2 Does the intended work scope involve operations which will increase contamination levels and for which methods to control contamination should be considered?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 9.3 Does the work scope involve operations such as welding, grinding, burning, or machining on contaminated surfaces and for which prework decontamination or other techniques should be utilized in order to prevent or minimize the spread of contamination?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 9.4 Does the work scope involve removal of contaminated materials or other components which will spread contamination if not properly handled or contained?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 9.5 Does the work scope involve insertion and removal of tooling and equipment into/from contaminated areas, which will spread contamination if not handled or controlled properly?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 9.6 Would some level of contamination control work enclosure effectively and personnel during installation?  
YES \_\_\_\_\_ NO \_\_\_\_\_

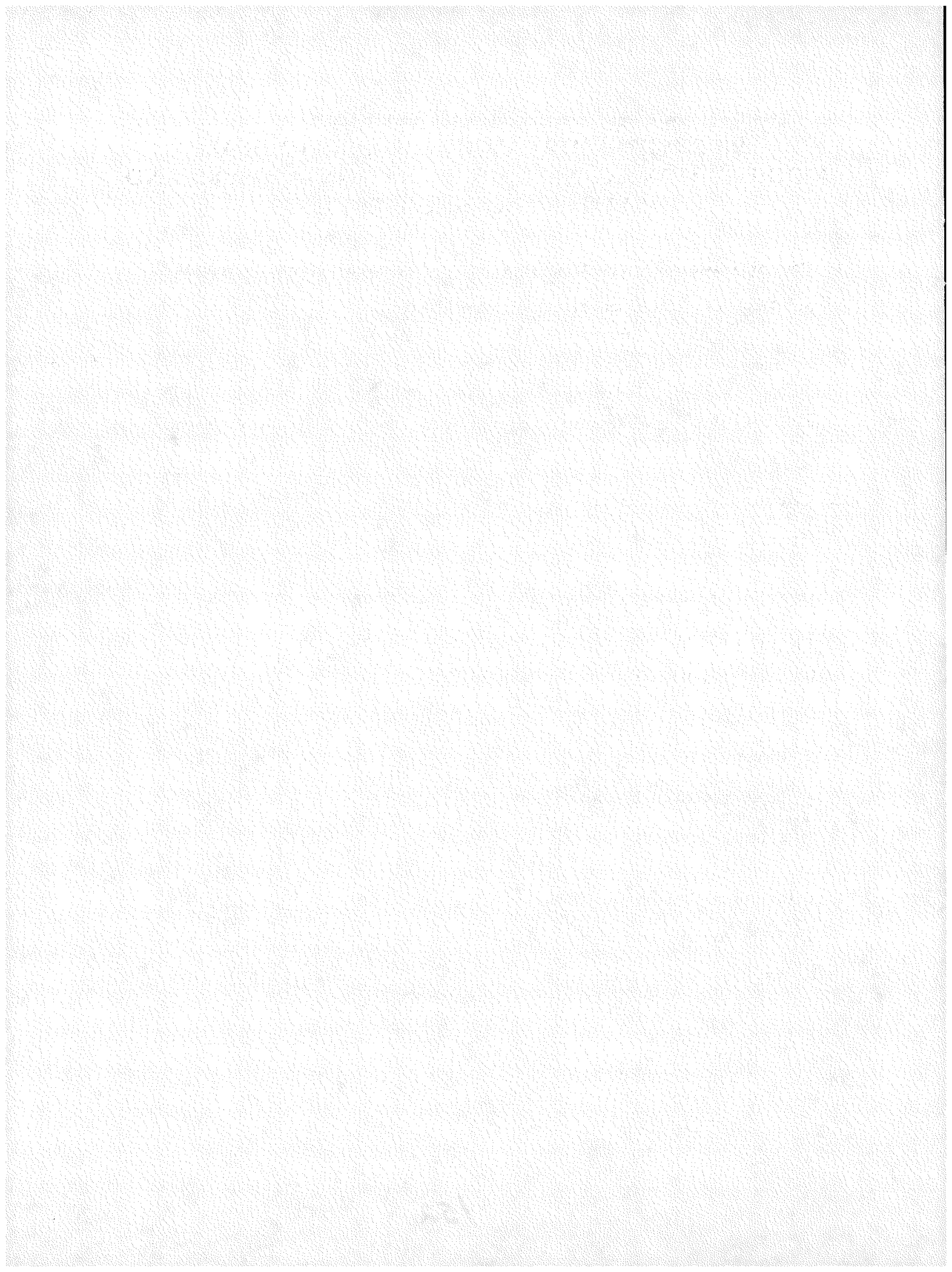
## 10. AIRBORNE CONTAMINATION CONTROL

The reviewer considers the following airborne contamination control considerations.

- 10.1 Are existing work area surface contamination levels of a magnitude which is likely to cause increased airborne activity levels during work activities?  
YES \_\_\_\_\_ NO \_\_\_\_\_
- 10.2 Will certain proposed work operations create an increase in work area airborne activity levels which could lead to a potential environmental release?  
YES \_\_\_\_\_ NO \_\_\_\_\_

10.3 Does the proposed work operation include any function which may cause an increase in airborne activity levels in other portions of the plant?

YES \_\_\_\_\_ NO \_\_\_\_\_



**APPENDIX B**  
**WORKSHEET FOR CALCULATION OF PHYSICAL**  
**MODIFICATION LABOR COSTS, RADIATION EXPOSURE, AND**  
**HEALTH PHYSICS SERVICES COSTS**

**1. Determine basic radiation conditions for a given modification of a nuclear power plant.**

a. Does nuclear power plant have an operating history?

YES \_\_\_\_\_ NO \_\_\_\_\_

b. If answer to (a) is yes, does the modification involve work in radiation fields?

YES \_\_\_\_\_ NO \_\_\_\_\_

c. If answer to (b) is yes, determine the system average dose rate for work environment.

\_\_\_\_\_ mrem/hr

**2. Determine the scope of the activity.**

(Removal, Installation, or Both) \_\_\_\_\_

**3. Determine labor productivity factors.**

a. Access and handling ( $F_a$ ) = \_\_\_\_\_

b. Congestion and Interference ( $F_c$ ) = \_\_\_\_\_

c. Manageability ( $F_m$ ) = \_\_\_\_\_

d. Removal Structural ( $F_{R1}$ ) = \_\_\_\_\_

e. Removal Ancillary Systems ( $F_{R2}$ ) = \_\_\_\_\_

f. Learning Curve Factor ( $F_{lc}$ ) = \_\_\_\_\_

**4. Determine total in-field labor hours.**

a. EEDB greenfield labor hours: \_\_\_\_\_ hours

b. Installation in-field hours \_\_\_\_\_ hours  
 (EEDB hours)(0.375)(1 +  $F_a$  +  $F_c$  +  $F_m$ )

c. Removal in-field hours \_\_\_\_\_ hours  
 If  $F_{R1} + F_{R2} > 0$ ,  
 (EEDB hours)(0.375)(1 +  $F_a$  +  $F_c$  +  $F_m$ )[(1+ $F_{R1}$ )(1+ $F_{R2}$ )-1]  
 If  $F_{R1} + F_{R2} = 0$ ,  
 0.33 (EEDB hours)(0.375)(1 +  $F_a$  +  $F_c$  +  $F_m$ )

- d. Combined installation plus removal (total) hours \_\_\_\_\_ hours  
 If  $FR_1 + FR_2 > 0$ ,  
 $(\text{EEDB hours})(0.375)(1 + F_a + F_c + F_m)(1+FR_1)(1+FR_2)$   
 If  $FR_1 + FR_2 = 0$ ,  
 $1.33 (\text{EEDB hours})(0.375)(1 + F_a + F_c + F_m)$

5. Determine collective radiation exposure and system-average dose rate.

collective radiation exposure = (in-field hours)(system-average dose rate)

If collective radiation exposure is  $\geq 1000$  mrem, an ALARA dose reduction factor of 0.8 is applied for system average dose rate as well as for collective radiation exposure.

ALARA-adjusted system average dose rate: \_\_\_\_\_ mrem/hr  
 $(\text{system-average dose rate})(0.8)$

ALARA-adjusted collective radiation exposure: \_\_\_\_\_ mrem  
 $(\text{collective radiation exposure})(0.8)$

6. Determine radiation productivity factor ( $F_r$ ).

$F_r = (0.191)(\text{ALARA-adjusted system-average dose rate})$  \_\_\_\_\_

7. Determine total labor cost. \$ \_\_\_\_\_

a. Adjusted installation labor cost \$ \_\_\_\_\_  
 $(\text{EEDB hours})[(0.625) + (0.375)(F_L)(1 + F_{1c})](\text{cost}/\text{hour})$   
 Where  $F_L = 1 + F_a + F_c + F_m$

b. Adjusted removal labor cost \$ \_\_\_\_\_  
 If  $FR_1 + FR_2 > 0$ ,  
 $(\text{EEDB hours})[0.625 + (0.375)(F_L)(1 + F_{1c})][(1+FR_1)(1+FR_2)-1](\text{cost}/\text{hour})$   
 If  $FR_1 + FR_2 = 0$ ,  
 $0.33 (\text{EEDB hours})[0.625 + (0.375)(F_L)(1 + F_{1c})](\text{cost}/\text{hour})$

c. Combined removal and installation costs \$ \_\_\_\_\_  
 If  $FR_1 + FR_2 > 0$ ,  
 $(\text{EEDB hours})[0.625 + (0.375)(F_L)(1 + F_{1c})](1+FR_1)(1+FR_2)(\text{cost}/\text{hour})$   
 If  $FR_1 + FR_2 = 0$ ,  
 $1.33 (\text{EEDB hours})[0.625 + (0.375)(F_L)(1 + F_{1c})](\text{cost}/\text{hour})$

8. Determine total health physics support costs. \$ \_\_\_\_\_

H.P. support costs =  $\left( \frac{\text{collective radiation exposure [mrem]}}{1000 \text{ mrem/rem}} \right) \left( \frac{\$8000}{\text{rem}} \right)$

## GLOSSARY

ALARA: As low as is reasonably achievable, economic and social factors being taken into account.

Collective Radiation Exposure: The total exposure of a group of individuals (see person-rem).

Crud: Corrosion and wear particulates which through neutron activation become radioactive.

Greenfield: A working environment unencumbered by radiation, congestion, accessibility, etc.

Person-Rem: A measure of the total exposure of a group of individuals which is the product of the total number of persons times their average individual radiation exposure.

Radiation Dose: A quantity (total or accumulated) of radiation received, most frequently expressed in millirem (mrem).

Stay Time: The period during which personnel may remain in a restricted area before accumulating the permissible dose.

System-Average Dose Rate: The average dose rate (associated with a particular plant system) per unit of time; usually expressed in mrem/hour.