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FINAL REPORT ON THE PRIORITIZATION OF
TASKS IN THE DRAFT LWR
SAFETY TECHNOLOGY PROGRAM PLAN

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FINAL REPORT ON THE PRIORITIZATION OF TASKS IN THE DRAFT
LWR SAFETY TECHNOLOGY PROGRAM PLAN

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FINAL REPORT ON THE PRIORITIZATION OF TASKS IN THE DRAFT LWR SAFETY TECHNOLOGY PROGRAM PLAN

1.0 INTRODUCTION

1.1 Objectives

The purpose of this report is to describe both the approach taken and the results produced in the SAI effort to prioritize the tasks in the Sandia draft LWR Safety Technology Program Plan (1). This work used the description of important safety issues developed in the Reactor Safety Study (2) to quantify the effect of safety improvements resulting from a research and development program on the risk from nuclear power plants. Costs of implementation of these safety improvements were also estimated to allow a presentation of the final results in a value (i.e., risk reduction) vs. impact (i.e., implementation costs) matrix.

The remainder of Section 1 will summarize the approach taken to solving the problem and the difficulties encountered in that approach. Section 2 will discuss in greater detail the methodology employed in the work, while the results will be presented in Section 3, and resulting recommendations will be noted in Section 4. Greater detail on the risk reduction potential and implementation cost analysis is presented in Appendices A and B, respectively.

1.2 Summary of Approach

The preliminary program plan is segregated into eight (8) subprograms each of which is composed of a number of research projects (sometimes referred to here as "tasks"). Since the approach being employed in the prioritization activity involved the use of the Reactor Safety Study risk model, it was necessary

to restructure the research projects (or tasks) in the program plan into activities the results of which could be quantified as to their risk impact and implementation cost. This restructuring involved the definition of sixteen "research programs" each of which is composed of research projects (tasks) from the Sandia program plan. The details of this process are discussed in Section 3.

Following definition of sixteen manageable research programs and the assignment of research projects (tasks) from the program plan which support their successful completion, the risk reduction potential associated with successful completion of these programs was calculated using a method developed by Parkinson (3). In addition, costs of implementation of these research programs were estimated using information on hardware and outage costs from the open literature.

Finally, value-impact matrices were prepared for both existing and future nuclear power plants. These matrices were constructed to rank the sixteen research programs. The risk reduction values of individual research projects (tasks) were determined by an unfolding process which is described in Appendix A. Implementation costs at the level of research projects (tasks) were not determined because of the inherent difficulty in that process.

Thus, the final results of this work are value-impact matrices, for both existing and future plants, on which risk reduction potential and implementation costs are plotted for all sixteen research programs. In addition, a listing of research projects (tasks) segregated by risk reduction potential is presented.

1.3 Difficulties Encountered

The major difficulties encountered in the prioritization work are itemized below:

- o Effectiveness of Research Programs Clearly, the risk reduction potential associated with a given research program is related to both the research dollars expended on the program, and the degree of maturity inherent in the technology being developed. In this analysis it was impossible to make quantitative statements on either of these topics. However, by evaluating the effect on plant risk resulting from various degrees of improvement associated with the research program, it was possible to understand the sensitivity of plant risk to the degree of success of the research program.
- o Reasonableness of Cost Estimates Because it is difficult to determine in advance of completion of a research program its detailed effect on plant cost, the accuracy of the cost estimates can be questioned. However, by considering the contribution to life cycle cost associated with equipment, procedures, and outages which might result from a research program, it was possible to estimate the potential for cost impact. It is these estimates which are reported here.
- o Uncertainties in the WASH-1400 Risk Model Although uncertainties in the risk model and results present in WASH-1400 have been the subject of considerable recent debate, it is acknowledged as the best current evaluation of accident "topology" (4). For this reason the WASH-1400 model was employed in this study. Since one of the

major limitations of WASH-1400 was that it treated only one Westinghouse PWR and one General Electric BWR, significant variations in which accident sequences are important would be expected among various reactor and plant designs. For this reason, where possible, the limitations of WASH-1400 have been acknowledged and quantitative estimates of risk reduction potential have been made for reactor concepts other than those in WASH-1400.

- o The Effect of Risk Measure on Research Program Value Significant variations in the values of a particular research program would be expected for various measures of risk. For example if risk were defined as "core melt probability," then research programs which address the effectiveness of containment systems would have no value, whereas the same systems would have significant value in reducing the integrated man-rem exposure from a complete spectrum of accidents. In Appendix A, risk reduction potential is developed for a number of measures of risk. In general, the effects of a research program on reductions in latent fatalities (related to total man-rem exposure) are reported in summary figures.

2.0 TECHNICAL APPROACH

The proposed light water reactor safety technology program consists of eighty-five individual research projects. Several of these projects are stand-alone in the sense that successful completion of that project can be identified with an improvement in a specific component, system, or procedure. Since risk models, such as WASH-1400, and cost models are generally developed in terms of plant components, systems, and procedures, the risk reduction (value) and costs (impact) of the stand-alone projects can be evaluated directly. However, the majority of the projects are not stand-alone. In other words, a specific component or procedural improvement requires successful completion of several projects. Furthermore, some of these projects may contribute to a variety of improvements. In this case, the interactions and dependencies between various projects make it extremely difficult to directly evaluate risk reduction and costs of individual projects.

An alternate approach is to define a set of integrated research programs. The objective of each program would be an improvement in a specified component or procedure. The risk reduction and costs of each program could then be calculated directly. Estimates for the contribution of each project to a defined program could be combined to obtain the risk reduction of individual projects.

After the value and impact of each research program has been calculated, a plot can be generated showing the relative position of each research program on value-impact coordinates. Figure 2.1 illustrates this interpretation for a hypothetical case with four research programs. Error bars attached to each point indicate the associated uncertainty. In this example, the relative error in the value parameter is larger than the error in the impact parameter for all research programs.

An alternative to plotting point estimates for each research program is the use of a value-impact matrix concept which effectively plots the number of research programs within given intervals of value and impact. Figure 2.2 replots the information of Figure 2.1 in the value-impact matrix format. The matrix has K value intervals and J impact intervals. Each research program is assigned to one and only one element of the K x J matrix; however, some matrix elements may contain several research programs.

Section 2.1 defines a set of sixteen (16) integrated research programs. Each program has a well-defined objective and is a logical combination of the various research projects. The methodology used to calculate the risk reduction of a research program and estimate the value of individual research projects is presented in Section 2.2. Finally, Section 2.3 illustrates the calculation of the costs for proposed programs.

2.1 Definition of Integrated Research Programs

Since evaluation of nuclear reactor risk is most conveniently performed in terms of specific components and operating procedures, the individual projects within the LWR safety technology program have been grouped into sixteen integrated research programs. Each program has a well-

Figure 2.1 Point-Estimates of Value-Impact.

Figure 2.2 Interval-Estimates of Value-Impact.

defined objective which can be identified with specific inputs of a risk evaluation model.

Table 2.1 lists the research programs and the proposed projects within each program. The identification of research projects is taken from Reference 1 and is used throughout the section. The first programs focus on component or system hardware improvements. In other words their objectives are to upgrade the hardware of a given component or within a class of components. The projects which contribute to these programs either focus directly on the objective or are supporting projects whose results can be applied to meeting the objective. The remaining programs emphasize minimizing transient frequency and accident mitigation methods.

Block diagrams illustrating the role of individual projects within the research programs are included to facilitate the discussion. The basic structure of these diagrams is shown in Figure 2.3. The objective of the program is stated in the oval at the top of the diagram. The series and parallel arrangement of blocks model the interaction of projects which aid in achieving the goal of the program. Each branch (or success path) of the block diagram is a coherent series of projects which assist in achieving the program objective. The branches are assumed to be independent, i.e., the success or failure of a given branch does not influence neighboring branches. The total success of the program obviously requires success in all branches. If only some of the branches are successful, the degree of program success will be equal to the sum of the contributions from the successful paths. The projects may be categorized as independent, dependent, or supportive with respect to a given success path. Independent projects form separate success paths and will contribute to the success of a program regardless of the other projects in the program. Dependent projects must be undertaken collectively and all successfully completed before any of them can contribute to the program success. A series of dependent projects can

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

S U M M A R Y S E C T I O N

S U M M A R Y S E C T I O N

S U M M A R Y S E C T I O N

S U M M A R Y S E C T I O N

1.0	IMPROVE SAFETY SYSTEMS
1.1	IMPROVE COMPONENTS
1.1.1	IMPROVE VALVES
1.1.2	OTHER COMPONENTS
1.1.3	INSTRUMENTATION
1.1.4	EQUIPMENT QUALIFICATION
1.1.5	MAINTENANCE & TEST PROCEDURE
1.1.6	RELATION: OPERATING MODES & SAFETY
1.2	IMPROVE SYSTEM
1.2.1	ALTERNATE SHUTDOWN COOLING SYSTEM
1.2.2	OPTIMIZE CONTAINMENT
1.2.3	SYSTEM SIMPLIFICATION
1.2.4	HYDROGEN CONTROL SYSTEMS
1.3	PLANT DESIGN IMPROVEMENT
1.3.1	DESIGN GUIDANCE
1.3.2	STRUCTURAL INTEGRITY, ASEISMIC DESIGN, IN-SERVICE INSPECTION
1.3.3	DESIGN VERIFICATION

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
7. ENHANCE FUEL PERFORMANCE
8. IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE
9. IMPROVE CONTAINMENT SYSTEMS
10. IMPROVE TEST AND MAINTENANCE
11. IMPROVE EMERGENCY CONTROL
12. IMPROVE DISTURBANCE CONTROL
13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
16. IMPROVE UTILIZATION OF RISK METHODS

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

S U M M A R Y S E C T I O N

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
7. ENHANCE FUEL PERFORMANCE
8. IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE
9. IMPROVE CONTAINMENT SYSTEMS
10. IMPROVE TEST AND MAINTENANCE
11. IMPROVE EMERGENCY CONTROL
12. IMPROVE DISTURBANCE CONTROL
13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
16. IMPROVE UTILIZATION OF RISK METHODS

2.0	MAN-MACHINE INTERACTION
2.1	EMERGENCY CONTROL
2.2	DISTURBANCE CONTROL
2.3	TRANSIENT CONTROL
2.4	PLANT PROTECTION SYSTEM
2.5	SAFETY MARGINS & SAFETY SYSTEM STATUS
2.6	HUMAN FACTORS
2.7	HUMAN ENGINEERING
2.8	EMERGENCY OPERATING PROCEDURES
2.9	ESSENTIAL SUPPORTIVE SYSTEMS
2.10	VERIFICATION AND EVALUATION OF NEW DESIGNS
2.11	FUEL HANDLING & MAINTENANCE
2.12	IMPLEMENTATION & DEMONSTRATION PLAN

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

RESEARCH PROGRAMS		TASKS FROM PROGRAM PLAN
		3.0 RISK METHODS UTILIZATION
		3.1 METHODS DEVELOPMENT
		3.1.1 HUMAN FACTORS
		3.1.2 PARTIAL FAILURES
		3.1.3 MULTIPLE ERRORS
		3.1.4 NON-INDEPENDENT FAILURES
		3.1.5 R&D SELECTION METHODOLOGY
		3.2 DESIGN DECISION
		3.2.1 ANALYTICAL METHODS DEVELOPMENT
		3.2.2 APPLICATION TO CURRENT DESIGN
		3.2.3 SYSTEMS INTERACTIONS/SENSITIVITY ANALYSIS
		3.3 ACCIDENT ANALYSIS
		3.3.1 GENERALIZED ACCIDENT ANALYSIS
		3.3.2 TMI-2 ACCIDENT SEQUENCE
		3.4 DATA BASE AND STATISTICS
		3.5 RISK EVALUATION
		3.5.1 RISK MANAGEMENT/LICENSING
		3.6 COMPREHENSIVE APPLICATION
		3.7 RELIABILITY & SAFETY METHODS DEVELOPMENT
		3.8 ALTERNATE MEASURES OF SAFETY & ACCIDENT CATEGORIES
1.	IMPROVE VALVE PERFORMANCE (MECHANICAL)	✓
2.	IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)	✓
3.	IMPROVE PUMP PERFORMANCE (MECHANICAL)	✓
4.	IMPROVE STEAM GENERATOR PERFORMANCE	✓
5.	IMPROVE PIPING PERFORMANCE	✓
6.	ADDRESS NRC UNRESOLVED SAFETY ISSUES	✓
7.	ENHANCE FUEL PERFORMANCE	✓
8.	IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE	✓
9.	IMPROVE CONTAINMENT SYSTEMS	✓
10.	IMPROVE TEST AND MAINTENANCE	✓
11.	IMPROVE EMERGENCY CONTROL	✓
12.	IMPROVE DISTURBANCE CONTROL	✓
13.	IMPROVE DESIGN GUIDANCE	✓
14.	IMPROVE EMERGENCY RESPONSE	✓
15.	IMPROVE SITING	✓
16.	IMPROVE UTILIZATION OF RISK METHODS	✓

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

SUMMARY SECTION

4.0	SAFETY DATA
4.1.1	PRIMARY SYSTEM ACCIDENT MODEL AND ANALYSIS
4.1.2	THERMAL/HYDRAULIC PRIMARY SYSTEM DATA
4.1.3	CORE DAMAGE ASSESSMENT
4.1.4	COOLANT CHEMISTRY FOLLOWING FUEL FAILURE
4.1.5	ATMOSPHERIC F.P. RELEASE, TRANSPORT AND DEPOSITION
4.1.6	GASEOUS EXPLOSION ASSESSMENT AND PROTECTION
4.1.7	CONTAINMENT FAILURE MODES
4.2	TRANSIENT BEHAVIOR
4.3	NRC UNRESOLVED SAFETY ISSUES
4.4	DNB/FUEL DAMAGE LIMITS

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
7. ENHANCE FUEL PERFORMANCE
8. IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE
9. IMPROVE CONTAINMENT SYSTEMS
10. IMPROVE TEST AND MAINTENANCE
11. IMPROVE EMERGENCY CONTROL
12. IMPROVE DISTURBANCE CONTROL
13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
16. IMPROVE UTILIZATION OF RISK METHODS

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
7. ENHANCE FUEL PERFORMANCE
8. IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE
9. IMPROVE CONTAINMENT SYSTEMS
10. IMPROVE TEST AND MAINTENANCE
11. IMPROVE EMERGENCY CONTROL
12. IMPROVE DISTURBANCE CONTROL
13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
16. IMPROVE UTILIZATION OF RISK METHODS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

SUMMARY SECTION

5.0

UTILITY TRAINING PROGRAM

5.1

UPGRADE TRAINING CERTIFICATION

5.2

HUMAN FACTORS & HUMAN
ENGINEERING

5.3

IMPROVE OPERATING PROCEDURES
AND DIAGNOSTICS

5.4

HUMAN ERROR RATE QUANTIFICATION

5.5

IMPROVED QUALITY ASSURANCE

TABLE 2.1 SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

6.0	EMERGENCY RESPONSE TEAM & PROCEDURES
6.1	EMERGENCY RESP. TEAM & PROC.
6.2	DEVELOPMENT OF IMPROVED COMMUNICATIONS & INFORMATION
6.3	DEVELOPMENT OF PLANT CHARACTER- IZATION INFORMATION
6.4	EMERGENCY EQUIPMENT POOL
6.5	ROBOT DEVELOPMENT
6.6	RADIOACTIVE CONTROL & MONITORING
6.7	USE OF NON-SAFETY SYSTEMS DURING EMERGENCY
6.8	DECONTAMINATION & ACCIDENT RECOVERY

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
7. ENHANCE FUEL PERFORMANCE
8. IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE
9. IMPROVE CONTAINMENT SYSTEMS
10. IMPROVE TEST AND MAINTENANCE
11. IMPROVE EMERGENCY CONTROL
12. IMPROVE DISTURBANCE CONTROL
13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
15. IMPROVE UTILIZATION OF RISK METHODS.

S U M M A R Y S E C T I O N

✓ ✓ ✓ ✓ ✓ ✓ ✓

✓

TABLE 2.1

SUMMARY OF THE
RESEARCH PROJECTS
WHICH COMPOSE THE
SIXTEEN RESEARCH
PROGRAMS

1. IMPROVE VALVE PERFORMANCE (MECHANICAL)
2. IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)
3. IMPROVE PUMP PERFORMANCE (MECHANICAL)
4. IMPROVE STEAM GENERATOR PERFORMANCE
5. IMPROVE PIPING PERFORMANCE
6. ADDRESS NRC UNRESOLVED SAFETY ISSUES
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13. IMPROVE DESIGN GUIDANCE
14. IMPROVE EMERGENCY RESPONSE
15. IMPROVE SITING
16. IMPROVE UTILIZATION OF RISK METHODS

RESEARCH PROGRAMS

TASKS FROM PROGRAM PLAN

SUMMARY SECTION

7.0	THREE MILE ISLAND ANALYSIS
7.1	SHORT-TERM STUDIES
7.2	PRIMARY SYSTEM STUDIES
7.3	CONTAINMENT BUILDING STUDIES
7.4	AUX. BUILDING STUDIES
7.5	MODELING STUDIES
8.0	SITING

Figure 2.3 Block Diagram of Typical Research Program.

form a success path. Finally, supportive projects increase the likelihood that an independent or dependent project will succeed, but they are not absolutely required. For example, in Figure 2.3, projects 2, 3, and 4 are dependent projects which form a success path. Project 5 (denoted by the "dangling" rectangle) supports the independent project 1 which forms a separate success path. The contributions of the two success paths are indicated by W_1 and W_2 respectively.

The research programs defined below are based on the proposed projects as outlined in Reference 1. Since many of these projects are still in the preliminary or planning stages, their scope and objectives are frequently and not surprisingly ill-defined and obviously subject to revision. In many cases, the activities from several projects overlap. Hence, the reader is reminded to recognize the limitations inherent in the program definitions.

2.1.1 Improved Valve Performance

The goal of the first research program is a general improvement in performance of valves. Since the structure of this program is similar to several other component oriented programs, it will be discussed in somewhat greater detail. As shown in Figure 2.4, the two success paths for this program are

- (1) project 1.1.1 (valves), and
- (2) supporting projects which affect the design and selection of valves.

Notably absent from this program are projects aimed at reducing test and maintenance errors. These projects are included in program 10, a separate program designed specifically to address test and maintenance errors. Furthermore relief valves are included in a separate research program and are also specifically excluded from this program. These assumptions limit program 1 to reducing valve related failures by incorporating hardware modifications.

Figure 2.4. Research Program 1

The primary contributor to achieving the program objective is through the valve project 1.1.1. Secondary contributions are of several types. Better quality assurance (QA) procedures during construction would reduce the likelihood that defective valves or improperly installed valves would exist in the plant. Furthermore, more effective in-service inspection would locate valves which had become defective during operation and allow repair/replacement. Equipment qualification projects would identify detrimental environmental conditions such as coolant chemistry or operating stresses and ensure that the selection criteria for the valve take proper account of these conditions. Fracture mechanics studies would support the effort. A better understanding of the relationship between the operating modes of the valve and plant safety would improve the overall system design.

2.1.2 Improved Relief Valve Performance

The goal of research program 2 is to improve the performance of relief valves. Once again only modifications of the hardware are considered. The composition of this program is analogous to program 1; consequently, the definition of the program is the same. Figure 2.5 contains the associated block diagram of the defined program.

2.1.3 Improved Pump Performance

The goal of research program 3 is to improve the performance of pumps. Only hardware related failures are addressed. Figure 2.6 contains the associated block diagram which is also identical in composition to program 1. Further description of the project interactions will be similar to that found in 2.1.1.

2.1.4 Improved Steam Generator Performance

The goal of research program 4 is to improve the performance of the steam generators with respect to their effect on plant safety. Figure 2.7 contains this information in block diagram form.

Figure 2.5. Research Program 2

Figure 2.6. Research Program 3

Figure 2.7. Research Program 4

2.1.5 Improved Pipe Design

Research program 5 is designed to improve the performance of piping. It is another hardware related program similar in composition to program 1. Figure 2.8 diagrams this research program.

2.1.6 Unresolved NRC Safety Issues

Research program 6 addresses issues unresolved within the scientific and technical communities which concern nuclear safety. Two of these programs are addressed directly in project 4.3. These are:

- (1) NRC Task A-11, Reactor Vessel Materials Toughness, and
- (2) NRC Task A-43, Containment Sump Reliability.

Project 1.3.2.5, Fluid-Structure Interaction Analysis Methods has been identified in this work as relevant to resolution of NRC-Task A-2, Asymmetric Blowdown Loads. Figure 2.9 illustrates the three unresolved issues addressed by projects in this overall nuclear safety program.

2.1.7 Enhanced Fuel Performance

The goal of research program 7 is to improve safety through improved fuel designs. Three paths leading to improved fuel design were identified among the eighty-five projects. Better assessments and quantification of DNB in fuels and better understanding of the processes resulting in fuel failure could both provide for reduced risk. In addition, the analysis of the core at TMI-2 could provide invaluable information in the understanding of core damage. The block diagram of this research program can be found in Figure 2.10.

2.1.8 Improved Shutdown Heat Removal Capability

The goal of research program 8 is to improve shutdown heat removal capability. This research program has two paths to improvement of the reliability of shutdown heat removal. Systems already designed and in place can yield improved reliability through improved quality assurance. Maintaining the elements of the shutdown heat removal system can have a noticable impact on safety due to the mitigation of possible common mode failures

Figure 2.8. Research Program 5

Figure 2.9. Research Program 6

Figure 2.10. Research Program 7

in redundant shutdown heat removal systems. Systems can also be simplified and redesigned (especially with the use of the knowledge gleaned from TMI-2 related studies). Risk methods can also provide a support role in the design of these systems as well as in identification of failure modes for aid in the direction of quality assurance programs. Figure 2.11 illustrates the organization of this research program.

2.1.9 Improved Containment Systems

Research program 9 concerns improvement of the containment and its associated safety systems. Figure 2.12 displays the projects which make up this program. There are two paths to optimization of the containment with respect to public risk. The first concerns the response of the containment to loads caused by accident environments. This includes protection against explosions and their effect on equipment and structures. The second path concerns review and simplification of active systems, such as the isolation system. This path addresses such things as improving QA and system design such that failures to isolate similar in nature to TMI-2 can be avoided. Both paths are contributed to by TMI-2 related containment building studies. In addition, achieving the goal of optimized containments requires risk methods development and use.

2.1.10 Improved Test and Maintenance

A significant source of safety component and safety system unavailability is human errors committed during test or maintenance procedures. The objective of research program 10 is to minimize the number and the consequences of test and maintenance errors and thereby increase the likelihood that the required safety systems will be available upon demand. The two success paths in this research program are:

1. Modify (simplify) plant design to minimize the impact of test and maintenance errors.

Figure 2.11. Research Program 8

Figure 2.12. Research Program 9

2. Reduce the frequency of the errors. This can be accomplished by upgrading the training and understanding of the human/machine interface by plant personnel and improving quality assurance during the performance of maintenance procedures. A knowledge of the current error rates would help to focus the program onto present problem areas.

This program is illustrated in Figure 2.13.

2.1.11 Improved Emergency Control

Improved emergency control, the goal of research program 11, would allow for better operator mitigation of accidents after their initiation. This program identifies four groupings of projects which would help in achieving this goal. A fundamental part of all four paths concerns both the identification of the problems and implementation of the proposed design changes. Risk methods would be utilized to identify the areas of primary concern and to scope out the hardware appropriate for the best solutions. The hardware would consist of better instrumentation and other supportive systems necessary to aid the operator in determining the best course of action. The four different paths define alternate routes between the planning and implementation phases. First, a better set of emergency procedures must be developed to cope with accidents. Similarly, systems must be designed more from a point of view of the human using them. Thirdly, potential uses of non-safety systems during emergencies must be scoped out and clearly identified so as to further improve emergency control. Finally, information on available safety margins and system status must be made available to the operator. This work includes improved understanding of the primary system and its response under accident situations. Figures 2.14a and 2.14b illustrate the options for improving emergency control.

2.1.12 Improved Disturbance Control

The goal of research program 12 is to improve disturbance control in nuclear reactors by improving plant response to variations in important operating parameters, fewer forced shutdowns will be required. In addition to improvement in availability of the plant, safety will be enhanced due to

Figure 2.13. Research Program 10

Figure 2.14a. Research Program 11

Figure 2.14b. Research Program 11

the reduction of the risk inherent in forced shutdown. Three approaches to improving disturbance control have been identified. In each approach planning with the support of phenomenological studies of transient behavior is necessary. As in the previous program hardware must be developed, demonstrated, and implemented to achieve better disturbance control. The first approach involves work in transient control. The second involves a better understanding of the plant protection system. Finally, understanding of relations between modes of systems, both operational and safety, and how they relate to potential shutdowns can lead to fewer shutdowns. These approaches to improved disturbance control are illustrated by block diagrams in Figure 2.15a and 2.15b.

2.1.13 Improved Design Guidance

The objective of research program 13 is to reduce the frequency of transient initiators by appropriate plant designs. Particular attention will be directed toward sabotage, earthquakes, and fires as initiators. Program 13 is supported by the projects on risk methods utilization and on design verification. Two options within these constraints also exist in addition to project 1.3.1. Designs can be simplified and therefore lead to a better understanding of the above mentioned initiators. In addition, a seismic design can be developed in order to mitigate seismic effects. This program is represented in Figure 2.16.

2.1.14 Emergency Response Teams

Research program 14 deals with the development of a emergency response team and the associated procedures. Two success paths for improving safety relative to this goal have been identified. The first addresses the use of an emergency equipment pool to provide more reliability for engineered safety features. This path would also have the support of the decontamination and accident recovery project by enhancing repairability. The second path deals with improved communications interface with the public. Since this would aid in reducing population exposures given an accident,

Figure 2.15a. Research Program 12

Figure 2.15b. Research Program 12

Figure 2.16. Research Program 13

it is supported by radioactivity monitoring and the use of robots for the same purpose. Both of these paths to completion of the program are dependent on risk methods utilization as well as the plant specific input necessary for the effective use of these methods. This program is illustrated in Figure 2.17.

2.1.15 Improved Reactor Siting

The goal of research program 15 is to reduce risk by improved siting of nuclear reactors. This program receives support from the project concerning atmospheric release, deposition and transportation models, and TMI modeling studies since this would lead to better understanding of population doses. This program is illustrated in Figure 2.18.

2.1.16 Risk Methods Utilization

The goal of research program 16 is to improve nuclear safety by the use of techniques developed under the program of risk methods utilization. The program consists of all the projects identified under that heading in the overall Sandia program. In order to develop a more complete understanding of nuclear risks which would be the payoff of such a program, it was assessed that all of these programs would be necessary. The more complete the development of the methodology, the more value the methods are to designing safer nuclear power plants. Figure 2.19 reflects this by listing all projects under 3.0 risk methods utilization with equal weight.

2.2 Evaluation of Potential Risk Reduction

As shown in Figure 2.20, the methodology used to evaluate the risk reduction associated with each research project consists of the following five steps:

- (1) determination of a baseline risk corresponding to the present generation of light water reactors,

Figure 2.17. Research Program 14

Figure 2.18. Research Program 15

Figure 2.19. Research Program 16

Figure 2.20 Methodology for Calculating Research Project/Program Values.

- (2) assessment of risk reduction after completion of each research program defined in Section 2.1,
- (3) evaluation of the contribution from each research project to its respective research program,
- (4) combination of the contributions derived in (3) to obtain "value" of individual research projects,
- (5) assignment of a qualitative measure (e.g., high, medium, and low) to the "value" of each research project from (4).

The assumptions and relationships derived to implement this procedure are detailed in Section 2.2.1. The model used to compute numerical values of risk was developed by Parkinson⁽³⁾ and is briefly discussed in Section 2.2.2 and in Appendix C.

2.2.1 Methodology

The public risk resulting from a nuclear reactor depends on a variety of factors such as plant components, systems design, operating procedures, and siting. Although the actual relationship between these factors and risk is extremely complicated, it can nevertheless be formally expressed as

$$R = f(\lambda_1 \lambda_2 \cdots \lambda_n \cdots \lambda_N) \quad (2.1)$$

where R is the risk and λ_n is a measure of the n -th factor affecting risk. In the present discussion, λ_n will generally represent the failure rate of the n -th component or system. However, it can also represent a specific operating or maintenance procedure. Even though the absolute magnitude of risk as determined by the model in Equation (2.1) may contain large uncertainties due to uncertainties in the failure rates, the relative risk corresponding to different sets of failure rates is nevertheless generally correct.

The first step in evaluating the value of research projects and programs is to determine the public risk associated with present generation light-water reactor. This baseline risk, denoted by R^* , is a function of $\lambda_1^* \dots \lambda_N^*$, the failure rates corresponding to a current generation plant. Symbolically,

$$R^* = f(\lambda_1^*, \lambda_2^*, \dots, \lambda_N^*) \quad (2.2)$$

The next step is to determine the risk reduction associated with each research program. Since the objective of each research program is to improve the performance of one or more systems, the end product of each program is ultimately a reduction in one or more component failure rates. Hence, the public risk after implementing the recommendations of the j -th program is

$$R_j = f(\lambda_1^* - \delta\lambda_{1j}, \lambda_2^* - \delta\lambda_{2j}, \dots, \lambda_N^* - \delta\lambda_{Nj}) \quad (2.3)$$

where $\delta\lambda_{nj}$ is the failure rate reduction in the n -th component resulting from the j -th research program. In general, only a small set of $\delta\lambda_{nj}$ are non-zero for a particular research program. Schematic diagrams on Equations (2.2) and (2.3) are shown in Figure 2.21.

The selection of an appropriate value for the non-zero $\delta\lambda_{nj}$ is the most difficult aspect of this methodology. The correct value is a function of

- (1) the objective of the research program, and
- (2) the degree of success in achieving the stated objective.

The degree of success, in turn, depends on

- (1) the state-of-the art,
- (2) the level of program funding,
- (3) the period of performance, and
- (4) the personnel or organizations involved.

Assessment of Risk Associated with Present LWRs

Assessment of risk after implementing recommendations of the j -th research project

Figure 2.21 Evaluation of Research Program Risk Reduction.

Since considerable uncertainty exists in these factors, engineering judgment must be exercised in assessing the $\delta\lambda_{ij}$. Guidance in making this determination was also provided by noting the level of success in similar previous efforts and by recent advances in the field. Although research programs may interact and profit from each other, the present analysis assumes that the success of a given program is independent of all other programs.

The reduction in risk due to completion of the j -th research program may be measured by a risk reduction factor F_j which is defined as

$$F_j = \frac{R^*}{R_j} = \frac{\text{baseline risk}}{\text{risk after completing } j\text{-th program}} \quad (2.4)$$

This particular definition was selected because it tends to minimize the impact of uncertainties in the absolute values of R^* and R_j .

After the program risk reduction factors F_j have been established, they can be used to estimate project risk reduction factors ϕ_k . In a manner analogous to Equation (2.4), suppose that F_{jk} is defined by

$$F_{jk} = \frac{R^*}{R^* - \delta R_{jk}} = \frac{\text{baseline risk}}{\text{risk after completing the } k\text{-th project in the } j\text{-th program}} \quad (2.5)$$

where δR_{jk} is the risk reduction due to the k -th project in the j -th program. Parkinson (3) has shown that a good estimate for ϕ_k is given by

$$\phi_k = F_{1k} F_{2k} \cdots F_{Nk} \quad (2.6)$$

or

$$\phi_k = \prod_j F_{jk} \quad (2.7)$$

In order to calculate the F_{jk} 's one needs to estimate the contribution of individual projects to each program. For example, if W_{jk} is the fractional contribution of the k -th project to the j -th program risk reduction, then

$$\delta R_{jk} = W_{jk}(R^* - R_j) \quad (2.8)$$

Substitution of Equation (2.8) into Equation (2.5) gives

$$F_{jk} = \frac{R^*}{R^* - W_{jk}(R^* - R_j)} \quad (2.9)$$

$$\begin{aligned} &= \frac{1}{1 - W_{jk}(1 - R_j/R^*)} \\ &= \frac{1}{1 - W_{jk}(1 - \frac{1}{F_j})} \end{aligned} \quad (2.10)$$

Since both the baseline failure rates and the improvements in failure rates have considerable uncertainty, it may be more appropriate to measure the project and program risk reductions qualitatively. The following five qualitative risk reduction categories have been defined and used in this study.

<u>Category</u>	<u>Risk Reduction Factor</u>
Very high	$x \geq 5.0$
High	$2.0 \leq x < 5.0$
Moderate	$1.5 \leq x < 2.0$
Low	$1.1 \leq x < 1.5$
Very low	$1.0 \leq x < 1.1$

In the discussion of research projects $x = \phi_k$, while $x = F_j$ in the discussion of research programs.

2.2.2 Light Water Reactor Risk Sensitivity Model

The primary tool in this analysis is a light water reactor risk sensitivity model developed by Parkinson.⁽³⁾ This model consists of fault trees, which combine components to represent plant systems, and event trees, which are used to model core melt accident sequences. The independent variables are point estimates for failure rates of various components. The dependent variable is the public risk due to core melt corresponding to an assumed set of failure rates.

The numerical evaluation of the fault trees and event trees is carried out in the computer code LWRSEN, which is described in detail in Appendix C. LWRSEN does not employ a consequence category smoothing model as WASH-1400. Hence, LWRSEN predictions of absolute public risk differ slightly from WASH-1400 results when identical failure rates are used in both models. This small discrepancy does not pose any significant problems because it is the difference in the calculated risk that is important for this project.

2.3 ASSESSMENT OF IMPLEMENTATION COSTS

Appendix B provides a discussion and quantification of estimated implementation costs for new and existing plants for each research program. Although level of detail varies between discussions, the general organization of each Appendix B Section is comprised of the following:

1. Summary of purpose of research programs and projects which make up the programs.
2. Summary discussion of approach to estimating costs including identification of concepts evaluated.
3. Base data to be utilized in deriving implementation costs.
4. Discussion of aspects of new plant design, construction and operation likely to be modified as a result of successful project completion and implementation. Quantification of new plant implementation costs.
5. Discussion of aspects of existing plant design, modification and operation impacts likely to result and quantification of existing plant implementation costs.
6. Summary discussion or table of implementation costs.

In cases where R&D could result in one of several concepts, implementation costs have in some cases been quantified for several of the candidate solutions. This method provides a reasonable basis for deriving specific costs associated with an action (procedure change, for example) or equipment requirements. Reported implementation cost will, therefore, occasionally vary over a wide range for the various possible solutions related to one research program.

Summary results of implementation cost quantification are presented in Section 3.2. For purposes of benchmarking reported costs, the following

sections discuss normalization and utilization of available data. It is important for the reader to realize that this discussion is an extreme simplification of methodology applied to calculate plant capital investment, escalation, interest and replacement power costs normalized to 1976 dollars. However, the numbers derived are appropriate for application to concept implementation cost estimating which is the intended application of the data.

2.3.1 Base Facility Costs

References 5 and 6 have been extensively utilized throughout this study due to the detailed breakdown they provide for BWR and PWR capital costs. The reported total base construction costs, in 1976 dollars, range between 490 and 499 dollars/KW installed or approximately 600 million dollars for a BWR and PWR of current size (approximately 1150 MW). Excluded from this estimate, however, are such items as interest during construction, escalation, fees, taxes, spare parts, unit transformer and transmission facilities, insurance, fuel costs and contingency.

These exclusions are highly significant to total plant costs. The parameter that is commonly used to quantify total plant cost is Investment Costs, in dollars/KW and includes the capital costs and the exclusions noted above. This factor is only meaningful when escalation can be calculated over a specified construction duration for specific rates of escalation. In 1976, interest during construction and escalation amount to approximately 40% of total plant costs over an approximately 5.5 year (66 month) construction duration. (reference 7). 1977 data (reference 8) indicates, however, that 95 month construction was the average for nine large nuclear projects entering commercial operation with a range of construction durations of 74 to 118 months. An extrapolation of construction duration trends over the past several years was recently performed (reference 9) to assist estimating plant cost for a nuclear plant entering operation in 1990. In this case, a 132 month construction duration was predicted with construction interest and escalation amounting to approximately 60% of total plant cost.

For the purposes of this study, a 95 month construction duration is assumed with the corresponding escalation and interest costs amounting to 50% of total investment costs. Referring back to the above discussion, this would amount to an additional ≈600 million dollars. Hence, for simplicity, capital cost data available directly from references 5 and 6 will be doubled to include the influence of escalation and interest in Engineering & Construction Support, Factory Equipment, Labor, and Site Materials.

Construction duration is a parameter that will be employed to account for significant variances in construction sequences. As indicated above, a 95 month duration requires ≈600 million dollars for interest and escalation. Any variation in the 95 month construction duration will be noted as + or - months. The impact will only be noticed when the component, structure or system has a direct bearing on critical path scheduling. Cost impact per month will be averaged to 7 million dollars per month.

2.3.2 Operation and Maintenance Costs

Outage rates directly attributable are reported as the average number of days per year current plants are unavailable to produce at or near capacity as a direct result of the component, system, structure or action identified in the Sandia tasks. These rates have been derived from available literature (references 10 through 15). In addition to the number of hours involved, costs associated with replacement power and significant changes in maintenance labor and materials are identified and factored into implementation costs. Replacement power cost is a factor that varies widely among utilities. Replacement power costs can be significantly affected by factors such as 1. whether a utility has sufficient reserve capacity to internally generate inexpensive

replacement power (such as surplus hydro) without utilizing peaking facilities (oil or gas turbines), or 2. if a utility must purchase power which a neighboring utility generates using peaking facilities. Replacement power costs can vary by a factor of 3 or 4. For this reason, time of day or season during which the outage occurs have a significant influence on whether replacement power is relatively cheap (system average demand is low) or expensive (during peak usage times). In our study, 1100-1200 MW nuclear units are assumed to maintain a 65% capacity factor with replacement power costs amounting to 300,000 dollars per day (excluding debt service) in 1976 dollars. It is further assumed that plant availability is limited to 90% of each year due to unavoidable scheduled outages such as refueling. Hence, the maximum replacement power costs that can be incurred for one year is approximately 72 million dollars/year. Likewise, the maximum benefit that can be derived from plant operation at maximum capacity amounts to 39 million/year. New plants will not incur replacement power costs of this magnitude for extended construction sequences, since the construction duration will be known and start of construction would be appropriately adjusted. Likewise, benefit is not realized for new plants in shortening construction duration in the replacement power costs area.

In common usage, O&M costs include fixed costs such as debt service, insurance, fixed O&M and administration and variable costs such as fuel cost, taxes and spare parts usage and replacement.

For the purpose of this study, cost areas not influenced by Sandia Tasks (insurance, fuel costs, taxes and debt service) are excluded. Fixed operation and maintenance, of which the major cost is labor, and administration and general expenses are quantified where appropriate. Fuel and other maintenance cost data utilized is either already reported in 1976 dollars or converted to 1976 dollars as appropriate. As such costs are passed directly on to consumers via the rate base, fuel and maintenance costs are not modified for either escalation or interest charges.

3.0 RESULTS

The risk reduction and cost associated with each of the research programs defined in Section 2.1 have been evaluated using the methodology described in Sections 2.2 and 2.3 respectively. The qualitative results of these evaluations are summarized in Section 3.1 and 3.2 and plotted in Section 3.3. The quantitative details of these calculations are given in Appendices A and B.

3.1 Qualitative Assessment of Program and Project Risk Reductions

The risk reduction associated with each of the research programs defined in Section 2.1 has been evaluated. The components, systems, and procedures improved by each program were identified. Engineering judgment was exercised to estimate the magnitude of the improvement in terms of a reduced failure rate for the given system or procedure. A quantitative value of the risk corresponding to the new failure rates is calculated using the computer code LWRSSEN. The risk reduction of the program is obtained by comparison with the baseline risk of a present generation LWR. Finally, a qualitative value of risk reduction is assigned to each program. The results are summarized in Table 3.1 which lists

- (a) the goal of each research program,
- (b) the qualitative risk reduction of each research program,
- (c) the sensitivity of the program's risk reduction to variations in the degree of success in achieving the stated objective

Qualitative estimates of risk reduction were also made for individual research projects. Table 3.2 lists the research projects within each qualitative risk reduction category, while Table 3.3 lists the projects in order and gives their corresponding risk reduction.

Table 3.1 Summary of the Risk Reduction Potential and Sensitivity
of the 16 Research Programs

<u>Research Goal</u>	<u>Risk Reduction Potential</u>	<u>Sensitivity</u>
1. Improved valve Performance	Very low	Insensitive to high reductions in failure rates.
2. Improved relief valve performance	Very low	same as above
3. Improved pump performance	Very low	same as above
4. Improved once thru steam generator design	Low	Based on on-site electric power recovery
5. Improved pipe performance	Moderate	Diminishing return after factor reductions on order of ten.
6. NRC unresolved safety issues	N.A.	Increase RSS failure probabilities by 1000 before these affect risk.
7. Improved fuel design	Very low	Bounded to be less than 5% reduction.
8. Improved shutdown cooling	High	High risk reduction at high reductions in failure probability.
9. Improved containment design	Very high	High sensitivity to all reductions.
10. Improved test and maintenance	High	High sensitivity to error reduction.
11. Improved emergency control	High	Ten reductions
12. Improved disturbance control	Moderate	Linear (very high) sensitivity
13. Improved design guidance	Moderate	Bounded due to random failure contribution.
14. Improved emergency response	Very high	Diminishing return past assessed value.
15. Improved siting	High	With very strict siting could be very high.
16. Risk Methods utilization	Very high	Sensitivity based on completeness of program.

Table 3.2 Summary of Value Category For All Research Projects
From the Preliminary Program Plan

<u>Very High</u>	<u>High</u>	<u>Moderate</u>	<u>Low</u>	<u>Very Low</u>
3.0	6.2	1.3.3	7.1	6.5
1.2.2	2.1	1.3.1	1.1.2	1.1.1
6.1	1.1.5	2.5	2.4	4.1.5
6.3	2.11	1.1.6	1.2.1	6.8
1.1.3	5.2	2.2	1.1.4	1.3.2.6
2.9	6.6	4.1.1	5.3	1.3.2.7
2.10	5.4	4.1.2	7.4	1.3.2.3
2.12	4.1.6	4.1.3	7.5	1.3.2.1
4.1.7	1.2.4	4.1.4	2.3	4.4
	5.1	4.2	2.6	
	1.2.3	6.4	2.7	
	6.7	7.2	2.8	
	8.0	7.3	1.3.2.2	
			1.3.2.4	

Table 3.3 Qualitative Risk Reduction Potential of Research Projects

<u>Project</u>	<u>Qualitative Risk Reduction</u>	<u>Project</u>	<u>Qualitative Risk Reduction</u>
1.0		2.6	Low
1.1		2.7	Low
1.1.1	Very Low	2.8	Low
1.1.2	Low	2.9	Very High
1.1.3	Very High	2.10	Very High
1.1.4	Low	2.11	High
1.1.5	High	2.12	Very High
1.1.6	Moderate	3.0	Very High
1.2		4.0	High
1.2.1	Low	4.1.1	High
1.2.2	Very High	4.1.2	High
1.2.3	High	4.1.3	High
1.2.4	High	4.1.4	Moderate
1.3		4.1.5	High
1.3.1	Moderate	4.1.6	High
1.3.2.1	Very Low	4.1.7	Very High
1.3.2.2	Low	4.2	Moderate
1.3.2.3	Very Low	4.3	N.A.
1.3.2.4	Low	4.4	Very Low
1.3.2.5	N.A.	5.0	
1.3.2.6	Very Low	5.1	High
1.3.2.7	Very Low	5.2	High
1.3.3	Moderate	5.3	Low
2.0		5.4	High
2.1	High	5.5	High
2.2	Moderate	6.0	
2.3	Low	6.1	Very High
2.4	Low	6.2	High
2.5	Moderate	6.3	Very High
2.6	Low	6.4	Moderate

Table 3.3 (cont.)

<u>Project</u>	<u>Qualitative Risk Reduction</u>
6.5	Very Low
6.6	High
6.7	Moderate
6.8	Very Low
7.0	
7.1	Low
7.2	Moderate
7.3	Moderate
7.4	Low
7.5	Low
8.0	Moderate

The details of the analyses used to obtain the results of Tables 3.1, 3.2, and 3.3 are given in Appendix A. Specifically, Appendix A describes

- (a) assessment of improved failure rates,
- (b) quantitative values of program risk reduction,
- (c) sensitivity of risk reduction to level of program success,
- (d) estimates of contribution of each project to the success of of a given program, and
- (e) quantitative values of project risk reduction.

3.2 Implementation Costs

Order-of-magnitude estimated implementation costs for the sixteen research programs are summarized in Table 3.4. Cost estimates have been provided for both new and existing plants. For simplicity in generating these costs, a new plant is defined as a project in which the results of Sandia R&D can be implemented without requiring redesign or plant modifications that would increase cost or delay the project.

As indicated in Section 2.3, costs are in approximate 1976 dollars and include interest charges and escalation of the magnitude incurred in plant construction. Hence these costs can be compared with the total project cost for a 1150 MW plant of approximately 1.2 billion dollars.

Usually, cost estimates are based on specific information on a particular system or structure configuration, bulk quantities of materials involved and other "knowns." In the sixteen Sandia research programs, however, the outcome of the R&D effort is not specifically known. This situation has required incorporation of an additional level of complexity to the task of estimating implementation cost. This problem has generally been accommodated for the sixteen programs by describing one or more than one

TABLE 3.4
SUMMARY OF PLANT LIFETIME
IMPLEMENTATION COSTS (MILLIONS OF DOLLARS)

<u>RESEARCH PROJECT NUMBER</u>	<u>NEW PLANTS</u>	<u>EXISTING PLANTS</u>
1. VALVES	<0-6	{ 15 }
2. RELIEF VALVES	<0-1	
3. PUMPS	<0	0
4. STEAM GENERATORS ⁽¹⁾	<0/33	60/100/240
5. PIPING	0-33	PARTIAL IMPLEMENTATION - 0 COSTS
6. UNRESOLVED SAFETY ISSUES	0	0
7. FUEL	0-50	0-50
8. SHUTDOWN & EMERGENCY COOLING	60	290
9. CONTAINMENT	2/10/11.5/150	22/38/86/250
10. TEST & MAINTENANCE	<u><0</u>	<u><0</u>
11. EMERGENCY CONTROL	<0	<0 + 27 (CONTROL ROOM MODIFICATIONS)
12. DISTURBANCE CONTROL		
13. DESIGN GUIDANCE	<u><0</u>	0-20
14. EMERGENCY RESPONSE	12	12
15. SITING	100	NOT APPLICABLE
16. RISK METHOD UTILIZATION	<0 (See discussion in Appendix B)	<0 (See discussion in Appendix B)

⁽¹⁾Cost data on multiple engineering concepts are presented.

reasonable engineering solution for each research program and evaluating implementation cost on that basis. As stated elsewhere in this report, the "reasonable engineering solutions" are not intended to express judgment as to the likely outcome of the R&D for either those solutions evaluated or those not evaluated. Rather, they are a necessary and convenient tool to base costs upon.

For containment and steam generators, several implementation costs are reported for both new and existing plants. In these cases, a single engineering solution would be sufficiently representative. Hence, multiple solutions were evaluated and reported.

Table 3.4 costs are characterized as "order-of-magnitude" costs. Given the lack of precise "engineering solutions" at the front end of the cost estimating task, the engineering solutions are conceptual. As such a detailed cost estimate for each solution is not warranted. Hence the costs discussions in Appendix B were derived from available data on major component costs, engineering and labor costs and others. These data have then been scaled in proportion to the type of structure, system or component under evaluation.

The reader is referred to Appendix B for the details of the approach and basis for each of the sixteen research projects' implementation costs.

3.3 Value Impact Matrices

The previous two sections discussed the results of the analysis of risk reduction potential and implementation cost of the sixteen research programs. In this section these results are combined into value-impact matrices. These matrices have been developed for both existing plants and future plants. In most cases the risk reduction potential is the same for both existing and future plants, while the implementation costs are considerably different.

Figure 3.1 and 3.2 are the value-impact matrices for existing and future plants. The coordinates are defined below:

<u>RISK REDUCTION POTENTIAL</u>	
<u>Category</u>	<u>Risk Reduction Factor</u>
Very High	$5.0 \leq x$
High	$2.0 \leq x \leq 5.0$
Moderate	$1.5 \leq x \leq 2.0$
Low	$1.1 \leq x \leq 1.5$
Very Low	$1.0 \leq x \leq 1.1$

<u>IMPLEMENTATION COST</u>	
<u>Category</u>	<u>Implementation Cost (\$ Millions)</u>
Very High	$50 \leq c$
High	$15 \leq c \leq 50$
Low	$5 \leq c \leq 15$
Zero	$-5 \leq c \leq 5$
Negative	$c \leq -5$

Figure 3.1 Value-Impact Matrix Depicting Research Program
Ranking For Existing Plants

Figure 3.2 Value-Impact Matrix Depecting Research Program
Ranking for New Plants

No attempt has been made in the value-impact matrices to reflect uncertainties in either implementation costs or in risk reduction potential]. These issues have been discussed in Appendices A and B.

3.3.1 Existing Plants

As shown in Figure 3.1, for existing plants, the best combination of high potential risk reduction and possible implementation cost are found in research program 10 (Improved Test and Maintenance). This conclusion is not surprising in light of two facts: (1) procedural changes are not necessarily costly and may in fact reduce operating cost; and (2) the reactor safety study showed that the dominant failure modes associated with many systems are related to testing and maintenance errors. Other research programs which have high risk reduction potential and low implementation cost for existing plants include:

- (5) Improve Piping Performance;
- (14) Improve Emergency Response;
- (11) Improve Emergency Control.

It should be noted that research program (12) Improved Disturbance Control is expected to have an associated implementation cost of nearly the same as research program (11). In fact, it is likely that the same equipment can be used in the implementation of the results of both research programs. Research program (12), however, is limited by its ability to reduce transient frequency. To account for the difficulty involved in reducing the frequency of transients, a moderate risk reduction factor of 1.5 was chosen. However, because of the nearly linear dependence of risk reduction on improvement factor, this program is certainly of considerable value.

Finally, it should be noted that the improved utilization of risk methods [research program (16)] has been assigned a moderate risk reduction potential and a low cost of implementation. This assignment belies the fact that improved utilization of risk assessment techniques is instrumental in the success of research programs 5, 11, and 14, all of which have significant potential to reduce plant risk, as noted above.

3.3.2 New Plants

As shown in Figure 3.2, for new plants, the research program with the best combination of low implementation cost and high risk reduction potential is the improved utilization of risk methods (16). This observation is reasonable because experience has shown that use of risk methods as an integral part of the design process can significantly reduce both plant cost and plant risk at the same time. Examples of these uses of risk methods are given in Section A.2.16 of Appendix A.

Other examples of research programs with high risk reduction potential and low implementation cost include:

- (10) Improved Test and Maintenance;
- (11) Improved Emergency Control;
- (12) Improved Disturbance Control;
- (13) Improved Design Guidance.

In addition, at slightly higher cost, a significant risk reduction potential exists for:

- (9) Improved Containment Systems;
- (14) Improved Emergency Response.

The observations which were made in Section 3.3.1 on research program (12), Improved Disturbance Control, are equally relevant to that program as it applies to future plants.

4.0 RECOMMENDATIONS

4.1 Possible Additions to LWR Safety Technology Program

This review of the Preliminary LWR Safety Technology Program Plan has revealed no major omissions in that plan. Some minor additions to existing research projects and some restructuring of the concepts presented in the plan might, however, serve to strengthen it. The SAI report which has been produced as a companion to this document (16), in which the literature issued subsequent to the TMI-2 accident has been reviewed for relevance to the program plan, has suggested a number of additions to existing research projects. These suggestions will not be restated here. Suggestions on limited restructuring of the plan are presented below for consideration by Sandia.

Two general topics which are strongly related to the success of the Sandia program are noted in the program plan, but are not emphasized to the degree which might be warranted by their importance. These topics are:

- o Assurance of Acceptance by the Technical Community;
- o Assurance of Adequacy of Support Systems.

The first of these topics, assurance of acceptance by the technical community, is discussed frequently within the program plan (e.g., in Section 2.0 p. 46), but because of its obvious importance might be segregated from the technical tasks and, thereby, accorded its deserved importance. Consideration should be given by Sandia to making such an activity a major subprogram area on an equal footing with the remaining eight subprograms.

Examples of the types of tasks which might be funded under such an "Assurance of Acceptability" subprogram include:

- o Formal solicitation of industry and regulatory opinions on important programmatic decisions [perhaps as an adjunct to the task on R&D Selection Methodology (3.1.5)]. Advisory task forces might be formed to continue this exchange of opinions and ideas;
- o Formal technical peer review of the results of important research projects funded under the eight technical subprograms;
- o Presentation of workshops and seminars on important technical issues. These might be used either at the outset of a new technical project to gather opinions and information on the state-of-the-art or at the conclusion of a major technical project to foster dissemination of information. These could be documented by "State-of-Technology" papers;
- o Establishment of formal information exchange ties with other domestic and foreign safety technology programs. This might include formal review of important research results such as the recently published German Reactor Safety Study.
- o Supporting of an information bulletin which would regularly disseminate, at no charge, the results of safety-related programs funded by Sandia/DOE as well as those supported by other agencies.

Because such an "Assurance of Acceptability" activity would cut across all of the remaining eight subprograms, and because it might require significant funding, consideration should be given to according it subprogram status.

The other addition to the current program plan which is worth considering is a separate task on assuring the adequacy of support systems. Although this activity is implicate in several of the other tasks (e.g., 3.1.4 Non-Independent Failures), it is sufficiently important in the assurance of plant safety that it might be given research project status under either Improved Systems (1.2) or Improved Plant Design (1.3). Approaches to evaluating the adequacy of support systems would clearly need to draw on tasks in the Risk Methods Utilization subsection (3.0).

4.2 Suggestions on Refinements to Prioritization Approach

The difficulties encountered in the present prioritization activity have been enumerated in Section 1.3. Corresponding to each of these difficulties are refinements which might improve the quality of the prioritization work. These refinements are treated below:

- o Effectiveness of Research Programs To develop an improved idea of the expected effectiveness of each of the research programs, it would be valuable to employ industrial expertise. The magnitude of this job can be considerably reduced by using the results of the current work to determine: (1) which research programs are the most effective in reducing risk; and (2) which produce the greatest changes in risk for a given fractional change in program achievements. By reviewing the details of the contribution to risk reduction, as reflected in the WASH-1400 model, and formulating questions on the expected success potential of the research programs in addressing these contributions, knowledgeable industry sources can be polled on their opinions of the relationship between research program cost and likelihood of success. The results of these surveys can then be used as a significant input to defining the course and funding level of high priority safety technology programs.

- o Reasonableness of Cost Estimates The best approach to improving the validity of the implementation cost estimates is to develop specific engineering concepts designed to reflect specific results expected from safety technology programs. Questions might be formulated as part of the polling process described above to solicit industry opinions on the engineering implications of expected results from safety technology programs. Final costing should be carried out by industry people with significant experience in the construction of such estimates.

- o Uncertainties in the WASH-1400 Risk Model There are two primary uncertainties in the WASH-1400 risk model which might influence the results of this study. The first results from the fact that nearly four years of risk assessment work performed subsequent to the publication of WASH-1400 have influenced the details of the accident sequences reported there. Developments in such areas as seismic events and common-cause failure analysis need to be incorporated in the WASH-1400 models to assure the validity of conclusions based on those models. The second source of uncertainty is that resulting from the significant variations in design from plant to plant. These design variations result in significant differences among plants in which sequences are most important. These differences were treated in the present analysis only when events such as the TMI-2 accident have focused on them.

These two uncertainties can be reduced by the construction of a series of detailed risk models which reflect both the state-of-the-art in risk assessment technology (and failure rate data) and the significant design variations which exist among operating reactors. Results from these models can then be used in a code such as LWRSEN (Appendix C) to assess the risk reduction potential and sensitivities of the sixteen research programs.

- o The Effect of Risk Measure on Research Program Value As noted in Section 1.3, the use of different measures of risk will result in different conclusions relative to the value of a research program. This problem is currently being addressed in the on-going project on R&D Selection Methodology.

In addition to addressing the difficulties encountered as discussed above, it would be of value to modify the LWRSEN computer code (Appendix C) to allow consideration of the following factors:

- a. To allow sensitivity analysis to be performed to account for the risk reduction potential associated with the results of several research programs conducted in parallel. This capability would allow evaluation of synergistic or masking effects associated with multiple programs to be identified.
- b. To allow evaluation of the effect of siting on risk, it would be useful to build in a generalized model to account for population and meteorological effects. A first attempt at this might be made by using the simple model presented in Reference (17).

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APPENDIX A

DETAILED DISCUSSION OF THE RISK REDUCTION POTENTIAL

APPENDIX A

DETAILED DISCUSSION OF THE RISK REDUCTION POTENTIAL

A.1 INTRODUCTION

This appendix contains two parts. The first contains the detailed presentation of the results of the risk reduction calculations which were performed for each of the sixteen research programs. The second part contains those results as applied to each of the individual projects which make up Sandia's Preliminary LWR Safety Technology Program Plan.

Each individual research program was analyzed for its risk reduction potential. This was done by the use of calculations from a risk model based on the WASH-1400 analysis. A research program was assumed to cause some reduction in the risk associated with a change in an input to the risk model. For example, improving valve performance would cause a reduction in the failure probability for valves and therefore a reduction in public risk.

These calculations were performed for both a PWR and a BWR where applicable. The risk analysis included up to four parameters: latent deaths, core melt probability, early deaths, and property damage. The above mentioned results are presented for different levels of success of each program. Based on these calculations a risk reduction potential was chosen for each research program. These calculations also indicate the sensitivity of risk to higher or lower levels of program effort. A summary of the results for all the research programs is provided in Figure A-0.

FIGURE A-0 SUMMARY OF RISK REDUCTION
POTENTIAL CALCULATIONS FOR
THE SIXTEEN RESEARCH PROGRAMS

RATIO BETWEEN RISK FOR AN RSS PWR AND A
PWR WHICH HAS BEEN MODIFIED TO ACHIEVE A
RISK REDUCTION RESULTING FROM THE HYPOTHESIZED SUCCESSFUL
COMPLETION OF A SPECIFIC RESEARCH PROJECT

NOTES

- α B&W Plant
β Change Once Through to U Tube
γ Change to Filtered Venting
δ RSS Site Comparison: High to Medium and
High to Low

RESEARCH PROGRAMS

LATENT FATALITY RISK

FACTOR OF IMPROVEMENT
ASSOCIATED WITH RESEARCH
PROJECT

CORE MELT PROBABILITY RISK

FACTOR OF IMPROVEMENT
ASSOCIATED WITH RESEARCH
PROJECT

3 10 30

3 10 30

1.	IMPROVE VALVE PERFORMANCE (MECHANICAL)	1.03	1.04	1.04	1.08	1.10	1.11
2.	IMPROVE RELIEF VALVE PERFORMANCE (MECHANICAL)	1.00	1.01 (5.47) ^α	1.01	1.02	1.03 (9.99) ^α	1.03
3.	IMPROVE PUMP PERFORMANCE (MECHANICAL)	1.02	1.03	1.03	1.07	1.09	1.09
4.	IMPROVE STEAM GENERATOR PERFORMANCE	6.69 ^β			3.07 ^β		
5.	IMPROVE PIPING PERFORMANCE	1.45	1.72		2.20	3.80	
6.	ADDRESS NRC UNRESOLVED SAFETY ISSUES	-	-	-	-	-	-
7.	ENHANCE FUEL PERFORMANCE	1.04	1.17	-	-	-	-
8.	IMPROVE SHUTDOWN COOLING SYSTEM PERFORMANCE	2.25	4.00	5.15	1.12	1.17	1.18
9.	IMPROVE CONTAINMENT SYSTEMS	9.53 ^γ			-	-	-
10.	IMPROVE TEST AND MAINTENANCE	2.35	4.12	5.21	1.18	1.25	1.27
11.	IMPROVE EMERGENCY CONTROL	1.25	1.33	1.35	1.02	1.02	1.02
12.	IMPROVE DISTURBANCE CONTROL	3.0	10.0	30.0	3.0	10.0	30.0
13.	IMPROVE DESIGN GUIDANCE	>2			>2		
14.	IMPROVE EMERGENCY RESPONSE	1.04	1.05	1.06	1.50	1.82	1.94
15.	IMPROVE SITING	2.15 ^δ	7.02 ^δ				
16.	IMPROVE UTILIZATION OF RISK METHODS	SEE EXAMPLES			SEE EXAMPLES		

A-2

A.2 RESEARCH PROGRAM DISCUSSION

A.2.1 Research Program 1

The goal of research program 1 is to improve valve safety related performance. This was assumed to lead to a reduction in the failure probability of all valves, except relief valves. The following tables contain the risk reduction factors for a given factor reduction in valve hardware failure probabilities.

PWR				
Factor	Early Fatalities	Latent Fatalities	Property Damage	Core Melt Probability
3	1.03	1.03	1.05	1.08
10	1.04	1.03	1.06	1.10
30	1.04	1.04	1.07	1.11

BWR				
Factor	Early Fatalities	Latent Fatalities	Property Damage	Core Melt Probability
3	1.05	1.05	1.05	1.05
10	1.07	1.07	1.07	1.07
30	1.08	1.07	1.07	1.08

The risk reduction potential associated with improved valve performance was assessed to be 1.05, or very low. This assessment was based on the assumptions that hardware failure rates would be unlikely to be reduced by much more than a factor of three and that the value of further reduction would be very little. It can be seen that the sensitivity of risk to valves diminishes rapidly after a factor of three reduction in valve failure probability. Not only is the risk reduction potential for improving valve hardware very low, but any effort to achieve significant improvement in performance is likely to be quickly wasted.

A.2.2 Research Program 2

The goal of research program 2 is improved relief valve performance. Relief valve failures have received much attention since TMI-2's pressurizer relief valve stuck open. The pressurizer relief valve is the only relief valve with noticeable risk reduction potential associated with it for a BWR. In the reactor design characteristic of Surry, the pressurizer relief valve is actuated much less frequently than the Babcock and

Wilcox reactor design at TMI-2. In the Surry reactor the risk reduction potential for a reduction in a stuck open relief valve failure probability is assessed to be extremely low, or 1.02. This assessment was based on the same assumptions as in research program 1. In the case of a B&W transient design incorporated in the rest of the Surry design, the risk reduction potential is much higher. Since a transient with a stuck open relief valve is equivalent to a small-small LOCA, the probability of small-small LOCAs was varied to model the incident of a stuck open relief valve on a B&W PWR. Because of this wide discrepancy in an essentially similar design, it was assessed that the set point on the relief valve was designed too low and will be fixed independent of this program. Therefore the Surry results were chosen for the final results. The results for both plants are presented below. The reduction of relief valve failure probability corresponds to a reduction of small-small LOCA probability from a base value of one every ten years. This results from ten transients per year and a stuck open relief valve demand failure probability of one in one hundred.

Surry PWR

Factor	Latent	Core Melt Probability
3	1.00	1.02
10	1.01	1.03
30	1.01	1.03
100	1.01	1.03

TMI "Assessed" PWR

10	5.47	5.56
100	7.01	9.11

It can be seen that in the Surry design there is no sensitivity to reductions in relief valve failure probability to lower than 10^{-3} per year.

A.2.3 Research Program 3

The goal of the third research program is to improve pump performance. As in the two previous programs only hardware-related failures were reduced in likelihood. The risk reduction for improved pumps is presented below.

PWR				
Factor	Early Deaths	Latent Deaths	Property Damage	Core Melt Probability
3	1.02	1.02	1.04	1.07
10	1.03	1.03	1.05	1.09
30	1.03	1.03	1.05	1.09

BWR				
Factor	Early Deaths	Latent Deaths	Property Damage	Core Melt Probability
3	1.01	1.01	1.01	1.00
10	1.01	1.01	1.01	1.01
30	1.01	1.01	1.01	1.01

The risk reduction potential for improved pump performance was assessed to be very low, or 1.02. The assumptions resulting in this assessment were also the same as research program 1. Its sensitivity is also very low for higher reductions in pump failure probability.

A.2.4 Research Program 4

The fourth research program assesses improving the safety design of once-through steam generators. An analysis of this can be done by comparing the effect of the U-tube or once-through steam generator designs on an otherwise Surry design. Then a weighting factor of one-sixth is applied to conservatively model B&W's share of the reactor market. The comparison yields a ratio of 6.69 in latent deaths and 3.07 in core melt probability. Applying the weighting factor yields 1.17 for the risk reduction potential, or a low potential. However, it must still be noted that the difference is very large for the reactors without the U-tube design; therefore, the project has more importance than the industry-wide effect indicates.

Another approach to evaluating the risk reduction potential associated with the steam generator research program is to consider the effect of reducing the frequency of transients related to the steam generator. For example, if it were possible to reduce the number of transients leading to reactor scram by one (1) per reactor year, the latent fatalities would be reduced by approximately 2% and the core melt probability by approximately 8%.

A.2.5 Research Program 5

The fifth research program is improved pipe design. This would lead to lower LOCA probabilities. Fewer LOCAs would have a very low effect on BWRs because of the dominance of the transient event in BWR risk. It would have a moderate effect on PWR risk, or a 1.50 factor reduction. This value was chosen because failure rate reductions were not likely to be much higher than three and BWR related risk reduction is very low. The four risk parameters for lower pipe failure rates for the PWR are presented below. (The sensitivity to risk for large reductions of LOCAs is also higher than the previous programs dealing with hardware-related failures.)

Factor	PWR			
	Early Deaths	Latent Deaths	Total Property Damage	Core Melt Probability
3	1.12	1.45	1.48	2.20
10	1.17	1.72	1.78	3.80

A.2.6 Research Program 6

Research program 6 is not strictly applicable to a risk model. The unresolved safety issues question the very design which is assumed in the risk model to be correct. All three of these questions require increases in the model's assessed failure probabilities of over one thousand before they contribute significantly to risk. It should be noted, however, that the containment sump issue is the most important since it leads to simultaneous failure of both the ECCS and containment cooling. The loss of containment cooling causes much greater consequences than loss of the ECCS alone. In fact, the risk of a nuclear reactor could be as much as fifty times greater if the containment sump was assumed to fail.

A.2.7 Research Program 7

Research program 7 addresses improved fuel design. It was assessed that a reduction of ZrO_2 reaction in fuel cladding would result in a low reduction of risk. The amount of energy added to the containment from hydrogen burning alone has a low effect on risk due to the fact that many accident sequences would result in overpressures anyway. There would be little or no reduction in core melt probability, but a slight redistribution to lower consequence accidents. The reduction in latent cancers and consequently the assessed risk reduction potential for this program has been determined to be 1.04 by LWRSEN calculations.

A.2.8 Research Program 8

The goal of research program 8 is to improve shutdown heat removal reliability. This reliability is measured by the auxiliary feed-water system and containment heat removal system in a PWR and the residual heat removal system in a BWR. By reducing those failure probabilities the following results are obtained.

PWR			
Factor	Early Deaths	Latent Deaths	Core Melt Probability
3	2.25	1.56	1.12
10	4.00	1.95	1.17
30	5.15	2.10	1.18

BWR			
Factor	Early Deaths	Latent Deaths	Core Melt Probability
3	1.76	1.72	1.79
10	2.40	2.31	2.48
30	2.68	2.56	2.78

For improving shutdown heat removal a high risk reduction potential, or a factor of 2.0, was chosen. In this case it was felt that system failure probabilities would likely be reduced between three and ten; however, this does not rule out the possibility of still higher risk reduction potential. There is additional return past this value, especially in the PWR, as is indicated by these sensitivity results.

A.2.9 Research Program 9

Research program 9 considers improvement of containment systems. In this case it was assumed that the risk reduction potential could be represented by a design which effectively mitigated overpressure failures, which are the dominant contribution to risk. A very high potential, or a factor of 9.53 on latent deaths, was chosen from an alternate containment study that was done by Sandia which considered filtered venting. The return in reduced risk for even further improved designs could be available as the containment is the primary mitigator of public risk.

A.2.10 Research Program 10

Research program 10 considers improved test and maintenance. This program actually is made up of two subprograms, both of which can be addressed by the risk model. In improving test and maintenance, one can either reduce a system's unavailability by keeping component downtime at a minimum, or one can assure that less errors are committed during the test or maintenance act. Human errors result in a high risk reduction potential, or a factor of 2.5. It was assumed human error rates could be reduced by a factor of more than three. Based on an assessment of each of the four risk parameters, an overall value of 2.5 was selected, since fatalities were weighted more heavily than the other parameters. Reducing maintenance downtimes also provides some moderate potential, or a factor of 1.5. It was assessed that assuming better designs with respect to maintenance downtime and better procedures could result in about a factor of two reduction in this contribution to risk. It is felt that this potential is bounded as such downtimes are limited by practical lengths of maintenance requirements. The results of both subprograms for the Surry PWR are presented below.

Human Errors in Maintenance

Factor	Early Deaths	Latent Deaths	Property Damage	Core Melt
3	2.40	2.35	1.72	1.18
10	4.46	4.12	2.24	1.25
30	5.88	5.21	2.44	1.27

Test and Maintenance Downtime

Factor	Early Deaths	Latent Deaths	Property Damage	Core Melt
3	2.18	1.84	1.57	1.14
10	3.58	2.54	1.93	1.20

It can also be noted that further reductions in risk are also possible due to the high sensitivity to greatly reduced maintenance errors.

A.2.11 Research Program 11

The goal of the eleventh program is to consider improved emergency control. This considers improving the response of onsite personnel to accident situations. The program considers three areas that result from this program which could cause reduced risk. First there is the reduced likelihood of operator error after the emergency begins. This results in a reduction of risk by a factor of 1.3. Human error rates were again assumed to be reducible by three, but higher reductions would produce little change in risk reduction potential. Also, one must consider the use of non-safety systems. This was viewed as resulting in an increased reliability of safety grade systems and was assessed at a factor of 2.0 reduction in risk. It was estimated that system reconfigurations and human adaptability could provide at least a factor of three reduction in heat

removal function unreliability. Finally, an improved understanding of the primary system would result in better operator response in bringing the reactor to hot shutdown. This was assessed by a factor of 1.5 reduction in risk. This increased knowledge would help to prevent operator error being a contributing factor in shutdown heat removal. This contribution has limited effect in many accident sequences due to automatic responses by systems. It was assessed to contribute to an overall reduction in shutdown heat removal unreliability of approximately a factor of ten when previously mentioned factors were considered. Therefore, an overall reduction of 3.0 was assessed. Dividing this by the previously assessed factor of 2.0, the risk reduction potential of 1.5 was assessed. The total risk reduction was obtained by multiplying these results. This yielded a high risk reduction potential, or a factor of 3.9 reduction in risk. The sensitivity to further reductions can also be demonstrated by the results presented below.

Reduced Human Errors

Factor	PWR		BWR	
	Latent Deaths	Core Melt Probability	Latent Deaths	Core Melt Probability
3	1.25	1.02	1.32	1.28
10	1.33	1.02	1.48	1.37
30	1.35	1.02	1.53	1.46

Better Shutdowns from Better Understanding

Factor	PWR		BWR	
	Latent Deaths	Core Melt Probability	Latent Deaths	Core Melt Probability
3	2.25	1.12	1.72	1.79
10	4.00	1.17	2.31	2.48
30	5.15	1.18	2.56	2.78

A.2.12 Research Program 12

Research program 12 considers improved disturbance control. This is represented by a reduction in the number of transient events. In addition a reduction in transient events results in less high cycle fatigue and therefore less pipe breaks. Because of this fact, this research program has essentially a linear reduction in risk. Therefore, if transient frequency is reduced by ten, risk will be reduced by ten. A moderate risk reduction factor of 1.5 was chosen due to pessimism on the factor reductions in transients. However, with a sensitivity as strong as linear this program should be pursued as much as possible.

A.2.13 Research Program 13

Research program 13 considers design guidance improvement with respect to fires, earthquakes, and sabotage. Since the risk model considered only random failures, other assessments had to be drawn upon. An earthquake analysis of Diablo Canyon indicates risks on the order of those due to random failures. Common cause estimates indicate a significant percentage of system failure rates due to common mode failures. Taking this into account a high risk reduction potential, or a factor reduction of 2.0, was assessed.

A.2.14 Research Program 14

The fourteenth research program considers emergency response teams and procedures. This emergency team would provide for risk reduction in two ways. The first considers the improved reliability of the long term heat removal systems, which would be affected by an emergency equipment pool. A moderate risk reduction potential of 1.5 was assessed based on improved residual heat removal results presented before. Reductions in heat removal capability were considered to be less than three due to the time required for a significant effect by an emergency response team. The second effect considers improved allocation of medical resources and better evacuation. This includes better radiation monitoring so that the response team can coordinate evacuation and so that medical resources can be applied to those most in need. Based on sensitivity studies performed on the CRAC code, a reduction by a factor of 4.0 on early deaths is achievable. Finally, the total risk reduction potential of this program was assessed to the multiple of the above two factors, or 6.0, a very high risk reduction potential.

A.2.15 Research Program 15

The goal of the fifteenth research program is to improve siting. This risk reduction potential was assessed to be high, or 2.0. This was based on a comparison of the risks of latent deaths from the highest population densities to the lowest and median population densities. The comparison of high to median population densities was chosen due to realistic assumptions on the limited areas where low population densities exist in conjunction with a need for power. Those results are presented below.

High to Median	2.15
High to Low	7.02

A.2.16 Research Program 16

The sixteenth research program was identified because examples of its use were available. These examples indicate great value in the utilization of risk methods. In addition this program is evaluated as a project that contributes to the other fifteen research programs. A comparison of those results indicates a similar classification of risk reduction potential, i.e., a very high potential. Some examples are presented below.

- 1) Reduction of risk from a LPIS check valve rupture after identification of this event by WASH-1400. Risk was reduced by at least a factor of 1.75.
- 2) Risk reduction potential identified by a wide variation in auxiliary feedwater systems on the order of 100. This reliability assessment, conducted after TMI by NRC, also found a number of single active failures. The variation in risk for similar plants with a factor of one hundred difference in auxiliary feedwater reliability could be as high as a factor of 17 in latent deaths.
- 3) Reliability methods were employed in the design phase of an auxiliary feedwater system as documented in a paper by Frank H. Rowsome, III, entitled "The Role of System Reliability Prediction in Power Plant Design" found in Power Engineering, February, 1977. A case study on the water source for auxiliary feedwater found one design error, and two cheaper, more reliable design variations. The one chosen resulted in a factor of 8 increase in reliability, and a cost reduction of 500,000 dollars per unit.

Clearly, the value of this methodology is demonstrated for use as both a managerial and troubleshooter role. In addition, the methods help to provide for a more complete analysis of reactor risks.

A.3 ANALYSIS OF INDIVIDUAL RESEARCH PROJECTS

An analysis of each of the individual projects was also performed. The block diagrams presented earlier define the interrelationships and importance of each project. Each node in the diagram defines more than one path for successful completion of the program. Weighting factors were chosen for each node to model each path's contributions. The weighting factors were based upon sparse data where available and engineering judgment. The risk reduction factors were then obtained by dividing up the reduced risk in proportion to their relative weight. Then new factors were chosen based on the following formula:

$$F' = \frac{1}{1-w(1-\frac{1}{F})}$$

where: w is the weighting factor
 F is the program risk reduction factor
 F' is the project risk reduction factor

Some projects were assessed to be dependent upon the successful completion of other projects. This is represented in the diagrams by programs in series. These programs were given the same weighting factors. All of the block diagrams are repeated at the end of this appendix with the chosen weighting factors and a brief explanation of their values.

Given these weighting factors and the risk reduction potential of each program, a risk reduction factor for each project was obtained. Some of the projects received contributions from more than one program. These contributions were combined by multiplication of all the factors. This has been found to be a reasonable estimate of the risk reduction potential, although it is usually an underestimate. Given these contributions, better emphasis can be made within each of those projects based on their contributions to differing goals. Table A-1 presents all of this information for each project. In this way a further review can be made of the results over those presented in the main body of this report.

Figures A-1 through A-16 depict the research projects (tasks) from the program plan which contribute to each of the sixteen research programs. The weighting factors applied to the projects are also shown in those figures.

Table A-1. Risk Reduction Potential for Individual Projects

1.1.1	Valves	1.03	valves other than relief valves (1)*	
		<u>1.01</u>	relief valves	(2)
		1.05	total contribution	
1.1.2	Other Components	1.01	pumps	(3)
		1.11	steam generator (U-tube vs. once-through)	(4)
		<u>1.26</u>	pipes	(5)
		1.42	total	
1.1.3	Instrumentation	3.90	emergency control need for new instrumentation	(11)
		1.50	disturbance control need for new instrumentation	(12)
		<u>5.85</u>	total	
1.1.4	Equipment Quality	< 1%	valves	(1)
		< 1%	relief valves	(2)
		< 1%	pumps	(3)
		1.03	pipes	(5)
		<u>1.23</u>	containment	(9)
		1.28	total	
1.1.5	T&M Procedures	<u>3.75</u>	T&M	(10)
		3.75	total	
1.1.6	Operating Modes and Safety	1.01	valves	(1)
		< 1%	relief valves	(2)
		< 1%	pumps	(3)
		1.05	pipes	(5)
		1.50	emergency control	(11)
		1.18	disturbance control	(12)
		<u>1.89</u>	total	

*# of contributing program

Table A-1. (Cont.)

1.2.1	Alternate Shutdown Cooling Systems	<u>1.33</u>	shutdown heat removal	(8)
		1.33	total	
1.2.2	Optimized Containment	<u>9.53</u>	containment design	(9)
		9.53	total	
1.2.3	System Simplification	1.33	shutdown heat removal	(8)
		1.10	containment design	(9)
		1.50	test and maintenance	(10)
		<u>1.04</u>	design guidance	(13)
		2.28	total	
1.2.4	Hydrogen Control Systems	<u>2.53</u>	containment design	(9)
		2.53	total	
1.3.1	Design Guidance	<u>1.82</u>	design guidance	(13)
		1.82	total	
1.3.2.1	Fuel Design	<u>< 1%</u>	Fuel design	(7)
		< 1%	total	
1.3.2.2	Environmental Effects on Materials	< 1%	valves	(1)
		< 1%	relief valves	(2)
		< 1%	pumps	(3)
		1.03	pipes	(5)
		<u>1.11</u>	containment	(9)
		1.15	total	
1.3.2.3	Fracture Mechanics	<< 1%	valves (1), relief valves (2), pumps (3)	
		<u>1.01</u>	pipes	(5)
		1.01	total	

Table A-1. (Cont.)

1.3.2.4	Nonlinear Analysis	<u>1.11</u> 1.11	containment design total	(9)
1.3.2.5	Fluid Structure Interaction Analysis	NA.	unresolved safety issues	(6)
1.3.2.6	Inservice Inspec- tion	<< 1% <u>1.01</u> 1.01	valves (1), relief valves (2), pumps (3) pipes total	(5)
1.3.2.7	Aseismic Design	<u>1.01</u> 1.01	design guidance total	(13)
1.3.3	Design Verifica- tion	<u>2.00</u> 2.00	design guidance total	
2.1	Emergency Control	<u>3.90</u> 3.90	emergency control total	(11)
2.2	Disturbance Con- trol	<u>1.50</u> 1.50	disturbance control total	(12)
2.3	Transient Control	<u>1.18</u> 1.18	disturbance control total	(12)
2.4	Plant Protection System	<u>1.43</u> 1.43	disturbance control total	(12)
2.5	Safety Margins	1.50 <u>1.18</u> 1.77	emergency control disturbance control total	(11) (12)

Table A-1. (Cont.)

2.6	Human Factors	<u>1.18</u>	emergency control	(11)
		1.18	total	
2.7	Human Engineering	<u>1.18</u>	emergency control	(11)
		1.18	total	
2.8	Emergency Operating Process	<u>1.11</u>	emergency control	(11)
		1.11	total	
2.9	Essential Supportive Systems	3.90	emergency control	(11)
		<u>1.50</u>	disturbance control	(12)
		5.85	total	
2.10	Verification Evaluation New Designs	3.90	emergency control	(11)
		<u>1.50</u>	disturbance control	(12)
		5.85	total	
2.11	Maintenance & Fuel Handling	3.75	test and maintenance	(10)
2.12	Implementation & Demonstration	3.90	emergency control	(11)
		<u>1.50</u>	Disturbance control	(12)
		5.85	total	
3.0	Risk Methods	1.02	valves	(1)
		1.01	relief valves	(2)
		1.01	pumps	(3)
		1.12	steam generator	(4)
		1.11	pipes	(5)
		1.50	shutdown heat removal	(8)
		1.29	containment design	(9)

Table A-1. (Cont.)

3.0	Risk Methods (Cont.)	1.25	test and maintenance	(10)
		1.33	emergency control	(11)
		2.00	design guidance	(13)
		<u>1.71</u>	emergency response	(14)
		14.2	total	
4.1.1	Primary System Accident Modeling & Analysis	<u>1.50</u>	emergency control	(11)
		1.50	total	
4.1.2	Thermal Hydraulic Primary System Data	<u>1.50</u>	emergency control	(11)
		1.50	total	
4.1.3	Core Damage Assessment	<u>1.50</u>	emergency control	(11)
		1.50	total	
4.1.4	Coolant Chemistry Following Fuel Failure	1.50	emergency control	(11)
		<u>< 1%</u>	fuels	(7)
		1.51	total	
4.1.5	Atmospheric Dis- persion	<u>1.05</u>	siting	(15)
		1.05		
4.1.6	Gaseous Behavior	<u>2.53</u>	containment design	(9)
		2.53	total	
4.1.7	Containment Fail- ure Modes	<u>5.14</u>	Containment design	(9)
		5.14	total	
4.2	Transient Behavior	<u>1.50</u>	disturbance control	(12)
		1.50	total	

Table A-1. (Cont.)

4.3	Unresolved Safety Issues	NA		
4.4	DNB/Fuel Damage	<u>< 1%</u>	fuel design	(7)
		< 1%	total	
5.1	Upgrade Training	<u>2.50</u>	test and maintenance	(10)
		2.50	total	
5.2	Human Factors, Engineering	2.50	test and maintenance	(10)
		<u>1.30</u>	emergency control	(11)
		3.25	total	
5.3	Improved Operating Process	<u>1.18</u>	disturbance control	(11)
		1.18	total	
5.4	Human Error Quantification	2.50	test and maintenance	(10)
		<u>1.08</u>	emergency control	(11)
		2.70	total	
5.5	Improved QA	< 1%	valves	(1)
		< 1%	relief valves	(2)
		< 1%	pumps	(3)
		1.03	pipes	(4)
		1.33	shutdown heat removal	(8)
		1.10	containment design	(9)
		<u>2.50</u>	test and maintenance	(10)
		3.80	total	
6.0, 6.1	Emergency Response Team and Procedures	<u>6.00</u>	emergency response	(14)
		6.00	total	

Table A-1. (Cont.)

6.2	Development of Improved Communications	<u>4.00</u>	emergency response	(14)
		4.00	total	
6.3	Plant Characteristic ?	<u>6.00</u>	emergency response	(14)
		6.00	total	
6.4	Emergency Equipment Pool	<u>1.50</u>	emergency response	(14)
		1.50	total	
6.5	Robot Development	<u>1.08</u>	emergency response	(14)
		1.08	total	
6.6	Radioactivity Control and Monitoring	<u>3.08</u>	emergency response	(14)
		3.08	total	
6.7	Use of Non-Safety Systems	<u>2.00</u>	emergency control	(11)
		2.00	total	
6.8	Decontamination	<u>1.03</u>	emergency response	(14)
		1.03	total	
7.0	TMI Analysis	<u>3.42</u>	emergency response	(14)
		3.42	total	
7.1	Short Term Studies	1.30	emergency control	(11)
		<u>1.08</u>	emergency response	(14)
		1.40	total	
7.2	Primary System Studies	1.03	fuel design	(7)
		<u>1.50</u>	emergency control	(11)
		1.55	total	

Table A-1. (Cont.)

7.3	Containment Bldg. Studies	1.13	containment design	(9)
		<u>1.33</u>	shutdown heat removal	(8)
		1.50	total	
7.4	Auxiliary Bldg. Studies	<u>1.33</u>	shutdown heat removal	(8)
		1.33	total	
7.5	Modeling Studies	1.13	containment design	(9)
		<u>1.05</u>	siting	(15)
		1.19	total	
8.0	Siting	<u>2.00</u>	siting	(15)
		2.00	total

The program directly addressing valves was believed to have more effect than programs where valve improvement would be a spinoff.

The support program weighting was related to cause data on outages.

In-service inspection and fracture mechanics were assessed to provide limited help since they are in their infancy.

Figure A-1. Research Program 1

The program directly addressing valves was believed to have more effect than programs where valve improvement would be a spinoff.

The support program weighting was related to cause data on outages.

In-service inspection and fracture mechanics were assessed to provide limited help since they are in their infancy.

Figure A-2. Research Program 2

The program directly addressing pumps was believed to have more effect than programs where pump improvement would be a spinoff.

The support program weighting was related to cause data on outages.

In-service inspection and fracture mechanics were assessed to provide limited help since they are in their infancy.

Figure A-3. Research Program 3

Risk methods were assessed to be very important since they identified the magnitude of the problem and its relation to safety.

Figure A-4. Research Program 4

The program directly addressing pipes was believed to have more effect than programs where pipes improvement would be a spinoff.

The support program weighting was related to cause data on outages.

In-service inspection and fracture mechanics were assessed to provide limited help since they are in their infancy.

Figure A-5. Research Program 5

Figure A-6. Research Program 6

Primary system studies directly address hydrogen generation while in the other programs it is only a byproduct.

Figure A-7. Research Program 7

Due to the influence of human error it was judged that verification of operability of present systems was as effective as designing new ones.

Risk methods were assessed to have a very important role in design and failure mode identification.

Figure A-8. Research Program 8

Identification and mitigation of failure modes was assessed to be much more effective than mitigating isolation failures.

Failure modes concerning overpressurization are much more important than other effects.

Both TMI related studies and risk methods have limited roles in this program.

Figure A-9. Research Program 9

Risk methods were assessed to be helpful in identifying failure modes and managing new procedure development.

Figure A-10. Research Program 10

Figure A-11a. Research Program 11

Actual equipment design was more important for reducing human errors than better procedures.

Risk methods provided a helpful role overall.

Figure A-11b. Research Program 11

Figure A-12a. Research Program 12

Figure A-12b. Research Program 12

Of the supportive programs, simplification of systems was estimated to be helpful, but design methods dominate this program.

Figure A-13. Research Program 13

Decontamination to improve reparability was not assessed to be very helpful. Monitoring was assumed to be much more important than use of robots or TMI data. Risk methods were assessed to have an important role in this program's management.

Figure A-14. Research Program 14

Locating a plant in lower population zones was assessed to be much more important than knowledge of transportation and deposition given a certain site.

Figure A-15. Research Program 15

Figure A-16. Research Program 16

APPENDIX B
DETAILED DISCUSSION OF
IMPLEMENTATION COSTS

B.01/02 IMPROVED VALVE AND RELIEF VALVE PERFORMANCE

Sandia research programs related to valves have the following general objectives:

1. Determine reliability and resolve identified problems associated with power and air operated valves.
2. Develop valve status indicators.
3. Determine cause and resolve reseating problems.
4. Develop better understanding of valve behavior under two phase flow.
5. Develop methodology for improved valve selection.

The programs encompass comprehensive aspects of valve design, selection qualification and maintenance of valves. The following sections present generalized cost data for valves, quantify valve performance impact on plant availability, and qualitatively discuss implementation costs for revised valve designs on new and existing reactors.

B.01/02.1 Quantification of Costs-Valves

"It has been estimated that the population of all valves approaches 10,000 for a 1000 MWe LWR plant. Fortunately, only a fraction of these, ~1/10, are located such that their failure or need of maintenance, test, or repair would result in a forced outage." (Reference 7) Estimates quantify valve problems as accounting for approximately 8% of all major outages (equivalent to about 3% of all outages) or requiring approximately 3-4 days per plant-year of unit outage. In replacement power costs then, valve problems require about 1 million per year or 30 million per plant operating lifetime in replacement power costs.

Unlike most portions of this study, a documented source of information was not discovered for valve cost. As a result the following quantification is based on discussions with informed sources and the author's best judgment.

<u>Description</u>	<u>Approximate Customer Cost (With Interest and Escalation)</u>
Large (26") quick-acting isolation valves	.2 million
Main steam relief valves (BWR) spring/power actuation	.15 million
10-12" check valves	.05 million
Low flow/pressure relief valves (spring loaded)	.01 million
1" globe w/actuator	.002 million
2" globe w/actuator	.006 million
4" globe w/actuator	<u>.01 million</u>
Estimated cost for 1000 critical valves	20-30 million

B.01/02.2 Areas of Potential Cost Impact

It is difficult to generalize what specific improvements will eliminate each type of valve problem identified in the Sandia Program Plan. However, it is believed that a combination of improved design, material selection, fabrication techniques, quality control during fabrication, inspection and examination techniques in shop and field, control of process environment, and in-service inspection will each play a significant role in reducing valve failures.

As structured, Program 2 is directed at safety and relief valves and Program 1 at all other valves. Production cost for all valves may increase due to alternate material costs, costs of quality assurance during manufacture, additional reject material and products from improved inspection and examination or testing. Engineering and labor costs may change as a result of additional front-end attention during selection process and additional care or modified methods during installation. The combination of these factors is estimated to increase valve costs by 10 to 40 percent.

Improved status indication for valves is being mandated by regulatory requirements for both new and existing plants. Sandia R&D, which is aimed at improving instrumentation in a cost-effective manner, by definition will have a minimal cost impact.

B.01/02.3 Implementation Costs - New Plants

Assuming that valve costs for 1000 critical valves increase 10-40 percent, the initial cost impact for new plants is estimated to be 2-12 million dollars. However, as discussed above, valve problems require approximately 30 million dollars in replacement power costs over the plant lifetime. Assuming 20 percent of forced outages are eliminated as a result of R&D results, the net implementation cost of Sandia research results is estimated to be between less than zero dollars and six million dollars for new plants. Assuming 10% of the 1000 valves, the cost of the valves, and the availability of the valves are attributable to relief valves, the estimated implementation cost for relief valves is <0 to 1 million.

B.01/02.4 Implementation Cost Existing Plants

Implementation costs for existing plants are very dependent upon the extent to which existing plants replace existing valves. Assuming

all 1000 critical valves are replaced, the cost impact due to valves alone would be 20-30 million. Salvage value for the replaced valves may be approximately 5 million. An outage (estimated to be one year) would cost 36 million in replacement power during which valves would be replaced. A 20% reduction in subsequent forced outages (assuming 15 years or 1/2 of facility lifetime remained) would "give back" 3 million of this cost. The total implementation cost of this approach is estimated to be 48-58 million dollars.

An alternate approach would be to replace valves at the time maintenance or repair was required. This approach would avoid most of the replacement power cost and yield some gain in future availability. Presumably only a fraction of the "1000 critical valves" would ultimately be replaced, however. On strictly a cost basis, if only 20% of the critical valves are replaced, the implementation cost for existing plants would be on the order of 1-2 million dollars.

In practice a combination of these approaches would likely be applied. For purposes of order-of-magnitude cost estimating, therefore, implementation cost for existing plants are estimated to be 15 million dollars. A breakdown between valves and relief valves is not attempted for existing plants.

B.03 IMPROVED PUMP PERFORMANCE

Sandia tasks related to pumps are aimed at minimizing cavitation problems, seal failures, hydrodynamic instabilities and other problems currently encountered. In the following sections, cost data on major light water reactor pumps, on pump failure impact on unit availability, and estimates of implementation costs of improved pump designs on new and existing reactors are presented.

B.03.1 Quantification of Costs - Pumps

Costs associated with BWR and PWR pumps are quantified in Table B.03.1. The majority of pump problems that have impacted plant availability (82% of all pump related outage time) have been a result of pump seal problems (reference 7). However, it is important to note that seal failure is often the result of vibration, debris and other influences. Major availability problems have been encountered in BWR recirculation pumps and PWR reactor coolant pumps totaling 9.4% of all major outage time (or approximately 4% of total outage time). Feedwater pumps have contributed an additional .4% of major outage time.

Although data are not readily available for number and cost of important plant pumps, total costs for an assumed 100 significant plant pumps is presented. These numbers are derived from judgment and cost data extrapolation.

Table B.03.1
Pump Cost Data

	<u>Total Factory Cost</u>	<u>Total Labor Cost</u>
BWR		
Recirc. pumps (2)	.5	.45
Feedwater pumps		
pumps (2)	.5	.07
turbine drives (2)	2.4	.3
PWR		
Reactor coolant pumps (4)	1	.6
Feedwater pumps		
pumps (2)	.5	.07
tubrine drives (2)	2.4	.3
Generic (pump & motor costs)		
25 gpm, 200' TDH, 10 HP, centrifugal	.006	.002
1100 gpm, 120' TDH, 50 HP, centrifugal	.036	.005
11,500 gpm, 200' TDH, 800 HP, centrifugal	.5	.02
<hr/>		
Total estimated costs for approximately 100 important pumps	20	4-5
<hr/>		

B.03.2 Quantification of Implementation Costs

Although a thorough discussion of pump problems is beyond this report (see reference 12), much of the current problems are thought to be solvable through better pump selection (engineering) and maintenance. Implementation cost for applying the results of R & D in this area, therefore, is quantified to be zero for new plants. Likewise, existing plants would be expected to benefit from this R & D although major replacement of equipment would be minimized. An implementation cost for existing plants below the lifetime average replacement power costs attributable to pump related outages of 30 million dollars would allow one considerable flexibility in implementing results aimed at improving pump performance while maintaining total implementation costs below zero dollars.

In conclusion, implementation costs for both new and existing plants are estimated to be zero dollars.

B.04 STEAM GENERATORS

Sandia tasks in this area are aimed at obtaining a better understanding of operating characteristics during emergency conditions with portions of the program aimed at studying the TMI-2 steam generators. It is probable that work in this area will also study steam generator performance during normal and near normal operating conditions. The following sections quantify current cost experience with PWR steam generators, discuss potential cost impact of improvements in design, and fabrication (including material selection) of steam generators for new and existing PWRs.

B.04.1 Quantification of Current Costs - Steam Generators

Steam generators represent a significant portion of PWR NSSS costs. Approximate steam generators costs (1976) for the three vendors with these contemporary configurations (including escalation and construction interest) are:

West:	7 million/each - with 4 total
B & W:	10.5 million/each - with 2 total
CE:	12 million/each - with 2 total

Steam generators, unlike piping systems and other components, do not require significant design and analysis work for each specific plant. Hence, major design and analytical engineering costs are distributed by the vendor over several plants minimizing engineering costs in comparison to fabrication costs. The above costs are assumed to include such distributed engineering costs.

A result of design changes to improve steam generator performance under emergency conditions can be reduced tube failure rate under normal conditions. Industry data (reference 7) indicates that steam generators have caused 23% of major outage times (9.2% of all outage, or an average of 10 days/year-plant) primarily because of tube inspection and problems from stress corrosion cracking and vibration. For the purposes of this evaluation of implementation costs, improvements are assumed to reduce PWR outages attributable to steam generators by one third, resulting in an annual savings in replacement power costs of 1 million dollars where the concepts evaluated are expected to improve availability.

B.04.2 Concepts to Improve Steam Generators Evaluated for Implementation Costs

The principal problems identified by Sandia tasks are those associated with boiling dry and refilling of steam generators that, under emergency conditions, could lead to structural or tube failures. The following general concepts have been evaluated with regard to implementation costs for new and existing plants. It is recognized that other, equally reasonable approaches could be defined and their exclusion from cost evaluations is not intended to express judgment as to the direction Sandia tasks should take.

1. Design S/G to sustain emergency conditions by increasing tube wall thickness (from current 1-2 mm) or utilize tube material less susceptible to tube failure under stress. (Note that plant thermal performance may be adversely affected.)
2. Increase margin (boil-dry time) available to avoid undesirable conditions by design or selection of larger volume S/G.
3. Provide additional diverse system(s) to avoid undesirable conditions.

B.04.3 Implementation Costs - New Plants

Concept 1 - Increase wall thickness/select new tube material

Total current costs for steam generator tubes is estimated to be 5 million dollars/plant. Implementation of Concept 1 is expected to require between 3 and 8 million additional costs/plant. As discussed above, reduction in unit unavailability can outweigh tube costs over the 30 year plant lifetime. Additional indirect costs (such as reduction in S/G efficiency) are not included in this estimate.

Concept 2 - Increase margin (time) to reach boil dry

The simplest means of accomplishing this objective is to utilize current U tube designs rather than once-through steam generators designs. Cost of implementation would be those costs associated with U-tube and once-through differential costs (approximately 6 million), different containment and structural costs, penalties associated with plant efficiency, if any, additional piping, auxiliary system costs, etc. Although this simplistic approach quantifies a cost impact, it is noteworthy that reasonable detailed comparisons by utilities have demonstrated that all three PWR designs are competitive. Concept 2 would be expected to have a positive impact on plant availability by allowing longer duration feedwater transients to be accommodated without causing scram. Reference 10 quantifies PWR availability gains through use of DAS systems as .6% availability improvement. Since both approaches would have equivalent results, the benefit from reduced replacement power costs would be in excess of steam generator differential costs. Hence, implementation costs for Concept 2 on new plants are quantified as zero dollars.

Concept 3 - Provide additional diverse system to maintain S/G secondary side level within limits

This is an area amenable to innovative design and engineering that could produce a spectrum of approaches. On the basis of the observation that emergency feedwater systems on PWRs are relatively comparable and that such systems are cost effective, it is assumed that an additional diverse system would be of approximately the same order of magnitude of cost as current systems. From reference 2, after applying a multiplier of 2 to account for escalation, interest and other factors as discussed in Section 2.3, implementation costs are estimated to be 30 million dollars, including water supply and structural costs. Although Concept 3 would occasionally reduce the necessity for reactor scram, it is probable that technical specifications or sound judgment would mandate shutdown during loss or degradation of normal feedwater. Hence, Concept 3 is not expected to positively impact availability.

B.04.4 Implementation Costs - Existing Plants

For all three concepts above, plants in need of modifications would incur similar order of magnitude costs as with new plants, however, 1 to 3 years of outage would be required for major equipment installation and modification. Including the cost of replacement power (at 72 million/year), existing plant implementation costs are estimated to be:

Concept 1 - 60 million (includes 1 year outage, 15 million gain in improved availability)

Concept 2 - 240 million (includes 3 year outage + new S/G)

Concept 3 - 100 million (includes 1 year outage)

B.04.5 Steam Generators - Summary of Implementation Costs

	<u>Costs (millions of dollars)</u>	
	<u>New Plant</u>	<u>Existing Plant</u>
Concept 1	<0 (gain)	60
Concept 2	0	240
Concept 3	30	100

B.05 IMPROVED PIPING PERFORMANCE

The summary objective of Sandia tasks in this area is to improve piping design towards minimizing piping failures. For the purpose of this study, cost data are provided on major system piping where significant risk reduction can be realized through improved performance. In addition to the cost of implementation, possible gains in plant availability that can be achieved through reduction in pipe failure rates are quantified. Implementation cost data are presented for solutions in the areas of improved design and materials selection that reflect the author's qualitative judgment as to which manner various failure modes can be lessened.

B.05.1 Causes of Failure in Piping

Available data suggest (reference 9) that the following reported causes of pipe failure have been significant between 1960 and 1976:

1. Vibration (25.1%)
2. Fabrication errors (12.8%)
3. IGSCC (11.3%)
4. Erosion (6.9%)
5. Thermal fatigue (5.4%)
6. Corrosion (2.9%)
7. Unknown (35.6%)

Of further significance are the following observations:

1. 54% of failures occurred in welds or in the weld heat affected zone.
2. 70% of BWR and PWR pipe failures occurred in piping six inches

or smaller (with 50% and 30% for BWR and PWR in one inch or less diameter piping).

Although nuclear piping failure rates and failure modes have received a significant amount of attention over the past few years, considerable work remains in this area. It is not the intent of this discussion to detail the complex subject of pipe failure modes and mechanisms and, as such, the following discussions are very general.

B.05.2 Quantification of Current Piping Costs

Table B.05.1 presents base data on representative major system piping costs for BWRs and PWRs. The data are organized to provide relative magnitude costs between design costs, factory costs of piping, site labor costs and restraints. As noted in this table, design costs are estimates relying upon engineering judgment. The majority of design costs can be attributed to the need for detailed, plant specific, structural analysis for the various load combinations and hanger/restraint design. As major piping is procured early into the design and construction of a project, structural analysis is performed to ensure restraint/hanger design is proper.

Factory piping costs average approximately \$10/lb (including escalation and interest during construction per discussion on base data). For the purpose of this evaluation, this number is applied independent of the type of material, size of piping, or fabrication process applied. Site labor cost is primarily attributed to the cost of installation and welding of piping. Restraint costs are provided since additional restraint is one means of improving piping performance (by reducing stress during normal and accident conditions), although it is important for the reader to realize that balance is necessary between rigidity and flexibility to properly accommodate the various load combinations to which piping systems are exposed.

Table B.05.1 - Piping Costs

<u>System</u>	<u>Design*</u>	<u>Costs (millions of dollars)**</u>		
		<u>Factory Piping Costs</u>	<u>Site Labor Costs</u>	<u>Restraints, Hangers, Supports</u>
Reactor coolant piping (PWR)				
2 inch and smaller	{.3}	0.1	0.3	{1}
2.5 inch and larger		2.5	7.2	
Residual heat removal (PWR)				
2 inch and smaller	{.2}	0.05	0.2	{.5*}
2.5 inch and larger		1.3	3.2	
Containment spray sys. (PWR)	.2	2	4	.5*
RHR (BWR)				
all piping	.3	2.6	6.7	1*
Estimated total* plant piping costs all systems	15	80	180	25

* Order of magnitude estimate based on engineering judgment and extrapolation from available data.

** Data derived from references 1 and 2

B.05.3 Concepts to Reduce Pipe Failures

It is currently impossible to generalize what specific improvements will eliminate each type of piping failure identified in B.05. However, it is believed that a combination of improved design, fabrication techniques, quality control during fabrication, improved inspection and examination techniques in shop and field, improved welding techniques and procedures, control of process environment (principally chemistry) and improved in-service inspection will each play a significant role in reducing pipe failures. The data upon which the Section B.05 failure causes are based are from the period 1960-1976. It is known that improvements have been made in each of the areas identified above, hence failure rates for plants that will be commencing operation in the future should be lower although the distribution of failure causes may differ.

B.05.4 Implementation Costs - New Plants

The following incremental changes are approximations of implementation costs for reduction in piping failure rates

<u>Concept</u>	<u>Total Cost Formula</u>	<u>Cost Differential (millions of dollars)</u>
Improved design	2(current design costs)	15
Improved fabrication techniques	1.3(fabrication costs)	24
Improved quality control	No significant change	--
Improved inspection and examination	1.1(fabrication costs)	8
Welding techniques and procedures	1.1(labor costs)	18
Control of process environment	No significant change	--
Improved ISI	No significant change	--
TOTAL		<hr/> 63

Improved design is estimated to double costs to account for increased design and structural analysis complexity that would result from an improved understanding of pipe failure causes. Improved fabrication techniques are factored at a .3 multiple of current costs to account for the complexity of fabrication techniques. Quality control during fabrication is not expected to increase costs and historically has been demonstrated to be cost effective.

Improved inspection and examination is thought to increase fabrication costs as a result of increased sensitivity of crack/flaw detection resulting in increased reject piping. Welding techniques and procedural changes are expected to increase direct labor hours and costs. Control of process environment, an area of considerably greater attention recently, is expected not to appreciably affect costs. Improved ISI, again assuming greater sensitivity, should not increase costs directly. However, this assumes that reasonable regulatory requirements to cope with very small cracks detected by improved ISI would not impact availability.

Current data (reference 7) indicate 3.3% of plant unavailability is due to snubber/restraint problems and 2.8% to piping. With 30% of total annual hours attributed to outages, elimination of 50% of the piping caused unavailability would represent a savings of 1 million/year/plant in replacement power costs. Over a 30 year lifetime, these savings would offset a total of 30 million dollars, one half of the implementation costs of improvements identified above.

In conclusion, implementation costs for new plants are estimated to be approximately 63 million dollars for all piping systems. However, a reasonable reduction of plant unavailability will offset half these costs over the plant lifetime resulting in an estimated implementation cost of 33 million/plant.

Cost effective application of techniques developed to only those systems that have demonstrated susceptibility and safety related systems would likely result in zero implementation costs.

B.05.5 Implementation Costs - Existing Plants

In existing plants, it is prohibitive to redesign or re-fabricate major quantities of piping. It is expected, however, that improved design and fabrication techniques will be utilized on existing plants when piping cracks or failures mandate replacement of significant quantities of piping. In this manner, improved technique costs will be approximately recovered by decreased plant unavailability as discussed in Section B.05.3.

Improved control of process environment and improved ISI, however, would be expected to be applied to existing plants. As discussed above, these techniques are not expected to impact costs.

In summation, total implementation of improvements in piping is prohibitively expensive for existing plants, whereas reasonable application has approximately a zero net cost impact.

B.06 NRC UNRESOLVED SAFETY ISSUES

Sandia tasks in this area are concerned with two short-term problems, reactor vessel materials toughness and PWR containment sump reliability. Inasmuch as the general consensus of the industry is that reactor vessel material toughness is an area where data are needed to demonstrate adequacy, as opposed to design changes being required to avoid a problem, major implementation costs are not expected to result. Hence, implementation costs are estimated to be zero for both new and existing reactors. It is important to realize, however, that future regulatory guidance and regulations could limit operational parameters such as heat up and cooldown rates, or pressurization rates. The most significant result of such measures would be to lessen plant availability as a result of slower power ascension and cooldown.

PWR containment sump reliability is an unresolved issue because of this system's criticality following an accident. The focus of Sandia interest in this subject is upon vortex suppression. Although this phenomenon is important to understand and factor into design processes, costs of studying and defining solutions are expected to far exceed implementation costs. For example, provision of weirs in the containment, surge tank(s) in the system, or minor revisions to piping or pump design result in very minimal implementation costs.

In conclusion, implementation costs for these two NRC generic safety concerns are quantified to be zero for new and existing plants.

B.07 ENHANCE FUEL PERFORMANCE - IMPLEMENTATION COSTS

Sandia tasks grouped into this research project are principally aimed at (1) obtaining a better understanding of the phenomena (i.e., stress corrosion cracking, PCI, creep collapse, fuel clad thermal ratcheting, strain cycling, irradiation impact on ductility and DNB) that can cause fuel cladding failure, (2) applying knowledge gained to improve fuel design or design methods, and (3) improving methods of detecting cladding failures or flaws while in service. The following discussion provides quantification of current fuel fabrication costs and provides a qualitative discussion of types and impact of changes in these areas. A distinction is not made between implementation cost for new and existing reactors assuming the physical dimensions of new fuel designs remain sufficiently equivalent to current fuel design so as to allow its use in existing plants. Although significant changes in fuel physical dimensions could be accommodated in new plants for the same order of magnitude of costs as currently required, implementation costs in existing plants would be prohibitive due to the necessity for vessel and internal design changes.

B.07.1 Quantification of Current Costs

Reference 5 provides data on costs (in 1976 dollars) for various steps of fuel production. These data have not been altered to account for escalation and interest during construction since fuel costs are passed on directly to consumers via the rate base, avoiding the need for long-term utility debt and resultant interest charges. Quantities reported are approximate for the total core, which is replaced at three year intervals for PWRs, four year intervals for BWRs. Costs are reported in millions of dollars.

Estimated Fuel Costs - Total Core

<u>Step</u>	<u>Costs</u>	<u>PWR Quantity</u>	<u>PWR Costs (1)</u>	<u>BWR Quantity</u>	<u>BWR Costs (1)</u>
(1) U_3O_8 concentrate (yellowcake costs)	\$40/lb U_3O_8	1,210,000	48	1,290,000	51
(2) Conversion U_3O_8 to UF_6	\$4.2/kg U	484,000	2	514,000	2
(3) UF_6 enrichment	\$81/kg U	482,000	39	512,000	41
(4) UO_2 fuel fabrication	\$158/kg U	80,700KgU= 92,743Kg UO_2	12.8	134,700KgU= 154,836	21.3

(1) Derivation of costs:

- (a) UO_2 converted to U via $M(UO_2)$ (.985 efficiency) $(1 - \frac{32}{238})$
- (b) UF_6 prior to enrichment (2%) = 3.8 multiplier to final fuel weight
 UF_6 prior to enrichment (3%) = 5.9 multiplier to final fuel weight
- (c) Conversion efficiency 99.5%
- (d) Conversion from KgU to lbs U_3O_8 - 1 KgU = 2.5 lbs U_3O_8

For our purposes of estimating implementation costs, annual fabrication costs will be averaged to 4 million/plant-year for both PWRs and BWRs, about 1/5th of fuel production costs. The above costs have been back calculated assuming 2% enrichment for BWR and 3% for PWR.

B.07.2 Implementation Costs and Concepts

As fuel and reactor designs have matured, changes have occurred in cladding thickness, fuel pellet size and geometry, enrichment, pellet material, pellet spacing (both pellet to pellet and pellet to clad) rod design (pressurization, gas plenum) and other areas to improve overall fuel and reactor performance. Continued refinement and similar modifications are expected to continue as knowledge and experience grow. The concepts that potentially represent significant (in terms of percentage increase over current fabrication costs) impact would be utilization of a different cladding material and utilization of a different fuel pellet composition.

It is the author's judgment that implementation cost might reasonably be expected to increase between zero and 40% in the area of current fabrication costs. Total impact upon costs over a 30 year lifetime would, therefore, range between 0 and 50 million dollars/plant. It is noteworthy, however, that these costs are insignificant in comparison to potential cost savings from alternate enrichment methods, variances in uranium mining and milling costs, and economic factors that are difficult to accurately predict over the project's lifetime.

Sandia tasks also address improving or developing the ability to detect (and locate) cladding failure or flaws while in service. Although current reactors have indirect means of determining quantity of fuel with cladding leaks (through radiation monitoring, cooling water chemical and radiological analysis) current technology does not provide a means of determining where in the core leakage is occurring and the severity of the individual fuel rod cladding failures. In addition,

no means currently exist (other than shutdown and defueling) of determining the physical state of fuel cladding in fuel rods. Current techniques for inservice inspection of accessible equipment are not considered practical for this application because of physical size limitations. Reactor cores do have the ability to obtain neutron flux and temperature measurements from fixed or transversing core probes. If feasible at all, the most likely concept of providing such capability would be one that combined these technologies sufficiently minaturized to allow transversing individual fuel rods or scanning through use of multiple devices to isolate failures or flaws. An equally attractive approach might utilize a tagging gas that is inserted into the fuel pins during fabrication and in core sensors. Data available on existing systems is not considered sufficiently representative to allow estimating implementation costs, however.

B.08 IMPROVED SHUTDOWN COOLING SYSTEM PERFORMANCE

Tasks in this area are aimed at (1) developing additional, completely independent shutdown (and emergency) cooling systems with a minimum dependency on operator action or active components, or, (2) improving existing systems by simplifying functions and design. The following sections quantify current costs of typical BWR and PWR safety and shutdown cooling systems, qualitatively discuss impact of changes on new and existing plants, and provide estimates of implementation costs.

B.08.1 Current Costs - Shutdown Cooling Systems

On a functional basis, shutdown cooling systems are those systems necessary to ensure (1) that adequate quantities of coolant are continually delivered to the reactor core, and (2) that adequate heat removal is continually provided to maintain core coolant temperatures within design limits. In BWRs and PWRs many systems are provided that can perform these functions during various conditions. Each of these systems has dependencies upon other systems for valve or pump motive power (electric, air or steam turbine) component cooling and seals, secondary cooling (RHR heat exchangers and heat sink), instrumentation to initiate and control operation, etc. Costs of representative systems dedicated to these functions in BWRs and PWRs are quantified in Table B.08.1. This cost data has been extracted from references 1 and 2. Where specific cost data are not available (such as for undistributed NSSS components), data for similar components has been adjusted and included within the estimate.

Table B.08.1

Representative Shutdown Cooling Systems (and ECCS)

	<u>Major Equipment</u>	<u>Costs (millions of 1976 \$)</u>
BWR		
RHR (includes LPCI)	2 Hx's, 3 pumps	16
HPIS	1 pump, 1 diesel (3000 gpm)	5
RCIC	1 turbine, pump	3
PWR		
RHR (includes LPIS)	2 Hx's, 2 pumps, etc.	11
HPIS	2 pumps	3
Safety injection system	2 tanks, valves ($\approx 4000 \text{ ft}^3$ total)	7
Both		
UHS	mechanical draft + pumps, piping	12

B.08.2 Implementation Costs - New Plants

Assuming the systems that are defined and conceptually engineered by Sandia tasks replace rather than supplement current systems, implementation costs for individual systems in new plants are expected to be of the same magnitude as current emergency and shutdown cooling systems; however, differences would likely occur in overall costs. Since current systems are often designed to perform a function during normal operation and more than one function during emergency or shutdown conditions, provision of systems that do not have multiple functions and shared piping, pump and other components will likely increase the number of systems in a nuclear plant. As demonstrated in Section B.05, piping costs amount to nearly half of the PWR RHR system costs. Hence, the cost impact of not sharing piping and other components between RHR and low pressure injection systems, for example, can be significant. In addition, additional systems will require increased building space.

It is the judgment of the author that implementation costs for Sandia programs under this chain would be in the range of 20-100 million dollars, arising principally from increased equipment and construction labor costs. For the purposes of this evaluation, a mean value of 60 million will be applied.

B.08.3 Implementation Costs - Existing Plants

Were one to require backfit of revised or simplified system design to existing plants, major cost impact would be felt in (1) replacement power over extended outage, (2) civil/structural modifications, and (3) equipment and labor costs. As envisioned, implementation of these task results would require modification of existing systems to simplify functions and provision of additional systems to perform specific emergency or shutdown cooling functions.

The total cost of implementing these systems is estimated to be the sum of these major contributions, or:

<u>Factor</u>	<u>Costs (millions)</u>
3 years outage	210
equipment/labor	60
structural allowance	<u>20</u>
TOTAL	290

B.09 IMPROVED CONTAINMENT FUNCTIONS AND SYSTEMS

The summary objectives of Sandia tasks in this area are to improve containment structural and system ability to control radiological releases to minimize public risk. For purposes of estimating implementation costs, several reasonable concepts have been evaluated for both new plants and existing plants to allow quantification of the range of implementation costs in a representative manner. Exclusion of other equally reasonable concepts is not meant to imply that such concepts are unlikely to be successful or cost effective.

B.09.01 Concepts Evaluated

1. Dual containment design
2. Seal systems on piping penetrating containment and/or piping connected to the Reactor Coolant Pressure Boundary
3. Design and control of filtered containment venting systems
4. Large hydrogen control systems

B.09.2 Quantification of Current Costs

References 1 and 2 provided the current costs data for structures, systems and components as tabulated in Table B.09.1. For structures and systems serving a similar function in BWRs and PWRs, average values have been presented. In cases where cost data are considered more representative in one type of LWR, such data are presented.

Table B.09.1 - Containment and Systems Current Cost

<u>Structure/System</u>	<u>Costs (millions of dollars)</u>
Containment structure	
Engineering and construction support	32
Factory equipment costs	4
Labor	42
Site materials	30
Construction duration	critical path
Seal systems on piping	
Instrument and compressed air systems	2.3
Main steam isolation valve leakage control system (BWR)	.2
Containment ventilation and related systems	
Standby gas treatment system (BWR)	3.3
High/low containment purge system (BWR)	.4
Offsite radiological and meteorological monitoring system	.6
In-plant radiation monitoring system	.8
Hydrogen control systems	
Factory equipment	1.5
All other categories	.5

B.09.3 Implementation Cost - New Plants

The order of magnitude implementation costs for new plants are presented below for each concept evaluated. In addition, the formula applied to estimate these costs is noted and a brief discussion of major qualifications is presented. As previously discussed, multiplication factors are based upon engineering judgment of the additional system capacity, flow or size, etc., of the new system as compared to the existing.

B.09.3.1 Dual Containment Design

Total Cost = 2(current containment costs) + six months
extended construction
Total cost added = 150 million

Discussion: Assumes a second, equally qualified containment structure is erected around primary containment. Six months of additional construction increases costs by approximately 7 million/month due to interest charges.

B.09.3.2 Seal Systems

Total Cost = 2(instrument and compressed air system) or
10(MSIV-LCS)
Total cost added = 2 million

Discussion: Representative of either positive or negative pressure systems, ignores civil/structural costs (at \$150/ft²), ignores

probable licensing requirement for additional containment isolation valve on all lines, ignores additional maintenance costs, replacement power costs due to Tech Spec unavailability forced outages.

B.09.3.3 Filtered Containment Venting System

Total cost	=	4(SGTS) + 1.5(purge) + 2(rad monitoring)
Total cost added	=	11.5 million

Discussion: Current SGTS costs representative of filtration system except sizing inadequate, purge system on existing designs almost adequate for venting to filtration, rad monitoring required within containment, process systems and on release points with associated protective system to ensure isolation when required.

B.09.3.4 Hydrogen Control System

Total cost	=	7(factory equipment) + 2(other categories)
Total cost added	=	10 million

Discussion: Much larger system required to accommodate potentially escalated design criteria for H₂ control systems to accommodate large metal-water source terms. Ignores civil/structural costs which are dependent upon size of systems developed.

B.09.4 Implementation Costs - Existing Plants

The order of magnitude implementation costs for existing plants are estimated in the following sections. For existing plants, although direct costs for equipment and structures are high, replacement power costs (at \$300,000/day) will be an overriding economic consideration during extended outages. Implementation costs noted include both direct and replacement power costs.

B.09.4.1 Dual Containment

Total additional cost	=	1(containment structure) + 2 years of outage
Total additional cost	=	250 million

Discussion: Above cost estimate assumes practicality of constructing second containment around primary containment from roof level of adjacent structures upward, although it is noted that such modifications would drastically alter structural response requiring re-analysis of all plant piping and equipment.

B.09.4.2 Seal Systems

Total additional cost	=	2(instrument and compressed air system) + 4 months outage
Total additional cost	=	38 million

Discussion: Includes notes associated with 09.3.2, ignores probable need for space to accommodate equipment and piping and assumes outage is

only necessary during major structural work or when plant process piping is being altered.

B.09.4.3 Filtered Containment Venting System

Total added cost = new plant costs + 1 year outage +
3 million civil/structural

Total added cost = 86 million

Discussion: Assumes existing systems can be modified to utilize ventilation duct work, instrument and control wire runs and penetrations, etc. Probably requires an additional qualified structure to accommodate equipment ($\approx 20,000 \text{ ft}^2 @ 150/\text{ft}^2$).

B.09.4.4 Hydrogen Control

Total added cost = new plant added costs + 1 month outage +
3 million

Total added cost = 22 million

Discussion: Assumes existing containment ventilation systems are utilized to transport containment atmosphere to a new qualified structure for hydrogen removal/recombining and then back to containment. This approach may not be sound from a risk reduction standpoint as large quantities of radioactive material would be carried in process ventilation systems out of the containment.

B.09.5 Summary of Containment Function and System Implementation Costs

Table B.09.2 summarizes the order of magnitude of estimated implementation costs. For new plants, the concepts evaluated range in cost between 2 and 150 million. For existing plants this range is estimated to be 22-250 million.

Table B.09.2 - Summary Implementation Costs (per plant)

<u>Concept</u>	<u>New Plant Added Costs</u>	<u>Existing Plant Implementation Costs</u>
1. Dual containment	150 (million)	250 (million)
2. Seal systems	2	38
3. Filtered cont. venting	11.5	86
4. H ₂ control	10	22

B.10 IMPROVED TEST AND MAINTENANCE

The following sections discuss the costs of implementing improved test and maintenance. The purposes of Sandia Tasks in this area can be summarized as (1) to reduce test and maintenance errors (hence assure system availability when required) and (2) to increase test and maintenance efficiency (to increase rate of problem discovery and repair prior to failure). In this section, no distinction is made between new plants and existing plants. However, one must note that equipment location and accessibility, system design, in-plant radiation levels and other factors will impact test and maintenance efficiency and costs. A detailed review of these factors and the direct and indirect impact upon plant operating costs and risk is worthy of study to provide guidance to power plant designers, however, plant to plant variations are ignored. As in other sections, improved plant availability is a significant offsetting cost to implementation costs of improved test and maintenance.

B.10.1 Quantification of Current Costs

Three major cost factors are associated with test and maintenance activities; labor, spare parts and plant unavailability. A distinction can be made in these areas for safety and non-safety systems. Since safety systems are infrequently used, (and due to their necessity to function properly when required) costs are predominately categorized as oriented towards testing. Non-safety systems, however, due to frequent operation and general lack of technical specifications (other than warranty related) require more maintenance than testing. In both cases, economics and safety require sufficient spare parts to either replace failed equipment or allow removal for testing or calibration without impacting availability.

Base plant reference order of magnitude data for current plant testing and maintenance activities are provided in Table B.10.1.

Table B.10.1 - Testing and Maintenance - Current Costs (1)

<u>Category</u>	<u># of Personnel</u>	<u>Costs (millions, 1976 \$)</u>
Plant Staff		
Management and administrative	76 @ 20,000/yr, avg. (5)	1.5
Plant operations	35	.7
Technical and engineering	23	.46
Plant maintenance	22	.44
TOTAL	156	3.1
Fixed and variable maintenance ⁽²⁾		1.4
Spare parts (supplies and expenses) ⁽³⁾		1.6
<hr/>		
	Percent of year ⁽⁴⁾	
Directly attributable unavailability due to test and maintenance errors.	7-10% (equivalent to $\approx$ one fourth of total plant unavailability)	Replacement power cost (for 30 year life at \$300,000/day $\approx$ 250 million)

- (1) Reference 5, normalized to 1976 dollars, using .6 multiplier of levelized costs for 70% capacity factor, 1200 MW unit.
- (2) Material costs incurred for onsite maintenance to repair or replace plant equipment
- (3) Unrecoverable material used during O & M including fluids, chemicals, resins, gases, lubricants, etc.
- (4) References 7 and 11.
- (5) Reported annual salaries from reference 5 probably are not representative of overhead and benefit. For purposes of order-of-magnitude cost estimates, altering of data would not be significant.

B.10.2 Implementation Costs - New and Existing Plants

In the major area of reducing test and maintenance errors, cost impact would be realized as a result of increased training for maintenance personnel, increased staffing requirements to either allow more time/function performed or perform observation and surveillance, design and implementation of systems to review and modify procedures, employment of more qualified individuals, utilization of regulatory agency personnel performing continuous audits and observations, or other similar techniques. Such approaches could double or triple staff maintenance personnel requirements amount to an additional .5-1 million dollars/year.

Implementation costs for improved detection of failing equipment or problem identification would also tend to increase fixed and variable maintenance and spare parts at a cost approximately equivalent to the above, i.e., 0.5-1 million. The economic benefit of decreased replacement power costs, however, of reducing test and maintenance induced failure rates by 20% will offset costs associated with improvements in these areas. Hence, the net implementation costs associated with test and maintenance are less than or equal to zero dollars for both new and existing plants.

B.11/12 IMPROVED EMERGENCY AND DISTURBANCE CONTROL

Studies are currently in progress that are attempting to determine the feasibility of both emergency and disturbance control. A distinction can be made between a disturbance control and an emergency control system from a risk reduction standpoint as discussed in Appendix A. However, since one system would reasonably be expected to perform both functions, implementation costs are estimated collectively.

Emergency and disturbance systems major design basis can be summarized as:

1. Provide capability of diagnosing and displaying plant, system and component conditions quickly and accurately.
2. Provide capability to inform operators of probable consequences of various actions.
3. Provide capability to recommend operator action during operation, transient and accident conditions.

In addition, Sandia tasks related to optimizing control room layout, utilizing human engineering and minimizing operator error through increased training and procedures relate directly to the ability of an operator to quickly and accurately assess plant status and initiate proper action.

B.11/12.1 Cost Implications

Each of the above three major design basis have cost implications in specific hardware or engineering areas. Computer hardware costs for such

a system are estimated to be in the \$100,000-\$300,000 range (reference 10). However, these costs are felt to be small in relation to the modeling and software costs. The order of magnitude of modeling and software cost, once developmental work is complete is estimated to be on the order of 1-5 million dollars.

From the standpoint of unit availability, disturbance analysis systems can realistically be expected to yield between 1 and 2.5% availability gain over a 30 year lifetime. This gain is equivalent to between 30 and 75 million dollars (reference 10).

Given the potential savings in replacement power of 30 million dollars, modeling and software costs of less magnitude would make such a system cost effective. For our purposes in estimating implementation costs, emergency and disturbance control systems are estimated to have an implementation cost of much less than zero dollars for both new and existing plants.

Also included in this research project are tasks aimed at optimizing control room layout, human engineering and minimizing operator error through training and procedural aids. In new plants, control room layout can be optimized at practically no additional cost. Existing plants would likely encounter outage time and be forced to repeat pre-op system checks prior to returning to operation. A 3-6 month outage for this purpose would require 18-36 million dollars in replacement power. Modified bench boards and panel annunciators, etc. would likely add on the order of another 1 million. Improved procedures and training, much like section B.09, Test and Maintenance, has great potential at insignificant cost for increasing plant safety and availability.

In summary, estimated implementation costs for these tasks are:

Costs (millions of dollars)

	<u>New plants</u>	<u>Existing plants</u>
Emergency/disturbance control system	<0	<0
Control room layout with increased human engr.	0	27 (average replacement power)
Procedures and training	0	0

B.13 IMPROVED DESIGN GUIDANCE AGAINST FIRES, EARTHQUAKES AND SABOTAGE

Tasks in this area are aimed at gaining a comprehensive understanding of these and other phenomena that can have significant potential for causing multiple failures and implementing that guidance in designing and modifying nuclear power plants. Because of the wide ranging implications to many structures, systems, and components, implementation of tasks in this chain are discussed qualitatively, with engineering judgment then being applied to quantify implementation costs.

B.13.1 Implementation Costs - New Plants

As discussed in Section B.04.2, the cost impact of backfitting modified and improved systems for protection against natural and man caused events has been expensive. However, given the fact that NRC regulatory requirements currently require substantial compliance with Branch Technical Position APCS 3-1 or Regulatory Guide 1.120 for fires, Regulatory Guide 1.60 and others for earthquakes, and a spectrum of Regulatory Guides, Sandia reports, and other documents for security and sabotage, it is doubtful that successful accomplishment of the Sandia tasks would significantly escalate these requirements. Rather, the expected outcome would be design guidance that could be systematically applied during the design phase to ensure a high degree of confidence that multiple failure potential has been reduced in these areas. It is concluded that since a minimum impact on quantity or type of equipment would be likely to result, the estimated implementation cost for new plants is estimated to be less than or equal to zero.

B.13.2 Implementation Costs - Existing Plants

Since the Browns Ferry fire in 1975, NRC requirements for fire protection have been defined and implemented in operating nuclear plants. Likewise, security requirements are presently being defined and are in various stages of implementation at operating plants. In general, very little has recently evolved in revised seismic regulatory criteria that has mandated backfit changes, although specific plants (Diablo Canyon, Trojan, S & W plants having utilized a specific piping code, etc.) have experienced lengthy outages and expensive modifications as a result of increased site specific seismic criteria or design errors that were discovered following construction. It is a fair characterization of industry sentiment to state that, if anything, the current conservative criteria and methods employed in nuclear plant seismic design results in many layers of conservatism being compounded in existing plants to the point that the ultimate capability of plants to withstand seismic events is many times in excess of required capability. There is in fact concern that such conservative criteria and techniques have made nuclear structures and systems excessively rigid, resulting in a lessening of overall safety by increasing LOCA susceptibility and decreasing the ability to withstand small seismic events. The analogy that one can draw to TMI experience with a small LOCA in a plant conservatively designed to withstand worst-case events is obvious.

In general, backfit costs for fire protection have been a result of providing system modifications to fire water, sprinklers in various areas, additional separation of redundant systems and loops, modification to cable trays and cable, instrumentation additions, structural upgrading to provide 2 or 3 hour fire barriers, and analytical costs. Full compliance has not been required where severe structural and layout modifications would be required. Modification costs for security systems have been for installation of access control devices (key cards, etc.), monitoring devices (closed-circuit TV) and operational costs

(plant security personnel, maintenance requirements and procedures, etc.). A representative cost of implementing these requirements over an existing plant's lifetime is (conservatively) estimated at 40 million dollars/plant.

Inasmuch as the Sandia tasks are aimed at providing design guidance, design plant improvements which can be cost effectively implemented for new plants are expected to result. Major modifications to plant layout and structures are, however, prohibitively expensive for existing plants. Therefore, since previous modifications have been made on balanced evaluation of implementation costs and risk reduction and future modifications should only be mandated where value/impact analysis demonstrates need, implementation costs are estimated to be 0 to 20 million per plant.

B.14 IMPROVED EMERGENCY RESPONSE

For purposes of estimating implementation costs, projects in this category are divided into the following categories:

1. Emergency response team, communications and data
2. Design features and support equipment

Estimated implementation costs presented in the following section are considered representative of order of magnitude costs for both new and existing plants.

Costs implications associated with emergency response teams, communications and data arise from (1) costs associated with selecting and training qualified personnel and (2) costs associated with establishing and maintaining procedures, communications and plant specific technical data. For purposes of estimating costs on a per-reactor basis, it is assumed that the following personnel, in addition to plant operational personnel, would initially be selected for training and performing response functions over and above current requirements for emergency response plans:

Engineers and scientists	25 @ 1 month/year
Technicians and off-site support	100 @ 2 weeks/year
Management	10 @ 1 month/year

The annual cost of such a team is estimated to be \$200,000 per plant year, or six (6) million over the plant lifetime.

Costs associated with communications and technical data would require an initial cost for establishment and maintenance costs. These costs are estimated at approximately two million over the plant lifetime.

Support emergency equipment would conceptually be stored at one or more centralized locations and disseminated as required. Assuming three such equipment pools in the U.S. comprised of filters, demineralizers, pumps, piping, heat exchangers, respirators, compressors, tanks, containers for contaminated material, shielding material, hydrogen recombiners, etc. (reference 13), initial set up cost would be expected to be between 20 and 100 million dollars with storage and maintenance costs estimated at one million/year. When distributed over 100 reactors, each with a thirty year life, costs would be on the order of one million dollars/plant.

Major plant specific costs would arise from need to design and provide piping interties to which emergency equipment could be connected, additional protection systems and interlocks and testing and maintenance. Lifetime costs are estimated to total approximately 3 million per plant, although wide variance would be expected from plant to plant and between new and existing plants.

Total implementation costs are estimated to be the sum of these factors or 12 million dollars per plant in 1976 dollars.

B.15 Reactor Siting

As discussed by Sandia, remote siting implementation costs are principally derived from (1) increased transmission losses, (2) increased construction costs, and (3) potential long distance transmission of cooling water and other factors. Offsetting factors include reduced population risk, reduced social/economic impact, and reduced licensing lead time. Applicants for construction permits for nuclear projects generally perform a fairly rigorous selection process to quantify costs associated with alternative sites. Such evaluations are also performed by the Regulatory Staff as necessary to fulfill the needs of NEPA and to document that the ultimately selected site does not have an "obviously superior" alternative.

Over plant lifetime, total implementation costs for remote siting will, of course, vary widely from one geographic region to another. The cost of transmission lines and transmission line losses over the 30 year project lifetime are on the order of \$500,000/mile for initial cost and approximate 1% loss per 100 miles of line normalized to our 1976 data base. Labor cost during plant construction, currently about 270 million (references 1 and 2, normalized per Section 2.3) could reasonably be expected to change an additional 10%, although again regional variations are significant. (Note also that craft labor, over 1 million man days/project, averaging even an additional 25 miles one way to work in three-man car pools, would utilize an additional million gallons of gasoline during construction.)

For the purposes of quantification, on the assumption that a typical plant would be sited 100 miles from the optimum location from the standpoint of a balance between weighing factors currently applied to siting, implementation costs are estimated (considered conservative) to average 100 million/plant. Implementation costs, of course, for existing plants are considered meaningless in this area.

B.16 IMPROVED RISK METHOD UTILIZATION

Sandia tasks in this area are aimed at quantifying safety goals and developing and utilizing risk methodology for design basis and design decisions for nuclear power plants. It must be recognized that implementation costs will be very dependent upon the ultimate safety goals that are established. In the past, regulatory requirements have continued to evolve and escalate with minimal attention to balanced risk reduction and cost-effective risk reduction. There is no reason to believe that this trend will reverse unless a uniform mechanistic approach is applied.

In the unlikely event that safety goals are set lower (higher risk) than existing plants can demonstrate, implementation costs for new plants would be negative. Existing plants, that are not likely to make expensive modifications unless required, would be expected to maintain current margin and experience a zero implementation cost. On the other hand, substantially higher safety goals would be expected to increase both new and existing plant costs. However, a one-time quantification of safety goals would tend to minimize the current practice of continual backfit so that even a higher safety goal (less risk) could be implemented in a cost-effective manner on plants.

As noted above, the past practice of utilizing deterministic criteria for specifying individual system design basis has occasionally been insensitive to overall risk reduction. As a result, imposed regulatory requirements, often costly, may or may not have been warranted in terms of risk reduction. Uniform systematic application of quantitative risk methods to new plant design, given a safety goal equivalent to that which current plants meet, will likely result in a one-time substantial savings, since dollars currently spent in preventing or mitigating very low probability events could be utilized elsewhere for more substantial risk reduction.

In conclusion, without prior quantification of safety goals and quantification of system and component reliability, implementation costs are unquantifiable. However, a safety goal that approximates that of existing reactors would be expected to stabilize reactor design and licensing and would result in a zero or negative implementation cost for new plants. For the purpose of quantifying costs, on the assumption that a quantitative safety goal approximates that which current plants meet, implementation costs are estimated to be less than zero for both new and existing reactors.

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APPENDIX C
DESCRIPTION OF LWRSEN COMPUTER CODE

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DESCRIPTION OF LWRSEN COMPUTER CODE

The LWRSEN computer code was written to calculate the values of public risk for light water nuclear reactors using the methodology developed in the RSS. The code calculates the sensitivity to changes in the basic inputs to the public risk calculation. These sensitivities are then output under certain formats depending on the type of sensitivity calculations performed. Basically, the three main subroutines, COMP, COMBIN, and ATTR, calculate respectively: (1) individual sensitivities; (2) system, generic, or combinations of sensitivities; and (3) combinations of sensitivities and breakdown by individual components.

Five basic inputs contribute to risk in this model. First, the probability of an accident-initiating event must be assessed. Then, then probability of system failure for systems which are needed to mitigate the effects of the particular initiating event is required. Given that those system failures which lead to core melt for a particular event tree are assessed, then the probabilities of containment failures are evaluated using models based on the containment conditions of the accident being examined. Assuming the containment fails, the consequence to the public will be determined by the associated radioactivity release. The consequence depends upon two other factors. They are the weather conditions and the population density and distribution. The present study assesses the effect on public risk from variation of the system failure probabilities.

The combinations of initiator probability and system failure probability are described by accident event trees. The event trees use system failure probabilities as input. These probabilities are determined by a reliability (or actually, unreliability) analysis of the system. Fault trees are used for system unreliability determination in this analysis. In this analysis, only the major parts of the RSS system fault tree analyses are retained.

The inputs to the system fault tree analysis are a number of different types of individual failures. These types of failures are further classified under generic categories. The category types were chosen based on the number of components of that type and the basic reliability classifications of failure modes. The PWR analysis contains more generic types than the BWR, due to the larger number of components and the higher level of detail necessary for the PWR sensitivity analysis. The fault tree reductions mentioned above are also made to fit the chosen generic categories. The generic categories for the PWR are human error, test and maintenance, electric power, control elements, valves, pumps, other hardware, and all hardware.

With the system failure probabilities, accident event trees, and containment failure probabilities, a determination of release category probabilities may be made. To translate these values to public risk, the RSS developed the Calculation of Reactor Accident Consequences (CRAC) code. Median values of the consequences for each release category were used. The weather and population data is representative of a northeast river valley site.

The computer code LWRSEN is written to reproduce the above methodology for point values of failure probabilities and consequences. The code contains three major routines for different types of sensitivity calculations. One routine calculates all the individual sensitivities and another calculates all the system and generic sensitivities. The third routine is a combination of both of the first two. Basically, the user first chooses the type of reactor, the consequence parameter, and the multiplicative factors for which the sensitivities are to be calculated. Then, the user decides whether to keep the RSS reduced fault trees or choose a different set of fault trees. The system failure probability equations are input for the method chosen. The code then calculates a base case of release category probabilities, consequence parameters, and

core melt probability. The user inputs a set of attributes for each component and indicates which attributes are to be varied to determine their sensitivities. The new system failure probabilities are calculated, followed by the new values of public risk to compare to the base case values.

The results obtained from LWRSEN correspond to the data and analyses presented in the RSS. Most importantly, the results are specific to the representative plants chosen for the RSS. In addition, the risk calculations are specific to a northeast river valley site and contain the approximations of the consequence code (CRAC) developed in the RSS. Nevertheless, the results are important since the general conclusions gleaned from a sensitivity study such as this should apply to almost all reactors of present design. In addition, the reactors chosen for the RSS were typical of many reactors in the U.S.

There are also differences between the RSS and this study. The technique of smoothing is dropped from the analysis of this study in order to provide clearer indications of sensitivity. Also, for all calculations except the variational or uncertainty analysis, point values rather than probabilistic distributions are used. Both of these effects will change the results obtained if they are included. For example, not including smoothing results in about twenty percent less early and latent deaths, and about fifty percent less property damage, than the RSS-reported results. The reduction is an even greater percentage when point values are used. In fact, point values have a tendency to underestimate unavailabilities, and consequently public risk. For this reason, as well as ease in understanding, all results are reported as being normalized by the point value calculations. Despite these limitations it is felt that LWRSEN is adequate to perform sensitivity analysis.

More complete documentation of the code is provided in the unpublished Master's thesis by W. J. Parkinson entitled "A Sensitivity Study of WASH-1400." This was completed in 1979 in the Department of Nuclear Engineering at Massachusetts Institute of Technology.

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