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APPLICATION OF THE ALAP CONCEPT TO OCCUPATIONAL EXPOSURE AT OPERATING LIGHT WATER REACTORS

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APPLICATION OF THE ALAP CONCEPT TO
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Abstract

The application of the as-low-as-practicable (ALAP) concept to radiation exposure of workers at light-water reactors (LWR's) has recently received increased attention. The purpose of this project is to investigate the means by which occupational exposure at operating LWR's can be reduced to the lowest practicable levels. Nine LWR stations, including 16 operating reactors, were studied in Phase I of the project to identify significant sources of exposure and to determine the magnitude of the exposures. A complete site review consists of compiling information from safety analysis reports, plant technical specifications, and radiation exposure records coupled with an on-site visit for discussions with plant personnel, observation of procedures, and measurement of radiation levels. In Phase II, specific problem areas are being studied in-depth with regard to corrective measures to reduce exposure. Information has been collected on exposure from valve maintenance and repair. Corrective measures will be evaluated with respect to ease of application and cost effectiveness. The results of this study will serve as technical backup for the preparation of regulatory guides.

Introduction

Recently much attention has been given to reducing exposures to the general population in the vicinity of operating nuclear power plants. Design objective quantities for annual radiation doses at the site boundary are now specified by 10 CFR 50. The population dose within a 50-mile radius of a new 1000-MWe plant is in the range of 10-100 man-rem. At most operating plants, occupational exposures have not received the same attention and only now are they being examined as carefully under the as-low-as-practicable (ALAP) philosophy. During 1973, collective radiation doses to workers ranged from a low of 74 man-rem at Pilgrim to a high of 5134 man-rem at Indian Point(1), where a great deal of special maintenance and repair took place. There is also a trend, especially noticeable at boiling water reactors (BWR's), toward an increase in occupational doses as the plants age. Furthermore, the average number of persons exposed at each plant has been increasing. There is no good basis for predicting future occupational radiation doses; however, the present data are sufficient to make it clear that something must be done to limit these doses.

Project Description

The current work is aimed at application of the ALAP concept to exposure of workers at light-water reactors (LWR's). The purpose of this program is to investigate the means by which the radiation exposure of workers at operating LWR's can be reduced to the lowest practicable levels.

The study was divided into four phases which overlap in time. Phase I, which is nearing completion, deals with a preliminary overview of the problem, including reviews of records and site visits to identify significant problem areas. In phase II specific problem areas will be studied in depth with regard to corrective measures to reduce exposure. These corrective measures will be evaluated with respect to ease of application and cost effectiveness. A suggested sequence of corrective measures, including alteration of both hardware and operating procedures, will be developed, and a cost-benefit comparison made to determine the extent to which the sequence should be implemented. Recommendations will be made regarding design considerations for new facilities. Phase III will consist of providing technical assistance in the drafting of regulatory guides as the specific problem areas are evaluated and corrective action is recommended. Phase IV will be an extension of the study to other nuclear facilities, including but not necessarily limited to high-temperature gas-cooled reactors, fuel reprocessing plants, and breeder reactors.

Following an extensive literature search, criteria were established for selecting nuclear power stations to be reviewed in depth. The completed site visit schedule is given in Table I. A great deal of emphasis was placed on these site reviews, as it was felt that the most relevant and accurate information could be obtained from plant management and personal observation rather than second-hand or edited sources.

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Table 1. Site Visits

Site	Reactor Type	Installed Capacity MWe	Cumulative Energy MWh x 10^6	Plant Status During Visit
A Unit 1	BWR	1098	5.7	Routine Operation
Unit 2	BWR	1098	1.2	Power Testing
B	BWR	75	4.3	Planned Outage
C	PWR	185	16.1	Routine Operation
D Unit 3	PWR	728	8.8	Forced Outage
Unit 4	PWR	728	7.4	Routine Operation
E	PWR	450	20.6	Refueling Outage
F Unit 1	BWR	210	13.8	Extended Outage
Unit 2	BWR	840	16.3	Refueling Outage
Unit 3	BWR	838	14.3	Routine Operation
G Unit 1	PWR	1085	5.5	Routine Operation
Unit 2	PWR	1085	2.5	Routine Operation
H	PWR	490	14.4	Refueling Outage
I Unit 1	PWR	911	~4.0	Routine Operation
Unit 2	PWR	911	~2.6	Routine Operation
Unit 3	PWR	911	~1.3	Routine Operation

General Results

A number of significant problem areas at LWR's have been identified, such as refueling (head removal, installation, and fuel handling); handling of radioactive waste; inservice inspections; and inspection, repair, and maintenance of particular components such as recirculation pumps, valves, and steam generators. Data supporting these observations came from exposure records at nuclear power plant (NPP) sites and from discussions with health physics and maintenance personnel at these plants. These are not startling observations since others(2,3) have reached similar if not the same conclusions. This is only a confirmation of earlier observations. Some of the other common problems which were mentioned at several sites included:

1. High exposure obtained from filter changes
2. Need for pump and valve isolation cubicles
3. Relocation of components out of high radiation fields
4. Lack of specifications of valve internals from vendors
5. Need for improved mock-up training for "hot" jobs
6. Valve packing failures
7. Valve malfunctions
8. Activation of molybdenum disulfide lubricant
9. Insulation removal and installation
10. Lack of communication

Various studies have revealed an "aging" effect on exposures at LWR sites. Curves illustrative of this fact are presented in Figure 1. In general, exposure rates can be predicted into the future for areas in the vicinity of components which will experience activated corrosion products (crud) buildup. Coupling the increased requirements for inservice inspection and unexpected maintenance and repair with the corrosion product build-up has resulted in dramatically rising cumulative radiation doses at several LWR's.

The extent of exposure during outages has been emphasized in several reports(1-3). It is estimated that two-thirds of the total annual radiation dose occurred during outages. Some individual plants vary in this respect, showing a range of 27-97% in actual studies, but these represent extremely unusual cases. A typical example of jobs and exposures incurred during refueling outages is shown in Table 2.

There is a trend toward standardization of nuclear plants such as the standardized designs exhibited by General Electric (GESAR) and Westinghouse (RESAR). While the reason for standardization was economy of time in licensing, it may also be a boon to ALAP. Caution is in order, however, since several generic deficiencies have been noted as recurring through several generations of plant design. For example, inadequate waste evaporators have been built at several generations of pressurized water reactors (PWR's). This suggests that the standardized plant may still contain poorly designed equipment and plant arrangements. Part of the problem in getting design changes incorporated into new plants is lack of communication. Basically, there is little feedback from the utility to the architect-engineer (AE) which results in changes in future plants.

Table 2. Radiation Dose During Refueling Outage at a Typical BWR

Job	Dose (man-rem)
Valve repair	28
Insulation removal and replacement	20
Control rod drive removal	8
Vessel internals inspection	10
Reactor head removal and replacement	29
Nondestructive testing inspection	7
Refueling operations	6
Miscellaneous	13
Total for outage	121

Table 3. Radiation Dose Due to Valve Maintenance

Nuclear Station	Man-rem (Valves)/ Man-rem (Total)	% Outage Dose due to Valve Main.
B	2.4/88	3%
B	4.8/125	4%
B	14/78	18%
B	6/97	6%
E	46/116	40%
I Unit 1	10/317	3%
I Unit 2	0.8/1.2	67%
I Unit 3	0.3/2.7	11%
Pilgrim[3]	30/121	25%
Monticello[6]	20/133	15%

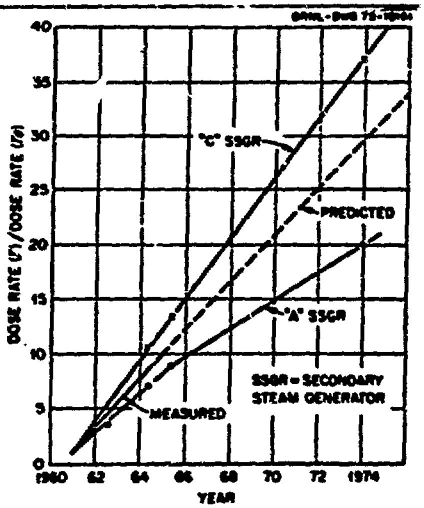

Fig. 1. Dose Rate Build-up at Nuclear Station "F"

Table 4. Valve Malfunction

Category	Survey 1 (1967-1971)	Survey 2 (1/71-7/72)	Survey 3 (5/72-9/72)	Survey 4 (9/72-3/75)
No. of malfunctions included in survey	171	121	81	715
Avg. malfunctions per plant per year	2.5	2.8	8.1	10
Functional type of valve involved				
Steam-line isolation valves		19 (16%)		123 (17%)
Other steam-service valves		12 (10%)		91 (1[illegible]%)
Regulator valves		6 (5%)		
Safety or relief valves		16 (13%)		159 (22%)
Associated system				
Steam service				214 (30%)
Isolation valves		19 (16%)		123 (17%)
Turbine systems		8 (7%)		
HPCI or RCIC systems		7 (6%)		
Emergency Core Cooling	37 (22%)		11 (14%)	80 (11%)
Reactor Coolant and Power	75 (25%)		49 (60%)	
Conversion				
Main Cooling				145 (20%)
Shutdown Cooling				47 (7%)
Coolant Purification				36 (5%)
Feedwater				24 (3%)
Auxiliary Cooling				13 (2%)
Secondary Shutdown				20 (3%)
Other Engineered Safety Features			8 (10%)	
Cause of failure				
Improper maintenance	44 (26%)	17 (14%)	31 (38%)	133 (19%)
External error[1]	89 (47%)			37 (5%)
Improper design or application	43 (25%)		26 (32%)	100 (14%)
Fabrication & Installation errors	19 (11%)			122 (17%)
Mechanical[2]		41 (34%)		84 (12%)
Leakage		17 (14%)		57 (8%)
Foreign Material Obstruction		15 (12%)		34 (5%)
Electrical[3]		15 (12%)		69 (10%)
Packing		17 (14%)		

[1]Includes operator error, poor procedures

[2]Includes worn or damaged drive components; loose parts; valve binding

[3]Includes torque limit switch failure, solenoid malfunction and circuit problems

During the initial site review (Nuclear Station A), the need for expanded ALAP records at nuclear stations became apparent. At this site, extensive use is made of special work permits (SWP's). The information on the SWP is sufficient, in most cases, for assigning doses to particular workers doing specific jobs. The SWP's were coded in order to make specific dose assignments. We have collaborated with this utility's health physics staff in collecting and evaluating (by computer techniques) approximately one plant year's equivalent of operating exposure data(4).

There is an increasing concern for performing cost-benefit analyses for ALAP modifications. Reasons for doing this are well-founded and include the following:

1. There is now enough published evidence to suggest a dollar value per man-rem.
2. The precedent of using such a dollar value has been set in the NRC position paper regarding 10 CFR 50 Appendix I.
3. The precedent of using a dollar value per man-rem would give utilities justification for expenditures and set guidelines on how much to spend to achieve reductions in radiation doses.
4. The nuclear industry has asked for cost-benefit analyses, as, for example, the recent public review of the revision of Regulatory Guide 8.8.

Also, cost-effectiveness studies must be done to determine man-rem savings per dollar spent on modifications. After assigning dollar values, it becomes a trivial exercise to determine whether the expenses for a suggested modification can be justified economically, but a follow-up study should also be performed to determine if the cost-benefit study was accurate.

Valve Study

The early identification of valves as a significant source of radiation exposure caused special emphasis to be placed on this problem. An in-depth study was conducted on valve maintenance and repair, although most information gathered was general in nature. The integrity and operability of valves have been a major concern at nuclear power stations since maintenance of valves causes a significant workload and leads to sizable personnel exposures. For several recent outages, valve related doses at several LWR's are given in Table 3.

Valve Malfunctions

In order to evaluate the extent of valve failures and the significance of these failures with regard to personnel exposures; a study of plant operating experience in this area was undertaken. A previous study along the same lines has been published(5). The present study covers the period from September, 1972 to March, 1975 in order not to duplicate the time frame of any previous study. A computer search was conducted on the Nuclear Safety Information Center (NSIC) files and yielded a tabulation of LWR valve failures by plant, plant type, valve type, associated system and cause of failure. Terminology was observed to present a serious problem and points up the need for standardized terminology in the industry. Also, in many cases, it was difficult to assign a single cause for failure when several causes were suggested. In spite of the inadequacies of the study, the results, presented in Table 4, are interesting and can be compared to the previous studies. It can be determined by simple addition that the cause of failure accounts for 109%, 100%, 70% and 90% of the cases for surveys one through four, respectively. In the first survey, multiple causes of failure were considered. The second survey assigned a single reason for failure to each case considered. For the third and fourth surveys, the cause of failure in some cases was undetermined or of a miscellaneous nature.

The survey did not consider all valve malfunctions reported within the period of the study since many cases were so ambiguous or uncertain that their inclusion was not deemed useful. Thus, there was some arbitrary sample selection. Also, some of the malfunctions occurred during preoperational or surveillance tests; but they were largely eliminated, again by sample selection.

While it appears from the data that the number of valve malfunctions per plant year is increasing, other ways of explaining the data may have equal justification. For instance, the increase may be explained by better reporting or by inclusion of "minor" failures which may have been overlooked in reporting of previous years. The fact that the sample size is large and that testing failures were deliberately removed from the data does give support to the conclusion that the reliability of valves may be decreasing.

For individual plants, a total of 860 valve failures were considered from the NSIC search. Of these, 515 occurred in BWR's having a total of 40.7 plant years of experience; this yields an average failure rate of 12.6 per plant year. The corresponding statistic for PWR's was 7.6 failures per plant year based on 345 failures in 45.3 plant years of experience. While the absolute failure rates admittedly are inaccurate, the large difference between BWR's and PWR's is significant at the 95% confidence level. A breakdown by reactor is presented in Table 5.

Table 5. Plant Specific Valve Malfunction Rate

BWR Plants	Malfunctions/ Operating Years	PWR Plants	Malfunctions/ Operating Years
Pilgrim 1	46/2.5	Robinson 2	21/2.5
Quad Cities 1	33/2.5	Conn. Yankee	24/2.5
Quad Cities 2	37/2.5	Indian Point 1	24/2.5
Big Rock Point	16/2.5	Indian Point 2	12/1.8
Arnold	16/1.0	Palisades	3/2.5
Oyster Creek	44/2.5	Oconee 1	17/1.9
Cooper	17/1.1	Oconee 2	10/1.3
Nine Mile Point	19/2.5	Turkey Point 3	12/2.4
Millstone I	16/2.5	Turkey Point 4	13/1.75
Monticello	39/2.5	Maine Yankee	11/2.4
Humboldt Bay	10/2.5	Prairie Island 1	17/1.25
Peach Bottom 2	28/1.5	Ft. Calhoun	13/1.6
Fitzpatrick	7/0.5	Surry I	37/2.5
Browns Ferry	32/1.6	Surry 2	18/1.9
Vermont Yankee	47/2.5	Pt. Beach 1	34/2.5
La Crosse	10/2.5	Pt. Beach 2	17/2.5
Dresden 1	13/2.5	Kewaunee	11/1.0
Dresden 2	46/2.5	Yankee Rowe	9/2.5
Dresden 3	39/2.5	Ginna I	34/2.5
		San Onofre	4/2.5
		Zion 1	21/1.75
		Zion 2	23/1.25
	515/40.7 = 12.6		345/45.3 = 7.6

The latest survey agrees with the previous surveys in supporting the conclusions that:

1. Malfunctions have occurred in all plant types and designs.
2. Valves from many vendors and of all sizes and types were found to have failed.
3. Causes for malfunction cover a broad spectrum.
4. External errors and failure of valve operators were responsible for many of the occurrences.

Corrective actions suggested by the survey include:

1. Repair and/or replacement of malfunctioning components on an individual basis.
2. Design modification for service conditions as opposed to theoretical conditions.
3. Increased frequency of surveillance in low radiation zones.
4. Procedural changes and training in the operation, testing and maintenance of valves.
5. Continual review of the status of valve reliability.

Other Valve Findings

A careful design analysis should include health physics as well as the usual engineering considerations. Current generation LWR's are beginning to exhibit component isolation for such items as major valves. There are still many instances, however, where minor valves are not considered separately from other components. Even where the valve itself is not a radiation source, workers may be exposed to high levels of radiation; one good example of this is the pressurizer spray valve where the pressurizer is the major source of exposure. Better placement of valves or isolation of valves in shielded cubicles would result in considerable dose reduction. In some PWR's, valves are located adjacent to the regenerative heat exchangers; this placement problem could be solved by relocation of the valves.

Design of a nuclear facility for easy removal of components in order to facilitate maintenance or replacement should be a primary ALAP consideration. With regard to valves, the use of designs which include quick removal mechanisms, such as Marman clamps*, should be encouraged. These devices have been designed for both high and low pressure systems and for systems having stringent release limits; however, few have been incorporated into LWR piping systems.

Other design considerations for maintaining exposures ALAP include minimization of crud traps in valve structures, use of valve materials which do not become activated appreciably, ease of maintenance (including, but not limited to, accessibility), ease of assembly and disassembly, availability of parts, and detailed specification of internal components. Some ALAP considerations are contrary to the best engineering design. As an example, cobalt used in stellite makes it hard and wear resistant but leads to high radiation levels from the activation of corrosion products in the core(7). While it may very well be best to continue with the use of stellite compounds, health physics considerations should be included in the decision-making process.**

*Registered trademark of Aeroquip-Marman.

**A major effort has been at the Douglas Point Power Station of Ontario Hydro to remove stellite components following radiation protection evaluations(8).

The features of a particular valve and the proper maintenance techniques are most effectively conveyed in a valve manual. The manual should include all pertinent valve design information, drawings, part identification, and spare part recommendations. In addition, a record of maintenance should be kept for each valve in order to evaluate its performance. These records help to establish the proper intervals for preventive maintenance. Also, specific instructions in the form of a procedure should be written for each maintenance operation since a number of valve malfunctions have been due to maintenance errors.

Fexitallic gaskets are finding more and more application, and deservedly so. They combine the best features of both metallic and nonmetallic gaskets by using a sandwich arrangement of Teflon or asbestos trapped between stainless steel layers. The Teflon provides a material ductile or soft enough to flow under compression to plug its own leaks; and the stainless steel is hard enough to resist erosion.

In a number of the plant visited, changes in valve packing had been made or were being contemplated. Specifically, the use of Grafoil* and other new types of packing has dramatically reduced the frequency of repacking. To be effective, packing frequently must be re-tightened. In nuclear applications, this involves additional exposure; thus one should select packing that remains resilient and does not require frequent tightening. Stuffing boxes should have space for six or more turns of packing. The gain from additional packing diminishes beyond this, because compressive stress occurs in the layer adjacent to the gland follower and diminishes through the succeeding layers(7).

In cases where applicable, packingless valves are being substituted for packed valves. Valves utilizing bellows seals are rapidly acquiring a reputation for being reliable and requiring minimal maintenance. So far, the only widely available bellows seal valves are for low pressure systems involving small diameter piping.

Corrosion Product Buildup and Removal

Radiation exposure from activated corrosion products (crud) continues to be the most significant source of occupational radiation at LWR's(2). Among the radionuclides in crud, ^{58}Co appeared to be the most abundant in a recent study by Babcock and Wilcox(9). Also appearing in significant quantities were ^{60}Co, ^{54}Mn, ^{95}Zr and ^{59}Fe. The plant chemistry program of EPRI's Nuclear Power Division includes defining the sources of primary system radioactivity and finding procedures for plant operation and decontamination which best limit in-plant exposure levels.

At Unit I of station "F", radiation levels have increased significantly (see Fig. 1). One means of reducing occupational exposure there is to remove partially the source of radiation. To this end, the station is planning a full scale primary system decontamination which has been scheduled for the first half of 1977(10).

Conclusions

It is the considered opinion of the investigators involved with this project that occupational exposures could be reduced at operating LWR sites. We estimate that radiation doses could be reduced 10-20% by modification of procedures and practices at the station, an additional 10-20% by minor modification of hardware and its arrangement and a factor of 2 to 10 if major plant modifications such as relocating major components were made.

Major plant modifications which will lead to significant reduction of radiation dose will also call for significant expenditures. These items will bear close scrutiny from a cost-benefit standpoint. A guideline of $1,000 per man-rem has been established as a non-occupational dose guideline; however, the need for additional effort in the region of individual dose near the dose limit has been emphasized by the International Commission on Radiological Protection(11). For the purposes of this project, modifications which cost less than $10,000 per man-rem will be considered justified. Modifications requiring greater expenditure will receive careful consideration and may be justified based upon current cost-benefit rationale. This is not to say that the choice of this figure is clearly defensible, but that in the absence of a definitive figure, this one seems reasonable.

The ALAP philosophy is still not understood nor practiced by tho operating staff at a majority of the LWR's studied. Station and utility health physicists are committed to controlling radiation exposure and to minimizing it whenever possible. This commitment alone is not sufficient; one needs the plans, procedures and designs which are the tools for accomplishing ALAP. Stations which do not have a formal ALAP plan, including implementation, cannot achieve ALAP exposures. Secondly, even if the health physicist has the tools at a given station, the results still depend upon acceptance by management and plant operating personnel. To many, ALAP only means making sure no one exceeds the maximum permissible exposure limit. Definitions and illustrations of ALAP should be prepared and distributed throughout the nuclear industry as an educational project.

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*Registered trademark of Union Carbide Corporation.

Research is needed to study prevention or minimization of crud buildup. Studies on crud buildup such as Babcock & Wilcox's study(9) at station "I" are necessary prerequisites. It would also be advisable to conduct additional research on decontamination techniques and procedures. While the primary system decontamination scheduled for station "F" Unit 1 should shed some light on this problem, much remains to be done in this area.

In order to avoid exposure in high radiation areas, the trend will have to be toward greater use of remote handling. To date, automated systems and those involving remote operation have experienced a great deal of down time which either puts everything back on manual operation or halts operation entirely. The resulting maintenance produces as much, or more, exposure than that which was to have been saved by the system involved. Here then, as in other areas, reliability is of the utmost importance. Based upon the valve malfunction study, it is a moot question as to whether reliability of nuclear components is improving or, in fact, degenerating.

Few common problems other than those already given could be definitely identified. Perhaps this was due to the diversity of the plants studied. As a result, a typical exposure for any plant operation has not been ascertained. It is our opinion that a "typical" plant does not exist at the present time. We were able to observe a spectrum of radiation exposure problems and make general conclusions. Perhaps when enough of the so-called "standard design" plants become operational, such things as the average or typical exposure during refueling will have some meaning. Even then, as it is now with the supposedly identical Naval reactors, each reactor will have its own personality. ALAP specifications are a long way from making recommendations of doses for specific jobs.

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