NUREG/CR-4381
BNL-NUREG-51918

Summary of Comparative Assessment of U.S. and Foreign Nuclear Power Plant Dose Experience

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Prepared for
U.S. Nuclear Regulatory
Commission

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Manuscript Completed - August 1985
Date Published - October 1985

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Prepared for
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN A3264

ABSTRACT

Data gathered at the 1984 BNL Workshop on Historical Dose Experience and Dose Reduction (ALARA) at Nuclear Power Plants and from recently published literature were reviewed and analyzed. Large differences were noted, between countries and between similar plants, for collective dose (man-rem) per plant and per unit of electricity generated (MWe-yr). During the period 1978-1982, for PWRs, the U.S. ranked highest in terms of collective dose per MWe-yr (1.2), and France, Sweden, and Finland were lowest (0.27-0.37). For BWRs, Japan, the U.S., and the Federal Republic of Germany ranked highest (2.2-1.9), and Finland and Sweden were lowest (0.08-0.32). Only a small portion of the differences could be attributed to average plant age, vintage, or rated capacity.

Fifteen factors were identified (in addition to age) which contribute to differences. In estimated order of importance, these were plant chemistry, water purification, materials selection for low cobalt and nickel, special tools, decontamination of primary systems, required multi-plant actions, worker motivation and commitment, permanent work force, management commitment to dose control, three or more reactors per site, design for reliability, passivation of primary systems, quality assurance, standardized plant design, and shielding.

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ACKNOWLEDGEMENTS

The project discussed in this document was sponsored by the Occupational Radiation Protection Branch, Office of Nuclear Regulatory Research, Division of Radiation Programs and Earth Sciences of the U.S. Nuclear Regulatory Commission. The authors gratefully acknowledge the guidance, input and comments provided by the Ad Hoc Dose-Reduction Advisory Committee members.

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Alternates for the Ad Hoc Dose-Reduction Advisory Committee members who contributed their time and effort are Robert Pavlick (Commonwealth Edison Co.), Rod Reed (TVA), James McHugh (Northeast Utilities), James Renshaw (AIF/GPU), D.T. Dexheimer (Bechtel), and Ronald Maxwell (TVA).

The authors also thank Marie Cooney for her care and skill in typing and preparation of the manuscript.

1 Introduction

The objectives of this study were to determine how collective dose equivalents at U.S. nuclear power plants compare with those of some technically advanced countries, and to evaluate factors that contribute to the differences.

Fifty health physicists and nuclear engineers from ten countries met at BNL May 29 - June 1, 1984, to exchange information and hold discussions at a Workshop on Historical Dose Experience and Dose Reduction (ALARA) at Nuclear Power Plants.(1) The results of evaluating data from this meeting and other data from recent publications (2-48) are summarized here.

2 Workshop Findings(1)

Participants at the Workshop experienced an unusual degree of openness in the discussion of problems in applying the ALARA philosophy. Successes and failures were candidly evaluated, to an extent beyond the normal sensitivities of corporate or utility policies. The format of an international workshop provides an effective way to exchange data and to discuss experiences and techniques that are developing in a dynamic technological field. Enough new ideas and unique approaches were presented to provide every operational group represented with several approaches that could be implemented to improve their own occupational exposure controls. Some were "nickel-dime" ideas:

- quick fasteners
- soft lead brick shielding
- portable ventilation blowers
- special tools and jigs
- easily removable insulation
- reducing the number of unnecessary observers

Other ideas require major modifications:

- low cobalt specifications for primary system components
- built-in ladders and platforms to replace temporary scaffolds
- monorails for repetitive lifting jobs
- additional fixed shielding
- separate rooms for pumps and valves
- improved control of water chemistry

Each participant took home more than 500 pages of material that was used as background data for the round table discussions. This can be selectively analyzed by various interested personnel to obtain specific data on:

- historic dose experience
- high-dose maintenance tasks
- steam generator maintenance
- refueling problems
- dose-reduction modifications

The recent research, as well as plant demonstrations, on steam generator and BWR primary system decontamination provoked lengthy discussions. The large percentage of time devoted to this topic is not surprising since the use of primary circuit decontamination with fuel in place has the future potential for being a highly effective dose-reduction technique.

The demonstration and exhibits on remote technology were not only informative but mind stretching. The use of improved sensing, transport systems, communications, artificial intelligence, and remote tooling has tremendous potential as a means of removing workers from high-radiation-exposure environments. This could be implemented, not in the distant future, but in the immediate future of next month or the next shutdown. We must start thinking today in terms of application of these technological changes for tomorrow.

It remains to be seen whether the participants really heard the message of ALARA applications from Canada, Finland, Switzerland, and Sweden. Many seemed to be startled by what they heard about not using outside contractors, different health physics practices, minimum radiation protection job coverage, and employee radiation protection training, as well as their low dose experience. Some seemed to discount these experiences as not applicable to working conditions and company policies in the U.S. Perhaps more analysis of what was presented and positive contemplation on possible application of lessons learned will result in bridging the assumed gap between the foreign programs and what is being done in the U.S. today.

There was essentially consensus that ALARA is a philosophy which is inherently difficult to apply. Compliance with the quarterly and annual dose limits is a relatively easy and straightforward procedure. But the ALARA concept must be gotten out of the procedural and paper-work stage into the work area by those who are doing the actual work in the radiation environment, namely, the maintenance, operational, construction, and HP staffs. The task of collective dose reduction is not just the responsibility of the HP group but demands the focus of attention of the designer, equipment suppliers, planners, operators, maintenance experts, and all levels of management, as well as the regulators.

Among the remaining problem areas were the following:

- A premium must be placed on acquired working skills and on keeping a stable plant staff. High maintenance staff turnover has distinct disadvantages.

- Prudent implementation of safety-related modifications and backfits should include site-specific value impact analyses, which take into account impacts on collective dose.

- Accelerated development is needed of BWR and PWR optimized chemistry specifications and of methods for primary system decontamination with fuel in place.

- Motivation techniques need to be refined to obtain increased worker and management support and commitment to ALARA goals.

- Labor union commitment is needed to reduce unnecessary worker dose.

3 Country Comparisons

In order to evaluate and understand reasons for country-to-country and plant-to-plant differences, data gathered have been plotted in several ways to illustrate the importance of different factors.

Figure 3-1 shows, for comparison, collective dose equivalent in man-rem/reactor/year for all plants in the United States, Japan, W. Germany, the Netherlands, Switzerland, Canada (Ontario Hydro), France, Sweden, the United Kingdom (C.E.G.B.), and Finland. U.S., Japanese, and W. German plants yield average collective doses about 2 to 10 times as high as those in the other countries. However, this gross comparison is insufficient for drawing conclusions since it does not properly reflect the influence of a number of important parameters such as type of reactor, output in MWe-yr, year of design or first commercial operation, and effective full-power years of operation.

Several countries in Figure 3-1 have both PWR (pressurized water reactor) and BWR (boiling water reactor) plants. However, the U.K. plants employ gas-cooled reactors, which produce much smaller quantities of activated corrosion products than do water-cooled ones. These corrosion products are major contributors to collective doses in most modern plants. The only U.S. gas-cooled plant (Fort St. Vrain in Colorado) has operated since 1974 at very low power levels (average to 1983 about 40 MWe compared with 330 MWe rating). Collective doses averaged only 2.5 man-rem/year during the period 1978-1982. This is low even when normalized by MWe generated.(3)

The Ontario Hydro plants use heavy water as coolant and differ considerably from light water reactors in plant design and operation. Results from these plants provide an interesting example of how dose reduction can be achieved if this is given a high priority in both design and operation, as described in more detail below.

Better comparisons of U.S. experience with that of other countries can be made by separating data from PWR and BWR plants and by normalizing dose data by power generated, i.e. expressing results in terms of collective dose equivalent (man-rem) per unit electricity generated (MWe-yr).

4 PWR Plant Comparisons, man-rem/MWe-yr

Figure 4-1 shows data on average collective dose equivalent for PWR plants for the period 1978-1982. Since smaller collective dose values are expected from a small plant than from a large plant, these data are expressed in terms of man-rem per MWe-yr of electricity generated by the plants. This ratio better reflects the relative efficiency of dose control. The results clearly show U.S. experience to be poor (1.2 man-rem/MWe-yr) relative to that of other countries, with France showing the best average (0.26 man-rem/MWe-yr).

To clarify the possible influence of plant vintage as a factor in these large differences, data on average collective dose were plotted vs. calendar year for specific countries and plants. Figure 4-2 shows man-rem per MWe-yr vs. calendar year (1970 to 1983) for PWR plants in the U.S.,(3) The Nether-

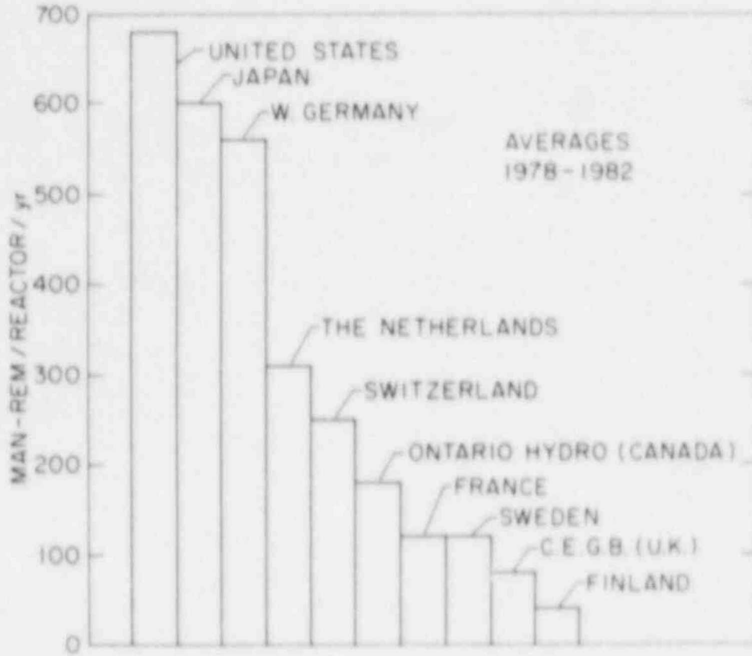

Figure 3-1
Collective dose equivalent per reactor per year,
5-year averages, 1978-1982

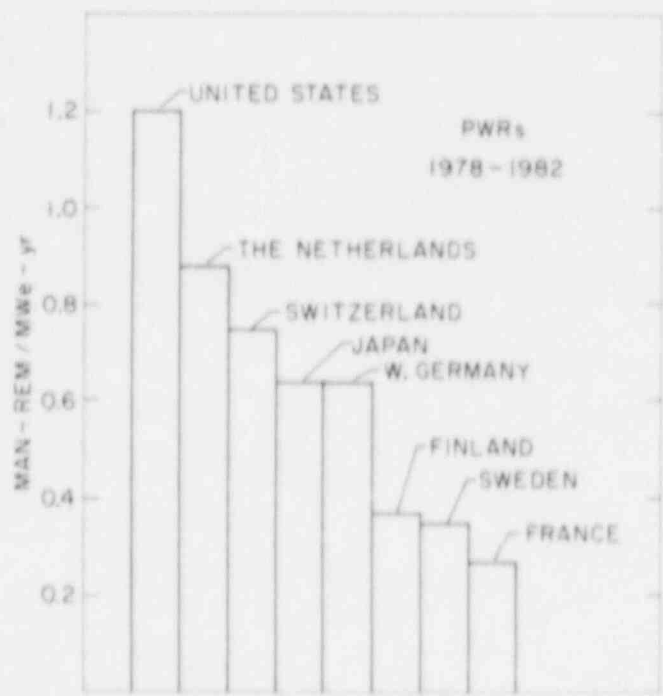

Figure 4-1
Collective dose equivalent per MWe-yr for PWR plants,
5-year averages, 1978-1982

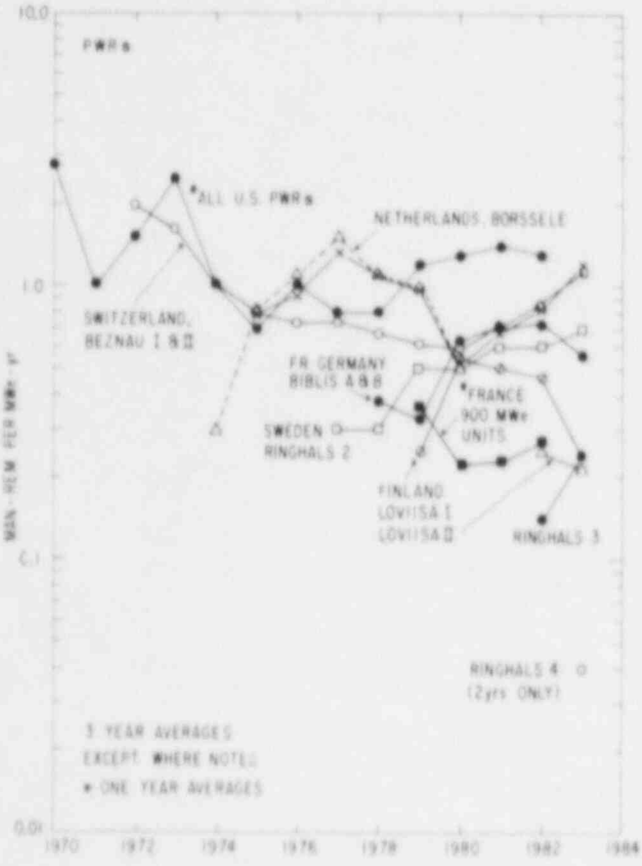

Figure 4-2
Collective dose equivalent per MWe-yr vs. calendar year for PWR plants

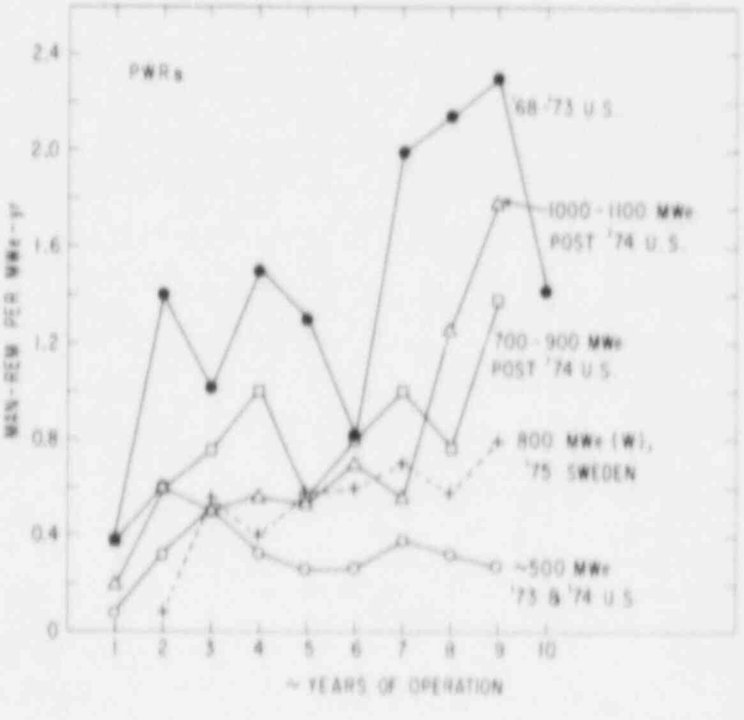

Figure 4-3
Collective dose equivalent per MWe-yr for selected PWR plants vs. approximate years of commercial operation

lands, Switzerland, Japan, W. Germany, Finland, Sweden, and France. For most, three-year averages were calculated and plotted to avoid large year-to-year variations due to refueling cycles, which are sometimes longer than one year. These data show that, for collective dose equivalent per MWe-yr, the average value for U.S. plants was among the highest, and the values for the most recent Swedish plants (Ringhals 3 and 4) were the lowest.

Reasons for differences are several: (a) The U.S. plants include older plants that are subject to more steam generator tube failures. (b) The French emphasize on standardization of plant design has two benefits: it makes worker training more effective because workers going from plant to plant find almost identical units; and it permits greater development and use of special tools such as multi-stud tensioner/detensioner equipment for reactor vessel heads, steam generator manway cover handling devices, automatic eddy current testing machines, and steam generator plugging machines. (c) The Swedish units were built with emphasis on design, shielding, plant layout, and careful control of primary system chemistry as well as use of automated equipment (as mentioned for the French plants). Segregation and individual shielding of highly active components keeps dose rates low during maintenance, and low contamination levels in working areas minimize the need for respiratory equipment and attendant loss of worker efficiency. (d) Operators of plants in Finland (Soviet designed plants) have achieved very low dose rates by carefully controlling primary water impurities, by avoiding high-cobalt stellite in primary systems, and by using larger steam generators, which have suffered relatively few tube failures, and which spread corrosion products over large surface areas.

In the Swedish data, note the progressive decreases in man-rem per MWe-yr as newer plants are brought on line, indicating successful incorporation of new design features, remote and automated tooling, and procedures to limit doses.

Projected doses for the proposed U.K. Sizewell "B" PWR plant include an average annual collective dose of 240 man-rem or 0.2 man-rem/MWe installed.(49) Assuming 67% average capacity factor, this would yield 0.3 man-rem/MWe generated.

For PWR comparisons, Figure 4-3 shows man-rem/MWe-yr vs. years of operation for U.S. plants of various sizes and ages and for Ringhals 2, the Swedish plant with the highest collective dose equivalent. U.S. plants, which went commercial in '68 to '73, show the highest average doses (0.38 to 2.3 man-rem/MWe-yr); the 500-MWe plants (Kewaunee and Prairie Island 1 and 2), commercial in '73 and '74, show the lowest (0.08 to 0.5 man-rem/MWe-yr); and larger U.S. plants and the Swedish plant are intermediate. The three plants with low doses had a total of only 29 steam generator tube defects (through 1980) or about one-third the average for post-'74 U.S. plants, whereas the pre-'74 U.S. plants experienced an average of 904 defects (through 1980). This confirms that the number of steam generator tube defects is a major determinant of collective dose, as is well known. However, Beaver Valley, Calvert Cliffs 1 and 2, Davis-Besse 1, and Zion 1 and 2 plants experienced no tube defects through 1980 yet had collective dose equivalents through 1980 of 1.0, 0.6, 0.24, and 0.6 man-rem/MWe-yr, respectively, showing that other factors are also important and can cause large variations from plant to plant. It is also of interest that the three 500-MWe PWR plants with low doses all had Fluor Power Services, Inc. as architect engineers (but no other U.S. plants did). For other U.S. plants of this approximate size the 5-year average collective dose equivalent per MWe-yr was 2.3 to 23 times as high during the 1978-1982 period, showing that plant size was not decisive.

5 BWR Plant Comparisons, man-rem/MWe-yr

Figure 5-1 shows man-rem/MWe-yr for BWR plants in Japan, the U.S.,(3) W. Germany, Switzerland, Sweden, and Finland. Japanese plants show the largest doses (2.2 man-rem/MWe-yr) and plants in Finland the lowest (0.08 man-rem/MWe-yr). The U.S. again shows rather poor experience, with 2.1 man-rem/MWe-yr. Data on collective dose equivalent per MWe-yr vs. calendar year for specific BWR plants and countries are given in Figure 5-2. Japanese data show an increase from 1.3 man-rem/MWe-yr in 1972 to about 5.1 man-rem/MWe-yr in 1977, followed by annual decreases to 2.1 man-rem/MW-yr in 1983. The Japanese experience reflects their emphasis on detailed and dose-intensive plant inspections and preventive maintenance activities during three-month annual shutdowns in earlier years. Many plants now tend to adopt a scheme of 13 months operation for each three months or less of outage.(48) U.S. data for all plants compared with data for plants that went commercial in the '74-'79 period suggest some reduction in average collective dose equivalent per MWe-yr. However, the improvement is small compared with the very impressive improvements shown by Swedish and Finnish BWR plants, which have shown progressive decreases: from about 0.8 man-rem/MWe-yr for the '75 Swedish plant (Ringhals 1) and about 0.25 man-rem/MWe-yr for the '71 and '75 plants (Oskarshamn 1 and 2), to about 0.15 man-rem/MWe-yr for the '75 and '77 plants (Barseback 1 and 2) and only 0.06 man-rem/MWe-yr for the '81 plants (Forsmark 1 and 2). The two Finnish plants that went commercial in '79 and '81 (TVO I and II) fit the general Swedish pattern of progressively lower doses for newer plants.

Both the Swedish and Finnish plants have reactor systems designed by ASEA-Atom, a Swedish steam supplier, which also acted as principal or contributing architect engineer on most of the plants. These plants have been designed with minimum cobalt content in primary system surfaces, very careful control over primary water impurities, and highly efficient reactor water purification systems. In general, to minimize introduction of corrosion products into the core, stainless steel with <0.05% cobalt or equivalent materialis used for parts in contact with water that flows toward the reactor core. Therefore, most reactor internals and water wetted surfaces in the primary system are made of stainless steel. Exceptions are minor parts such as springs, bolts, etc., which are made of nickel base alloys; and feedwater pipes outside the containment, feedwater heater housings, and end plates, which are made of carbon steel.(5)

Projected doses for U.S. BWR plants being designed are lower than doses for currently operating plants. Reduction by a factor of about two is expected from design improvements (e.g. improved feedwater spargers, better plant layout), and by another factor of about 1.7 from source reductions due to more stringent criteria for materials selection and more careful control of plant chemistry.(6)

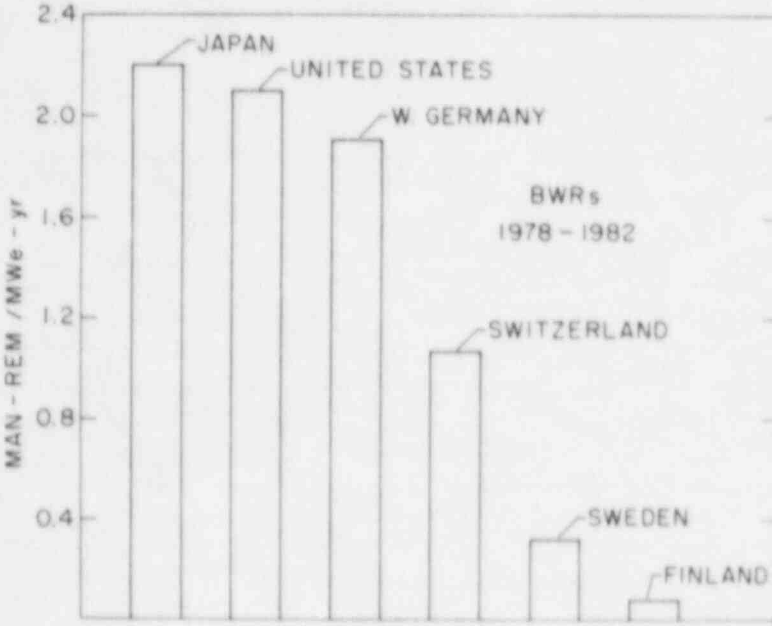

Figure 5-1

Collective dose equivalent per MWe-yr for BWR plants, 5 year averages, 1978-1982

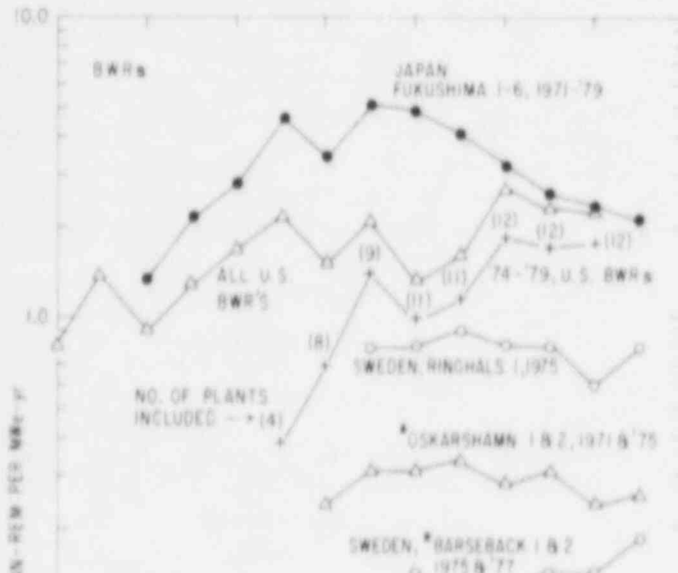

Figure 5-2 Collective dose equivalent per MWe-yr vs. calendar year for BWR plants

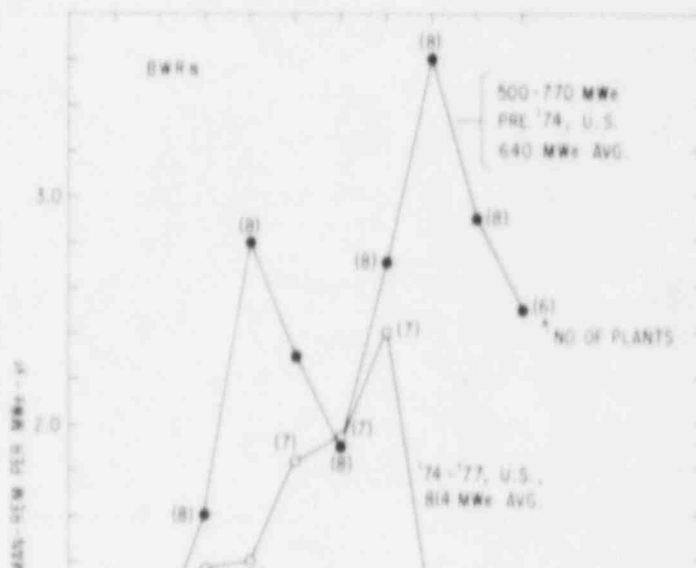

Figure 5-3 Collective dose equivalent per MWe-yr vs. approximate years of commercial operation for selected BWR plants

Data on collective dose equivalent vs. years of operation for selected BWR plants (Figure 5-3) show that pre-'74 U.S. plants had somewhat higher values for dose equivalent per MWe-yr than post-'74 plants. The trend for U.S. plants is generally upward for the first few years of operation, whereas both the Swedish and Finnish plants have leveled off in about two years. The increases in U.S. plants may reflect the larger contribution of cobalt-60 (with its several year build-up time constant). The Swedish success may have been influenced also by the goal of 0.2 man-rem/MWe installed capacity suggested by the Swedish National Institute of Radiation Protection about 10 years ago. This is equivalent to about 0.3 man-rem/MWe-yr generated, a very ambitious but apparently achievable goal.(7)

6 Dose vs. Plant Capacity and Number of Reactors per Site

Data on collective dose equivalent vs. MWe-yr (3) were evaluated for the years 1978-1982 for U.S. PWRs and BWRs. For PWRs the scatter in points (0.2 to 7.0) was large, indicating that any effect of capacity on collective dose equivalent was small compared with effects of other factors. The BWR data points were less scattered (0.9 to 7.4) and indicated a possible small decrease in collective dose equivalent per MWe-yr with plant size when small plants (47 to 64 MWe) were compared with those having a capacity >500 MWe, but, this finding has limited statistical significance because of the limited number of small plants.

Comparisons of average collective dose equivalent per MWe-yr for sites with one, two or three reactors per site revealed no significant differences between one-reactor and two-reactor sites. The values 0.8 man-rem/MWe-yr for the only 3-reactor PWR site and 0.9 man-rem/MWe-yr for the only 3-reactor BWR site were well below the averages for one- and two-reactor sites. Although the data base is limited (i.e. two sites), these results may reflect the greater effectiveness of planning, training, and management at large facilities. This may also be a factor in the excellent experience at French PWR sites since two-thirds of their reactors are at sites with 3, 4, or 5 reactors. On the other hand, the Japanese site with 6 BWRs (see Figure 5-2) shows a poor record. Thus, multiple reactors per site is probably an important factor but, like other factors, not sufficient in itself to assure low collective dose equivalent results.

7 Ontario Hydro Experience(2)

Ontario Hydro employs pressurized heavy water reactors (HPWRs). Large collective doses received at their Douglas Point Nuclear Generating Station during 1967 to 1969 led to a major commitment by senior management in 1970 to improve dose control during both design and operation. They emphasized elimination of stellite (high cobalt content) alloys, addition of shielding, improvements in water purification systems and in ventilation and air-drying systems (for airborne tritium control), and improved reliability and maintainability. The results are remarkable, as seen in Figure 7-1. Collective dose equivalent per MWe-yr values were reduced from about 38 mSv (3.8 man-rem) in 1972 to about 3 mSv (0.3 man-rem) in 1981. During this same period U.S. values at light water reactors fluctuated between 10 and 20 mSv/MWe-/yr (1 and 2 man-rem/MWe-yr) with no apparent long-term improvement.

An important aspect of the Ontario Hydro approach is the use of highly trained station workers for a major portion of all work. The number of workers per reactor has gone down from about 600 in 1970 to about 300 in 1982. During the same period in the U.S., the number of workers per reactor has increased from about 300 to about 1100. Station personnel now receive about 80% of the collective dose in Ontario Hydro plants compared with about 20% in U.S. plants. This difference in workforce complement is believed to be an important element in the Canadian success.

8 Factors Affecting Dose

From the data evaluated to date it is clear that plants in the U.S. have higher collective dose equivalents per reactor and per MWe-yr generated than plants in most other countries. Important factors affecting dose at nuclear power plants were identified in the workshop and in earlier studies by Catalytic, Inc.(8) The results of one study, indicated that pH control (PWRs) and feedwater purity controls (BWRs), material control to minimize cobalt and nickel in primary systems, high temperature filtration, and dilute chemical decontamination of primary systems each had potential for reducing annual collective doses by >50%; that remote surveillance and diagnostics had significant potential (though <50%); and that robotics had somewhat more than 50% potential but would require long-term development. These and other items, which have been identified in this work, are listed in Table 8-1, each with an estimated weighting factor, based on the authors' judgement, which is the expected ratio of collective dose in plants with poor control over the item to that in plants with good control. This weighting is, of course, crude and subjective. Further information on each item can be found in the references, especially in recent publications of the BNL ALARA Center.(9-12)

Probably of greatest importance is adequate maintenance of chemistry controls in both primary and secondary water since this affects corrosion product formation, transport, and deposition and is a major factor in avoiding steam generator tube failures in PWRs and major pipe cracking problems in BWRs, (13-26) which are major contributors to very large collective doses in each type of plant. Similarly, optimum design and operation of primary and secondary water purification (filtration) systems is very important since removal of activated corrosion products before deposition is essential to keeping dose rates and related collective doses low.(13-26) Weighting factors of 1.7 and 1.6, respectively, were assigned to chemistry control and purification. Materials selection (minimum cobalt and nickel, and use of stainless steel primary piping to minimize corrosion and deposition) was also given a weighting of 1.6.(27-32) Decontamination of primary systems and components, (8,33-44) and use of special tools, robotics, and remote surveillance (12,18) were each weighted at 1.5. Recent studies by S. Cohen and Associates (45) indicates that NRC-initiated multi-plant actions accounted for 40% of typical plant doses during the five-year period 1979-1983; on the assumption that some other countries had many fewer mandated actions, this item was estimated to account for a weighting factor of 1.4, at most. Items given a weighting factor of 1.3 were worker motivation and commitment, permanent vs. transient work force, management commitment, three or more reactors per site, and design for reliability.(46) Passivation of primary systems,(18) quality assurance during design, construction and operation,(47) standardized plant design, and extra shielding and segregation of highly active components (46) were weighted at 1.2.

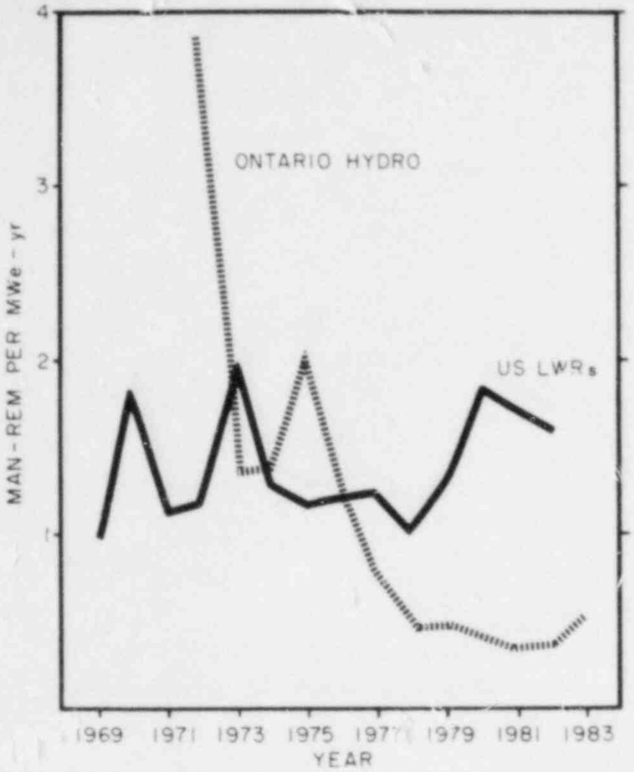

Figure 7-1

Collective dose equivalent per MWe-yr vs. calendar year for Ontario Hydro PHWR plants and U.S. light water plants

Table 8-1 Important Factors Affecting Dose at Nuclear Power Plants

	Estimated Weight
• Primary and (for PWRs) secondary system chemistry (pH, O_2, conductivity, Fe,Cl)................................	1.7
• Optimum design and operation of primary and (for PWRs) secondary water purification systems.........................	1.6
• Minimize cobalt and nickel in primary system, use SS piping.....	1.6
• Use of special tools, robotics, and remote surveillance.........	1.5
• Decontamination of primary systems and components...............	1.5
• Multi-plant actions required by regulatory agencies.............	1.4
• Worker motivation and commitment................................	1.3
• Permanent vs. transient work force..............................	1.3
• Management commitment and organization for dose control.........	1.3
• Three or more reactors per site.................................	1.3
• Design for reliability..	1.3
• Passivation...	1.2
• Quality assurance during design, construction, and operation....	1.2
• Standardized plant design.......................................	1.2
• Shielding and segregation of highly active components...........	1.2
Product =	106

The product of the 15 weighting factors listed in Table 8-1 is about 106. Thus, if each item operates independently, differences as large as a factor of 106 could be expected between collective doses in plants with good control over all items and in those with poor control. Since some items are probably correlated (e.g. three or more reactors per site; plant standardization; good quality assurance during design, construction and operation; and permanent vs. transient work force), somewhat smaller differences would be expected. Also, any plant or country is unlikely to be deficient in every item. Considering this list of significant variables, it is not surprising to find collective doses in various plants and countries differing by an order of magnitude (factor of 10). Nor is it surprising that it is difficult to find clear correlations indicating high importance of any one factor since to do so would require careful control of, or accounting for, all the 14 other factors.

9 Conclusions

Based on the data discussed above, the conclusion is that occupational exposures are higher, on average, at U.S. nuclear power plants than at plants in the other industrialized countries for which data were available. Exposures are higher in the U.S. (a) for both PWR and BWR plants, (b) when expressed as collective dose per plant per year, (c) when normalized by MWe generated, (d) when compared as a function of years of plant operation, and (e) when compared by age of plant or year of first commercial operation.

No single factor is responsible for the large differences between plants or between countries. About 15 factors are considered important, with several contributing as much as 50% to differences. Some of the additional occupational exposure is attributable to multi-plant actions required by the NRC. This exposure is presumably justified by the added public and worker safety the actions are intended to provide. Additional cost-benefit studies are needed to evaluate the optimum balance between occupational exposures and accident probabilities and consequences, and to determine the cost effectiveness of improvements in the other factors contributing to differences.

High doses occur primarily during outages, and critical-path time is frequently extended because of needs for radiation protection and contamination control. Many improvements are being implemented which reduce both costs (e.g. through labor or critical-path time savings) and collective doses.(12) Attention to all 15 factors listed in Table 8-1 will be required to ensure that doses are as low as reasonably achievable (ALARA) at U.S. nuclear power plants.

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NRC FORM 335 (2-84) NRCM 1102, 3201, 3202 — U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)	NUREG/CR-4381 BNL-NUREG-51918
2. TITLE AND SUBTITLE	Summary of Comparative Assessment of U.S. and Foreign Nuclear Power Plant Dose Experience
3. LEAVE BLANK	
4. DATE REPORT COMPLETED (MONTH / YEAR)	August 1985
5. AUTHOR(S)	John W. Baum and John R. Horan
6. DATE REPORT ISSUED (MONTH / YEAR)	October 1985
7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)	Safety and Environmental Protection Division Building 535 A Brookhaven National Laboratory Upton, New York 11973
8. PROJECT/TASK/WORK UNIT NUMBER	
9. FIN OR GRANT NUMBER	A-3264
10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)	Division of Radiation Programs and Earth Sciences Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, DC 20555
11a. TYPE OF REPORT	Formal
b. PERIOD COVERED (Inclusive dates)	September 1983-October 1985
12. SUPPLEMENTARY NOTES	

13. ABSTRACT (200 words or less)

Data gathered at the 1984 BNL Workshop on Historical Dose Experience and Dose Reduction (ALARA) at Nuclear Power Plants and from recently published literature were reviewed and analyzed. Large differences were noted, between countries and between similar plants, for collective dose (man-rem) per plant and per unit of electricity generated (MWe-yr). During the period 1978-1982, for PWRs, the U.S. ranked highest in terms of collective dose per MWe-yr (1.2), and France, Sweden, and Finland were lowest (0.27-0.37). For BWRs, Japan, the U.S., and the Federal Republic of Germany ranked highest (2.2-[illegible]9), and Finland and Sweden were lowest (0.08-0.32). Only a small portion of the differences could be attributed to average plant age, vintage, or rated capacity.

Fifteen factors were identified (in addition to age) which contribute to differences. In estimated order of importance, these were plant chemistry, water purification, materials selection for low cobalt and nickel, special tools, decontamination of primary systems, required multi-plant actions, worker motivation and commitment, permanent work force, management commitment to dose control, three or more reactors per site, design for reliability, passivation of primary systems, quality assurance, standardized plant design, and shielding.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS	Radiation Protection, Nuclear Power Plants, ALARA, Remote Handling Equipment, Occupational Safety, Radiation Doses
b. IDENTIFIERS/OPEN-ENDED TERMS	Dose Reduction
15. AVAILABILITY STATEMENT	Unlimited
16. SECURITY CLASSIFICATION (This page)	Unclassified
(This report)	Unclassified
17. NUMBER OF PAGES	
18. PRICE	

120555078877 1 1AN
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555