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Dose Reduction and Optimization Studies (ALARA) at Nuclear Power Facilities

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Introduction

Brookhaven National Laboratory (BNL) has been commissioned by the Nuclear Regulatory Commission (NRC) to study dose-reduction techniques and effectiveness of as low as reasonably achievable (ALARA) planning at LWR plants. These studies have the following objectives:

- Identify High-Dose Maintenance Tasks
- Identify Dose-Reduction Techniques
- Examine Incentives for Dose Reduction
- Evaluate Cost-Effectiveness and Optimization of Dose-Reduction Techniques
- Compile an ALARA Handbook on Data, Engineering Modifications, Cost-Effectiveness Calculations, and Other Information of Interest to ALARA Practioners

High-Dose Maintenance Tasks

A review of the available literature reveals that a detailed analysis of data on nuclear power plant doses as a function of specific jobs was reported in 1974 by Pelletier et al. in a study done for the Atomic Industrial Forum (1). At that time few plants had computerized data bases on task and job specific doses, however, by utilizing information on radiation work permits and in other plant records they were able to identify a number of the high-dose maintenance jobs. Those identified with doses greater than one person-rem are listed in order of decreasing dose in Table 1. For many jobs, data is based on a single plant and, therefore, may not be representative. While one expects wide variations in dose depending on time since start-up, the data reported by Pelletier (1) did not show a good correlation with time since start-up. Therefore, for those jobs for which data was available from more than one plant, an average was calculated. The number of plants used to calculate these averages is shown in the first data column in Table 1. Further study is needed to determine the specific tasks performed during accumulation of these job-related doses. A more recent and more detailed study on doses for specific jobs, and related to specific components and systems was done by Warwan et al. (2) for EPRI. Typical data from this study is shown in Tables 2 and 3 for jobs exceeding 5 man-rem at a BWR and PWR plant, respectively. For the PWR plants, data are given for four refueling cycles. Total doses for items listed for the four cycles were 61, 268, 322, and 434 man-rem, respectively. Thus, the well-known early increase in dose and tendency to level off with time is apparent.

Dose-Reduction Techniques

Two studies of importance in terms of dose-reduction techniques are the AIF/NESP study on design features (3) and the AIF report on engineering techniques and modifications (4). The former report includes information on 119 subjects. It does not include cost information nor does it serve as a complete checklist during plant design. However, it does provide a useful summary of features which should be considered.

*This investigation was supported by Nuclear Regulatory Commission contracts A-2708 and A-3259 to the Safety and Environmental Protection Division, Brookhaven National Laboratory.

The AIF report on engineering techniques does include some cost information, but total costs and benefits achievable are plant specific, therefore, appropriate cost-effectiveness calculations are not possible without further study.

The data contained in the AIF assessment is summarized in order of decreasing cost per man-rem saved in Tables 4 and 5 for PWR and BWR reactors, respectively. These costs do not include health-effect costs nor costs or savings due to changes in critical-path times. The costs may also not adequately reflect savings due to reduced work times and reduced crew changes in future years. Since critical-path costs and reduced workers savings in the cost/benefit equations are generally as important or more important than health-effects costs, it is essential to evaluate them.

On the other hand, the results tabulated illustrate that for some modifications the cost per man-rem saved is less than the usually employed health-effects value of $1000 per man-rem. This means that these modifications are likely to be cost-effective provided critical-path time is not increased and even if no savings in future work or crew changes are caused.

Other hardware and procedural changes which are being considered are those listed in the Westinghouse Electric 1980 edition of their Nuclear Digest. These modifications and likely dose reductions are shown in Table 6. Costs typically associated with installation of these modifications will be evaluated and results obtained will be included in our future work.

Incentives for Dose Reduction

As health physicists we have strong incentives for reducing exposures since this is so basic to our profession. However, operators of an electric generating plant have very powerful monetary incentives which at times are in competition with dose-reduction objectives.

Incentives which may aid in achieving dose reduction include:

- Monetary, resulting from related reduction in critical-path time, smaller required work forces, etc.
- Desire for improved personnel relations which results from worker recognition that plant management is concerned with worker health and safety
- Desire for reduced NRC surveillance and reporting
- Minimizing insurance costs
- Good public relations
- Goals, such as annual reduction in dose per plant or per unit power generated

Available data on these and other incentives will be gathered and analyzed for effectiveness.

Cost-Effectiveness and Optimization Studies

Questions of cost-effectiveness of dose-reduction techniques have been considered by a number of groups and authors (5-9). The ICRP document (5) illustrates the concept of optimization which is the final objective in an ALARA program.

In general, costs of protection <u>increase</u> markedly as doses are reduced to very low values. Simultaneously, health effects costs <u>decrease</u> as dose is reduced. The total cost curve, thus, has a minimum at some intermediate dose point as shown on Figure 1. This minimum represents the optimum with respect to readily assessed costs. Of course, other factors may influence the dose point which is judged best by plant management. For example, if the total cost curve has a small slope left of its minimum, it may be decided that additional benefits not easily quantified--such as good personnel, NRC or public relations--justify expenditures to keep doses even lower than those predicted at the minimum.

In optimization studies, one usually deals with marginal (differential) costs. This means one need not evaluate all costs and all benefits to justify a modification. It is assumed that the system is near optimum with respect to overall costs and benefits (for example, relative to competing methods of electricity generation), and the marginal effects of a proposed modification is then evaluated based on all the known costs and benefits which are affected.

Another convenient way of plotting data is shown on Figure 2, taken from the BEIR II report (6). Here marginal costs and marginal benefits are depicted vs. dose. The point at which the marginal cost curve crosses the marginal benefit curve is the optimum. Uncertainties in both cause uncertainty in the optimum. Here again, if costs do not increase too rapidly with decreasing dose, one is inclined to select the lowest dose crossover point (D_5 rather than D_6).

In making cost-effectiveness calculations, it is important to include all relevant and quantifiable costs and benefits before drawing firm conclusions. Careful consideration must be given to large cost factors such as plant outage and effects on hiring needs as a function of worker doses. When this is done, the value used for health effects costs is added to other costs.

Some plants use a dollar per man-rem value which is based on the cost of hiring a worker @ $25,000/yr divided by the permissible dose 5 rem/yr, or $5,000/man-rem (7). This value does not include health effects costs but is only an estimate of costs which will be incurred by increased worker needs.

An important parameter in a typical evaluation is the present worth factor, i_f, or annuity factor which depends upon interest rates and amortization times. This factor is given by:

$$i_f = \frac{(1+i)^n - 1}{i(1+i)^n}$$

where n is the number of years over which costs are amortized and i is assumed interest rate (usually the current rate of borrowing money). For a typical 30 year amortization at 12%, the present worth factor is 8.06.

The product of the present worth factor, the dollar value per man-rem saved, and the man-rem per year saved gives the justifiable cost of capital investment at time zero. Thus, at $5,000 per man-rem, an investment of 8.06 x $5,000 = $40,300 per man-rem per year saved is justified using the 12% interest rate and 30 year amortization period. Note that this is considerably less than one would estimate using 1 rem/yr saved times 30 years and evaluated at $5,000 per man-rem (i.e., 1 x 30 x $5,000 = $150,000 not $40,300). The difference is, of course, due to the added cost of borrowing money.

More detailed evaluations of costs and benefits are suggested by Pelletier et al. (8). Their methods involve considerations of:

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More detailed evaluations of costs and benefits are suggested by Pelletier et al. (8). Their methods involve considerations of:

- Plant outages
- Wages paid plant workers
- Fringe benefits for plant employees
- Hourly rates for outside workers
- Certification costs for outside workers
- Training time for outside workers
- Personnel dosimetry costs
- Bioassay costs
- Mock-up training costs
- Continuous on-the-job time
- Ingress/egress, job status, briefing, and orientation times
- Suit-up and clean-up times
- Administrative dose limits
- Dose utilization factors

Using Pelletier's methods one arrives at detailed cost estimates. If this detail is available, one may be able to do optimization calculations using iterative computer techniques and optimizing each element in the cost function.

Hall et al. (9) have developed an analysis technique which employs an index (apparent reduction potential) to prioritize potential exposure reduction projects and an achievability index which is based on cost/benefit analyses.

Cost-effectiveness methods of analysis are in an early stage of development in radiation protection as illustrated by the above. It should be helpful to assemble a number of examples of methods used successfully in the decision making process and begin sorting out methods most useful at different levels of application, e.g., plant design, retrofitting, plant operation, etc.

ALARA Handbook

As information is gathered on this project, we are considering the development of a loose-leaf notebook type handbook which could conveniently be updated as needed. The types of information we hope to obtain may be organized into the following sections:

- Data on high-dose maintenance tasks
- Data on dose-reduction techniques
- Examples of cost-effectiveness calculations
- Data on high reliability components
- Information on robatics
- Names and addresses of ALARA engineers and health physicists
- ALARA references

Contributions to the ALARA Handbook will be solicited and authorship or source will be acknowledged. Contributors would, of course, be on the mailing list for the Handbook and its updates. By this mechanism we hope to aid in documenting the growing body of ALARA knowledge and techniques, and facilitate exchange of useful information which will make the process even more effective.

For further information or to give us your suggestions we welcome your calls (516-282-4214) or letters. Your suggestions and cooperation are greatly appreciated.

References

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2. E. A. Warman et al., Occupational radiation exposure reduction technology planning study, EPRI NP-1862, Technical planning study TPS 7961 (1981).

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5. International Commission on Radiological Protection Publication 22, Implications of commission recommendations that doses be kept as low as readily achievable, a report by Committee 4 (1973).

6. Considerations of health benefit-cost analysis for activities involving ionizing radiation exposure and alternatives, EPA 520/4-77-003. A report of Advisory Committee on the Biological Effects of Ionizing Radiations (1977).

7. R. C. Rodgers et al., Cost benefit analysis for occupational exposure. Presented at Health Physics Society Annual Meeting, Minneapolis, Minnesota, June 18-23, 1978.

8. C. A. Pelletier and P. G. Voillequé, Potential benefits of reducing occupation radiation exposure, AIF/NESP-0101R. Prepared for The Atomic Industrial Forum, Inc. (1979).

9. T. M. Hall et al., Determining effectiveness of ALARA design and operational features, NUREG/CR-0446, UNI-TR-3 RH (1979).

Table 1. High Dose Maintenance Tasks.*

Job Description	No. of Plants In Average	Average Exposure (man-rem)
Work on pressurizer	4	16.7
Torus Modification	3	14.6
Install & remove shield plugs	1	11.9
Inspect jet pumps	1	11.8
Clean-up in containment	2	11.7
Routine Auxiliary and Intermediate building inspection and operation	1	9.1
Work on residual heat removal system (including 6.3 man rem for valve work)	1	8.2
Work on residual heat removal system	2	7.7
Main Steam Flow Restriction Nozzle Repair	1	6.5
High Pressure Coolant Injector Nozzle Repair	1	6.2
Core Components, Work Inside Reactor Vessel	5	5.5
Guillotine Shields	3	4.9
Work on pressurizer relief valves	1	4.4
Work on chemical volume control system	2	4.4
Seal water system maintenance work	1	4.2
Safety Injection System (Including Low Pressure Safety Injector)	1	3.6
Containment Leak Testing	1	3.6

*Data from C. A. Pelletier, et al, 1974. (Ref. 1)

Table 2

BWR Plant B Summary of Doses Recorded Where Specific Job/Component/System Exceed 5 Man-Rem *

Job Description	Component Description	System	Man-Rem
Clean, Grind & Test	CRD Return Nozzles	Nuclear Boiler System	59
Insulation and Welds	Drywell	Undefined	45
Wiring	ACAD/CAM	Nuclear Boiler System	39
Rebuild	Spare CRDs	CRD Hydraulic	19
Repair	Valve-1201-72	RWCU Filter Demin.	17
Cleanup	Drywell & Refueling Flow	Undefined	16
Remove and Replace	CRDs	CRD Hydraulic	16
Inspect and Replace	Receive Pump Seal	Recirculation	14
Repair	Valve-1201-43	RWCU Filter Demon.	11
Repair	Condensate Pump	Reactor Protection System	10
Inspect and Repair	Snubbers	Undefined	9
Remove and Replace	Aux. Cleanup Pump	RWCU Filter Demin.	8
Replace Light Glass	"B" Receive Pump	Recirculation	8
Remove	CRD Return Nozzle Sleeve	Nuclear Boiler System	6
Inspection	Torus Area	Undefined	6
TOTAL			283
Overall Total			460
% of Overall Total			62%

*Data from Warman, et al, 1981. (Ref. 3)

Table 3

PWR Plant C Refueling Doses
By Job Description *

Job Function	Total Dose (Man-Rem) 1st Refueling	2nd Refueling	3rd Refueling	4th Refueling	Average
Steam Generator Work	-	-	92	183	138
General Entry and Miscellaneous Work	8	88	46	36	44
Reactor Vessel Head Removal and Replacement	32	42	28	20	31
Eddy Current Testing Steam Generator Tubes	-	28	26	26	27
Defueling/Refueling Operations	14	32	16	16	20
NSM Work	-	-	14	25	20
Inservice Inspection	-	11	20	25	19
Reactor Vessel Head Work on Storage Stand	8	8	3	51	18
Valve Repair or Replacement	-	27	26	20	18
Reactor Coolant Pump Seal and Motor Repair	-	22	19	8	16
Letdown Cooler Replacement	-	-	10	8	9
General Cleanup and Decontamination	-	8	6	10	8
Incore Instrument Work	-	1	16	6	8
Specimen Work	-	1	-	-	1
TOTAL	61	268	322	434	

*Data from E. Warman, et al, 1981. (Ref. 3)

Table 4 - Summary of Engineering Modifications for BWR's *

BWR Tasks	Engineering Modifications	Estimated Annualized Cost ($)	Net Annual Man-rem Saved	Cost ($) Per man-rem Saved
Routine Visual Inspection	Install viewing windows in various areas of plant (5 windows)	1,000	7.5	130
General Maintenance	Scram discharge line modifications; cut holes in header to allow hydrolazing	800	5	160
Recirculation Pump Maintenance	Supply clean water to recirculating pump seals	5,000	20	250
Control Rod Drive Maintenance	Install electropolishing tank & electropolish the spud end of the CRD	8,000	10	800
Condenser Tube Maintenance	Improve helium leak detection	5,000	6	830
Refueling & Inspection	Locate fuel sipping cans near reactor cavity	1,000	1	1,000
Control Rod Drive Maintenance	Provide shielded water filled tank for disassembly & initial decontamination	7,000	6	1,200
Inservice Inspection--Primary System	Provide clearly identified & easily replaced section of insulation above weld	20,000	13	1,600
Inservice Inspection--Primary System	Install acoustic emission instrumentation on the vessel & primary coolant loop	90,000	43	2,100
Control Rod Drive Removal	Install semi-remote device for removing & replacing CRD's	65,000	31	2,100
General Maintenance	Improve working conditions, communications and radiation monitoring	11,000	5	2,200
RWCP Maintenance	Provide expansion loops and cooled seal water for RWCU pumps	20,000	7	2,900
Recirculating Pump Maintenance	Install permanent work platform around the pumps	6,000	2	3,000
Recirculating Pump Maintenance	Provide remote motor oil sampling and replacement capability	5,000	1.5	3,300

Table 4 - Summary of Engineering Modificatins for BWR's (cont'd.)

BWR Tasks	Engineering Modifications	Estimated Annualized Cost ($)	Net Annual Man-rem Saved	Cost ($) Per man-rem Saved
Safety Relief Valve Maintenance	Install a permanent hoisting device in drywell to remove and replace safety relief valves	5,000	1.5	3,300
Solid Waste Handling	Provide shielded fork-lift truck	12,000	3	4,000
TIP Repair Work	Provide remote cable cutting and disposal tools for TIP repair	10,000	2	5,000
MSIV Maintenance	Install a leakage control system	100,000	20	5,000
Primary Source Term Reduction	Magnetic filter in feed water	1,400,000	194	7,200
Refueling & Inspection	Use automatic sampling system for sipping fuel elements	30,000	4	7,500
Primary Source Term Reduction	High temperature filter in reactor coolant loop	750,000	97	7,700
Reactor Water Cleanup--Pump Maintenance	Reroute RWCU suction piping to downstream of heat exchanger	72,000	8	9,000
Reactor Vessel Open/Close--Stud Tension, Detensioning & Stud Removal	Provide remotely operated device	100,000	11	9,100
Snubber Inspection and Maintenance	Replace the hydraulic snubbers in drywell with mechanical snubbers	300,000	22	13,600
Solid Waste Handling	Install remote handling equipment	100,000	5	20,000
MSIV Maintenance	Replace y-pattern globe valve MSIV's with ball valves	800,000	18	44,000
Reactor Cavity Cleanup	Develop remote cleaning equipment	200,000	3	67,000
Radwaste Evap. Maintenance	Install multi-skid integral shielded units from improved material	400,000	5	80,000
Refueling & Inspection	Utilize improved BWR-6 refueling platform	300,000	1.8	167,000
MSIV Maintenance	Develop and apply automated lapping tools	700,000	4	175,000

*Data from report by AIF, Subcommittee on Engineering Techniques for Reducing Occupational Exposures, 1980. (Ref. 4)

Table 5 - Summary of Engineering Modifications for PWR's *

PWR Tasks	Engineering Modifications	Estimated Annualized Cost ($)	Net Annual Man-rem Saved	Cost ($) Per man-rem Saved
Steam Generator Maintenance and Tube Plugging	Develop integrated portable shielding system	10,000	50	200
Steam Generator--Eddy Current Testing	Develop equipment to remotely install & remove the test devices	23,000	18	1,300
Steam Generator--Eddy Current Testing	Use method of completely remote installation & removal of "finger walker"	34,000	15	2,200
General Maintenance	Improve working conditions, communications and radiation monitoring	11,000	5	2,200
Steam Generator--Primary Head Access	Manway tensioning and handling device requiring only one operation	12,000	4	3,000
Primary Source Term Reduction	High temperature, coolant filter	750,000	225	3,300
Solid Waste Handling	Provide shielded fork-lift truck	12,000	3	4,000
Steam Generator Maintenance and Tube Plugging	Develop better tools & equipment for semi-remote inspection & plugging	100,000	20	5,000
Filter Cartridge Replacement	Install additional shielding plus use remote tools for opening & removing filter cartridge	30,000	6	5,000
Reactor Cavity Water Cleanup	Use high flow (250 gpm) clean-up system on skid mount	10,000	2	5,000
Steam Generator Maintenance and Tube Plugging	Develop fully remote equipment for tube plugging & automatic welding	680,000	90	7,500
Reactor Vessel Open/Close--Study Tension, Detensioning & Stud Removal	Provide remotely operated device	100,000	11	9,100
Primary Valve Maintenance	Perform a valve evaluation study	150,000	10	15,000
Residual Heat Removal Pump Maintenance	Use pumps with split couplings as replacement RHR pumps	70,000	4	17,500

Table 5 - Summary of Engineering Modifications for PWR's (cont'd.)

PWR Tasks	Engineering Modifications	Estimated Annualized Cost ($)	Net Annual Man-rem Saved	Cost ($) Per man-rem Saved
Solid Waste Handling	Install remote handling	100,000	5	20,000
Incore & Primary Instrumentation	Water vacuum incore detectors during withdrawal	25,000	1	25,000
Reactor Vessel Open/Close	Several separate improvements to handling equipment, tool design, personnel access, etc.	160,000	4	40,000
Reactor Vessel Open/Close	Replace head system with integrated design that combines lifting rig, seismic platform & cooling system, etc.	580,000	14	41,000
Filter Cartridge Replacement	Replace existing system with remotely operated back flushable filters	800,000	12	67,000
Reactor Cavity Cleanup	Develop remote cleaning equipment	200,000	3	67,000
Reactor Cavity Water Cleanup	Use high flow (600 gpm) cleanup system on skid mount	140,000	2	70,000
Radwaste Evap. Maintenance	Install multi-skid integral shielded units from improved material	400,000	5	80,000
Refueling Operations--Movement of Core Components & Fuel	Automated, higher speed refueling machine with improved fuel assembly gripper, automatic movement of bridge	250,000	2	125,000
Inservice Inspection Primary System--Containment Piping	Develop & implement automated inspection equipment	520,000	2	260,000
Reactor Coolant Pump Seal Maintenance	More efficient seal replacement system plus improved seal design	800,000	4	200,000

*Data from report by AIF Subcommittee on Engineering Techniques for Reducing Occupational Exposures, 1980. (Ref. 4)

Table 6 - Hardware and Procedural Techniques to Reduce Radiation Exposure in Nuclear Plants *

Item	Forward Fit	Backfit	Annual Man-rem Savings
Thermocouple Column Seal Clamp Redesign	•	•	2
Reactor Vessel Flange Cleanup Method	•	•	4
Reactor Vessel Head O-Ring Spring Clip	•	•	2
Permanent Reactor Cavity Seal Ring	•		3
Reactor Coolant Pump Seals Maintenance System	•	•	8
Optimized Valve Packing	•	•	10
Reactor Cavity Wall Cleanup System	•	•	1
Reactor Vessel Headstand Modification	•	•	1
S/G Primary Manway Cover Handling Fixture	•	•	4
Stud Spin-out Tool	•	•	6
Reactor Vessel Stud Tensioning/Detensioning Procedure	•	•	5
Integrated Reactor Vessel Head Package		•	5
Control Rod Change Fixture--Drive and Control System Upgrade	•	•	2
Reactor Coolant Pump Electrical Quick Disconnects	•	•	1
Control Rod Drive Mechanism Quick Disconnect Panel	•	•	2
Upper Head Electrical Test Box	•	•	1
Fuel Transfer Tube Quick Acting Hatch	•	•	4

*Data from Westinghouse Electric 1980 Edition of Nuclear Energy Digest.

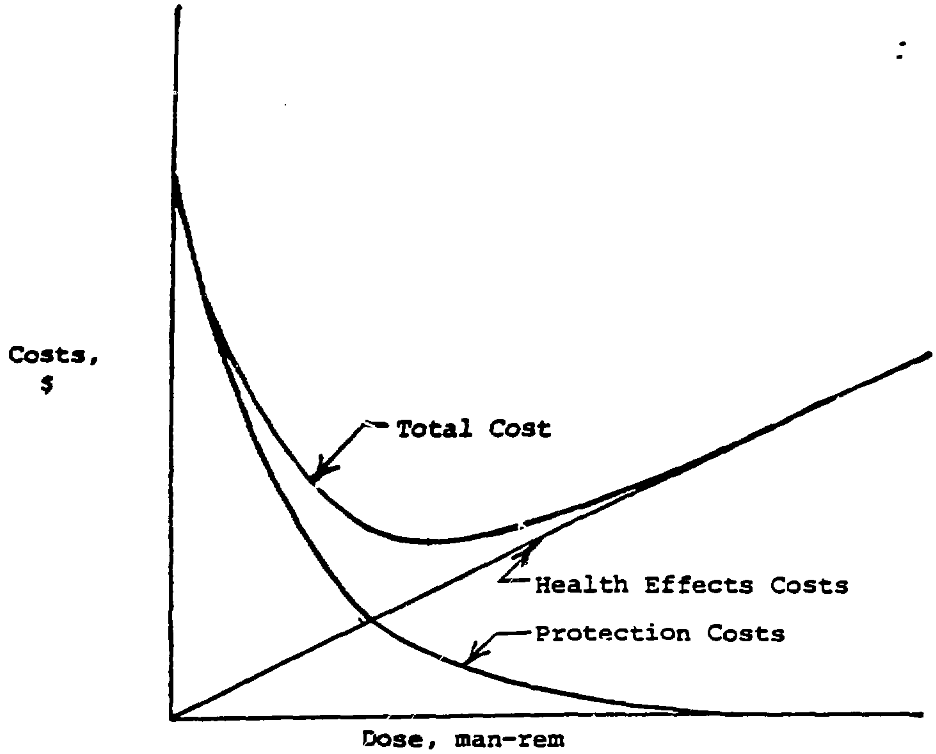

Figure 1 - Costs vs. Dose

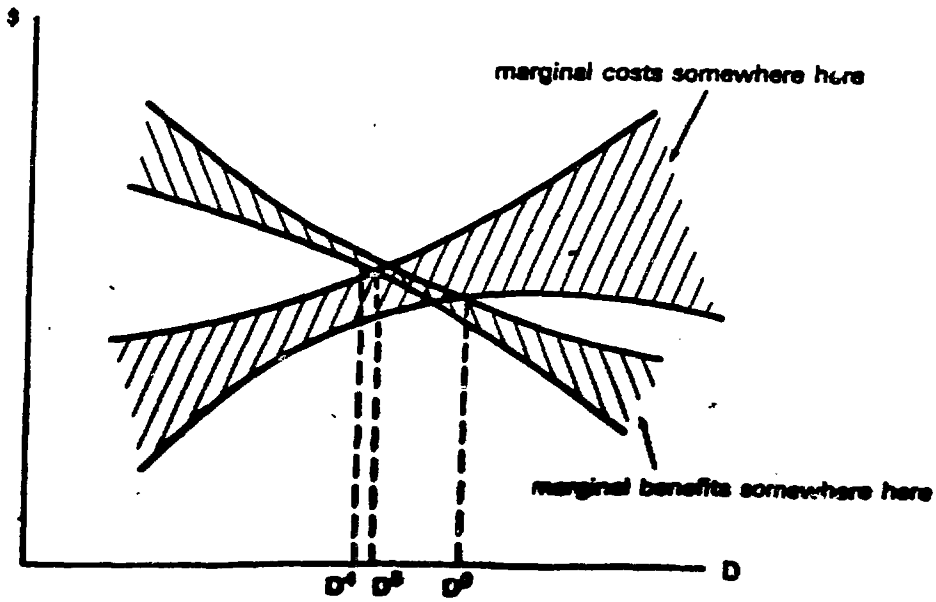

Figure 2. Costs vs. Dose*

*From BEIR II Report, 1977.