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MEASURED RADIATION FIELDS IN COMMERCIAL NUCLEAR POWER PLANTS

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Abstract—This paper presents a compilation of experimental data on radiation fields found in commercial nuclear power plants. Exposure rates for systems and components are described by average values, although these averages may be significantly low (by orders of magnitude) near localized "hot spots". Conditions for, and exposure rates from, important fields are cited for both normal and abnormal operating conditions. Away from hot primary components, exposure rates for both γ and neutron fields typically range from 0 to 1000 mrem h^{-1}. Photon fields are most frequently the result of decay from neutron activated materials or fission product deposits. Neutron fields exhibit well-moderated spectra, with few neutrons above 750 keV. There seems to be no correlation between γ and neutron fields in a typical nuclear power plant outside the reactor core.

1. INTRODUCTION

As part of a program to assess the potential for mobile robots in nuclear power plants, a survey was conducted to determine *typical* neutron and photon radiation fields which could be expected during normal operations, shutdowns and abnormal situations. Because of the difficulty in obtaining this type of information, we have synthesized and integrated data and present it below. While we believe this information to be "representative" for design purposes, the reader is cautioned that the exposures quoted can vary substantially depending on the particular plant, location and situation. As such, these values should be interpreted as "order of magnitude" estimates.

In order to protect plant personnel and electronics from radiation exposure, statements such as: "near steam generators, exposure rates of X mrad h^{-1} of Y eV γs can be expected" are desired. However, such statements can rarely be made. As yet, the fundamental knowledge of the mechanisms that lead to radiation buildup in power plants has not been applied to these problems, although trends have been observed. In addition, quoted field values frequently do not describe how or precisely where the measurements were made. As a result, the best one can hope for is a range of values and an understanding of the general factors which influence the magnitude and spectrum of the γ and neutron radiation fields.

In Section 2 we present a summary of operating and shutdown exposure rates for boiling water reactors (BWRs) and pressurized water reactors (PWRs). In Section 3, the principal factors which influence variations in these field strengths are discussed. In Sections 4 and 5, the γ and neutron fields, respectively, are individually addressed. Section 6 examines extreme accident fields. Section 7 summarizes the material presented.

2. AVERAGE FIELD STRENGTHS

The assimilated radiation field data are presented in Tables 1–5, and Figs 1–2. All values can be assumed to represent the total combined neutron and γ field strengths, except as noted. Table 1 presents a compilation of shutdown and at-power data for selected PWR systems and components. The data are derived from three general sources—studies which compare the accuracy of different detector types, studies which monitor radiation buildup in a few specific components over many plants during shutdown, and new reactor startup test reports. The studies which compare different neutron detector types highlight the difficulty of providing accurate data in intense fields (Rathbun, 1983), but also provide data on the specific components measured. The studies which monitor a few specific components show large variations between measured radiation fields at identical positions in different plants, but again provide good data on these components. The startup testing reports provide fairly complete mappings of intense, at-power fields, but are expected to represent less accurate data. This data will also not show the effects of radiation buildup normally present at more mature plants.

The at-power data presented in Table 1 show a large range of values. The most intense fields shown are near the vessel head and directly above the vessel. These locations do not benefit from the cylindrical biological shield, and have large neutron components. The reactor coolant pumps also show large neutron and γ field intensities. The variation in reported data ranges over an order of magnitude for both the neutron and γ fields. The data presented for the reactor coolant piping system also varies by an order of magnitude, with the most intense radiation measured between the reactor coolant pump and steam generator. The intense fields present at the adjacent components may be contributing to this higher value and therefore not reflect radiation being emitted solely from the piping. Steam generator data are shown for both inside and outside the steam generator shielding, and clearly show the benefitial effect of the shield.

Table 2 presents average *shutdown* PWR field data, taken primary from Beal *et al.* (1987) in a condensed format. During shutdown, one can expect the majority of the radiation to consist of γ fields. The dose rates in Table 2 are thus

Table 1. PWR system/component dose rates

System/component	Dose rate (rem h^{-1}) Shutdown	 Operating
Reactor equipment		
Reactor vessel		
Above (during vessel operations)	0.025–1.4	—
Keyways (below)	0.7–200[1]	—
Under vessel head	5–15[1]	394–1300 (n)
Refueling machine	—	60 (n)–75[2]
Operating deck (edge of reactor cavity)		0.6[1] (γ) 5–7.7 (n)
Main heat transport system		
Main coolant pumps	0.065–0.360	2–22 (n) 2–25[1] (γ)
Reactor coolant piping system	0.02–0.270	2.3[3]–35[4](γ)
Steam generators (internal)		
Channel head exposure ranges	6–24	—
<4.5 EFPY[5] average	9	—
>4.5 EFPY average	12–15	—
At manway and inside	5.1	—
Steam generators (external)		
Inside bioshield	0.025–12	3–13.75
Outside bioshield	0.11	0.16–2.75
Pressurizer	0.095	5.5
Residual heat removal system		
RHR pumps	0.1	0.050
RHR piping and heat exchanger	0.065	0.065
Other measured positions		
Valves (miscellaneous)	0.075–1	—
Spent resin loading area	2	1–20
Regenerative heat exchanger	0.5–5	—

(Scaglia and Bergmann, 1987; Beal *et al.*, 1987; Bradshaw, 1987; Roberson *et al.*, 1984; White *et al.*, 1984; VEPCo, 1979; Vance *et al.*, 1978; Vergnaud, 1984; Uhrig, 1977)

[1] Values listed as rad h^{-1}. For γ rays, 1 rad^{-1} h^{-1} is approximately equal to 1 rem h^{-1}.

[2] Value is quoted as 60 rem h^{-1} neutrons. A value of 75 rem h^{-1} total field strength is obtained by using nearby γ/neutron field intensity ratios.

[3] Value quoted is rad h^{-1}. A conversion factor of unity is assumed.

[4] Measured by contact on pipe between reactor coolant pump and steam generator, and presented as rad h^{-1}.

[5] Plant operating time in units of effective full power years (EFPY).

averages of typical γ-field values from several plants and excludes data taken near hot spots. For example, hot spots in reactor coolant piping have yielded 2 rem h^{-1} shutdown γ fields although the expected field strength is an order of magnitude less. The most intense shutdown field reported, up to 200 rem h^{-1}, occurs under the reactor vessel in the keyways.

Table 3 gives broad area averages for PWR containments when the plant is operating *at-power*, whereas Tables 1 and 2 primarily present data near specific systems or components. In this table, γ and neutron contributions are explicitly delineated. Note that these broad area averages are significantly lower than the measured values near the primary components. The area around the reactor cavity includes some spots close to hot primary components, however. The generic category of other levels includes middle and lower levels of containment. Because of the biological shield, the middle level dose values are typically smaller than the operating level. The same is true for the lower level, although to a lesser degree. Figure 1 presents a coherent view of selected data from Tables 1–3 schematically.

Data for BWRs are given in Tables 4 and 5, and Fig. 2. Table 4 presents shutdown and at-power data for selected BWR systems and components of particular importance to personnel exposure. However, no at-power radiation maps of the drywell were obtained. This may be partially because the drywell is not intended to be habitable during operation, frequently having intense radiation fields (estimated on the order of 10^2 rem h^{-1}) and an inert atmosphere. Except for rather simple instrumentation, most conventional instrumentation packages could not withstand this environment for an extended period. Operating data for outside the drywell were primarily obtained from the Fermi-II BWR.

Tables 4 and 5 present a more complete picture of the shutdown radiation fields at BWRs. As with PWRs, large variations in radiation fields on individual components are seen. For example, values of 0.025 to 1.2 rem h^{-1} are reported on recirculation line piping, although the average value across several plants was only 0.260 rem h^{-1}. Similarly, the reactor water cleanup (RWCU) pump inlet data extend from 0.015 to 2.58 rem h^{-1}, but the average over several plants was 0.375 rem h^{-1}. For the RWCU pump outlet, it is interesting that the operating value quoted for a new plant is less than some shudown values at more mature plants. Possible reasons for this are discussed in Section 3 below. Figure 2 shows a schematic view of selected data from Tables 4 and 5.

Table 2. PWR system shutdown dose rates (>25 mrem h^{-1})

Description	Average dose rate[1] (mrem h^{-1})
Reactor equipment	
Reactor vessel closure and attachments	650
Reactor vessel studs, fasteners, seals and gaskets	140
Reactor vessel upper and lower internals	800
Control rod drives	1400
Main heat transport system	
Main coolant pumps and drive	65
Main coolant pumps foundations/skids	40
Reactor coolant piping system	270
Steam generators	
—at manway and inside steam generator	5100
—manway vicinity and general area	110
Pressurizer	95
Pressurizer relief tank	32
Residual heat removal system	35–65
Safety injection system	
Boron injection tanks	70
Safety injection system piping system	55
Containment spray system	
Containment spray instrumentation and control	120
Liquid waste system	
Primary equipment drain system	
Tanks, pumps and motors	250
Equipment drain filter	50
Equipment drain piping system	35
Miscellaneous drain waste system	
Tanks, pumps and motors	170
Waste filters, demineralizers	150
Miscellaneous waste piping system	75
Chemical waste system	
Tanks, pumps and motors	60
Regenerative chemical waste system	
Demineralizers, filters and evaporator	100
Solid waste system	
Dry active waste volume	
Tanks, pumps and motors	120
Filters	2000
Fuel handling and storage	
Transfer systems	210
Reactor service and fuel storage pool	
Spent fuel pool cleaning and purification equipment	85
Reactor makeup water system	
Reactor makeup water tank	120
Coolant treatment and recycle	
CVCS[2] heat transfer equipment	80
CVCS tanks and pressure vessels	140
CVCS purification and filtration equipment	1800
CVCS piping system	95
Boron recycle system pumps, motors, tanks and equipment	100
Boron recycle system purification and filter equipment	38
Auxiliary cooling systems	
Nuclear service water system	
Cooling tower piping system	80

(Roberson *et al.*, 1984; Beal *et al.*, 1987)

[1] Average of across-plant typical values.

[2] Chemical and volume control system.

Table 3. Containment operating dose rates

Broad area	Dose rate (mrem h^{-1}) (range of values)
Operating level, general area	
γ	75 (15–500)
n	530 (3–2200)
Operating level, around reactor cavity	
γ	400 (20–2000)
n	2600 (90–12,500)
Other levels, general area	
γ	17 (3–500)
n	11 (8–200)
Other levels, around reactor cavity	
γ	100 (36–4000)
n	310 (90–6000)

(Ryan, 1983; Endres *et al.*, 1981; Uhrig, 1977; SMUD, 1975; Champion *et al.*, 1984)

3. PRINCIPAL FACTORS AFFECTING FIELD STRENGTHS

In an effort to understand the sources of the wide range of radiation levels measured at identical locations in similar plants, a number of studies have examined the sources of the shutdown radiation fields, and the variables which primarily influence these fields for BWRs and PWRs. Some results from these efforts are presented below.

For BWRs, reactor water quality, ^{60}Co and feedwater iron contamination play significant roles in the radiation buildup in BWR primary piping (Anstine, 1983). In fact, BWR drywell radiation fields are determined principally by primary piping system radioactivity. BWR hot spots have been found to develop from the accumulation of corrosion products (Earls and Blok, 1986).

Although the size of the reactor water cleanup (RWCU) system and the type of condensate treatment demineralizers do not correlate to radiation buildup, the exposure rates in the RWCU system are usually higher than in the recirculation lines because of the hot spots formed by crud deposition in low flow areas. Recirculation lines are both a major source of drywell exposure and are geometrically similar from plant to plant. However, exposure rates on BWR recirculation lines do not necessarily reflect buildup throughout the primary system (Anstine, 1983).

For PWRs, the buildup of fields outside of the core depends on the quantity of corrosion and erosion products being activated. Thus, similar to BWRs, preventing field formation requires the elimination of corrosion and/or prevention of corrosion product deposition in systems external to the core (Burg *et al.*, 1980, Scaglia and Bergmann, 1987). One other interesting insight regarding PWR exposures is that exposure rates outside of PWR steam generators (one of the main sources of personnel exposure in PWRs) do *not* necessarily correlate to those found inside the steam generator channel head.

A number of additional factors beyond the specific component surveyed or level of corrosion present influence the measured radiation fields, and thus the accuracy and spread of the measured radiation fields. These include:

1. Shutdown vs operating condition (including percentage of full power), as well as time after shutdown and effective full power years (EFPYs) of reactor operation. However, operating floor dose rates are relatively uniform at each

Table 4. BWR system/component dose rates

System/component	Dose rate (rem h^{-1}) Shutdown	Operating
Reactor equipment		
Reactor vessel operations	0.04–0.30	
Control rod drives	0.11–0.26	
Main heat transport system		
Recirculation line	0.025–1.2	—
Main steam line	0.002–0.250	3–8
Main stream isolation valve	0.075	0.4–8
Feed heater pump	0.125	
Feed heaters		0.8–2
Feedwater spargers	0.240	
Residual heat removal system		
RHR heat exchanger	0.2–0.7	0.1
Reactor water cleanup system		
Pump inlet	0.015–2.58	—
Outlet	0.015–3.04	1.5
Casing	0.025–2.00	
Valve	0.11	
Regenerative heat exchanger	0.010–2.8	1
Nonregeneative heat exchanger	0.005–0.260	
Drain lines from heat exchangers	3–15	4
Phase separator		$\leqslant 100$
Turbine building floors		0.01–6
Moisture separator and reheaters	0.2–2	2
Waste systems		
Spent resin tank	0.45	
Waste packing room	0.2–15	

(Anstine, 1983; Beal *et al.*, 1987; Palino *et al.*, 1987; Roberson *et al.*, 1984; White *et al.*, 1984; Vance *et al.*, 1978)

power level (Uhrig, 1977). For older plants as a whole, PWR radiation fields level off after ∼1 EFPY and BWR fields after ∼4 EFPY [Beal *et al.*, 1987; Burg *et al.*, 1980]. Water chemistry has received increased consideration over the last several years, so these two findings may no longer be as generally applicable. Steam generator channel exposures have been seen to level off at ∼10–20 rem h^{-1} after 5–6 EFPY, and even decline slightly thereafter (Scaglia and Bergmann, 1987). Similarly, in BWRs, the high levels found in the recirculation piping system (∼800 mrem rad h^{-1}) reach maximum values after 4–5 EFPY (Anstine, 1983).

2. Decontamination of component hot spots nearby. Cases are cited of an order-of-magnitude change in exposure rates over 1 m of piping (Anstine, 1983; Sejvar *et al.*, 1981).
3. Significant cladding failures.
4. Component wall thickness. Interestingly, PWR steam generator wall thickness has been found not to significantly affect external fields (Scaglia and Bergmann, 1987).
5. Plant elevation. Measurements made on a given component at an elevation corresponding to core midplane are frequently different than those below or above.
6. Coolant levels.
7. Insulation type and thickness.
8. Instrumentation used for the measurement (Scaglia and Bergmann, 1987; Rathbun, 1983).

While these factors have been identified, it has not been possible to quantitatively estimate their impact on the range of measured field strengths.

4. γ-RAY EXPOSURES

Once a significant radiation field or hot spot is identified, it is informative to determine its radiation type and spectrum. Depending on the location, low (∼100–500 keV), medium (∼500–1000 keV) and/or high (>1000 keV) energy photons can be major contributors to exposure. For example, high energy fields are dominant in PWR containments (e.g. near steam generators) and on BWR turbine floors. In PWRs, radiation under the vessel is primarily from high-energy photons resulting from phenomena related to capture and inelastic scattering of neutrons. In particular, 90% of these γs have an energy greater than 1 MeV and 60% have energies greater than 2 MeV (Earls and Blok, 1986). The PWR steam generator channel heads (where photons of up to 8 MeV can be found) represent another primary source of high-energy radiation fields. For BWR turbine floors during operation, high-energy ^{16}N photons dominate the spectra and contribute up to 80% of the exposure there. Nevertheless, when comparing *plantwide* operating vs shutdown conditions, it has been found that no large difference exists in the relative amounts of low- vs high-energy photons (Robertson *et al.*, 1984). This suggests that plant history, especially water chemistry, is a critical factor in the magnitude of the radiation fields encountered.

The major categories of γ radiation areas are:

(1) fields dominated by high-energy fission γs;
(2) fields caused by short-lived radioactive noble gases;
(3) fields dominated by decay photons from radioactive atoms in neutron activated or fission product deposits, and by the scattered photon continuum that results from these deposits.

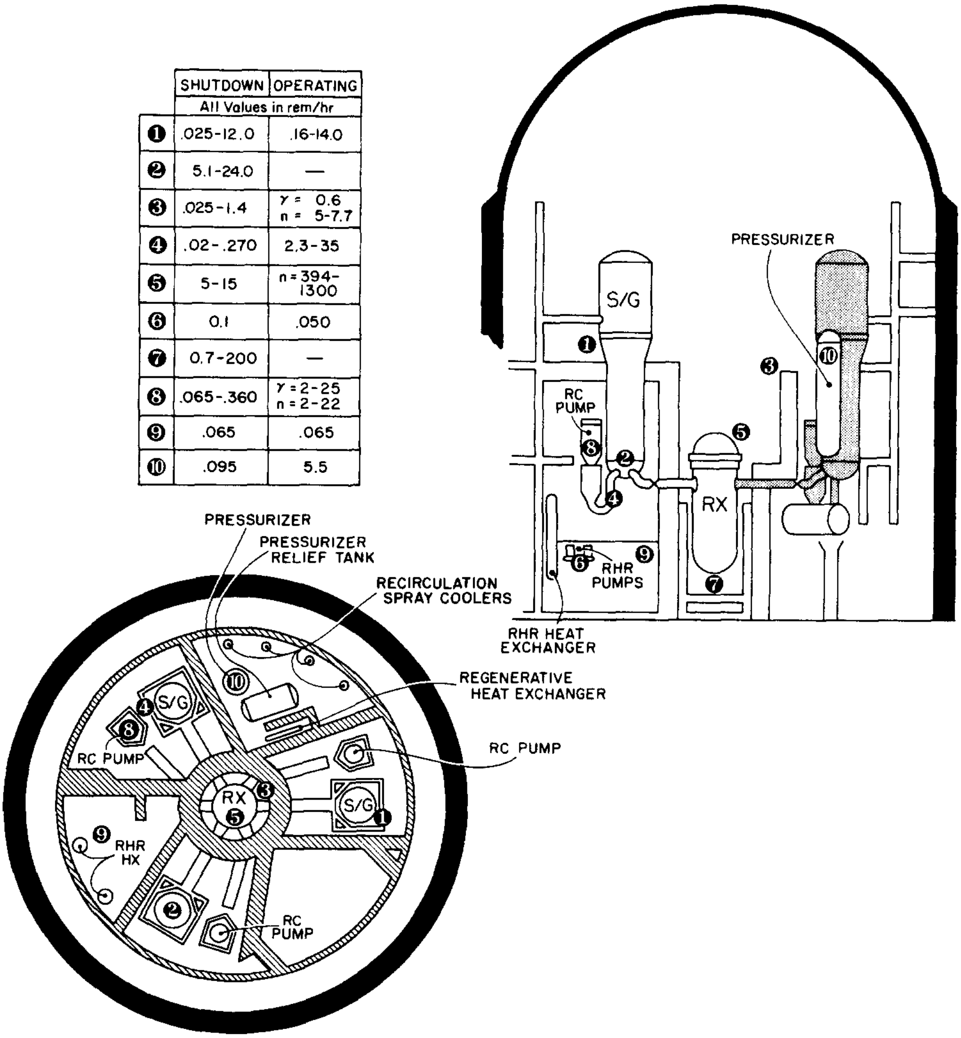
The first category is found only during operation. The third category is the most prevalent for both shutdown and operating reactors. The neutron activated fission product isotopes that normally contribute to the background energy spectrum

Table 5. BWR system shutdown dose rates (>25 mrem h^{-1})

Description	Average dose rate[1] (mrem h^{-1})
Reactor equipment	
Reactor vessel closure and attachments, studs, fasteners, seals, gaskets, core support and shroud assembly	40
Jet pump assemblies	4400
Fluid distribution assemblies	210
Steam dryer assembly	800
Control rods	170
Control rod drives	110
Main heat transport system	
Reactor recirculation pumps and motors	90
Recirculation piping system	240
Reactor recirculation instrumentation and control	200
Residual heat removal system	
RHR pumps and drivers	60
RHR heat exchangers	320
RHR piping system	100
RHR instrumentation and control	80
Reactor core isolation cooling system	
RCIC pumps, motors and equipment	90
RCIC piping system	100
High pressure core spray system	
HPCS pumps, motors and strainers	30
HPCS piping system	100
Low pressure core spray system	
LPCS piping system	190
Standby liquid control system	
SLCS piping system	55
Liquid waste system	
High-purity system	
High-purity collection tanks, pumps, motors and equipment	280
Low-purity system	
Low-purity collection tanks, pumps, motors and equipment	190
Low-purity waste piping system	60
Detergent waste system	
Detergent waste tanks, pumps, motors and equipment	40
Detergent waste filter, demineralizers, R/O unit package	65
Chemical waste system	
Chemical waste tanks, pumps, motors and equipment	40
Solid waste system	
Dry active waste volume reduction centrifuge, pumps, motors and equipment	200
Solid waste system piping system	250
Fuel handling and storage	
Spent fuel pool cleaning and purification	
Pumps, motors, equipment, filters and demineralizers	400
Spent fuel pool cleaning and purification piping system	40
Reactor water cleanup system	
RWCU system pumps, motors and heat exchangers	120
RWCU purification and filter equipment	80
RWCU piping system	120
Auxiliary cooling systems	
Plant chilled water system pumps, motors and heat transfer equipment	80
Feed water system	
Feed water piping	70
Feed water valves	850
Other turbine plant equipment	
Main vapor system piping	50
Main vapor system valves	260
Main vapor system instrumentation and control	100

(Roberson *et al.*, 1984; Beal *et al.*, 1987; White *et al.*, 1984)

[1] Average of across-plant typical values.



	SHUTDOWN	OPERATING
	All Values in rem/hr	
①	.025-12.0	.16-14.0
②	5.1-24.0	—
③	.025-1.4	γ = 0.6 n = 5-7.7
④	.02-.270	2.3-35
⑤	5-15	n = 394-1300
⑥	0.1	.050
⑦	0.7-200	—
⑧	.065-.360	γ = 2-25 n = 2-22
⑨	.065	.065
⑩	.095	5.5

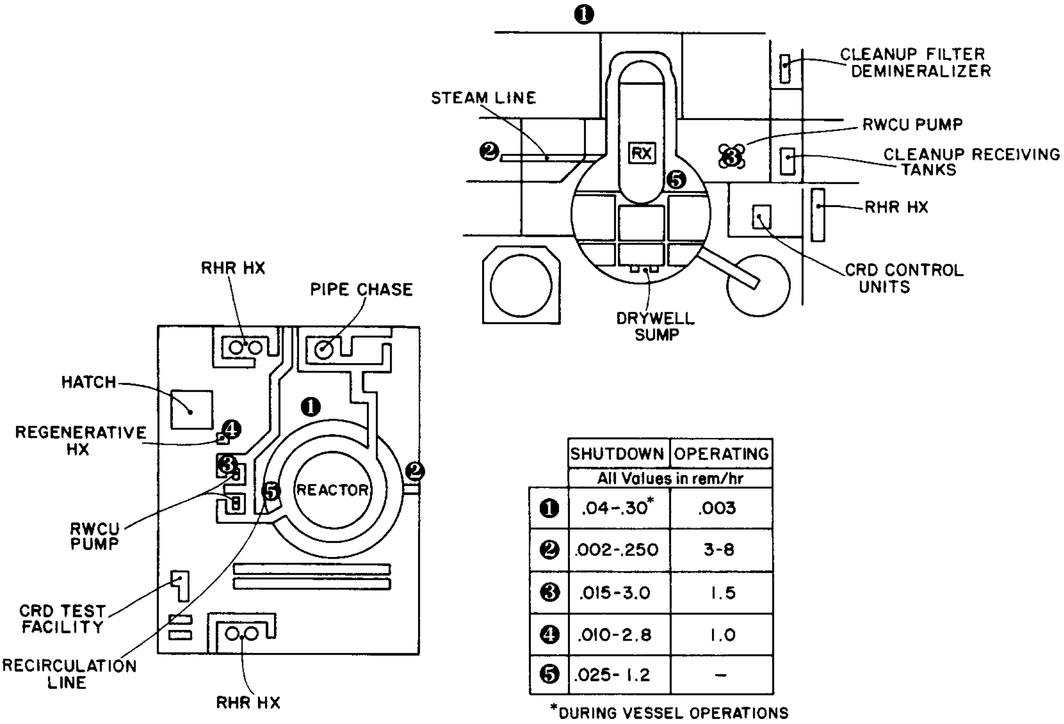
Fig. 1. PWR system/component exposure rates.

are listed in Table 6. ^{60}Co has been found to be the greatest contributor to exposure, and its buildup results from crud deposited near low flow, dead-leg areas and becoming incorporated in corrosion films (Roberson *et al.*, 1984; Anstine, 1983). ^{137}Cs and ^{16}N have also been found to contribute significantly to exposure (Roberson *et al.*, 1984). The maximum flux of the scattered photon continuum is expected between 50 and 150 keV, just above the sharp rise in the photoelectric cross section for atoms in shielding materials. As crud (i.e. the long half-life radioactive deposits) builds with age, the relative contribution of low-energy photons to dose declines (Roberson *et al.*, 1982, 1984). Under normal operating conditions, *plantwise average* γ exposures range from about 0 to 1000 mrem h^{-1}, with an overall average on the order of 10 mrem h^{-1} (Roberson *et al.*, 1984; White *et al.*, 1984; VEPCo, 1979; SMUD, 1975).

5. NEUTRON EXPOSURE

For operating reactors it is also important to consider the neutron exposure, especially with respect to potential radiation damage. Using a γ detection system to locate high neutron backgrounds is generally not feasible, since away from the vessel there is little correlation between γ and neutron exposures, with γ/neutron ratios ranging from 0.08 to 100. Usually, only a small percentage of the total radiation exposure is due to neutrons because intense neutron fields are not as prevalent throughout the plant as γ fields (Ryan, 1983).

Determining the significant component of the neutron background (i.e. fast, epithermal or slow) is difficult. In some cases only the fast neutrons streaming from the vessel are significant contributors to the exposure (Uhrig, 1977). Sub-



	SHUTDOWN	OPERATING
	All Values in rem/hr	
①	.04-.30*	.003
②	.002-.250	3-8
③	.015-3.0	1.5
④	.010-2.8	1.0
⑤	.025- 1.2	–

*DURING VESSEL OPERATIONS

Fig. 2. BWR system/component exposure rates.

stantial neutron leakage from the reactor cavity occurs (Vergnaud *et al.*, 1984):

(1) in the upper part of the reactor pit, in the air gap between the vessel and the biological shield wall, resulting in streaming into the refueling cavity and the operating deck (up to 5 rem h^{-1});

(2) around coolant pipes, leading to escape into reactor coolant pump casemates (5–22 rem h^{-1}) and the operating deck above (0.36–2.1 rem h^{-1});

(3) into the keyways below the vessel;

(4) in the ionization chamber openings on the operating deck (Kosako *et al.*, 1984; Champion *et al.*, 1984); and

(5) near the reactor vessel flange gap (Butler *et al.*, 1979).

In most other cases, the contribution of high-energy neutrons to the dose is very small. Average energies are usually less than 100 keV with few neutrons having energies greater than 750 keV (Cummings *et al.*, 1983; Endres *et al.*, 1981). In general, thermal neutrons make up about 40%, epithermal 50%, and fast neutrons 10% of the total flux spectra (Ryan, 1983; Earls and Blok, 1986). Under normal operating conditions away from the vessel, plantwide average neutron exposure rates can be expected to range from 0–1000 mrem h^{-1}, with an overall average on the order of 10 mrem h^{-1} during operation (Endres *et al.*, 1981; VEPCo, 1979; SMUD, 1975; Walker and Davis, 1977).

6. ACCIDENT CONDITIONS

Under abnormal conditions such as an accident, exposures can reach critical levels so quickly that shielding both equipment and personnel becomes difficult. Electronic failures at Chernobyl began at 600–800 rad h^{-1}, and the robot used there was completely disabled at 2000 rad h^{-1} (Tulenko, 1987). Fields reached 10^5 rad h^{-1}. [A calculation has been performed to simulate a gap release leading to escape of the fission product inventory from the fuel for power plants of U.S. design and similar results of $\sim 10^4$ rad h^{-1} were obtained (Kenoyer *et al.*, 1982).] Currently, the basement of the TMI plant has a field of ~ 1200 rad h^{-1}. Locating sources of this magnitude will not be difficult if they are confined to "hot spots", but in the case of a gaseous release, the release will create its own background to the extent that detecting its source will be difficult. Neutron fields will not be the major concern in such accident situations, since the fission product release is thought to produce the more significant hazard.

7. SUMMARY

Of the many factors to be accounted for when considering the expected radiation fields to be encountered, several points stand out. Plant γ exposure rates were found to typically range from 0 to 1000 mrem h^{-1}, although near the vessel and localized hot spots, substantially larger values exist. Excepting areas such as BWR turbine floors, low-energy scatter photons dominate the spectra during both operating and shutdown conditions. These photons originate mainly from neutron activated corrosion and fission product accumulations, with ^{60}Co being the major contributor to dose. Additional isotopes of concern during operation are ^{16}N and ^{137}Cs. Water chemistry has been shown to be a critical factor

Table 6. Sources of the photon background energy spectrum

Isotope		γ-energy (keV)	Half-life (days)
Neutron activated			
Sb	124	602.7, 722.8, 1691	60.2
Ar	41	1294	0.0763
C	15	5298	2.83×10^{-5}
Co	58	810.8	70.91
	60	1173, 1332	1924
Cr	51	320.1	27.70
D	(n, γ)	2200	
Fe	59	1099, 1292	44.51
	(n, γ)	4200, 5900, 6000, 7300, 7600	
Mn	54	834.8	312.2
	56	846.8	0.1075
Mo	99	140.5, 739.6	2.748
	101	192.0, 505.9, 9,590.9, 1013	0.01014
Ni	65	1482, 1116	0.1050
N	16	6129, 7115	8.25×10^{-5}
Sn	113	391.7	115.1
	125m	332.0	6.61×10^{-3}
Xe	133	81.00	5.25
	135	249.8	0.379
Zn	65	1116	243.8
Zr/Nb	95	756.7, 724.2, 235.7, 7,778.2, 568.9, 1091	64.03
Zr	97	743.4	0.7
Other:			
Annihilation		511	
Lead X-rays		~200	
(Roberson *et al.*, 1984; Berry and Diegle, 1979)			
Fission products			
Cs	134	604.7, 795.8	753.7
	137	661.7	11,010
I	131	364.5	8.040
	132	667.7, 772.6	0.950
	133	529.9	0.867
	134	847.0, 884.1	0.365
	135	1260, 1132, 526.6	0.2744
	136	1313, 1321	9.68×10^{-4}
Kr	83m	9.39	0.0775
	85m	151.2	0.187
	85	514	3913
	87	402.6	0.053
	88	2392, 196.3	0.118
	89	220.9, 585.8	0.00219
	90	1119, 1218, 5395	3.74×10^{-4}
Sr	89	909.2	50.52
Xe	133	81.00	5.25
	135m	768.9	0.0106
	135	249.8	0.379
	137	455.5	0.00267
	138	258.4, 434.5, 1768, 2016	0.00979
	139	218.6, 296.5, 174.9	4.6×10^{-4}
(Pigford, 1972)			

in overall plant exposure rates. The exposure rates tend to level off after ~1 yr in PWRs and ~4 yr in BWRs, although for steam generators (a significant contributor to exposure in PWRs) and on BWR recirculation piping systems and turbine floors, the fields level off after ~5 yr. Away from the vessel, neutrons are generally not significant contributors to total doses, and no correlation appears to exist between γ and neutron doses.

The specific values presented here are meant to provide rough estimates of the expected field strengths found in shutdown and operating BWRs and PWRs. In order to be useful for shielding purposes, in certain cases the values presented may be conservatively high. Nevertheless, the data presented here represent the best estimates to date. In order to form a more comprehensive database on operating plants, those having additional information are encouraged to respond directly to the authors.

REFERENCES

Anstine L. D. (1983) Report EPRI-NP-3114-SY, Electric Power Research Institute.

Beal S. K., Britz S. C., Cohen S. C., Goldin A. S. and Goldin D. J. (1987) Report NUREG/CR-5035, U.S. Nuclear Regulatory Commission.

Berry W. E. and Diegle R. B. (1979) Report EPRI-NP-522, Electric Power Reserch Institute.

Bradshaw R. W. (1987) Report EPRI-NP-4998, Electric Power Research Institute.

Burg R. J., Flynn J. J., Gregg B. R. and Nilsen R. (1980) Report DOE/ET 34004-1.

Butler H. M., Ohnsorge W. F. and Auxier J. A. (1979) *Trans. Am. Nucl. Soc.* **30,** 611.

Champion G., Bevilacqua A., Lloret R., Mourgues M. and Vergnaud T. (1984) *Proc. Am. Nucl. Soc. Top. Mtg Reactor Phys Shielding*, p. 448.

Cummings F. M., Endres G. W. R. and Brackenbush L. W. (1983) Reports NUREG/CR-1769 and PNL-4471, U.S. Nuclear Regulatory Commission.

Earls C. E. and Blok J. (1986) Report EPRI-NP-4823, Electric Power Research Institute.

Endres G. W. R., Aldrich J. M., Brackenbush L. G., Gaust L. G., Griffith R. V. and Hankins D. E. (1981) Reports NUREG/CR-1769 and PNL-3585, U.S. Nuclear Regulatory Commission.

Kenoyer J. C., Pickett B. D. and Desrosiers A. E. (1982) *Trans. Am. Nucl. Soc.* **43,** 618.

Kosako T., Matsumoto J., Sekisuchi A., Tabeda S. and Takita T. (1984) *Proc. Am. Nucl. Soc. Top. Mtg Reactor Phys Shielding*, p. 472.

Palino G. F., Hobart R. L. and Sawochka S. G. (1987) Report EPRI-NP-5455, Electric Power Research Institute.

Pigford T. (1972) *IEEE Trans Nucl. Sci.* **19,** 15.

Rathbun L. A. and Endres G. W. R. (1983) Reports NUREG/CR-2893 and PNL-4395, Pacific Northwest Laboratories.

Roberson P. L., Endres G. W. R., Fox R. A., Haggard D. L., Holbrook K. L. and Rathbun L. A. (1982) Report PNL-SA-10743, Pacific Northwest Laboratories.

Roberson P. L., Endres G. W. R., Fox R. A., Haggard D. L., Holbrook K. L. and Rathbun L. A. (1984) Reports NUREG/CR-3569 and PNL-4915, U.S. Nuclear Regulatory Commission.

Ryan, R. M. (1983) Report NUREG/CR-2524, U.S. Nuclear Regulatory Commission.

Scaglia L. A. and Bergmann C. A. (1987) Report EPRI-NP-5234, Electric Power Research Institute.

Sejvar J., Crotzer M. E. and Frank F. J. (1981) Report EPRI-NP-858, Electric Power Research Institute.

SMUD (Sacramento Municipal Utility District) (1975) Rancho Seco Startup Report.

Tulenko J. S. (1987) University of Florida Monthly Report.

A Remote Telepresence Robotic System for Inspection and Maintenance of Nuclear Power Plants (unpublished).

Uhrig, R. E. (1977) St Lucie unit 1 Startup Physics Testing Report to the U.S. Nuclear Regulatory Commission.

Vance, J., Waver C. L. and Lepper E. M. (1978) Atomic Industrial Forum Report on The Potential Impacts on Operating Nuclear Power Plants of a 500 MREM/YEAR Occupational Exposure Limit.

VEPCo (Virginia Electric Power Co) (1979) North Anna Startup Report.

Vergnaud T., Bourdet L., Champion G. and Nimal J. C. (1984) Neutron dose rate in the upper part of a PWR containment—comparison between measurements and TRIPOLI-2 calculations. *Proc. Am. Nucl. Soc. Top. Mtg Reactor Phys Shielding.*

Walker R. E. and Davis D. K. (1977) St Lucie Unit 1 Neutron Streaming Report to the U.S. Nuclear Regulatory Commission.

White J. R., Eversole R. E., Farnstrom K. A., Harvey H. W. and Martin H. L. (1984) Report NUREG/CR-3717, U.S. Nuclear Regulatory Commission.