THERMAL TMI 4/5/79 9:52

705062

REPOSITORY DOE-FORRESTAL

COLLECTION MARKEY FILES

BOX No. 3 OF 6

FOLDER THREE MILE ISLAND
MARCH 28, 1979

VOLUME II Part 2

three mile island

A REPORT TO THE COMMISSIONERS AND TO THE PUBLIC

MITCHELL ROGOVIN
director

GEORGE T. FRAMPTON, JR.
deputy director

NUCLEAR REGULATORY COMMISSION
SPECIAL INQUIRY GROUP

1007159

Table II-22 contains daily data from the NRC TLDs for the period March 31 through April 7, 1979. These data were used by the Ad Hoc Interagency Dose Assessment Group. With the exception of the first day of NRC TLD data, the data for the exposure period of April 1 through May 1, 1979 were used by the President's Commission to determine the population dose for this period.[147] These results are discussed in more detail in Section II.B.4.a.

The TLD data indicate that the major offsite releases of radioactive materials occurred on the first day. The highest readings were obtained on site and at Kohr Island (see TLDs 16S1 and 16A1 in Table II-20). These readings indicate that the plume traveled to the north-northwest. The other high TLD readings (station 14S1) indicated that portions of the plume may have migrated to the west-northwest for short periods of time. With the exception of the Kohr Island dosimeter, all of the high readings were on site. The highest net TLD reading offsite location, about 2 miles to the southwest, was 27 mrem.

During the period of April 1 to April 3, 1979, only the Kohr Island dosimeter and the dosimeter located near the observation center indicated a dose in excess of 10 mrem. Higher readings exceeding 10 mrem were noted on site. During the period March 31 to April 3, the data indicate that no significant offsite releases occurred. Only four onsite readings exceeded 10 mrem, the highest being approximately 30 mrem.

f. Findings and Recommendations

We find that:

- Several organizations including the Federal Government responded to the accident and capably undertook the enormous task of environmental monitoring.
- The TLDs placed by Met Ed as part of its environmental radiation monitoring for routine operation provided adequate data to characterize the radiation levels in the environment attributable to the accident.
- Data from the supplementary TLDs placed in the environment by the NRC, the HEW, and the EPA following the accident were of limited use because of the different number and types of TLDs employed and the lack of information regarding background history and response characteristics of the TLDs.
- The Atmospheric Release Advisory Capability (ARAC), a computer system with the capability of predicting plume behavior and location, was a tool available for use in responding to the accident but was not effectively used within the NRC (see Appendix II.5).

We recommend that:

- The NRC reevaluate its requirements for environmental radiological monitoring to ensure that monitoring of released radioactive materials in both normal and accident conditions is at least as adequate as the environmental monitoring that occurred in response to the accident. This reevaluation should include:
  - the location and number of TLDs permanently installed in the site environs;
  - stations to monitor airborne (particulate, gaseous, and iodine) activity;
  - the placement of fixed real-time instrumentation for monitoring radiation in site environs.

4. ESTIMATES OF DOSES AND POTENTIAL HEALTH CONSEQUENCES OF RELEASES OF RADIOACTIVE MATERIALS

Several independent studies using different analytical techniques have estimated the radiation exposure and resultant dose from the TMI-2 accident to the public. These studies have concluded, and we agree, that the adverse health consequences attributable to the population dose are minimal at worst.

Onsite occupational exposures during the accident were also relatively low. Only three exposures in excess of the NRC quarterly exposure limits were recorded despite high radiation fields in the auxiliary building. The adverse health consequences attributable to these exposures will be minimal at worst. The total collective occupational dose that will accrue as a result of this accident cannot be determined until recovery operations are complete.

a. Population Dose Assessment

Met Ed had TLDs in place on and around the site environs at the time of the accident (see Section II.B.3). Beginning on March 31, 1979, NRC placed additional TLDs around the site. The Met Ed and the NRC TLD data were used to assess population dose resulting from the accident.

The Environmental Protection Agency (EPA) and the Department of Health, Education, and Welfare

1007160

TABLE II-22. NRC TLD data-radiation exposures for periods from March 31 to April 7, 1979 (includes background)[150]

Station	3/31-4/1 mR	4/1-4/2 mR	4/2-4/3 mR	4/3-4/4 mR	4/4-4/5 mR	4/5-4/6 mR	4/6-4/7 mR
N-1	1.0 ± 0.1	0.3	0.37 ± 0.08	0.32 ± 0.08	0.28 ± 0.08	0.32 ± 0.04	0.43 ± 0.05
N-2	(wet)	0.3	0.45 ± 0.05	0.40 ± 0.06	0.33 ± 0.08	0.48 ± 0.15	0.40 ± 0.05
N-3	1.2 ± 0.3	0.3	0.43 ± 0.05	0.32 ± 0.08	0.34 ± 0.09	0.47 ± 0.05	0.50 ± 0.11
N-4	1.0 ± 0.1	0.3	0.48 ± 0.08	0.33 ± 0.05	0.37 ± 0.05	0.42 ± 0.02	0.48 ± 0.10
N-5	(wet)	0.3	0.58 ± 0.08	0.37 ± 0.5	0.35 ± 0.05	0.48 ± 0.10	0.52 ± 0.08
NE-1	7.0 ± 2.1	0.2	0.45 ± 0.08	0.32 ± 0.04	0.45 ± 0.05	0.38 ± 0.04	0.45 ± 0.08
NE-2	(wet)	0.3	0.48 ± 0.09	0.37 ± 0.10	0.33 ± 0.08	0.47 ± 0.10	0.47 ± 0.12
NE-3	1.6 ± 0.5	0.3	0.42 ± 0.09	0.38 ± 0.08	0.37 ± 0.08	0.46 ± 0.05	0.45 ± 0.10
NE-4	2.1 ± 0.5	0.3	0.37 ± 0.05	0.38 ± 0.04	0.33 ± 0.05	0.40 ± 0.09	0.43 ± 0.05
E-1	25.0 ± 8.1	0.4	0.53 ± 0.1	0.32 ± 0.04	2.6 ± 0.60	0.50 ± 0.09	0.48 ± 0.08
E-5(E-1a)	8.4 ± 4.6	0.3	0.73 ± 0.2	0.38 ± 0.08	1.7 ± 0.45	1.2 ± 0.27	0.32 ± 0.04
E-2	4.3 ± 0.5	0.3	0.55 ± 0.7	0.55 ± 0.10	0.38 ± 0.08	0.45 ± 0.10	0.35 ± 0.08
E-3	2.1 ± 0.4	0.4	0.42 ± 0.1	0.40 ± 0.06	0.50 ± 0.06	0.48 ± 0.08	0.32 ± 0.08
E-4	2.5 ± 0.4	0.3	0.4 ± 0.1	0.35 ± 0.14	0.42 ± 0.19	0.43 ± 0.04	0.22 ± 0.04
SE-1	10.1 ± 2.0	0.3	9.1 ± 1.6	0.43 ± 0.10	0.92 ± 0.19	0.40 ± 0.00	0.55 ± 0.06
SE-2	3.5 ± 0.5	0.3	4.4 ± 0.7	0.87 ± 0.16	0.38 ± 0.08	0.35 ± 0.05	0.25 ± 0.05
SE-3	2.3 ± 0.6	0.3	2.8 ± 0.7	0.57 ± 0.10	0.45 ± 0.05	0.40 ± 0.06	0.25 ± 0.05
SE-4	3.0 ± 0.4	0.3	2.1 ± 0.4	0.30 ± 0.06	0.53 ± 0.08	0.47 ± 0.08	0.25 ± 0.05
SE-5	2.5 ± 0.7	0.3	0.13 ± 0.1	0.42 ± 0.04	0.37 ± 0.08	0.62 ± 0.31	0.38 ± 0.13
S-1	1.6 ± 0.1	0.4	2.2 ± 0.4	1.1 ± 0.05	0.37 ± 0.05	0.35 ± 0.05	0.40 ± 0.00
S-2	1.0 ± 0.2	0.4	1.5 ± 0.2	0.52 ± 0.08	0.32 ± 0.10	0.35 ± 0.05	0.43 ± 0.08
S-3	1.2 ± 0.3	0.4	1.5 ± 0.3	0.47 ± 0.05	0.40 ± 0.06	0.40 ± 0.06	0.55 ± 0.10
S-4	1.2 ± 0.2	0.3	1.4 ± 0.2	0.33 ± 0.05	0.45 ± 0.10	0.55 ± 0.18	0.42 ± 0.08

1001161

SW-1	0.9 ± 0.1	0.8	1.2 ± 0.3	1.1 ± 0.18	0.37 ± 0.08	0.37 ± 0.10	0.45 ± 0.05
SW-2	0.9 ± 0.2	0.5	1.3 ± 0.3	0.37 ± 0.12	0.30 ± 0.09	0.43 ± 0.08	0.38 ± 0.08
SW-3	1.1 ± 0.3	0.4	0.78 ± 0.1	0.65 ± 0.10	0.45 ± 0.10	0.38 ± 0.08	0.42 ± 0.02
SW-4	0.9 ± 0.1	0.5	0.75 ± 0.1	0.62 ± 0.10	0.45 ± 0.14	0.50 ± 0.14	0.50 ± 0.09
W-1	3.0 ± 1.9	1.2	1.4 ± 0.24	1.7 ± 0.35	1.3 ± 0.29	0.57 ± 0.10	0.48 ± 0.08
W-2	0.9 ± 0.1	0.5	1 ± 0.1	0.62 ± 0.04	0.72 ± 0.04	0.37 ± 0.08	0.38 ± 0.08
W-3	1.1 ± 0.1	0.5	0.78 ± 0.2	1.1 ± 0.15	0.42 ± 0.08	0.38 ± 0.08	0.47 ± 0.08
W-4	1.0 ± 0.2	0.4	0.67 ± 0.1	0.42 ± 0.10	0.45 ± 0.14	0.45 ± 0.05	0.57 ± 0.08
W-5	1.2 ± 0.2	0.6	0.4 ± 0.15	0.65 ± 0.12	0.60 ± 0.13	0.40 ± 0.06	0.57 ± 0.14
NW-1	0.9 ± 0.2	1.7	1.3 ± 0.25	0.30 ± 0.06	0.38 ± 0.08	0.52 ± 12	0.53 ± 0.04
NW-2	1.2 ± 0.5	0.4	0.62 ± 0.08	0.40 ± 0.15	0.33 ± 0.05	0.35 ± 0.05	0.38 ± 0.08
NW-3	1.4 ± 0.7	0.8	0.63 ± 0.12	0.40 ± 0.25	0.38 ± 0.04	0.40 ± 0.09	0.42 ± 0.05
NW-4	5.5 ± 1.8	0.3	0.4 ± 0.06	0.30 ± 0.06	0.37 ± 0.08	0.32 ± 0.04	0.45 ± 0.10
NW-5	4.6 ± 2.0	0.4	0.42 ± 0.04	0.42 ± 0.21	0.32 ± 0.04	0.48 ± 0.08	0.45 ± 0.05
S-1a	Not in Service until 4/5/79					0.35 ± 0.05	0.43 ± 0.05
SE-4a	Not in Service until 4/5/79					0.33 ± 0.05	0.25 ± 0.05
W-3a	Not in Service until 4/5/79					0.65 ± 0.39	0.45 ± 0.10
NE-3a	Not in Service until 4/5/79					0.38 ± 0.08	0.57 ± 0.08
N-1a	Not in Service until 4/5/79					0.50 ± 0.19	0.47 ± 0.04
N-1b	Not in Service until 4/5/79					0.40 ± 0.06	0.50 ± 0.06
N-1c	Not in Service until 4/5/79					0.40 ± 0.09	0.45 ± 0.08
N-1d	Not in Service until 4/5/79					0.35 ± 0.05	0.50 ± 0.06
N-1e	Not in Service until 4/5/79					0.40 ± 0.06	0.44 ± 0.08
N-1f	Not in Service until 4/5/79					0.47 ± 0.15	0.37 ± 0.08

1001162

(HEW) also placed TLDs around the site. Because the limit of sensitivity of these dosimeters was about 10 mR, they did not provide data useful to dosimetric calculations. If significant quantities of radioactive material had been released after April 1, however, these dosimeters would have been of great value in determining the dose to the offsite population. Additional radiological monitoring in the environment by the Department of Energy (DOE), Met Ed, NRC, and the Commonwealth of Pennsylvania confirmed that radiation levels off site were quite low and remained so during the course of and subsequent to the accident (see Section II.B.3).

Ad Hoc Interagency Dose Assessment Group Study— The Ad Hoc Group[151] analyzed the TLD data available through April 7. The group determined that the most likely collective population dose as a result of the accident was 3300 person-rem for the period March 28 through April 7. The Ad Hoc Group estimated that the possible doses ranged from 1600 person-rem to 5300 person-rem. In developing these estimates, several simplifying assumptions were made. As a result, several factors known to reduce estimates of exposure were not taken into account, including: (1) shelter factor (the protection afforded to people remaining indoors), (2) population redistribution, (3) actual organ doses which are smaller than the air dose calculated from the net TLD exposure, and (4) overresponse of the dosimeters supplied by Teledyne Isotopes, Inc. In addition, a conservatively small value for background was subtracted.[151]

The highest value (5300 person-rem)[152] resulted from inclusion of data from NRC TLDs for the first day of their deployment, which yielded dose values higher than could be substantiated by other TLDs or by field or aerial measurements. The Ad Hoc Group believed that insufficient background subtraction could have been the cause.

Two other methods used to estimate the population dose were presented in the Ad Hoc Group's report. One method used standard meteorological dispersion calculations and an estimated source term to calculate the population dose. By this method, the population dose was estimated to be 2600 person-rem.[153] The other population dose estimate was based on radiation measurements made from DOE helicopters. This method resulted in a population dose estimate of 2000 person-rem.[154] A subsequent recalibration of the DOE instruments indicated that they were overresponding to the radiation emitted by ^{133}Xe, indicating that the initial DOE population dose estimate may be high.

Task Group on Health Physics and Dosimetry of the President's Commission — This Task Group estimated the offsite population dose by several methods. The primary estimate was based on the same TLD data analyzed by the Ad Hoc Group, plus certain additional data available after April 7. This Task Group concluded that the most probable population dose was 2800 person-rem,[155] without accounting for the shelter factor. With a shelter factor, the estimate of the population dose was 2000 person-rem.[156]

In arriving at its population dose estimates, the Task Group evaluated the energy-response characteristics of the TLDs, and the accuracy and precision of the measurements made. These factors were used to establish the bounds of population dose values from 600 person-rem to 6500 person-rem.

The Task Group determined that the first batch of TLDs deployed by NRC, which had been used by the Ad Hoc Group to derive its maximum estimate of population dose, was irradiated during storage and transit prior to deployment.[157] Because the contribution from this irradiation to the total dose could not be ascertained, these data were not included in the Task Group's dose assessment. Apparently, the use of a shielded shipping container and a control dosimeter was not considered either for the deployment or retrieval of the dosimeters. This situation should not have occurred and is not in accord with acceptable practice.

The Task Group used three computer models with different meteorological modeling and dispersion calculations, and a source term, to make additional population dose estimates.[158] The estimates are shown in Table II-23.

The Task Group concluded that the "most likely collective (population) dose," as determined by these methods was 500 person-rem. They also stated that even if the results were in error by as much as a factor of 10, the "highest likely collective dose" was 5000 person-rem; and the "lowest likely collective dose" was less than 50 person-rem.[159]

TABLE II-23. Population dose estimates using computer models

Computer Model	Population Dose (person-rem)
ADPIC	276
AIRDOS-EPA	390
TMIDOS	970

Other Collective Dose Estimate—Using an independent computer model for atmospheric dispersion and dosimetry, and an estimated source term considerably larger than that used by the Task Group of the President's Commission, Woodard[160] calculated the population dose to be about 3500 person-rem for the period from March 28 to April 30, although releases were effectively terminated by March 31. No corrections were made for occupancy or shielding. The uncertainties in this calculation were estimated to be within a factor of 2 depending upon whether the plume was elevated or not. The range is from a low value of 2098 person-rem to a high value of 6836 person-rem.[161]

TMI Special Inquiry Group—We analyzed the offsite population dose estimates of the studies discussed above. The estimates are summarized in Table II-24. The studies were independently performed with different methodologies, yet arrived at similar population dose estimates. Each of the dose estimates was comprehensive in its analyses of the potential pathways of the plume and the potential error sources in the data. The maximum population dose estimates indicate that the population dose could not have exceeded 5000 person-rem.

Based on our review of the population dose studies, we deemed it unnecessary to perform an additional independent analysis of the raw data. We find that the collective dose as determined by the TLDs is within the ranges estimated by the Ad Hoc Interagency Dose Group and the Task Group on Health Physics and Dosimetry of the President's Commission. Correcting for occupancy factors, shielding, and reductions in the population due to voluntary evacuation, the population dose is believed to be somewhere in the lower end of those ranges, or about 2000 person-rem.

TABLE II-24. Population dose estimates

Source	Population Dose (person-rem)
Ad Hoc Interagency Population Dose Assessment Group	3300
President's Commission, Task Group on Health Physics and Dosimetry	2800 2000*
Woodard (Pickard, Lowe, & Garrick)	3500
ADPIC	300
AIRDOS-EPA	400
TMIDOS	1000

*Includes shelter factor.

There are no data or methodologies available by which to establish the collective dose with any greater accuracy. Among the factors that contribute to the inability to improve the collective dose estimates are the uncertainties associated with individual TLD determinations at the level of doses measured, the sparcity of the data, and the influence of the many factors that contribute to additional exposures of the TLD for which correction factors cannot now be ascertained. However, the placement of the TLDs and the prevailing wind directions at the time of the accident indicate that the close-in TLDs properly measured the radiation emanating from the plume. Furthermore, because the health effects implications do not change in this range of population doses, it is not necessary to attempt to estimate the range of the population dose more accurately. We find that despite the uncertainties in the TLD data, the data were adequate to characterize the magnitude of the collective dose to the population.

Additional Offsite Dosimetry—The HEW Public Health Service[164] attempted to determine offsite exposure from photographic film present in stores in the TMI area during the first 3 days after the accident. The Public Health Service concluded that even if the fogging noted on the purchased films was attributed to radiation exposure, the total dose would be less than 5 mrad. Some of these films were from the Middletown, Pa. area, adding further evidence that the offsite population exposures were low, in agreement with the TLD readings.[162]

Met Ed deployed several of its personnel TLD badges around the site as an additional means of determining onsite doses. The data from these badges were compared to the data from the environmental dosimeters. These data were very erratic and the results ranged from a factor of 6 higher to a factor of 10 lower than the environmental monitoring TLD data. No correlation or explanation for these wide variations could be established, so the results could not be used in the population dose assessment.

b. Maximum Individual Offsite Dose

The maximum individual offsite dose would be received by a person near the plant in the path of the

1007164

plume. Based on the TLD data, the maximum dose would be received by an individual located on the east bank of the Susquehanna River. The Ad Hoc Interagency Dose Assessment Group estimated this dose to be 83 mrem (expressed as less than 100 mrem).[163] The Health Physics and Dosimetry Task Group of the President's Commission estimated the dose to be between 20 and 70 mrem.[164] Its estimate included correction factors for occupancy and dosimeter overresponse and is in close agreement with the Ad Hoc Group estimate. Our review of the available data and analytical methodologies employed by both groups verified these estimates.

The highest actual individual offsite dose identified was received by an individual who was on Hill Island for short periods of time during the accident. The Ad Hoc Group calculated a most probable dose of 37 mrem[165] to this individual. The President's Commission estimate was about 50 mrem.[164] Our review of the available data and analytical methodologies used by both groups verified these estimates.

We find that the maximum offsite individual dose was less than 100 mrem.

c. Internal Dose Assessment

Radionuclides that enter the body result in a radiation dose to that individual. The dose is dependent upon many factors, the most significant of which are the degree of uptake, localization, the residence time of the radionuclide(s), and the type and energy of the emitted radiation(s). The routes of intake of radionuclides into the body are well known, and the environmental sampling program before and after the accident is designed to detect and measure radionuclide concentrations in the environment. When these concentrations have been determined, the resultant internal dose to members of the public can be estimated. As described in Section II.B.2.f, the only radionuclides released to the environment in measurable amounts, as a result of the TMI accident, were noble gases and, to a much lesser extent, radioiodines.

Noble gases, when inhaled, do not chemically react within the body, and the major fraction is promptly exhaled. A small amount of the noble gases passes into the blood, a small fraction of which is dissolved in body fat. Even this fraction has a relatively short residence time. Thus, the dose received from internal exposure to noble gas is very small in comparison to the external dose that would be received by a person in or near a cloud of noble gas.

Radioiodines behave physiologically in the same manner as stable iodine. The thyroid gland concentrates and uses iodine. Radioiodine entering the body is taken into the blood; a fraction (about 25%) is taken up by the thyroid gland and remains for a significant period of time.

The report by the Health Physics Task Group of the President's Commission presented internal dose assessments. Based on the maximum concentration measured, hypothetical maximum individual doses were calculated. Because of scarcity of positive data (the majority of the environmental samples yielded negative values, below minimum detectable limit), no population dose assessment from internal exposure was performed.

The Task Group estimated maximum internal doses to individuals offsite from the ^{131}I intake to be 6.9 mrem to the thyroid of a newborn child and 6.5 mrem to the thyroid of a 1-year-old child. On site, they estimated the maximum dose to an adult thyroid to be 53 mrem.[166] The Task Group also estimated maximum internal whole body dose from the other radionuclides, such as ^{133}Xe, to be 0.3 mrem and the lung dose to be 3 mrem. These estimates agree with those reported by the Ad Hoc Group.[167]

Further confirmation of the type of radionuclides released by TMI and the small internal population dose was provided by whole-body counting. Several hundred people residing in the environment of TMI underwent this procedure and all results were negative for radionuclides that could have been released during the accident. We find that the contribution of internal exposure to the population and individual dose was small compared to the dose from external irradiation.

d. Skin Dose Assessment

In case of an immersion in a plume of xenon-133 (the major radionuclide released), the skin dose from beta radiation could be up to four times higher than the whole-body gamma dose.[168] The maximum permissible dose to the skin, however, is six times that of the whole body.[169]

Points of plume touchdown and data from TLDs on integrated beta dose were not reported. In any case, any individual in the plume would have benefited from shielding afforded by clothing. For these reasons, the Health Physics Task Group did not quantitatively assess the skin dose from beta radiation.[168]

The health effects of skin exposure are considerably smaller than those from whole-body exposure. Thus, the possible additional skin exposure would

1007165

not have any discernible effect. The Ad Hoc Group reached similar conclusions.[170]

e. Occupational Exposure

Met Ed reported three accident-related whole-body exposures in excess of the NRC quarterly limit of 3 rem. These doses were 3.9, 4.1, and 4.2 rem. In addition, two workers received overexposures to their hands. These doses have been calculated by the NRC at about 50 rem to skin of the forearm of one worker and about 150 rem to the fingers of the other[171]. The worker who received 150 rem to his fingers is the same individual who received a whole-body exposure of 4.2 rem. (On August 27, 1979, six workers received overexposures to the skin and extremities. The doses, as measured by TLDs, were up to 50 rads to the skin and between 40 and 150 rads to the extremities.)[172]

The potential for severe, additional overexposures existed during the first few days of the accident. Extremely high radiation fields, in excess of 1000 R/h, existed in the auxiliary building.[173] Moreover, unauthorized entries to the building were made in violation of station health physics procedures. Although a person could have been severely overexposed, there is no evidence that anyone was.

The total estimated occupational collective dose through June 30 was about 1000 person-rem.[174] Table II-25 shows the number of individuals monitored and the collective occupational doses received for the period March through September 1979.

Table II-26 shows the number of individuals who received whole-body doses in excess of 100 mrem during the period from March through September 1979. The data in this table were extracted from Met Ed's TLD personnel dosimetry report.

The collective dose received by the 1596 individuals receiving doses in excess of 100 mrem is approximately 800 person-rem. These data show that no individual has received a dose in excess of the allowable annual limit of 5000 mrem.[172] The average dose received by these 1596 individuals was 10% of that limit.

Table II-27 contains the dose accumulation rate for the seven individuals receiving more than 3000 mrem during that 7-month period. The table shows that most of the relatively high individual exposure occurred during the first month after the accident.

The collective occupational dose is smaller than that received by the surrounding population, although it will continue to rise during recovery operations. Moreover, the Health Physics and Dosimetry Task Group of the President's Commission concluded, after its review of the procedures and data regarding the occupational exposures resulting from the accident, that "the available data on occupational exposure at Three Mile Island must be treated with caution. It may be incomplete."[174] We agree with this conclusion.

We find that the accident at TMI-2 resulted in several exposures in excess of regulatory limits to plant personnel in the first few days following the accident. We find further that the collective occupational dose and the extent of overexposure is not large in relation to the radiation fields and contamination levels encountered during the accident, although the actual collective occupational dose is not precisely known.

f. Health Effects of Low Level Ionizing Radiation

The human health effects of ionizing radiation may be classified as: (1) acute somatic effects, (2) developmental or teratogenic effects, (3) late somatic effects, and (4) genetic effects.

Acute somatic effects involve various forms of radiation sickness occurring shortly (a few days or weeks) after whole-body doses of about 100 rad or more. Teratogenic effects involve various kinds of developmental abnormalities following irradiation *in utero*. Such effects have been observed in animals following doses as low as 5 rad[176] and in humans following doses exceeding 50 rad.[177] There is no evidence associating much smaller doses of radiation to developmental effects.[178,179]

The radiation exposures caused by the accident resulted in individual doses considerably smaller than those associated with acute and teratogenic effects. The most important effects of radiation on man which may be caused by low level radiation are those which may appear, or continue to appear, at long intervals of time after exposure in the individual irradiated (late somatic effects) or in his or her progeny (genetic effects). (As used in this report, "low level" or "low dose" refers to doses below individual occupational dose standards of 5000 mrem per year).

Late Somatic Effects — The most important late somatic effect of low doses of radiation is the increase of incidence of cancer. Most human studies on populations exposed to radiation (e.g., atomic bomb survivors in Hiroshima and Nagasaki, radium dial painters) indicate that radiation-induced life

1007166

TABLE II-25. Occupational dose March 1 to September 30, 1979[175]

Month	Number of Dosimeters Distributed	Collective Dose (person-rem)
March	1131	334
April	4504	140
May	5282	350
June	2973	159
July	2500 (approx.)	63
August	2500 (approx.)	63
September	2472	36

TABLE II-26. Occupational doses in excess of 100 mrem March 1, 1979 to September 30, 1979

Dose Range (mrem)	100–250	251–500	501–750	751–1000	1001–2000	2001–3000	3001–4000	4001–5000	More than 5000
Number of Individuals	648	465	213	118	129	16	4	3	0

TABLE II-27. Dose accumulation rate for individuals receiving more than 3000 mrem from March 1, 1979 to September 30, 1979[175]

	Dose (mrem)						
Period	Indiv. A	Indiv. B	Indiv. C	Indiv. D	Indiv. E	Indiv. F	Indiv. G
03/01-03/31	4100	4120	1785	3575	2230	1785	2360
04/01-04/30	160	10	915	40	990	915	1335
05/01-06/30	15	30	45	220	100	45	180
07/01-09/30	30	15	395	70	345	395	210

shortening is largely due to increased cancer mortality.[180,181]

Radiation-induced cancer is detectable only in a statistical sense. A particular case cannot be attributed to radiation[182]. Human evidence for radiogenic cancer comes from epidemiological studies conducted on relatively large population groups exposed to doses much larger than those experienced by the population in the vicinity of the Three Mile Island Station. Numerous animal studies confirm the carcinogenic properties of radiation, but those studies also necessarily involved exposure to relatively large doses. Cancers induced by radiation are indistinguishable from those occurring from other causes. Radiogenic cancer thus can only be inferred on the basis of an excess above the expected natural incidence.

Theoretical considerations suggest that at any level of radiation, no matter how small, some carcinogenic potential exists. Thus far, nearly all human data rely on observations at high dose levels and high dose rates (doses generally greater than 50

1007167

rem and dose rates on the order of rads per minute) and the risk factors given in most scientific publications[183,184,185] are derived from these data. To quantitatively assess the health consequences of the incremental radiation exposure received by the population as a result of the TMI-2 accident, it is necessary to determine how the risk factors derived from relatively high doses and dose rates can be used in estimations of health effects resulting from doses of a few millirads to tens of millirads of low LET radiation. (LET, linear energy transfer, is the average amount of energy lost by particle per unit of track length; low LET radiation characteristics of beta rays (electrons), X-rays and gamma rays, are radiations to which the population in the vicinity of TMI was exposed.)

One way of determining radiation risk factors, which serves as the basis of current radiation exposure standards, is to assume that the effects observed at high doses from high dose rates can be directly and linearly extrapolated to low doses delivered at very much lower dose rates, and that there is no dose (or threshold) below which there is no health risk. Applying these assumptions results in a linear, nonthreshold, dose-rate independent, dose-effect relationship.

The majority of the scientific community considers that the linear, nonthreshold extrapolation represents the upper limit of effects at very low doses, and that the risk factors derived using such an extrapolation probably overestimate the actual risk.[186] This view is stated in relevant publications of the National Academy of Sciences (BEIR I and BEIR III)[185,187] and the United Nations (UNSCEAR 77).[188] Both BEIR I and BEIR III indicate that the actual risk could be appreciably smaller for low level irradiation, and even zero. However, they also indicate that, because of the greater killing of cells at high doses and high dose rates, extrapolations based on effects observed under such conditions may be postulated to underestimate the risks. In most cases, however, the linear hypothesis probably overestimates rather than underestimates the risk from low level, low LET radiation.

BEIR III further states that it is not known whether dose rates of gamma or X-radiation of around 100 mrad/year are detrimental to exposed people; any somatic effects would be indistinguishable from those occurring naturally or caused by other factors. The observed variations in incidence (from place to place and from year to year) are far greater than any likely effect of radiation delivered at such dose rates.

The 1977 UNSCEAR report is consistent with the view of BEIR I and BEIR III that the linear nonthreshold extrapolation describes the upper limit of risk. UNSCEAR concluded that at doses of a few rad, the estimates are likely to be too high and the actual rate might be substantially lower. UNSCEAR also states that the risk from irradiation due to radionuclides deposited within the body is not different from that from external radiation, provided that the absorbed dose to a given tissue is the same from both modes of irradiation. Thus, the risk from the total radiation dose received by the population is the same whether the dose is received from external exposure or from radioactive materials that might have been ingested or inhaled.

Upper limits of possible premature cancer deaths resulting from this accident can be estimated using the linear, nonthreshold dose-response relationship. However, in addition to dose response relationships, several other assumptions must be made in derivation of risk estimates. The ongoing human studies suffer from many imperfections: imprecise dose determination, limited number of subjects, and inability to control variables. Because these studies are not completed, many assumptions have to be made, including: (1) the duration of increased risk following irradiation, (2) latent period (time interval between irradiation and detection of effect), and (3) whether the risk following a given population dose should be expressed by some number of excess cancers, regardless of natural incidence (absolute risk), or as a fractional increase of the natural risk in a given population (relative risk). Because of the numerous assumptions that have to be made, the risk coefficients and risk estimation models published by various scientific organizations differ.[189]

The Radiation Health Effects Task Group of the President's Commission on the Accident at Three Mile Island applied risk factors and models published by various national and international risk assessment bodies, as discussed above, to estimates of doses received by the population as a result of the TMI-2 accident. Table II-28, taken from this Task Group's report, contains the ranges of projected numbers of lifetime excess cancer among the offsite population.[190] This table also shows the ranges of the estimated additional risk of developing cancer by the maximally exposed individuals in the vicinity of Three Mile Island Station. Our analysis yields the same values.

We find, therefore, that it is extremely unlikely that any individual will suffer discernible ill effects, during his or her lifetime, from radiation exposure associated with the TMI accident. The effects on the population as a whole, if any, will certainly be nonmeasurable and nondetectable.

1007168

TABLE II-28. Summary of various projected lifetime cancer numbers or risk estimates for whole-body external gamma radiation doses to offsite TMI population (within 50 miles)*[190]

Source of Estimates Or Risk Factors	Projected Numbers of Cancers At 3000 Person Rem**			Cancer Risk Max. Exposed Person (approx. 70 mrem)**		
	Fatal	Non-Fatal	Total	Fatal	Non-Fatal	Total
Ad Hoc Group	0.6	0.6	1.2	$1.4/10^5$	$1.4/10^5$	$2.8/10^5$
EPA***						
General Pop.	0.3-1.6	0.3-1.6	0.6-3.3	--	--	--
Adults	0.24-0.5	0.24-0.5	0.5-1.0	$(0.7\text{-}1.4)/10^5$	$(0.7\text{-}1.4)/10^5$	$(1.4\text{-}2.8)/10^5$
Children < 10 yr.	0.06-1.2	0.06-1.2	0.12-2.4	$(0.7\text{-}14)/10^5$	$(0.7\text{-}14)/10^5$	$(1.4\text{-}28)/10^5$
Reactor Safety Study						
Upper Bound Model	0.3	0.3	0.6	$0.9/10^5$	$0.9/10^5$	$1.8/10^5$
Central Model	0.06	0.06	0.12	$0.17/10^5$	$0.17/10^5$	$0.34/10^5$
Lower Bound Model	0.0	0.0	0.0	0.0	0.0	0.0
UNSCEAR 1977	0.30	0.30	0.60	$0.7/10^5$	$0.7/10^5$	$1.4/10^5$
ICRP 1977	0.3	0.3	0.6	$0.7/10^5$	0.7^5	$1.4/10^5$

* Values obtained by applying projections or risk coefficients yielded by models in listed reports to TMI dose estimates used in this report.

** 3,000 person-rem 50% higher than most probable actual total collective dose, and 70 mrem the dose the maximally exposed individual estimated by HP&D Task Group.

*** Range for general population the sums of lower range values and upper range values for adults and children < 10 years. Extraordinarily high upper range values for children and general population due to inclusion of causally questionable association of high risk of childhood cancer with in utero diagnostic irradiation and to projection of the assumed high relative risk of radiogenic cancer in children (0-9 years) to the 50+ age group in the BEIR 1972 relative risk model used.

Genetic Effects—When cells are exposed to ionizing radiation, the chromosomes of the cell nuclei may be damaged by the production of gene mutations, involving alterations in the elementary units of heredity that are localized within the chromosomes or by the induction of changes in the structure or number of the chromosomes. When such changes are induced in the germ cells, they may be transmitted to descendants of the irradiated subject. This has been clearly established in experimental studies on short-lived animal species.

Although similar genetic changes may also be induced in humans, none has yet been demonstrated, perhaps because the effect is too small to detect with the data resources available or with present methods of observations. Direct human information is therefore limited.[177] Studies of Japanese children conceived after their parents were exposed to atom bomb radiation have not demonstrated an observable increase in genetic defects.[191] For lack of human data, estimates of the genetic risk to population from low dose and dose rates are based on linear extrapolation from low dose laboratory mouse data. The 1972 BEIR report estimated that spontaneous human mutation rates may be increased between 0.5 and 5.0% per rem of gonadal dose, which is equivalent to a mutation doubling dose of 20 to 200 rem.[192] (A doubling dose is that dose which doubles the frequency of any given effect.) The 1977 UNSCEAR Report provides similar estimates.[193] Although such risk values are difficult to translate into actual health effects, the 1972 BEIR report has estimated that a cumulative dose of 5 rem per generation might be expected in the United States to produce between 60 and 1000 genetically determined illnesses of various sorts per million live births.[49] This would represent a 0.1 to 1.6% increase over the expected incidence of 60 000 cases.

The estimates of genetic effects given in the draft BEIR III Report are not notably different from those cited above: 5 to 75 additional serious genetic disorders per million live births in the first generation following parental dose of 1/rem. Such a parental

1007169

dose will, according to BEIR III estimates, result over all time (i.e., over many future generations) in a total increase of 60 to 1100 serious genetic disorders per million liveborn offspring.[195]

The ranges of risk estimates underscore the limited understanding of genetic effects of radiation on human population. But even the upper values of risk estimates are small compared to the current estimates of the existing incidence of serious human disorders of genetic origin—about 107 000 per million liveborn offspring.[196]

g. Radiation Doses Due To Natural Background and Medical Practice

In estimating the potential health impact of radiation doses received by the population in the vicinity of the Three Mile Island Station, it is useful to maintain a perspective by comparing these doses to radiation doses that the same population receives from other sources, mainly natural background and medical X-ray procedures. Mankind (and all other living things) has been exposed to ionizing radiation since the beginning of time. There are three primary sources of this natural exposure: (1) solar and galactic cosmic radiation, (2) very long-lived radioactive materials present in the earth's crust, and (3) radioactive materials produced by cosmic radiation in the atmosphere. Some of the naturally occurring radioactive materials are chemically indistinguishable from nonradioactive materials normally present in the human body and are therefore always present inside our bodies (e.g., potassium-40, carbon-14).

The average dose to the gonads and bone marrow of people living in areas of normal background radiation is shown in Table II-29. The average annual dose in the United States, shown in Table II-30, is not significantly different. The doses in these tables are averages. Natural background radiation varies widely; even large local variations are possible, as shown in Tables II-31 and II-32. People living at high altitudes or in areas of high external terrestrial radiation receive much higher doses.[197]

On the basis of a nationwide survey conducted by the U.S. Department of Health, Education, and Welfare, it is estimated that in 1970, out of a population of 200 million persons, 130 million had one or more X-ray examinations.[198] The most commonly performed procedures, radiographic chest examinations and dental examinations, result in a mean dose to total active bone marrow of about 10 mrad per examination. The annual per capita rate for each of these examinations is about 0.3. Some other examinations, although performed with lesser frequency, cause much higher mean marrow doses; e.g., upper GI series, 535 mrad; barium enema, 875 mrad; pelvimetry, 595 mrad. It is estimated that in 1970 the active marrow dose per each adult in the U.S. population from medical X-ray procedures was approxi-

TABLE II-29. Global annual per capita doses from normal exposure to natural sources of radiation (in mrad)[199]

Radiation Source	Gonads	Active Marrow
External Irradiation		
Cosmic rays	28	28
Terrestrial radiation	32	32
Internal Irradiation		
Potassium-40	15	27
Radon-222	0.2	0.3
Other Nuclides	2	4
ROUNDED TOTAL	78	92

TABLE II-30. Average annual doses from natural natural background radiation in the United States (in mrem)[200]

Radiation Source	Gonads	Active Marrow
Cosmic radiation	28	28
Cosmogenic radionuclides	0.7	0.7
External terrestrial	26	26
Radionuclides in body	27	24
ROUNDED TOTALS	82	79

TABLE II-31. Selected estimates of natural "background" radiation levels in the United States (annual dose rate [mrem/year])[201]

Location	Cosmic Radiation	Terrestrial Radiation	Internal Radiation	Total
Atlanta, Georgia	44.7	57.2	28	130
Denver, Colorado	74.9	89.7	28	193
HARRISBURG, PENNSYLVANIA	42.0	45.6	28	116
Las Vegas, Nevada	49.6	19.9	29	98
New York, New York	41.0	45.6	28	115
PENNSYLVANIA	42.6	36.2	28	107
Washington, D.C.	41.3	35.4	28	105
UNITED STATES (range)	40–160	0–120	28	70–310

TABLE II-32. Examples of differences in annual doses due to natural background variations[202]

Natural Background Variation	Estimated Difference in Annual Doses
Living in Denver, Colo. compared to Harrisburg, Pa.	+ 80 mrem/yr
Living in a brick house instead of a wood frame house	+ 14 mrem/yr
Added dose from potassium-40 due to being male instead of female (There is 25% less potassium in women than men.)	+ 4.8 mrem/yr

mately 100 mrad.[203] The genetically significant dose (GSD) from medical X-ray procedures is estimated at 20 mrem per person in 1970.[204] (GSD is the gonad dose from medical exposure that, if received by every member of the population, would be expected to produce the same total genetic effect on the population as the sum of the individual doses actually received.) This lower estimate is due to the fact that in most X-ray procedures the dose to the gonads is lower than the mean marrow dose, and in calculation of GSD, the dose to the gonads is weighted, based on the expected number of future children that the irradiated individual will have.

In addition to natural background and medical X-ray procedures, there are other sources of radiation exposure to the general population; e.g., diagnostic use of radiopharmaceuticals, consumer products containing radioactive material, and air travel. The contribution of these radiation sources to the total population dose is small compared to the dose due to natural background and medical X-ray procedures. The average dose, of 1.4 mrem, received by the approximately two million people as a result of the TMI-2 accident is less than 1% of the annual dose from both natural background and medical practice.

h. Cancer Incidence and Mortality in the United States

Cancer is the second leading cause of death in the United States, after heart disease. In 1976, there were 377 312 reported deaths in the U.S. from

1007171

cancer, which corresponds to 175.8 cancer deaths per 100 000 people and accounts for 19.8% of all deaths.[205] The American Cancer Society estimated that in 1979 there would be 765 000 new cases of cancer in the United States and 395 000 people will die from it, which corresponds to the death rate of 180 per 100 000 people.[206] The estimated cancer death rate for the United States varies from 57 in Alaska to 250 in Florida (not adjusted for population age distribution). The estimated death rate in Pennsylvania is 208.[207] Based on this estimate, we calculate that among the more than two million people living within 50 miles of the Three Mile Island Station, there will be approximately 4000 cancer deaths per year unrelated to the accident.

The American Cancer Society estimates that, if the present rates continue, 25% of all people in the United States will eventually develop cancer and 15% will die from it.[208] Applying these approximate statistics to the population within 50 miles of the Three Mile Island Station indicates that approximately 325 000 people in that area would normally die of cancer.

The natural incidence of cancer varies considerably depending on the type and site of the cancer, age, sex, geographic location, dietary habits, environment, and other factors. Because cancers induced by radiation are indistinguishable from those occurring naturally, it is usually impossible to determine in cases of low level radiation exposure if this radiation was causative in induction of a few of the many thousand cancer cases normally expected in a given population.

I. Summary of Health Effects

Our analysis of the potential health effects resulting from radiation exposure due to the TMI-2 accident is in accord with the conclusion of the Radiation Health Effects Task Group of the President's Commission.[209] As a result of the radiation exposure to the offsite population within 50 miles of the TMI site, the projected incidence of fatal cancer is less than one; and fatal plus nonfatal cancers is less than 1.5, with zero not excluded. This projection is to be contrasted to the nearly 541 000 cancers (325 000 fatal and 216 000 nonfatal) expected in this population over its remaining lifetime that are not related to the TMI accident.

The additional lifetime fatal cancer risk to the individual receiving the maximum probable dose offsite (less than 100 mrem) is about 1 in 100 000. The additional risk of fatal cancer to an individual receiving the average offsite dose (1.4 mrem) is about 1 in 5 000 000. This risk is additive to the existing risk of fatal cancer of about one in seven. The risk of nonfatal cancer is about the same as the risk of fatal cancer, and the combined normal risk is about one in four.

The additional cancer risks due to internal irradiation and skin irradiation are very small compared to the above values and can be regarded as being included in the values presented above for whole-body gamma irradiation. Even if the cancer risks defined above were to be expressed, the resultant cancers would not be detectable among the population in the vicinity of TMI-2. (Note that zero additional incidence is not excluded.)

The whole-body external occupational exposure of 1000 person-rem has potential total cancer risk of less than 0.5 (zero not excluded). The risk to the maximally occupationally exposed individual (4.2 rems) is about 1.2 in 1000 for both fatal and nonfatal cancers.

The potential incidence of genetically related ill health is considerably smaller than that of producing a fatal or nonfatal cancer. This risk is estimated to be about 0.002 cases per year, and about one case per million live births for all future human existence. This contrasts with an estimated 3000 cases per year of genetically related ill health among the offspring of the population in the vicinity of Three Mile Island based on present birth rate (28 000 births per year), and not related to the accident.

In our view, the fact that there will be no, or very minimal, adverse health effects from the accident has not been understood by the public. We believe that the public misconception that the risks associated with this accident, and with radiation in general, are much greater than they are in fact is due to the failure to convey credible information regarding these risks in an understandable form. Thus, we believe that substantial efforts are necessary to educate the public to eliminate the apparent gap between "real" and "perceived" risks of radiation.

Summary of Findings

We find that:

- despite the uncertainties in the offsite TLD data, it was adequate to characterize the magnitude of the collective dose to the population (Section II.B.4.a);
- the collective dose as determined by the TLDs is within the ranges estimated by the Ad Hoc Interagency Dose Assessment Group and the Task Group of the President's Commission. Correcting for occupancy factors, shielding, and reductions in the population due to voluntary evacuation, the

1007172

population dose is believed to be somewhere in the lower end of those ranges, about 2000 person-rem.

- the maximum offsite individual dose was less than 100 mrem (Section II.B.4.b);
- the contribution of internal exposure to the population and individual dose was small compared to the dose from external irradiation (Section II.B.4.c);
- the accident resulted in several exposures in excess of regulatory limits to plant personnel in the first few days following the accident (Section II.B.4.e);
- the collective occupational dose and the extent of overexposure is not large in relation to the radiation fields and contamination levels encountered during the accident (Section II.B.4.e); and
- it is extremely unlikely that any individual will suffer discernible ill effects, during his or her lifetime, from radiation exposure associated with the TMI-2 accident. The effects on the population as a whole, if any, will certainly be nonmeasurable and nondetectable. (Section II.B.4.f).

5. RADIATION PROTECTION PROGRAM

The production of power by nuclear energy entails exposure to radiation of plant personnel, as well as a risk of exposure to the general public. The primary functions of a radiation protection, or health physics, program are to maintain those exposures below limits specified in applicable Federal and State regulations and as low as reasonably achievable (ALARA).

The potential for exposure to both onsite and offsite populations increases under non-normal conditions: when the plant is undergoing major maintenance or refueling, or accident conditions. Consequently, radiation protection functions assume greater importance during such conditions.

Exposure and resultant doses can be kept ALARA by proper engineering design, good work practices, monitoring, and preplanning of the tasks to be performed. A good radiation protection program requires a concerted effort and mutual understanding on the part of management, operations, and radiation protection personnel. The program also requires an adequate staff of well-trained individuals who are supplied with appropriate instrumentation and protective devices and who have the authority to control access to radiation areas. An effective program also includes continual training and refresher courses for all plant personnel, maintenance of equipment, personnel monitoring, and the maintenance of accurate exposure records.

Fulfillment of these radiation protection functions and goals, especially during normal power operations, entails a large amount of routine work; for example, the conduct of area radiation surveys; wipe testing for contamination control; collection and analyses of air and water samples; maintenance of access control to radiation areas; issuance and control of dosimetric devices; maintenance of dosimetry records; and calibration of instruments.

Radiation protection is frequently perceived as no more than a "meter reading" and sample collecting function. The management at Three Mile Island Station, as well as a large segment of the nuclear industry, had this misconception. Radiation protection was regarded as distinctly secondary in importance to power operations and a "necessary evil." The NRC similarly did not attach great importance to radiation protection.

The radiation protection program at Three Mile Island Station was seriously deficient. Many of its deficiencies were made evident by the accident, but they were, or should have been, known well before March 28, 1979. The Three Mile Island Station program, although apparently below average, was not significantly worse than radiation protection programs at other nuclear power stations. The NRC's regulation of radiation protection programs has similarly been inadequate.

a. The Regulatory Framework

The NRC has promulgated regulations regarding radiation protection programs in 10 C.F.R. Parts 19, 20, and 50. In addition, the NRC Regulatory Guides (particularly Series 8 Guides) and Standard Review Plans (particularly Chapters 12 and 13) provide guidance regarding radiation protection programs.[210] Industry standards are established by the American National Standards Institute (ANSI). Other guidance is provided by sources such as the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurement (NCRP), and the U.S. Bureau of Mines.

The technical specifications, a part of the operating license, require that a utility establish and maintain a radiation protection program that complies with 10 C.F.R. Part 20. The NRC's Office of Nuclear Reactor Regulation (NRR) approves the procedures that the utility initially establishes and any modification or amendment of them. The NRC's Office of Inspection and Enforcement (IE) reviews the operation of the radiation protection program.

1007173

The technical specifications for TMI-2 carry only minimal specific reference to the radiation protection program. Section 6.11 states:

> 6.11 RADIATION PROTECTION PROGRAM*
>
> Procedures for personnel radiation protection shall be prepared consistent with the requirements of 10 C.F.R. Part 20 and shall be approved, maintained, and adhered to for all operations involving personnel radiation exposure.[211]

The NRC staff reviewed Met Ed's radiation protection program proposed in Chapter 12 of the TMI-2 FSAR[212] and discussed the review in Section 12 of the Safety Evaluation Report (SER).[213] It appears that the NRC staff review of radiation protection programs, including Met Ed's, focused on their adequacy in the conduct of normal and anticipated operational occurrences.[214] "Anticipated operational occurrences" are defined by NUREG-0115 and NUREG-0117 as "unplanned releases of radioactive material from miscellaneous actions such as equipment failures, operator error, administrative error, that are not of consequence to be considered an accident." It was implicitly assumed by the NRC staff that the program and procedures developed for normal operation would readily extrapolate to abnormal conditions. The error in this assumption was demonstrated by the accident at TMI-2.

b. Implementation and Weaknesses of the Radiation Protection Program

The deficiencies in TMI's radiation protection program, as well as the weaknesses in NRC regulation and the radiation protection response to the accident are discussed below.

Design— Consideration of radiation protection is a central part of the design of a nuclear power station. Traditionally, consideration of design has been focused on providing shielding and radiation protection facilities adequate to support normal operations and anticipated operational occurrences. During the course of the accident, the plant's design bases were exceeded, resulting in serious radiation protection problems. As a consequence, the role of radiation protection in design will have to be increased.

Shielding— The NRC staff's shielding design review[215] concluded that expected exposure to operating personnel was consistent with the requirements of 10 C.F.R. Part 20 and the ALARA concept during normal operations and anticipated operational occurrences. Met Ed classified plant areas into radiation zones based on maximum design dose rates and expected frequency and duration of occupancy. It described the location, size, and shape of significant sources of radiation in the auxiliary and fuel handling buildings and the containment structure. Source term calculations were based on: (1) 2772-MW thermal power, (2) a failed fuel rate of 1%, and (3) an acceptable set of estimated leakage rates and partition factors. Pipes, demineralizers, tanks, evaporators, pumps, and sampling points containing radioactive materials were located in shielded areas or compartments, and Met Ed proposed to use labyrinths, shield valve galleries and penetrations, reach rods, remote valve actuation, and portable shielding to maintain exposures ALARA. The assumptions used in Met Ed's shielding calculations were considered conservative and acceptable to the NRC staff.

The NRC staff's review of TMI-2 considered shielding for the primary coolant sample lines within TMI-2 but did not consider shielding these lines when they passed into TMI-1 where the primary coolant sampling room that serves both units is located. The highly radioactive primary coolant resulting from the accident and the failed TMI-2 fuel produced high radiation fields in TMI-1, reducing accessibility in those areas through which the lines passed. We find that the design of TMI-2 and the NRC staff's review of this design did not adequately consider the relationship between TMI-1 and TMI-2.

Although the NRC staff's conclusions regarding the adequacy of shielding design were valid for normal operation, highly radioactive primary coolant and wastewater were contained in the piping and tanks during the accident and produced radiation levels higher than anticipated by the design bases. We find that the shielding was not adequate to cope with the accident.

Ventilation Systems—The NRC staff's review of the TMI-2 ventilation systems[216] concluded that their design would ensure that personnel were not exposed to normal or abnormal airborne concentrations exceeding those in 10 C.F.R. Part 20, and was consistent with the ALARA concept by: (1) maintaining air flow from areas of low radioactivity potential to areas of high radioactivity potential, (2) preventing recirculating air in the auxiliary and fuel handling buildings, (3) maintaining a negative pressure in the auxiliary and fuel handling buildings with respect to the atmosphere, and (4) periodically purging the containment structure with outside air through high efficiency particulate air and charcoal filters. Various other areas of the plant contained

1007174