RADIOLOGICAL CONSEQUENCES OF THE THREE MILE ISLAND ACCIDENT

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SITE AND ENVIRONS

The Three Mile Island Nuclear Station (TMI) is located on an island in the Susquehanna River approximately 14 km southeast of Harrisburg, Pennsylvania. The station is operated by a private utility, the Metropolitan Edison Company, and consists of two reactors, Unit 1, a 2535 megawatt (thermal) pressurized water reactor (PWR), and Unit 2, a 2772 megawatt (thermal) PWR. Unit 1 went into commercial operation on September 2, 1974 and Unit 2 went into commercial operation on December 30, 1978, approximately 3 months prior to the accident.

Three Mile Island is one of a number of islands in the Susquehanna River. It is located approximately 275 m from the east bank of the river and approximately 2 km from the west bank. Several private residences are located along the east shore within 0.8-1.2 km of the reactor buildings. Approximately 200 summer cottages are located on the nearby islands. Goldsboro, a community of approximately 900 people, is situated approximately 1.9 km west of the site and Middletown (approximately 10,000 people) is located 4.0 km to the north. Major population centers in the area are Harrisburg ($\sim$70,000 people) which is 14 km NW and York ($\sim$50,000 people) which is 21 km South. There are approximately 2,000,000 people residing within 80 km of the TMI site.

THE ACCIDENT

Three Mile Island Unit 2 was operating at 97 percent (916 MWe) of its licensed power level on the morning of March 28, 1979. At 0400 a series of events resulted in a substantial loss of primary coolant and the reactor's core being partially uncovered for several periods during the next 16 hours. High cladding temperatures resulted in metal-water reactions between the zirconium fuel cladding and the water (or steam). Oxidation and failure of the cladding resulted, releasing substantial quantities of fission products into the coolant and production of hydrogen. A primary coolant sample collected on March 29 shows the degree of the fission product contamination (Table I).

RADIOACTIVE MATERIALS RELEASED: PATHWAY AND QUANTITY

The fission products released to the coolant were transported to the auxiliary building in the primary coolant through the normal coolant purification system. The noble gas radionuclides and a fraction of the radioiodines were stripped into the gas phase and leaked into the supporting equipment buildings. Ventilation air transported these gases to the auxiliary building stack (10 feet below the top of the containment building) through high efficiency particulate filters (HEPA) and a charcoal absorber.

Although substantial noble gas activity was released, estimates range from 2.4-14 MCi, the water-to-air partition process and the filters reduced radioiodine release, estimated to be 15 Ci. The distribution of the noble gases released is shown in Table II, along with the core inventory of these radionuclides at the time of the accident.

TABLE I. The Major Radionuclides in a Sample of Reactor Coolant Taken on March 29, 1979.*

Nuclide	Half Life	Coolant Concentration μCi/cc
Iodine-131	8 d	1.3×10^4
Iodine-133	20.8 h	4.6×10^4
Cesium-134	2 y	6.3×10^1
Cesium-136	13 d	1.8×10^2
Cesium-137	30 y	2.8×10^2
Barium-140	12.8 d	21.0×10^1
Strontium-89/90	50 d/29y	5.3

*Reactor coolant sample taken at approximately 1700 on March 29. Sample was analyzed by the Bettis Atomic Power Laboratory, Pittsburgh, Pa.

TABLE II

Radionuclides Released to the Environment as a Result of TMI-2 Accident.

RADIONUCLIDE	HALF-LIFE	QUANTITY IN CORE AT TIME OF SHUTDOWN (Curies)	QUANTITY RELEASED ESTIMATED (Curies)	ESTIMATED FRACTION OF TOTAL RELEASED
Kr-88	2.8 hours	6.92×10^7	3.75×10^5	0.15
Xe-133	5.2 days	1.42×10^8	1.58×10^6	0.63
Xe-133m	2.2 days	2.11×10^7	2.25×10^5	0.09
Xe-135	9.1	3.31×10^7	3.0×10^5	0.12
Xe-135m	15.3 min.	2.60×10^7	2.5×10^4	0.01
I-131	8.0 days	6.55×10^7	15	*

* On an estimated fractional basis of total nuclides released, iodine-131 was very small.

Almost all (99%) of the noble gas emissions occurred in the period from March 28 until April 1 and 70% of these releases occurred within the first 36 hours. Radioiodine releases persisted until the end of April due to evaporation of liquids in the auxiliary building and degeneration of the charcoal filter performance.

Releases of fission products in liquid effluents were very small and consisted primarily of radioiodine and cesium-137. The total activity released in liquid effluents during the first three months following the accident was 0.23 Ci of iodine-131 and 0.24 Ci of other radionuclides.

RADIOLOGICAL MONITORING RESULTS

The U.S. Nuclear Regulatory Commission requires all reactor licensees in the United States to have an environmental monitoring program. In addition, each reactor is to have an emergency plan. Once it was realized that significant radiological releases might occur, the licensee dispatched teams to determine radiation levels offsite, particularly in the anticipated plume direction. Several State and Federal agencies also responded to the emergency and established environmental monitoring programs, sampling air, milk, water, vegetation, foodstuff and deploying additional thermoluminescent dosimeters (TLD's). The U.S. Department of Energy (DOE) used helicopters for tracking and measuring the activity in the plume. Metropolitan Edison used helicopters for monitoring on the site. During the 3 months following the accident, several thousand sample analyses were performed by the Commonwealth of Pennsylvania and several U.S. Federal agencies including the Department of Health, Education and Welfare, Bureau of Radiological Health and the Environmental Protection Agency.

Environmental

As a result of increasing in-plant radiation levels, beginning around 0700 on March 28, monitoring teams were dispatched to make radiation measurements outside the plant both onsite and offsite. Initial measurements made onsite starting at 0748 and offsite starting at 0832 were less than the minimal detectable level of the instruments (1 mR/hr). Radiation levels first began to increase at 1020 on March 28 when onsite monitoring teams detected exposure levels of 3 mR/hr. The instruments used for the offsite survey were Geiger-Muller detectors and ion chamber (RO-2) survey type instruments. Many of the reported readings were open window measurements and reported as β,γ-mR/hr, which is an undefined exposure rate. Where "β,γ" readings are known, they are so indicated. The instruments were not calibrated against a beta source, nor were they calibrated for an immersion situation. What the influence is on the total reading of the beta component is not known. These levels generally increased over the next 12 to 13 hours. Peak onsite radiation exposure rates of 300-365 (β,γ) mR/hr were reached between 2130 and 2330. Offsite radiation exposure rates were generally very low (maximum of 3 mR/hr). A reading of 50 mR/hr measured along the east river bank at 1548 was the highest reported offsite exposure rate. Noble gas emissions continued to be high until late in the morning of March 29. A reading of 30 mR/hr was recorded in Goldsboro (1.9 km WSW) at 0600 on March 29.

The maximum onsite dose rate on March 29 was 150 mR/hr (β,γ) at 0532. During the remainder of March 29, onsite levels were generally less than 10 mR/hr and offsite levels less than 1 mR/hr and did not exceed 2 mR/hr. Wind direction throughout the night of March 28-29 was generally in a northwesterly direction (toward Harrisburg). During the afternoon of March 29, a helicopter above the stack measured 3 R/hr (β,γ), 400 mR/hr gamma.

A second period of noble gas emissions occurred on March 30-March 31. This release resulted from intentional venting of the waste tanks in the auxiliary building required to reduce excessive pressure buildup in the tanks. Onsite exposure rates associated with this release reached a peak of 110 mR/hr. The highest offsite levels were 5-15 mR/hr at a point approximately 1.6 km to the south. However, a helicopter reading taken ~40 meters above the stack was 1.2 R/hr (β,γ) at 0800 hours. The reading could not be repeated, indicating a probable puff release.

Radioiodine Analyses

Offsite radioiodine was detected in analyses of milk samples collected for the first seven days following the accident with 68 positive iodine-131 results out of 264 samples collected. The concentrations ranged from 1 to 41 pCi/l (the 41 pCi/l was in a sample of goat's milk, which was not used for human consumption). In the subsequent 2 weeks, only 8 out of 80 samples taken by the U.S. Food and Drug Administration yielded positive results. Concentrations ranged from 15-36 pCi/l.

Initial measurements of airborne radioiodine concentrations made using portable air sampling equipment having charcoal adsorption cartridges were reported as 10^{-9}-10^{-10} μCi/ml at Goldsboro at 0900 and 0940 on March 28. However, laboratory gamma spectrometric analysis of the second cartridge by the Pennsylvania Bureau of Radiation Protection showed that this activity was primarily due to xenon-133 and xenon-135 and that actual radioiodine concentrations were less than 10^{-11} μCi/ml. The highest reported offsite radioiodine concentrations and measurable deposition occurred in mid-April in conjunction with replacement of the effluent filters in the auxiliary building, onsite 4 x 10^{-10} μCi/ml, offsite 1 x 10^{-10} μCi/ml.

In Plant

The highest radiation levels encountered by Met Ed personnel were in the auxiliary and fuel handling buildings. Radiation levels in excess of 1000 R/hr were measured during the first days of the accident at entrances to the cubicles containing tanks of primary coolant. General area radiation levels in these buildings ranged from 5 R/hr to 100 R/hr. Radiation levels in the reactor control room and other areas were generally low, less than 0.5 mR/hr. Due to the airborne activity (noble gases) in the Health Physics Control Station, counting and gamma spectrometry facilities had to be evacuated.

Population Exposure

The ground surveys that were performed and the analyses of local foods indicated that there was no measurable deposition of radioactive materials released from TMI. Of primary concern, however, was the need to assess the dose to the population and evaluation of the potential long-term consequences.

As part of Metropolitan Edison's environmental monitoring program, 20 TLD stations both on and offsite were located around the site at the time of the accident at distances up to 22 km. In addition, ten stations had a quality control TLD of a different type. Commencing on March 31, the Nuclear Regulatory Commission (NRC) placed an additional 37 TLD's around the TMI site. These were analyzed daily for a period of one week and at longer intervals thereafter.

The first evaluation of the population dose was performed by Battist, et. al[2], using the TLD's in place at the time of the accident and those subsequently placed by the NRC. This was accomplished by an interpolation equivalent to plotting the measured doses for each sector on logarithmic coordinate graph paper and joining the measured values by straight line segments. The intersection of each line segment with a standard distance for the grid was taken as the dose at that distance. In instances where the net dose calculated for a location was not greater than zero, this method could not be used. In such cases, linear interpolation was used to estimate the doses at standard distances.

Doses at distances beyond the outermost dosimeter or within the innermost dosimeter were estimated by extrapolation using the assumption that the dispersion in a sector is proportional to distance to the (-1.5) power. A DOE analysis concludes that their airborne measurements and the TLD data suggest a more rapid decrease of exposure with distance, more consistent with an exponential function or a power function with an exponent of (-2). The (-1.5) power assumption is therefore conservative, yielding a higher collective dose.

Doses for the standard distances in sectors in which no measurements were made were estimated by interpolating linearly between the dose values of the adjacent sectors for which measured data were available.

The mean dose within each sector segment was estimated by weighting the dose, H(r), by the area within the sector

$$\bar{H} = \frac{\int_{r_1}^{r_2} H(r)\,r\,dr}{\int_{r_1}^{r_2} r\,dr}$$

where $\bar{H}$ is the mean dose, H(r) is the dose as a function of distance, r, and r_1 and r_2 are the inner and outer radii of the sector segment, respectively.

The collective dose for each sector segment is the product of the corresponding mean dose and the population in that sector. The sum of the collective doses for all sector segments and periods is the total collective dose for the entire assessment area for the total period under consideration.

Utilizing the available TLD data, a range of collective dose equivalent estimates were determined. These values ranged from 1600 to 5300 person-rem, with the most probable value being 3300 person-rem. This range resulted from different sets of dosimeter data used in individual determinations.

The highest value, 5300 person-rem, was the result of including all of the NRC and Metropolitan Edison dosimeters. However, the first day's set of NRC TLD data contained several inconsistencies. Later analyses[3] indicated that these dosimeters were most likely exposed prior to deployment and that no controls were included to evaluate these effects. Use of the Metropolitan Edison dosimeters, including the quality control badges, resulted in a collective dose equivalent of 3300 person-rem. The other two values, 2800 and 1600 person-rem, were obtained by using the TLD data within 10 km of the plant; first including all of the TLD data, and later by excluding the NRC TLD data.

A second evaluation of the TLD data was performed by Auxier, et. al.[3] Their estimate of the collective dose equivalent was 2800 person-rem. Taking into account the shelter factor for the low photon energy of xenon-133 reduced the collective dose equivalent estimate to 2000 person-rem.

The agreement between these independent analyses is quite good, and the collective dose equivalent is in the range of 1600-3300 person-rem. Attempts were also made to determine the collective dose equivalent using meteorological dispersion calculations.

In-Plant Exposures

Although high radiation fields existed in the auxiliary building, and several entries were made, only three individuals exceeded NRC's quarterly whole-body exposure limits of 3 Rem. The exposures were 4.1, 3.6, and 4.2 Rem, respectively. In total, during the seven-month period following the accident, only seven individuals received doses in excess of 3 Rem. The total collective occupational exposure through September 30 was approximately 1200 person-rem.

In August 1979 several workers were contaminated by beta activity when working in contaminated areas. Extremity exposures were high, approximately 40-50 Rem, due to residual contamination. No whole-body exposures in excess of regulatory limits were reported.

DISCUSSION

Although the accident at TMI Unit 2 was the most severe reactor accident to date, the release of several megacuries of radioactive noble gases resulted in a relatively small population exposure estimated to be in the range of 1600 to 3300 person-rems, as determined from TLD measurements. The sparseness of the data and the extrapolation of individual dosimeter results to assess the dose to the population in a large sector contribute to the uncertainty. However, the continual low offsite exposure readings, lack of residual ground activity and other dosimeters placed in the environs of the site by Federal agencies all tend to confirm that the population dose could not have been significantly different than that defined above. The maximum individual offsite dose was stated to be less than 100 mrem in the Ad Hoc group study,[2] and about 50 mrem by Auxier, et.al.[3]

In-plant personnel exposures have been maintained at reasonable levels. The fact that only three overexposures were recorded on the first two days of the accident is remarkable in view of the high radiation fields that existed. However, the cleanup operations could result in a significant collective worker dose unless significant health physics control is exercised.

The defense-in-depth concept under which nuclear plants are designed worked well in practice. Radiological releases were quite small in view of the magnitude of the fuel damage. The containment building, requirement of filtered pathways, and backup systems all functioned to minimize the potential radiological consequences. However, the accident indicated that better health physics instrumentation and personnel training is required to obtain more meaningful survey results and to control in-plant exposures.

HEALTH EFFECTS

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 1; and fatal plus non-fatal cancers is less than 1.5, with zero not excluded. This is to be contrasted to the nearly 541,000 cancers (325,000 fatal and 216,000 non-fatal) expected in this population over its remaining lifetime, 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 individual offsite dose (1.4 mrem) is about 1 in 5,000,000. The risks of non-fatal cancer induction are the same as those for fatal cancers.

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. (Note that zero additional incidence is not excluded.)

The whole-body external occupational exposure of 1,000 person-rem has potential total cancer risk of less than 0.5 (zero not excluded). The risk to the maximally occupationally exposed individual (4.1 rems) is about 1.2 in 1,000 for both fatal and non-fatal cancers.

The potential incidence of genetically related ill-health is considerably smaller than that of producing a fatal or non-fatal 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 3,000 cases pwer year of genetically related ill health among the offsprings of the population in the vicinity of TMI based on present birth rate (28,000 births per year), and not related to the TMI 2 accident.[5]

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