

**A Review
of
Dose Assessments
at
Three Mile Island
and
Recommendations
for Future
Research**

Prepared for the TMI Public
Health Fund

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August 15, 1984



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Preface

At the request of the Three Mile Island Public Health Fund*, this critical study of the public literature on TMI dose assessments has been prepared to help the Fund decide whether or not any further scientific work needs to be undertaken in connection with dose assessments. Because it has become clear in carrying out this review that significant issues do remain unresolved--issues that might bear on the ultimate health effects projected to occur as a result of the accident--recommendations have been developed that indicate how gaps in the literature on the TMI dose assessment might be closed by further research and analysis. These recommendations are found at the end of the report in the form of proposed projects relating to each issue judged unresolved by this review.

The findings of this report, and necessarily the recommendations based on them, are preliminary in nature, based on information and analysis of the TMI accident dose

*The Three Mile Island Public Health Fund was established as a result of a settlement of litigation surrounding the Three Mile Island accident, In re: Three Mile Island Litigation, C.A. No. 79-0432 (M.D.Pa., November 9, 1981). The purpose of the Fund is to investigate possible detrimental consequences of the accident and to improve radiation monitoring and emergency planning in the TMI area, as well as to investigate the health effects of low level radiation and to develop a program of public education on the operation of the facility at TMI. The Fund is under the supervision of Judge Sylvia H. Rambo, United States District Judge for the Middle District of Pennsylvania. The Fund is being administered by David Berger, Attorneys At Law, chief counsel for the Fund.

assessment literature in the public domain. Such findings are subject to modification as more information becomes available. In order to bring to light as much new information as possible, the following next steps are recommended to the Public Health Fund.

1) That a dosimetry workshop be convened, with invitations to all researchers reviewed in this study as well as specialists with expertise in relevant areas. This workshop would provide an opportunity for investigators to clarify their work and to respond to questions raised about their analyses. The exchange of ideas promoted might in itself resolve a number of uncertainties that still exist as to the assessment of doses at Three Mile Island. In addition, the workshop attendees would be invited to comment upon projects proposed to deal with remaining uncertainties.

Depending upon the outcome of the workshop, an update of this report may be desirable.

2) That as part of the preparation for the workshop, the Fund commission and distribute to the attendees a series of preliminary quantitative calculations so that the relative importance of the issues raised in this report can be assessed and commented upon at the workshop. These proposed calculations, which are included as part of Section 7.0, consist primarily of preliminary analysis of data collected after the TMI accident, but not utilized by previous investigators.

3) That in conjunction with the publication of the report, a call be issued for additional information not yet incorporated into the public record. If sufficient data are made available, an addendum to this report would be appropriate.

4) That those proposed projects that are the most time-crucial (e.g. monitoring of cleanup efforts) be developed and instituted as soon as possible and that other projects be reviewed for implementation by the TMI Health Fund.

1.0 Introduction

Presented in this report are the results of an extensive study of the public literature on the radiological aspects of the Three Mile Island accident. The study set itself three basic objectives. The first objective was to search out, bring together, and review critically all information in the public record relevant to estimating the release of radioactive material from Three Mile Island and the consequent dose of radiation to the exposed population. The second objective was to locate and bring together all important yet unanalyzed public information related to dose assessment for possible later analysis and calculation. The third objective of the study was to develop a series of recommendations to the Public Health Fund for future projects in the dose assessment area. (These projects are discussed in Section 7.0.)

As will be shown in this report and documented in the appendices, a great number of questions remain about the radiation doses caused by the accident. Because the major studies on this subject were undertaken in the months soon after the March 28, 1979 accident, and completed under considerable pressure for immediate findings and reassurances, it is not surprising that these official studies cannot provide complete, scientifically justifiable answers. Subsequent studies in the scientific and engineering literature have not resolved the residual uncertainties.

Some of the questions that remain about the radiological aspects of the accident may never be answered, but a great many may be answerable upon successful completion of the research projects proposed at the end of this report.

Problems remain, it should be emphasized, not because investigators have been incompetent. On the contrary, the investigators reviewed in this study were found to have been extremely clever in using a combination of inference and science to extract information from limited data. Problems remain because a great deal of crucial data does not exist, or is unreliable. Researchers have been forced to replace the missing information with assumptions and to manipulate, as best they can, the unreliable data. It is hoped that this review, by bringing together the full range of dose estimates provided in the literature and by highlighting, often critically, the assumptions and methods employed to reach those estimates, will serve as a first step in reaching a better understanding of the radiation-induced health consequences of the TMI accident.

It should be noted that this report does not critically examine the quantitative connection that is made in the TMI literature between radiation doses and projected health effects. The only detailed discussion of health effects found in this report (in section 6.0), is connected with clarifying how the health effects projections that accompany published dose assessments would have changed had an uncer-

tainty range been assigned that encompasses all of the dose estimates found in the literature. Thus, this report is concerned with the first step in projecting health effects, i.e. dose assessment.

The report is organized as follows: after a description of the literature upon which the report is based, all dose assessments located in the literature are presented. The next sections outline the problems with the existing dose assessments (with reference to the Appendices where more complete and technical reviews are provided). In Section 7.0, proposed projects, designed to answer many of the outstanding questions, are listed and described. A bibliography of relevant papers and reports makes up the final section.

As has been indicated, supporting documentation for the conclusions and recommendations is contained in the appendices.

Appendix A, which has been written for the non-specialist, reviews and evaluates the literature on the doses resulting from noble gases. Appendix B (which is primarily technical) outlines a method, unavailable to early investigators, to make use of inventory accounting calculations during the deliberate venting of Krypton-85 from the containment building atmosphere in 1980 as a check on calculated noble gas releases from the time of the accident. This appendix has been prepared based on research carried out

by Daniel Pisello, Ph.D. Appendix C, which like Appendix A has been written for the non-specialist, reviews and evaluates the literature on doses to the thyroid resulting from the release of radioiodine to the atmosphere and also reports on a selection of published but incompletely analyzed data.

Technical Appendix D compares inhalation and ingestion pathways for radioiodine in cows. This comparison has proved helpful in assessing the importance of discrepancies that exist in studies that have analyzed concentrations of radioiodine in milk samples. Technical Appendix E, written by Thilo Koch, Ph.D., comments on the possibility of using research results developed in Germany to assess the magnitude of hypothetical emissions of radioiodine from the secondary loop at TMI. Appendix F, researched under subcontract by Gordon Thompson, Ph.D., investigates the public (and worker) health impacts of the cleanup of TMI-2, considering both actions already initiated and those planned for the next several years, as outlined in the planning literature, in particular, the NRC's Programmatic Environmental Impact Statement (PEIS) of March, 1981.*

*It must be noted, however, that a December 1980 supplement to this PEIS (NUREG 0683, Supplement #1), published after the completion of Appendix F, has very substantially raised its estimate of occupational radiation doses to be expected: from a March 1981 estimate of 2,000-8,000 person-rem to a current estimate higher by a factor of about six: 13,000-46,000 person-rem.

2.0 Description of the Existing Literature on TMI Dose Assessment

Four comprehensive studies of the radiological aspects of the TMI accident were undertaken in the initial months after the accident. These were studies by the President's Commission on Three Mile Island (Kemeny Commission),* the Nuclear Regulatory Commission's special inquiry group (NRC's Rogovin Report),** the NRC's Staff Report on the accident (NUREG-0600),*** and an interagency task force composed of representatives from the Environmental Protection Agency, the Department of Health, Education and Welfare, and the NRC (Ad Hoc Dose Assessment Group.)# In addition, a private study (TDR-TMI-116)## undertaken for General Public Utilities by a consulting firm, Pickard, Lowe and Garrick, Inc., was so

*J.A. Auxier et al., "Report of the Task Group on Health Physics and Dosimetry to the President's Commission on the Accident at Three Mile Island," (Report of the Kemeny Commission Staff, Washington, D.C., October 1979).

**M. Rogovin, G. Frampton, Jr., Three Mile Island: A Report to the Commissioners and to the Public, (Report of the Nuclear Regulatory Commission Special Inquiry Group, Washington, D.C., undated).

***U.S. Nuclear Regulatory Commission, Investigation into the March 28, 1979 Three Mile Island Accident, (Report NUREG-0600, Washington, D.C., 1979).

#Ad Hoc Dose Assessment Group (Battist et al.), "Population Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station," (Report NUREG-0588, Nuclear Regulatory Commission, Washington, D.C., May 10, 1979).

##Pickard, Lowe and Garrick, Inc., "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident," (Report TDR-TMI-116, Revision 0, 1979).

widely cited in public documents, and copies of it so easily obtainable, that it has achieved de facto status as a public document itself.

A number of other reports have been issued dealing with particular radiological issues at TMI, and related papers have been published in technical journals. Some of these additional reports and papers represent the delayed publication of work carried out by consultants to the major investigating groups, but a good many represent new work. For instance, as part of a 1981 review of dose assessments carried out by Technology for Energy Corporation* at the request of the Nuclear Safety Analysis Center, new estimates were made of the amount of noble gases released.

Another group of papers and reports in the literature does not deal directly with dose assessment, but contains information about the reactor during the accident or contains other information relevant to assessing doses. (For example, papers published on the efficiency of filters in TMI-like environments bear on the issue of determining the efficiency of the actual filters at Three Mile Island.) As a result, the initial literature search carried out for this report revealed the existence of a large body of potentially relevant information.

To ensure thoroughness in locating this information, 185

*P.K. Knight, J.T. Robinson, F.J. Slagle, P.M. Garrett, (Technology for Energy Corporation), "A Review of Population Radiation Exposure at TMI-2" (Report NSAC-26, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, CA, August 1981).

computerized data bases were searched, of which 47 contained entries for TMI. (See Bibliography, Section 8.0, for a list of the 47 data bases utilized.) These data bases yielded for initial review some 300 papers and reports published as of August, 1982 which appeared to have some potential bearing on TMI dose assessment. A final update was carried out as of October 1983, in which an additional 100 papers were located bringing the total to 400. Of these 400 papers and reports, some 100 proved directly relevant and are listed in Part II of the Bibliography. Also included in this list are a few reports that were not found by computer search, but were cited in other papers or suggested by people knowledgeable in the field. No doubt there exists additional information--especially unpublished information--relevant to the TMI Dosimetry that has not yet been located. If readers of this report are aware of such information, it would be helpful to include it in updates of this report. References should be sent to the principal investigator, Dr. Jan Beyea. (c/o David Berger, Attorneys at Law, 1622 Locust Street, Philadelphia, PA 19103).

Considerable data on TMI have been published but not analyzed--especially data concerning environmental monitoring of radiiodine and radiocesium. Preliminary analysis of certain of these data for the purpose of determining their consistency with particular hypotheses about the accident can be made in a straightforward way. This report recommends that such analysis and approximate calculations be made expeditiously in conjunction with the proposed TMI dosimetry workshop.

3.0 Doses Received at Three Mile Island

The focus of most TMI research, and of this review, is on the "population dose." A population dose, as opposed to an individual dose, is the cumulative sum of the radiation doses delivered to an exposed population. That is, three hundred people receiving a 1-rem dose to the thyroid gland would have received a 300-rem thyroid population dose. Population doses are important because they can give, if carefully interpreted, a rough approximation of the total number of cancers that may result in the exposed population from the doses delivered to whatever organ or organs are under consideration. In general, population doses can be estimated more accurately than individual doses.

A number of population doses are of possible interest at Three Mile Island:

- 1) the population dose delivered to the "whole body" from radiation, primarily from noble gases such as Xenon-133 in the passing radioactive cloud;
- 2) the population dose delivered to the thyroid gland from inhaled or ingested radioiodine; and
- 3) long-term population doses delivered to various organs and the whole body from any long-lived radionuclides, such as radiocesium or radiostrontium that were deposited on the ground or inhaled.*

*Radioactivity deposited on the ground would continue to irradiate the population as the radioactivity decayed. Inhaled radioactivity, if it is both long-lived and retained in the body, can give a delayed radiation dose.

The range of population dose estimates appearing in the literature for some of these categories appears in Table 1. Many of the entries are question marks because no assessment has as yet been made. (Such lack of information suggests in itself the incompleteness of the available literature.) In the three sections that follow, the measuring devices available to researchers and the general methods employed to reach their estimates for each of the dose categories listed above are briefly summarized and reviewed.

3.1 Doses to the Whole Body

The TMI literature contains a substantial range of whole-body population dose estimates from the noble gases released in the initial accident--from 276 to 63,000 person-rem delivered to the general population within 50 miles (see Table 1, column 1). Such a divergence is sufficient to indicate the degree of uncertainty on this question.*

Researchers estimating the whole-body population dose approached it in one of two general ways. One group of analysts assumed they knew how much radioactivity was re-

*These numbers were calculated without taking into account self-evacuation and shielding afforded by buildings. As indicated in Appendix A, they should probably be reduced by 25% or so as a result. They should be increased--possibly doubled--to account for the neglect of doses beyond 50 miles.

Table 1

Range of TMI Population Doses Appearing in the Literature by Time Period and Organ
(in Person-Pem)

Time Period	Dose to Whole-body from Short-lived Isotopes /e.g., noble gases ⁷		Dose to Whole-body from Long-lived Radiocesium		Dose to Thyroid from Radioiodine		Dose to Bone from Radiostrontium	
	within 50 miles	beyond 50 miles	within 50 miles	beyond 50 miles	within 50 miles	beyond 50 miles	within 50 miles	beyond 50 miles
Initial Accident	276-63,000 ^{a)}	(equal to 50 mile dose?)	?	(equal to 50 mile dose?)	1,280 ^{b)}	(equal to 50 mile dose?)	?	?
Krypton Venting	c)	c)					d)	d)
Clean-Up:								
Projected Doses to Workforce			13,000-46,000 ^{e)}				?	?
Projected Doses to Population from Clean-Up			10 ^{e)}	?			?	?

a) These doses should probably be reduced by about 25% to account for building shielding and self-evacuation. See Appendix A.

b) Considered to be a significant overestimate by analyst.

c) Insignificant in comparison to doses received in the initial accident.

d) One paper on this subject has not been analyzed at this time.

e) On the basis of new information (the NRC Programmatic Environmental Statement Supplement #1, December 1983), the workforce dose has been raised from the original estimate of 2,000-8,000 person-rem. The NRC has not yet revised its projected dose to the population, but on the basis of the magnitude of the change in the first figure, it is possible that the projected population dose of 10 person-rem will prove to be substantially underestimated.

leased (usually 2.4 million curies) and therefore calculated the total population dose using standard meteorological dispersion methods. The quantitative results for this "source term" method are shown in Table 2. The second group of analysts did not assume they knew how much radioactivity was released, but used extrapolations of off-site dose monitoring data (as best they could) to estimate the total population dose. The quantitative results of these calculations are shown in Table 3. This method produces considerably higher values for the population dose than does the first group when a low release is assumed, but is in approximate agreement with a 7-17 million curie release.

Each of the studies listed in Tables 2 and 3 is reviewed in detail in Appendix A. The conclusions reached there are, briefly, as follows:

-The most serious reservations about the source term (Table 2) studies involve the set of assumptions used to estimate the release of radioactive noble gases. As a substitute for a vent stack monitor that went off-scale early in the accident and remained off-scale for most of the release, the investigators relied solely on stripchart monitors in the auxiliary building, out of the direct path of the escaping radioactivity, and assumed that a constant ratio between these monitors and the off-scale monitor would have existed. Because of changes over time in,

Table 2
Fifty-Mile Whole-Body Population Doses Projected
from an Estimated Noble Gas Release^{a)}

<u>Investigator</u>	<u>Meteorological Model</u>	<u>Release Estimate (Millions of Curies)</u>	<u>Person-Rem</u>
Kemeny Commission Group			
Subcontractor:			
Lawrence Livermore Laboratory	ARAC Code	2.4	276 ^{b,c}
Oak Ridge Laboratory	AIRDOS-EPA Code I	"	390 ^b
Oak Ridge Laboratory	TVA Code	"	970 ^b
Miller et al. (Oak Ridge)	AIRDOS-EPA Code II	"	1500 ^d
Technology for Energy Corp. (Knight et al.)	XODOQ/GASPAR Codes	7-17	3000 - 7000 ^e

- a) All analysts except for Technology for Energy for Corporation (TEC) assumed the same time dependence for the release as supplied by the Kemeny Commission. The results for all but the TEC data differ because the assumed meteorological models differ. The TEC results differ because of the larger assumed release. Shielding from buildings and self-evacuation has not been taken into account. Doing so might reduce listed doses by 25%.
- b) As reported in Kemeny Commission's "Report of the Task Group on Health Physics and Dosimetry," October 31, 1979.
- c) See also, Knox et al., Utilization of the Atmospheric Release Advisory Capability (ARAC) Services during and after the Three Mile Island Accident. (Report UCRL-52959, Lawrence Livermore Laboratory, Livermore CA 1980.)
- d) A report released by Oak Ridge subsequent to the Kemeny Commission report indicated this higher population dose figure. It was obtained using the same computer code. However, assumptions about the release height were changed. In the second calculation, it was assumed that a ground level release was a closer approximation to actual dispersion conditions. See Charles W. Miller, Sherri J. Cotter, Robert E. Moore, Craig A. Little, "Estimates of Dose to the Population within Fifty Miles due to Noble Gas Releases from the Three Mile Island Incident," Presented at ANS/European Nuclear Society Thermal Reactor Safety Conference, Knoxville, TN Volume 2, pp. 1336-1343. (April 7-11, 1981.)
- e) Knight et al., (Report NSAC-26) p. III-14. Doses were corrected in their report for shielding (i.e., they were reported as 2200-5300, not 3000-7000). But in order to make the results consistent with the other entries in the table, the correction has been removed.

Table 3

Fifty-Mile Whole Body Population Dose Estimates Obtained by
interpolation and Extrapolations of Environmental Data*

<u>Investigator</u>	<u>Person-Rem</u>	<u>Limitations of Methodology**</u>
Department of Energy (Hull) ^{a)} (Based on Geiger Counter Readings)	2,000	Helicopter missed releases in first few days; May have missed center of plume on other occasions.
Ad Hoc Dose Assessment Group ^{b)} (Based on TLD Readings)		
I	5,300 ^{c)}	"Holes" in TLD coverage; limited data points available for interpolation and extrapolation.
II	3,700 ^{d)}	
III	2,800 ^{e)}	
IV	1,600 ^{f)}	
Meteorological		
V-a	2,600 ^{g)}	Assumes that the time dependence of release is uniform.
Interpolation	3,400 ^{h)} , (12,000 ⁱ⁾)	
Kemeny Commission Task Group ^{j)} (Repeat of Ad Hoc Group's Methods I-IV)	1,000 - 6,600	Same limitations as methods I-IV of Ad Hoc Group.
Pickard Lowe and Garrick, Inc., (Woodard) ^{k)} (Meteorological interpolation of TLDs)	3,500, (12,000 ^{l)})	Assumes that the relative time dependence of the release can be taken from stripchart monitors.
Takeshi (Interpolation of late TLD readings backwards in time) ^{m)}	16,200	Assumes that meteorology was the same between two time periods when, in fact, it was not.
Kepford (Interpolation of late TLD readings backwards in time) ⁿ⁾	63,000	Same limitations as in Takeshi method.

* These estimates apparently do not take building shielding, self-evacuation or doses beyond 50 miles into account. For the purposes of this review, it is assumed that these effects cancel each other out.

** These limitations are discussed in detail in Appendix A.

Footnotes

Table 3

- a) As reported in Appendix A of reference cited in footnote b).
- b) Ad Hoc Population Dose Assessment Group, (Battist et al.) "Population Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station. A preliminary assessment for the period March 28 through April 7, 1979," May 10, 1979.
- c) Extrapolation/interpolation based on all Metropolitan Edison and NRC TLDs.
- d) Extrapolation/interpolation based on Metropolitan Edison TLDs only.
- e) Extrapolation/interpolation based on all Metropolitan Edison and NRC TLDs located within 8 miles.
- f) Extrapolation/interpolation based on Metropolitan Edison TLDs within 8 miles.
- g) This is the value given in the Ad Hoc Group's Report, using meteorological interpolation, as opposed to the value given in the subsequent paper published in Health Physics. The analysis was based on Metropolitan Edison TLDs. The number of detectors included was not specified in the analysis.
- h) Value given in Health Physics paper. W. Pasciak, E. Branagan, Jr., F.J. Congel, and J. Faircobent, "A method for calculating doses to the population from XE-133 releases during the Three Mile Island accident," Health Physics 40, 457-465 (1981).
- i) This is the value that would result from including three additional Metropolitan Edison TLDs in the analysis. This value is not explicitly stated in the Health Physics paper, but derived for this review using information given by the authors.
- j) This is essentially a check of the Ad Hoc Dose Assessment Group's work. Report of the Task Group on Health Physics and Dosimetry, Tables B1 and B4, and p. 133.
- k) Pickard, Lowe and Garrick, Inc. Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident, (Report TDR-TMI-116, Revision 0, 1979) pp. 4-17.
- l) Distant TLDs were not used in this calculation. Had they been, the calculated value would have exceeded 3500 person-rem. The 12,000 figure has been derived for this review in analogy with the estimate given under method V-b.
- m) Seo Takeshi, "Excerpts from the author's review published in Nuclear Engineering [Japanese review], Vol 26, No.3" (unpublished mimeographed notes, Kyoto University Nuclear Reactor Laboratory, Kyoto, Japan, no date).
- n) Chauncey Kepford, "Testimony before the NRC Atomic Safety and Licensing Board, August 20, 1979, in the matter of Public Service Electric and Gas Co., Salem Generating Station Unit #1," Docket #50-272 (1979).

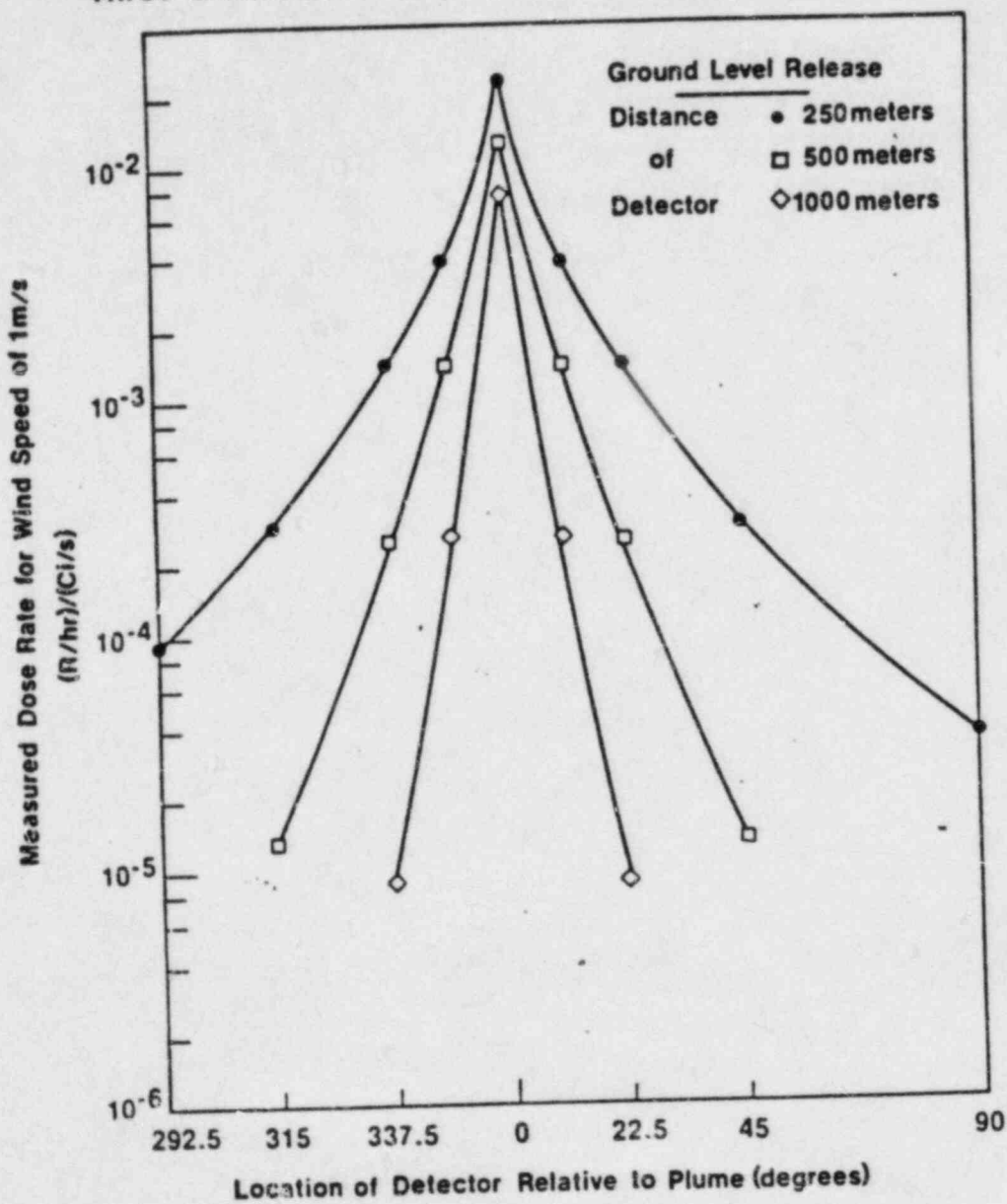
1) the radioactive composition of releases, 2) the radioactive atmosphere in the auxiliary building itself, and 3) the varying pathways of escaping radioactivity, this assumption of a constant and determinable ratio is highly questionable.

-The most serious reservation about the environmental monitoring (Table 3) studies stems from the necessity to rely (in all cases except the DOE Helicopter measurements which have their own more serious limitations) on the set of thermoluminescent dosimeters (TLDs) in place at the time of the accident. There is evidence in the literature that these original TLDs left significant angular gaps through which bursts of radioactivity might have passed entirely undetected or only partially detected. Figure 1, reproduced from an Atomic Industrial Forum Study, depicts graphically the fall-off in measurement efficiency when a burst of radiation is not centered on the registering dosimeter.*

*Charles D. Thomas, Jr., James E. Cline, Paul G. Voilleque (Science Applications Inc), "Evaluation of an Environs Exposure Rate Monitoring System for Post-Accident Assessment" (Report AIF/NESP-023, Atomic Industrial Forum Inc., National Environmental Study Project, Rockville, Maryland, December 1981).

Figure 1. Adapted from Thomas et al. (Report AIF/NESP-023)

Angular Variation in Measurement of Xenon-133 Dose for Three Distances Under One Set of Weather conditions*



*So-called F-stability class

(Projects designed to use this type of information to obtain more accurate environmental measures of noble gas radiation are described in section 7.0.)

A second reservation about the use of TLD measurements based on the original Met Ed set of TLDs is that a second set placed later by the NRC indicated a substantially greater population dose for the period when the two sets could be compared. Some investigators accepted the lower readings and virtually ignored the higher ones; others accepted the later higher readings and attempted to extrapolate from them alone. The particular procedures followed are discussed in Appendix A, but both procedures are problematic.

-The most serious reservation about the data provided by DOE Helicopter Geiger Counter readings has to do with the fact the bulk of the readings do not begin until two days after the initial release. This and other reservations are discussed in Appendix A.

It should be noted that the highest value for the whole-body dose (63,000 person-rem) found in the literature appears to be close to an upper limit under any set of assumptions for the noble gas dose within 50 miles from the TMI accident. That is to say, if it is assumed that the entire inventory of Xenon-133 (140 million curies), plus the accompanying

Xenon-135, Krypton-87 and Krypton-88, were released from the reactor during the accident, and then the meteorological model for dispersion giving the highest dose per curie released is applied (see entry under Miller et al in Table 2), it appears that the whole-body population dose would be approximately 75,000 person-rem within 50 miles.*

In the concluding section of this review, proposed projects are described which are designed to come to grips, as far as may be possible, with problems in the estimation of the whole-body dose from noble gases. In addition, certain preliminary calculations of published data not utilized in the literature on TMI dose assessment are identified. These calculations should be made and the results presented to the proposed dosimetry workshop, as suggested in Section 2.0 above.

*75,000 person-rem equals the ratio of 140 million curies to 2.4 million curies multiplied by the maximum population dose given in Table 2 for this size release (1500 person-rem). 75,000 is not a strict upper limit because the angular distribution of the released radioactivity may, in reality, have differed from the distribution assumed in the calculation taken from Table 2. Also, should a release have occurred during the first hour, there would have been copious amounts of very short-lived noble gases present that should also be included in the population dose calculations. On the other hand, the assumption of a 100% release of noble gases is too pessimistic. Clearly, a more detailed upper limit calculation is desirable. Such a calculation (including the contribution of other isotopes) is proposed in Section 7.0 as a future research project.

3.2 Doses from Radioiodine

The official estimate of the amount of radioiodine released is 15 to 30 curies* based on one interpretation of in-plant data. However, an alternative analysis of in-plant data carried out by an independent researcher indicates that the actual release could have been much higher, amounting to 5,100 to 64,000 curies.** Although other studies and data appearing in the literature do not make as explicit estimates of radioiodine releases, the information reported has been converted to an approximate release magnitude format, in order to determine whether the results are consistent with a low or high release. Paradoxically, the remaining studies also appear to fall into a high or low category, with none falling in between. For instance, a reassessment of one attempt in the literature to relate milk data to the release magnitude suggests that many hundreds of times more radioiodine was released during the first two days of the accident than was estimated to have been released in the official studies.***

In contrast with this first set of milk data, a different but more limited set of milk data can be interpreted

*See, for example, the Rogovin Report, Part II, Vol. II.

**See Appendix C, Section 2.3.2, for a discussion of Takeshi's analysis.

***Since one government-commissioned report begins from a hypothetical assumption of 10,000 curies of radioiodine released, it is possible that other researchers have also been aware of this possibility (see Appendix C, Section 3.6.1).

as supporting the official release estimate. In addition, we have found that iodine limits determined by actual measurements on people (as part of the public whole-body counting program) do turn out to be consistent with a 15-curie or smaller release. However, these measurements were limited to people living within 3 miles, so that radioiodine blown down or up river would not be likely to have been detected. (This measurement does serve to restrict the direction of any large release.)

Analysis of the data from grass samples and meadow voles can also be interpreted to support a 15-curie release. No easy resolution of these contradictions with the first set of milk data is possible.

To summarize the conclusions reached in Appendix C, the most important problems revealed in the literature in connection with assessing radioiodine releases and doses involve the following:

-For in-plant measurements of released radioiodine, there are gaps in the monitoring data due to the loss of filter cartridges. Furthermore, the calibration of the charcoal cartridges and filters is at issue. There is evidence that both water vapor and the temporary attachment of noble gases may have blocked sites for radioiodine, producing inaccurately low readings. In addition, some possible pathways for airborne releases have not

been adequately considered. Finally, 11 million curies of radioiodine have not yet been traced--radioactivity that conceivably could have escaped via a liquid pathway.

-For environmental measurements the most important issue (as mentioned above) is the lack of agreement between the measured radioactivity in various samples of cow's milk and other data. In addition, insufficient use (i.e. collection of data with no further analysis) has been made of information from other environmental sources--that is, grass samples and radioactivity found in other animals. In part, analysis is hampered by the lack of baseline information on appropriate metabolic processes: the passage of radioiodine into the thyroid gland for meadow voles, rabbits, and other animals, the hydrolysis of methyl iodide in cows and its passage into milk. As in the case of the noble gases, furthermore, problems remain in the angular distribution of environmental samples.

Proposed projects designed to remedy, as far as may be possible, these uncertainties are described in the final section of this report.

3.3 Doses from Radiocesium

Only limited environmental sampling for radiocesium was carried out after the accident. A great deal of the data that was recorded is suspect because too many readings from different sites show or are recorded to show exactly the same value.* No judgement is attempted here as to whether such identical readings are the result of instrument or human error, but little reliance can be placed on such data without further clarifications. Consequently, there is no hope at this time of being able to use past measurements to determine a geographical pattern for radiocesium deposition on the ground. (The possibility of making new measurements to locate radiocesium still remaining from the accident is discussed in the proposed project section of this report.) In order to determine an estimate for the dose from radiocesium, or at least a limit to the dose, it is necessary to rely on general reports of the magnitude of the environmental measurements. Cesium-137 levels measured after the accident were found to range up to 100 nanocuries per square

*E.W. Bretthauer, R.F. Grossman, D.J. Thome, A.E. Smith, "Three Mile Island Nuclear Reactor Accident of March 1979 Environmental Radiation Data: A report to the President's Commission on the Accident at Three Mile Island," (Report EPA-6-0-4/81-013B, Environmental Protection Agency, Las Vegas, Nevada, 1981).

meter.* (A nanocurie is one billionth of a curie.) However, these levels were not attributed to the accident but were presumed to be due to residual global fallout from past weapons tests. In the absence of confirmation of this presumption (which could have been checked by testing for the ratio of Cesium-134 to Cesium-137), it is not scientifically valid to conclude that no radiocesium from the accident was present. Calculations should be made for the proposed dosimetry workshop which would at least set upper limits to the radiocesium releases from the accident and therefore give the participants some idea of the maximum relative importance of the possible dose contribution. A method of determining an upper limit of this type is described in section 7.0.

Because of the scantiness of the radiocesium data and the lack of attention given to it by investigators, there has been no need to prepare a special appendix on radiocesium.

*K. Miller, C. Gogolak, M. Boyle, J. Gulbin, "Radiation Measurements Following the Three Mile Island Reactor Accident" (Report EML-357, Department of Energy, New York, New York, May, 1979).

4.0 General conclusions of this Review

The findings of this review are, in summary, given below. Documentation is provided in Appendices A and C.

1) Monitoring equipment in place at the time of the Three Mile Island accident, as is well known, was poor and liable to error. This includes both the in-plant monitors, such as the vent-stack monitor that went off-scale, and the charcoal cartridges for radioiodine (some of which were lost), and the thermoluminescent dosimeters which were distributed in insufficient numbers outside the plant.

2) Environmental sampling, hastily instituted in the chaotic aftermath of the accident, was insufficiently coordinated. Sampling did not cover all directions from TMI adequately. In addition to problems in calibration and labelling, there was little or no redundancy in measurement --redundancy that would have made it possible to check measurements against one another.

3) In their analysis of the information collected, the early official studies are subject to the following limitations. On the one hand, they easily accepted monitor readings that may be open to legitimate question. On the other hand, they rejected as anomalous a number of high environmental readings without sufficient rationale. Finally, in many cases, they did not make full use of statistical techniques that would have allowed better use to be made of the data collected.

4) Additional data remain to be analyzed. Some data collected early (e.g., radioiodine grass measurements) have not been officially analyzed as a contribution to determining radioiodine release rates. Other data only became available for analysis after the initial studies were completed. (For example, as discussed in Section 7.0, and in Technical Appendix B, 'it appears possible to use the Krypton-85 deliberate venting in July, 1980 to gain information about release of all other noble gases.) Still other data will only become available as the cleanup progresses (e.g., the tracking of long-lived I-129 as an indication of in-plant release pathways for I-131).

For all these reasons, it appears that the official estimates for whole-body and thyroid population doses should not be regarded as final at this time. Such a statement is not meant to imply that, in fact, the official dose estimates have been proven wrong, but only to judge that much greater uncertainty than heretofore acknowledged should have been assigned to the doses delivered to the population and, as a result, to the estimated health effects projected from the doses.

At the same time, as already suggested in findings 3 and 4 above, it should be stressed that many uncertainties that now exist can be reduced by further scientific and statistical work with existing data and by the revelations of new data. For instance, in the course of this literature

review and analysis, it has become obvious that continued study would pay rich scientific dividends, especially in those areas that were relatively neglected in the aftermath of the accident, such as radioiodine and radiocesium releases. In addition, there may exist unpublished studies and information that would have an important bearing on the conclusions of this review. Although use has been made of what is probably the most important and comprehensive private study, TDR-TMI-116 (which was prepared by Pickard, Lowe and Garrick, Inc. at the request of General Public Utilities), additional unpublished information probably exists that is extremely important.*

The Public Health Fund will no doubt want to take appropriate measures to encourage those with relevant private and unpublished information to bring it into the public domain. The first step should be to convene a dosimetry workshop, at which the methodology and dose estimates may be debated and, to the extent possible, resolved. Such a workshop would serve as a forum for the authors of the papers reviewed in this report to clarify their work, to respond to the conclusions of contradictory studies and of this review, and to comment on the proposed projects of section 7.0.

*This review has already paid dividends in this regard. An important study on pathways for radioiodine in cows, commissioned by the NRC, had "fallen through the cracks," according to the project manager and had not been released eighteen months after completion. After our inquiry, the study was published.

5.0 Need for Additional Dosimetry Analysis

When considering the TMI accident, it is important to bear in mind that the overwhelming bulk of the dangerous radioactivity released from the fuel was probably contained within the reactor complex and certainly was not released into the air.* This fortunate result was due to the fact that most radioactivity passed through and (except for the noble gases) condensed in water before reaching the atmosphere. Had water not scrubbed the condensible radioactivity from the escaping gases, the consequences would likely have been much more serious. Table 4, reproduced from an earlier study on TMI performed for the Council on Environmental Quality,** shows the projected consequences for three alternate scenarios of increasing severity. Although the probability of such releases is a subject of intense debate at the current time, the very possibility of such releases occurring should serve to put the actual accident in perspective.

*Note, however, that at least 11 million curies of the radioiodine core inventory is unaccounted for (see the discussion in Appendix C, Section 2.1). Until the missing radioiodine is traced somewhere within the reactor complex, it is premature to conclude that there were no pathways by which radioiodine entered the river. In any case, this amount of inorganic radioiodine could not have entered the air or it would have easily been detected. Even airborne organic radioiodine in quantities of this order would have left traces that would have been detected.

**J. Beyea, "Some Long-Term Consequences of Hypothetical Major releases of Radioactivity to the Atmosphere from Three Mile Island," (Report PU/CEES 109, Center for Energy and Environmental Studies, Princeton University, December, 1980).

Table 4*

Table 1: Summary Table. Some Long-Term Consequences of Hypothetical Accidents at Three Mile Island^a

(Not including any early illnesses or deaths which might be associated with high doses to unevacuated populations a few tens of miles from the reactor.)

ACCIDENT DESIGNATION	HYPOTHETICAL RELEASES TO ATMOSPHERE	RELATED CANCER DEATHS ^{b,c} (Low/High ^d)	TYPHOID MORTAL CASES ^e (Low/High)	TEMPORARY AGRICULTURAL RESTRICTIONS	AREAS REQUIRING DECONTAMINATION OR LONG-TERM RESTRICTIONS ON OCCUPATION ^f
THI-0	10% of noble gases (similar to actual accident)	0/4		0	0
RELEASES GREATER THAN ACTUALLY OCCURRED					
THI-1	60% of noble gases	1/23		0	0
THI-2	32 Iodines plus 60% noble gases	2/250	200/27,000	23,000mi ² g ¹	0
THI-2s	THI-2 plus 10% of Cesium	15/2000	200/27,000	23,000mi ² g ¹	7mi ²
THI-4a	50% of Cesium	100/12,000		3700mi ² h ²	650mi ²
THI-5a	"PWR" release with complete core melt	200/23,000	3500/430,000	175,000mi ² g ¹	1400mi ²
CONSEQUENCES ASSUMING THE REACTOR CORE HAD BEEN IN OPERATION FOR MUCH LONGER THAN 3 MONTHS (MATURE CORE)					
THI-2b	THI-2 plus 10% of Cesium	65/8300	200/27,000	23,000mi ² g ¹	35mi ²
THI-4b	50% of Cesium	440/43,000 ¹⁾		18,000mi ² h ²	4300mi ²
THI-5b	"PWR" release ¹⁾	310/60,000 ¹⁾	3500/430,000	175,000mi ² g ¹	1200mi ²

Footnotes for Table 1

- a) All accidents are assumed to take place under "typical" meteorological conditions. Wind shifts and changes in weather are ignored. Details can be found in the supporting tables in Appendix B and in the technical discussion in Appendix E. Health effects are recalled for people living beyond 30 miles.
- b) Cumulative total over a 75 year period after the accident. The range of genetic defects would be equal, very roughly, to the range of delayed cancer deaths.
- c) The low number is for the most favorable wind direction (Eastern Maryland), assuming the most optimistic coefficient relating dose to health effects, and evacuation out to 30 miles. (Without evacuation, the low number would be a factor of 2-3 higher depending on the accident.)
The high number is for the least favorable wind direction (N.Y.C./Boston) and assuming the most pessimistic coefficient relating dose to health effects. (Evacuation is also assumed out to 30 miles, but has a small impact on the high results.)
See Appendix E for a discussion of the dose/health-effect coefficient range used.
- d) Reduces high value by a factor of about 4 to obtain the prediction which would result using the Reactor Safety Study model under average weather conditions. Multiply by 4 to obtain the prediction which would result using health effects coefficients based on data of Mankum, Stewart and Kneale. See Appendix E.
- e) Cumulative total over a 25 year period after the accident. A blank entry implies a small number.
- f) Areas in which the projected dose exceeds 10 rem in 30 years. See Table B-V in Appendix B for details.
- g¹) Milk restrictions during the grazing season (see Table B-IV). Much of this area would be water for a year from the west.
- h²) First year crop restrictions. (Harvested food not suitable for children.) See Table B-V. Much of this area could be water for a year from the west.
- 1) A PWR accident as defined in the Reactor Safety Study.
- 2) This number possibly could be reduced in half if massive decontamination or relocation efforts were undertaken in urban areas to avoid low-level radiation doses.

* Reproduced from J. Beyer, "Some Long-Term Consequences of Hypothetical Releases of Radioactivity to the Atmosphere from Three Mile Island," (Report PU/CEES #109, Princeton, N.J., 1980)

Even though the actual accident was nowhere near as severe as the worst case described in Table 4, in fairness to the population surrounding TMI, it is important to continue efforts to estimate the full dose delivered. The best efforts of the scientific community have yet to be put forward to find out whether high readings have been rejected justifiably; informed criticisms of official estimates have yet to be granted a response.

Even if there were no doubts about the significance of the population doses received at TMI, it would be worthwhile to pursue the analysis of the TMI dosimetry further in order to guide future monitoring and emergency planning programs.

The TMI data provide a testing ground for theoretical models of dose pathways and proposed emergency measures. Resolving as many loose ends as possible at TMI should improve the possibility that important observations will be made relevant to emergency planning and monitoring. For example, it has already become clear from this preliminary study of the dosimetry that in order to minimize radioiodine in milk, not only should cows be kept indoors after a release of radioactivity and kept from grazing, but they should be shifted to feed that has been stored indoors or brought from distant locations, rather than allowed to eat baled hay that may have filtered radioiodine from the air. The licking and chewing of the ground, habitual to cows, should also be

restricted.

As for monitoring, much work is still needed. Despite the flurry of post-TMI NRC requirements, it is not clear that any better information about radioiodine or radiocesium dispersion would result should an accident occur in the future at another reactor. Because of changes in instrumentation, better information would be available about the amount of noble gases released from the reactor vent stack, but the authorities to our knowledge still have no adequate way of determining the distribution of radioiodine or of radiocesium deposited on the ground. A post-accident plan for environmental sampling of deposited radioactivity is needed to ensure that data are taken from all angular sectors.

Some improvements in monitoring methodology can also be recommended as a result of this dosimetry review: potential biological monitors such as the meadow vole, rabbit, goat, honeybee, etc. should be "calibrated" by measuring their uptake of deposited radioactivity. They would then become quite useful in future radiological incidents as a check on the soil and grass environmental sampling program. One of the most frustrating aspects of trying to make sense out of the TMI data is the lack of redundancy in measurements. Human errors and equipment malfunctions will always lead to measurement errors. In the absence of independent measure-

ments that can be used to separate errors from real effects, it may be difficult to explain discrepancies and therefore difficult to assure the public that the true nature of a release is known.

Changes in monitoring procedures are also indicated. In trying to make sense out of TMI data, it became obvious in the course of this study that measurements of different airborne radioisotopes should be made on the same air sample, so that relative isotope ratios can be extracted with confidence. In this way useful information could be obtained that was independent of meteorological uncertainties. Only one (accurate) measurement of this sort was found to be available in the TMI monitoring data.

There is, of course, another important reason for pursuing the TMI dosimetry, beyond learning more about monitoring and emergency planning: there is a substantial population surrounding Three Mile Island that has been five years waiting for information that they can trust concerning dose levels. The complete peer review of dose estimates that can be arranged by the Public Health Fund, through a forum such as the proposed dosimetry workshop and subsequently by commissioning new studies to resolve uncertainties, will help to ensure that the full TMI story (or as much of it as can possibly be obtained scientifically) will come to light.

6.0 A Summary of Health Impacts Described or Implicit in the Literature

Dose assessments are of interest because they represent the first step in estimating the projected health impacts of a radiological incident. Many of the studies under review, in particular the official reports, proceed to projections of delayed health impacts based on various dose assessments. Had the official studies considered all estimates, including those of independent investigators, they would have obtained a wider range of health effects estimates. The extent of the increase is discussed in this section in order to assess the possible significance of dose assessment discrepancies located in the literature. However, because this study did not review the literature on the health effects of low-level radiation, no consideration of uncertainties in this part of the calculation is undertaken.

The conversion of population dose to health impacts for low-level radiation is conventionally accomplished by applying dose-response estimates researched and published by the National Academy of Sciences.* Although uncertainty exists about such low-level radiation risks, the Academy projects 0.6 to 2.0 delayed cancer deaths per 10,000 person-rem. Thus, on the basis of their assumed collective dose of

*National Academy of Sciences, Committee on the Biological Effects of Ionizing Radiation, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, (National Academy Press, Washington, D.C., 1980).

approximately 3000 person-rem for noble gases (see above, Section 3.1 and Table 3), the Kemeny Commission and the Rogovin Report projected that no fatal cancer was likely to occur within 50 miles as a result of the accident.*

In the review of the literature on the noble gas population dose, as reported in Section 3.1 of this report (and in more detail in Appendix A), estimates of up to 63,000 person-rem are discussed. Thus, had the official studies included projections for such an estimate, they would have obtained the value of

$$\frac{63,000 \times 2.0}{10,000} = 12.6$$

maximum cancer deaths for the exposed population of 2.3 million within 50 miles. In summary, then, the number of delayed cancer deaths that would be projected based on the noble gas dose estimates in the literature reviewed for this

*Kemeny Commission, op. cit.; Rogovin Report, op. cit., Part II, Vol. II. The highest official projection of the harmful consequences of the accident was given by the then Secretary of Health, Joseph Califano, at a press conference in May of 1979. Mr. Califano estimated that one fatal cancer would be expected as a result of the initial noble gas release.

report (and using official dose-response coefficients) ranges from zero to thirteen. As discussed earlier, a 63,000 person rem dose is probably an upper limit, although there are still some unresolved questions about very early releases and although certain corrections might increase the total somewhat if the population beyond 50 miles is considered.* In any case, the total number of delayed fatalities projected from the released noble gases can be limited to approximately thirteen using conventional dose/response coefficients, even for the most pessimistic study in the literature.

*Self-evacuation and building shielding probably lower the maximum by 25%, while the inclusion of post-50 mile doses might multiply the new product by a factor of 2, for a net 50% increase. (See Appendix A). Still unresolved, however, is the possibility of a hypothetically large release of very short-lived noble gases during the first hour which, conceivably, could raise the total.

7.0 Toward a Better Understanding of the TMI Accident:
Current Uncertainties and Proposed Projects

In order to give the Advisory Board of the Public Health Fund an idea of the elements which would make up a more complete dosimetry study, a discussion has been prepared for this final section of the report of uncertainties that remain to be addressed. Suggestions, in the form of possible projects, have been proposed for addressing them. Whenever a future study is suggested, whether related to dosimetry or emergency planning, it is given a "Proposed Project number" for purposes of reference. Table 5, which is included at the end of this section, provides a succinct description of each project and the dose estimate with which it is associated.

1. Inconsistencies in Estimates of the Amount of Released Noble Gases. Different measurements of the number of curies of noble gas released are inconsistent and the discrepancies not obviously resolvable. Two of the most highly publicized estimates differ by more than a factor of four (2.4 million curies and 10 million curies). Other studies indicate that the discrepancy could even be larger. The controlled Krypton-85 venting, carried out in June and July of 1980, offers a new opportunity to make this estimate, as is proposed in Appendix B. Prior to the convening of a dosimetry workshop, calculations should be made using this method to determine whether or not the results will likely be consistent with other estimates. (Proposed Project #1a.)

Discussion of the various estimates of noble gas releases among all investigators is Proposed Project #1b, which could most appropriately take place as part of a dosimetry workshop.

2. Inadequate TLD Calibrations. Based on analysis of published papers, the TLD calibrations appear inadequate. Since 50% of the cumulative dose delivered to those TLDs used in the early time period has been estimated from theoretical calculations to be due to noble gases other than Xenon-133, such as Krypton-88 and Xenon-135, it is inappropriate to rely on calibrations made with Xenon-133 alone, as appears to have been done for some of the studies appearing in the literature. In any case, proper calibration of TLDs for a mixture of isotopes that is also changing in time due to radioactive decay is a non-trivial problem that requires more attention than it has been given. The TLD calibrations should be made not only a function of time and isotope mix, but also a function of the distribution of airborne radioactivity (which, in turn, is a function of the stability of the atmosphere).* (Proposed Project #2.)

*There are two reasons for making measured or calculated calibrations a function of the shape of the radioactive cloud: first, it is more accurate to do so. Second, the TMI detectors were constructed so that contamination of the gamma ray sensors by beta rays inadvertently occurred. The relative contribution of the beta rays to the detected signal can depend quite sensitively upon the shape of the radioactive cloud.

3. Possible Gaps in the TLD Monitoring Perimeter. From the general literature on angular limitations in TLD measurement capacity (see above Section 3.1 and Figure 1), it appears clear that thermoluminescent dosimeters at TMI were spaced too far apart to guarantee that all releases of noble gases were fully detected.

Because there were only 20 monitoring stations, the average angle between stations was 18° . A wind vector midway between two detectors would then fall, on average, half of 18° , or 9° from a TLD. (In some cases half of the angle between TLDs was much more than 9° , in some cases less.) Inspection of Figure 1 shows that a TLD 9° away from a wind vector-- especially one of the distant TLDs located beyond 1000 meters--would lose a great deal of its sensitivity. Consequently, there must have existed "windows" in the monitoring perimeter between some of the TLDs.

Although the existence of these gaps is rather easy to document from the existing literature, their significance is more difficult to assess without further work. Prior to the proposed dosimetry workshop, it would be advisable in this regard to produce TLD efficiency ratings for the full 360° compass surrounding Three Mile Island and to compare any resulting gaps in the perimeter with the actual hourly direction of the wind during the early days of the accident. This production and associated delineation of windows will be Proposed Project #3a.

A concerted effort should be made to collect and develop alternative evidence concerning the magnitude of any radioactivity that might have passed undetected through TLD windows. Four projects are proposed. First, there may be isolated pieces of information that are not yet part of the public record. A call for information, concentrating on particular geographic areas, may well, even at this late date, produce useful results. (Proposed Project #3b.)

Second, evidence that might prove useful in assigning approximate limits to radioactivity within TLD windows could come from film badge monitoring data routinely accumulated and recorded for hospital and other specialized workers. Data of this form from the Harrisburg International Airport were sent to us by a local resident indicating that around the time of the accident 10-45 millirem were accumulated by monitors that normally never show any readings. Although this particular data may be too close to TLD locations to fall into a window in the TLD perimeter, its existence suggests the possibility that similar information might exist at locations that do fall into TLD windows. Information of this type has not yet been published. (Proposed Project 3c.) It should be noted that an "ad hoc" attempt to convert ordinary photographic film into radiological data was carried out after the accident. Five photographic film samples were collected from local stores and analyzed by the Bureau of

Radiological Health (BRH).* Unfortunately, all but one of these samples appears to fall close to a TLD direction, indicating that the BRH data will not prove as useful as it would have had the locations been different. (Even though the BRH work probably does not provide much useful information about the TMI accident, the work is potentially very important for monitoring in general. It suggests that ordinary, inexpensive film could be very useful in future incidents at nuclear installations if samples were distributed over a wide angular range. The low cost of photographic film would allow such monitors to be set at sufficiently narrow angular intervals around a reactor to eliminate all windows.**)

*R.E. Shuping, "Use of Photographic Film to Estimate Exposure Near the Three Mile Island Nuclear Power Station" (Report FDA 81-8142, Department of Health and Human Services, Food and Drug Administration, Bureau of Radiological Health, Rockville, Maryland, February, 1981). The conclusions of this paper are somewhat ambiguous because the orientation of the film cylinders (i.e., the direction the cylinder was pointing relative to the passing radiation) was not recorded. The investigators limit the dose to 5 to 10 millirems or less, though if the cylinders were aligned differently a limiting dose of 50 millirems is in accord with the evidence.

**Based on the BRH work, the most unambiguous way to use film monitors to detect radiation is to measure the oscillation in density along the film after it is developed (the oscillations are due to absorption effects in the central cylinder). It appears that the sensitivity of the film could be increased for monitoring purposes by inserting lead rods into the cylindrical axis of the film, thereby causing greater density oscillations on the film when developed.

A third proposed project would be more theoretical. In the absence of any other information about radioactivity carried in the direction of a hypothetical TLD window, it is possible to set upper dose limits using theoretical meteorological dispersion calculations. For instance, a "worst case" calculation could be performed in which 100% of the noble gases in the core were assumed released in one direction during the worst meteorological conditions that occurred for that wind direction during the accident. (Some preliminary calculations along these lines should be presented to the dosimetry workshop--Proposed Project 3d.)

Finally, because upper limits obtained in this manner are likely to be quite high (50 rads?), it may be possible to gain more restrictive information, as discussed next, using crude experimental techniques that have been developed in a field completely unrelated to human dose assessment. For instance, Edward Radford of the Public Health Fund Advisory Board has suggested that post-accident measurements could still be made using thermoluminescent techniques that are used in archeological dating. As an example, bricks or tiles located in ordinary housing could be used as crude radiological monitors. The key idea here is that, were the radiation from the accident sufficiently high, the resulting defects in the brick would be great enough in number to be detected using thermoluminescent techniques. The sensitivity of this method for a range of common materials should be

explored to determine whether or not the method would be more useful than a simple upper-limit calculation. (Proposed Project 3e.)

An alternative method for dealing with the significance of any gaps in the TLD coverage would be to use a "Bayesian" statistical analysis to gain some insight into the likelihood of various noble gas population doses within the 276-63,000 person-rem range. The procedure would involve guessing at hundreds of different time-dependent source terms for the noble gas release, and then calibrating for each how much of the dose would have been missed by the TLDs given the actual meteorological history. Next, the resulting population dose associated with each time-dependent function chosen would be calculated. It is quite possible that most reasonable guesses at the source-term's time dependence would lead to population dose estimates that center around some mid-range value. By performing the calculation for a wide range of source-term scenarios, a histogram of dose estimates could be generated that would help in assessing the likelihood that the true dose exceeded the most frequent value calculated. (Proposed Project #3f) As part of this calculation, attention should be given to the population dose beyond 50 miles, and it would also be of interest to break down the population dose within 10 miles of the plant. One by-product of this project would be a more accurate determination of the maximum population dose.

4. Missing Radioiodine. As mentioned in Section 3.2 above, at least 11 million curies of the core radioiodine inventory is unaccounted for at this time. As the cleanup progresses, it will become possible to measure where residual, long-lived Iodine-129 is deposited in the reactor. Such measurements may provide information about the paths short-lived radioiodine took at the time of the accident, i.e., the Iodine-129 will have left a trail that can still be followed. Subject to the approval of the court, the Fund might want to commission an independent analysis of this methodology and its sensitivity. (Proposed Project #4a.) It may also be necessary to appoint someone to promote and monitor Iodine-129 measurements that might be carried out by the utility or government agency. In general, the Health Fund should consider monitoring all attempts to account for the missing radioiodine. (Proposed Project #4b.) It seems especially important to make an independent assessment of whether or not this missing radioactivity could have escaped via a liquid pathway, since liquid pathways have not been carefully investigated in this review. Some future efforts should be made in this direction. (Proposed Project #4c.)

5. Gaps in In-Plant Monitoring Data for Airborne Radioiodine Releases. Information available about the amount of radioiodine released to the atmosphere in the first 15 to 42 hours of the accident is limited and unsatisfactory. For radioiodine (unlike noble gas) there were measurements of the

amount of radioiodine released from the vent stack, but it was acknowledged from the beginning that records from the monitoring cartridges for the first 15 hours were lost or mislabeled. Subsequent investigations indicate that the raw data is suspect out to 42 hours from the start of the accident. (See Appendix C, Section 2.4.)

To get around this gap in the data, analysts substituted data from feeders to the vent stack coming from the fuel handling and auxiliary buildings, and implicitly assumed there were no filter bypasses and no radioiodine contributions from other feeders to the vent stack. However, as indicated in Appendix C, alternative pathways need to be properly considered. (Proposed Project #5a)

For instance, there was at least one known release pathway to the vent stack that bypassed the fuel handling and auxiliary buildings (through the so-called "relief tank vent header"). In addition to this, a number of other escape pathways were possible--especially at the time when the ventilation system was turned off. Radioactivity conceivably could have gone out the air intake tunnel. (The NRC had warned Metropolitan Edison during the accident that turning off the ventilation system could lead to a ground level release.*) In addition, there may have been releases of

*U.S. Nuclear Regulatory Commission, Investigation into the March 28, 1979 Three Mile Island Accident by the Office of Inspection and Enforcement (Report NUREG-0600, Washington, D.C., 1979), p. II-A-42.

radioiodine from the secondary side (see #6 below). Thus, there were even possible pathways that could have bypassed the vent stack itself. Once again, analysis of I-129 left on surfaces in the reactor (see above, Proposed Project #4) may prove helpful in determining the true escape paths for radioiodine.

Because it has been estimated that more than 100,000 curies of radioiodine may have been airborne in the containment building,* it is particularly important (for both airborne releases of radiocesium as well as radioiodine) to determine whether or not the containment building atmosphere was in fact isolated from direct contact with the external environment for the first 42 hours, with all leakage paths occurring through water. The literature provides evidence in the event-by-event descriptive records of the accident that raises the question as to whether the containment atmosphere was continuously isolated--an assumption that has been made in all studies to date.** The most striking reason

*C.A. Pelletier, P.G. Voilleque, C.D. Thomas, J.A. Daniel, F.A. Schlomer, J.R. Noyce, "Preliminary Radioiodine Source-Term and Inventory Assessment" (Report GEND-028, EG & G Idaho, Idaho Falls, March 1983). The model developed by these authors projects that a maximum of 0.2% of the radioiodine in the core (which in turn is known to be 70 million curies) was airborne at any one time. The cumulative quantity of radioiodine estimated to be airborne was estimated to be 5 times higher.

**The main pathway of concern is the reactor building purge system. It may have leaked before the containment building was isolated and during the intermittent periods when isolation was defeated.

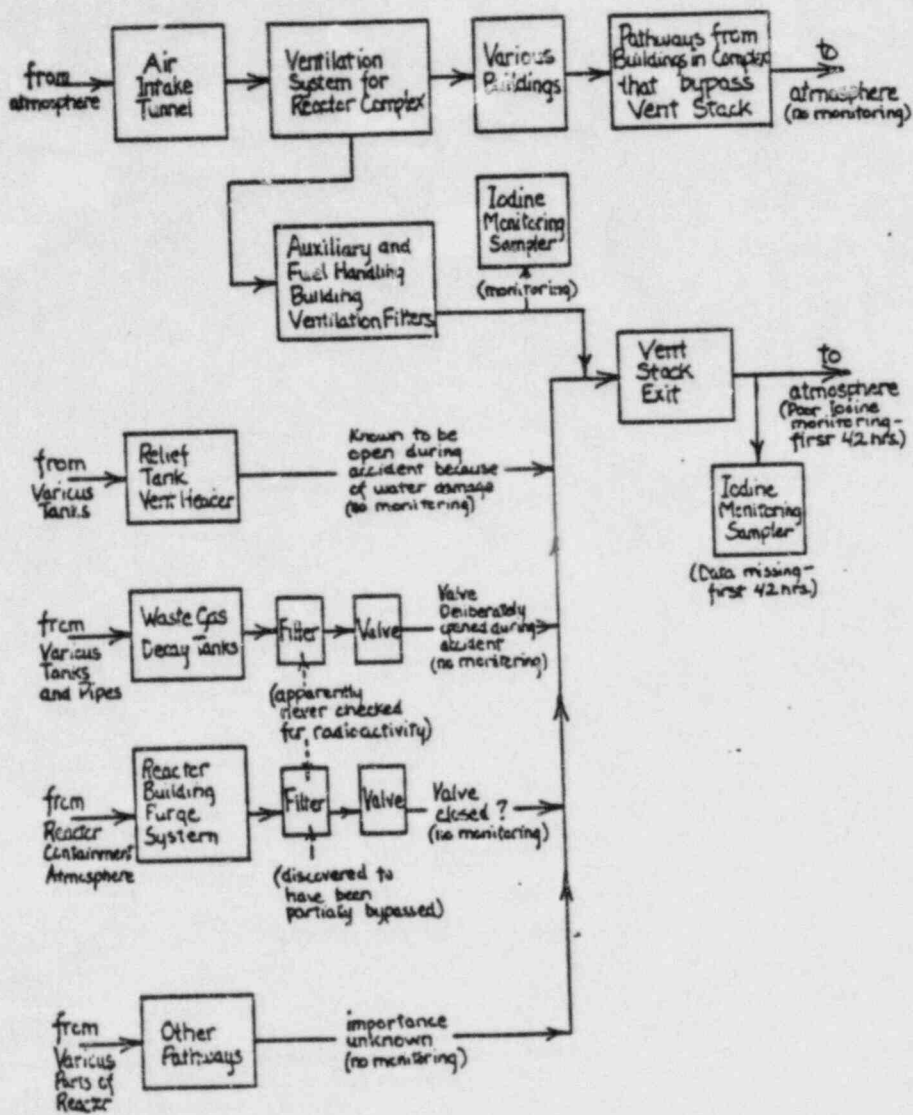
for considering this pathway has to do with the likely inoperability of the filters that should have served as the last line of defense against radioiodine release from the containment building. It was discovered in early 1982* that a bypass existed around the filters between the containment building and the vent stack. Steel plugs that were supposed to block interconnecting drain pipes were missing. In 1980 the holes were covered with "tuck" tape, as preparation for the Krypton venting, but evidently there was not even tape in place at the time of the original accident.

Figure 2 indicates some of the escape pathways discussed in this section that would be of particular concern for Proposed Project #5a.

In addition to the search for unmonitored release pathways, it is also important to clear up certain inconsistencies that exist concerning the calibration of the vent stack monitoring system. As discussed in Appendix C, there is the possibility that the high level of noble gases simultaneously present in the vent stack, as well as the high concentration of water vapor, may have interfered with the efficiency of the collection of radioiodine. Proposed

*Ronald R. Bellamy, "HEPA Filter Experience During Three Mile Island Reactor Building Purges" in 17th DOE Nuclear Air Cleaning Conference, M.W. First, Ed. (Conf-820833, Department of Energy, Washington, D.C., 1983).

Figure 2 Schematic Diagram of Some Relevant Pathways for Airborne Radiiodine at TMI



Project #5b would investigate this matter. (Questions about the efficiency of the vent stack monitor for organic forms of radioiodine will be discussed below in #7.)

6. Emissions from the Secondary Side of the Reactor.

Official studies did not include estimates for this release pathway, even though there is general acknowledgement in the literature that secondary side steam was released into the atmosphere. A method is proposed in Appendix E for using general computer calculations to estimate possible releases of radioiodine that may have occurred from the secondary side of the reactor. Collecting the information on the TMI reactor necessary to use this method, as well as the actual analysis, is proposed as Project #6.

7. Uncertainties in the Chemical Form of the Released Radioiodine. The chemical form of the released radioiodine is unclear, i.e., it is not clear what percentage was organic (e.g., methyl iodide) and what percentage was inorganic. Most analysts have assumed that the release was all inorganic. And indeed, some measurements appear to confirm this, i.e., a limited number of measurements made on airborne samples taken outside of the reactor.* On the other hand, some analysts

*E.W. Bretthauer, R.F. Grossman, D.J. Thome, A.E. Smith, "Three Mile Island Nuclear Accident of March 1979 Environmental Radiation Data: A Report to the President's Commission on the Accident at Three Mile Island" (Report EPA-600/4-81-013B, Environmental Protection Agency, Las Vegas, Nevada, 1981), pp. 2-3.
(con't on following page)

assume, based on reports of vent stack measurements, that the release was evenly divided between the two forms.* Finally, there is completely contradictory evidence based on analyses of auxiliary building exhaust filters indicating that 97% of the release may have been organic.**

Once the possibility is allowed that the ratio of the two forms of radioiodine may be unknown, the complexity of trying to make sense out of the data available on radioiodine at TMI goes up enormously, especially because of the lack of basic information about the behavior of organic iodine.

Proposed Projects #7a - 7d are designed to gain more information about organic radioiodine as it relates to the TMI accident. For instance, there is a need to determine the efficiency with which the in-plant radioiodine cartridge

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See also, Ad Hoc Dose Assessment Group, "Population Dose and Health Impact of the Accident at Three Mile Island Nuclear Station: A Preliminary Assessment for the Period March 28 through April 7, 1979" (Report NUREG-0588, Nuclear Regulatory Commission, Washington, D.C., May 10, 1979), Appendix B, pp. B-2-4.

*Pickard, Lowe and Garrick, Inc., "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident" (Report TDR-TMI-116, Revision 0, 1979) p. 5-5.

**See Table II-4 of Rogovin Report. M. Rogovin and C. Frampton, Jr., Three Mile Island: A Report to the Commissioners and to the Public, (Report NUREG-0600, Report of the Nuclear Regulatory Commission Special Inquiry Group, Washington, D.C., undated) p. 359.

monitors detected organic radioiodine. (Proposed Project #7a.) There is also a need to determine the efficiency of environmental monitors for organic radioiodine. (Proposed Project #7b.) To help in interpreting the quantities of radioiodine found after the accident in cows' and goats' milk, as well as in the carcasses of meadow voles and rabbits, it would be helpful to determine the metabolic pathways that organic iodine follows in such animals. (Proposed Project #7c.) Finally, a review of the behavior of organic radioiodine in humans is in order, especially in connection with calculating radiation doses following inhalation or ingestion. (Proposed Project #7d.)

8. Uncertainties in Environmental Monitoring of Airborne Radioiodine. Airborne measurements of radioiodine made with portable equipment are so spotty and wide in their range that they provide little guidance. Also, there is some question as to their accuracy in light of the large noble gas background. In any case, the usefulness of these measurements is limited because the bulk of them do not occur during the first 42 hours when in-plant monitoring was weak. Of somewhat more use are the 8 fixed radioiodine monitoring stations that were in place at the time of the accident. Yet not all analysts who made dispersion calculation for radioiodine at TMI attempted to test their models against these particular data. Proposed Project #8a involves asking these analysts to do so.

The ratio of radioiodine to noble gases measured in a plume passing Albany, New York is consistent with a release of inorganic radioiodine comparable to or smaller than the official radioiodine release estimate. However, TMI to Albany is only one direction in which radioiodine might have blown during the first 42 hours. Because Albany is hundreds of miles from the site, the Albany measurement cannot be expected to represent a complete sampling of the release. In particular, there is no reason to expect, without further study, that every burst of radioiodine would have been detected--including hypothetical bursts that might explain other data. Long-range meteorological modelling could shed light on this question. (Proposed Project #8b.) Also important will be a determination of the response of the Albany detectors to organic iodine. (This task is covered under Proposed Project #7b discussed earlier.)

9. Difficulties in Interpreting the Lack of Reported Radioiodine in Humans. As mentioned in Section 3.2, attempts to detect radioiodine in humans were made after the accident. Some 760 people living within three miles of TMI were counted for 10 minutes in a whole-body counter beginning on April 10, 1979. The results indicated less than 2 nanocuries of Iodine-131 in all cases. Although it is not clear that the correct calibration factor was used for radioiodine located in the thyroid, any error is probably not significant. (The official reports which criticize this study on those grounds

are excerpted in Appendix C.) If these calibrations are nevertheless acceptable, the measurements provide strong evidence that any large release would have had to occur while the wind was blowing away from locations in which the 760 people in the sample lived, worked or went to school. Releases up or down river may have missed people living within 3 miles. It would be useful, however, to go into the individual case files to confirm the geographical distribution of the 760 people. (Proposed Project #9a.) As part of any full dosimetry study, it would be worthwhile to try to do more with the data obtained from whole body counting than was done originally, in the hope that greater sensitivity could be obtained. (Proposed Project #9b.) For instance, the original "energy spectra" could be added together for many individuals thereby improving the "signal to noise" ratio. (The detection limit would increase by the square root of the number of spectra summed.) In this way there would be a better chance of finding the presence of radioiodine in the data. If all 760 spectra were added, the resulting improvement in sensitivity should be sufficient to detect a release smaller than 15 curies.

10. Uncertainties in Interpreting Milk/Radioiodine Data.

The average amount of radioiodine found in a large sample of cows' milk is far too high to be consistent with the official release estimate, unless farmers blatantly disregarded instructions to keep cattle on stored feed. Assessment of

alternate pathways to cows' milk implies a much higher release of radioiodine.

This contradiction was not recognized during the official inquiries into the TMI accident because the analysts who compared radioiodine in milk with modeling calculations found nothing particularly alarming. However, the key assumption was made that 10% of the diet of TMI cows was obtained from grazing. (Even with this assumption, the milk concentrations predicted by a group from Oak Ridge National Laboratory based on a 15 curie release* were low by a factor of four.) Yet the accident did not occur during the grazing season, and farmers were specifically instructed to keep their cows on stored feed as a result of the accident. So the question becomes, "If cows were on stored feed and only 15 curies of radioiodine were released, how did that level of radioiodine get into cows' milk?" One possibility is that the radioiodine entered cows by inhalation rather than ingestion. In Appendix D of this report, this hypothesis is investigated. It appears that the inhalation mode would contribute approximately two hundred times less radioiodine to milk than a 10% diet of contaminated grass. Thus, if inhalation were the sole pathway to milk, and taking into account the

*C.D. Berger, B.H. Lane, S.J. Cotter, C. W. Miller, S.R. Glandon, "Population Dose Estimation from a Hypothetical Release of 2.4×10^4 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station, Unit 2" (Report ORNL/TM-7980, Oak Ridge National Laboratory, Oak Ridge, TN, September 1981).

factor of four discrepancy between the Oak Ridge model predictions and actual measurements, it could be argued that the actual radioiodine release was many hundreds of times as much as the assumed 15 curie release.

The high estimates implicit in cows' milk samples appear to contradict the grass measurements made at TMI, which can be interpreted as supporting a low 15 curie release as shown in Appendix C. The interpretation is based on noting that the peak quantities of radioiodine deposited on grass are consistent with the official estimate of 15 curies. The reported concentrations have the correct proportion to peak quantities measured after the release of some 20,000 curies of radioiodine in the Windscale accident in England in 1957. However, it should be noted that some of the grass measurements reported by the Department of Energy are so uniform as to suggest incorrect labelling--possibly because the values represent upper limits and not actual detection of radioiodine. Such readings have been discounted for this study.

It should also be noted that a second set of milk measurements are consistent with the official release estimate. Part of the discrepancy with the first set of milk measurements may be due to the fact that various measurements tended to sample different geographical regions. Grass and milk measurements were not taken uniformly in all angular sectors. Comparison of grass sampling locations with the various sets of milk data is in order. (Proposed Project #10a.)

Another possible explanation of the grass/milk discrepancy may lie with the chemical form of the radioiodine. Perhaps the hypothetical, extremely high curie release was in the form of organic methyl iodide. (See above, Proposed Projects #7a - 7d.)

Methyl iodide does not stick to surfaces very easily, so a large release would not show up in grass or soil samples. And essentially no monitoring of airborne methyl iodide took place. Cows would indeed inhale methyl iodide, which in turn would be trapped in their bodies. However, to enter cows' milk, the methyl iodide in the cows would have to be "hydrolyzed." That process does not happen in humans very quickly, but no one has measured the rate at which methyl iodide might enter cows' milk. (Measurement of this rate is proposed as part of Project #7b.)

It should be noted that a large methyl iodide release would not imply a large thyroid dose in humans, but the contribution of inhaled methyl iodide to the whole body dose would be larger per curie inhaled than for inorganic radioiodine. (Estimating methyl iodide's contribution to the whole body dose per curie inhaled is part of Proposed Project #7d mentioned earlier.)

If the large hypothesized radioiodine release were inorganic rather than organic, there exist other pathways besides inhalation that must be considered as alternatives to the 10% grazing assumption:

- 1) If cows were allowed outside for exercise, they may have ingested deposited radioactivity, even though they were not allowed to enter pastures, by licking or chewing the ground--a practice common to cows.
- 2) If cows were fed baled hay stored outdoors, they may have ingested radioiodine that was filtered from the air by the hay itself.

As discussed in Appendix C, accounting for such alternative pathways would reduce the estimate of released radioiodine derived from the milk data.

Choosing among the various hypotheses discussed in this section will be difficult without more data. Interviews with farmers from whose cows the milk samples were drawn should prove useful in this regard. Conducting such interviews is Proposed Project #10b.

11. Uncertainties in Interpreting Radioiodine Concentrations Found in Animals. Radioiodine reported in meadow voles should be carefully analyzed for consistency with the official release estimate for the few wind directions in which vole data are available. A theoretical calculation of vole ingestion of contaminated vegetation has been performed in parallel with this report and reported here (see Appendix C, Section 3.4). However, the calculation is provisional because there is at present no way of accurately knowing the uptake of radioiodine for the vole and the metabolic pathways followed. Instead of relying on rather weak assumptions--

which include an assumption about the fraction of contaminated material in the voles's diet and the assumption that voles resemble humans in their processing of radioiodine-- it would be preferable to "calibrate" the meadow vole (and all other animals that may be useful in future monitoring such as rabbits and squirrels). Calibrating, or in other words measuring the uptake of radioiodine in these animals when exposed to known levels of radioiodine deposition, is Proposed Project #11a.

One measurement of radioiodine in rabbit thyroids has been reported* but not analyzed. The reported concentration appears high and should be compared with model predictions. (Proposed Project #11b.)

12. Complexity of Environmental Data. Because there remain so many inconsistencies in the environmental radioiodine data and because the data were so geographically spotty, it would be extremely useful in evaluating competing theories to have a universal map of the area that would indicate the location of all radioiodine measurements taken at TMI, and their results. Preparation of such a map is Proposed Project #12.

13. Inadequate Data on Radiocesium Distribution. As discussed in Section 3.3 above, peculiarities in the Department of Energy's measurements of deposited radiocesium (i.e.

*See Appendix C, Section 3.5.

identical values) prevent their use in analysis, and consequently make impossible any estimate of the geographical deposition of radiocesium and its resulting dose. Discussions with the original investigators may help to resolve this discrepancy. In any case, radiocesium's long life allows fresh samples to be taken for analysis even now. Carrying out such measurements is Proposed Project #13.

In order to make a rough assessment of the importance of such an experimental project, it is suggested that a preliminary upper-limit calculation be carried out in preparation for the dosimetry workshop. As mentioned in Section 3.2 above, about 100 nanocuries per square meter of radiocesium were measured in the vicinity of the reactor. Rather than assuming that all of this radiocesium originated from past weapons tests, it is possible to use the 100 nanocuries per square meter figure to set a limit on the reactor's contribution. Assuming, say, that 25% of the measured contamination (25 nanocuries) could have originated from the accident without being noticeably higher than the background level from weapons fallout, it would be possible to calculate a resulting population dose (both accumulated to date and projected 25 years into the future).*

*Taking into account the shielding effects of building walls and of the leaching of the cesium into the ground, a whole-body dose of 10 rem would accumulate over 30 years from an initial ground concentration of Cs-137 equal to 30,000 (con't on next page)

14. Lack of Explanation for Taste Sensations Reported at the Time of TMI Accident. Sensations experienced by people in the vicinity of TMI at the time of the accident (for example, a metallic taste in the mouth) suggest that certain chemical agents may have accompanied the release of noble gases. Since any gas not soluble in water would have been released, a study of the possible chemical gases that would be produced in a TMI-like event may be very important. Such chemicals might have the potential to cause health effects. (Proposed Project #14.)

15. Lack of Availability of Private Data. Considerable data from the time of the TMI accident may remain in private hands. Some of these data have already been mentioned in Proposed Project #3b as part of the effort to close the TLD windows. In addition to the specific data discussed in that section, a concerted effort should be made to get all such privately held data into the public record. (Proposed Project #15a.)

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nanocuries per square meter. See J. Beyea and F. von Hippel, "Nuclear Reactor Accidents: The Value of Improved Containments" (Report PU/CEES 94, Center for Energy and Environmental Studies, Princeton University, Princeton, N.J. 08544, January 20, 1980), p.II-8.

This means that a 1 rem dose to an individual would result from an initial concentration of 3,000 nanocuries/m². Therefore 25 nanocuries (i.e. 25% of 100 nanocuries) would cause an accumulated dose to the individual of 0.0083 rem. Multiplying this individual dose by the number of people living within 10 miles of the plant (137,000) implies a collective dose of 1100 person-rem. The contribution for people exposed beyond 10 miles is more difficult to estimate, but it should be attempted in an approximate way for the dosimetry workshop.

Such newly gathered data, and other raw data already extant but unanalyzed, should be pressed into service. Developing appropriate analyses of this data is Proposed Project #15b.

16. Future Doses from TMI Cleanup. The long process of cleanup at TMI may itself produce releases of radioactive material and associated health effects. These possibilities are explored in Appendix F of this report, which has been prepared under subcontract. The breadth of public concern expressed about the cleanup at the March 19, 1983 TMI symposium suggests that the Public Health Fund will want to give cleanup dose assessment a relatively high priority. Since the NRC has increased by a factor of six its own estimates of projected occupational doses it is probable that public concern about re-estimates of the population dose will remain high. Monitoring cleanup activities at the reactor site seems a modest first step for further dosimetry work related to the cleanup. (Proposed Project #16.)

TABLE 5 : LIST OF PROPOSED PROJECTS

PROPOSED PROJECT & DESCRIPTION	ASSOCIATED DOSE ESTIMATE	PROJECT SCOPE & METHOD
1a Recalculation of Estimate of Released Noble Gases.	Whole body population dose from noble gas release.	* Preliminary calculations to be made prior to dosimetry workshop, using method outlined in Appendix B (controlled venting of Krypton-85, June-July, 1980).
b Reconciliation of Source Term Noble Gas Release Estimates.	" "	* May be resolvable at dosimetry workshop, or further analysis may be warranted
2 Recalibration of Thermoluminescent Dosimeters (TLDs) as a function of time, isotope mix & atmospheric distribution of radiation.	Whole body population dose from noble gas environmental measures.	* May be resolvable in laboratory experiments with meteorological consultation.
3a Analysis of TLD perimeter coverage, based on angular efficiency of TLDs, their deployment at TMI, hourly wind vectors, timing & height of releases.	Whole body population dose from noble gas environmental measures & source term release; use for future monitoring.	* Preliminary analysis to be made prior to dosimetry workshop, based on TLD efficiency ratings, TLD deployment & TMI meteorological records. Additional analysis if needed.
b Collection of new data for "window" in TLD coverage.	" "	* Public information outreach & search, followed by analysis of new data.
c Collection of available data for "windows" in TLD coverage.	" "	* Collection of hospital film badges, photographic film & other known radiation-sensitive material from defined geographical "window" areas.

(Table 3 con't)

3d	Calculation of upper-dose limits assuming "worst case" (100% release into TLD window during wind vector in that sector).	"	"	* Preliminary calculation upper limits to be produced for dosimetry workshop.
e	Archeological dating techniques applied to brick within TLD windows.	"	"	* Sensitivity to be explored & discussed at workshop for possible implementation.
f	Statistical reanalysis of available TLD data by varying scenarios of time release.	"	"	* Statistical "Bayesian" analysis based on available data.
4a	Feasibility of accounting for missing radioiodine by tracking & measuring long-lived residual Iodine-129.	Thyroid population dose from radioiodine source term release.		* Theoretical calculation based on I-129 inventory & instrument sensitivity.
b	Monitoring of Iodine-129 measurement during cleanup.	"	"	* Long term project to continue throughout cleanup.
c	Investigation of possible liquid pathways for radioiodine.	"	"	* Engineering project, partially dependent on 4a.
5a	Analysis of efforts to substitute alternative airborne radioiodine hypotheses for data missing from vent stack monitor.	"	"	* Preliminary analysis of additional pathways, bypasses & containment isolation to be presented to dosimetry workshop; additional analysis if needed.
b	Investigation of calibration & efficiency of vent stack (& filter radioiodine monitoring).	"	"	* May be resolvable in laboratory experiments duplicating (as far as possible) actual TMI conditions.
6	Possible radioiodine emissions from the secondary side of the reactor.	Additional thyroid population dose from radioiodine source release.		* Method proposed in Appendix E, based on German computer modeling for secondary side release estimate, to be discussed at dosimetry workshop. Collection of TMI data & analysis to follow.

(Table 5 con't)

7a	Investigation of the chemical forms of released radiiodine: determination of in-plant monitor efficiency in detection of (organic) methyl iodide.	Thyroid & whole body dose from radiiodine source release & environmental monitors.	<ul style="list-style-type: none">* Wide discrepancies in estimates of proportions of organic & inorganic radiiodine releases to be discussed at dosimetry workshop.* Monitor efficiency may be resolvable in laboratory experiments duplicating (as far as possible) actual THI conditions.
b	Determination of environmental monitor efficiency for methyl iodide.	" "	<ul style="list-style-type: none">* May be resolvable in laboratory experiments with meteorological consultation.
c	Determination of metabolic pathways for methyl iodide in animals exposed to releases, & possible hydrolysis into goats' & cows' milk.	" "	<ul style="list-style-type: none">* May be resolvable in animal physiological experiments.
d	Determination of behavior of ingested or inhaled methyl iodide in human beings.	" "	<ul style="list-style-type: none">* Physiological consultation.
8a	Analysis & comparison of air-borne radiiodine release estimates with fixed radiiodine environmental monitors.	Reconciliation of population dose estimates from source release & environmental measures.	<ul style="list-style-type: none">* Analysis performable with existing data.
b	Long-range meteorological modeling to analyze radiiodine/noble gas ratio in Albany, NY plume.	Check on maximum thyroid dose estimate.	<ul style="list-style-type: none">* Meteorological consultation to determine feasibility.
9a	Geographical distribution of humans tested for radiiodine in post-accident counter.	Thyroid population dose from environmental measures.	<ul style="list-style-type: none">* Case record search & mapping project.
b	Statistical reanalysis of available human radiation data by combination of individual energy spectra.	" "	<ul style="list-style-type: none">* Statistical analysis based on data that may have been saved.

(Table 5 con't)

10a	Investigation of inconsistencies in interpretation of radioiodine in cows' milk & grass samples.	Reconciliation of thyroid population dose estimates from environmental measures & source release.	* Creation of map for milk samples & grass samples. Discussion of ingestion & inhalation pathways at dosimetry workshop. (See also Proposed Projects 7a-7d)
b	Interviews with farmers from whose cows milk samples were drawn.	" "	* Survey questionnaire designed with animal husbandry consultation & inspection of sample sites.
11a	Calibration of radiiodine uptake for small animals for known levels of radioiodine.	Thyroid population dose from environmental measures; future use in environmental monitoring.	* Resolvable in animal physiological laboratory experiments.
b	Analysis of collected data on rabbit thyroid.	" "	* Analysis performable with existing data.
12	Unification & coordination of all environmental measures of radioiodine.	Thyroid population dose from environmental measures.	* Creation of large-scale maps of TMI environment & plotting of all environmental data.
13	Investigation into distribution & dose from radiocesium.	Whole body population dose from long-lived radiocesium.	* Preliminary analysis of data to be made for dosimetry workshop. Possible resampling of area.
14	Investigation into non-radioactive toxic chemical releases.	Non-radioactive health effects.	* Consultation with chemical & toxicological consultants.
15a	Outreach effort for additional unpublished data.	Additional data for all dose estimates.	* Public information outreach & search. (See also 3b)
b	Developing analysis plans for all such data.	" "	* Designing & carrying out analyses of relevant data.
16	Monitoring cleanup activities at TMI	Additions to all estimated population doses/worker doses.	* Long-term project to continue throughout cleanup.

8.0 Bibliography

8.1 Data Bases Containing Entries for the TMI-2 Accident

<u>DATA BASE NAME</u>	<u>SUBJECT COVERAGE</u>
AGRICOLA	AGRICULTURE
AQUALINE	WATER RESEARCH
AQUATIC SCIENCE	AQUATIC SCIENCE
ASI	US FEDERAL STATISTICS
BHRA	FLUID ENGINEERING
BIOSIS PREVIEWS	LIFE SCIENCE
BOOKS IN PRINT (BBIP)	CURRENT BOOKS
CA SEARCH (CHEM)	CHEMISTRY
CIS	US CONGRESS
COMPENDEX (COMP)	ENGINEERING
CONFERENCE PAPERS	SCIENCE
DISSERTATION INDEX (DISS)	UNIVERSITY RESEARCH
EI ENGINEERING MEETINGS	ENGINEERING
ECONOMIC ABSTRACTS	ECONOMICS
ENERGY (DOED)	DOE DATABASE
ENERGY LINE (EICI)	ENERGY
ENVIROLINE (EIVI)	ENVIRONMENT
ENVIRONMENTAL BIBLIOGRAPHY	ENVIRONMENT
EPB	ENVIRONMENT
ERIC	EDUCATION
FED REG	US FEDERAL REGISTER
FFSTA	FOOD SCIENCE
FOODS ADLIB	FOOD TECHNOLOGY
GEOARCHIVE	GEOSCIENCE
GEOREF	GEOSCIENCE
GPO MONTHLY CATALOG	GOVERNMENT PUBLICATIONS
HEALTH PLANNING (HLTH)	HEALTH CARE
INSPEC (INSP)	PHYSICS, ELECTRONICS
IRL LIFE SCI	LIFE SCIENCES
LC MARC	LIBRARY OF CONGRESS
LEGAL RESOURCE INDEX	LAW JOURNALS
MANAGEMENT CONTENTS (MGMT)	BUSINESS
MEDLINE (MESH)	MEDICINE
METADEX	METALS
NATIONAL NEWSPAPER INDEX	MAJOR NEWSPAPERS
NIMH (NCMH)	MENTAL HEALTH
NTIS	GOV'T SPONSORED RESEARCH
OCEANIC ABS	MARINE SUBJECTS
PAIS DATABASE	SOCIAL SCIENCE
PATSEARCH (PATS)	PATENTS
POLLUTION ABS (POLL)	ENVIRONMENT
PSYCH ABS (PSYC)	PSYCHOLOGY
RAPRA	RUBBER AND PLASTICS
SCI SEARCH	SCIENCE CITATIONS
SOCIAL SCISEARCH (SSCI)	SOC SCI CITATIONS
SSIE (SMIE)	CURRENT RESEARCH
US POL SCI	POLITICAL SCIENCE

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*U.S. Senate Committee on Environment and Public Works, Subcommittee on Nuclear Regulation, Nuclear Accident and Recovery at Three Mile Island: A Special Investigation, (July 2, 1980)

Wahlen, M., Kunz, C.O., Matuszek, J.M., Mahoney, W.E. and Thompson, R.C., "Radioactive Plume from the Three Mile Island Accident: Xenon-133 in Air at Distance of 375 Kilometers," Science 207, 639-40 (1980)

*Wong, B.A., DeNee, P.B., "Characterization of an Aerosol Sample from Three Mile Island Reactor Auxiliary Building," (Unpublished report, Lovelace Biomedical and Environmental Research, Albuquerque, NM, January 1981)

Woodard, K., Potter, T.E., "Assessment of Noble Gas Releases from the Three Mile Island Unit 2 Accident," (Presented at the American Nuclear Society Meeting, San Francisco, CA, November 12, 1979)

Zack, R., Mayoh, K.R., "Soil Ingestion by Cattle: A Neglected Pathway," Health Physics 46, 426-431 (1984)

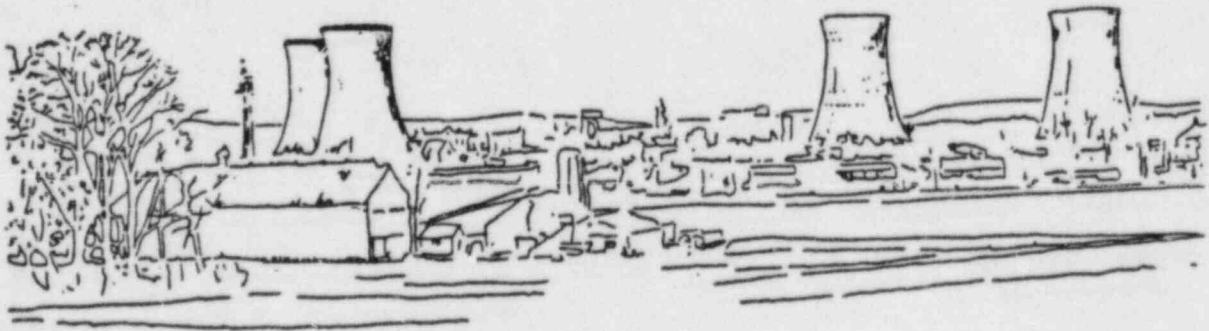
A Review of Dose Assessments
at Three Mile Island
and
Recommendations for Future Research

APPENDICES TO THE REPORT

Prepared for the TMI Public Health Fund

Jan Beyea, Principal Investigator

August 15, 1984



Appendix A

Review of Estimates of the Whole Body Collective Dose
Delivered to the Population from the Passing Cloud.

Al.0 Introduction

Serious limitations are associated with every study that attempts to estimate the whole-body population dose of radioactivity at Three Mile Island. These limitations are understandable: because of the inadequacy of monitoring equipment in place at the time of the accident, all investigating groups found it necessary to make one or more key unconfirmable assumptions. In other words, they did the best they could in spite of the gaps in the available data. This appendix, however, reviews each study and focuses on the limitations that prevent any of them from being conclusive.

All investigators to date have limited themselves to doses within 50 miles. Such a limit does not appear to be a major oversight in this case, but its results should be corrected at some later date. A rough estimate made for another study* indicates that the population dose beyond 50 miles might double the total.** In the remainder of this appendix, discussion will

*Jan Beyea, "Some Long-Term Consequences of Hypothetical Major Releases of Radioactivity to the Atmosphere from Three Mile Island," (Report PU/CEES #109, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey: December 1980), p. 12.

**For a 1.4% release of noble gases, Beyea's calculations referenced above indicated a post-50-mile population dose ranging from 300 to 1200 person-rem depending upon the wind direction assumed. This range can be compared with the 275 to 1500 person-rem range within 50 miles (continued)

be restricted to doses within 50 miles.

The population dose estimates given in this appendix do not take into account building shielding--a factor which might reduce them all by about 25%,* In addition, the impact of self-evacuation has not been included, although this effect has been estimated to have been negligible (due to the delayed start of the evacuation).**

For the purposes of this review, it has been assumed that the neglect of the post-50 mile population dose cancels out the neglect of building shielding and self-evacuation.

A2.0 Methods of Analysis

Two general methods have been used to estimate whole-body population doses resulting from the TMI accident. As we shall see, the two methods do not give consistent results.

Both methods begin by superimposing a grid upon a population map of the area. Estimates of doses to individuals are then made

(continued from previous page)

calculated in Table A-2 of this review, assuming a release similar in magnitude.

Within the limitations of this rough comparison, it appears that the population dose beyond 50 miles is comparable in magnitude to the population dose within 50 miles.

*For example, see Kemeny Commission, "Report of the Task Group on Health Physics and Dosimetry." (October 31, 1979), Appendix C and Report NSAC-26, p. D-2 (see footnote below for full citation) Independent calculations made for this literature review also support this result.

**P.K. Knight, J.T. Robinson, F.J. Slagle, P.M. Garrett, (Technology Energy Corporation), "A Review of Population Radiation Exposure at TMI-2" (Report NSAC-26, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, August 1981) p. VI, S-3,4.

at each of the more than one hundred grid locations and multiplied by the population surrounding the grid point in order to determine a "local" population dose at each grid point. Finally, the local population doses are summed to give the total population dose. Although the two methods to be discussed are similar in their overall approach, they differ in the way dose estimates are made at each grid point.

The first method begins with estimates (in curies) of radioactivity released from the source at defined times, puts each estimate through a meteorological dispersion model with values for wind, temperature, etc. corresponding to the defined time, and projects doses (in rems) to various grid points (see Figure A1-a). The second method begins with environmentally monitored and measured dose data and interpolates between or extrapolates from those monitor locations to the grid points (see Figure A1-b).

It should be noted that the distinction between the two approaches becomes somewhat blurred when the interpolation is carried out by means of a meteorological model. This "meteorological interpolation" procedure is equivalent to working backwards from the environmental dose measurements to infer a release magnitude. The inferred release magnitude is then used with the meteorological model to project doses at all other locations as in the first method (see Figure A1-c).

The two general methods are discussed in sections 3.0 and 4.0 below, as they are exemplified in specific studies under review. A list of investigators performing analyses by each method is given in Table A-1.

Figures A1-a-c

METHODS FOR ESTIMATING DOSES AT LOCATIONS WITHOUT MONITORS

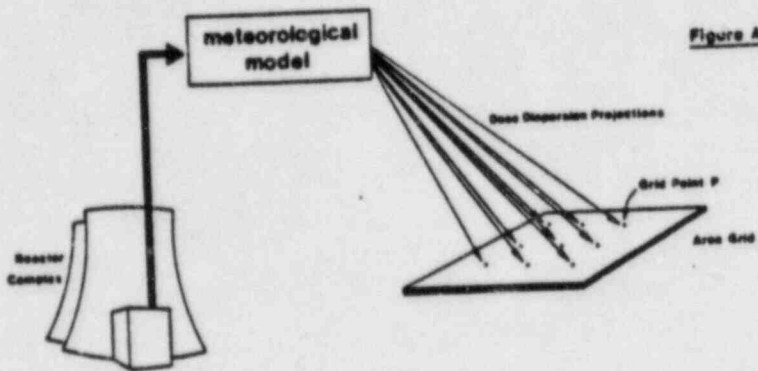


Figure A1-a

Projection from estimate of released radioactivity

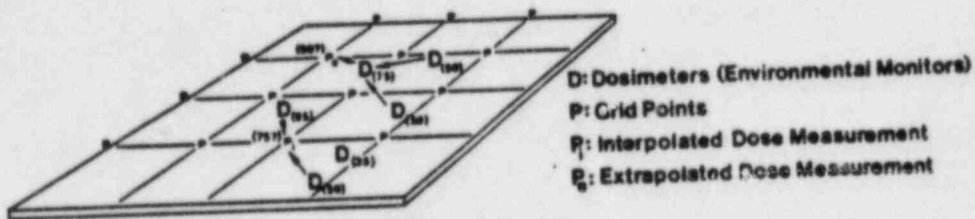


Figure A1-b

Interpolation/extrapolation (from dosimeter readings)

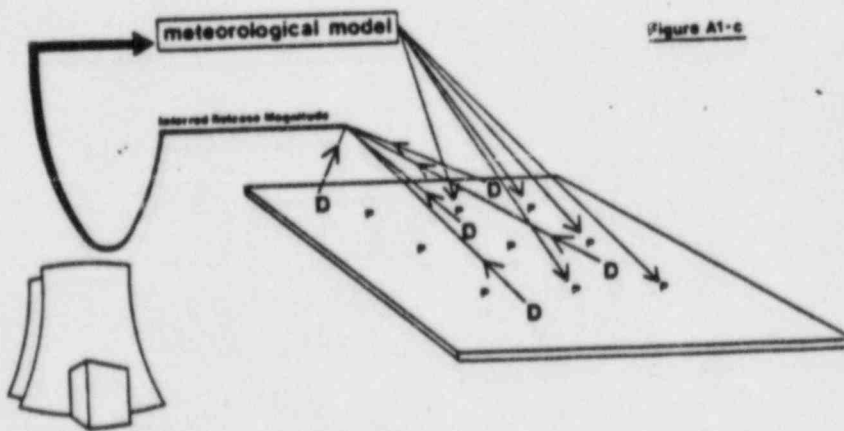


Figure A1-c

Interpolation/extrapolation (meteorological)

TABLE A-1

List of Investigators Who
Have Made Whole-Body Population Dose Estimates
for the Accident at TMI

First Method^{a)}

Kemeny Commission Task Group (Auxier et al.)
Oak Ridge National Laboratory (Miller et al.)
Technology for Energy Corporation (Knight et al.)

Second Method^{b)}

Department of Energy (Andrew Hull)
Ad Hoc Dose Assessment Group (Battist et al.)
Kemeny Commission Task Group (Auxier et al.)
Pickard, Lowe, Garrick, Inc. (Keith Woodard)
S. Takeshi
C. Kepford

-
- a) In this method the amount of curies released at each time interval is estimated from in-plant information. This so-called "source term" is then used as input to a meteorological model to project doses at all locations.
- b) In this method doses at all locations are extrapolated from, or interpolated between, actual dose measurements obtained in the field. All of the analysts listed, except for the Department of Energy, made use of thermoluminescent dosimeter (TLD) readings. The Department of Energy relied on helicopter Geiger counter readings.

A3.0 Estimates Derived from In-Plant Release Data: the Source Term Method

A3.1 Kemeny Commission Task Group (Auxier et al.)

The "source term method" begins with an estimate, based on in-plant data, of the amount of released radioactivity (the source term), which is assumed to have exited by way of the main reactor release point, the vent stack. Because the TMI vent stack monitor went off scale during most of the release, it was necessary to estimate the quantity of released radioactivity by indirect means. The method used by the staff of the President's Commission on Three Mile Island (Kemeny Commission Task Group, Auxier et al.) involved an analysis of those radiation monitors in the auxiliary building that did not go off scale.

Although the connection between these monitors and the radioactivity leaving the reactor complex is not immediately obvious, it is not unreasonable to expect some correlation. In the first place, a great deal of radioactivity passed out of the reactor through this building in one way or another. For instance, water pumped from the reactor floor to a tank in the auxiliary building overflowed, releasing noble gases into the auxiliary building air. This radioactivity in turn either escaped from leaks in the building or was carried by the ventilation system to the vent stack. In addition, considerable radioactivity made its way out of the reactor complex through ducts that pass through the auxiliary building before connecting to the vent stack. Since gamma

radiation from the noble gases can pass through the duct walls, radiation monitors in the auxiliary building would have detected some fraction of this radioactivity on its way to the vent stack.

Because the monitors in the auxiliary building were not exposed to the full scale release of radioactivity, their stripchart recorders did not go off scale, and therefore they supply some information for the entire duration of the release. Although there is no unambiguous way to establish the correlation between the stripchart data and the actual release history, the Kemeny Commission analysts made two assumptions in order to make sense out of the information available to them. First, it was assumed that the readings on the continuously moving stripcharts were proportional to the total amount of radioactivity being released at any moment in time. This assumption of a constant proportionality is highly questionable. The monitors were measuring gamma radiation from many sources, e.g., from radioactive isotopes in the air within the auxiliary building as well as from the radioactive isotopes inside exhaust and ventilation ducts. Although radiation from radioactive isotopes on their way to the vent stack would have contributed to the total readings on these monitors, the relative contribution from each of the various sources may have changed with time. For instance, suppose that during the first half of the release, radioactivity left the reactor by way of a duct that passed close to the radiation monitors, while during the second half of the release, radioactivity left by way of a duct that passed far from the monitors. In such a hypothetical case, the signal recorded by the monitors would not have had the

same relationship to the true release during both time periods.*

Examples of pathways far from the stripchart monitors are

- 1) a possible path "backwards" through the air inlet tunnel during the period in which the ventilation system was turned off** (see Figure A-2),

*Mathematically, the point can be made as follows: the total release, $S(t)$, is equal to the sum of releases from different pathways. Thus, $S(t) = \sum S_i(t)$. The effective signal $S^1(t)$, received by a radiation monitor, is given by $S^1(t) = \sum B_i S_i(t)$, where the factors B_i take into account a) the effective distance between each pathway and the monitor, and b) the relative absorption that takes place in any intervening matter.

For proportionality to exist between $S(t)$ and $S^1(t)$ at all times, each release through each pathway must have the same relative time dependence. Even this condition is not sufficient because the B_i factors themselves were not all constant in time. Absorption effects would have changed in time because the mix of gamma ray energies changed. High energy gammas were plentiful at the beginning of the noble gas release, but greatly reduced compared to the (low energy) gammas from Xenon 133 by the end of the release.

**The ventilation system for Unit 2 was turned off at 11:04 on 3/28 according to the NRC's chronology of events. [U.S. Nuclear Regulatory Commission, Investigation into the March 28, 1979 Three Mile Island Accident by the Office of Inspection and Enforcement, (Report NUREG-0600, Washington, D.C., 1979).] The time at which the ventilation system was restarted is not clear. The following qualitative remarks are given in the text of NUREG-0600, p. II-3-21:

"Shift Foreman B stated that the Unit 2 ventilation system supply fans tripped and remained off because of high radiation levels, but the exhaust fans operated continuously except for a few brief periods when the ventilation systems were turned off in an attempt to reduce the release rates. Securing the fuel-handling building and auxiliary building ventilation systems early on March 28 and again on March 29 caused exposure rates to increase significantly in the Unit 2 auxiliary building, thus hampering emergency activities. Perhaps more important was the fact that control room airborne radioactivity levels started increasing when the ventilation systems were shutdown...Because of the need to ensure habitability of the control room and to keep dose rates as low as possible in the auxiliary building to facilitate emergency activities, the ventilation systems were subsequently kept in operation."

- 2) a pathway through the relief valve vent header* (see Figure A-3),
- 3) a possible pathway through the atmospheric relief valves in the secondary side (discussed in section C2.2 of Appendix C. See Figure C-1).

It is important to recognize that large amounts of radioactivity could have escaped through these paths without being detected by the stripchart monitors. One has to conclude that a constant proportion between readings of the auxiliary building stripchart monitors and total released radioactivity is unlikely.

In addition to the first assumption about proportionality made by the Kemeny Commission Task Group, it was necessary to make a second assumption in order to convert the actual stripchart readings to curies released. The task group had to determine the proportionality constant, or scale factor. For this purpose, investigators compared the stripchart readings with the vent stack monitor at a time when it finally had come back on scale. They assumed this ratio applied at earlier times.

This is rather a strong assumption to make, since it requires assuming first, that all radioactivity exited through the vent stack; and second, that it exited by the same mixture of internal paths that was dominant when the vent stack monitor reading was finally taken. Furthermore, the composition of the

*The mechanical drawings for the auxiliary building indicate that the relief valve header enters the vent stack far from the stripchart monitors.

Figure A-2. Schematic Diagram of Air Flow at TMI and Some Relevant Mobile Gas Pathways.

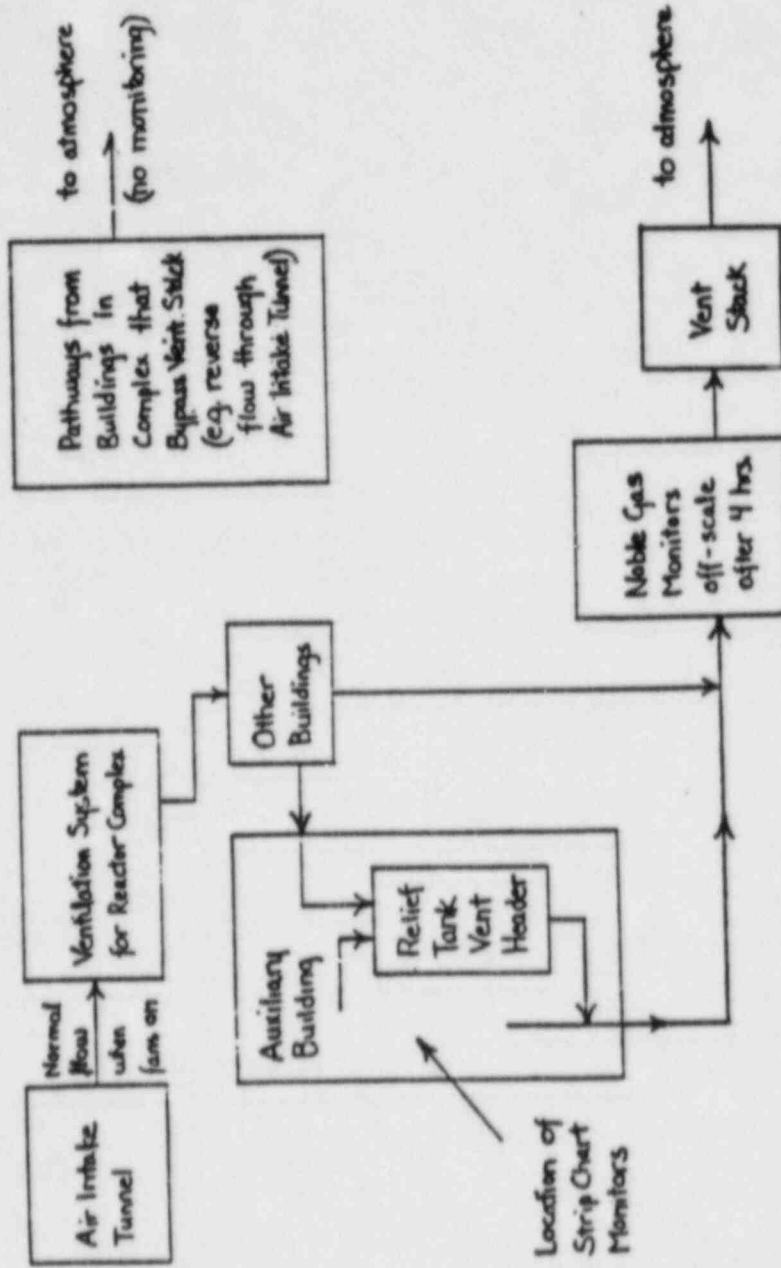
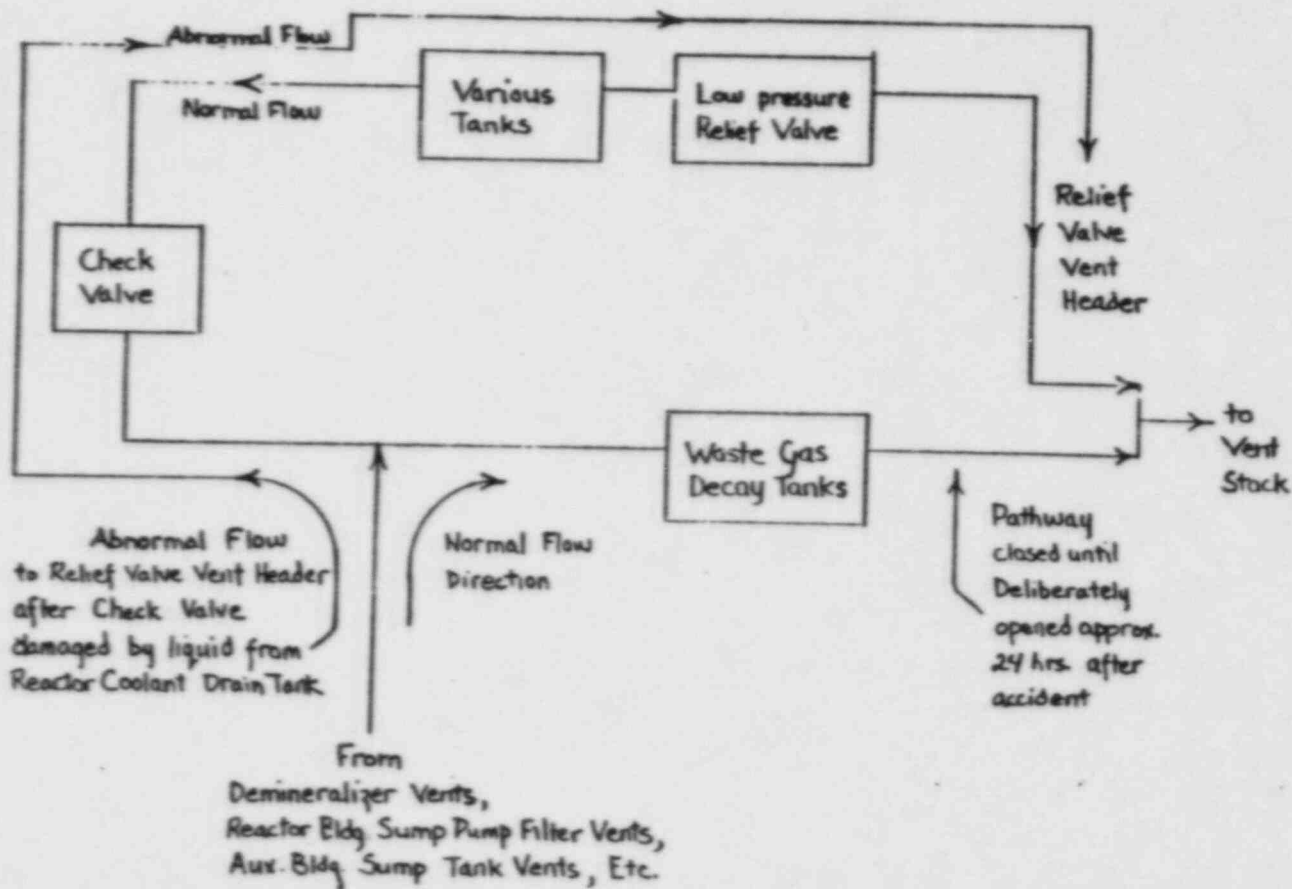


Figure A-3. Relief Tank Vent Header Pathway.



release would itself have changed over time. The vent stack readings taken at the end of the release would have all been due to low energy gamma rays from Xenon-133, whereas "harder" gamma rays would have been present early in the release. Thus, the attenuation of gamma rays through ducts, pipes and other materials should have been different at different times.

The one piece of evidence supporting the Kemeny Commission calibration comes from comparison with a "grab sample" of air taken around noon on March 31, 1979 from the stack itself. The amount of radioactivity measured in that sample was reported to agree with the calibrated stripchart reading within 10%.^{*} However, because no additional information about this potentially important measurement is available, it is not possible to make an independent assessment of its reliability. Furthermore, as will be discussed below in Section A3.3, a 1981 reanalysis of grab sample data indicates that such measurements fluctuated in relationship to the stripcharts by a factor of one hundred at different times.^{**} Thus, even if the measurement used by the Kemeny Commission staff is accepted exactly as interpreted by them, the measurement only serves to establish that the pathway followed by the radiation escaping at that one time (about noon on March 31) was the same as at the end of the release.

*Kemeny Commission, (Auxier et al.) "Report of the Task Group on Health Physics and Dosimetry," (October 31, 1979), pp. 139-140.

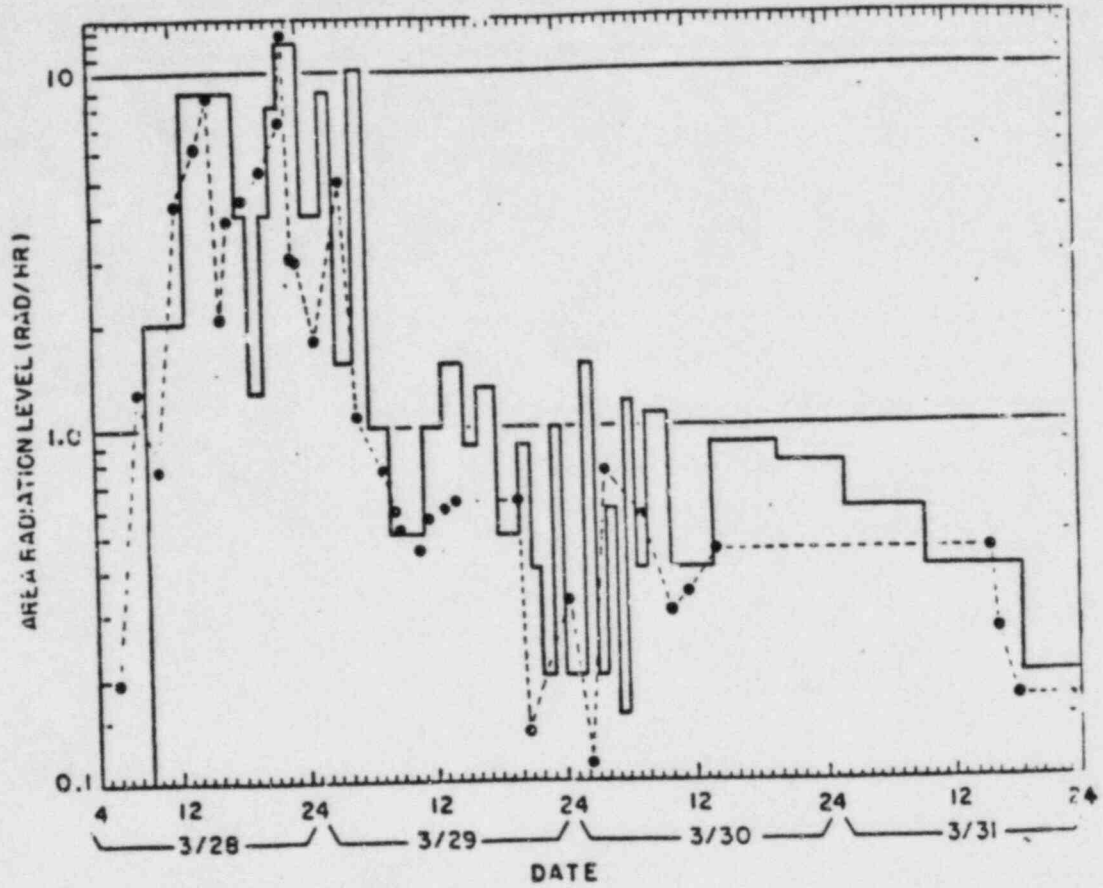
**P.K. Knight, J.T. Robinson, F.J. Slagle, P.M. Garrett, (Technology Energy Corporation), "A Review of Population Radiation Exposure at TMI-2" (Report NSAC-26, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, August 1981), pp. III-14,15.

Grab sample measurements can not confirm the calibration for times when samples were not taken.

In any case, given the Kemeny Commission assumptions, their method of analysis produced an estimate that 2.4 million curies of noble gases were released, with the level of release varying in time, as indicated in Figure A-4. When this release estimate or "source term" was used as input to various dose-projecting meteorological models made available by subcontractors to the Commission, the first three population dose estimates shown in Table A-2 resulted. (The three values differ because different models, or different model parameters, were used.)

*It appears that some of the model calculations did not properly account for the turbulent wake of the reactor building and cooling towers. Other inconsistencies are discussed in the footnotes to the Table.

Figure A-4
Relative Time Dependence of Release Assumed By
Various Analysts Based on Stripchart Monitors in the Auxiliary Building



(Circles = Kemény Commission Task Group*)

(Solid Line = Woodard and Potter)**)

*This data has been read off another graph and superimposed upon the chart provided in the paper by Woodard and Potter.

**See below, Section 3.3.

Table A-2
Fifty-Mile Whole-Body Population Doses Projected
from an Estimated Noble Gas Release ^{a)}

<u>Investigator</u>	<u>Meteorological Model</u>	<u>Release Estimate (Millions of Curies)</u>	<u>Person-Rem</u>
Kemeny Commission Group			
Subcontractor:			
Lawrence Livermore Laboratory	ARAC Code	2.4	276 ^{b,c}
Oak Ridge Laboratory	AIRDOS-EPA Code I	"	390 ^b
Oak Ridge Laboratory	TVA Code	"	970 ^b
Miller et al. (Oak Ridge)	AIRDOS-EPA Code II	"	1500 ^d
Technology for Energy Corp. (Knight et al.)	XODOQ/GASPAR Codes	7-17	3000 - 7000 ^e

- a) All analysts except for Technology for Energy for Corporation (TEC) assumed the same time dependence for the release as supplied by the Kemeny Commission. The results for all but the TEC data differ because the assumed meteorological models differ. The TEC results differ because of the larger assumed release. Shielding from buildings and self-evacuation has not been taken into account. Doing so might reduce listed doses by 25%.
- b) As reported in Kemeny Commission's "Report of the Task Group on Health Physics and Dosimetry," October 31, 1979.
- c) See also, Knox et al., Utilization of the Atmospheric Release Advisory Capability (ARAC) Services during and after the Three Mile Island Accident. (Report UCRL-52959, Lawrence Livermore Laboratory, Livermore CA 1980.)
- d) A report released by Oak Ridge subsequent to the Kemeny Commission report indicated this higher population dose figure. It was obtained using the same computer code. However, assumptions about the release height were changed. In the second calculation, it was assumed that a ground level release was a closer approximation to actual dispersion conditions. See Charles W. Miller, Sherri J. Cotter, Robert E. Moore, Craig A. Little, "Estimates of Dose to the Population within Fifty Miles due to Noble Gas Releases from the Three Mile Island Incident," Presented at ANS/European Nuclear Society Thermal Reactor Safety Conference, Knoxville, TN Volume 2, pp. 1336-1343. (April 7-11, 1981.)
- e) Knight et al., (Report NSAC-26) p. III-14. Doses were corrected in their report for shielding (i.e., they were reported as 2200-5300, not 3000-7000). But in order to make the results consistent with the other entries in the table, the correction has been removed.

A3.2 Oak Ridge National Laboratory (Miller et al.)

After the completion of the Kemeny Commission studies, Miller et al. of the Oak Ridge National Laboratory, analysts who had served either as staff or consultants to the Commission, repeated the population-dose calculations independently. In this second study, they retained the earlier assumption of a 2.4 million curie release of noble gases. They also accepted as their meteorological model the same AIRDOS-EPA computer code they had previously used. The single substantial change in the input to the model was the substitution of a ground-level release for the 50-meter release height assumed in all previous calculations of dispersion. As can be seen in Table A-2, the 50-mile person-rem estimate obtained by a change in this one variable is 3.8 times higher than that of the identical meteorological model, 1.5 times higher than the TVA model also run by Oak Ridge, and a full 5.4 times higher than the estimate obtained by the Livermore Laboratory model.

A3.3 Technology for Energy Corporation (Knight et al.)

At the request of the Nuclear Safety Analysis Center, Knight et al.* of the Technology for Energy Corporation reviewed the TMI population dose estimates. Their report, published in 1981, contained some new analyses of the data that are of interest. In particular, following essentially the same methodology as the Kemeny Commission, but making use of 10 grab samples between 3/31 and 4/30 to calibrate the stripchart monitors they analyzed, they estimated

*P.K. Knight, J.T. Robinson, F.J. Slagle, P.M. Garrett, (Technology Energy Corporation), "A Review of Population Radiation Exposure at TMI-2" (Report NSAC-26, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, August 1981).

a release of 7 to 17 million curies, as opposed to the much lower value obtained by the Kemeny Commission Task Force. Their population dose estimates were correspondingly higher: 3000 - 7000 person-rem (before correcting for building shielding).^{*} The fact that grab sample calibration factors showed a hundred-fold variation lends strong support to the hypothesis stated previously, that the stripchart monitors were not always sampling the full release.

A3.4 Reservations About the Use of In-Plant Release Data and the Possibility for Independent Release Estimates

In examining the methodology and the results obtained by the calculations of the first or source term method, three reservations must be noted:

A. The two assumptions that were used to derive the release estimates--the assumption that the ratio between vent stack releases and stripchart readings is constant over long periods, and the assumption that the ratio can be determined on the basis of delayed vent stack measurements or even ten grab samples--do not appear to be tenable.

B. Even when calculations begin by accepting one hypothesized release (2.4 million curies), the results obtained by varying the meteorological model or its parameters are too disparate (276-1500 person-rem) to place much confidence in any one of the individual calculations.

^{*}The values in their report (2270-5300) were quoted after correction for building shielding. (See page III-14). We have cited their uncorrected values to allow comparison with the values calculated by other groups.

C. In the case of the 2.4 million curie release estimate, every calculation but one produces lower estimates of population dose than any estimate derived from environmental dose measurements (see Table A-4 below).*

Of these three reservations, A, B, and C, the most important is A, concerning the tenability of assumptions that were used to derive the release figures.

It is possible to relax the assumption that the overall scale of the release can be reliably calibrated with the grab samples or delayed vent stack measurements. The thermoluminescent dosimeter (TLD) dose measurements can be used to determine the overall scale factor--an approach taken by Woodard and Potter** in their work for General Public Utilities. They used the relative time dependence shown on the stripcharts as input to a meteorological model, increasing the scale of the release until they found agreement with TLD readings close to the plant. They obtained 10 million curies in this way, not 2.4 million curies--a factor of four discrepancy from the Kemeny Commission estimates, but within the TEC range of 7-17 million. (Had Woodard and Potter included all of the TLD data regardless of distance, they would have obtained a much higher estimate than 10 million curies.)

*To be precise, the very lowest Kemeny Commission repetition of the Ad Hoc Committee's environmental estimate (1000 person-rem)--see Table A-4--is lower than the very highest (Miller et al.) source term estimate of 1500 person-rem.

**K. Woodard, T.E. Potter "Assessment of Noble Gas Releases from the Three Mile Island Unit 2 Accident." Presented at the American Nuclear Society Meeting, (San Francisco, CA, November 12, 1979) This study is not included among studies formally reviewed in this appendix because it confined itself to an estimate of release (rather than dosage). The Pickard, Lowe, Garrick Inc. study, supervised by Woodard and using the Woodard and Potter method to obtain population doses, is discussed in Section A4.4 below.

Clearly, if the approach taken by Woodard and Potter is accepted, the low population doses (276-1500 person-rem) shown in Table A-2 should be multiplied by at least a factor of four.

The factor of four discrepancy in total release obtained by the different analysts does not appear to be explainable by the choice of stripchart monitors used. (Although Woodard and Potter did use an average of stripchart monitors rather than the single monitor used by the Kemeny Commission Consultants, the difference does not seem to be too great. See Figure A-4 above.) The discrepancy, however, can be explained in other ways: either the scale factor used in the Kemeny Commission method was incorrect for the reasons already discussed, or the TLD readings used by Woodard and Potter were inaccurate because the TLDs were incorrectly calibrated. (This possibility is discussed later.)

In view of this discrepancy and the criticisms made earlier about the method, it would obviously be helpful to have an independent way of estimating the total release, a method that depends neither on stripchart monitors nor TLDs. Andrew Hull of Brookhaven Laboratory made one such independent estimate using helicopter data. He obtained 2.9 million curies.* However, as will be discussed in Section 4.1, there are many problems with the helicopter method. Analysis of this data requires extrapolating backwards in time to overcome the fact that the helicopter data is only useful after two days into the accident. This is such a heroic assumption about the first two days'

*A.P. Hull, "A Critique of Source Term and Environmental Measurements at Three Mile Island" (Unpublished Report, Brookhaven National Laboratory, Upton, New York, no date), Table II.

release that Hull's method cannot be considered a reliable check on other determinations.

In addition to their stripchart analysis, Technology for Energy Corporation made a new type of estimate of the noble gas release. * In this second method, the TEC group attempted to track the total quantity of noble gases that would have been carried to the auxiliary building in water released from the main cooling loop. Since any gases carried to the auxiliary building would have escaped, this method can give an estimate of the total release from the auxiliary building, provided one knows the quantity of noble gases in the water. An upper limit on this latter quantity--the concentration of noble gases in liquid--can be obtained by first estimating the percentage of noble gases that left the fuel and then assuming that all the released noble gases entered the water.

To obtain an estimate of the amount of noble gases released from the fuel, TEC relied on measurements of the amount of one particular noble gas found in the containment, namely, Krypton-85, which had the advantage of being long-lived enough for reliable measurements to be made. Because the fraction of short-lived noble gases released from the fuel at the time of the accident was probably the same as the fraction of Krypton-85 released, information about Krypton-85 could be used to estimate how much Xenon-133 and other short-lived gases were released.

In this way, TEC estimated that no more than 29.6 million curies could have been released from the auxiliary building.

*Knight et al., op cit, Chapter IV.

TEC was also able to put a lower limit on the release (5.5 million curies). Thus, their analysis indicates a range of 5.5 million to 29.6 million curies,* (a range, incidentally, which tends to contradict the low estimates obtained by the Kemeny Commission Task Group and by Andrew Hull). Note that the TEC method only provides information about releases from the auxiliary building. It does not account for any release from other pathways such as an escape from the containment building itself during a hypothetical failure of isolation.

In the course of this review it was found that, in principle, data on Krypton-85 could be used in a different way to provide an estimate of the total noble gas release that would not require any assumptions about release pathways. This method, described and developed in Appendix B, is proposed as a project for further research. It is based on information that did not become available until the venting of the residual Krypton-85 gas in June of 1980, many months after the principal reports on the TMI accident had been completed.

Briefly, the method is based on the recognition that the percentage of Krypton-85 released from the reactor can be determined by an accurate accounting process. The initial inventory in the core must be accounted for in four ways: as residual gas in the fuel rods; as gas that escaped in the original accident; as gas that leaked out between the original accident and June 1980; or as the gas that was released during the deliberate venting. Because the amount of Krypton-85 released during the venting was actually measured, the magnitude of the last component is known.

*Knight et al., op. cit., p. IV-9.

The fraction of radioactivity estimated to have been retained in the fuel can be taken from published estimates based on radio-cesium accounting. (It is certain that more Krypton-85 would have left the fuel than cesium.) If all of the missing Krypton-85 is presumed to have been lost during the initial accident, it is possible to obtain a figure for the fractional amount of Krypton-85 that escaped from the reactor at that time. Assuming that the release percentage was similar for all noble gases, knowledge of the Krypton-85 release percentage gives the percentage for Xenon-133.

It would be useful to perform the implied calculations in time for the dosimetry workshop, as proposed in the main report.

A3.5 Summary of Noble Gas Release Estimates

A summary of the various noble gas release estimates that have been made to date for the TMI accident is shown in Table A-3. Included in the Table is a reassessment of the Woodard and Potter method that averages as many of the TLD data points as possible rather than averaging only the restricted set they chose. Although the authors did not present a calculation of this type, the appropriate scaling factor of $3\frac{1}{2}$ can be taken from another paper, as discussed in Section A4.2.1.

It will be seen that the range of estimates in Table A-3 is very wide, varying from 2.4 to 35 million curies.

Note that the largest release estimate given in the table, because it is based on environmental monitors, could include contributions from very short-lived radioisotopes that may have been

Table A-3

Estimates of the Amount of Noble Gases Released During the TMI Accident

<u>Estimate</u> (Millions of Curies)	<u>Analyst</u>	<u>Method</u>
2.4	Kemeny Commission Task Group ^{a)}	Delayed calibration of distant stripchart recorders against vent stack monitor.
10	Woodard and Potter ^{b)} (Pickard Lowe and Garrick, Inc.)	Calibration of stripchart recorder using <u>nearby</u> TLD detectors.
2.9	Andrew Hull ^{c)}	Extrapolation backward in time using delayed helicopter data.
7-17	Technology for Energy Corporation ^{d)}	Similar to Kemeny Commission, but based on 10 grab samples for calibration.
5.5-30	Technology for Energy Corporation ^{e)}	Based on tracking noble gases in cooling water to auxiliary building.
(35?)	Reassessment of Woodard & Potter data made for this review ^{f)}	Calibration of stripchart recorders using an average of TLD data points near and far.
?	Proposed Project	Method proposed in Appendix B: Determination of percentage of long-lived Krypton-85 combined with assumption that the percentages for other noble gases were the same.

- a) Kemeny Commission (Auxier et al.) "Report of the Task Group on Health Physics and Dosimetry " (October 31, 1979).
- b) K. Woodard, T.E. Potter "Assessment of Noble Gas Releases from the Three Mile Island Unit 2 Accident." Presented at the American Nuclear Society Meeting (San Francisco, CA, November 12, 1979).
- c) A.P. Hull, "A Critique of Source Term and Environmental Measurement at Three Mile Island" (Unpublished Report, Brookhaven National Laboratory, Upton, New York, no date), Table II.
- d) P.K. Knight, J.T. Robinson, F.J. Slagle, P.M. Garrett, (Technology Energy Corporation), "A Review of Population Radiation Exposure at TMI-2" (Report NSAC-26, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, August 1981) p. III-14,15.
- e) Ibid, p.IV-9.
- f) (Reassessment made for this study by multiplying 10 million curies by a factor of 3½.) The original method used by Woodard & Potter is based solely on nearby TLD detectors. Should more distant TLDs be included in a weighted average, it appears that their original estimate would increase by a factor of 3½ based on analysis appearing in another paper. (See the discussion in Section 4.2.1 about the inclusion or exclusion of distant TLD readings.)

released during the first two hours. Releases of this type through the vent stack can be ruled out because the vent stack monitor remained on scale for about the first four hours. Although no pathway other than the vent stack is known to have been open during the first two hours, ignorance of a pathway is not equivalent to knowledge that no such pathway actually existed.

And although computer simulations of the accident suggest that core damage did not begin until late into the second hour,^{*} the simulations are too complex to allow an independent assessment to be made of the uncertainty that should be attached to their predictions. Fortunately, any releases during this early period would probably have registered on some TLDs, given the direction of the wind.^{**} In fact, it is possible that the relatively high TLD readings found in the south/southwesterly directions can be explained by an early release of short-lived noble gases.

*C.M. Allison, T.M. Howe, G.P. Marino, "Initial SCDAP Predictions of the TMI-2 Event" (Report EGG-M-21682, preprint of a paper for the 10th Water Reactor Safety Research Information Meeting, EG&G Idaho, Idaho Falls, October 1982); see also

K.H. Ardron, D.G. Cain, "TMI-2 Accident: Core Heat-Up Analysis" (Report NSAC-24, Electric Power Research Institute, Nuclear Safety Analysis Center, Palo Alto, CA, January 1981); and, see also,

F. Tanabe, K. Yoshida, K. Matsumoto and T. Shimooke, "Post-Facta Analysis of the TMI Accident (I): Analysis of Thermal Hydraulic Behavior by Use of RELAP4/MOD6/U4/J2," Nuclear Engineering and Design, 69, pp 3-6, (1982).

**Wind directions for 28 March are shown in Figure C-4 in Appendix C.

A4.0 Estimates Derived from Environmental Monitoring Data

The second method used to estimate whole-body doses at TMI involved analysis of environmental dose data, taken either from cumulative TLD readings or from instantaneous geiger counter readings. A summary of the numerical results obtained by six groups of analysts who used these data to derive whole-body population doses is given in Table A-4. For convenience, a brief indication of the limitations associated with each calculation is also listed there. These limitations are discussed in detail in Sections A4.1 to A4.5.

A4.1 Department of Energy (Hull)

A consultant for the Department of Energy, Andrew Hull of Brookhaven Laboratory, took as base data instantaneous geiger counter measurements made by the Department of Energy from a helicopter. Hull interpolated between the helicopter dose readings, or extrapolated from them, using a "power law" method beyond 10 miles.* **

Although the Department of Energy helicopter was able to collect considerable data, the analysis of the data is inherently difficult to perform and suffers from a number of unavoidable weaknesses. First, the bulk of the measurements were not started until two days after the accident, necessitating an extrapolation backwards to "pre-helicopter" time.

*The DOE findings are reported in Appendix A of the Ad Hoc Population Dose Assessment Group, Population Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station, A preliminary assessment for the period March 28 through April 7, 1979. (May 1979).

**A.P. Hull, "Estimate of External Whole Body Radiation Exposure to the Population Around Three Mile Island (TMI) Nuclear Station." [Brookhaven National Laboratory, Upton, New York, not dated]

TABLE A-4

Fifty-Mile Whole Body Population Dose Estimates Obtained by
Interpolation and Extrapolations of Environmental Data*

<u>Investigator</u>	<u>Person-Rem</u>	<u>Limitations of Methodology</u>	
Department of Energy (Hull) ^{a)} (Based on Geiger Counter Readings)	2,000	Helicopter missed releases in first few days; May have missed center of plume on other occasions.	
Ad Hoc Dose Assessment Group ^{b)} (Based on TLD Readings)		"Holes" in TLD coverage; limited data points available for interpolation and extrapolation.	
I	5,300 ^{c)}		
II	3,300 ^{d)}		
III	2,800 ^{e)}		
IV	1,600 ^{f)}		
Meteorological	V-a	2,600 ^{g)}	Assumes that the time dependence of release is uniform.
Interpolation	V-b	1,400 ^{h)} , (12,000 ⁱ⁾)	
Kemeny Commission Task Group ^{j)} (Repeat of Ad Hoc Group's Methods I-IV)	1,000 - 6,600	Same limitations as methods I-IV of Ad Hoc Group.	
Pickard Lowe and Garrick, Inc., (Woodard) ^{k)} (Meteorological interpolation of TLDs)	3,500, (12,000 ^{l)})	Assumes that the relative time dependence of the release can be taken from stripchart monitors.	
Takeshi (Interpolation of late TLD readings backwards in time) ^{m)}	16,200	Assumes that meteorology was the same between two time periods when, in fact, it was not.	
Kepford (Interpolation of late TLD readings backwards in time) ⁿ⁾	63,000	Same limitations as in Takeshi method.	

* These estimates apparently do not take building shielding, self-evacuation or doses beyond 50 miles into account. For the purposes of this review, it is assumed that these effects cancel each other out.

Footnotes

Table A-4

- a) As reported in Appendix A of reference cited in footnote b).
- b) Ad Hoc Population Dose Assessment Group, (Battist et. al.) "Population Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station. A preliminary assessment for the period March 28 through April 7, 1979," May 10, 1979.
- c) Extrapolation/interpolation based on all Metropolitan Edison and NRC TLDs.
- d) Extrapolation/interpolation based on Metropolitan Edison TLDs only.
- e) Extrapolation/interpolation based on all Metropolitan Edison and NRC TLDs located within 8 miles.
- f) Extrapolation/interpolation based on Metropolitan Edison TLDs within 8 miles.
- g) This is the value given in the Ad Hoc Group's Report, using meteorological interpolation, as opposed to the value given in the subsequent paper published in Health Physics. The analysis was based on Metropolitan Edison TLDs. The number of detectors included was not specified in the analysis.
- h) Value given in Health Physics paper. W. Pasciak, E. Branagan, Jr., F.J. Congel, and J. Faircobent, "A method for calculating doses to the population from XE 133 releases during the Three Mile Island accident," Health Physics 40, 457-465 (1981).
- i) This is the value that would result from including three additional Metropolitan Edison TLDs in the analysis. This value is not explicitly stated in the Health Physics paper, but derived for this review using information given by the authors.
- j) This is essentially a check of the Ad Hoc Dose Assessment Group's work. Report of the Task Group on Health Physics and Dosimetry, Tables B1 and B4, and p. 133.
- k) Pickard, Lowe and Garrick, Inc. Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident, (Report TDR-TMI-116, Revision 0, 1979) pp. 4-17.
- l) Distant TLDs were not used in this calculation. Had they been, the calculated value would have exceeded 3500 person-rem. The 12,000 figure has been derived for this review in analogy with the estimate given under method V-b.
- m) Seo Takeshi, "Excerpts from the author's review published in Nuclear Engineering [Japanese review], Vol 26, No.3" (unpublished mimeographed notes, Kyoto University Nuclear Reactor Laboratory, Kyoto, Japan, no date).
- n) Chauncey Kepford, "Testimony before the NRC Atomic Safety and Licensing Board, August 20, 1979, in the matter of Public Service Electric and Gas Co., Salem Generating Station Unit #1," Docket #50-272 (1979).

A second weakness in the DOE measurements derives from the fact that unlike the TLD readings, these measurements were instantaneous. Thus, the helicopter may have missed the center of the plume, thereby underestimating overall dose, during some of its forays. One indication that this indeed occurred comes from assessing their report on the behavior of doses beyond 10 miles. DOE reported that doses fell off exponentially with distance, a result that would be very hard to explain based on meteorological dispersion theory, but a result that would be easy to explain by assuming that it became increasingly difficult to find the plume centerline as the helicopter moved farther away from the plant. Should a more theoretically consistent "power law" extrapolation formula be used beyond 10 miles, the total cumulative population dose predicted by this method would increase--perhaps by a factor of three, i.e., an increase from 2000 person-rem to 6000 person-rem.

A third weakness in the DOE measurements is the fact that the helicopter team apparently did not measure the vertical distribution of radioactivity in the plume, but measured only along its own flight path, at heights ranging from 500 to 1000 feet. Although it would be possible to use a meteorological model to convert the 500-1000 feet data to ground level data, this was not done in the analysis of the DOE data. Instead, it was assumed that doses at ground level were identical to those measured above ground. This simplification probably leads to an underestimate of doses (See Section A3.2). However, not all problems with the DOE analysis tend to produce underestimates of the population dose. The following problems tend to cause overestimates, as

indicated by Hull* :

- 1) Uncalibrated geiger counter data ,
which Hull believes tended to cause overesti-
mates by a factor of two.
- 2) The assumption that plume centerline data
measurements reflected doses over an entire
22.5 degree sector, which might cause an over-
estimate by a factor of two to three.

It should be noted that the three weaknesses stated above apply not only to the DOE population dose estimates but also to the 2.9 million curie noble gas release estimate made by Hull** and mentioned earlier in Section A3.4.

A4.2 Ad Hoc Dose Assessment Group (Battist et al.)

After the accident, representatives from the Nuclear Regulatory Commission, the Environmental Protection Agency, and The Department of Health, Education, and Welfare formed a group to assess the doses resulting from the release. This "Ad Hoc Dose Assessment group" (Battist et al.) relied on TLD dose readings and a variety of spatial interpolation methods, including meteorological interpolation.*** The problem with an approach based on TLD readings (as their first four calculations are)

*Ad Hoc Population Dose Assessment Group, p. A-4.

**A.P. Hull, "A Critique of Source Term and Environmental Measurement at Three Mile Island" (Unpublished Report, Brookhaven National Laboratory, Upton, New York, no date), Table II.

***Ad Hoc Population Dose Assessment Group, "Population Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station, a Preliminary Assessment for the Period March 28 through April 7, 1979 " (May 10, 1979).

is that the angular detection range of the set of 20 Metropolitan Edison TLD monitoring stations by no means equals 360 degrees. As can be seen in Figure A-5, under certain stable atmospheric conditions, the angular sensitivity of detectors is very narrow.* The average angle between Metropolitan Edison detectors would be 18° , so that a wind vector passing midway between the angular positions of two detectors would lie, on average, then, half of 18° or 9° , from a TLD. Inspection of Figure A-5 shows that a TLD 9° away from a wind vector--especially one of the distant TLDs located beyond 1000 meters--would lose a great deal of its sensitivity.

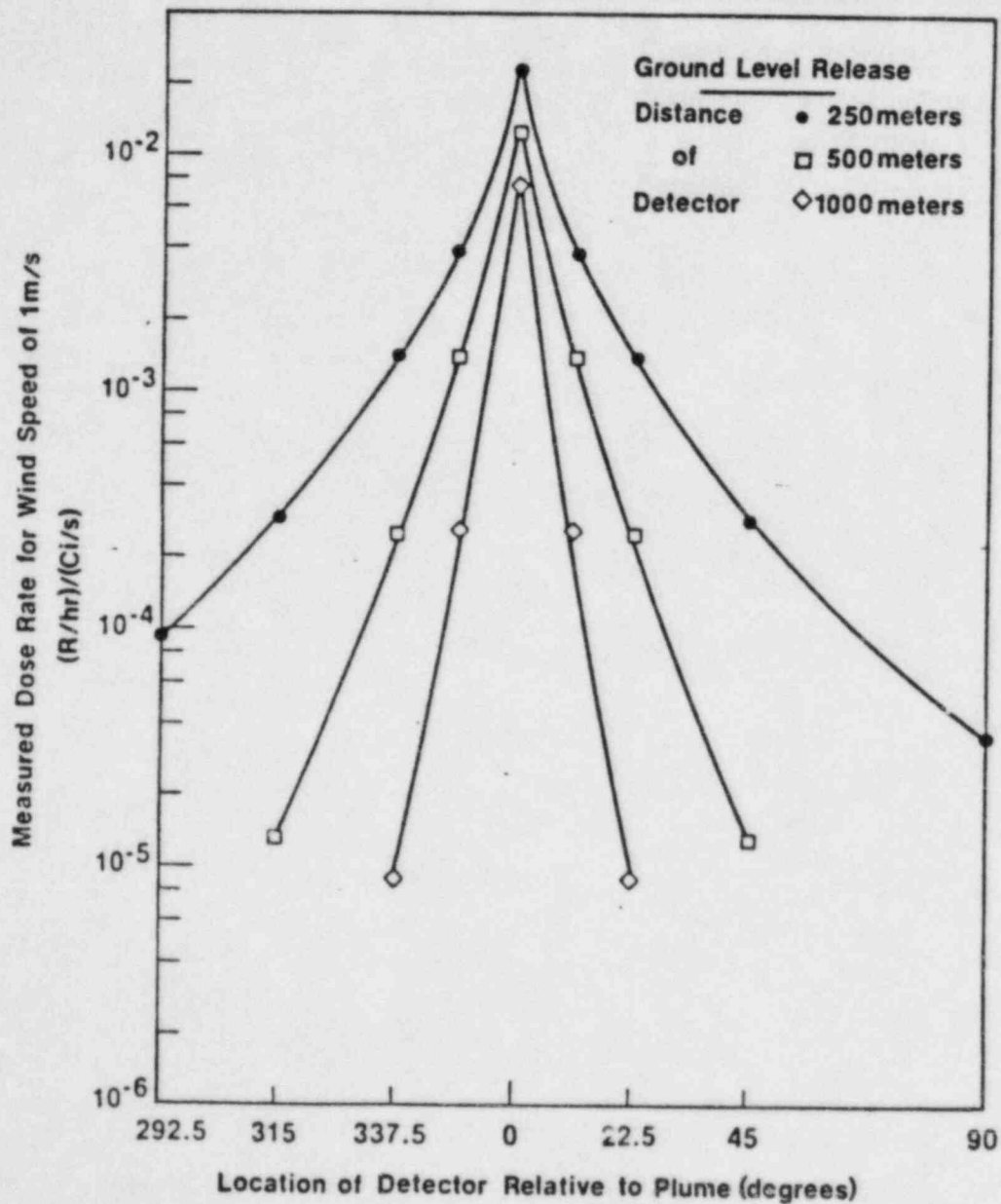
Because there were only 20 TLD locations, it is therefore obvious that there must have been "holes" or "windows" in the TLD perimeter. These holes can only be disregarded if the wind were not blowing through them. (Wind directions corresponding to the first 48 hours are shown in maps in Appendix C (Figures C-4 to C-7). As a result, it must be understood that the Ad Hoc Group's first four population dose estimates can only be lower limits that exclude contributions to the total population dose from undetected radioactivity.

*Charles D. Thomas, Jr., James E. Cline, and Paul G. Vollieque (Science Applications Inc.). "Evaluation of an Environs Exposure Rate Monitoring System for Post-Accident Assessment" (Report AIF/NESP-023, Atomic Industrial Forum Inc., National Environmental Studies Project, Rockville, Maryland, December, 1981), p. 2-7. See also,

Lahti et al, "Assessment of X-Ray exposures Due to Finite Plumes," Health Physics 41, 319-340 (1981).

Figure A-5. (Adapted from Thomas et al. Report AIF/NESP-023)

Angular Variation in Measurement of Xenon-133 Dose for Three Distances Under One Set of Weather conditions*



*So-called F-stability class

A standard and generalized disclaimer to the methodology was noted in the Report of the Ad Hoc Assessment Group:

. . . it is evident that any approach to assessing the collective dose depends strongly on a relatively small number of measurements. No amount of sophisticated analysis can change this fundamental limitation.

However, the authors go on to soften this unequivocal statement:

On the other hand, it is also clear that the data do allow reasonable estimates of the collective dose to be made.*

A basis for this optimistic remark cannot be found in the report, nor is a definition given for "reasonable estimate." This unexplained optimism about the adequacy of the limited data available should be kept in mind when assessing the reliability of the first four dose estimates derived by the Ad Hoc Group, all of which are based on interpolation and extrapolation from a small number of data points to more than 100 grid points. Rather than paraphrase a description of their

*Ad Hoc Population Dose Assessment Group, op. cit., p. 41

method, a quotation is provided directly from their report:

The first step in estimating doses based on the TLD measurements for each period is to estimate the doses at each location on the standard grid. This was accomplished by an interpolation which was equivalent to plotting the measured doses for each sector on a logarithmic coordinate graph paper and joining the measured values by straight line segments. The interpolation 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 dose 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.

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

The (four) estimates derived by the Ad Hoc Group using this interpolation/extrapolation method differ only in the choice of TLDs to be included in the analyses. (At the time of the accident, Metropolitan Edison had TLDs deployed at twenty sites at various distances from the reactor. On March 31, NRC placed TLDs at 37 additional locations.) The Ad Hoc Dose Assessment Group used various subsets of these dosimeters as described below:

*Ad Hoc Population Dose Assessment Group, op. cit., p. 35

Four approaches were used in estimating the total collective dose for the period March 27-April 7. Each utilizes data from the Metropolitan Edison TLD stations for the period March 28 through March 31, since there were no NRC TLD's in place before March 31.

For the first calculational approach, all Metropolitan Edison data for the period March 28-March 31 were used for estimating the collective dose for the periods March 28-29 and March 29-31 (3200 person-rem). The NRC data, which are all from offsite locations, provided the data for the periods from April 1 through April 7 . . . A strength of this method is that it utilizes the maximum possible number of individual observations and therefore would be expected to be least dependent on any one of them. Since the NRC locations are nearly all offsite, they provide better general coverage of the populated areas surrounding the plant. However, there are limitations to using this method. For example, a positive net measurement may easily represent nothing more than a low estimate of the background for that location. If the location is distant from the facility and is the only measurement in the sector, it can contribute to a significant overestimate in the collective dose. Another limitation of this method lies in the uncertainty of the background values for the NRC locations. As indicated previously, these background values are believed to be low. The continuing rise in the collective dose in later periods, when there is no reason to expect any significant contribution from the facility, confirms this expectation. The collective dose through April 7 using this methodology is 5300 person-rem and is believed to be a high estimate for the reasons given.

The second approach is based on the Metropolitan Edison TLD data only. This approach has the advantage of using a consistent set of data with the same dosimeter type and locations throughout the period. The background values are reasonably well known by experience for these stations. A disadvantage to this approach is that there are only 20 dosimeters, so that three sectors (NE, ESE, W) have no measurements at all and seven (NNE, SSE, SW, WSW, WNW, NW) have only one. . . The total collective dose through April 6 using this approach is 3300 person-rem. April 6 becomes the cutoff point in this method because of the 3-day dosimeter cycle under which the Metropolitan Edison TLDs were deployed and read out.

A third approach is based on a subset of the dosimeters used in the first method. Those locations outside 8 miles were dropped from the analysis, eliminating 5 Metropolitan Edison and 7 NRC stations. This has the advantage of minimizing the effect of exposure uncertainties at those locations which are least likely to have been exposed to radioactive material from the facility. The disadvantage is that a significant dose at a distance greater than 8 miles in a direction where there are other dosimeters nearer to the facility will be missed completely. Note that this substantially reduces both the March 28-31 Metropolitan Edison dosimeter contribution to the collective dose and the contribution from the first day of NRC observations. The total collective dose through April 7 using this approach is 2800 person-rem.

The fourth approach is based on using those Metropolitan Edison TLD data from locations that are not more than 8 miles from the facility. Again the method has the advantage of a consistent base of data for the entire period and the disadvantage of making a small data base even smaller. The effect of eliminating the distant stations is to reduce the collective dose calculated for the period. Using approach four, the collective dose through April 6 is 1600 person-rem.

A4.2.1 Pasciak et al.

The fifth and final approach taken by the Ad Hoc Group to estimate population doses involved a clever use of meteorological interpolation and extrapolation. A brief account of this work was included in the Ad Hoc Group's report. A revised and more carefully detailed version was subsequently published by Pasciak et. al. in Health Physics.** The Health Physics version is discussed here.

In this method, it was assumed, though not clearly brought to the attention of the reader, that the release rate (in curies

*Ad Hoc Population Dose Assessment Group, op. cit., pp. 37-41.

**W.E. Pasciak, E. Branagan, Jr., F.J. Congel & J. Faircobent, "A method for calculating doses to the population from Xe-133 releases during the Three Mile Island accident," Health Physics 40, 457-465 (1981).

per second) was constant over time periods for which TLD data was available, e.g., constant over the 28 hour period from 4 a.m., March 28 to 8 a.m., March 29, when one batch of TLDs was collected, and constant over the 44 hour period from 8 a.m., March 29 to 4 a.m., March 31, when a second batch was collected. Such an approach was necessary because of the cumulative nature of TLD readings. To be "read," TLDs are first brought back from the field to a laboratory for assessment. Only the total amount of radiation dose accumulated prior to the laboratory reading is obtained, not any information about the time dependence of the dose. The obvious way to treat the time dependence of the release, in the absence of any other information, is to assume the release was constant between readings. Although it is perhaps "obvious," such an assumption seems questionable given the pulsed nature of the radioactivity recorded on the stripchart monitors discussed previously. Nevertheless, having made this constant release assumption, which is equivalent to "ironing out" any pulses of radioactivity, it was possible to work backwards from the TLD readings to obtain an estimate of doses accumulated at every other location during the same time period.

The analysis is quite technical, and readers without a technical background may find themselves lost in parts of the following discussion. The approach taken is similar to the meteorological interpolation method depicted in Figure A1-c, in which actual dose measurements are used to infer a curie release estimate. The authors did not actually give the release information in curies, but in other units proportional to curies. Therefore, in order to compare their results with results from other studies, it

was necessary to convert their value for this review. A low value of either .64 million curies or 2.2 million curies was obtained, depending upon whether or not three distant TLDs are excluded from, or included in, the analysis.**,** This low curie range is surprising given corresponding population dose estimates obtained from the same data, which are at least eight times higher than the population doses projected by meteorological models for a 0.64 to 2.2 million curie release.***

Although the curie-conversion calculations performed for this review are quite crude--and therefore not reliable enough to be included in Table A3 above--the low results do suggest an inconsistency, unless Pasciak et al. has been misinterpreted. Of particular concern is the fact that Woodard and Potter obtained a ten million curie release figure using a method that should have

*Assumes all the release was in the form of Xenon 133 and ignores finite cloud corrections.

**The authors of this paper determined a quantity, \bar{K} , which is proportional to the number of curies released, Q : $\bar{K} = Q \times DF$, where DF is a dose conversion factor which depends on the average gamma disintegration energy. $DF = 0.25 E_g$, where E_g has units of Mev per disintegration when K is measured in Rads $-m^3/sec$. [Slade, Meteorology and Atomic Energy, 1968, eq 7.35a, p.339] Since E_g varies by more than an order of magnitude between the short-lived isotopes, Kr 85^m, 88, Xe 135 and the relatively long-lived Xe133, the value of E_g is time dependent, ranging between .088 and .22 Mev over the period of 6 hours after shutdown to one day (Average gamma energy values for E_g are, .081, .160, .246, and 1.740 Mev for Xe133, Kr 85^m, Xe135, and Kr 88 respectively. [Radiological Health Handbook, U.S. H.E.W., 1970.] Initial inventories of 170, 24, 34, and 68 million curies, respectively, have been taken from the Reactor Safety Study, (US Nuclear Reg. Commission 1975, WASH-1400).

To make the calculation consistent with the assumptions used in the paper by Pasciak et. al., it appears necessary to assume that the entire release is Xenon 133. Thus, $Q = \bar{K} / (0.25 \times .088)$. \bar{K} values given in the paper were 14,000 using the reduced set of TLDs and 49,000 using the larger set of TLDs.

***For instance, the 2.2 million curie release estimate stated above corresponds to 12,000 person-rem (see Table A-4). Yet as indicated previously in Table A-2, a similar release (2.4 million curies) was found in other studies to produce a population dose at least eight times lower (i.e., less than 1500 person-rem).

given equivalent results. (Their work is discussed earlier in Section A3.3.) It seems imperative to repeat the meteorological interpolation/extrapolation calculation of Pasciak et al. using a more sophisticated meteorological model than originally used.

In their analysis, the authors of the Health Physics paper concentrated on population doses, not release estimates. Even there, however, discrepancies are obvious upon inspection of their results. In particular, the quality of the fit to the TLD data was poor, as can be seen from Table A-5, which has been reprinted from their article. The column labelled K, aside from a scale factor, gives the ratio of TLD doses measured to TLD doses projected by the authors' model. If the methodology chosen were completely valid and self-consistent, each entry in the column would be similar. Instead, there is an enormous variation, even when the highest values are eliminated--a variation that suggests that either the quality of the TLD data was very poor or that more is going on there than can be captured by a constant release model.

In the Health Physics paper, a value of 3400 person-rem was calculated based on a subset of the complete Metropolitan Edison TLD data. Five data points located beyond eight miles were dropped on the grounds that the readings were so low that the uncertainty in the measurements prevented them from being reliable. Yet, the net readings for the excluded data points (gross reading minus background) were comparable to some net readings within 10 miles that were kept in the analysis. Thus,

Table A-5

(Reprinted from Health Physics, 40, 461, 1981).

W. PASCIAK *et al.*

Table 1. Proportionality constant "K" derived from dosimetry and meteorological data for two release times

Station	First time period 3/28 (4 a.m.) to 3/29 (8 a.m.)			Second time period 3/29 (8 a.m.) to 3/31 (4 a.m.)		
	Dose, ^a mR	Meteorological dispersion, ^{**} sec/m ³	K† 10 ³ R-m ³ /sec	Dose, ^a mR	Meteorological dispersion, ^{**} sec/m ³	K† 10 ³ R-m ³ /sec
152	83.0	3.0E-5	2.8	19.7	2.0E-5	0.98
1C1	7.8	8.6E-7	9.1	2.9	1.2E-6	2.4
252	31.5	2.5E-6	13.	32.2	1.7E-5	1.9
452	21.1	1.6E-6	13.	124.	2.9E-5	4.3
4A1	6.4	3.0E-7	21.	34.0	1.6E-5	2.1
4G1	1.3	4.5E-9	290.	0.9	1.7E-7	5.3
552	17.6	3.0E-6	5.9	49.0	4.6E-5	1.1
5A1	4.7	6.0E-7	7.8	8.0	1.7E-5	0.47
7F1	4.4	0.	--	7.5	1.7E-5	0.44
7G1	4.2	0.	--	7.1	1.7E-5	0.42
8C1	2.5	1.6E-7	16.	0.7	2.9E-7	2.4
952	11.0	3.0E-6	3.50	0.7	1.7E-7	4.1
9G1	4.5	9.0E-9	500.	10.5	1.9E-6	5.5
10B1	24.8	1.1E-6	23.	25.0	3.6E-5	1.6
10B1	28.8	1.1E-6	26.	1.0	2.4E-7	4.2
1151	201.0	2.0E-5	10.	14.8	6.5E-6	2.3
12B1	5.6	2.6E-6	2.2	107.0	1.2E-4	0.89
1452	118.0	3.0E-5	3.9	9.2	3.6E-6	2.9
1452	135	3.0E-5	4.5	48.7	4.0E-5	1.2
15G1	3.0	7.0E-6	0.43	1.6	6.0E-8	27.
1651	1020.0	4.0E-5	26.	83.3	4.8E-5	1.7
16A1	441.0	2.0E-5	22.	45.0	1.9E-5	2.4
16A1	896	2.0E-5	45.	--	--	--

^aDoses are based on TLD readings for the indicated station. Doses have been corrected for background radiation.

^{**}Meteorological dispersion values (i.e., \bar{X}/\bar{Q}) are based on real time meteorological data averaged over the indicated time period. The meteorological data were obtained at the onsite meteorological tower.

[†]The proportionality constant "K" is obtained by dividing the dose at a particular station for the appropriate time period by the corresponding meteorological dispersion factor (i.e., \bar{X}/\bar{Q}).

exclusion of the distant data points was an inconsistent procedure.

A more complete analysis would have kept all data points, but used a statistical fitting routine (such as a Chi square regression technique) that can explicitly weight data points according to their certainty.* In this way, all data points, whether located within or beyond 8 miles, would have been treated on an equal footing. (Such an analysis should be carried out in a more comprehensive dosimetry study.)

Although the authors did not explicitly indicate the population dose that would have been calculated had a larger set of TLDs been kept in their analysis, they did present enough intermediate information to allow a determination of this quantity to be made by readers of their paper. Working from their results, it appears that a 3½-fold increase in population dose would result, i.e., 12,000 person-rem, should three more data points be included.**

This procedure still leaves two TLDs out of the analysis. The remaining two data points could not be included in their analysis because the readings were anomalous. No wind direction readings were recorded for the angular sectors containing those TLDs even though a net reading on the TLDs was recorded. Thus, the corresponding K-value entries in Table A-5 (those indicated with dashes) are actually infinite because they have a zero

*To do so, an estimate of the uncertainty in the background readings would have to be determined. The necessary estimate could be obtained from analyzing the year-to-year fluctuation in readings recorded by Metropolitan Edison over a multi-year period.

**Although population doses were not presented for both cases, values for the intermediate parameter, "K," were. As indicated on pp. 460 and 461, K turned out to be 14×10^3 rads-m³/sec when the five TLDs were excluded and 49×10^3 rads-m³/sec when only two TLDs were excluded. Since K is proportional to population dose, the ratio of the two K values is the same as the ratio of population dose for the two cases.

divisor. There are at least two explanations for these apparently anomalous readings:

1. The actual dose may have been zero, but the background underestimated. (This is apparently the explanation favored by the authors. Note that this possibility could be handled without excluding data points, using the statistical fitting technique mentioned earlier.)

2. The readings may have been real, but the wind direction readings at the TMI meteorological station may have been incorrect. That is, the wind may really have blown in the relevant directions for some portion of the measurement period, but not when wind direction was actually recorded by the recording instruments. (The fact that the amount of radioiodine found in milk is also anomalously high for at least one of these directions suggests that the wind-wandering hypothesis is quite possible.) Examination of a wider set of wind data from the area, some of which were recorded at shorter intervals (or even instantaneously) may help in resolving this anomaly.

In addition to the problems mentioned so far, the paper by Pasciak et al. seems vulnerable in three additional respects: TLD calibrations, background subtraction and meteorological modelling.

A. Calibration. It appears that the authors assumed that the release consisted solely of Xenon-133. Contributions to the dose from more energetic gamma rays coming from other radioisotopes were not included in converting TLD readings to dose.

This assumption would be of no significance if the TLDs responded "linearly" with gamma ray energy. However, the TLD detectors apparently respond non-linearly, requiring that attention be paid to the mix of gamma ray energies.

B. Background Subtraction. Background data was obtained from readings accumulated the previous year. One subcontractor for this review was worried that the readings may have been anomalously high in that year because of the contribution from a Chinese weapons test. If this were the case, doses would have been underestimated. Averaging several years' readings before the accident would tend to reduce this problem.

C. Technical Considerations about Meteorological Modelling.

1. A "semi-infinite cloud" approximation was used instead of taking into account the finite size of the actual plume.
2. A ground-level release was apparently assumed rather than a release from the 160-foot vent stack. (Note that changing the assumed release height has a very complex effect on meteorological interpolation methods.)
3. It is not clear how the reactor building turbulent wake was assumed to broaden the plume. Neither was it clear whether the cooling towers' wakes were taken into account for wind directions in which the plume would be affected by the towers.

Preliminary review of these modeling assumptions suggests that accounting for all of these effects would tend to increase the population dose estimates.

Perhaps the most serious limitation of this meteorological

interpolation method as developed by Pasciak et al. has been mentioned earlier, i.e., the assumption that the release was constant during periods when doses were being accumulated on TLD cartridges. From examining the data contained in the Health Physics paper, it would appear that this restrictive assumption could have been partially relaxed. There were sufficient TLDs available to allow division of each of the two measurement periods into several time intervals with corresponding (unknown) release rates. In this way, (rough) information about the time dependence of the release could have been extracted from the data. That there is more information in the data than has so far been exploited can be seen by examining the variation in ratios between measured and projected TLD readings shown previously in Table A-4. As has been mentioned earlier, these ratios fluctuate enormously. A variation in release rate during each measurement period might explain these ratio fluctuations as well as explain the apparent anomalies in the TLD measurements that were removed from the data set. (An analysis of this sort should be carried out in a complete dosimetry study.)

The impression should not be left, however, that improvements of the sort mentioned could completely compensate for limitations in the TLD coverage. It still would be necessary to assume that the release was constant over the time periods chosen for analysis. In effect, this method is forced to assume that there were no large bursts of radioactivity that might have occurred while the wind was blowing through a hole in the TLD perimeter.

A 4.3 Kemeny Commission Task Group (Auxier et al.)

A Kemeny Commission Task Group repeated the basic interpolation/extrapolation method used by the Ad Hoc Dose Assessment Group for its first four calculations.* They obtained similar results. Obviously, these calculations are subject to the same limitations that were discussed under the section devoted to the Ad Hoc Group's work.

A4.4 Pickard, Lowe and Garrick, Inc. (Woodard)

A calculation of population dose for General Public Utilities was carried out by Pickard, Lowe and Garrick under the supervision of Keith Woodard,** an analyst with extensive experience in dose assessment.

The basic method used has already been described in Section A3.3. It makes use of TLD data points and meteorological interpolation. However, instead of assuming a uniform release rate of radioactivity over long time intervals as did Pasciak et al., the relative time dependence of the release was taken from the stripchart monitors. TLD measurements "close to the plant" (but otherwise unspecified) were then used to set the overall scale of the release. Had the more distant TLD data been included, the Pickard, Lowe and Garrick estimate would have increased.

*Kemeny Commission, (Auxier et al.) "Report of the Task Group on Health Physics and Dosimetry," (October 31, 1979), p. 108.

**Pickard, Lowe and Garrick, Inc., "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident," (Report TDR-TMI-116, Revision 0, 1979) pp. 4-17.

In a sense, this calculation is actually a mixture of the two basic methods, although it is the TLD measurements that determine the overall magnitude of the population dose. These calculations are subject to the basic limitations discussed in sections A3.1 and A4.2: first, there are many reasons to expect that releases occurred through pathways that would not have registered on the stripchart monitors; second, any releases that occurred during a time when the wind was blowing through a TLD "hole," would not have been detected. If both conditions existed (the second certainly did on many occasions), then the radiation not measured could be very substantial.

A4.5 Takeshi and Kepford

The last two population dose estimates to be discussed were made by 1) Seo Takeshi, associated with the Kyoto Nuclear Reactor Laboratory and 2) Chauncey Kepford, a nuclear critic, associated at the time with the Environmental Coalition on Nuclear Power. Similar methods were used by both analysts in separate studies. *,**

Concerned about the limited TLD coverage available during the first few days, when only the original Metropolitan Edison TLDs were in place, Takeshi and Kepford concentrated their attention on the TLDs that were deployed in greater numbers after March 30th. Noting that these later TLD measurements gave better spatial coverage, Takeshi and Kepford worked backwards from them to estimate the population dose for the first few days. Thus their method corresponds to extrapolation in "time" rather than in space.

*S. Takeshi, "Excerpts from the author's review published in the Japanese journal, Nuclear Engineering, Vol. 26, No. 3." (unpublished mimeographed notes, Kyoto University Nuclear Reactor Laboratory, Kyoto, Japan, not dated).

**Chauncey Kepford, "Testimony before the NRC Atomic Safety and Licensing Board, August 20, 1979, in the matter of Public Service Electric & Gas Co., Salem Generating Station Unit #1. Docket #50-272," (1979).

They divided the release duration into two time periods: before March 30th and after March 30th. For the first period only the original Metropolitan Edison TLDs were available for population dose estimates. (Population dose estimates were made using interpolation/extrapolation procedures similar to those described earlier in Section A4.2.) For the second period, readings were available from both the Metropolitan Edison TLDs and the NRC TLDs. Takeshi noticed that in this second period there was a discrepancy between the total population dose estimates obtained from the set of Metropolitan Edison TLDs and the total obtained from the NRC instruments. In fact, the NRC readings, with their greater angular coverage, indicated a population dose at least five times greater during the time when the two sets of measurements could be compared--an indication that the Metropolitan Edison TLDs were only picking up a fraction of the total dose. Assuming that the same fraction applied to the earlier period, it then follows that the total population dose estimated using the Metropolitan Edison detectors should be multiplied by a factor of five or so.

Takeshi did not perform the calculation in such a direct fashion. Instead he used the equivalent equation:

$$\text{NRC}_1 = \frac{\text{ME}_1 \times \text{NRC}_2}{\text{ME}_2} \quad 1)$$

where NRC_1 is the hypothetical NRC measured dose from period 1, ME_1 and ME_2 are the measured Metropolitan Edison doses from periods 1 and 2 and NRC_2 is the measured dose from period 2. (Total dose would then equal $\text{NRC}_1 + \text{NRC}_2$.)

Thus, the results of the NRC TLD measurements are multiplied by a scale factor, S, (equal to the ratio of the Metropolitan Edison measured doses for the two periods) to obtain the dose during the first period. Using the above equation, with a value of S equal to 20, Takeshi calculated a population dose of 16,200 person-rem. Kepford, using slightly different assumptions, derived a higher value of 63,000 person-rem. Kepford used a lower scale factor than did Takeshi ($S=10$), but a much higher population dose for the second time period. The reason for this difference is threefold:

1. Kepford reanalyzed the NRC TLD data, extrapolating doses beyond 10 miles with a linear function that varied inversely with distance rather than inversely as the 1.5 power of distance (the choice of both the Ad Hoc Dose Assessment Group and Takeshi).
2. Kepford included NRC TLD readings from March 31 to April 1, whereas Takeshi only included NRC readings starting from April 1.
3. Takeshi assumed a conservative (i.e., higher) background value, which led to a reduction in the population dose estimate by about 30% compared to the estimate obtained using the background method described in the Ad Hoc Group's report, which Kepford accepted.

It appears both analysts made reasonable assumptions to fill the gaps in the data. At this point, there is no clear way to choose between their individual assumptions. However, further analysis should help in resolving these questions.

In any case, the equation used by these analysts is only valid under the assumption that the wind behaved in an identical fashion during the two periods. Takeshi was aware of this requirement, but argued that other factors compensated for any overestimation that might well result:

Although the calculation is an estimation which ignores factors such as possible changes in meteorological conditions, there is evidence that the actual dose could probably be far greater since 37 dosimeters can hardly be sufficient in number.*

That is to say, Takeshi believed that even the 37 NRC dosimeters were insufficient in number to adequately assess the population dose. No judgement is attempted here on this contention; nevertheless, the basic wind assumption required by this method appears to be contradicted by the actual wind data.

A4.6 Suggestions for Further Research Based on Environmental Measurements.

It should be possible to improve the reliability of the Takeshi/Kepford approach by repeating the calculations using actual wind data to account explicitly for wind differences between the two periods. These calculations should be repeated in a complete dosimetry study, thereby making meteorological modelling an integral part of the methodology.

It is true that even such a revised methodology could be criticized on the grounds that the radioactivity release rates

*S. Takeshi, op. cit.

might have had a completely different time dependence during the two periods. Without knowing the time dependence of the release, there seems to be no way of unambiguously scaling the NRC TLDs to obtain the population dose accumulated in the first time period. However, Bayesian statistical methods might prove useful here to indicate the probability of various scale factors. That is, even assuming a wide range of hypothetical release rate behaviors, it might turn out that the great majority of the resulting scale factors fall in a narrow range.

An alternative approach to modifying the Takeshi/Kepford methodology would be to integrate their insights, which are an implicit critique of the methodology used by other analysts, into studies that would avoid those pitfalls. As has been indicated earlier, the NRC TLDs imply a greater population dose than the Metropolitan Edison TLDs for the period in which the two sets overlap. This contradiction casts suspicion on all of the methods previously discussed which rely solely on the Metropolitan Edison TLDs.

This contradiction might be removable by adjusting the interpolation schemes used with the Metropolitan Edison TLDs. For instance, in making the interpolations, it might well be possible to adjust the meteorological model to fit both the Metropolitan Edison data and the NRC data simultaneously. In this way uncertainties in the parameter choices for the meteorological model might be removed. Certainly it will not be possible to have confidence in any meteorological modeling interpolation scheme until the model is adjusted so it can

reasonably explain both the NRC TLD data and the Metropolitan Edison data--unless, of course, some of the data can confidently be eliminated from consideration.

Whatever the approach taken, attempts should be made to resolve the discrepancy between the two sets of TLD measurements in a more complete dosimetry study. There are four obvious explanations that should be analyzed:

1. There may have been background subtraction problems with one or both of the data sets that led to incomplete dose estimates. For instance, concern was expressed in the Ad Hoc Group's report about the absence of true background readings available at the time for the NRC TLDs. However, this problem should now be resolvable. Background readings for the NRC dosimeters should now be available from current readings. If not, new measurements could be made at any time as part of a full dosimetry study.

2. There may have been a calibration problem with one or both of the data sets that led to inaccurate dose estimates.

3. The interpolation schemes used with Metropolitan Edison TLDs may have been deficient for one or more of the reasons discussed above.

4. Some of the data points may be spurious. In fact this was the position taken by the Kemeny Commission Task Force about some of the data points included by Kepford in his analysis.

It is worth examining the reasons given by the Kemeny Commission Task Group for rejecting the NRC readings in the March 31 - April 1 period.

In the preliminary report, attention was called to high doses predicted by NRC TLDs, placed from March 31 to April 1, compared with estimates from the TLDs placed by Met Ed. Reevaluation of the calibration and processing of these TLDs did not eliminate the inconsistency. However, review of the procedures for the placement and the collection of the NRC TLDs raised the possibility that considerable exposure was received by these TLDs during the placement and collection periods.

The high collective dose predicted by the NRC measurements are due mainly to readings at locations of 8 to 15 miles from the plant. In several directions, these readings are higher than those closer in--a situation which, though not impossible, is highly improbable. The TLD readings at 9.6 and 13.8 miles in the northwest direction have the greatest impact on the estimate of collective dose. These high readings were referred to as the "northwest anomaly" in hearings before the House Committee on Science and Technology on June 13, 1979. Procedures for deploying and collecting one of these (Station NW-4) were examined in order to determine possible reasons for spuriously high readings.

The reading from the Station NW-4 TLD exposed at 9.6 miles from TMI for 22 hours included exposure over a 12-hour transit time, during which it was being distributed or collected. The TLDs were stored beforehand, in a trailer for 2-1/2 hours near the station with the highest dose rate, and moved in and out of areas with variations of a factor of 10 in dose rate, shielded only by the trailer or the auto in which they were distributed. An estimated irradiation history for this TLD, assuming no shielding, is shown in Figure B-6. Exposure rates at each time were estimated by assuming an $r^{-1.5}$ decrease with distance and calculating the radial distance of the automobile at that time. The intended exposure period was from 1:45 p.m. on March 31 to 12:04 p.m. on April 1. From about 8:00 a.m. to 10:30 a.m., the TLDs were stored in a trailer near the site, with no special precautions to shield them. The average dose rate a short distance away was 1.11 mrem per hour. Even if a factor of two or three reduction due to shielding in the trailer is assumed, the dose accumulated during this period, as estimated from the area under that portion of the curve, could be several times the dose accumulated at Station NW-4 during the intended exposure period from 12:00 noon to 6:00 p.m. on April 1, when the TLDs were on the front seat of the automobile.

No control dosimeters were used to estimate the dose received during the distribution and collection periods. It therefore seems highly likely that some of

the dose received by the TLDs at low-dose rate locations, such as Station NW-4, was received during transit periods through high-dose rate areas. Consequently, these measurements have been rejected in the evaluation of the collective dose.*

The approach taken by the Kemeny Commission Task Group appears to be highly selective regardless of whether the particular complaints are justified. One particular set of data is analyzed in much greater detail than all other sets. In addition, the analysts assume that it is the higher readings that must be spurious, not the lower ones. They try to find an explanation for readings at 8 to 15 miles being spuriously high, but do not try to find an explanation for readings within 8 miles being spuriously low. In any case, insufficient detail is provided to allow a skeptical reviewer to check the sample calculation that was used as the basis for rejecting the data for this period. As a result it is not possible at this time to assess whether the assumptions that went into the calculation are reasonable. It is not even clear where the basic collection and distribution history came from. Nor is information provided about the collection and distribution of the TLDs not rejected. It should also be noted that Takeshi's estimates begin with April 1, thus rendering much of their criticism irrelevant to his work.

Certainly, there are questions that can be raised about the TLD data--all of the TLD data--concerning calibrations,

*Kemeny Commission, (Auxier et al.) "Report of the Task Group on Health Physics and Dosimetry," (October 31, 1979), pp. 124-27.

background subtraction, limited coverage. At this point, there is enough justification to make a plausible case for throwing all the data out for one reason or another.

However, as with the paper by Pasciak et al., we find analysts selectively throwing out data that would lead to a higher population dose estimate. And once again this is done without entertaining alternative hypotheses. A more careful analysis would have investigated the release and modeling assumptions necessary to explain the higher NRC readings. Only if those assumptions turned out to be physically unreasonable, would it have been justifiable to accept the explanation adopted so easily by the Task Group.

A5.0 Conclusion

Two general approaches, eleven separate studies and nineteen calculations of the estimated whole-body population dose at TMI have been reviewed in this appendix. None can be regarded as without fault in their methodology, and no calculation can be regarded as definitive. The estimated whole body population dose varies from a low of 276 person-rem to a high of 63,000, but methodological considerations do not make it possible to choose, or average, or otherwise obtain a reasonable "best estimate."

In studies of the first approach--that of source release measurement--the most serious problem is the need to rely, in one way or another, on stripchart monitors far from much of the escaping radioactivity.

In studies of the second approach--environmental monitor measurement--the most serious problems are the angular gaps in TLD coverage, not corrected until three days after the accident when new TLDs were added by the NRC. Neither of these problems will consent to go away, but if a consistent and reliable methodology is used that takes into account the many insights developed by previous investigators, a combination of sophisticated statistical techniques should be able to provide considerably more accuracy to the estimation.

In stating that the available data, as analyzed to date, cannot rule out releases of noble gases totaling as high as 40 million curies, nor population doses as high as 63,000 person-rem, it is clear that this review parts company with the official assessments of the TMI accident. On the other hand, it must be emphasized that statements in this report that the population dose could range as high as 63,000 person-rem do not mean that the population dose in fact reached that level. The range given in this report is an estimate of the state of scientific ignorance, and should not be interpreted as favoring either high or low values at this time.

Appendix B

A Method for Estimating the Noble Gas Release from TMI-2
Using the Krypton-85 Inventory Measured in the Contain-
ment Atmosphere during the Venting in June-July, 1980.

TECHNICAL APPENDIX

In this appendix a method is outlined for obtaining an independent estimate of the quantity of noble gases released during the TMI accident, using data that was not available during the time that the official analyses were made of the accident.

Measurements performed during the venting of the TMI-2 containment building atmosphere in June and July of 1980 indicated that, just prior to the venting, the containment atmosphere contained 44,000 Ci of Kr-85,* or, corrected for radioactive decay, 48,000 Ci at shutdown on March 28, 1979.**

*U.S. Nuclear Regulatory Commission, (Final) Programmatic Environmental Impact Statement Related to Decontamination and Disposal of Radioactive Wastes Resulting from March 28, 1979, Accident, Three Mile Island Nuclear Station, Unit 2 (Report NUREG-0683, Washington, D.C., March 1981), Volume I, Table 5.8, p. 5-21.

**Measurements of containment air samples taken before venting had yielded significantly larger estimates of Kr-85. For instance, the pre-venting estimate for shutdown given in the Draft Programmatic Environmental Impact Statement was 62,000 Ci. [U.S. Nuclear Regulatory Commission, Report NUREG-0683, Washington, D.C., July 1980, Table 6.1-1, p. 6-2.]

Bishop et al calculated 60,500 Ci as corrected to shutdown. [W.N. Bishop, D.A. Nitti, N.P. Jacob, J.A. Daniel, "Fission Product Release from the Fuel Following the TMI-2 Accident," in Proceedings of the American Nuclear Society/European Nuclear Society Topical Meeting: Volume I, Thermal Reactor Safety, (Knoxville, TN, April 6-9, 1980), Table I, p. 627.]

These larger values have been attributed to instrument errors and uncertainties in knowledge of the building free volume. [U.S. Nuclear Regulatory Commission, (Final) PEIS, (Report NUREG-0683, March 1981), op. cit., p.iii, fn.]

The Kr-85 measured in the containment building represented all of the Kr-85 retained in the reactor complex. (Noble gases that were in the reactor coolant system had been removed by degassing in the makeup tank and subsequently vented back into the containment.*) Yet, the measured 48,000 curies amounts to only 50% or so of the initial Kr-85 inventory in the core, whereas more than 50% of Kr-85 and other noble gases should have been released from the fuel, based on measurements of radiocesium found in coolant water. Presumably, the "missing" Krypton-85 escaped from the reactor.

To extract quantitative information about the magnitude of the missing radioactivity, it is necessary to make use of the equation for the Krypton-85 mass balance -- an equation which is based on certain undeniable facts:

- 1) The initial inventory of noble gases either remained in the fuel or was released from the fuel.
- 2) Those gases released from the fuel either remained in, or leaked from, the containment before the deliberate venting.

Therefore, if one knows the inventory I , of Kr-85 at shutdown, the fraction, f , released from the fuel, and the amount, C , retained in the containment after the initial

*Bishop et al., op. cit., p. 624.

release, one can calculate the amount, A, of Kr-85 that escaped to the atmosphere during the accident. The formula is:

$$A = fI - C \qquad 1)$$

Determination of "I"

Estimates of the total inventory, I, can be obtained directly from the literature. The results of four separate calculations of I at shutdown are presented in Table B-1. The inventory labeled "LOR-2" was obtained using a version of ORIGEN modified by Babcock & Wilcox and is reported by Bishop et al.* The "ORNL" inventory was calculated using the Oak Ridge version of ORIGEN and was reported by private communication.** The "Heidelberg" inventory was calculated using an unspecified version of ORIGEN and was reported by Franke and Teufel.***

*Bishop et al., op. cit., Table IV, p. 627.

**Private communication from Oak Ridge National Laboratory.

***B. Franke, D. Teufel, "Radiation Exposure Due to Venting TMI-2 Reactor Building Atmosphere" (Institute for Energy and Environmental Research, Heidelberg, Federal Republic of Germany, June 12, 1980), Table 1.

Table B-1

Comparison of core inventories at shutdown for TMI-2 obtained from different sources.
(Curies)

<u>Isotope</u>	<u>LOR-2</u>	<u>ORNL</u>	<u>Heidelberg</u>	<u>Draft PEIS</u>
Cs-137	8.45E5	8.50E5	9.07E5	8.98E5
Cs-136	5.44E5	-	-	-
Cs-134	1.68E5	1.75E5	3.41E5	2.52E5
Sr-90	7.77E5	7.53E5	8.17E5	8.24E5
Sr-89	6.23E7	6.24E7	8.01E7	8.97E7
Xe-133	1.45E8	1.41E8	-	-
Xe-131m	4.10E5	-	-	-
Kr-85	9.63E4	9.76E4	1.04E5	-
<u>Cs-134</u> <u>Cs-137</u>	.199	.205	.375	.230

Calculation of "f"

The ratio of Cs-137 measured in the water to the total production of Cs-137 (LOR-2 result) implies that 60% of the cesium was released from the fuel. Because krypton is more volatile than cesium, a greater percentage of the krypton should have been released. However, the 60% cesium figure establishes a lower bound for f. Multiplying this lower bound estimate by the LOR-2 production value for Kr-85 gives a minimum value of 57,780 Ci for the amount of Kr-85 released from the fuel. Assuming a 70% value for f, along with the same LOR-2 production value, gives 67,410 Ci of Kr-85 released from the fuel. Finally, the assumption of a 100% release from the fuel would imply that the full 96,300 curies should have left the fuel.

Calculation of "C"

The amount, C, retained in the containment after the initial release equals the 44,000 curies vented in June 1980 (corrected to 48,000 Ci at shutdown) plus any slow leakage from the building of Krypton-85 that occurred before the venting:

$$C = 48,000 + \text{Delayed Leakage}$$

2)

Information about this delayed leakage term is not given in the published literature. Presumably, knowledge of the containment pressure during the 14 months prior to the venting would allow an estimate of this leakage to be made. (Making such an estimate would be a suitable project for any full dosimetry study.)

Calculation of "A"

For illustrative purposes, it is useful to assume that the delayed leakage term is zero. It is then possible to evaluate equation 1) to obtain an estimate for A. The results for the amount of escaped Kr-85 are shown in the last column of Table B2 using three estimates for the fuel release parameter, f. The lowest escape percentage, corresponding to a minimum f of 60%, is 10.2%. The value rises to 20.2% for an f of 70% and to 50.2% for the maximum f of 100%.

Implications for Release of Other Noble Gases

Having obtained information for A, the next step in the proposed method would be to apply the percentages determined above to other noble gases. The rationale for this is that, physically and chemically, all of the inert gases should have behaved in the same way.

Table B-2

Percentage of Krypton 85 Released to the Atmosphere During the Initial Accident (March-April 1979) for Three Assumed Fractions of the Amount Released from the Fuel^{a)}

Assumed Fraction of Noble Gases Released from Fuel "f"	Krypton-85 Inventory "I"b)	Kr-85 Retained in Containment After Initial Release "C"c)	Amount Released in the Deliberate Venting June 1980 d)	Amount of Kr-85 Released to Atmosphere in the Initial Release "A"e)	% of Kr-85 Released to Atmosphere in the Initial Release March-April, 1979 ^{f)}
60%	96,300	57,780	48,000	9780	10.2%
70%	96,300	67,410	48,000	19410	20.2%
100%	96,300	96,300	48,000	48300	50.2%

a) Assuming no delayed leakage to the atmosphere of Kr-85 in the 14 months before the deliberate venting in June of 1980.

b) "LOR-2" value from Table B-I.

c) Percentage (given in Column 1) of Column 2.

d) Under the assumption of no delayed leakage, this term equals the amount vented in June 1980.

e) Difference of numbers in the preceding two columns.

f) Determined from the ratio of the numbers in the preceding column to the numbers in the second column.

Based on Unit 2's actual history, Bishop et al have estimated that 145 million curies of Xenon-133 were in the fuel at the time of the accident.* To be precise, this number would have to be reduced somewhat to account for radioactive decay occurring while the gas was held up in the reactor. On the other hand, the numbers should be increased to account for the fact that Iodine-133 decays into Xenon-133, thereby providing another source of xenon not already considered. The net impact of these two competing effects should be evaluated as part of a full dosimetry study.

*Bishop et al., op. cit., Table I, p. 627.

Appendix C

Radioiodine: Releases and Dose Estimates

Cl.0 Introduction

There are three major puzzles associated with the behavior of radioiodine at Three Mile Island:

- 1) At least 11 million curies of the core's radioiodine inventory is unaccounted for.
- 2) The amount of airborne radioactivity inferred from milk measurements is much higher than the amount inferred from other environmental measurements.
- 3) The chemical form of the released radioiodine is unclear, i.e., it is not clear what percentage was organic (e.g., methyl iodide) and what percentage was inorganic.

As in Appendix A, the first of these puzzles may be considered a source term problem, the second a problem of environmental monitoring. In this appendix, they will be discussed in Sections 2.0 and 3.0, respectively.

The third puzzle--the percentage of organic versus inorganic radioiodine--represents a complication both to source term measurements and to environmental monitoring. Most analysts have assumed that the release was all inorganic. And indeed, some measurements appear to confirm this, e.g., a limited number of measurements made on

airborne samples taken outside of the reactor.* On the other hand, some analysts assume, based on reports of vent stack measurements, that the release was evenly divided between the two forms.** Finally, it should be noted that there is completely contradictory evidence, based on analyses of auxiliary building exhaust filters, indicating that 97% of the release may have been organic.***

Once the possibility is allowed that the ratio of the two forms of radioiodine may be unknown--to be determined from the available information at the same time that the release magnitude is to be determined--the complexity of trying to make sense out of the data goes up enormously. The calibration of detecting instruments is different for the two forms, and the amount expected to end up on grass and soil per curie released is different, as is the amount expected to end up in

*E.W. Bretthauer, R.F. Grossman, D.J. Thome, and A.E. Smith, "Three Mile Island Nuclear Reactor Accident of March 1979 Environmental Radiation Data: A report to the President's Commission on the Accident at Three Mile Island" (Report EPA-600/4-81-013B, Las Vegas, Nevada, 1981) pp. 2-3.

See also, Ad Hoc Dose Assessment Group, "Population Dose and Health Impact of the Accident at Three Mile Island Nuclear Station: a preliminary assessment for the period March 28 through April 7, 1979" (Report NUREG-0588, Nuclear Regulatory Commission, Washington, D.C., May 10, 1979) Appendix B, pp. B2-4.

**Pickard, Lowe and Garrick, Inc., "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident" (Report TDR-TMI-116, Revision 0, 1979) p. 5-5.

***See Table II-4 of Rogovin Report. M. Rogovin and G. Frampton, Jr., Three Mile Island: A report to the Commissioners and to the Public, Volume II, Part 2 (Report of the Nuclear Regulatory Commission Special Inquiry Group, Washington, D.C., undated) p. 359.

milk. Furthermore, the two chemical forms of radioiodine cause different radiation doses after being inhaled or ingested, because they follow different biological paths through the body. This complication will be discussed where it applies in the sections that follow.

C2.0 Source Term Issues and Estimates

C2.1 Liquid Pathways: the Missing Radioiodine

A very thorough and comprehensive report, "Iodine-131 Behavior During the TMI-2 Accident," was prepared for the Nuclear Safety Analysis Center by Science Applications, Inc.* In this 1981 report (hereafter referred to as "NSAC-30,") the authors point out that the fraction of the core inventory of radioiodine that can be tracked and measured outside the fuel is much smaller than the fractions for either radiocesium or Krypton-85:

Thirty-six percent (36%) of the core ^{131}I is accounted for. . . . By way of comparison, 51% of the ^{137}Cs , 68% of the ^{134}Cs , and 71% of the ^{85}Kr originally in the core have been accounted for. . . (NSAC-30, p. 2-1)**

This is puzzling, because it is unlikely that less iodine was

*C. A. Pelletier, C. O. Thomas, Jr., R. L. Ritzman, F. Tooper, "Iodine Behavior During the TMI-2 Accident," (Report NSAC-30, Nuclear Safety Analysis Center, Electric Power Research Institute, Palo Alto, California, September 1981)

**Note that a more recent accounting suggests that even less than 36% of the iodine has been located. The new estimate is 17 to 28 percent. [C.A. Pelletier, P.G. Voilleque, C.D. Thomas, J.A. Daniel, E.A. Schlomer, J.R. Noyce, "Preliminary Radioiodine Source term and Inventory Assessment" (Report GEND-028, E.G.&G, Idaho Falls, March 1983)]

released from the fuel than cesium. If we assume that equal amounts of radioiodine and radiocesium escaped from the fuel, it appears that 15 to 32% of the radioiodine inventory has ended up in some unknown location.* Taking the more conservative 15% figure, it appears that at least 11 million curies of radioiodine have not yet been traced**--about one million times as much radioiodine as has been officially acknowledged to have been released to the environment.

When these 11 million curies are compared, not with the total inventory, but with the 23 million curies actually located and measured in liquids outside of the fuel, the discrepancy is seen to be much greater than can be explained by accounting errors. Fully 30% of the radioiodine released from the fuel has not been traced. The authors of the NSAC-30 report go on to give five possible explanations for what happened to the missing radioiodine:

1. It stayed in the fuel or reacted with core material and stayed in the core.
2. It was scavenged by containment spray liquid that never reached the sump and, therefore, has not been measured yet.
3. It plated out on air cooler surfaces during the accident and has not been measured yet.
4. Because of its volatility, the radioiodine evolved from the sump water after the accident and deposited on building surfaces.
5. It is in sump sediments. (NSAC-30, p. 2-1.)

*The 15% figure is derived by subtracting the iodine percentage quoted from the percentage for ^{137}Cs . The 32% figure is derived the same way, except that the percentage for ^{134}Cs is used.

**11 million = 15% of 70 million curies. The 70 million curie figure for core ^{131}I is provided in NSAC-30, p. 2-1.

Each of these five explanations seems possible, and all should be checked when conditions allow, but one hypothesis is conspicuous by its absence--namely the possibility that the radioiodine escaped from the reactor. We add this hypothesis to the list as item 6:

6. The missing radioiodine escaped from the reactor by a liquid pathway. (An airborne pathway for such a large release can be ruled out by environmental measurements made after the accident.)

In examining the plumbing diagrams for TMI-2, it appears that a number of pathways for liquid releases should be examined in order to check the official estimate that much less than one curie of radioiodine escaped by a liquid pathway.*

In a first escape category are possible releases by those pathways that normally contain radioactive effluents and are therefore monitored. For example, there is a real question about the total radioactivity of the liquid release that took place through the normal radioactive liquid waste effluent system--a system that connects directly to the Susquehanna River. Five known discharges into the river were not sampled for radioactivity, including one from the start of the accident at 0400 until 0900.** Although no samples were taken, the fact that a radiation alarm near the discharge point did not trigger provides evidence (assuming the alarm was working) that any release of radioactivity was small. Supportive

*U.S. Nuclear Regulatory Commission, Office of Inspection and Enforcement, Investigation into the March 28, 1979 Three Mile Island Accident by the Office of Inspection and Enforcement. (Report # NUREG-0600, Washington, D.C., 1979,) p. II, 3-24

**Pickard, Lowe and Garrick, Inc., Report TDR-TMI-116, op. cit. p. 3-3.

evidence can be found in the fact that subsequent sampling did not detect radioiodine. (Had 11 million curies of radioiodine passed out of the reactor before 0900, it seems reasonable to expect some small fraction of it would have adhered to plumbing surfaces in the plant or even in the Susquehanna River--a residue that would have been detected later. That is not to say, however, that the residue of a release considerably smaller than 11 million curies, but still significant, would have been detected in subsequent measurements.)

A second category of liquid releases that should be considered includes releases by those pathways that are not meant to contain radioactive effluents and are therefore not monitored. Because radioactive water from the leaking pilot-operated relief valve (PORV) contaminated the gas-handling system, backing up into a number of tanks and pipes, it is quite possible that radioactive liquid entered parts of the reactor not designed to handle such intrusions. And because the drains in those parts of the system are not monitored, there is no immediate proof that radioactive liquid did not escape through them. On the other hand, checking every TMI plumbing diagram to locate theoretically plausible escape pathways would be an incredibly complex task.

Fortunately, there is a straightforward method for determining whether or not any of the aforementioned hypotheses are correct. As the authors of NSAC-30 point out:

The key to understanding what happened to the radioiodine in containment at TMI-2 now lies with ^{129}I measurements of the

reactor building surfaces. Iodine-129 has a half life of sixteen million years compared to 8 days for ^{131}I . A carefully planned and executed program of measurement is needed to distinguish among alternatives 2,3,4, & 5 (mentioned earlier). ^{129}I should also be measured in letdown/makeup components, e.g., filters and demineralizer resin. (NSAC-30, p. 2-1)

(Note that ^{129}I would have dispersed and reacted chemically in the same way as did shorter lived radioiodines.) In light of the possibility that the missing 11 million curies of radioiodine may have escaped by a liquid pathway (hypothesis "6"), all possible escape paths should be searched for I-129, regardless of preconceptions about which escape paths are possible and which are not. No one really knows the condition of every valve and every drain pipe at TMI, whether leaking or non-leaking. With the approval of the court, the TMI health fund should press to have I-129 data collected, should monitor the data collection program, and should ensure that collected data are made available for analysis.

C2.2 Secondary Side Release Pathway

The official view on radioiodine releases is that 15 - 30 curies escaped through the vent stack. However, there is evidence that other minor airborne leaks may have occurred, including leakage from the secondary side of the reactor.

Steam Generator B is known to have been contaminated, due to a leak between it and the primary cooling water. It was assumed in the official studies that because Steam Generator B was isolated at 0527 of the first day, and supposedly not contaminated until 0626, no leak to the atmosphere could have taken place through the "atmospheric relief valves" that were

known to be emitting steam.* More careful consideration suggests that the location of radioiodine in the secondary side is still at issue.

0400-0527. It is still not known why the operators were having trouble with the water level in Steam Generator B (the trouble that led to the isolation decision at 0527). There was no such trouble with Steam Generator A. A leak in Steam Generator B may well have been the problem, with possible release of radiation through the atmospheric relief valves.

0527-0626. The evidence for contamination at 0626 is indirect. It comes not from the generator itself, but from a monitor of generator exhausts. The generator may have been contaminated well prior to 0626.**

If steam Generator B were contaminated early enough, some radioactive water would have exited from the reactor through the atmospheric relief valves as a mixture of steam and fine droplets.

*NUREG 0600, op. cit., p. II-3-4.

**Information for the period 0400 - 0626 was taken from NSAC-30, Appendix C, p. C-2.

Given the published estimates of the concentration of radioiodine in the secondary side water, and the results of a German study on secondary loop emissions, it appears that a small airborne release is possible (see Appendix E). Such a release might double the official release estimate. Although a doubled estimate remains below radiological significance, the possibility nevertheless suggests that emission of radioiodine from the secondary side has not been given sufficient attention prior to this review.

Another hint that radioactivity may have escaped from the secondary side, either as a liquid or a gas, comes from variations in measurements of radioiodine in the steam generator itself. A concentration measurement at 1030 on March 30th is interpreted in NSAC-30 to imply 840 curies of radioiodine in Steam Generator B, while a subsequent measurement on the same day indicated only 400 curies:

It is not known whether the difference in the two measurements on 3/30 represents a real loss of ^{131}I or whether there was something wrong with the measurements. Only the counting sheet for the 3/30, 2045 hr. measurement is available and nothing unusual is evident. (NSAC-30, Appendix C, p. C-2.)

If the 440 curie loss is real, then several questions arise: What happened to it? What would concentration measurements prior to 3/30 have shown: if there were loss mechanisms operating on 3/30, were there perhaps greater "losses" before 3/30?*

In the course of reviewing the reactor plumbing diagrams for TMI-2, it has become obvious that another possible pathway

*In addition to the loss of radioiodine, some loss of radiocesium is also apparent. Table C.3 of NSAC-30 shows data beginning at 2045 on March 30th for long-lived Cesium 137 in the steam generator. By April 5th the Cesium concentration in Steam Generator B had dropped by 33%.

for radioactivity exchange should be examined, namely the possibility that radioactivity from the leaking pilot-operated relief valve (PORV) entered the secondary side: contaminated water from the reactor vessel is known to have overflowed through the PORV into the reactor drain tank, and afterwards forced its way out through the drain tank pressure relief valve into gas lines. Much attention has been given to how this liquid in the gas lines contaminated various parts of the water-gas treatment system, damaging valves and leading to noble gas releases. Not mentioned so far has been the fact that this system also connects to secondary side gas relief lines, suggesting that part of the liquid from the PORV may have backed up into the secondary side (see Figure C-1).

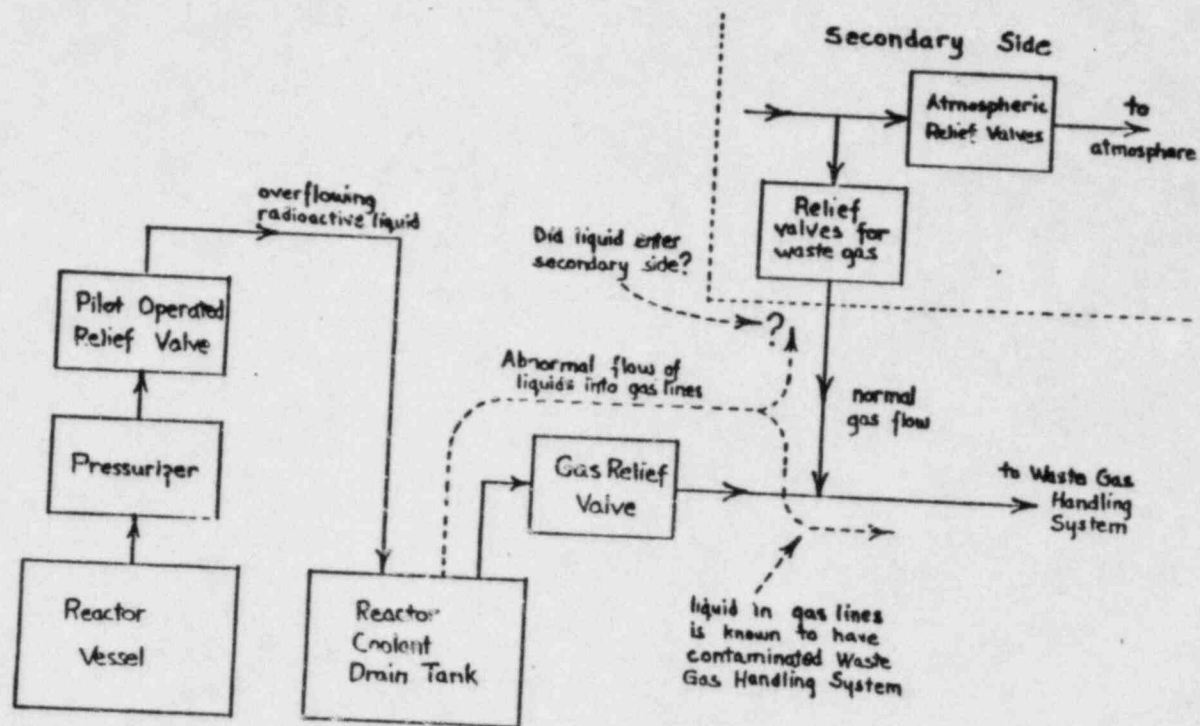
As a result, three new scenarios should be considered:

- 1) Radioactivity in the secondary side might have escaped through the damaged waste gas system.
- 2) Liquid from the steam generator might also have entered the waste gas system.
- 3) Radioactive gases and aerosols from the leaking PORV might have entered the secondary side at a time when pressure was low, and possibly exited during the atmospheric steam dumps.

Perhaps some of the radioactivity in Steam Generator B came by way of this last pathway, that is, it did not all come from a direct leak to the primary side as has been assumed until now.*

*Although this possibility may appear at first sight to be contradicted by the fact that only Steam Generator B was apparently contaminated, further analysis is warranted. It is true that Steam Generator A did not show similar contamination levels and certain samples from pump discharges "showed no radioiodine activity." (NUREG-0600, op. cit., p. II-3-4).
(continued on following page)

Figure C-1
 Possible Indirect Path by which Secondary Side Water
 Could Have Been Contaminated by Radioactive Primary Water



In any case, there seems to be a clear need for a more complete study to reassess possible interactions between the primary and secondary sides of the reactor.

C2.3 Problems with "Calibration" of In-Plant Radioiodine Measurements.

C2.3.1 Measuring Charcoal Efficiency

Escape through the vent stack, the normal path for residual gases that are not trapped by filters, was the only release pathway given careful scrutiny by the official studies. About 15-30 curies were estimated to have been released. There are a number of reasons to suspect that this number is low and some to suggest that it is too high.

The 15-30 curie estimate was derived from or extrapolated from in-plant radiation measurements. (Gaps in the measurement data will be discussed in Section C2.4.) Unlike the noble gas monitors, the radioiodine equipment did not saturate (their equivalent to going off scale). A number of questions nevertheless remain about the calibration* of the radioiodine filter and cartridge measurements, all of which depend upon knowing the efficiency with which radioiodine attaches itself to charcoal

(continued from previous page:)

However, the circulating water pumps had been turned off at 0500 on 3/28 (in order to switch the steam generators to the atmospheric relief valves). Consequently, circulation in the secondary side would have deteriorated after this point.

*"Calibration" is used figuratively here since no scale is attached to these filters. As discussed in the text, to "calibrate" a filter means to establish, for particular atmospheric and environment conditions, the efficiency with which particular radioactive particles or gases are entrapped.

under the conditions that held at the time of the accident. Two types of radioiodine measurements are of major importance:

Ventstream Cartridge Measurements. Radioiodine in air-streams leaving the auxiliary building, the fuel handling building, and the vent stack itself was measured by drawing off air from the ducts and passing it through charcoal cartridges. The cartridges were removed to a measurement room from time to time to record the amount of radioiodine accumulated since the last cartridge change.

Exhaust Filter Measurements. Additional information about radioiodine leaving the auxiliary building and the fuel handling building was obtained from analysis of charcoal filters that were in place at the time of the accident in ventilation exhaust ducts in these buildings. Although these filters were designed for radiation protection, not for monitoring, post-accident analyses of the radioiodine deposited on them has been used to extract useful information.*

At least three independent variables--humidity, the form of radioiodine, and the presence of other gases--effect the efficiency with which charcoal entraps or absorbs radioiodine. Furthermore, the effects of these variables are interdependent: that is, for example, charcoal efficiency for methyl iodide and for

*See Rogovin and Frampton, Three Mile Island: A Report to the Commissioners and to the Public, Vol. II, Part 2 (Report of the Nuclear Regulatory Commission Special Inquiry Group, Washington, D.C., undated), pp. 355-59.

inorganic iodine may be expressible in some ratio at Humidity A; the ratio may be quite different at humidity B. In table C-1 each of these variables and their interdependence is listed,* both for the ventilation cartridges and the exhaust filter. In each case there were two times when the effect of these variables should have been investigated, first in the calibration process and second in the analysis of the results for the various reports produced. As can be seen in Table C-1, in most cases these effects were neglected.

One omission should be singled out for further comment, namely the interaction of charcoal and radioiodine in the presence of noble gases. The high concentration of xenon gas might have affected the efficiency of charcoal for retaining radioiodine (assuming 30 curies of radioiodine released, the ratio of xenon to radioiodine was over 100,000 to 1). Although xenon is a noble gas, it can attach itself to charcoal temporarily, thereby possibly blocking sites to which radioiodine might otherwise be bonded. In other words, both cartridges and filters may have been temporarily saturated by xenon, dramatically lowering the efficiency of radioiodine entrapment and thus allowing much higher levels of radioiodine to escape without detection.**

*A fifth condition, namely the representativeness of the sampled air, is also listed for the ventstream cartridges, since their readings are based on air drawn off from airstreams. Because essentially all air that passed through the exhaust ducts passed through the exhaust filters, the representativeness of a sample is not an issue in the filter case.

**This possibility has been pointed out by Dan Pisello. In considering the noble-gas-saturation hypothesis, it would be useful to compare the noble gas release history with the wind direction data (continued on following page.)

Table C-1

Analysis of Charcoal Efficiency Determinations
in On-site Calibration Procedures and in Analysis of Results

	<u>Ventstream cartridges</u>	<u>Exhaust filters</u>
Location	auxiliary building, fuel-handling building, vent stack	auxiliary building, fuel-handling building
Humidity	no adjustment made in efficiency calibrations; no correction noted or applied in reports	theoretical correction (95% relative humidity assumed) applied in reports
Forms of Radioiodine	not considered in efficiency calibration; no analysis in reports	considered in efficiency calibration
Presence of Noble Gases	not considered in efficiency calibration; mentioned, but no correction applied in reports	not considered in efficiency calibration; mentioned in TMI literature, but no correction applied in reports
Interdependence of the effects of humidity, form of radioiodine, noble gases	not considered in efficiency calibration; no correction applied in reports	not considered in efficiency calibration; no correction applied in reports
Air sample representativeness	not considered in calculation of total radioiodine; sampling weaknesses (leaks in sampling ducts, incomplete mixing of air) mentioned for auxiliary and fuel-handling building in NSAC-30 report, not considered for vent stack	not applicable

The fact that the presence of large quantities of noble gases do affect radioiodine measurements is mentioned in several places in documents concerning the TMI accident, yet this effect appears to have been overlooked in the iodine release rate calculations. This oversight should be corrected in a full dosimetry study. Theoretical chemical analysis will help, but it is possible that experiments may be necessary to determine the importance of the noble-gas effect.

C2.3.2 Evidence Pointing to Incorrect Calibration

Discussion so far in this section has been limited to theoretical and procedural problems in calibration. Evidence that makes it possible to infer incorrect calibration has been discussed by Takeshi.* Takeshi begins his analysis by examining the time dependence of the reported radioiodine release rate from the vent stack (see Figure C-2). Referring to the variation

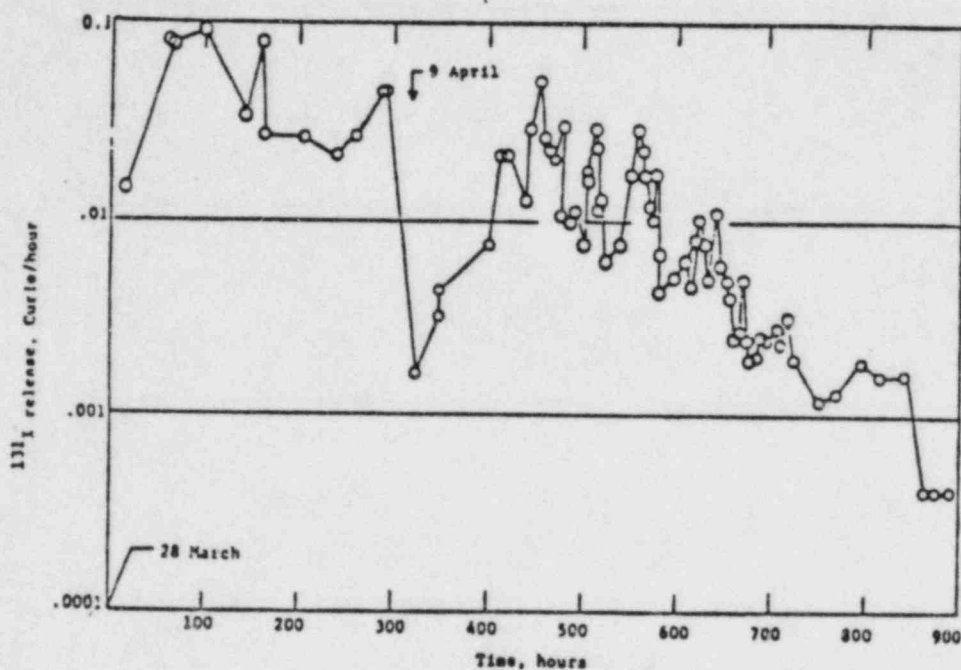
(continued from previous page)
available for the period. If the high noble gas bursts occur when the wind is blowing towards locations where low concentrations of radioiodine were found, the "saturation" hypothesis can be ruled out. Conversely, if the high noble gas bursts should occur at times when the wind was blowing towards the locations with high milk radioiodine measurements (to be discussed later), the hypothesis would be supported.

A second way that noble gas contamination could have affected charcoal calibrations would be by direct reaction between noble gas radiation and the "activated" part of activated charcoal. See Victor R. Deitz, "Charcoal Performance Under Simulated Accident Conditions" (Presented at 17th DOE Nuclear Air Cleaning Conference, Washington, D.C., undated.) Calculations made both by the author of the work cited and by this review conclude that the dose was too small for a significant effect.

*Seo Takeshi, "Excerpts from the author's review published in Nuclear Engineering [The Japanese Journal], Volume 26, No. 3" (unpublished mimeographed notes, Kyoto University Nuclear Reactor Laboratory, Kyoto, Japan, undated).

Figure C-2

Reported Rate of Release of ^{131}I from the Vent Stack as a Function of the Total Time after 28 March 1979.*



*Reproduced from V.R. Deitz, J.B. Romans and R.R. Bellamy, "Evaluation of Carbons Exposed to the Three Mile Island Accident" Presented at DOE/Harvard Air Cleaning Lab, Nuclear Air Cleaning 16th Conference (San Diego, October 20-23, 1981).

in the intervals between measurements shown in Figure C-2, he states,

it is clear that during the period before April 14 the average sampling intervals were seven to eight times longer than after April 14.

Takeshi suspects the accuracy of the data before April 14 because of the coincidental decline in release rate immediately after more frequent sampling begins in the period from 400 - 900 hours.

It seems reasonable to explain this strange behavior of the monitored iodine releases as follows: For the first two weeks the charcoal cartridges were changed only every day or every two days because there existed a real danger that workers replacing the cartridges would be exposed to extremely high iodine concentration in the ventilation system. There also existed unusual amounts of aqueous vapor. Under those conditions the absorbent capacity of the cartridges must have been rapidly minimized resulting in the unusually low level of iodine concentration as shown in Figure 3 [our Figure C-2].

If the data beyond 400 hours is ignored and one extrapolates backward from the later data to get the release rate at earlier times, it is certainly true that a higher release estimate would result. However, Takeshi takes an approach slightly different from extrapolation to estimate the total release. He assumes that the ratio on April 20th between the radioiodine release rate (given in Figure C-2) and noble gas release rate (not shown in Figure C-2) holds for all earlier times--a rather heroic assumption. (This ratio is 1 to 8800 when corrected for radioactive decay.) He then divides his estimate of the noble gas release

(45 million curies) by 8800 to obtain a total of 5100 curies of radioiodine. The noble gas estimate used is high. Should this method be applied to the range of noble gas release estimates discussed in Appendix A (e.g., 2.4 million, 10 million, and 30 million curies), the corresponding radioiodine release estimates would be 270, 1100, and 3300 curies, respectively.

When considering Takeshi's hypothesis about the cartridges, it should be noted that the excess radioiodine he calculates would presumably be organic in form (e.g., methylodide), rather than inorganic, because degradation of the cartridges due to excess humidity is likely to have affected their ability to detect organic components without significantly disturbing their ability to detect inorganic components. On the other hand, a large inorganic component in Takeshi's calculated release cannot be completely ruled out, because cartridge degradation can also affect detection of inorganic iodine in extremely wet conditions--conditions which cannot be excluded as a possibility for the vent stack environment.

In assessing the reliability of Takeshi's method, it must be recognized that the assumption of a constant ratio between radioiodine and noble gases is questionable, for one reason, because much of the late radioiodine may have originated from resuspension of methylodide from charcoal--long after the noble gases would have dissipated. Thus, the radioiodine/noble gas ratio could easily have been less than 1 in 8800 in the earlier

period.*

On the other hand, there is some evidence that the ratio was actually greater during the earlier period. For instance, Takeshi points to a higher ratio (1/700) obtained from vent stack data taken very early in the accident (0655 on March 28**). Assuming this ratio held for succeeding days, which (once again) is a heroic assumption to make, Takeshi divides 45 million curies of noble gas by 700 and calculates that 64,000 curies of radioiodine may have been released. However, the radioiodine measurement used in this estimate by Takeshi was not taken in the same way that the measurements discussed previously in this section were taken. The measurement in question was obtained by counting the total radioactivity on the charcoal cartridge while it was in place. The cartridge was not removed and specifically analyzed for radioiodine (after a delay to allow temporarily bonded noble gases to evolve). As a result, it is now believed that the reading that Takeshi made use of for his

*For instance, Dietz, Romans and Bellamy performed experiments with methyl iodide and TMI filters, finding that methyl iodide evolves for long periods after the initial exposure. ("Evaluation of Carbons Exposed to the Three Mile Island Accident," Presented at DOE/ Harvard Air Cleaning Lab/Nuclear Air Cleaning Conference, San Diego, October 20-23, 1981). The TMI release data shown in Figure C-2 is similar in some ways to the experimental curves given in their paper. However, it is not clear what fraction of the data shown in Figure C-2 actually refers to methyl iodide as opposed to inorganic iodine. Thus, the paper by Dietz et. al. may not be directly relevant. In any case, it would be interesting to try to combine the work done on re-suspension by Dietz et al. with Takeshi's method.

**NUREG-0600, op.cit., Table II-3-3, p. II-3-76.

second estimate was excessively high, representing a combination of radioactivity from radioiodine and noble gases.

This same phenomenon of noble gas interference was found with portable field survey meters, as will be discussed in Section 3.1 below. Additional evidence is provided by the results of an experiment carried out after the accident, indicating that charcoal cartridges retain 0.03% of xenon flowing through them for a 17-minute sampling period.* Even though 0.03% is a small fraction when compared to the almost 100% efficiency that might hold for inorganic radioiodine, there was perhaps 300,000 times as much noble gas as iodine in the air early in the accident,** so that it is quite plausible that xenon would contribute a larger signal during the time the xenon adhered to the cartridges. Nevertheless, it is not certain that the entire reading on March 28 was caused by extraneous noble gas radioactivity. The reading may have included a large component of radioiodine.

Even if both of Takeshi's radioiodine release estimates should turn out to be too high upon further analysis in a more complete study, he has made an important observation about "coincidental" change in the shape of the curve of the radioiodine release rate. His suggestion that the cartridges were degraded by humidity, especially during the lengthened sampling intervals, should be carefully analyzed. Certainly the

*J. E. Cline, "Retention of Noble Gases by Silver Zeolite Iodine Samples," Health Physics 40, 71-73 (1981).

**According to the official estimates, a characteristic ratio would be 5 million curies divided by 15.

assessments he makes are plausible enough to suggest that questions about the radioiodine release magnitude will have to be settled, if such questions can be settled at all, by examining the environmental measurement data for radioiodine. (Environmental measurements are discussed later in Section 3.0.)

C2.4 Gaps in the Vent Stack Monitoring Data

In addition to questions about the accuracy of the calibration of the vent stack cartridges, as discussed in the last section, equally important questions must be pursued about the completeness of the vent stack monitoring data. A cursory reading of the official studies carried out on the TMI accident (e.g., the Rogovin report) would lead one to the conclusion that the official 15-curie estimate for released radioiodine, unlike the estimate for noble gases, is solidly and unambiguously based on measurements taken in the vent stack--measurements that appear to be reasonably accurate, provided the calibrations of the vent stack cartridges are accepted. However, a footnote to the reported iodine release data covering the crucial first 15 hours indicates the actual vent stack data is missing for this period! To get around this gap in the data, analysts substituted data from monitors in feeders to the vent-stack located in the fuel handling and auxiliary building ventilation systems) and implicitly assumed that there were no filter bypasses and no iodine contributions from other feeders to the vent stack.

In the course of this review, however, evidence has been found that radioiodine may well have been released from pathways

other than those mentioned in the official studies, and at a greater rate. (See Figure C-3 for a diagram of possible escape paths.) For instance, as discussed in Appendix A, there was at least one known pathway by which radioactivity escaped to the vent stack (through the so-called "relief tank vent header") that bypassed the fuel handling and auxiliary building cartridge monitors entirely. This pathway also bypassed all charcoal filters. Of equal concern is the possibility of leakage of substantial amounts of airborne radioiodine from the containment building itself. None of this material would have registered on upstream auxiliary or fuel-handling building monitors. In attempting to account for 11 million curies of missing radioiodine, two of the five hypotheses entertained by the authors of NSAC-30, cited at the beginning of this appendix, allow for airborne radioiodine (conceivably up to or exceeding the full 11 million curies) in the containment building atmosphere.*

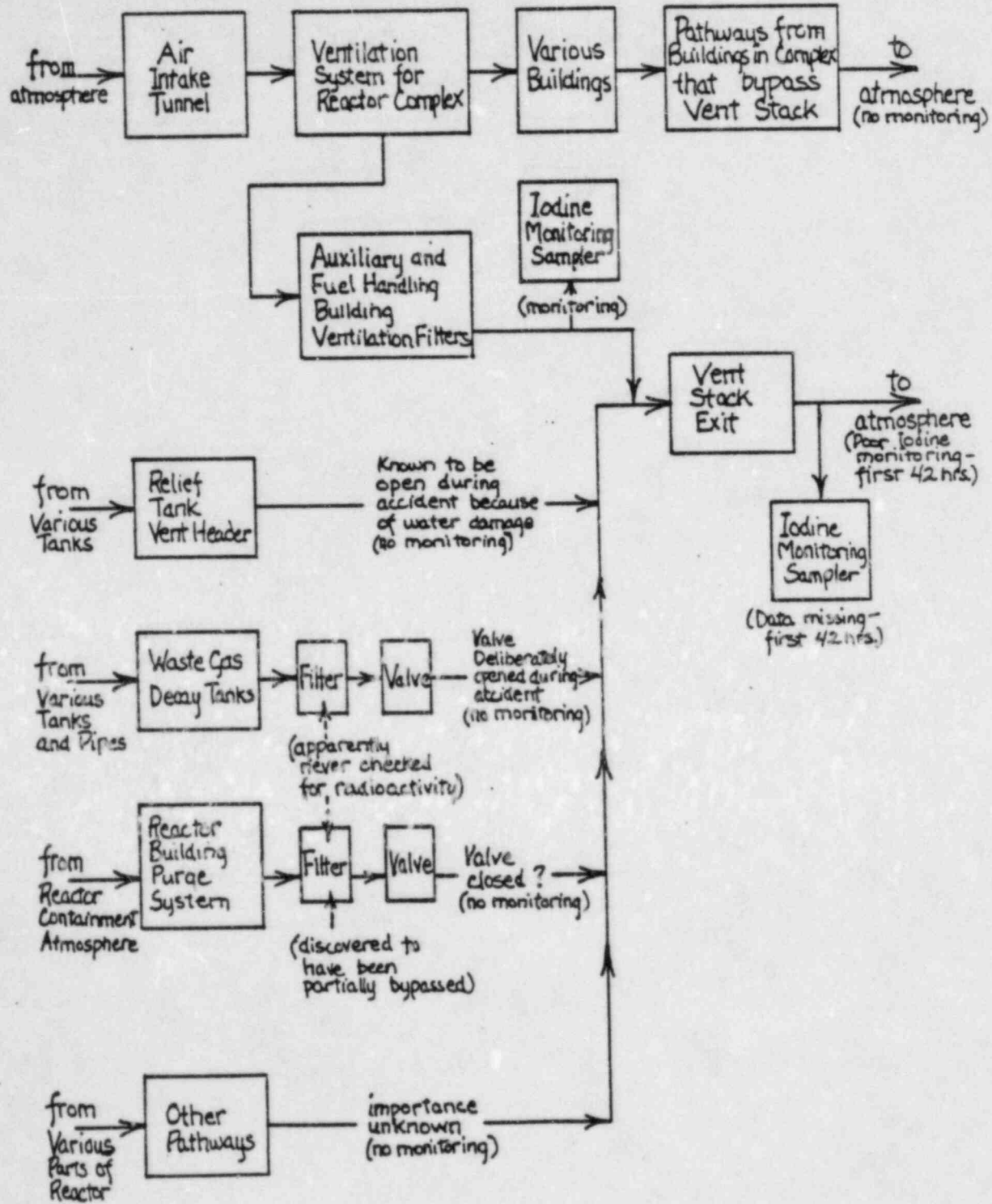
One simulation model of radioiodine transport suggests that 700,000 curies of Iodine 131 were actually made airborne during the accident, (with a maximum of 140,000 curies airborne at any one time).**

With radioiodine airborne in the reactor building, a leak through the reactor building purge system early in the accident would have allowed radioiodine to escape from the vent stack during the period when the direct stack monitoring data are missing.

*See Section 2.1 above. NSAC-30 hypotheses 3 and 4 assume that the missing radioiodine condensed on certain surfaces. In order to condense, the radioiodine must first have been airborne.

**C.A. Pelletier, P.G. Vollique, C.D. Thomas, J.A. Daniel, E.A. Schlomer, J.R. Noyce, "Preliminary Radioiodine Source-term and Inventory Assessment" (Report GEND-028, E.G. & G., Idaho Falls, March 1983). It was estimated in the report that approximately 1% of the iodine originally in the fuel was made (continued)

Figure C-3. Schematic Diagram of Some Relevant Pathways for Airborne Radioiodine at TMI



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Such leaks would have been possible before the containment building was isolated and during the periods when isolation was defeated by the operators. Furthermore, the filters that would have served as the last line of defense against radioiodine release from the containment building were probably ineffective. It was discovered in early 1982* that a bypass existed around the filters between the containment building and the vent stack. Steel plugs that were supposed to block interconnecting drain pipes were missing. In 1980 these holes were covered with "tuck" tape, as preparation for the Krypton venting, but evidently there was not even tuck tape in place at the time of the original accident.

The possibility of there existing even one radioiodine escape path other than those through the auxiliary building or fuel-handling building ventilation system compromises the official 15-curie release estimate. Because of the missing cartridges, no record would have been left had a large burst of radioiodine escaped through the purge system during the first 15 hours. Making matters worse is the fact that NSAC-30 investigators found not only the data from the first 15 hours missing but data for the next 27 hours also unreliable due to the absence of identifying labels.**

(continued from previous page)
airborne during the accident, and the maximum air concentration during the accident resulted from transport of 0.2% of the original core inventory. Conversion to curies has been made using the 70 million curie estimate for core inventory given in NSAC-30, p.2-1.)

*Ronald R. Bellamy, "HEPA Filter Experience During Three Mile Island Reactor Building Purges" in 17th DOE Nuclear Air Cleaning Conference, M.W. First, Ed. (Department of Energy, Washington, D.C., Conf-820833, 1983.)

**NSAC-30, op cit, p. 9.

C2.5 Vent Stack Bypasses

It must also be kept in mind that there are a number of possible pathways that bypass the vent stack completely--pathways that have simply been ignored in the official analyses. Possible releases from the secondary side have already been discussed in Section C2.2 above. Another case: at one point the ventilation system was turned off, despite a warning by the NRC that in so doing a ground level release (as opposed to an elevated stack release) could result.* With the ventilation system

*NUREG-0600, op. cit., p. II-A-42. The ventilation system for Unit 2 was turned off at 1104 on 3/28. The time at which the ventilation system was restarted is not clear for the sequence of events given in NUREG-0600. However, the following narrative account is provided:

Shift Foreman B stated that the Unit 2 ventilation system supply fans tripped and remained off because of high radiation levels, but the exhaust fans operated continuously except for a few brief periods when the ventilation systems were turned off in an attempt to reduce the release rates. Securing the fuel-handling building and auxiliary building ventilation systems early on March 28 and again on March 29 caused exposure rates to increase significantly in the Unit 2 auxiliary building, thus hampering emergency activities. Perhaps more important was the fact that control room airborne radioactivity levels started increasing when the ventilation systems were shutdown. . . because of the need to ensure habitability of the control room and to keep dose rates as low as possible in the auxiliary building to facilitate emergency activities, the ventilation systems were subsequently kept in operation. (NUREG-0600, p. II-3-21.)

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b

turned off, radioactivity could have leaked from a number of locations, including perhaps the air intake tunnel.

C2.6 Need for a Program to Search for Residual I-129 in the Reactor Complex.

Nowhere can any language be found in the official literature that would serve to alert the non-specialist either to the significance of the aforementioned gaps and calibration problems associated with the vent stack monitoring data or to the significance of paths that bypass the vent stack. Whether or not attention to these questions during the official inquiries would have led to any answers is not certain. In any case, it is fortunate that there is still a chance to learn a great deal about radioiodine pathways at TMI by implementing a carefully planned search for any residual, long-lived Iodine-129 deposited on surfaces throughout the reactor ventilation and exhaust systems. (Such a search would compliment the Iodine-129 program proposed for other parts of the reactor in NSAC-30 and discussed earlier in Section 2.1.) Because Iodine-129 would have behaved chemically and physically in essentially the same way as Iodine-131, detection of Iodine-129 would be tantamount to detection of past deposition of Iodine-131.

The first place to look for Iodine-129 traces would be in the reactor building purge system, especially inside the piping that bypassed the filters and inside the valves to the vent stack--valves that were supposedly closed. Next, measurements should be made along the vent stack itself. Finally, all pathways

that bypass the vent stack should be checked, including the air intake tunnel.

The possibility that methyl iodide dominated the radioiodine release reduces the chances that detectable deposits of Iodine-129 will be found throughout the exhaust system. (Methyl iodide does not stick easily to surfaces.) Nevertheless, there are still good reasons for pursuing such a search. First of all, even a negative finding would be useful. Second, even small traces of inorganic Iodine-129 could provide valuable clues to alternative pathways that organic radioiodine may have taken during the accident.

C3.0 Environmental Monitoring of Radioiodine

With the vent stack radioiodine measurements compromised, especially during the first 42 hours, it becomes important to determine if the environmental data collected subsequent to the accident can shed any light on radioiodine releases.

Unlike the noble gases, inorganic radioiodine sticks easily to grass and ground, and all kinds of iodine, whether organic or inorganic, are easily absorbed after breathing by humans or animals. Consequently, radioiodine leaves traces that can be detected many days after the original release. The fact that actual or formal monitoring equipment in place at the time of the accident was inadequate did not therefore rule out the detection of hypothetical bursts of radioiodine released in the first

42 hours. In fact, with the advantage of hindsight, it is clear that had the authorities been concerned about mapping out the actual radioiodine release, rather than convincing themselves that the release was small, they could have done so in the first few weeks after the accident using soil and grass measurements alone.

Unfortunately, even though many grass samples were taken, the sampling did not cover all wind directions from the reactor. Cross-checking of radioactivity measurements by employing other techniques at the same location was not performed, and insufficient quantities of grass were taken in each sample to allow enough positive readings to be obtained so that an adequate map of the deposition could be made.* Thus, as we shall see, analysis of the environmental data, like the analysis of inplant data, gives ambiguous results about the amount of radioiodine released.

C3.1 Airborne Measurements.

The earliest readings on portable radioiodine monitors taken outside the reactor in air were very high--as much as 100,000 times the amount that would be expected based on the official release estimate. These initial high readings, taken with portable equipment, were attributed to noble gas contamination. Subsequent (delayed) laboratory analysis of some of the field

*Estimates of the contamination per square meter should have been made so that sample sizes could have been adjusted to match the sensitivity of detection equipment. Had grass samples been 100 times larger than actually taken, the number of readings above the detection limit would have increased enormously.

samples tended to confirm this hypothesis,* showing readings roughly consistent with the official release estimate. (There is, however, no discussion of how these portable units would have responded to methyl iodide.) As a result of the possible noble gas contamination, the bulk of the portable survey data for radioiodine--that which was not checked in the laboratory--appears to be useless.

Information from the regular, fixed environmental monitoring stations is also of limited use. Only eight of the twenty stations (see Table C-2) were equipped with charcoal cartridges designed to accumulate radioiodine for periodic measurement.** As shown in Appendix A, the complete set of twenty stations was insufficient to avoid windows in the noble gas monitoring system; eight stations for radioiodine were clearly inadequate to characterize the radioiodine release. During the crucial first 42 hours, when vent stack release data is either missing or unreliable (see Section C2.4 above), these stations miss most of the prevailing wind vectors. As Figures C-4 - C-7 demonstrate, radioiodine could have been blown in many directions, especially to the NNW, without being detected.

Nevertheless, the airborne monitoring data is still of some use. For times when the wind was blowing towards one of the eight stations, it can be used to rule out release rates much greater

*NUREG-0600, op. cit., p. II-3-79.

**Again no information is provided on the efficiency with which these units would detect methyl iodide.

Table C-2

Regular Environmental Monitoring Locations

<u>Licensee Designation</u>	<u>Radioiodine Monitoring</u>	<u>Location</u>	<u>Distances and Direction</u>
1S2**	yes	North Weather Station	0.4 mi N
2S2		North Bridge	0.7 mi NNE
4S2**		Top of Dike	0.3 mi ENE
5S2**		Top of Dike	0.2 mi E
9S2		South TMI	0.4 mi S
11S1**		Mech. Draft Cooling Tower	0.1 mi SW
14S2		Shelley Island***	0.4 mi WNW
16S1**		North Boat Dock	0.2 mi NNW
4A1		Laurel Road	0.5 mi ENE
5A1**	yes	Ob. Center Bldg.****	0.4 mi E
16A1		Kohr Island***	0.4 mi NNW
10B1		Shelley Island***	1.1 mi SSW
12B1	yes	Goldsboro Air Station	1.6 mi WSW
1C1	yes	Middletown Substation	2.6 mi N
8G1**	yes	Fallmouth Substation	2.3 mi SSE
7F1**	yes	Drager Farm****	9 mi SE
4C1**		Rt. 241****	10 mi ENE
7G1		Columbia Water Plant	15 mi SE
9G1	yes	York Med Ed Station	13 mi S
15G1**	yes	West Fairview Substation****	15 mi NW

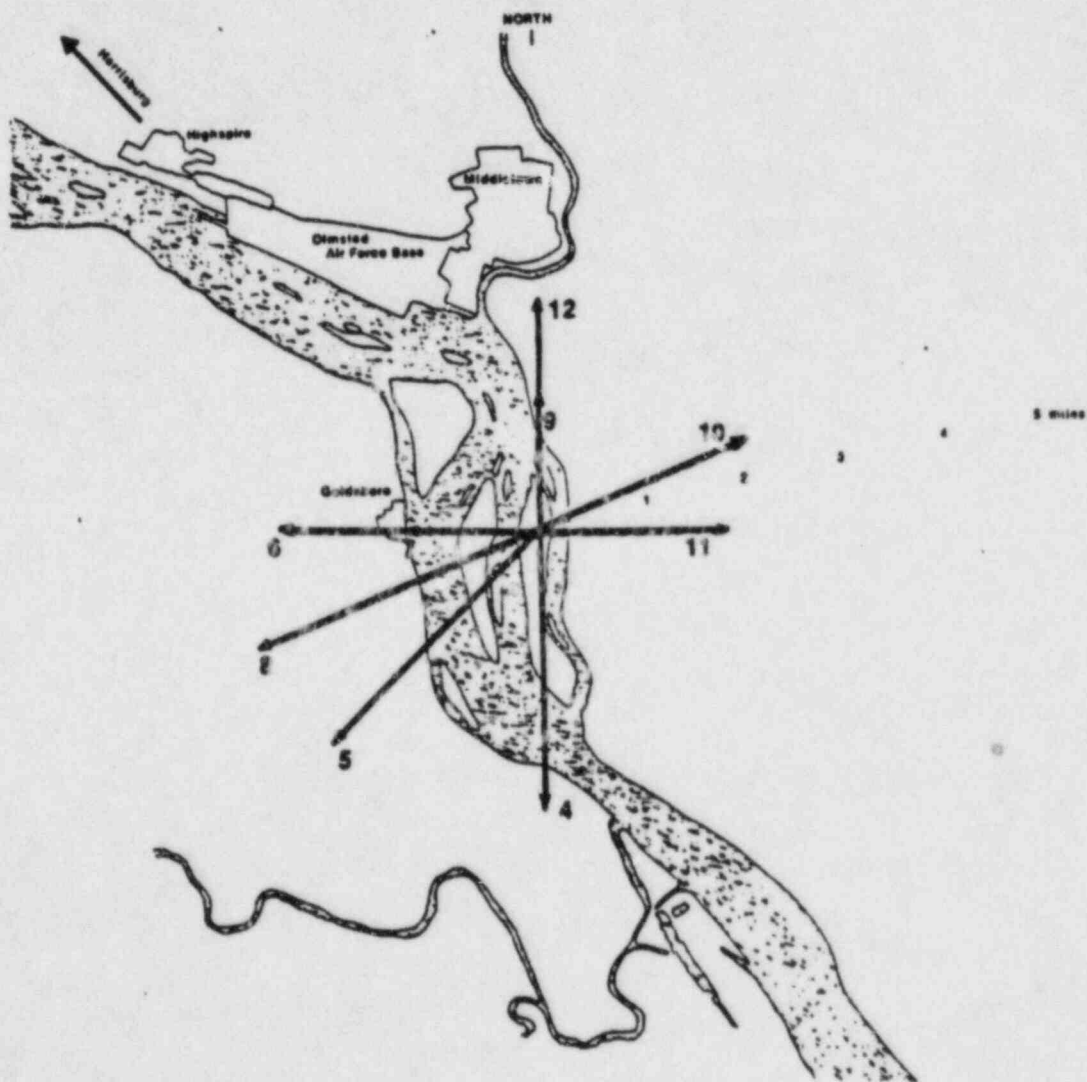
*Relative to a point midway between the two containment buildings.
**Location also has RMC TLD for quality control purposes.
***Island locations contained two Teledyne TLDs on 3/28/79.
****Location also has a dosimeter which is readout on a monthly basis.

Source: NUREG-0600, op. cit., p. II-1-48.

Figure C-4

TMI WIND VECTORS 28 MARCH 1979 HRS. 4-12*

1.5 cm. = 1 m/s

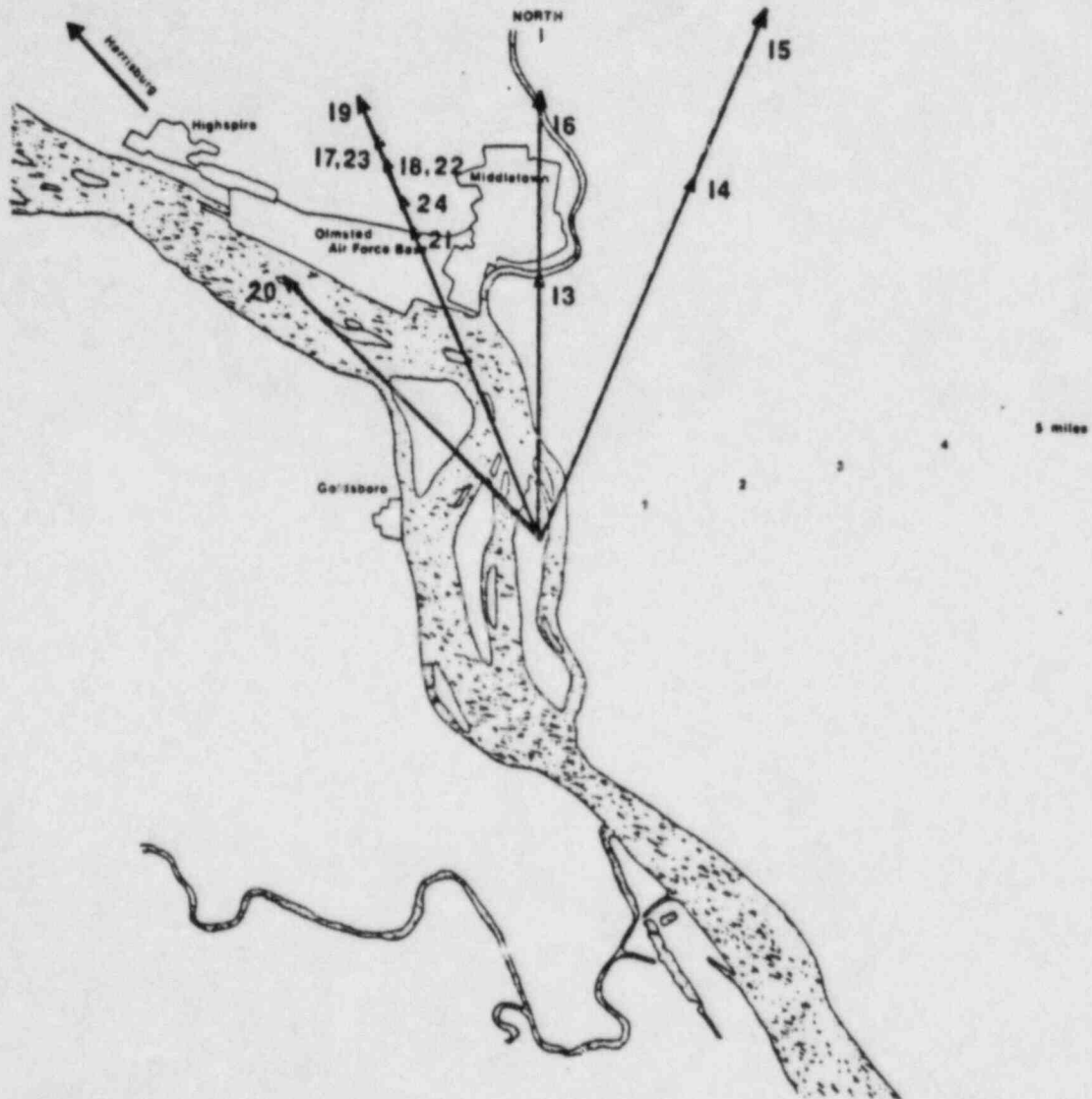


*The number by each vector refers to the hour of measurement.
1 m/sec. is approximately 2 miles per hour.

Figure C-5

TMI WIND VECTORS 28 MARCH 1979 HRS. 13-24 *

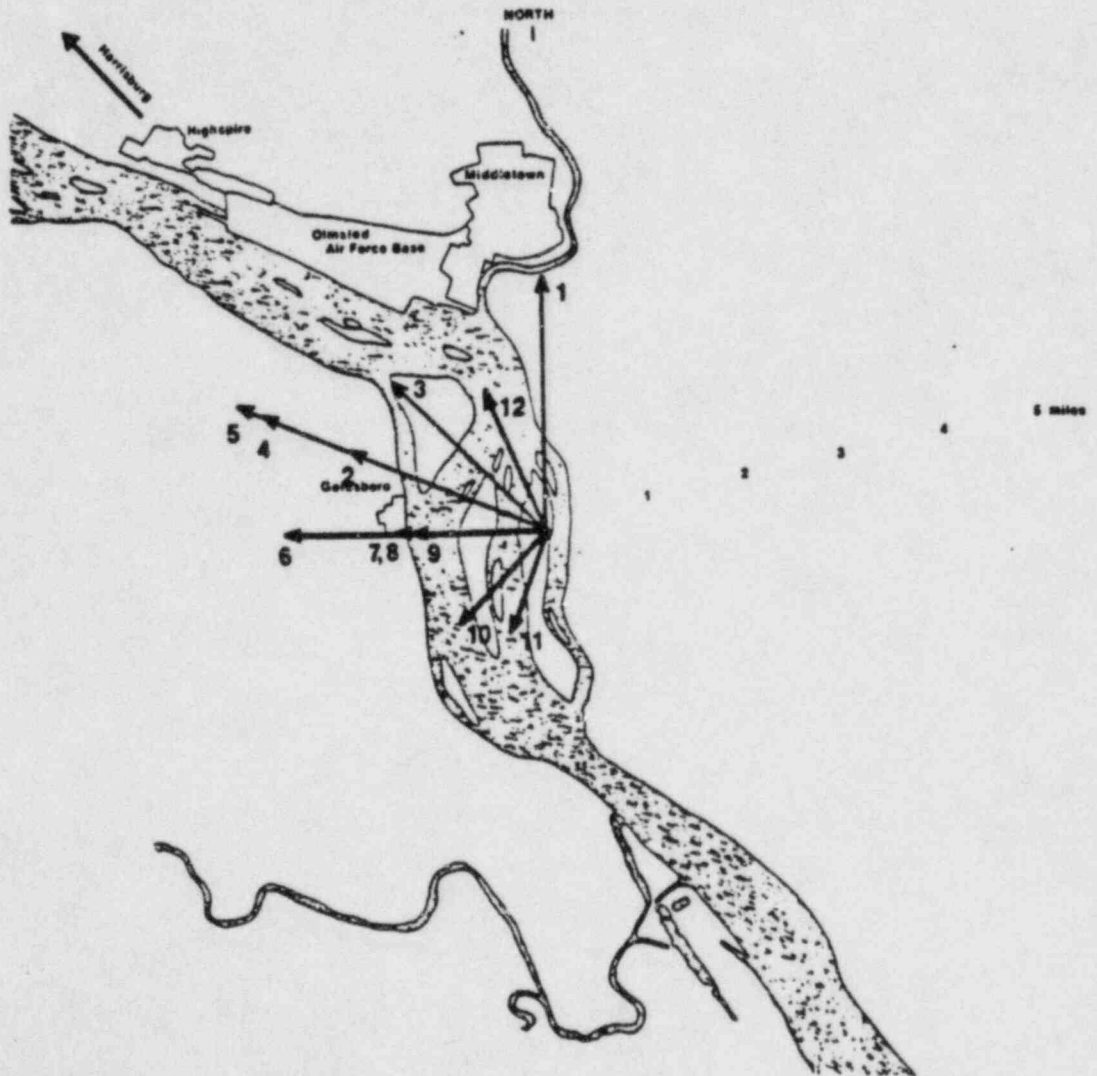
1.5 cm. = 1 m/s



*The number by each vector refers to the hour of measurement.
1 m/sec. is approximately 2 miles per hour.

Figure C-6

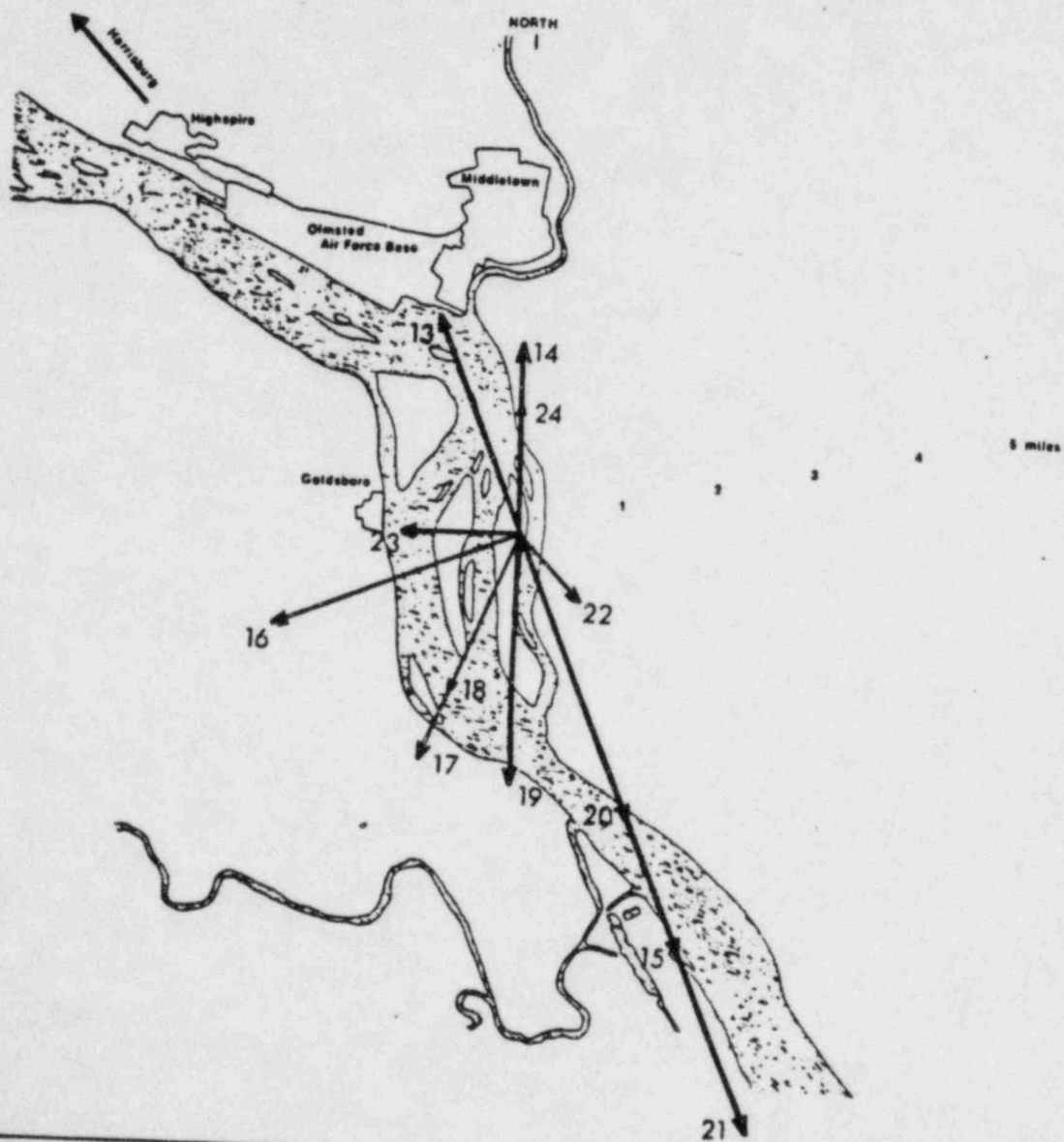
TMI WIND VECTORS 29 MARCH 1979 HRS. 1-12 *
1.5 cm. = 1 m/s



*The number by each vector refers to the hour of measurement.
1 m/sec. is approximately 2 miles per hour.

Figure C-7

TMI WIND VECTORS 29 MARCH 1979 HRS.13-24 *
1.5cm. = 1 m/s



*The number by each vector refers to the hour of measurement.
1 m/sec. is approximately 2 miles per hour.

than those indicated in the vent stack data. A comparison of the measured results with model calculations based on the vent stack release data agreed within about a factor of 12.* That is, the model tends to overpredict by an average factor of six when it overpredicts and it tends to underpredict by an average factor of two when it underpredicts. Given the fact that the measured data was aggregated over six days or more, and therefore should be relatively easy to fit, it cannot be said that there is good agreement with the model. Nevertheless, the results tend to support the hypothesis that the radioiodine release rates were lower on average than those indicated by the vent stack data, at least for times when the wind was blowing toward the radioiodine monitoring stations.

One isolated measurement of airborne radioactivity is also worth mentioning.** Noble gases were detected a few days after the accident in a radioactive plume 375 kilometers away in Albany, New York. Although no radioiodine was detected within the sensitivity of the measuring equipment, it is still possible to usefully compare the limit on radioiodine detection with measured noble gas activity. Although the authors of the paper did not make such a calculation themselves, it is so straightforward to do so that we have made the calculations for this review in order to determine where this paper belongs in the

*Pickard, Lowe and Garrick, Inc., Report TDR-TMI-116, op. cit., Table 5-2.

**M. Wahlen, C. Kunz, J. Matuszek, W. Mahoney, R. Thompson, "Radioactive plume from the Three Mile Island Accident: Xenon-133 in air at a distance of 375 km.," Science 207, 639-40 (1980)

spectrum of environmental monitoring papers. The results indicate that the ratio of radioiodine curies to Xenon-133 was less than 7.10^{-7} to 1.* If this ratio were characteristic of the entire release, it would give a total radioiodine release ranging from less than 1.6 curies to less than 7 curies of radioiodine (depending upon whether a total Xenon-133 release of 2.4 or 10 million curies is assumed). Although the radioiodine detection limit supports a small (15 curies or so) release of radioiodine, it should be realized that the air mass that arrived at Albany may not have contained the emissions from the earliest period when a large burst of radioiodine might have escaped.** Also, no information was given about whether or not the radioiodine detection equipment used was sensitive to methyl iodide. Nevertheless, the measurement provides further support for the conclusion that there were periods of time when the radioiodine release rate was as small as stated in the official studies. In addition, unless the Albany measurement was not capable of detecting methyl iodide, this finding tends to contradict Takeshi's release estimates (discussed in Section C2.3.2 above) which are based on assuming a high iodine/xenon ratio over the entire release period.

C3.2 Grass Measurements

Analysis of grass samples for many locations were made by the Department of Energy, the Nuclear Regulatory Commission and

*Obtained by dividing the 8×10^{-4} pci/m³ Iodine-131 detection limit value by 1230 pci/m³ of Xenon-133. (1230 is the average of the two values given in the report, 1390 and 1060.)

**The air mass containing the radioactivity arrived in the Albany area sometime between 1230 EST March 29 and 1500 EST March 30. If moving at an average speed of 4 meters/sec (about 8 miles/hr.), the air mass would have taken 26 hours to reach Albany.

the Metropolitan Edison Company. Radioiodine was found on many of these samples, but most were below the limits of detection. As part of this review, the positive measurements, as well as a sampling of the negative ones, were plotted on a map of the area. It was found that the grass samples were not taken uniformly in all angular sectors. The data is quite limited in certain sectors, particularly in directions which will turn out to be of interest later--directions in which radioactivity initially moving upriver would have eventually blown over land due to the windings of the river.

Some of the grass measurements reported by the Department of Energy are so uniform as to suggest incorrect labeling. Until this issue is resolved, it is premature to recommend a thorough modeling analysis of the results. On the other hand, the peak concentration reported (0.9 nanocuries/per square meter of Iodine-131 measured on 4/15/79 at a distance of one half mile southeast of the plant*) can be compared with peak concentrations reported in another accident, at Windscale, England, in which the amount of radioiodine released was determined.

First, however, the measured value must be corrected for radioactive decay. (Since the number of nanocuries of radioiodine decreases with time due to radioactive decay, the concentration would have been higher had it been measured earlier.) The 0.9 nanocuries per square meter on 4/15 is equivalent to about 3.5 nanocuries per square meter at the start of the accident.

*This measurement was taken by the NRC. Similar results (0.73 nanocuries/m²) were obtained by DOE at a similar location at the same time. [E.W. Bretthauer, R.F. Grossman, D.J. Thome, and A.E. Smith, "Three Mile Island Nuclear Reactor Accident of March 1979 Environmental Radiation Data: A Report to the President's (continued on following page)

This peak value of 3.5 nanocuries per square meter can be compared with the peak value of 17,000 nanocuries per square meter measured in October of 1957 following the accident at Windscale, England, in which about 20,000 curies of radioiodine were released.* Scaling the 20,000 curie Windscale figure by the ratio of 3.5/17,000 gives 4 curies, a number which is not wildly inconsistent with the official TMI estimate of 15 curies. Of course it has to be borne in mind that TMI data are much scarcer than Windscale data. It is unlikely that those making the measurements at TMI happened upon the hottest spot. And in light of the fact that the TMI grass measurements may have missed certain bursts of radioiodine--especially bursts blown upriver--the results of the analysis given here only support the official release rate estimates for those wind directions in which measurements were made. A final caveat must be included about methyl iodide. Because methyl iodide does not stick easily to grass, a large release of methyl iodide would not have shown up in the grass measurements.**

(continued from previous page)
Commission on the Accident at Three Mile Island," (Report EPA-600/4-81-013B, U.S. Environmental Protection Agency, Las Vegas, Nevada, 1981.) The Measurement was found on page 2 of Table 9-E. The DOE measurement was found on page 50 of Table 11-E.]

*The peak grass measurements shown in maps of deposition at Windscale occur at about 0.5 miles and again at about 2 miles. A.C. Chamberlain, Royal Meteorology Society Journal 85, (1959), Figure 1, p. 352. For additional discussion of the Windscale accident, see J. Crabtree, Ibid., p. 362.

**Of course, if the same percentage of methyl iodide was released at Windscale and TMI, this caveat would be irrelevant to the calculation. However, the measured deposition velocity at Windscale (0.003 meters/sec.) appears to rule out a large methyl iodide release there.

C3.3 Measurements of Absorbed Radioactivity in Humans

Some 760 people living within three miles of TMI were counted for a period of 10 minutes in a "whole body counter," beginning on April 10, 1979.* The hope was to identify or set limits on any specific radioisotopes in excess of normal radioactivity found in the body (i.e., above the 100 nanocuries of radioactive potassium (K-40) that occurs naturally in humans.**) However, the Kemeny Commission staff did not think very highly of the procedures followed and tended to discount the measurements:

To summarize, it was impossible for this task group to assess internal dose based on in-vivo measurement, even though there was a multitude of data available for analysis.

For ^{131}I in particular, the task group had this to say,

Some question is raised as to the appropriateness of the electronics settings. The gain of the signal amplifiers from the detector should be adjusted so that the energy region of the net spectra best incorporates all of the likely isotopes to be found. In the case of a nuclear plant, a key one is I-131 with its primary photon energy of 364 kev. Both of the subcontractors have set the gain of their amplifiers in such a way that the I-131 photopeak is very close to the low end of the spectrum. This is certainly not the most optimum setting. The energy region that these spectra are suited to is the K-40 region, which although beautifully centered in the middle of the page, is not an isotope of any concern at TMI or any other nuclear facility. Other difficulties encountered with both of these whole-body count systems involve geometry problems that could lead to significant errors in quantifying any given isotope. However, these problems are inherent in "shadow-shield" type whole-body counters, ** such as those employed by RMC and Hegelson.

*R.D. Gotchy, The Whole Body Counting Program Following the Three Mile Island Accident. Technical Report April-September 1979, (Report NUREG-0636, U.S. Nuclear Regulatory Commission, Washington, D.C., 1980.)

**Auxier et al., op. cit., p. 155.

Despite these limitations, it does not seem wise to discount the information completely. Data at TMI is so sparse that none of it should be ignored unless there is convincing evidence that it is completely useless. It is better to extract as much information as possible, bearing in mind that the derived results may carry great uncertainty. In this spirit, it is worthwhile to convert the whole-body radioactivity results to a release estimate. It is only in this way that the whole-body counting results can be put into perspective with the other published papers.

In the case of ^{131}I , the data showed a completely null result, i.e., no radioiodine was noted in any individual down to a reported detection limit of 2 nanocuries. Assuming that the detection limit is correctly stated, it appears that this result is quite consistent with a 15 curie or lower release. In other words, 2 nanocuries per person would not be expected to be found in many individuals. The average value caused by inhalation of radioiodine might be 0.1 nanocuries per person, with large fluctuations about the average.* Some additional

*For instance, the amount of radioiodine inhaled is given by the integrated product of breathing rate multiplied by the concentration per unit volume multiplied by the exposure time. These last two are generally combined in the literature into one factor, called the "X/Q" factor. An average "X/Q" of 10^{-6} would result in about 4 nanocuries inhaled per 15 curies released. 4 nanocuries would have decayed to 2 nanocuries by the time of the measurement, assuming the average radioiodine release occurred on April 6 and the average measurement took place on April 14. The concentration would have been reduced by an additional factor of 3 to 0.66 nanocuries in a few days due to elimination from the body (see U.S. NRC, Reactor Safety Study, Wash-1400, Vol. VI 1975, p. D-25).

For comparison purposes, a release averaged over all wind directions uniformly would have a X/Q of 0.17×10^{-6} at 2 kilometers (assuming uniform mixing in the reactor wake), i.e., (continued on following page.)

radioiodine may have been ingested from milk, contributing perhaps another 0.1 nanocuries on the average.*

Even if one assumes that a 2 nanocurie detection limit overstates the sensitivity of the measuring equipment, the fact that no radioiodine was found in any individual is useful information. It probably rules out a release above, say, 150 curies of radioiodine while the wind was blowing in the direction in which the 760 people in the sample lived, worked or went to school, i.e., all directions presumably except up or down the river. (Any excessively high release up or down river would probably have missed people living within 3 miles and therefore would have been missed in the whole body counting data.) This radioiodine limit is particularly important because it probably also applies to methyl iodide** (once again only in those directions covered by the 760 "human dosimeters").

As part of any full dosimetry study, it would be worthwhile to establish a more rigorous upper limit on the release.

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the average expected concentration for a 15 curie release would be 0.11 nanocuries. Actual X/Qs would be higher or lower for various wind directions and distances, so that fluctuations about 0.11 nanocuries per person would be expected. (A breathing rate of $2.7 \times 10^{-4} \text{ m}^3/\text{sec}$. has been assumed.)

*Berger et al. calculated that the contribution to the 50 mile population dose from milk was twice that from direct inhalation. "Population Dose Estimate for a Hypothetical Release of 2.4×10^6 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station Unit 2" (Report ORNL/TM-7980, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1981.) However, the population living within 3 miles probably drank milk from more distant locations, reducing in their case the relative contribution of the milk pathway. Thus, it is more reasonable to take the milk contribution equal to the inhalation contribution.

**Assuming that, as would be expected, methyl iodide is eliminated from the body more slowly than inorganic forms of iodine.

For that purpose it would be useful to reanalyze the original whole-body data, if it is available, to obtain greater sensitivity for radioiodine. The original energy spectra could be added together for many individuals thereby improving the "signal-to-noise" ratio*. If 100 spectra were added, the detection limit for the average would drop to 0.2 nanocuries. If all 760 spectra were added, the corresponding limit would be 0.07 nanocuries-- a level of sensitivity that would be sufficient to detect a 15 curie or even smaller release.

C3.4 Radioiodine in Meadow Voles

Two groups reported finding radioiodine in meadow voles: one group actually removed the vole thyroids to track its path;** the other group merely identified the radioiodine without determining its location in the voles.*** No attempt was made in either case to work backwards from the findings to a check or an estimate of the quantity of radioiodine released. Consequently, as it stands, the existing literature cannot be used to compare vole results to other environmental measurements, especially to measurements on cow's milk that will be shown (see below, Section 3.5) to be in conflict. Fortunately, the principal investigator for this review became interested enough in the vole problem to perform calculations on his own (under the auspices of the National Audubon Society). The results are reported below.

*The detection limit would decrease by the square root of the number of spectra summed.

**W. Field, E. Field, D. Zegers and G. Steucek, "Iodine 131 in the Thyroids of the Meadow Vole (*Microtus Pennsylvanicus*) in the Vicinity of the Three Mile Island Nuclear Generating Plant," Health Physics 41, 297-301 (1981).

***S. Morris, P. Mehrle, "A Report on Radionuclide Analyses Done (continued on following page)

One factor complicating the necessary calculations is the absence of research on the metabolic behavior of radioiodine in voles. Such information should be obtained experimentally in a complete dosimetry study, but for these calculations, it has been assumed that, as in humans, one-third of the radioiodine consumed by the vole ends up in the thyroid. Given this assumption, it is possible to convert the vole measurements into measurements of radioiodine concentration in the grass eaten by the vole. Such a derived concentration may then be compared with both actual sample grass measurements and with meteorological predictions of radioiodine concentration in the grass of the vole habitats (assuming the official 15 curie release).

Table C-3 shows the results of model calculations--adapted from the paper by Field et al.--that attempt to predict:

- 1) how much of the official (15 curie) estimate of radioiodine would have been deposited per square meter at each of the two sites studied (a purely meteorological dispersion calculation--see Table footnotes b,c),
- 2) the resulting quantity of radioiodine per gram of vegetation (see Table footnote d), and
- 3) how much vegetation the voles would have had to have eaten at each site to accumulate the amount measured in their thyroids. As shown in Table C-3, column 5, the model is internally consistent in this regard in that it predicts the same amount of vegetation eaten by voles at the two sites. Or, in other words, the ratio between radioiodine per gram of vegetation and radioiodine

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Via Gamma-Ray Spectroscopy on Wildlife Samples from Areas in Close Proximity to the Three Mile Island Nuclear Generating Station near Harrisburg, Pennsylvania," (Mimeographed report U.S. Fish and Wildlife Service, Columbia, Missouri, June 11, 1979).

measured in the vole thyroids is the same for both sites. The prediction for the amount of radioiodine per gram of grass is about four times higher than a measurement made by Metropolitan Edison Company at a location fortuitously midway between the two vole sites. (The agreement might be even closer than a factor of four if a correction factor is included to account for the soil mixed in with the grass collected in the Metropolitan Edison sample. *) Agreement within a factor of four is also found for the amount of radioiodine projected to have been retained in the vole's thyroid. About 37 grams of grass would have had to have been eaten by the voles in order to produce the measured thyroid radioiodine concentration. Over the same period, the voles would have eaten about 160 grams of food. Thus, if all the vole's food were vegetation, the model would predict 160/37 times as much radioiodine as was found, i.e., a factor of about 4 more.** As a result, it appears that the vole thyroid measurements are consistent with a radioiodine release estimate which is lower by about a factor of four than the official estimate of 15 curies.

*The average prediction for the two vole sites in Table C-3 is 0.31 picocuries per gram. On 4/5/79, 0.11 picocuries per gram of grass was found 1.1 miles ENE of the reactor. (This amount of radioactivity would have decayed to 0.071 picocuries per gram on 4/10/79, the average date used in the table.) [B.A. Hilton, R. F. Grossman, "Three Mile Island Nuclear Reactor Accident of March 1979. Environmental Radiation Data: Update 2, Volume I," (Report EPA-600/4-81-014A, Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada, March 1981), Table 17-E.]

The Metropolitan Edison samples are described as follows, "grass collected along with soil taken from three 6" by 6" areas." (Ibid., Table 16e.) Depending upon the amount of soil included in the part of the sample actually counted, the reported concentration may have been based on an excessive weight.

**It should be noted that some filtering of radioactivity may have occurred in the overgrowth at the vole sites in the upper levels of the pasture. As a result, the voles eating at ground level may have consumed grass with less radioiodine than the average. Accounting for this effect would lead to better agreement.

Table C-3

Model Predictions of the Amount of Radioiodine Deposited on Vegetation and Consumed by Voles

	Curies assumed released in sector (a)	Deposited radioiodine in nanocuries per m ² re- maining on 4/10/79 (b,c)	Picocuries of radioiodine per gram of vegetation (d)	Average radioiodine measured in vole thy- roids in picocuries (e)	Grams of vegetation eaten to accumulate measured radioiodine in thyroids (f)	Total diet for same period (in grams) (g)
Vole site II (h)	.37	0.21	0.17	2.2	39	160
Vole site III (i)	.82	0.57	0.46	5.6	36	160

(a) Obtained by weighing the time dependent radioiodine release shown in Table II-3 of the Rogovin report (p.356) by the percentage of time the wind was blowing in the 22.5° sector containing the vole site.

(b) Assuming 1) a 0.003 m/sec. deposition velocity (consistent with the average value measured for radioiodine after the Windscale accident);

2) Half of the release was methyl iodide and hence did not stick to ground surfaces;

3) An average wind speed of 3 m/sec. consistent with the meteorological data;

4) An initial plume shape matching the turbulent wake of the buildings near the vent stack. This was accomplished by using a vertical dispersion coefficient of 50 meters in a Gaussian plume model. Since the atmosphere was quite stable during this period, no significant additional dispersal would have taken place by the time the radioactivity reached the vole site. The radioactivity was assumed to be spread uniformly in a horizontal direction over a 22.5 sector.

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- 5) Weathering rate of .002 per hour [Berger et al., "Population Dose Estimate from a Hypothetical Release of 2.4×10^4 Curies," Appendix B.] Such a rate leads to a reduction of a factor of 2 in ground concentration by 4/10/79.
 - 6) Radioactive decay reduces concentration by a factor of 2 on the average.
- (c) Average over 22.5° sector (east for site II, northeast for site III).
- (d) Assuming 700 (wet) grams of grass per square meter and 57% deposition of the radioiodine onto grass. Note that the pastures from which the voles were taken were uncut for two years. (The 700 gram figure has been taken from NRC Regulatory Guide, V. 109 (Rev. 1). It is equivalent to a value of 3.6 tons per acre, which is reasonable for an unfertilized field. Grass yields were discussed on 4/13/82 with Victor Lechtenberg, Associate Director, Purdue University Agricultural Experimental Station, Purdue University. The assumed percentage deposition on grass (57%) is based on Berger et al., op. cit.)
- (e) William R. Field, Elizabeth H. Field, David A. Zegers, and Guy L. Steucek, "Iodine 131 in Thyroids of the Meadow Vole (*Microtus Pennsylvanicus*) in the Vicinity of the Three Mile Island Nuclear Generating Plant," *Health Physics* 41, 297-301 (1981). It is assumed that 1) the voles eat predominantly "wet" grass rather than grass that has fallen and dried out; 2) that one third of the ingested radioiodine ends up in the thyroid.
- (f) Three times the ratio of the entries in the two preceding columns, which is equivalent to assuming that two-thirds of the radioiodine is eliminated from the vole before being absorbed by the thyroid. Because we are not aware of any data on this subject for voles, we have taken the same value for the fraction eliminated as has been measured for humans. [USNRC, *Reactor Safety Study*, 1975, Vol. VI, p. D-25]
- (g) Reference (e) states that voles eat one-third of their weight per day. Average weight of a vole is 50 grams [W.H. Burt and R.P. Grossenheider, *A Field Guide to the Mammals*, 3rd Ed. (A Peterson Field Guide, 1976)], implying that voles eat about 16 grams per day.
- (h) 2.3 km east of the plant.
- (i) 1.9 km northeast of the plant.

The necessary caveats to such a finding are as follows:

- 1) The diet of the meadow vole may be low in the grass that would contain radioiodine.
- 2) The vole thyroid may not absorb radioiodine with as high an efficiency as the human thyroid.
- 3) The assumed proportions of inorganic radioiodine and organic radioiodine (methyl iodide) may not be accurate.

Each of these caveats should be addressed in a complete dosimetry study, but the low values for these preliminary calculations are ironic in that the authors of the vole thyroid paper have been criticized for claiming that they found any radioiodine at all.*

Although the measurements discussed so far are the only ones taken directly on vole thyroids, the results given in the second vole paper are just as important. At the request of the U.S. Fish and Wildlife Service, a vole was trapped on April 25, 1979, at a distance of 0.5 miles east of the TMI reactor. The analysis was conducted at the University of Missouri Research Reactor facility,** where 56 picocuries of radioiodine were found in the body of the vole. Although the measurement is a whole body measurement, it is probable, again assuming that radioiodine works in voles as in humans, that by 4/25 all or almost all radioiodine not eliminated by the vole had made its way to the thyroid. When appropriate adjustments are made to the

*For instance, the Director of the Environmental Protection Agency's TMI field station published a sarcastic letter of criticism about the vole paper in Health Physics, suggesting that the techniques used were faulty and had led to an overestimate of radioiodine, and possibly a completely false signal. See W. P. Kirk, "131I in Thyroids in Meadow Voles near Three Mile Island Nuclear Generating Station," Health Physics 44, 175-177 (1983).

**S. Morris, P. Mehrle, op. cit.

reported number of picocuries, a comparison can be made with the first vole study, with both results referenced to a common date. The necessary radioactive decay correction increases the 56 picocuries to 205 picocuries as of 4/10/79.* This number, while still small, is fifty times greater than the average 4 picocuries of radioiodine found in the first set of measurements. Part of the discrepancy can be explained by the fact that the higher measurement was taken closer to the reactor (at 0.5 miles rather than 1.1 - 1.4 miles). But it is doubtful that meteorology can make up the entire factor of fifty discrepancy.

C3.5 Radioiodine in Rabbits, Goats, and Sheep

In addition to the findings on meadow voles, and to the considerable attention devoted to the study of radioiodine in cows' milk (see below, Section 3.6), a limited amount of data exists on radioiodine in animals such as rabbits and goats. For example, 550 picocuries of radioiodine per gram, referenced to 4/10/79, were found in the thyroids of rabbits trapped at locations 1 to 3 miles northeast of the reactor.** This high number has not yet been analyzed in accordance with the model

*That is, 205 picocuries on 4/10/79 would have decayed to 56 picocuries by 4/25/79. There is a slight ambiguity involving the 4/25 data that has been resolved by communication with Dr. Morris of the University of Missouri Research Reactor facility who analyzed the samples for radioactivity content. To the best of his recollection, the radioactive measurements made by him were corrected for radioactive decay to the 4/25 date of entrapment. (Private communication, 8/15/1983.)

**The actual reading was 160 picocuries per gram on 4/29/79. Adjustment to 4/10 is provided for comparability with the vole measurements in Section C3.4 above. [S. Morris, P. Mehrle, Jr., op. cit.]

presented in Section 3.4, however. A high concentration of radioiodine was also found in goats' milk, (the peak concentration reached 100 picocuries per liter on April 24.)^{*} The fact that the concentration for goats was higher than for cows may be due to different metabolic processes, to different local deposition, or to the fact that goats may have obtained a higher percentage of food from grazing than did cows.

For completeness, it should be noted that some critics of the official studies of the TMI accident have privately pointed to radioiodine measurements in European sheep as potential indicators of a large release from TMI. Although a factor of 1000 reduction in radioiodine signal might be expected 3000 miles west of TMI, it would be closed-minded to reject a causal connection without analysis. Consequently, some modeling work should be carried out on this subject as part of a full dosimetry study.

C3.6 Radioiodine in Cows' Milk

Comparisons of the amount of radioiodine found in cows' milk with model predictions appear to be wildly inconsistent. Some model calculations support the official release. But others indicate that the amount of radioiodine found in cows' milk appears far too high to be consistent with the official release figure, unless farmers blatantly disregarded instructions to keep cattle on stored feed.

^{*}D. Baker, R. Schreckhise, and J. Soldat, "Pathways of Iodine-131 to Milk Following the Three Mile Incident," (Letter Report, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, 1983).

C3.6.1 Review of Three Milk Studies

In the aftermath of the accident, checks were made by two groups to compare milk radioiodine measurements with model projections, assuming a 15 curie radioiodine release. In the first study the model projections were reported to overestimate the measured milk concentrations at three locations by a factor of 10 to 50.* Few details were provided, however. In the second study, projections made for a 15 curie release underestimated the measured milk concentrations. (See Table C-4.) The underestimate was quite large when the radioiodine was assumed to be released as a vapor, but only lower by about a factor of four, on average, when the released radioiodine was assumed to be in the form of a 5-micron particle.** However, in both cases the calculations were performed assuming that 10% of the diet of TMI-area cows was obtained from grazing. This appears to be a highly questionable assumption: the accident did not occur during the grazing season; most farmers in the area rely on stored feed even during the grazing season; and farmers were specifically instructed to keep their cows on stored feed as a result of the accident.*** The next question is inescapable: If cows were on

*The sites were not identified. [Pickard, Lowe and Garrick, Inc. (Report TDR-TMI-116), pp. 5-6.]

**C.D. Berger et al., op.cit.

***In response to a question about compliance with the Pennsylvania Department of Agriculture's recommendation that cows be kept indoors after the accident, Mr. Furrer of the Bureau of Animal Husbandry said:

1. The accident occurred at a time of the year when cows are generally kept indoors on stored feed.

(continued on following page.)

Table C-4

Summary of Results of Berger et al

(Summary of Comparison Between Predicted and Observed Levels
of ^{131}I in Milk Resulting from a 15 Ci ^{131}I Release at TMI Unit 2.)

Compass Direction	Sector	Distance (miles)	Avg. Measured Activity (picocurie per liter)	Max. Measured Activity (picocurie per liter)	Predicted Activity (picocurie per liter)	
					(a)	(b)
NNW	2	9	12.51	18	0.83	3.51
WNW	4	5	1.34	22	0.82	2.01
W	5	15	2.31	16	0.07	0.75
S	9	12.5	1.60	30	0.01	0.11
SE	11	1	21.75	33	1.17	11.64
E	13	2	5.56	23	4.10	5.50

(a) ^{131}I as a vapor.

(b) ^{131}I as a 5-micron particle

stored feed and only 15 curies of radioiodine were released, how did that much radioiodine make its way into cows' milk?

The NRC was evidently interested in this question and commissioned a third, more investigative, study by Battelle Pacific Northwest Laboratory. (We learned of this contract by accident, as a result of the computer search turning up a reference to it. Upon contacting the NRC, we learned that the study had been completed eighteen months earlier, but had "slipped through the cracks" and had not yet been reviewed for release. We were promised that this oversight would be corrected and indeed the study was released in the form of a "letter report" in June of 1983.) This study, by D.A. Baker et al.,* concluded that the major pathway by which radioiodine initially entered milk was inhalation, not grazing. From certain experimental data on the inhalation of radioiodine by cows, Baker and colleagues concluded that the peak amount of radioiodine found in milk

(continued from previous page)

- 2) Those that weren't kept indoors were still fed stored feed under normal end of March conditions.
- 3) In the initial period after the accident, compliance with recommendation that cows be kept indoors was very high. Near 100%. However, farmers were told the results of milk analyses on the first day. As they found out that results of milk contamination analyses were "insignificant," some of them probably left cows outside. (Private communication with Elizabeth Speer, 2/14/1983.)

*D.A. Baker, R.G. Schreckhise, and J.K. Soldat, "Pathways of Iodine-131 to Milk Following the Three Mile Island Incident," (Letter Report to NRC, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, June 1983).

at three sites near radioiodine monitoring stations was not unreasonable given the airborne radioiodine concentration measured at nearby locations. Thus, it was not necessary, according to this study, to assume any grazing took place at all--at least at the sites studied.*

Now if one set of data can be explained assuming an inhalation pathway, calculations assuming a 10% grazing pathway should overpredict by far the amount of radioiodine in milk--as was the case with the Pickard, Lowe and Garrick study. This was certainly not the case with the results of Berger et al., which predicted less than the measured amount. (A summary of the conclusions of the three studies on radioiodine in milk is provided in Table C-5.) Perhaps the explanation for the discrepancy between the results of Berger et al. and other analysts lies in the fact that different analysts have used different milk data. That is to say, more radioiodine may have been released or deposited in certain directions and locations than others. In order to unravel this puzzle, it will obviously be necessary to go back to the raw data to try to make comparisons on the same milk data. This conclusion should also serve to identify the need for developing a unified map of environmental sample sites to be utilized with wind and other appropriate meteorological variables.

*In the past, little quantitative attention has been given to the possibility of inhalation of radioactivity by cows in potential reactor accidents, because the grazing pathway was generally thought to be so much more important. If practices in animal husbandry are changing, however, so that grazing is in general becoming a less important source of food, research practices must change in consonance.

Table C-5

Conclusion of Studies Performed on Radioiodine in Milk
Prior to This Review
(Assuming a 15 Curie Release)

<u>Analysts</u>	<u>Conclusion</u>
Pickard, Lowe and Garrick ^{a),b)}	10% grazing assumption <u>overpredicts</u> radioiodine concentrations in milk at 3 sites by a factor of 10 to 50.
Berger et al ^{a),c)}	10% grazing assumption <u>underpredicts</u> radioiodine concentrations in milk at many sites by a factor of four on average.
Baker et al ^{d)}	initial peak concentrations of radioiodine in milk appear to be consistent with an inhalation pathway and do not require any grazing to explain the results, at least right after the accident.

a) It should be noted that the two grazing - pathway studies may not have considered the same time dependence for the radioiodine release. The Pickard, Lowe and Garrick study assumed a radioiodine release consistent with the radioiodine vent stack measurements discussed earlier. The time dependence assumed in the paper by Berger et al., is not clear. It appears from the text of their paper that the Iodine release rate has been taken proportional to the noble gas release; yet the actual data given in their table, showing the amount of radioisotopes released into each angular sector, does not bear the text out in an obvious way. Perhaps certain correction factors were applied.

b) Pickard, Lowe, Garrick, Inc. "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident," (Report TDR-TMI-116, Revision 0, 1979), pg. 3-3.

c) In this study, calculations were made for both a 15 curie release and a 10,000 curie release of radioiodine. The results for the 15 curie release are reported here. [Berger et al, "Population Dose Estimate from a Hypothetical Release of 2.4×10^6 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station, Unit 2" (Report ORNL/TM-7980, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1981).]

d) D.A. Baker, R.G. Schredkhise, and J.K. Soldat, "Pathways of Iodine-131 to Milk Following the Three Mile Incident", (Letter Report, Pacific Northwest Laboratory Battelle Memorial Institute, Richland, Washington, 1983).

In any case, the data reported by Berger et al. appears to contradict the official release estimate. In order to obtain a rough indication of the magnitude of the discrepancy it is necessary to obtain a value for the amount of radioiodine concentrations in milk, should the pathway to milk be changed to inhalation rather than grazing. As shown in Appendix D, to get the same milk concentration via inhalation of 5-micron particles, 180 times as much radioiodine would have to have been released using the basic model reported in the paper by Berger et al. However, the discrepancy is actually larger. Inspection of Table C-4 (see above) indicates that for 5-micron particles the ingestion model underpredicts in most cases. As stated earlier, the average discrepancy is a factor of four. Thus, to match the measured milk data given in Table C-4, assuming an inhalation pathway, the 180 figure would have to be increased by another factor of four. Consequently, the resulting discrepancy (a factor of 720) is enormous and serves to separate this milk data from all other environmental measurements.

It is interesting to note that the study by Berger et al. was commissioned specifically to calculate the whole-body dose that would be delivered by a 10,000 curie release of radioiodine.* It is quite possible that someone else made the same inhalation pathway analysis as was made in Appendix D and commissioned a

*The study was requested of analysts at Oak Ridge National Laboratory under a Department of Energy contract.

study to check whether or not such a large release would cause any radical change in the total whole-body population dose.

C3.6.2 Reconciliation of High Milk Results with Other Environmental Measurements

There are two ways that a large release of radioiodine could be consistent with other environmental measurements:

- 1) The release could have been inorganic in form, but restricted to wind directions in which other data are missing. Whether this is the case with the measurements of Berger et al. will have to be checked against the raw data. Two of the sites appear to be in similar directions as those chosen for analysis in the paper by Baker et al., but at different distances. In these cases, agreement is closest between the two papers, but a large discrepancy still remains.
- 2) The release could have been in the form of organic iodine, e.g., methyl iodide. In this case, no wind direction restrictions would be required because methyl iodide neither sticks to grass very well nor would it be detected easily by radioiodine monitoring equipment.

In evaluating the methyl iodide hypothesis, it should be noted that essentially no monitoring of airborne methyl iodide took place. Cows would indeed inhale methyl iodide, which in turn would be trapped in the body. However, to enter cows' milk, the methyl iodide in the cows would have to be "hydrolyzed." That does not happen in humans very quickly, but apparently no one has measured the rate at which methyl iodide does enter cows' milk. It is therefore impossible to evaluate the methyl iodide hypothesis properly at the present time. In view of the need to promote the inhalation pathway to at least equal status with ingestion, the necessary background research should be performed.

In any case, the health significance of inhaled methyl iodide would be small. Methyl iodide when inhaled by humans does not get picked up by the thyroid gland. There might be an increase in the whole-body dose but the increase would likely be less than a few thousand person-rem.*

The factor of 720 discrepancy referred to earlier would only apply to methyl iodide, not the inorganic form. There exist other non-inhalation pathways into cows for inorganic radioiodine that have not yet been mentioned. For instance, even cows that were

*This estimate should be checked in a more complete dosimetry study. Berger et al. indicated that 10,000 curies of inorganic radioiodine would contribute 1600 person-rem to the whole-body dose. Although the calculation is somewhat different for methyl iodide (no ground dose but longer body residence time,) a large difference should not result.

In pursuing research on methyl iodide in humans, it would incidentally be of interest to determine whether breathing methyl iodide may be responsible for the metallic taste reported by local residents at the time of the accident.

not grazing on pasture could have ingested deposited inorganic radioiodine by licking or chewing the ground--a practice that is common to cows.* A rough calculation made for this review suggests that a cow might need only to lick 1.5 square feet per day to obtain as much radioactivity as would be inhaled. Thus it does seem possible that the "licking" pathway could be more important than the inhalation pathway. One paper which summarized research on soil ingestion by cattle appeared in the literature as this Appendix was being finalized. The reported measurements indicate that dairy cattle ingest soil in amounts less than 1% of the total dry-matter intake in situations where feeding involves little or no grazing.** Although the result does not precisely indicate the relative amount of radioiodine that would be absorbed by way of the two pathways, it does make it unlikely to expect that a cow could lick enough ground to ingest as much radioactivity as would be ingested from a 10% diet of contaminated grass. However, more research is needed in this area before a definite conclusion can be drawn. For the moment, it would not be unreasonable to hypothesize that the release of inorganic radioiodine implied by the high milk measurements would still be greater than 15 curies even when the soil ingestion pathway is taken into account.

In evaluating the reasonableness of the first, inorganic release hypothesis above, it is extremely important to compare the milk locations of the paper by Berger et al. with the locations

*A second possible pathway might be associated with cows licking their calves. A third possible pathway might be baled hay or other stored feed itself. Baled hay might serve as an efficient filter of airborne radioactivity, especially if it were located outdoors or in a well-ventilated barn. (However, baled hay would not be expected to absorb as much radioiodine per gram as dispersed grass.)

**R. Zach, K.R. Mayoh, "Soil Ingestion by Cattle: A Neglected Pathway," Health Physics 46, 426-431 (1984), p. 429. The percentage of soil ingestion rises to an average of 4-8% when cows are in pasture.

at which grass measurements were made. The compass directions with the highest radioiodine concentrations in milk were NNW, W and S. However, greater precision in these directions will be necessary for comparison with the grass data.

Before attempting to analyze the discrepancies between the papers by Baker et al. and Berger et al., it is necessary to digress for a moment to explain some of the inherent difficulties in the method used by Baker et al.--a method that analyzes the peak radioiodine concentration in milk rather than the average concentration. The ideas behind this highly technical paper are very good, but the authors were forced to rely on inadequate data concerning airborne radioiodine concentrations--variables which enter their calculations in a fundamental way. The only available measurements on airborne radioiodine were taken at stations at least 20° off angle from the farm at which milk measurements were taken. This angular separation appears too great to allow reliable extrapolation.* As discussed in Appendix A, the general alternative to extrapolation is meteorological modeling. However, the one set of meteorological projections of radioiodine concentrations made at TMI are inadequate. As discussed earlier in Section 3.1, projections made for the Pickard, Lowe and Garrick, Inc. study appear to be off by a factor of twelve,** suggesting that meteorological modeling may not

*There appears to be a poor correlation between the airborne radioiodine concentration and the milk radioiodine concentration shown in the paper by Baker et al. It is true that the first peak in airborne radioiodine concentration is followed by a peak in milk radioiodine, but subsequent airborne peaks do not show up in the milk data.

**See Report TDR-TMI-116, op. cit., Table 5-2.

solve the problem in this case.*

Table C-6 compares milk concentrations found at the farms studied by Baker et al. with the farms studied by Berger et al. There are two wind directions that contain sites studied by both. In one case, radioiodine concentrations differ by about a factor of three. The discrepancy would presumably be larger if corrections were made for the different distances of the sites studied by the two groups. In the other case, the concentrations differ by a factor of eight for average concentration, but only a factor of 1.7 in peak concentration. Some of this discrepancy might be explained by the different distances of the sites studied by the two groups. Another possibility to consider is that one of the models used is drastically incorrect. For instance, perhaps the model used by Berger et al. underestimated the deposition of radioiodine.**

*There are other more technical problems with the methodology used by Baker et al. The authors did not have available to them a reliable "response function" that would indicate the time dependence of radioiodine in milk following a brief or "spike" inhalation of radioiodine. In the first part of their paper, they assume that radioiodine would instantaneously enter milk (with subsequent concentration decreasing with a one-day half life). In the second part of their paper they implicitly assume that the response function is shaped so that inhalation, over a few days can be treated as if it were a "spike" input. A more consistent calculation should be made, although it is doubtful that the results would change significantly.

**Underestimation could occur in at least two ways: 1) If terrain heights were neglected, airborne concentration could be underestimated in elevated terrains, and therefore net deposition on the ground would be underestimated. But this would only occur for an elevated release, and it appears that the paper by Berger et al. assumed a ground level release. 2) Deposition velocity used in the calculation might be incorrect. Close in to the plant, higher deposition velocities lead to higher net deposition per square meter, whereas at greater distances a high deposition velocity can lead to reduced net deposition because so much material has been depleted (continued on following page.)

Table C-6

Comparison of Milk Radioiodine Concentrations Used in Two Studies

<u>Analysts^{a)}</u>	<u>Compass Direction</u>	<u>Distance (Mi)</u>	<u>Average Concentration^{b)} (picocurie per liter)</u>	<u>Peak Concentration (picocurie per liter)</u>
Baker et al Berger et al	-- NNW	-- 12.5	-- 12.5	-- 18
Baker et al Berger et al	WNW (294°) WNW	3.5 5	0.6 ^{c)} 1.34	7.4 ^{c)} 22
Baker et al Berger et al	-- W	-- 15	-- 2.31	-- 16
Baker et al Berger et al	-- S	-- 12.5	-- 1.6	-- 30
Baker et al Berger et al	SE (140°) SE	1.6 1	2.8 21.75	20 33
Baker et al Berger et al	-- E	-- 2	-- 5.56	-- 23
Baker et al Berger et al	ENE (65°) --	1.1 --	0.8 --	8.5 --

a) Pickard, Lowe and Garrick, Inc. is not listed because no information is given in Report TRD-TMI-116 concerning the locations of the farms analyzed.

b) 30 day average concentrations for the paper by Baker et al have been taken from the raw data given in their paper. Averages for the paper by Berger et al have been taken directly from their paper. However, the time period for the averaging was not specified. A communication with C. Berger indicated that to the best of her recollection, the averaging period was 30 days.

c) Approximate due to missing data.

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As a check of the Berger et al. model, it would be useful to see how well the model they used would reproduce the airborne radioiodine concentrations at the (8) monitoring stations from which radioiodine data were taken.

At the present time, however, there is no obvious way to decide whether either one of the approaches taken by the different analysts is to be preferred.

C3.7 Resolving the Discrepancies in the Radioiodine Environmental Measurements

The data available on radioiodine appears to be confusing and contradictory. There is a clear need for construction of a detailed map of the TMI area that would indicate the location of every piece of environmental data--grass, air and milk measurements. In addition, the complete set of milk and air time series data must be checked against various hypotheses. Interviews with farmers would help to reconstruct the actual feeding and exercise patterns followed.

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from the plume before arrival at the site that there is little left for deposit. This possibility cannot make too much difference in this case, however, because data have been analyzed by Berger et al. for both nearby sites and sites as far away as 15 miles.

C4.0 Doses from Released Radioiodine

Only two papers were located in the literature that attempted to relate radioiodine releases to thyroid population doses. In one case (Pickard, Lowe and Garrick, Inc.) a 15 curie release was assumed and a 1280 person-rem thyroid dose calculated out to 50 miles.* In the second case (Berger et al.,) a 10,000 curie release was hypothesized and a 90,000 person-rem dose calculated out to 50 miles.** The origin of the 10,000 curie figure is somewhat obscure. The authors did not maintain in their 1981 paper that such a release actually occurred. Instead, they justified their calculation solely as a continuation of work started by the Kemeny Commission (in 1979) on TMI accident sequences that might have occurred had the accident developed differently. No reasons were given for choosing the particular value of 10,000 curies, nor was it explained why a separate calculation was necessary for this release when a simple scaling of the results for 15 curies would ordinarily be sufficient. In any case, even if the 90,000 person-rem figure is taken as purely hypothetical, it can be used to provide a consistency check on the first paper.

Although the two results--1280 and 90,000 thyroid person-rem--appear at first sight, to vary appropriately with the assumed releases, there is a major discrepancy when the results are compared quantitatively. The dose magnitudes are only

* 180 person-rem is the contribution from inhalation, 1,100 person-rem from milk ingestion. [Pickard, Lowe and Garrick, Inc., "Assessment of Offsite Radiation Doses from the Three Mile Island Unit 2 Accident," (Report TDR-TMI-116, Revision), July 1979.)]

** C.D. Berger, B.H. Lane, S.J. Cotte, C.W. Miller, S.R. Glandon, "Population Dose Estimation from a Hypothetical Release of 2.4×10^6 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station, Unit 2," (Report ORNL/TM-7980, Oak Ridge National Laboratory, Oak Ridge Tennessee, Sept. 1981)

in the ratio of 1-to-70, whereas the release magnitudes are in the ratio of 1-to-666. No obvious explanation for this inconsistency is apparent in comparing the models used by the different groups.

However, the paper by Berger et al. was not as precise about the dose pathways that were included in the 90,000 person-rem thyroid calculation as it was about the pathways included in the dose to the whole body. It is possible that the thyroid number was calculated assuming that the dose to humans came from inhalation of airborne radioactivity and not from drinking of milk. A 1-to-70 ratio would then be quite reasonable. Although such an assumption would appear to be inconsistent with the rest of the paper,^{*} the assumption would be consistent with the hypothesis discussed in Section C3.6 that a large release of radioiodine is necessary to explain the high milk data if grazing is rejected as the source of radioiodine in milk. To check the possibility that the 90,000 figure was indeed an inhalation calculation, a number of intercomparisons were made, as part of this dosimetry review, to test for consistency. The internal evidence supports the inhalation conjecture.^{**}

*e.g., It is stated on page 3 of the paper by Berger et al. that ingestion was included in the collective population dose calculation.

**The first piece of evidence is that the 180 person-rem inhalation dose calculated in the first paper scales to 120,000 person-rem (which is very close to 90,000) when multiplied by the 1-to-666 release ratio. The second piece of evidence is less direct, but just as relevant. The authors (Berger et al.) reported a figure for the whole-body population dose calculated for the released radioiodine (1600 person-rem) as well as reporting 90,000 person-rem for the thyroid dose. The 56-to-1 ratio for these numbers appeared low based on radioiodine studies carried out in the past by the principal investigator (Beyea). Therefore, a simple relative calculation was made from first principles, relating the thyroid dose from inhaled radioiodine to the whole-body dose from radioiodine deposited on the ground. Ignoring the milk pathway, the results indicated that the thyroid dose should have been 78

On the other hand, the possibility that a large radioiodine release might actually have occurred was never discussed in the paper. As stated earlier, the authors never maintained that anything but the official 15-curie release took place. According to their paper, they addressed the alternate accident sequence problem at the request of personnel from Los Alamos National Laboratory and Sandia Laboratory. Perhaps, these individuals were aware that a 10,000 curie release might be consistent with the milk data and, if so, that the resulting thyroid dose should be calculated assuming inhalation only. If no one was aware of this possibility, it is rather a remarkable coincidence that the internal evidence in the paper suggests a sophisticated knowledge of both the release magnitude necessary to explain the high milk data* and the pathway to humans that would be appropriate to use for dose calculations.

In any case, whether by accident or not, it appears that a calculation exists in the literature that can be used to assign

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times higher than the dose to the whole-body (assuming a deposition velocity of 0.01 m/sec., as was assumed in the paper by Berger et al., and a ground shielding factor of 0.33).

Consequently, it is difficult to see how only a 56-to-1 ratio could have been calculated by the authors if the milk pathway were actually included. Furthermore, evidence is available that it is the 90,000 person-rem thyroid number that is inconsistent rather than the whole-body number. In fact, the whole-body number can be used to correctly predict the thyroid inhalation dose given in the Pickard, Lowe and Garrick, Inc. paper. (1600 person-rem times an inhalation/whole-body ratio of 78 to 1 implies an inhalation dose of 125,000 person-rem for every 10,000 curies released. For 15 curies released the prediction would be 199 person-rem, a value which is quite close to the inhalation number given by Pickard Lowe and Garrick of 180 person-rem.)

*As discussed in Section 3.6, a release 720 times 15 curies, or 10,800 curies, would lead to sufficient radioiodine in milk to explain the data.

a thyroid dose (90,000 person-rem) to the release hypothesis discussed in Section C3.6. However, until further discussion of these matters can be held with the various researchers who have made thyroid dose calculations (perhaps at the proposed dosimetry workshop), it would be premature to make any definitive statements. Consequently, discussion of thyroid dose has been confined to this section and not mentioned in the main report.

It should be noted that the paper by Berger et al. concluded that 90,000 person-rem would cause less than one case of thyroid disease (0.36 cases to be precise). However, this conclusion appears to be based on an incorrect interpretation of the dose-effects coefficient used to make the calculation (four cases per million exposed persons per year per rem). The 0.36 number, which equals $4 \times 10^{-6} \times 9 \times 10^4$, is in reality the number of cases per year, not the total number of cases. To calculate the total number expected over the life of the exposed population, it would be necessary to multiply 0.36 by an appropriate "plateau" period--possibly 20 to 30 years. Discussion of this calculation would be warranted at the proposed dosimetry workshop.

Appendix D

Quantitative Comparison of Inhalation and
Ingestion Pathways in Cows

TECHNICAL APPENDIX

This technical appendix provides an estimate of the ratio between the amount of radioiodine entering cows' milk via ingestion of vegetation and the amount of radioiodine entering cows' milk via inhalation. The advantage of computing a ratio is that it is independent of location and the airborne concentration of radioiodine.

The first step in the calculation involves determining the ratio between the number of curies ingested by a cow and the number of curies inhaled. Table D-1 shows the results for a particle with deposition velocity of 0.01 meters/second. Tables D-2 and D-3 outline the terms that enter the calculation.

The next step in the calculation involves deciding whether inhaled radioiodine is less likely, more likely, or just as likely to enter milk as ingested radioiodine. Based on a discussion with Frances Kallfelz of the Large Animal Clinic at Cornell University's Veterinary College, it is assumed that the amount of radioiodine breathed is as likely to end up in milk as if it were ingested.* Experimental evidence has been located that supports this statement.**

*Private communication, 2/9/1983

**As reported in the paper by Baker et al. (See Bibliography), Voilleque found that inhalation of 0.74 microcuries of radioiodine over a half hour period led to a peak milk concentration (continued on next page of text.)

Table D-1

Ratio of Curies Ingested to Curies Inhaled for Cows Obtaining
10% of Their Food from Grazing

$$\text{Ratio for "5-micron" particle} = 18000 v_d^a = 180^b)$$

a) As shown in Table D-2. v_d is the assumed deposition velocity.

b) Deposition velocity of 0.01 meters per second is assigned to a 5 micron particle in the paper by Berger et al. (Berger et al, "Population Dose Estimate from a Hypothetical Release of 2.4×10^6 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station, Unit 2" (Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/TM-7980, (September 1981)7.

Table D-2

Factors Involved in Calculating the Ratio of Curies Ingested by Cows to Curies Inhaled by Cows (for Cows Obtaining 10% of their Food from Grazing)^{a)}

$$\text{Desired Ratio} = \frac{\text{Curies ingested as calculated in Table D-3}}{\text{Curies inhaled } ^b)}$$

$$\frac{24V_d X}{bX} = \frac{24V_d}{b} = 18,000V_d$$

where b = cow breathing rate which we take to be .0014 cubic meters/second^{c)}

V_d = deposition velocity in meters/second

X = integrated air concentration in units of curies per cubic meter multiplied by exposure time.

- a) Assuming a burst release of radioactivity rather than a continuous release. The ratio would change slightly for a continuous release.
- b) The number of curies inhaled is simply equal to the breathing rate multiplied by the airborne concentration multiplied by the exposure time.
- c) Based on relative metabolic rates calculated by taking the ratio of weights to the 3/4 power, i.e.

$$\left[\frac{650 \text{ kg (weight of average dairy cow)}}{70 \text{ kg (weight of average human)}} \right]^{3/4}$$

(Private communication from Francis Kallfelz, Veterinary College, Cornell University, 2/9/1983.) The breathing rate for humans has been taken to be 2.7×10^{-4} meters/second. (U.S. NRC, Reactor Safety Study.)

Table D-3

Calculation of Curies Ingested by Cows Using Parameters in
Paper by Berger et al (10% of Cows' Food Coming from Grazing)

The amount of radioiodine deposited per square meter (X = integrated air concentration in units of curie-seconds per square meter) (V _d = deposition velocity in units of meter/second)	V _d X
Fraction of curies deposited on grass	0.57 ^{a)}
Amount of kilograms of grass per square meter	0.28 ^{a)}
(Dry) kilograms of grass ingested by cow per day	15.6 ^{a)}
(Dry) kilograms of forage assumed ingested per day at TMI in paper by Berger et al	1.56 ^{a)}

Curies ingested in first day:

$$\frac{1.56 \times 0.57 \times V_d X}{0.28} = 3.2 V_d X$$

$$\begin{aligned} \text{Total curies ingested in all days}^b &= 7.6 \times 3.2 V_d X \\ &= 24 V_d X \end{aligned}$$

a) From Appendix B of C.D. Berger, B.H. Lane, S.J. Cotter, C.W. Miller, S.R. Glandon "Population Dose Estimates from a Hypothetical Release of 2.4×10^6 Curies of Noble Gases and 1×10^4 Curies of ^{131}I at the Three Mile Island Nuclear Station, Unit 2". (Report ORNL/TM-7980, Oak Ridge National Laboratory, Oak Ridge, TN, September, 1981.)

b) 7.5 days is the combined environmental meanlife of the Iodine 131 (Radioactive meanlife = 11.5 days; weathering meanlife = 20 days according to paper by Berger et al.)

Having made the assumption that the same proportion of radioiodine inhaled or ingested enters cows' milk, the ratio of 180 given in Table D-1 can be applied directly to determine the ratio of radioiodine in milk for the two pathways, i.e., a cow obtaining 10% of its food from nearby grass contaminated with radioiodine is projected to end up with 180 times more radioiodine in its milk than it would if it only breathed radioiodine. Obviously to make a calculation of this sort, numerical values for a number of parameters must be chosen. To be consistent with the use to which the calculations have been put in Appendix C, the parameters have been matched with the paper by Berger et al. whenever possible.

(continued from last page of text)

of 1400 picocuries per liter, decaying thereafter with a two and one half day half life. Assuming that the rise time before the peak is one day, the total radioiodine leaving the cow in the form of milk is .066 microcuries, or 0.8% per liter of the ingested quantity. This percentage is very close to the 1% per liter measured for ingestion. USNRC, Reactor Safety Study, 1975, Figure VI-E-8. However, no information about particle size for the radioiodine used in the experiment by Voilleque was available. Conceivably, the results might not hold for all particle size cases.

Appendix E

Radioiodine Releases from the Secondary Loop During the TMI-2 Reactor Accident

In investigations of the TMI-2 accident, little or no attention has been given to the possibility of radioiodine emissions from the secondary side of the reactor. This appendix, produced by Dr. Thilo Koch, considers how a model developed and utilized in Germany may be adapted for use in further TMI investigations when the necessary additional data has been collected.

Progress Report
to the
Three Mile Island Public Health Fund

Subcontract on

Radioiodine Releases from the Secondary Loop
During the TMI-2 Reactor Accident

An investigation into the possibility of gaining
quantitative information on radioiodine releases
from the TMI-2 secondary loop

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May 6th, 1983

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Introduction

Due to the high chemical and biological activity of iodine, releases of radioiodine from a nuclear power plant may constitute a major public health risk. The radioiodine releases to the environment during the TMI-2 accident therefore need to be closely investigated.

Before dose assessment can be accomplished, the following questions require answers:

1. How much radioiodine (iodine 131 and iodine 129) was released?
2. When were the iodine isotopes released?
3. What release pathways contributed significantly to the total amount released?

In terms of question three, a number of release pathways for radioiodine have so far been considered in some detail. Data records and follow-up inquiries indicate that secondary cooling loop emissions of radioiodine and perhaps other relevant radionuclides should be included in the investigation on the adequacy of the TMI dosimetry.

Having dealt with secondary cooling loop emissions of German PWRs in the course of an elaborate research study financed by the Federal Department of Research and Technology, we were asked to investigate whether or not quantitative information on radioiodine releases from the TMI-2-secondary cooling loop could be developed.

On the basis on the NSAC-30 Report on Radioiodine and the Rogovin Report, Vol. II, part 2, we have attempted to define the problems involved with the quantification of secondary loop emissions during the accident.

Before going into the details, it should be noted, that the complexity of the secondary loop necessitates the use of a computer simulation code, derived from a refined and detailed secondary circuit model, if a somewhat accurate analysis of the secondary loop emission is desired. Whether a detailed analysis is desirable or not, depends on the significance of this release path as com-

accurately known, the significance of secondary loop emissions may be based on rough estimates.

In the above mentioned IFEU-study the detailed computer simulation code SEKEM 4 was developed and successfully tested for the German KWU-Biblis B powerplant. Principally the variability of SEKEM 4 allows for the computer code to be applied to the TMI-2 secondary loop.

In the following sections of this study we will attempt to point out: (1) what data is basic for a rough estimate on radioiodine releases from the secondary loop; and: (2) also what programming effort is needed to apply the SEKEM 4-code to the TMI-2 secondary loop.

There are four factors that essentially determine the quantity of secondary loop emissions of radioiodine:

1. primary loop concentration
2. steam generator (SG) leakage
3. decontamination factors in both the primary and the secondary circuit
4. mass flow rates in the secondary circuit

Accordingly the four following sections shall point out the problems of obtaining rough estimates and the feasibility of a detailed analysis.

1. Quantification of primary loop radioiodine concentrations

In order to derive at secondary loop releases, the specific activity of radioiodine or its concentration in the primary coolant must be known. Under normal operation conditions, this poses no great problem, since the radioiodine content inside the fuel rods may be calculated using the ORIGEN-code, and the primary coolant concentration is usually calculated as an equilibrium value assuming 1% fuel rod leakage.

As the Rogovin Report illustrates, the reactor cooling system (RCS) behaved much differently during the accident, and with respect to the specific activity of radioiodine the following problems need to be resolved:

1. There was a reactor scram, and the fission induced production of radioiodine within the fuel ceased, altering the equilibrium source-term conditions. Furthermore the RCS underwent numerous and drastic pressure and temperature gradients (spikes) which influenced the fuel rod leakage. Spiking factors of 50 to 100 for I-131 during power ramps in other PWR were observed. The fuel damage finally caused an additional activity spike by several orders of magnitude.

We therefore found an irregularly spiked time-dependent radioiodine input function into the reactor coolant water and steam, with a marked jump after approx. 3 hours into the accident. When heavy fuel damage occurred, the release of radioiodine was no longer diluted to the fluent water coolant but to the gas and steam bubble.

2. Parallel to the time-dependent fuel rod input functions, the rapid changes in mass flow (let-down, make-up and coolant flowed through the stuck open PORV) prohibited equilibration of radioiodine in the RCS. Therefore the specific activity of radioiodine varied not only in time but also in space during the accident. To assume a primary steam generator concentration equal to that in the reactor coolant is

tenuous at best and leads to an overestimation of the secondary loop releases.

3. Considering the specific radioiodine activity entering the SG it must be kept in mind, that for longer periods of time the RCPs were not running, mass flow through the OTSGs was low, with considerable amounts in a steam phase, thereby changing the leakage characteristics of the SGs. On the basis of the information at hand, it does not seem feasible to derive a sound time dependent radioiodine concentration inside the OTSGs. Moreover it is doubtful whether this is possible even on the basis of accident data records.

In terms of a rough estimate, one would perhaps assume the following: The coolant Iodine-131 concentration equals approx. 10^4 $\mu\text{Ci/ml}$ on 3/29/79, according to NSAC/30, throughout the primary loop (ignoring space and time variations).

Without having seen the available data records, it is impossible to give a fairly good estimation error range. To be on the safe side at least one order of magnitude should be envisaged.

Regarding the applicability of the SEKEM 4 code, we may either use a time-constant radioiodine concentration of the primary coolant and neglect all steam phase phenomena, or a time-dependent concentration function. In both cases thorough analysis of the data records is required.

2. Quantification of steam generator leakages

The second basic parameter to be quantified is the steam generator leakage. Under normal operation, implying a small leak rate, the leakage may be calculated back from main steam and measurements of radioiodine concentrations in the demineralizer. This calculation assumes a certain pressure and temperature dependent decontamination factor in the SG and, of course, the mass-fluxes. Large leakages should lead to a scram and may be calculated by comparison of the pressure history in both the primary and the secondary SG-volumes.

Taking the TMI-2 accident into account, the following problems arise:

1. The pressure and temperature history of both the primary and the secondary SG-volumes need to be known in order to derive the leak-rate governing differential pressure across the SG-tubing.
2. The leak rate alters with a change in fluid dynamics, e.i. a change in coolant phase. Both SGs boiled dry repeatedly with the water level changing over the whole length of the SG-tubes (presumably leaving the leak uncovered with water). As stated in the first section, primary coolant circulation was irregular, natural circulation did not occur until late into the accident. Additionally the hot leg was repeatedly superheated and the SG-tubes were filled with steam for some time.
3. Only insufficient measurements of radioiodine activity in the secondary loop are reported. To be correlated with the time-dependent pressure difference, the measurements seem to have been too few and at the wrong place (no steamline measurements are mentioned in the reports).

Even though the time-dependent pressure difference of the SG tubing eventually may be derived from available data re-

cords, the rapid changes in the coolant phase altering the fluid dynamics, coupled with the lack of reliable information on the radioiodine activity in the main steam, make it a difficult task to estimate the time-dependent leak rate of OTSG B.*

An estimation of an average leak rate for OTSG B on the basis of the two reports is not feasible for us at the moment.

Provided a time dependent leak rate could be established, some adjustments in the computer code SEKEM 4 would be necessary and feasible.

* OTSG A is said to have been tight although there is no reliable proof of this assumption in the reports.

3. Quantification of radioiodine decontamination factors

A thorough evaluation of secondary loop releases of radioiodine must take into account the prevailing iodine decontamination factors (DF) in both the primary and secondary loop. Since decontamination factors are a function of the time-dependent pressure and temperature, they too become time-dependent.

The IFEU-study on secondary loop emissions includes a theoretical model on phase distribution and decontamination factors, which shows that the DF depends on two distribution factors: the mass distribution factor, which gives the quantity of steam or water as a fraction of the total massflow, and: the activity distribution factor, which gives the quantity of a certain nuclide in the steam phase as opposed to the liquid phase. The first factor is closely related to the so-called "residual moisture" and is highly dependent on pressure, temperature and humidity. The second factor is determined by the chemical and physical properties of the nuclides.

Obviously it will take some careful study of the data records to develop the pressure and temperature history and to derive from it, estimates of the "residual moisture" necessary to quantify the DF. As the DF-values range from 1 to 10^4 , secondary loop releases may easily be over- or underestimated. For conservatism the DF in the primary loop may be set equal to 1, implying that there was no decontamination between the liquid and gas phase, and in the SG equal to $10 \pm 100\%$ to account for the possibility of dehumidification processes.

With respect to the DF, application of the SEKEM 4 code poses no problem. Although the code normally calculates the DF at different parts of the circuit, present values may be easily inserted.

4. Secondary loop circuitry and quantification of mass-flows

The radioactivity in the primary and secondary loop is carried along by the coolant-water or steam. Under normal operating conditions, a high-mass flow of the primary coolant guarantees good mixing and quick equilibration of the radioactivity from the fuelrods. High massflow within the secondary loop leads to higher releases of steam from the high pressure drainage depressurizer and the degassing of the feedwater tank. High steam releases are identical with high releases of radioactivity in case of SG leakages. In order to determine steam releases, the mass-flow rates in the secondary loop must be known (mass flow rates in the main steam lines, feedwater line, condenser and hotwell etc.).

During accident conditions with a scram and turbine trip, the SGs are used as main heat sinks. With a turbine trip, the main steam is directly bypassed to the condenser. If the condenser is not operating, steam can be released to the atmosphere through the atmospheric dump valves.

Since mass-flow data are not directly available, they must be reconstructed on the basis of the data records. The following problems need to be especially considered:

1. Is the evidence, that only OTSG B was leaking, conclusive?
2. Both steam generators boiled dry, with the OTSG A boiling dry twice. Did this affect any steam releases from the high pressure system and/ or the feedwater degassing?
3. Two periods of atmospheric steam-dump can be recognized (Color Plate III, Rogovin Report Vol. II), the first lasting two hours, the second nearly five hours.

How much steam was released during the atmospheric steam-dump?

Reconstruction of the steam-dump may be possible, if the combined information on feedwater input and secondary side water level is carefully analyzed.

4. What is the feedwater input history of both steam generators?
5. At what time did the leak in SG B occur? The analysis of the charcoal cartridges of HP-R-219 does not provide this important information since the sampling time was too long. In fact, a considerable radioiodine release during the first 18 hours due to atmospheric steam dumping could not have been registered by the HP-R-219 monitor located in the TMI-2 stack, and would even have reduced the concentration results of the first sampling period.

Although the accidents progress is well described in the Rogovin Report, it does not answer the above questions and mass-flow rates cannot be deduced. A steam generator mass balance between feedwater input and mainsteam output (either to the condenser or through the atmospheric dump valve) cannot be undertaken on the basis of the reports at hand. Furthermore the significance of steam releases during condenser operation cannot be concluded without some knowledge of the time-dependent circuitry and mass-flow rates.

Great attention must be paid to the atmospheric steam dump (see next section). In attempting a rough estimate for the SG B steam dump during the first dumping period, we would calculate a low release of 8 000 kg of steam, coolant capacity of 25 000 gal and a temperature of approx. 550° F, assuming a boiling dry of SG B with a 5% operating range. The actual steam release could have been much higher but even for a rough estimate more detailed studies are necessary.

In respect to the SEKEM 4 code we see no real problem in applying the code to the TMI-2 block.

5. The Quantification of secondary loop radioiodine concentrations

Given the primary circuit concentration, the leak-rate of the steam generator, the decontamination factors and the mass flows, the secondary loop concentration can be calculated by employing the SEKEM 4 code.

According to the NSAC 30 Report, iodine 131 was measured in secondary liquids and the condenser off-gas-monitor indicated that OTSG A was "tight" (having concentrations of less than 3×10^{-3} $\mu\text{Ci I 131/ml}$) and the OTSG B was leaking, (having concentrations ranging from 2.2 to 7.9 $\mu\text{Ci I 131/ml}$). The report does not say where the liquid samples were taken and what kind of analysis was done. It is concluded that the activity in the secondary liquids was 440 Curies and the concentrations was 4.0 $\mu\text{Ci/ml}$, taking about 95 % of the capacity of the secondary side e.i. 25 000 gal into account.

The rise of the radiation level detected by the condenser-off-gas-monitor is believed to have been caused by a 7 second opening of the OTSG B to the rest of the secondary loop, leading to a sharp rise from background level and a gradual decrease. Although the samples of the secondary liquids were measured two days after the accident, the difference in radioiodine concentrations in OTSG A and OTSG B strongly indicates that there was no substantial leakage of OTSG A. On the basis of these measurements it could be concluded that the total I 131 activity in the secondary loop was 440 Curies trapped in the steam generator B, thus defining an upper limit to secondary loop releases. Compared to the measured I 131 inventory of the various water tanks of a total of 2.3 million Curies, 440 Curies in OTSG B seem negligible. But assuming only a 10 % release of the secondary loop inventory, this is nearly three times the 15 Curies of iodine supposed to have escaped the reactor (NSAC 30); and even a 1 % release of the 440 Curie secondary loop activity would still amount to a 30 % increase of above the 15 Curies radioiodine release.

Using the low rough estimate of 8 000 kg released during the first atmospheric steam dump of SG B (see section 4) and assuming a steam concentration of 4 $\mu\text{Ci/ml}$, a radioiodine release of 32 Curie can be arrived at , which is double the total I 131 release assumed in the Rogovin Report.

These figures should be understood in a more qualitative way. Under realistic assumptions the secondary loop releases of radioiodine may be of the same order of magnitude as the total releases taken into account, without considering the secondary loop.

With appropriate data, the SEKEM 4 code could calculate how much of the 440 Curie I 131 secondary inventory was finally released to the environment.

6. Conclusion

In the event of an accident, all factors, relative to the quantification of secondary loop releases of radioiodine, are time-dependent and vary at different locations in both the primary and the secondary loop. A calculation of secondary loop releases on the basis of the Rogovin Report (Vol. II, Part 2) and the NSAC 30 Report alone does not seem feasible. Data records during the accident and follow-up studies must be carefully analyzed in order to develop convincing quantitative information. On the basis of already developed time-dependent functions, the IFEU-computer code SEKEM 4 may be utilized for a sound determination of the TMI-2 accident secondary loop releases of radioiodine. Although some program adjustments will be necessary in order to model the TMI-2 facility correctly, from the present outlook, no principal difficulties should arise.

Secondary loop releases of radioiodine have so far been neglected, seriously underestimating the significant contribution of those releases. In fact rough estimates on the basis of the Rogovin Report and the NSAC 30 Report show that the secondary loop releases may be of the same order of magnitude as the total releases that have so far been officially reported. Furthermore, many other radionuclides endangering human health also need to be considered in terms of secondary loop emissions, if the TMI accident dosimetry is to be accurately reconstructed.

Appendix F

A Review of the Cleanup
of Three Mile Island Unit 2

Readers should note that this appendix was completed before the NRC revised upward its estimate of the occupational radiation exposure that will result from the cleanup.* Although it was anticipated that the NRC would increase its 2,000 to 8,000 person-rem estimate, the six-fold increase (to 13,000 to 46,000 person-rem) was more than expected.

* Supplement to the NRC's Programmatic Environmental Impact Statement (Report NUREG 0683, Supplement #1, December 1983).

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A Review of the Cleanup
of Three Mile Island Unit 2

by

Gordon Thompson

assisted by

Howard Gold

10 May 1983

A report submitted to Jan Beyea, agent for the
Three Mile Island Public Health Fund Advisory Board.

1. Introduction/Summary

The purpose of this review was to determine the public health significance of actual and potential events associated with the cleanup, so as to assist the board in its allocation of research budgets.

Based on an extensive review of relevant documents, we have selected subjects which warrant more extensive study. None of these items appears to have major public health implications, except for some potential severe accidents. One subject (disposal of processed water) has socio-economic and psychological stress implications.

The body of this report is supported by four appendices, addressing: major documents, cleanup schedule, occupational exposures, and offsite waste shipments.

2. The Investigators

The principal investigator for this review was Gordon Thompson, consultant in energy, environment, and international security issues.

Research assistance was provided by Howard Gold, who is completing a graduate program in Urban and Environmental Policy at Tufts University. Gold has served as a consultant to firms doing work on hazardous and low-level radioactive waste management, and energy policy analysis.

3. Documents Reviewed

A sequential list of the major relevant documents is given in Appendix A. Of these documents, the most comprehensive is the NRC's Programmatic Environmental Impact Statement (PEIS), issued in March 1981.⁽¹⁾

An additional key source is the series of weekly reports issued by the NRC's TMI Program Office. Unless referenced otherwise, data cited in our review have been taken from these weekly reports.

4. Cleanup Schedule

A comparison of the projected and achieved schedules is provided in Appendix B. Without the devotion of considerably greater effort, it was not possible to estimate the degree of completion of the various ongoing tasks. However, based on the completed milestones, it seems that the schedule projected in the PEIS (see Figure B.1) was not grossly in error.

It should be noted that contaminated areas in the auxiliary building and in the reactor building have been bypassed (see later discussion of shielding in the reactor building). Decontamination of these areas may present difficulties in the future. The director of the NRC's TMI Program Office has pointed out that radioactivity tends to "soak into" concrete surfaces and to bond to corrosion layers on metal surfaces ⁽²⁾.

The schedule for removal of the reactor vessel head has been delayed due to two circumstances:

- * high radiation levels under the head may prevent the previously envisaged "dry" head lift
- * NRC has disapproved the licensee's procedures for load testing and operation of the polar crane (see our later discussion of alleged unsafe practices).

5. Occupational Exposures

The PEIS projected a cumulative dose of between 2000 and 8000 person-rem for the entire cleanup, with the greatest exposure for any cleanup phase occurring during decontamination of the reactor building.

Appendix C provides a comparison of projected and actual worker exposures. As for the overall cleanup schedule, it was not possible for us to estimate the degree to which actual experience has matched the projections. However, it does appear that doses will exceed 2000 person-rem. From May 1st, 1979, to the end of 1982, workers at TMI-2 accumulated 1258 person-rem of exposure.

Exposures at TMI appear to have been lower than at typical operating nuclear plants. For 1981, NRC data show 201 person-rem at TMI-1 and 146 person-rem at TMI-2, compared with 779 person-rem at the average operating LWR (see Appendix C).

According to GPU, almost 5 million person-hours of labor have been expended at TMI-2 from 1980 through 1982, with no employee receiving more than 5 rem per year (compared to four such exposures at the average PWR) ⁽³⁾.

Inside the reactor building, a shielding program was initiated early this year, to reduce worker exposures (see Appendix C). Although this has been effective in the short run, the radioactivity must be removed eventually (see our previous discussion on the effect of delay).

6. Environmental Monitoring

NRC operates an on-site continuous air sampler and publishes weekly results for the concentrations of I-131 and Cs-137. These have typically been less than 8×10^{-14} microcurie/cc.

NRC also operates a TLD direct monitoring network, at 59 off-site locations. Two sets of TLD's are placed at each location. Each set contains two lithium borate and two calcium sulfate phosphors. Both sets are read on a quarterly basis (Prior to July 1, 1981 the TLD change frequency was monthly). Readings have consistently indicated levels which are not above natural background.

The licensee operates a monitoring program, as described in the PEIS (Chapter 11). This includes an on-site groundwater monitoring program, using wells as shown in Figure 1.

Periodic sampling of TMI groundwater began in January 1980, in an effort to detect any potential leakage from the contaminated water in the basement of the reactor building. Such leakage has not been detected. The program did identify some groundwater contamination which was attributed to

leakage from the borated water storage tank (BWST).

Pre-TMI monitoring data suggest that surface water, drinking water, and precipitation in the TMI area will normally contain an average of 300 picocurie/l of tritium (with values as high as 600pCi/l within the expected range). The highest TMI groundwater contamination was recorded in test boring 17 on March 23, 1982, with tritium at a level of 1.1 million picocurie/l. This can be compared with the maximum permissible concentrations of 3 million picocurie/l in unrestricted areas, and 20,000 picocurie/l in drinking water.

Although tritium is the predominant radioisotope detected in the groundwater, sporadic trace levels of radioactive cesium (Cs-134 and Cs-137) have been detected in test boring 2. On June 1, 1982, 11 picocurie/l of antimony-125 was detected in test boring 17 (concentration was reported to be just above the lower limit of detection). Subsequent samples from this boring did not show detectable antimony.

EPA operates an extensive monitoring system, as described in the PEIS (Chapter 11). Radiation has generally been at background levels except during periods of krypton venting.

DOE, the Commonwealth of Pennsylvania, the State of Maryland, and a number of local communities operate a variety of monitoring systems, also described in Chapter 11 of the PEIS.

During the krypton venting in June and July, 1980, it appears that official monitoring may have been deficient. The group, Accord Research and Educational Associates Inc., by measuring Sr-90 to Kr-85 ratios in the plume at (moving) points of high concentration, estimated that 7 millicuries of Sr-90 and 20 millicuries of Cs-137 were released during the venting.⁽⁴⁾ EPA air sampling evidently relied on fixed sample points. Incidentally, these estimated releases are much greater than those shown in the PEIS (Table 10.1),

which indicates atmospheric releases during decontamination of the reactor building at 5 microcuries of Sr-90 and 80 microcuries of Cs-137.

7. Off-site Radioactive Waste Shipments

It was feared at one time that the TMI site would become a long-term interim storage site for various radioactive wastes which could not meet regulations for shallow land burial. DOE has now agreed to take these wastes, in the form of demineralizer resins, damaged fuel, and fuel debris, for research and development purposes.

Appendix D provides a comparison of projected and actual shipments. As for other areas of our review, it was not possible to accurately compare projections and achievements. It appears, however, that the natures and numbers of shipments are generally falling within the bounds laid out in the PEIS.

The fate of this material, while in DOE hands, is a matter deserving of further consideration.

8. Disposal of Processed Water

At the conclusion of the cleanup, when all contaminated water has been processed, there will probably remain about 1.5 million gallons of water containing radionuclides as shown in Table 1.

The PEIS devoted considerable attention to various options for disposing of this tritium-contaminated water. Table 2 summarizes those options, with the NRC's estimate of off-site doses in some instances.

As for the krypton venting, it can be expected that there will be public concern about disposal options involving releases to the local environment. It will be recalled that the city of Lancaster and the Susquehanna Valley Alliance went to court to prevent the licensee from commencing the discharge of this water to the Susquehanna river in 1979.

Even if the NRC's estimate of 30 person-rem of exposure (see Table 2) for local releases is correct, there may be

significant socio-economic effects and psychological stress. Economic effects on Chesapeake Bay fisheries deserve particular consideration.

For completeness, it should be pointed out that the Savannah River Plant typically releases about 350 thousand Curies of tritium annually. ⁽⁵⁾

9. Potential Accidents

While substantial quantities of radioactivity remain on site, there are possible accident scenarios whereby a release of major public health significance could occur.

Perhaps the most serious of these scenarios are those involving criticality, fire, or loss of water from the primary circuit or refuelling canal, during the defuelling operation. As Snyder (NRC) has pointed out, such events have a small, but non-zero, probability ⁽²⁾.

In the context of atmospheric releases from such accidents, it is worth noting that the present practice is to leave the reactor building doors open during personnel entries.

In May, 1982, a health physics technician was unable to leave the building due to jamming of airlock doors (freeing the doors took nearly an hour). Procedures have now been modified so that the personnel airlock in the equipment hatch is used for ingress, while both doors of the other airlock will be kept open during building entries, in order to expedite worker egress.

It is intended to keep both airlocks open during future entries, as the tempo of work increases. The potential of this practice to lead to atmospheric releases of radioactivity during accidents deserves further consideration. That potential would be even more significant if the equipment hatch were opened, as might be envisaged at some stage of defuelling and primary circuit decortamination.

Warning has been given to the NRC of the dangers associated with the possible existence of zirconium hydrides in the core region (and perhaps elsewhere in the primary circuit) ^(6,7).

These hydrides, in powder form, may react violently with air. Although the NRC regards such an event as unlikely (see page 13-80 of the PEIS), this matter also deserves further consideration.

10. Allegations of Unsafe Practices

Beginning in March this year, there have been various press reports about such allegations made by existing and past employees of the licensee. A hearing was held before the Subcommittee on Energy and Environment, House Interior and Insular Affairs Committee, on April 26th.

The most serious allegations concerned load testing and operation of the polar crane in the reactor building. This matter is relevant to our previous discussion of potential accidents because the dropping of a heavy load (eg the pressure vessel head) could initiate an accident.

Based on the limited review we have undertaken, it is not possible to pass judgement on the safety of current practices.

11. Recommendations for Further Study

The major task which we recommend can best be described as oversight. We propose that a single individual should become familiar with the cleanup and follow a number of its elements. In addition, we recommend two lesser tasks: reviews of the disposal of processed water, and of the disposition of high-active wastes by DOE.

The tasks would be as follows:

(i) Oversight

The investigator should follow, over a number of years, the cleanup in all its on-site manifestations. Special attention should be paid to:

- * schedule
- * occupational exposures
- * potential accidents

- * unsafe practices
- * environmental monitoring, both on and off-site.
- * tendencies to ignore future problems (eg bypassed contamination, sludge in the reactor building basement)
- * waste shipments.

This oversight function should, ideally, remain effective until all wastes are removed from the site and decontamination is complete.

(ii) Review of Disposal Options for Processed Water

This investigator should independently review the PEIS, and other, options for disposal of this water. The experience of the krypton venting should be examined for points of guidance.

(iii) Review of DOE's Disposition of TMI-2 Wastes

These wastes will constitute a potential public health hazard even when they have all been transferred to DOE. Therefore, an investigator should follow DOE's management of these wastes. That effort will also yield a more general benefit, because management of other DOE-controlled wastes will receive public oversight in the process of following TMI-2 wastes.

12. Notes

- (1) "Final Programmatic Environmental Impact Statement related to decontamination and disposal of radioactive wastes resulting from the March 28, 1979, accident at Three Mile Island Nuclear Station, Unit 2", NRC report NUREG-0683 (2 Vols) March 1981
- (2) Bernard J. Snyder, Director of TMI Program Office (NRC), "Status of the TMI-2 Cleanup", testimony to the U.S. Senate Committee on Environment and Public Works, 20 May 1982

- (3) Herman Dieckamp, President of GPU Nuclear, testimony to Subcommittee on Energy and the Environment, House Interior and Insular Affairs Committee, as reported in Nucleonics Week, 28 April 1983, pp 4-5.
- (4) J. Harvey, R.C. Piccione, and D.M. Pisello, "Measurement of Strontium-90 Released in Venting of the TMI Unit 2 Containment Atmosphere: June 28 - July 11, 1980", pp A-173 to A-180 (Public Comments on the Draft Version, of the PEIS (see note (1))).
- (5) "Background Information Document: Proposed Standards for Radionuclides", EPA report EPA 510/1-83-001 (Draft), March 1983, Table 2-A
- (6) D.M. Pisello, "The Zirconium Connection", pp A-180 to A-187, source as note (4).
- (7) E.A. Gulbransen, letter to B. Snyder, page A-1, source as note (4).

Table 1

NRC Estimate of Radioactivity in Contaminated Water
from TMI-2 Cleanup, after Processing

Radionuclides	Total Radioactivity in Processed Water (Ci) ^D	
	Best Case (SDS/EPICOR II) ^C	Worst Case (SDS) ^C
H-3	2900	2900
Sr-89	6×10^{-6}	0.6
Sr-90	3×10^{-5}	9
Ru-106	0.04	21
Sb-125	0.07	54
Te-127m	0.1	51
Cs-134	<0.3	0.9
Cs-137	0.6	5
Ce-144	0.02	5

^aThe total volume of stored processed water would be slightly over 1.5 million gallons if no clean water were added and none was lost by evaporation. The origins of this water are: 743,000 gallons from the AFHB that has already been processed by EPICOR II, 700,000 gallons of contaminated water in the reactor building basement that has not yet been processed, and 96,000 gallons of water in the primary system of the reactor that also remains to be processed (see Tables 7.23 and 7.24). If the processed water were released to the river, the rate and the mixing with uncontaminated water would be adjusted so that the concentration of radionuclides in the river would be well below the threshold level for deleterious effects in aquatic species or humans.

^bValues are rounded to one or two significant digits.

^cSee Section 7.1.3.3 for a discussion of these systems.

(adapted from Table 10.2 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol.1, March 1981)

Table 2

NRC's Comparison of Alternatives for Disposal of Processed Water from TMI-2 Cleanup

Disposal Alternatives	Years to Complete	Release Pathways					Potential Regulatory Obstacle			Offsite Gases ^d Person-rem	Cost ^c (\$10 ⁶)	Permanent Disposition
		To Atmosphere	To River	To Land	To Subsurface Water	To Ocean	NRC Licensing	EPA Permitting	State/Local			
Long-Term Onsite Storage												
1. In liquid tanks ^a	200	*										
2. As concrete slabs	200	*		*						NA 30 ^e	5600 2300	No No
Onsite Disposal												
3. SLB trenches	5 ^b			*			*					
4. Underground injection	5 ^b				*		*		*	NA	1400	Yes
Offsite Disposal												
5. Deep well injection	5 ^b				*		*		*	NA	250	Yes
6. Ocean disposal	5 ^b					*	*		*	NA	3760	Yes
7. SLB facility	1			*			*		*	NA NA NA	7700 4100	Yes Yes Yes
Discharge to Environs												
8. Release to river	< 1		*									
9. Natural evaporation	1	*	*							30	100	Yes
10. Forced evaporation	< 1	*	*							30 30	500 250	Yes Yes

E11

^aAfter storage alternatives 2 through 10 are applicable.

^bBased on potential licensing and permitting delays.

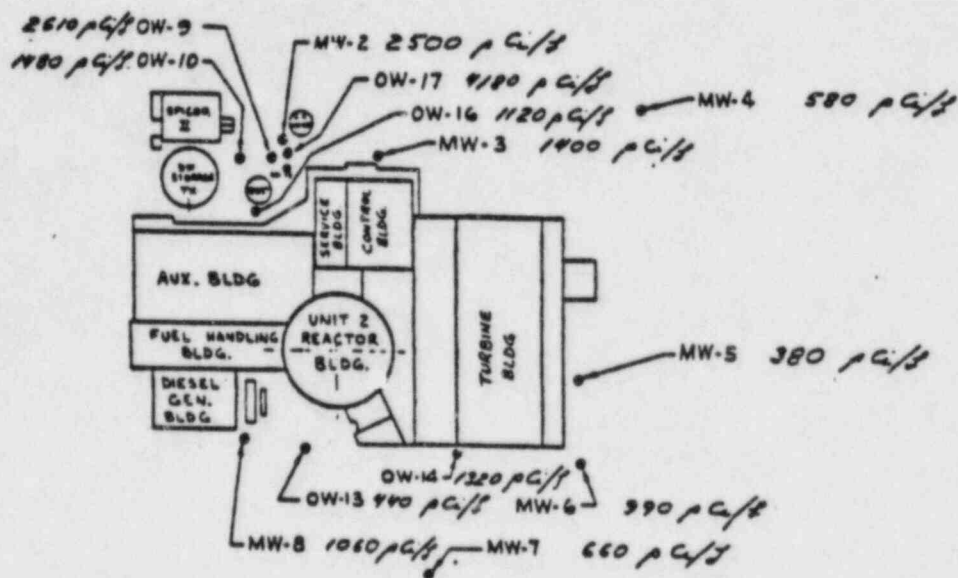
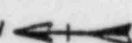
^cBased on the low cost values in Table 7.42.

^dBased on the SDS/EPICOR II process effluent.

^eBased on loss of all tritium in the concrete slab.

(adapted from Table 7.43 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol.1, March 1981)

Figure 1

Ground Water Monitoring Wells at TMI - 2NORTH 

COMMENTS:

1. MW-1 LOCATED IN NORTH PARKING LOT @ COORDINATES N 301,460.04
E 2,286,538.94
990 pCi/l
2. OW-15 LOCATED ON SOUTH END OF ISLAND @ COORDINATES N 292,985.44
E 2,287,765.09
220 pCi/l

Notes

- (i) Chart from NRC's TMI Program Office Weekly Status Report, 30 August - 6 September, 1980.
- (ii) Water samples taken weekly from each of the 15 wells.
- (iii) Sample results (picocuries per liter) are for samples taken 7 July, 1980. Tritium was the only isotope identified.

Sub-Appendix ATMI-2 Cleanup: Sequential List of Major Documents

prepared by Howard Gold, 3 May 1983

- October 3, 1979
"Environmental Assessment for Use of EPICOR-II at Three Mile Island, Unit-2", NRC report NUREG - 0591
- October 16, 1979
NRC memorandum and order directing the licensee to use the EPICOR-II System for cleanup of the water in the auxiliary and fuel handling building (AFHB).
- November 21, 1979
Policy statement by NRC announcing the intent to prepare a programmatic environmental impact statement on the decontamination and disposition of radioactive waste resulting from the March 28 accident.
- March 1980
Draft environmental assessment issued by NRC listing alternatives for the decontamination of the reactor building atmosphere.
- May 1980
"Final Environmental Assessment for Decontamination of the Three Mile Island Unit 2 Reactor Building Atmosphere", NRC report NUREG - 0662.
- June 12, 1980
NRC Memorandum and Order authorizing licensee to remove gaseous effluents (Kr-85) from the reactor building by controlled purging; Commission orders: Docket No. 50-320.
- July 1980 "NRC Plan for Cleanup Operations at TMI-2", NRC report NUREG - 0698.
- August 14, 1980
"Draft Programmatic Environmental Impact Statement related to decontamination and disposal of radioactive wastes resulting from March 28, 1979 accident" (Docket No. 50-320). Formal notification was published in the Federal Register on August 22, 1980, initiating a 45-day period for public comments. The comment period was subsequently extended to November 20, 1980.

March 9, 1981

"Final Programmatic Environmental Impact Statement" (PEIS) issued by NRC. This considered a wide range of alternatives for: decontaminating the TMI-2 facility; defueling the reactor; and disposing of the radioactive wastes; together with the potential impacts of these activities on the environment, members of the public, and plant workers. NRC report NUREG - 0683.

April 28, 1981

Policy statement by NRC, in conjunction with PEIS, that cleanup should be expedited consistent with maintaining public health and safety. This outlined NRC policy for review and approval of subsequent cleanup operations.

June 1981

"Safety Evaluation Report Related to the Operation of the Submerged Demineralizer System at Three Mile Island Nuclear Station, Unit No. 2". NRC report NUREG - 0796.

July 15, 1981

Memorandum of Understanding reached between DOE and NRC specifying interagency procedures "Concerning the Removal and Disposition of Solid Nuclear Wastes from Cleanup of the Three Mile Island Unit 2 Nuclear Plant".

February 1982

Revision of the "NRC Plan for Cleanup Operations at Three Mile Island Unit 2". This reviews cleanup progress, updates cleanup schedule, and discusses NRC's role in ongoing and future cleanup activities by GPU Nuclear. NRC report NUREG - 0698, Rev. 1

March 15, 1982

Memorandum of Understanding (MOU) between NRC and DOE, a revision to the existing MOU signed July 15, 1981. Identifies changes in the proposed disposition of the reactor fuel and the makeup and purification system demineralizer resins (believed to be highly contaminated in the accident). The DOE agreed that the entire reactor core will be shipped to one of its facilities for selected research and development. Also signed was an Agreement in Principle between DOE and General Public Utilities for the "Acquisition of the Damaged TMI-2 Reactor Core by DOE".

March 16, 1982

Errata Sheet for NUREG - 0698, Rev.

Sub-Appendix B

TMI-2 Cleanup: Projected and Achieved Schedules

prepared by Gordon Thompson and Howard Gold, 6 May 1983

Projected Schedule

In November, 1980, the licensee projected that the cleanup would be completed, except for minor decontamination, by the Spring of 1986. Figure B.1 shows the projected schedule.

The NRC's most recently published Plan for Cleanup Operations, published in February 1982, contains an estimated schedule based on licensee projections as of October, 1981. This schedule is shown in Figure B.2.

Comparison of these two schedules suggests that the earlier projection was more accurate. The later projection shows fuel removal beginning in the middle of 1983, which seems unlikely.

At a meeting of the NRC's Three Mile Island Advisory Panel, held on February 2, 1983, representatives from GPU Nuclear provided an overview of the latest TMI-2 Recovery Program Estimate. Five different alternatives were presented, yielding estimates for program completion ranging from December 1987 to December 1989. This presentation, together with our personal conversations with NRC staff, makes it apparent that the cleanup schedule remains indefinite.

Achieved Schedule

The chronology of major events has been as follows:

March 28, 1979 et seq.

The accident involved the release of hundreds of thousands of gallons of contaminated water from the primary system into the basement of the reactor building (sump water). Additionally, primary system coolant entered the auxiliary and fuel handling building (AFHB), contaminating its floors, walls and storage tanks. The containment atmosphere was contaminated with radioactive gases and steam. Interior surfaces of both the reactor building and the AFHB were coated with thin deposits (plateout). The reactor core suffered substantial damage.

October 16, 1979

NRC authorized the use of a 3-stage demineralization system, designated as EPICOR-II, for decontaminating water with intermediate levels of radioactivity (between 1 and 100 microcuries/ml) held in the AFHB tanks and sumps.

(Note: It appears that 500,000 gallons of contaminated water were generated during the accident, and up to 250,000 additional gallons during decontamination.)

June 12, 1980

NRC authorized the licensee, GPU Nuclear, to remove Krypton-85 from the reactor building by controlled purging to the atmosphere.

June 28-July 11, 1980

Venting of the reactor building released 44,000 Ci of Kr-85. Future purges, of less than 100 Ci, were also made prior to worker entries into the reactor building.

July 23, 1980

After the overcoming of jamming problems with airlock doors, and the purging of the reactor building atmosphere, the first containment entry was made. This initiated a series of programmed entries for the purpose of data collection and equipment maintenance.

August 12, 1980

Processing of auxiliary building water, using the EPICOR-II system, was suspended. As of that date, this system had processed 500,000 gallons of contaminated water.

March 1981

NRC approved the shipment and disposal of 22 EPICOR-II resin liners containing low levels of radioactivity.

April 23 - June 27, 1981

The 22 EPICOR-II second and third stage liners were shipped from TMI to the commercial waste disposal site at Hanford, Washington, for final burial.

May 19, 1981

A high-specific-activity first-stage EPICOR-II liner (PF-16) was shipped to Battelle Columbus Laboratories for analysis. Although this analysis did not show significant degradation of the ion exchange medium, a measurable amount of hydrogen gas (of concern for potential flammability) was detected.

June 18, 1981

NRC approved Metropolitan Edison Company's plans to use the submerged Demineralizer System (SDS), an underwater ion-exchange system, to process the highly contaminated water in the reactor building sump and the reactor coolant system.

July 10 - August 9, 1981

Processing of approximately 150,000 gallons of intermediate radioactivity water from the Auxiliary Building Reactor Coolant Bleed Tank (RCBT) through the SDS was carried out. Results showed greater than 99% removal of Cs-137 and Sr-90.

September 11, 1981

The EPICOR-II system, after undergoing modification, was restored to use and began 'polishing' SDS processed water. The polished water is stored on-site in the processed water storage tanks.

September 22, 1981

Following minor system changes, the transfer of water from the Unit 2 Reactor Building Sump to the SDS Feed Tanks was begun. The next day, processing of reactor building sump water was initiated. Approximately 635,000 gallons were treated over the next eight months.

October 27, 1981

A series of reactor building (RB) entries, characterized as the 'gross decontamination experiment', was begun. The aim of this program was to characterize the RB contamination, and to survey the effectiveness of the decontamination methods used.

May 17 - May 20, 1982

The reactor cooling system (RCS) was put through the first of many feed and bleed cycles, to permit processing of RCS water. Since the RCS is a recirculating loop which cannot be drained without exposing the reactor core, it is being decontaminated in a recirculation, or by-pass mode, as opposed to a once-through operation. Processing of RCS water commenced the next day with the SDS.

May 21, 1982

The first SDS waste vessel was shipped from TMI to the Pacific Northwest Laboratory, Hanford, Washington.

July 21, 1982

A closed-circuit television inspection of the reactor core (the "Quick Look" inspection) was performed. Subsequent inspections inside the reactor vessel took place on August 4 and August 12.

August 17, 1982

The first of 49 EPICOR-II first-stage liners or "prefilters" (PF) was shipped from TMI to the Battelle Columbus Laboratories. Later PF shipments have gone to the Idaho National Engineering Laboratory (INEL) in Scoville, Idaho.

September 1982

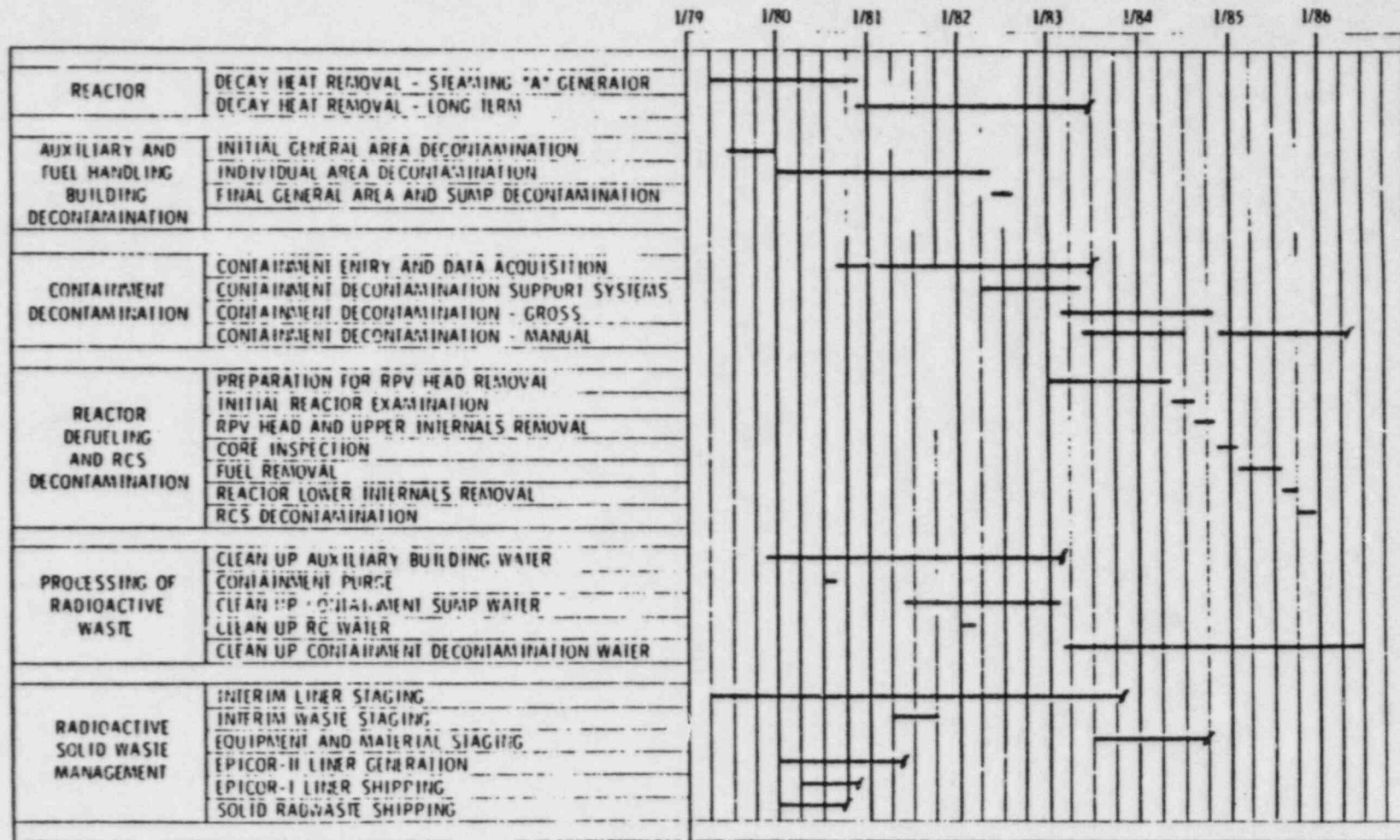
A reactor decontamination program was begun, including decontamination of the reactor building, the polar crane, and the inside surfaces of the "D" rings (the concrete shields around each steam generator). Decontamination methods being used include hot water and high pressure flushes. The contaminated water is periodically drawn from the reactor building sump and processed through the SDS.

September 1982 - present

Although a variety of evaluation programs have been performed, and decontamination has continued, no major milestones have been achieved.

Figure B.1

Licensee Estimate of TMI-2 Cleanup Schedule, as of November 1980



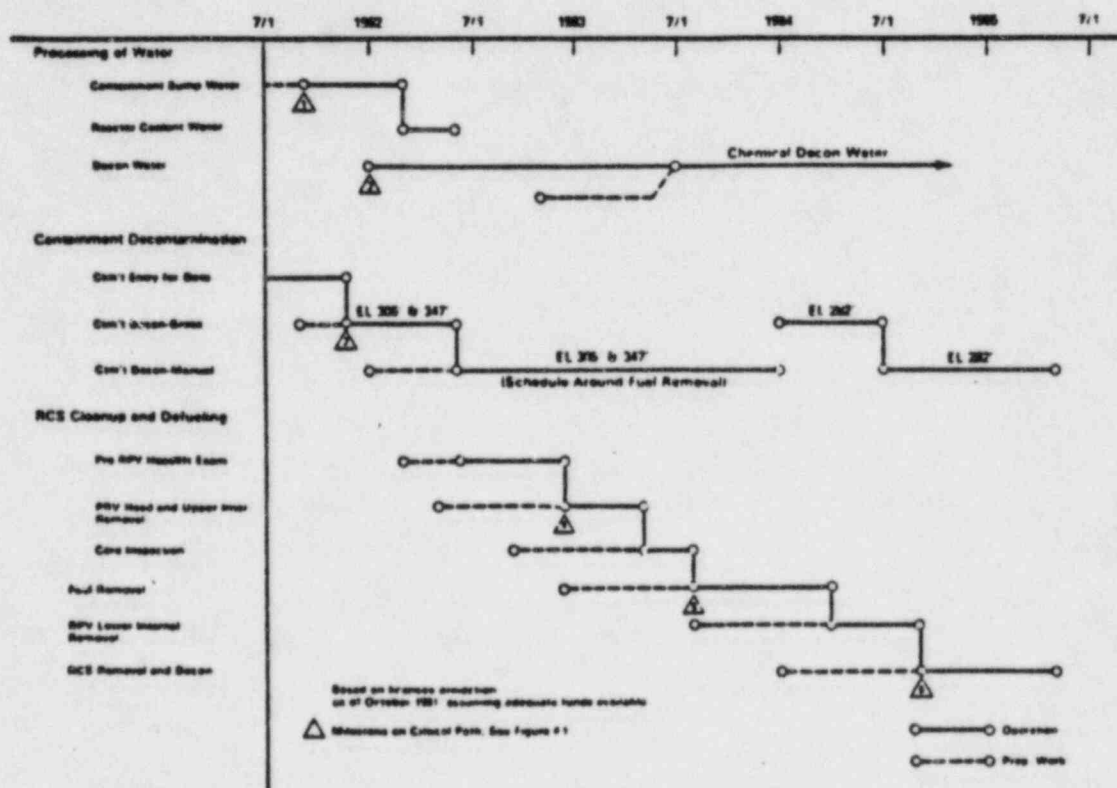
— CONSTRUCTION, PROCESSING ACTIVITIES
 —/— ACTIVITY CONTINUED AS NEEDED

(adapted from Figure 1.4 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol.1, March 1981)

Figure B.2

NRC Estimate of TMI-2 Cleanup

Schedule, as of February 1982



Notes

- (i) This figure adapted from Figure 4.2 of NRC Plan for Cleanup Operations at TMI-2, NRC report NUREG-0698, Rev.1, Feb.1982.
- (ii) Dates on the top line indicated as 1982, 1983, etc. mark the beginning of that year.

Sub-Appendix C

TMI-2 Cleanup: Projected and Actual Worker Exposures

prepared by Gordon Thompson and Howard Gold, 9 May, 1983

Projected Exposures

The NRC has estimated worker doses for different cleanup operations, as shown in Table C.1. A cumulative dose of between 2000 and 8000 person-rem was projected, for the entire cleanup.

Actual Exposures

Exposures through 1982, as indicated by the licensee's TLD's, are shown in Table C.2.

These exposures appear to be lower than those at typical operating plants. From data reported to the NRC from 70 LWR's for the year 1981, it appears that the average collective dose, per reactor, was 779 person-rem (which was slightly lower than the 791 person-rem per reactor reported in 1980). The average collective dose, per pressurized water reactor (PWR), was 656 person-rem (boiling water reactors had an average approximately 50% higher).⁽¹⁾

If the cleanup of TMI-2 is assumed to have commenced on May 1st, 1979, the cumulative cleanup dose through 1982 sums to 1258 person-rem. This suggests that the lower estimate (2000 person-rem) in Table C.1 is optimistic.

Reactor Building Decontamination

In the PEIS, the decontamination of the reactor building was determined to be the cleanup activity which could result in the highest occupational dose (see Table C.1). The NRC's cleanup plan projected for the decontamination:

"First, by means of a gross decontamination, it should be possible to decrease the radiation exposure and contamination levels in the reactor building to acceptable occupational exposure levels so that worker occupancy-intensive activities such as hands-on decontamination work related to fuel removal can be carried out. Subsequent to the gross decontamination, manual decontamination efforts will be employed to cleanup the facilities such that fuel removal and, subsequently, decommissioning or refurbishment operations can be initiated."⁽²⁾

At present, the decontamination of exposed reactor building surfaces is being reevaluated since past decontamination surveys have indicated that recontamination was occurring at rates which significantly reduce the long-term effectiveness of the original decontamination. The reactor building air-cooler fans were thought to be a contributing factor to this recon-

tamination. To determine if this is the case, tests have been conducted to see if there would be a significant reduction in airborne particulate activity when the recirculation fans were shut down. A preliminary test showed this not to be so.

The limited amount of exposure (available person-rem) permitted for the specialized work force has been identified as a potential limiting factor for the projected work scheduled during the first half of 1983. In response to this, a dose rate reduction program was initiated by the licensee during January 1983. GPU designed and constructed shielding around high radiation sources in the reactor building.

Figure C.1 depicts the floor plan for the 305 ft elevation. It shows the before-and-after radiation rates for three personnel traffic areas, following the installation of radiation shielding materials around the enclosed stairwell and the core flood tank B during January and February, 1983. Metal equipment hatches and open stairwell areas have also been shielded (in March) to provide further reduction in the dose rate arising from high-radiation sources in the reactor building basement.

Although substantial reductions in present dose-rates have been achieved by this shielding, it will be noted that the contamination must be removed eventually.

It appears, from reading the earlier reports of worker entries into the reactor building, that the maximum total body exposure for any member of an entry team (during each entry) had been calculated not to exceed 500 mrem. Most exposures seem to have been kept below this level although some slightly higher exposures were reported to occur during surveys of 'hot spots'.

The rise in reported worker exposures for 1982, contrasted to the previous year (see Table C.2), is presumably attributable to the increase in the number of reactor building entries. The table below summarizes the number of person-hours inside the reactor building and the cumulative exposure (in person-rem) for building entries. These entries are divided into two phases, namely prior to the gross decontamination experiment entries (1-16), and during the gross decontamination experiment entries (17-56).

	<u>Entries 1 through 16</u> (7/23/80 to 9/24/81)	<u>Entries 17 through 56</u> (10/27/81 to 3/31/82)
Total person-hours	199	507
Total person-rem	63	115
	(~317 mrem/hr)	(~227 mrem/hr)

The early worker entries chiefly involved data collection and equipment maintenance, and some experimentation with cleanup methods. This was followed by a larger-scale experimental program of entries to carry out and evaluate the effectiveness of various decontamination techniques.

The more recent entries, especially since September 1982, have been involved extensively with actual gross decontamination work in the reactor building. In the year that followed the "gross decontamination experiment" (4/1/82 - 3/31/83) the rate of reactor building entries accelerated greatly. A tally from weekly reports indicates about 120 work crew entries for that year (cumulative exposure levels for this period are not yet available). From the beginning of 1983, entries were continuing at the rate of about five per week. However, in April, cleanup activities slowed because of a reassessment and evaluation of various tasks and operating procedures.

Overexposures

There have been several incidents which resulted in overexposure of workers. For example, in 1979, a group of cleanup workers suffered overexposure while trying to contain a leak of highly contaminated water in the auxiliary building. In 1980, another leak of highly contaminated reactor coolant caused high airborne levels of radioactivity and contaminated several workers. Another important incident occurred the following year as described in an NRC report:

"Upon exiting the RB, the entry team underwent routine "frisking" for radioactive contamination. Contamination was found on the skin of all four individuals. The primary areas of contamination included the buttocks, elbows, and knees. Personnel decontamination procedures were initiated and after several hours, three of the four individuals were decontaminated on July 1, 1981. The buttock of the fourth individual was not completely decontaminated until the following day.

The skin contamination apparently resulted from climbing on contaminated crane surfaces in perspiration-soaked protective clothing. Following several instances of personnel exhaustion during RB entries, the licensee relaxed the criteria for use of plastic protective clothing in the RB to reduce fatigue and the crane inspection team was wearing only two sets of protective clothing. The outer layer of protective clothing was advertised by the manufacturer as water impermeable. The same type of protective clothing had been worn during the initial climb on the crane with no instances of skin contamination. The second crane climb was physically more demanding and all team members exited from the RB exhausted with the inner layer of protective clothing completely soaked. The licensee is evaluating the available information to determine what combination of protective clothing is required for future entries."⁽³⁾

In November 1981, work on the polar crane resulted in another individual becoming exhausted and contaminated. While making his exit, he stopped and required assistance in order to leave the reactor building. In the process his full-face respirator and some protective clothing were removed. The worker suffered contamination on small areas of his hair and skin. Medical examination on site showed a whole body radionuclide count of approximately 50 nanocuries.

Dosimetry

A Blue Ribbon Panel was appointed by the NRC in late 1979 to examine the TMI-2 Radiological Protection Program (The panel's findings and recommendations were published in NUREG-0640.). Based upon the panel's recommendations for improvements, the licensee upgraded the program. Following the inspections and evaluations conducted during 1980-1981, the NRC's TMI Program Office radiation specialist staff concluded that GPU's Radiological Protection Program was adequate to support major cleanup activities. This conclusion was contingent upon GPU continuing to emphasize commitments to program implementation and expanding the radiological control and training staffs as the pace of the cleanup accelerated. Further, the NRC required an upgrading of the personnel dosimetry program, as of October 1981. Information on the success of this upgrading is not to hand.

Effective February 1st, 1983, the TMI site initiated use of a modified TLD, intended to provide better beta monitoring in mixed beta/gamma radiation environments.

ALARA

As of the week of 3-9 April, 1983, the NRC had requested a meeting with GPU to discuss over-all dose reduction and ALARA (as low as reasonably achievable) programs. This meeting was scheduled to take place on April 18th at the NRC Office of Nuclear Reactor Regulation in Bethesda.

Notes

- (1) TMI Program Office weekly report of 11-17 July, 1982.
- (2) NRC Plan for Cleanup Operations at TMI-2, report NUREG-0698, Rev 1, February 1982, Page 4-5.
- (3) TMI Program Office weekly report of 28 June - 5 July, 1981.

Table C.1

NRC Estimate of Cumulative Doses and Health Effects
for Workers Involved in Cleanup of TMI - 2

Document Section	Operation	Cumulative Occupational Dose (person-rem)	Health Effects ^a	
			Additional Cancer Deaths in Work Force	Additional Genetic Effects Among Offspring of Work Force
4.5.1	Maintenance of the Reactor in Safe Condition	8	0.001	0.002
5.1.5.1	Decontamination of the Auxiliary and Fuel Handling Buildings	375 - 550	0.05 - 0.07	0.10 - 0.14
5.2.5.1	Decontamination of the Reactor Building	660 - 3000	0.09 - 0.4	0.2 - 0.8
6.2.5.1	Reactor Coolant System Inspection	52 - 580	0.007 - 0.08	0.014 - 0.15
6.3.5.1	Removal of RPV Head and Internals	150 - 450	0.02 - 0.06	0.04 - 0.12
6.4.5.1	Core Examination and Defueling	580 - 1350	0.08 - 0.2	0.15 - 0.4
6.5.5.1	Decontamination of Primary System Components	108 - 1740	0.014 - 0.2	0.03 - 0.5
7.1.5.1	Liquid Waste Treatment	43 - 121	0.006 - 0.016	0.01 - 0.03
8.1.5.1	Handling and Packaging of Process Solid Wastes	17	0.002	0.004
8.2.5.1	Handling and Packaging of Chemical Decontamination Solution Wastes	3 - 10	0.0004 - 0.001	0.0008 - 0.003
8.3.5.1	Handling and Packaging of Solid Wastes	39 - 99	0.005 - 0.013	0.01 - 0.03
9.5.1.1	Transfer from Storage and Truck Loading	11 - 38	0.001 - 0.005	0.003 - 0.009
9.5.1.1	Transportation ^b	6 - 360	0.001 - 0.05	0.002 - 0.09
Totals		2000 - 8000 ^a	0.3 - 1	0.5 - 2

^a Values have been rounded to one or two significant digits; totals have been rounded to one significant digit.

^b Different routes and different estimates for the expected exposure during transit lead to a large range in the transportation estimates; see Sec. 1.5.1.1.

(adapted from Table 10.5 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG - 0683, Vol 1, March 1981)

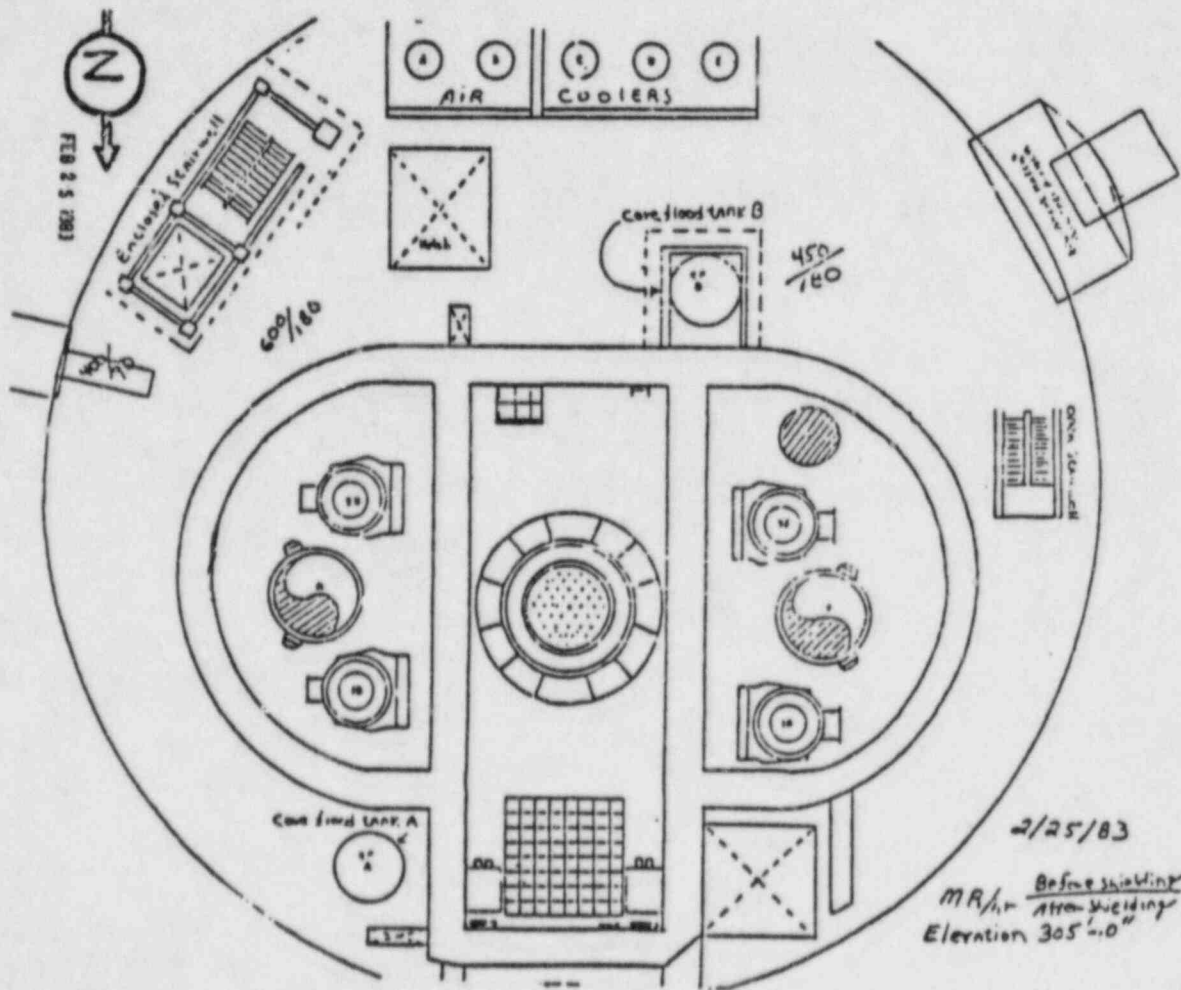
Table C.2TMI Occupational Exposures, 1979 - 1982
(person-rem)

<u>Period</u>	<u>Unit I</u>	<u>Unit II</u>
1/1 - 3/17/1979	351	7
3/28 - 4/30/1979	68	138
5/1 - 12/31/1979	<u>303</u>	<u>516</u>
Total 1979	722	661
1/1 - 12/31/1980	169	207
1/1 - 12/31/1981	201	146
1/1 - 12/31/1982	NA	389

Notes

- (i) These data are from thermoluminescent dosimeters (TLD's), as reported to NRC by the licensee.
- (ii) Data prior to 1982 are from the NRC's TMI Program Office weekly report of 24-30 October, 1982.
- (iii) Data for 1982 are from the weekly report of 6-12 February, 1983.

Figure C.1
Effect of Radiation Shielding in the
TMI-2 Reactor Building, as of
February 1983



(Adapted from Enclosure B, TMI Program Office weekly report of 19-26
February 1983)

Sub-Appendix D

TMI-2 Cleanup: Waste Shipments from the Site - - Projected and Actual

prepared by Gordon Thompson and Howard Gold, 9 May, 1983

Projected Shipments

Most of the radioactivity generated by the accident fell into one of two categories: fuel and fuel debris within the primary circuit; and contaminated liquids.

Much of the liquid inventory of radioactivity has been transferred, and most of the remainder will be transferred, to solid media. Table D.1 indicates the solid forms which the NRC projected, in its PEIS, to arise during this process. Reactor building sump water was expected to be the major source of liquid-carried radioactivity.

Via the Submerged Demineralizer System (SDS), much of the activity in the sump water has been transferred to zeolite liners. Table D.2 shows the PEIS estimate of the numbers and characteristics of zeolite liners expected to be generated during processing of the sump water and other contaminated liquids.

Organic ion-exchange resins have been used in the EPICOR II System. The first-stage (prefilter) liners remove most of the radioactivity from the contaminated water, achieving loadings up to 1800 curies per liner. Table D.3 shows the PEIS estimate for generation of these high-specific-activity resins.

Organic resins in the second and third stages of EPICOR II receive much lower activity loadings. Table D.4 shows the PEIS estimate for generation of these low-activity resins.

Fuel and fuel debris will account for a significant number of high-activity shipments. The PEIS projects (Table 9.5) that between 56 and 183 fuel cask shipments will be needed for this material.

A variety of other solid waste forms are expected to arise, including sludges, evaporator bottoms, filters, ash, contaminated hardware, and trash.

The total number of shipments in various categories, as projected by the PEIS, is shown in Table D.5.

Actual Shipments

Low-level radioactive solid wastes associated with the cleanup operations, including compacted trash, booties, gloves, and dewatered resins (with radioactivity less than 1 microcurie/ml) have been routinely shipped to

commercial low-level burial sites. On two occasions, burial permits have been suspended because of improper packaging of wastes⁽¹⁾.

For some higher activity wastes, such as the spent ion-exchange media from water treatment systems, two interim staging modules were constructed on-site for temporary storage. Each module contains 60 storage cells. At one time these facilities contained all the spent resins which were generated by the EPICOR II system.

Starting in April 1981, and continuing over a three month period, 22 EPICOR liners which qualified for disposal at commercial radioactive burial facilities were shipped to U.S. Ecology in Richland, Washington. The higher activity prefilter liners (up to 1800 Ci of Cs-137 and Sr-90 per liner) were kept in storage at the TMI-2 site.

In July of 1981, the NRC and DOE signed a Memorandum of Understanding, intended to ensure that TMI does not become a long-term waste disposal facility⁽²⁾. Discussions between DOE, NRC, and GPU led to the DOE decision to receive the EPICOR II prefilter (PF) liners at government-controlled facilities for research and development purposes⁽³⁾.

A program to ship the EPICOR II prefilters was established by GPU, which included steps for inerting, sampling, and integrity inspection by the NRC, prior to the transfer of PF's to the DOE. The prefilter liners and their shipping casks (standard type B) are inerted with nitrogen (using a special remotely operated inerting tool provided by DOE) as an added safety precaution to ensure that no combustible gases will arise during shipment. The first in a series of 49 such shipments began on August 17, 1982, and was received at the Battelle Columbus Laboratory in West Jefferson, Ohio. All PF shipments since then have gone to the Idaho National Engineering Laboratory (INEL) in Scoville, Idaho. Through March 1983, 33 prefilters were sent, and the remaining ones are scheduled to be shipped off site by August 1983.

Shipment of the highly radioactive Submerged Demineralizer System (SDS) waste zeolite liners has also begun. These 10 ft³ waste vessels contain high levels of mixed fission products, predominately Cs-137 and Sr-90. Under its Memorandum of Understanding with the NRC, DOE is also taking possession of and retaining these wastes.

On May 21, 1982, the first SDS liner was sent from TMI to Richland, Washington for characterization and vitrification testing. This was the first of a group of 12 liners, six of which had already been shipped as of March 1983. Table D.6 summarizes these SDS liner shipments. Procedures for preparing the waste vessels changed after the initial SDS liner shipment. Since that time, waste liners have been vacuum dried and loaded with a palladium catalytic recombiner to maintain non-combustible gas conditions during the shipping period. They are also monitored and sampled prior to shipment. The shipping casks are also inerted with nitrogen as an additional safety measure.

In a revised Memorandum of Understanding signed between the NRC and DOE on March 15, 1982, the DOE has also agreed to accept the entire reactor core for selected research and development. Also, DOE agreed to take possession of the makeup and purification system demineralizer resins and retain them for research and development activities, and ultimate disposal.

At the present time, progress has been made by GPU and DOE in preparation for the eventual processing and disposal of these spent resins, located in the two reactor coolant system purification demineralizer vessels. External gamma scans have indicated that approximately 15,000 Ci of mixed fission product activity exists within each vessel (predominately as Cs-137), having been deposited on the resins during the accident. The two 4 ft diameter, 7 ft high stainless steel vessels, which each contain approximately 60 ft³ of organic resins, are located within the auxiliary building demineralization cubicles. GPU is currently characterizing the internal conditions within the vessels and sampling the resins to determine the optimum methods for processing and disposal. The actual shipment of this waste material to a DOE facility is anticipated to occur towards the end of 1983.

Notes

- (1) On June 10, 1980, NRC Region V and Washington State inspectors examined a shipment of 128 drums of low-level waste that was received at the Washington burial site from TMI-2. The inspection revealed that one drum had a broken locking ring and four drums had loose locking rings. The State of Washington banned Metropolitan Edison Company from use of the burial site for six days. Again, on May 5, 1982, the State of Washington suspended the TMI-2 burial permit. This action occurred after U.S. Ecology received a TMI-2 shipment with an open 55 gallon drum. The right to use the Washington burial site was restored on May 18.
- (2) A letter from John E. Minnich, representing the Citizens Advisory Panel for the Decontamination of Three Mile Island, Unit 2, dated February 23, 1981, urged Secretary of Energy James Edwards to arrange for the removal of 50 containers of high-level waste [EPICOR II prefilter liners] from TMI. The letter stated: "We are extremely concerned that Three Mile Island has become a storage site for waste"; "...that Three Mile Island was never intended for such purposes"; "...it is our feeling that the removal of the waste would grant some relief to the anguish of many citizens of the area."
- (3) One liner (PF-16) had already been shipped to the Battelle Columbus Laboratory on May 19, 1981, for detailed examination (after approximately 16 months in storage). This transfer was part of a DOE sponsored resin characterization program to further develop technology and expand knowledge for processing high-specific-activity resins and to evaluate liner compatibility.

Table D.1

NRC Projection of Solid Radioactive Waste Forms from TMI-2

Cleanup: Waste from Processing of Contaminated Liquids

Source of Treated Liquid Waste	Curie Inventory in Untreated Liquid ^a		Process Solid Waste Forms ^{b,c}					
	Minimum	Maximum	Filters	Zeolites	Organic Resins	Evaporator Bottoms	Bitumen	Sludge
1. AFHB accident water	55,000 ^d	55,000 ^d	X	X ^e	X ^e			
2. Reactor building sump water	500,000	500,000	X	X	X			X
3. RCS water	20,000	20,000		X	X			X
4. RCS flush & drain water	20,000	100,000	X	X	X			
5. AFHB/reactor building decontamination solutions								
(a) Aqueous	90	90			X			
(b) Chemical	70	70				X	X	
6. RCS decontamination solutions								
(a) Aqueous ^f	2,000	20,000	X	X	X			
(b) Chemical ^f	2,000	20,000				X	X	
Total	600,000	700,000						

^aExclusive of H-3 and noble gases--rounded to two significant figures.

^bWaste form combinations are alternative-dependent--see Section 7.1.3.

^cX indicates process solid waste form could be generated and is considered.

^dCuries removed by system through September 22, 1980.

^eSome liners contain zeolites mixed with organic resins.

^fMutually exclusive alternatives; one waste form will be produced, not both.

(adapted from Table 8.1 of Final Programmatic EIS on TMI-2 cleanup, NRC report NUREG-0683, Vol.1, March 1981)

Table D.2

NRC Estimate of Radioactive Waste from TMI-2 Cleanup, in the form of

Ion-Exchange Media: Packaged Zeolite Liners (as used in SDS).

Source of Treated Liquid Waste	Packaged Liner Characteristics ^a					
	Minimum Generation			Maximum Generation		
	Number of Liners	Maximum Curies per Liner	Maximum Surface Radiation Level (R/hr)	Number of Liners	Maximum Curies per Liner	Maximum Surface Radiation Level per Liner (R/hr)
1. Reactor building sump water	6	120,000	100,000	54	10,000	8,000
2. RCS water ^b	2	10,000	8,000	6	5,000	4,000
3. RCS flush and drain water ^c	2	10,000	8,000	12	10,000	8,000
4. Aqueous RCS ^d decontamination solutions	1	2,000	1,600	6	5,000	4,000
Total	11			78		

^aEach liner contains 8 ft³ of zeolite.^bMinimum based on modified EPICOR II system; maximum based on modified SDS.^cMinimum based on modified EPICOR II removal of 20,000 Ci; maximum based on modified SDS removal of 100,000 Ci.^dMinimum based on SDS/Modified SDS removal of 2,000 Ci; maximum based on SDS/Modified SDS removal of 20,000 Ci.

(adapted from Table 8.13 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG - 0683, Vol.1, March 1981)

Table D.3NRC Estimate of Radioactive Waste from TMI-2 Cleanup,in the form of Ion-Exchange Media:High-Specific-Activity Organic Resins (as used in EPICOR II)

Source of Treated Liquid Waste	Minimum Generation		Maximum Generation	
	Volume (ft ³)	Curies ^a	Volume (ft ³)	Curies ^a
1. AFHB accident water ^b	1,360	54,500	1,380	54,500
2. RCS water	540	19,900	540	19,900
3. RCS flush and drain water	540	19,900	2,690	99,500
Total	2,460	94,000 ^c	4,610	174,000 ^c

^aDetailed information on EPICOR II is proprietary. Curies were estimated from actual performance with AFHB liquids extrapolated to other sources.

^b46 high-specific-activity prefilter liners in storage as shown in footnote c on Table 8.2.

^cRounded to nearest thousand.

Notes

- (i) This table adapted from Table 8.7 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol.1, March 1981
- (ii) First-stage liners in the EPICOR-II System, which provide the high-specific-activity waste, have a volume of 30 ft³ per liner.

Table D.4

NRC Estimate of Radioactive Waste from
TMI-2 Cleanup, in the form of Ion-Exchange

Media:Low-Activity Organic Resins (as used in EPICOR II)

Source of Treated Liquid Waste	Minimum Generation		Maximum Generation	
	Volume (ft ³)	Ci	Volume (ft ³)	Ci
1. AFHB accident water ^a	1200	260	1200	260
2. RB sump water				
SDS/Modified SDS	200	75	-	-
SDS/EPICOR II	-	-	390	80
3. RCS accident water				
SDS/Modified SDS	200	30	-	-
Modified EPICOR II ^b	-	-	540	100
4. RCS flush and drain ^c				
SDS/Modified SDS	200	60		
Modified EPICOR II	-	-	1970	500
5. Water Based RCS Decon- tamination	140	1	140	5
Total	1940		4240	

^aEPICOR II system resins in storage.^bWaste volumes based on staff estimate.^cBest case removes 20,000 Ci; worst case removes 100,000 Ci.Notes

- (i) This table adapted from Table 8.8 of Final Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol.1, March 1981
- (ii) Second and third-stage liners in the EPICOR-II system, which provide the low-activity waste, have volumes of 30 ft³ and 130 ft³, respectively

Table D.5

NRC Projection of Number of Radioactive
Waste Shipments Arising from TMI-2 Cleanup

Type of Waste	Best-Case Conditions	Worst-Case Conditions
Low-level solids		
Drums - trash	13 ^a	108
LSA boxes - trash	86	149
LSA boxes - equipment and hardware	2	28 ^b
LSA boxes - mirror insulation	16 ^c	-
Immobilized decontamination liquids		
Unshielded drums	14	20
Shielded drums (evap. bottoms)	None	119
Shielded ion-exchange materials		
AFHB water	69	69
Reactor building sump water	8	33
RCS accident water	3	13
RCS flush and drain water	3	49
RCS decontamination solutions	2	6
Shielded drums		
Accident sludge	6	7
Spent filters	1	5
Incinerator ash	34 ^a	-
Miscellaneous shielded shipments		
Contaminated equipment	13 ^b	-
Mirror insulation	-	86 ^c
Core filters	6	6
Irradiated hardware	15	105
Zeolite system filters	6	11
Damaged fuel assemblies (and core debris)	56	183
Totals	353	997

^aBest case for trash drums includes generation of 34 shielded incinerator ash drums.

^bContaminated equipment can be packaged in unshielded 80 ft³ LSA boxes (worst-case conditions) or shielded 70 ft³ liners (best-case conditions).

^cMirror insulation can be packaged in unshielded 80 ft³ LSA boxes (best-case conditions) or shielded 70 ft³ liners (worst-case conditions).

(adapted from Table 9.6 of Programmatic EIS on TMI-2 Cleanup, NRC report NUREG-0683, Vol. 1, March 1981)

Table D.6

Shipments of Submerged Demineralizer System (SDS) Liners from TMI

<u>Liner</u>	<u>Date of Shipment</u>	<u>Activity (Ci)</u>	<u>Receiver</u>	<u>Comments</u>
#1 D(10015)	5/21/82	13,000	Pacific Northwest Laboratory (PNL) Hanford Operations Facility, Richland, Washington	Research and development on characterization and vitrification
#2 (D10012)	12/31/82	> 112,000	PNL	Vacuum recombiner demonstration test ...to show that a catalytic recombiner would maintain non-combustible gas mixtures and vacuum conditions.
#3 (D10016)	1/21/83	~ 113,000	PNL	From this liner and D10012, three glass logs (7ft long and 8in dia) were to be formed (vitrification). These logs were planned to be tested to determine their resistance to leaching. Further testing may involve DOE's basalt geologic test and evaluation facility in Richland.
#4 (D10013)	2/13/83	97,000	Rockwell Hanford Facility	Research and development on special containers for waste disposal.
#5 (D10017)	3/4/83	59,000	Rockwell Hanford Facility	
#6 (D10018)	3/25/83	53,000	Rockwell Hanford Facility	
#7 (D20028)	Scheduled for 4/14/83			