UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

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Dr. Max Carbon

SUBJECT: THE EFFECT OF IRRADIATION HISTORY ON CORE DECAY HEAT PRODUCTION

This report is provided in reply to your question: What would have been the decay heat power available at TMI-2 for various power histories?

The differences between the decay heat production for the TMI-2 core at the time of the accident and for the end-of-cycle equilibrium core for the first hours and days are probably not significant and are smaller than the uncertainties in the fraction of heat producing isotopes that might be boiled out of very hot fuel. The fission-product and actinide decay power (in MW) for the TMI-2 core at the time of the accident (96.6 effective full power days) and for the end-of-cycle equilibrium core are displayed in Table I*.

A study of the TMI-2 core for various irradiation intervals shows that the one-month irradiation results in the highest total decay power at all cooling times (the time following reactor scram) less than 60 seconds. The fission-product contribution is responsible for the elevated heating rate at this time. The decay heat power increases as irradiation time increases for all other cooling times. Table II displays total decay power (normalized to the total core power prior to shutdown) following continuous irradiation at full power.

All of the above calculations assume that all sources of decay heat remain in the fuel. Approximately 8% of the initial decay heat is attributed to noble gases (see Table III). The (total) fission-product heating listed in the tables has an uncertainty of about 2 to 5% depending on the cooling time. There is no uncertainty for the actinide heating although it is thought to be very small and insignificant.

The method of data generation is presented in a note at the bottom of Table III. Table IV displays some characteristics of fission-product isotopes. Table V shows the total amount of curies in the TMI-2 core at the time of the accident.

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Attachments: as stated (Table I thru V)

*The basic information in the tables is from TMI-2 Decay Power: LASL Fission-Product and Actinide Decay Power Calculations for the President's Commission on the Accident at Three Mile Island (LA-8041-MS, October 1979).

cc: ACRS Members
ACRS Technical Staff

TABLE I

COMPARISON OF CALCULATED DECAY POWER OF TMI-2 WITH END-OF-CYCLE EQUILIBRIUM CORE

Cooling Time	Total Core Decay Power, MW		RATIO (Eq. CORE / TMI-2)
	TMI-2	Eq. Core	
1.00+0 s[a]	1.68+2	1.63+2	0.97
4.00+0 s	1.48+2	1.45+2	
1.00+1 s	1.30+2	1.28+2	0.98
4.00+1 s	1.03+2	1.03+2	
1.00+2 s	8.60+1	8.70+1	1.01
4.00+2 s	6.52+1	6.70+1	1.03
1.00+3 s	5.28+1	5.46+1	
1.00+0 h	3.56+1	3.73+1	1.05
2.00+0 h	2.84+1	3.03+1	
5.00+0 h	2.14+1	2.38+1	1.11
1.00+1 h	1.74+1	1.99+1	1.14
2.00+1 h	1.39+1	1.65+1	
5.00+1 h	8.93+0	1.15+1	1.29
(4.17 DAYS) 1.00+2 h	6.59+0	8.90+0	
2.00+2 h	4.55+0	6.57+0	1.44
5.00+2 h	2.59+0	4.31+0	
1.00+3 h	1.56+0	3.02+0	
2.00+3 h	8.83-1	2.03+0	2.29
5.00+3 h	3.23-1	1.02+0	
1.00+0 y	1.40-1	6.09-1	
1.00+4 h	1.15-1	5.36-1	4.66
2.00+4 h	4.35-2	2.54-1	
5.00+4 h	1.13-2	8.36-2	7.40

[a] Read as 1.00×10^{0} seconds.

TMI-2 FSAR DATA

RATED POWER — 2772 MW_{TH}

AVERAGE ENRICHMENT — 2.57 wt % of U^{235}

FUEL WEIGHT — 204,820 lbs. of UO_2

TOTAL MASS OF U — 82057.2 Kg

FULL POWER DENSITY — 33.8 KW/Kg

SPECIFIC RATED POWER — 280.75 W/cm^3

TABLE II

SUMMARY OF TMI-2 FUEL DECAY POWER SURVEY CALCULATIONS

FISSION-PRODUCT AND ACTINIDE DECAY POWER FOLLOWING CONTINUOUS IRRADIATIONS AT 33.8 kw/kg.

Total Decay Power Fraction of Operational Power

Cooling Time(s)	Irradiation Period Length: 1-s	10-s	100-s	1000-s	1-hour	1-day	1-week	1-mo.	1-year	2-year	3-year
1.00+00	3.18-03	1.49-02	3.08-02	4.31-02	4.94-02	5.78-02	6.03-02	6.26-02	6.02-02	5.85-02	5.71-02
4.00+00	1.57-03	9.25-03	2.35-02	3.56-02	4.19-02	5.03-02	5.28-02	5.50-02	5.34-02	5.20-02	5.08-02
1.00+01	7.20-04	5.19-03	1.71-02	2.89-02	3.52-02	4.36-02	4.61-02	4.83-02	4.72-02	4.62-02	4.53-02
4.00+01	1.76-04	1.58-03	8.45-03	1.89-02	2.51-02	3.34-02	3.59-02	3.79-02	3.77-02	3.71-02	3.66-02
1.00+02	6.48-05	6.15-04	4.19-03	1.28-02	1.88-02	2.71-02	2.96-02	3.15-02	3.17-02	3.14-02	3.10-02
4.00+02	1.23-05	1.21-04	1.09-03	6.29-03	1.14-02	1.93-02	2.19-02	2.37-02	2.43-02	2.42-02	2.40-02
1.00+03	5.10-06	5.08-05	4.87-04	3.55-03	7.40-03	1.48-02	1.73-02	1.91-02	1.98-02	1.98-02	1.97-02
4.00+03	1.07-06	1.06-05	1.05-04	9.10-04	2.51-03	8.01-03	1.05-02	1.22-02	1.31-02	1.31-02	1.31-02
1.00+04	2.99-07	2.97-06	2.95-05	2.78-04	8.66-04	4.84-03	7.25-03	8.49-03	9.96-03	1.00-02	1.01-02
4.00+04	5.10-08	4.93-07	4.91-06	4.84-05	1.68-04	1.96-03	3.60-03	5.63-03	6.38-03	7.08-03	7.21-03
1.00+05	1.66-08	1.49-07	1.47-06	1.46-05	5.20-05	8.68-04	2.43-03	3.56-03	4.80-03	5.07-03	5.32-03
4.00+05	4.83-09	3.14-08	2.97-07	2.95-06	1.06-05	2.27-04	9.74-04	1.83-03	2.94-03	3.14-03	3.31-03
1.00+06	2.79-09	1.10-08	9.35-08	9.18-07	3.29-06	7.48-05	3.99-04	9.77-04	1.94-03	2.09-03	2.22-03
4.00+06	2.03-09	3.42-09	1.73-08	1.56-07	5.58-07	1.32-05	8.48-05	2.82-04	9.30-04	1.07-03	1.19-03
1.00+07	1.92-09	2.36-09	6.68-09	5.00-08	1.75-07	4.13-06	2.80-05	1.08-04	4.95-04	6.28-04	7.43-04
4.00+07	1.88-09	1.93-09	2.39-09	7.04-09	2.05-08	4.47-07	3.09-06	1.28-05	1.15-04	1.95-04	2.68-04
1.00+08	1.88-09	1.89-09	1.99-09	3.05-09	6.12-09	1.04-07	7.12-07	3.03-06	3.43-05	6.64-05	1.00-04
4.00+08	1.88-09	1.88-09	1.91-09	2.21-09	3.09-09	3.10-08	2.05-07	8.72-07	1.07-05	2.18-05	3.45-05
1.00+09	1.88-09	1.88-09	1.90-09	1.84-09	2.65-09	2.05-08	1.32-07	5.59-07	7.31-06	1.52-05	2.35-05
4.00+09	1.87-09	1.87-09	1.88-09	1.91-09	2.00-09	4.81-09	2.24-08	9.12-08	2.07-06	5.01-06	7.64-06
1.00+10	1.87-09	1.87-09	1.88-09	1.89-09	1.92-09	3.03-09	9.91-09	3.76-08	1.15-06	2.82-06	4.09-06
4.00+10	1.87-09	1.87-09	1.87-09	1.88-09	1.92-09	2.98-09	9.54-09	3.51-08	5.23-07	1.05-06	1.40-06
1.00+11	1.86-09	1.86-09	1.86-09	1.87-09	1.91-09	2.91-09	9.12-09	3.29-08	3.30-07	5.44-07	6.80-07
4.00+11	1.82-09	1.82-09	1.82-09	1.83-09	1.85-09	2.62-09	7.31-09	2.47-08	1.99-07	2.93-07	3.44-07
1.00+12	1.74-09	1.74-09	1.74-09	1.75-09	1.76-09	2.20-09	4.91-09	1.47-08	9.63-08	1.21-07	1.38-07
4.00+12	1.40-09	1.40-09	1.40-09	1.40-09	1.40-09	1.43-09	1.60-09	2.23-09	7.25-09	9.41-09	1.08-08
1.00+13	9.40-10	9.40-10	9.40-10	9.40-10	9.40-10	9.40-10	9.41-10	9.45-10	1.09-09	1.61-09	2.47-09

ONE MONTH IRRADIATION

TABLE III

DECAY HEAT SOURCES IN TMI-2
TOTAL CORE VALUES IN MW VS COOLING TIME[a]
LASL - 7/79

(TOTAL)

COOLING TIME	NOBLE GAS (Kr + Xe)	HALOGENS (I + Br)	NOBLE GAS + HALOGENS	SPECIAL[b] SET	ALL FISSION PRODUCTS	ACTINIDES	ACTINIDES + FISSION PRODUCTS
1.00 + 0 s	1.39 + 1[c]	1.88 + 1	3.27 + 1	5.53 + 1	1.61 + 2	6.83 + 0	1.68 + 2
4.00 + 0 s	1.25 + 1	1.70 + 1	2.95 + 1	5.03 + 1	1.41 + 2	6.82 + 0	1.48 + 2
1.00 + 1 s	1.12 + 1	1.52 + 1	2.64 + 1	4.55 + 1	1.23 + 2	6.81 + 0	1.30 + 2
4.00 + 1 s	8.49 + 0	1.20 + 1	2.05 + 1	3.63 + 1	9.62 + 1	6.76 + 0	1.03 + 2
1.00 + 2 s	6.59 + 0	9.82 + 0	1.64 + 1	2.99 + 1	7.93 + 1	6.66 + 0	8.60 + 1
4.00 + 2 s	4.11 + 0	8.02 + 0	1.21 + 1	2.32 + 1	5.90 + 1	6.19 + 0	6.52 + 1
1.00 + 3 s	2.78 + 0	7.69 + 0	1.05 + 1	1.97 + 1	4.74 + 1	5.48 + 0	5.28 + 1
1.00 + 0 h	1.71 + 0	6.65 + 0	8.37 + 0	1.36 + 1	3.17 + 1	3.83 + 0	3.56 + 1
2.00 + 0 h	1.30 + 0	5.42 + 0	6.72 + 0	1.01 + 1	2.51 + 1	3.29 + 0	2.84 + 1
5.00 + 0 h	7.85 - 1	3.70 + 0	4.48 + 0	6.68 + 0	1.84 + 1	3.07 + 0	2.14 + 1
1.00 + 1 h	5.01 - 1	2.94 + 0	3.44 + 0	5.23 + 0	1.45 + 1	2.89 + 0	1.74 + 1
2.00 + 1 h	3.32 - 1	2.25 + 0	2.59 + 0	4.03 + 0	1.13 + 1	2.56 + 0	1.39 + 1
5.00 + 1 h	1.75 - 1	1.43 + 0	1.60 + 0	2.71 + 0	7.15 + 0	1.77 + 0	8.93 + 0
1.00 + 2 h	1.18 - 1	8.66 - 1	9.85 - 1	1.88 + 0	5.63 + 0	9.65 - 1	6.59 + 0
2.00 + 2 h	6.85 - 2	3.89 - 1	4.57 - 1	1.19 + 0	4.26 + 0	2.88 - 1	4.55 + 0
5.00 + 2 h	1.35 - 2	5.66 - 2	7.01 - 2	6.01 - 1	2.58 + 0	9.94 - 3	2.59 + 0
1.00 + 3 h	1.08 - 3	6.40 - 3	7.48 - 3	3.48 - 1	1.56 + 0	6.84 - 4	1.56 + 0
2.00 + 3 h	1.55 - 4	1.70 - 4	3.25 - 4	1.66 - 1	8.83 - 1	3.69 - 4	8.83 - 1
5.00 + 3 h	1.40 - 4	3.83 - 9	1.40 - 4	3.66 - 2	3.22 - 1	3.60 - 4	3.23 - 1
1.00 + 0 y	1.36 - 4	1.38 - 10	1.36 - 4	1.48 - 2	1.40 - 1	3.57 - 4	1.40 - 1
1.00 + 4 h	1.35 - 4	~ 0	1.35 - 4	1.29 - 2	1.15 - 1	3.57 - 4	1.15 - 1
2.00 + 4 h	1.25 - 4	~ 0	1.25 - 4	7.63 - 3	4.32 - 2	3.60 - 4	4.35 - 2
5.00 + 4 h	1.00 - 4	~ 0	1.00 - 4	4.74 - 3	1.09 - 2	3.80 - 4	1.13 - 2

[a] The last three columns were included in Table III provides the α, β, and γ components for these three columns.
[b] Special set includes all halogens (Br and I) plus requested Te, Ru, Cs, Ba, and Sr nuclides.
[c] Read 1.39 + 1 as $1.39 \times 10^{+1}$, etc.

* → NOTE ON METHOD OF DATA GENERATION:

1. Actinide heating computed with EPRI-CINDER code.
2. Fission product heating uses pulse functions from new ANS 5.1 decay heat standard up to 20 hours, including corrections for absorption using CINDER-10. EPRI-CINDER used for longer times to get accurate effect of absorption on heating (CINDER-10 and EPRI-CINDER agree within ~1%).
3. Noble gas, halogens and special set columns generated by CINDER-10.

NOTE: See Appendix C for graphical plots of gas fractions and detailed contributions of each noble gas and halogen.

TABLE IV

Characteristics of Important Short-Half-Life Fission-Product Isotopes

Isotope	Half-Life	Activity in Kilocuries per Megawatt of Thermal Power: Shutdown	Activity in Kilocuries per Megawatt of Thermal Power: 1 Day after Shutdown	Boiling Point (°C)	Volatility	Health Physics Properties
Br-83	2.3 h	3	0	59	Highly volatile	External whole-body radiation, moderate health hazard
-84	32 m	6	0	59	Highly volatile	
-85	3 m	8	0	59	Highly volatile	
-87	56 s	15	0	59	Highly volatile	
Kr-83m	114 m	3	0	−153	Gaseous	External radiation, slight health hazard
-85m	4.4 h	8	0.2	−153	Gaseous	
-87	78 m	15	0	−153	Gaseous	
-88	2.8 h	23	0.1	−153	Gaseous	
-89	3 m	31	0	−153	Gaseous	
-90	33 s	38	0	−153	Gaseous	
I-131	8 d	25	23	185	Highly volatile	External radiation, internal irradiation of thyroid, high radiotoxicity
-132[1]	2.3 h	38	0	185	Highly volatile	
-133	21 h	54	25	185	Highly volatile	
-134	52 m	63	0	185	Highly volatile	
-135	6.7 h	55	4.4	185	Highly volatile	
-136	86 s	53	0	185	Highly volatile	
Xe-131m	12 d	0.3	0.3	−108	Gaseous	External radiation, slight health hazard
-133m	2.3 d	1	0.7	−108	Gaseous	
-133	5.3 d	54	47	−108	Gaseous	
-135m	15.6 m	16	0	−108	Gaseous	
-135	9.2 h	25	4	−108	Gaseous	
-137	3.9 m	48	0	−108	Gaseous	
-138	17 m	53	0	−108	Gaseous	
-139	41 s	61	0	−108	Gaseous	
Te-127m	105 d	0.5	0.5	Released from oxidizing uranium		External radiation, moderate health hazard
-127	9.4 h	2.9	0.5	Released from oxidizing uranium		
-129m	34 d	2.3	2.3	Released from oxidizing uranium		
-129	72 m	9.5	0	Released from oxidizing uranium		
-131m	30 h	3.9	2.2	Released from oxidizing uranium		
-131	25 m	26	0	Released from oxidizing uranium		Health hazard from I-132 daughter[1]
-132	77 h	38	31	Released from oxidizing uranium		
-133m	63 m	54	0	Released from oxidizing uranium		External radiation, moderate health hazard
-133	2 m	54	0	Released from oxidizing uranium		
-134	44 m	63	0	Released from oxidizing uranium		
-135	2 m	55	0	Released from oxidizing uranium		

[1] Thirty-eight kilocuries of I-132 per megawatt of thermal power are generated in the reactor by decay of Te-132. Analyses that follow also consider the I-132 formed outside the reactor by decay of Te-132 released from a reactor accident.

From Beattie, 1961.

Characteristics of Important Long-Half-Life Fission-Product Isotopes

Isotope	Half-Life	Activity in Kilocuries per Megawatt of Thermal Power: After 1 Yr of Irradiation	Activity in Kilocuries per Megawatt of Thermal Power: After 3 Yr of Irradiation	Boiling Point (°C)	Volatility	Health Physics Properties
Kr-85	10.4 y	0.12	0.62	−153	Gaseous	Slight health hazard
Sr-89	54 d	39	39	1366	Moderately volatile	Internal hazard to bone and lung
-90	28 y	1.2	6.0	1366	Moderately volatile	
Ru-106	1.0 y	5	10	4080	Highly volatile oxides, RuO_3 and RuO_4	Internal hazard to kidney and GI tract
Cs-137	33 y	1.1	5.3	670	Highly volatile	Internal hazard to whole body
Ce-144	282 d	30	50	3470	Slightly volatile	Internal hazard to bone, liver, and lung
Ba-140	12.8 d	53	53	1640	Moderately volatile	Internal hazard to bone and lung

From Beattie, 1961.

SOURCE: NUCLEAR POWER REACTOR SAFETY BY E.E. LEWIS

TABLE IV

CURIES IN TMI-2
TOTAL CORE VALUES VS COOLING TIME[a]
[CINDER CALCULATIONS (LASL)]
7/79

COOLING SEC	TIME HOURS	ALL FISSION PRODUCTS	NOBLE GAS (Kr + Xe)	SPECIAL SET[b]	HALOGENS (Br + I)	ACTINIDES	TOTAL ACTINIDES + FP
1	2.78 - 4[c]	1.19 + 10	1.14 + 9	4.42 + 9	1.11 + 9	2.61 + 9	1.45 + 10
4	1.11 - 3	1.11 + 10	1.06 + 9	4.18 + 9	1.05 + 9	2.61 + 9	1.36 + 10
1.0 + 1	2.78 - 3	1.03 + 10	9.87 + 8	3.94 + 9	1.00 + 9	2.60 + 9	1.29 + 10
4.0 + 1	1.11 - 2	8.80 + 9	8.23 + 8	3.44 + 9	8.49 + 8	2.58 + 9	1.14 + 10
1.0 + 2	2.78 - 2	7.78 + 9	7.03 + 8	3.08 + 9	7.54 + 8	2.55 + 9	1.03 + 10
4.0 + 2	1.11 - 1	6.40 + 9	5.34 + 8	2.61 + 9	6.63 + 8	2.38 + 9	8.78 + 9
1.0 + 3	2.78 - 1	5.52 + 9	4.33 + 8	2.28 + 9	6.39 + 8	2.11 + 9	7.63 + 9
3.6 + 3	1.0	4.25 + 9	3.44 + 8	1.75 + 9	5.77 + 8	1.52 + 9	5.77 + 9
7.2 + 3	2.0	3.69 + 9	3.11 + 8	1.46 + 9	5.03 + 8	1.32 + 9	5.01 + 9
1.8 + 4	5.0	3.06 + 9	2.68 + 8	1.15 + 9	3.87 + 8	1.24 + 9	4.30 + 9
3.6 + 4	10.0	2.59 + 9	2.36 + 8	9.83 + 8	3.16 + 8	1.17 + 9	3.76 + 9
7.2 + 4	20.0	2.13 + 9	2.00 + 8	8.25 + 8	2.42 + 8	1.03 + 9	3.16 + 9
1.8 + 5	50.0	1.60 + 9	1.44 + 8	6.28 + 6	1.49 + 8	7.18 + 8	2.32 + 9
3.6 + 5	100.0	1.26 + 9	1.08 + 8	4.94 + 8	9.27 + 8	3.91 + 8	1.65 + 9
7.2 + 5	200.0	9.57 + 8	6.28 + 7	3.75 + 8	4.93 + 7	1.18 + 8	1.08 + 9
1.8 + 6	500.0	6.07 + 8	1.24 + 7	2.39 + 8	1.21 + 7	4.37 + 6	6.11 + 8
3.6 + 6	1000.0	3.95 + 8	9.66 + 5	1.50 + 8	1.83 + 6	3.22 + 5	3.95 + 8
7.2 + 6	2000.0	2.30 + 8	1.07 + 5	7.86 + 7	4.99 + 4	1.54 + 5	2.30 + 8
1.8 + 7	5000.0	7.94 + 7	9.32 + 4	2.59 + 7	1.24 + 0	1.49 + 5	7.95 + 7
3.1536 + 7	8760.0 (1 yr)	3.55 + 7	9.06 + 4	1.45 + 7	1.92 - 1	1.47 + 5	3.56 + 7
3.6 + 7	10000.0	2.98 + 7	8.98 + 4	1.29 + 7	1.92 - 1	1.46 + 5	2.99 + 7
7.2 + 7	20000.0	1.26 + 7	8.34 + 4	6.18 + 6	1.92 - 1	1.39 + 5	1.27 + 7
1.8 + 8	50000.0	4.10 + 6	6.69 + 4	2.41 + 6	1.92 - 1	1.20 + 5	4.22 + 7

[a] CINDER-10 calculations for fission products, EPRI-CINDER for actinides.

[b] Special set includes all halogens (Br and I) plus requested Te, Ru, Cs, Ba, and Sr nuclides.

[c] Read 2.78 - 4 as 2.78×10^{-4}, etc.

NOTE: See Appendix C for graphical plots of gas fractions and detailed contributions of each noble gas and halogen.