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SUBJECT: Activity in the HFIR Primary Coolant System after a Meltdown of the Fuel in Reactor

TO: W. R. Gall

FROM: H. A. McLain

Summary

An estimate was made of the fission product activity which would result in the HFIR primary coolant system following a meltdown of the fuel element within the reactor. The rare gases and the halogens appear to be the main contributors to the gamma activity in the coolant system immediately after the meltdown, and iodine appears to be the main contributor 24 hours after the meltdown.

DISCLAIMER

Introduction

Shielding is being planned for the HFIR primary coolant system to provide protection against radiation in case of a meltdown of the fuel element in the reactor. Fission products are released from the fuel in varying amounts during the meltdown, and some of them may adhere to the walls of the cooling system. Demineralizer and off-gas facilities are being planned to provide cleanup of the primary coolant water. This report is a summary of the work of estimating the activity in the cooling system after such a meltdown.

Release of Fission Products from Meltdown of the HFIR Fuel

On the basis of the melting of several irradiated aluminum-clad fuel plate specimens,[1] Parker and Creek[2] stated at a meeting of interested persons that the release of the following percentages of fission products during the melting of the HFIR fuel would be conservative:

Element	% Released
Krypton	100
Xenon	100
Bromine	10
Iodine	10
Selenium Molybdenum Tellurium Technicium Ruthenium	$\leq$ 1 for oxide fuels ~ 0 for alloy fuels
Rubidium	< 0.1
Cesium	< 0.1
Strontium	< 0.1
Barium	< 0.1
All others	0

These values are based on experiments on the melting of the fuel specimen in air.[1] Melting these specimens in a pool of water would result in the escape of less than 1% of the halogens and less than 50% of the rare gases to the air.[2] The other fission products are retained in the water. For the purposes of these calculations, it is assumed that all of the fission produces released from the fuel are kept within the water system immediately after the meltdown of the fuel.

The buildup of the fission products in the HFIR fuel can be estimated from charts prepared by Blomeke and Todd.[3] For the purposes of these calculations, it is assumed that the HFIR core contains 6 kg of U-235 which has operated for 10 days at 100 Mw.[4] The charts prepared by Blomeke and Todd are based on a fission cross section for uranium of 580 barns. An "effective neutron flux" which was used for these calculations was computed using this cross section and it is 3.48×10^{14} neuts/$cm^2 \cdot$sec. Table I shows the amount of fission products mentioned above in the HFIR core after 10 days operation at 100 Mw. Using the above values of the percentages of fission products released into the coolant during the meltdown, the amounts of fission products in the cooling system immediately after the meltdown of the HFIR core were calculated and are shown in Table I.

Adsorption of the Fission Products on the Coolant System Walls

Little is known regarding the adsorption of the fission products released during the meltdown on the walls of the coolant system, particularly at the HFIR conditions.[5] The effect of temperature and pH on this deposition is not well known, and quantitative information is limited. Edwards, et al,[6] ran tests in a mild steel loop at 180 psi and 60°C. This loop was pretreated with a sodium silicate solution to provide a protective layer against the corrosion of the mild steel. The inpile section of this loop was aluminum and it contained an unclad piece of enriched uranium-zircaloy alloy. The pH of the water in this loop was usually 5.5 to 6.5, but it occasionally had risen to 8.5. On the basis of the information presented in this report,[6] the following atom ratios of fission products deposited on the walls to those dispersed in the coolant are assumed:

Element	$\frac{\text{atoms fission product on surface}}{\text{atoms fission product in coolant}}$	
	pH = 7.0	pH = 5.0
Kr, Xe	0	0
I, Br	2.0	3.0×10^2
Se, Mo, Tc, Ru	1.0	1.3×10^3
Te	15.0	1.5×10^3
Ba, Sr	2.5	5.0×10^1
Rb, Cs	0	0

Since the values at a water pH of 5.0 are higher and since the reactor probably will be operated at this condition,[7] the ratios at this pH are used. Assuming that the deposition of the fission products on the cooling system surface is uniform, a system volume of 30,000 gal, and a surface area of 35,000 ft^2,[8] the fission product activities immediately after meltdown are shown in Table I.

TABLE I

Fission Product Activity in the HFIR Primary Coolant System after Meltdown

Isotope	Half-Life	Core Content After 10 Days Operation, Atoms	Isotope in Coolant System After Meltdown Atoms	Coolant Activity Immediately After Meltdown dis/ml sec	Surface Activity Immediately After Meltdown dis/cm^2 sec	Coolant Activity 24 hours After Meltdown dis/ml sec	Surface Activity 24 hours After Meltdown dis/cm^2 sec
Kr-83m	114m	1.46×10^{20}	1.46×10^{20}	1.30×10^{8}		1.21×10^{4}	
Kr-85m	4.36h	1.02×10^{21}	1.02×10^{21}	4.0×10^{8}		4.2×10^{-2}	
Kr-85	10.27y	8.0×10^{21}	8.0×10^{21}	1.54×10^{5}		7.3×10^{-4}	
Kr-87	78m	5.7×10^{20}	5.7×10^{20}	7.4×10^{8}		9.7×10^{-6}	
Kr-88	2.77h	1.65×10^{21}	1.65×10^{21}	1.01×10^{9}		1.12×10^{-2}	
Kr-89	3.18m	4.1×10^{19}	4.1×10^{19}	1.31×10^{9}			
Kr-90	~ 33s	6.2×10^{18}	6.2×10^{18}	1.15×10^{9}			
Kr-92	3.0s	3.5×10^{17}	3.5×10^{17}	7.1×10^{8}			
Xe-131m	12.0d	2.5×10^{20}	2.5×10^{20}	1.47×10^{6}		1.09×10^{3}	
Xe-133m	2.3d	1.25×10^{21}	1.25×10^{21}	3.8×10^{7}		3.0×10^{4}	
Xe-133	5.27d	9.1×10^{22}	9.1×10^{22}	1.22×10^{9}		5.2×10^{5}	
Xe-135m	15.6m	7.7×10^{19}	7.7×10^{19}	5.0×10^{8}		3.1×10^{6}	
Xe-135	9.13h	1.97×10^{20}	1.97×10^{20}	3.7×10^{7}		1.21×10^{6}	
Xe-137	3.9m	6.16×10^{19}	6.16×10^{9}	1.61×10^{9}		1.88×10^{-11}	
Xe-138	17m	2.5×10^{20}	2.5×10^{20}	1.50×10^{9}			
Xe-139	41s	8.8×10^{18}	8.8×10^{18}	1.31×10^{9}			
Xe-140	16s	2.7×10^{18}	2.7×10^{18}	1.03×10^{9}			
Br-82	35.87h	7.1×10^{17}	7.1×10^{16}	1.12×10	1.16×10^{4}	6.7	6.9×10^{3}
Br-83	2.4h	1.82×10^{20}	1.82×10^{19}	4.3×10^{4}	4.5×10^{7}	4.0×10	4.1×10^{4}
Br-84	30m	9.1×10^{19}	9.1×10^{18}	1.03×10^{5}	1.07×10^{8}	3.3×10	3.4×10^{4}
Br-85	3.0m	1.22×10^{19}	1.22×10^{18}	1.38×10^{5}	1.44×10^{8}		
Br-87	55.6s	8.5×10^{18}	8.5×10^{17}	3.1×10^{5}	3.2×10^{8}		
Br-88	15.5s	1.97×10^{18}	1.97×10^{17}	2.6×10^{5}	2.7×10^{8}		
I-130	12.6h	6.0×10^{18}	6.0×10^{17}	2.7×10^{2}	2.8×10^{5}	6.7×10	7.0×10^{4}
I-131	8.05d	4.8×10^{22}	4.8×10^{21}	1.41×10^{5}	1.46×10^{8}	1.21×10^{5}	1.25×10^{8}
I-132	2.4h	1.53×10^{21}	1.53×10^{20}	3.6×10^{5}	3.7×10^{8}	3.5×10^{4}	3.7×10^{7}
I-133	20.8h	2.2×10^{22}	2.2×10^{21}	5.0×10^{5}	5.2×10^{8}	2.5×10^{5}	2.6×10^{8}
I-134	52.5m	1.08×10^{21}	1.08×10^{20}	7.0×10^{5}	7.2×10^{8}	5.2×10^{-3}	5.4
I-135	6.68h	6.5×10^{21}	6.5×10^{20}	5.5×10^{5}	5.7×10^{8}	4.4×10^{4}	4.6×10^{7}
I-136	86s	1.22×10^{19}	1.22×10^{18}	2.9×10^{2}	3.0×10^{5}	1.36×10^{2}	1.42×10^{5}
I-138	5.9s	9.1×10^{17}	9.1×10^{16}	8.4×10^{4}	8.8×10^{7}		
I-139	2.7s	5.5×10^{16}	5.5×10^{15}	1.89×10^{4}	1.97×10^{7}		

TABLE I (continued)

Isotope	Half-Life	Core Content After 10 Days Operation, Atoms	Isotope in Coolant System After Meltdown Atoms	Coolant Activity Immediately After Meltdown dis/ml sec	Surface Activity Immediately After Meltdown dis/cm^2 sec	Coolant Activity 24 hours After Meltdown dis/ml sec	Surface Activity 24 hours After Meltdown dis/cm^2 sec
Se-77m	17.5s	1.40×10^{14}	1.40×10^{12}	3.8×10^{-1}	1.69×10^{3}		
Se-79m	3.9m	3.7×10^{17}	3.7×10^{15}	3.1×10	1.34×10^{5}		
Se-79	6.5×10^{4}y	1.06×10^{21}	1.06×10^{19}	3.4×10^{-5}	1.10×10^{-1}	2.4×10^{-5}	1.08×10^{-1}
Se-81m	56.5m	1.20×10^{18}	1.20×10^{16}	1.66×10	8.8×10^{4}	3.6×10^{-6}	1.62×10^{-2}
Se-81	17m	9.4×10^{17}	9.4×10^{15}	4.3×10	1.95×10^{5}		
Se-83	25m	1.20×10^{19}	1.20×10^{17}	3.8×10^{2}	1.69×10^{6}		
Se-84	≈ 2m	6.0×10^{18}	6.0×10^{16}	2.4×10^{3}	1.06×10^{7}		
Mo-99	67h	6.0×10^{22}	6.0×10^{20}	1.17×10^{4}	5.3×10^{7}	8.9×10^{3}	4.0×10^{7}
Mo-101	14.6m	1.93×10^{20}	1.93×10^{18}	1.04×10^{4}	4.7×10^{7}		
Mo-102	12m	1.34×10^{20}	1.34×10^{18}	8.7×10^{3}	3.9×10^{7}		
Te-125m	58d	6.0×10^{16}	6.0×10^{14}	4.9×10^{-4}	2.5	4.7×10^{-4}	2.4
Te-127m	90d	8.0×10^{20}	8.0×10^{18}	4.1	2.2×10^{4}	4.0	2.0×10^{4}
Te-127	9.3h	2.4×10^{20}	2.4×10^{18}	2.9×10^{2}	1.52×10^{6}	5.1×10	2.7×10^{5}
Te-129m	33d	8.3×10^{21}	8.3×10^{19}	1.18×10^{2}	6.2×10^{5}	1.14×10^{2}	5.9×10^{5}
Te-129	72m	1.40×10^{20}	1.40×10^{18}	1.32×10^{3}	6.8×10^{6}	1.14×10^{2}	5.9×10^{5}
Te-131m	30h	2.2×10^{20}	2.2×10^{18}	8.3×10^{2}	4.3×10^{6}	3.2	1.65×10^{4}
Te-131	24.8m	1.94×10^{20}	1.94×10^{18}	5.3×10^{3}	2.8×10^{7}	3.9	1.92×10^{4}
Te-132	77h	4.9×10^{22}	4.9×10^{20}	7.2×10^{3}	3.7×10^{7}	7.1×10^{3}	3.7×10^{7}
Te-133m	63m	1.03×10^{21}	1.03×10^{19}	1.11×10^{4}	5.8×10^{7}	1.52×10^{-3}	7.9
Te-134	44m	7.9×10^{20}	7.9×10^{18}	1.22×10^{4}	6.3×10^{7}	1.67×10^{-6}	8.7×10^{-1}
Te-135	< 2m	2.3×10^{19}	2.3×10^{17}	7.8×10^{3}	4.1×10^{7}		
Tc-99m	6.04h	5.5×10^{20}	5.5×10^{18}	1.19×10^{3}	5.4×10^{6}	9.3×10^{3}	4.1×10^{7}
Tc-101	14.0m	1.85×10^{20}	1.85×10^{18}	1.04×10^{4}	4.7×10^{7}		
Tc-102	< 25s	4.6×10^{18}	4.6×10^{16}	8.6×10^{3}	3.9×10^{7}		
Tc-107	< 1.5m	6.3×10^{17}	6.3×10^{15}	3.3×10^{2}	1.48×10^{6}		
Ru-103	41d	6.9×10^{22}	6.9×10^{19}	9.2×10	4.1×10^{5}	8.8×10^{2}	4.0×10^{6}
Ru-105	4.5h	6.3×10^{20}	6.3×10^{17}	1.83×10^{2}	8.2×10^{5}	8.3×10	3.8×10^{4}
Ru-106	1.0y	1.05×10^{22}	1.05×10^{19}	1.57	7.1×10^{3}	1.55×10	7.0×10^{4}
Ru-107	4m	2.2×10^{18}	2.2×10^{15}	4.3×10	1.94×10^{5}		
Rb-86	19.5d	4.5×10^{18}	4.5×10^{15}	1.63×10		7.5×10^{-8}	
Rb-88	17.8m	1.73×10^{20}	1.73×10^{17}	9.9×10^{5}		1.26×10^{-1}	

TABLE I (continued)

Isotope	Half-Life	Core Content After 10 Days Operation, Atoms	Isotope in Coolant System After Meltdown Atoms	Coolant Activity Immediately After Meltdown dis/ml sec	Surface Activity Immediately After Meltdown dis/cm^2 sec	Coolant Activity 24 hours After Meltdown dis/ml sec	Surface Activity 24 hours After Meltdown dis/cm^2 sec
Rb-89	15.4m	1.96×10^{20}	1.96×10^{17}	1.30×10^{6}			
Rb-90	2.74m	4.3×10^{19}	4.3×10^{16}	1.60×10^{6}			
Rb-91	14m	1.46×10^{20}	1.46×10^{17}	1.06×10^{6}			
Rb-92	80s	1.97×10^{19}	1.97×10^{16}	1.50×10^{6}			
Cs-134	2.0y	1.32×10^{18}	1.32×10^{15}	1.28×10^{-1}		6.0×10^{-10}	
Cs-136	13d	1.34×10^{20}	1.34×10^{17}	7.3×10^{2}		3.1×10^{-6}	
Cs-137	26.6y	1.56×10^{23}	1.56×10^{20}	1.14×10^{3}		7.1×10^{-5}	
Cs-138	32m	4.8×10^{20}	4.8×10^{17}	1.53×10^{6}			
Cs-139	9.5m	1.48×10^{20}	1.48×10^{17}	1.59×10^{6}			
Cs-140	66s	1.79×10^{19}	1.79×10^{16}	1.66×10^{6}			
Sr-89	54d	1.25×10^{23}	1.25×10^{20}	3.2×10^{3}	5.5×10^{5}	2.2×10^{3}	3.7×10^{5}
Sr-90	28y	1.54×10^{23}	1.54×10^{20}	2.1×10	3.6×10^{3}	1.45×10	2.4×10^{3}
Sr-91	9.7h	9.2×10^{21}	9.2×10^{18}	3.2×10^{4}	5.5×10^{6}	3.9×10^{3}	6.5×10^{5}
Sr-92	2.7h	2.7×10^{21}	2.7×10^{18}	3.3×10^{4}	5.8×10^{6}	4.8×10	8.2×10^{3}
Sr-93	7m	1.20×10^{20}	1.20×10^{17}	3.4×10^{4}	5.9×10^{6}		
Sr-94	20m	3.2×10^{19}	3.2×10^{16}	3.2×10^{4}	5.5×10^{6}		
Ba-137m	2.60m	2.9×10^{16}	2.9×10^{13}	2.2×10	3.9×10^{3}	1.25×10^{-2}	2.1
Ba-139	85m	1.39×10^{21}	1.39×10^{18}	3.3×10^{4}	5.7×10^{6}	1.04×10	1.73×10^{3}
Ba-140	12.80d	1.32×10^{23}	1.32×10^{20}	1.43×10^{4}	2.5×10^{6}	9.3×10^{3}	1.57×10^{6}
Ba-141	18m	2.9×10^{20}	2.9×10^{17}	3.2×10^{4}	5.6×10^{6}		
Ba-142	6m	8.9×10^{19}	8.9×10^{16}	3.0×10^{4}	5.1×10^{6}		
Ba-143	30s	6.6×10^{18}	6.6×10^{15}	2.6×10^{4}	4.6×10^{6}		

Removal of Fission Products from the Primary Coolant System

The active fission products released into the HFIR primary coolant system upon the meltdown of the fuel are removed by either decay or by the cleanup system. The cleanup system has provisions for removing the dissolved materials from the coolant water.

For the purposes of calculations, it is assumed that the isotopes deposited on the cooling system walls are in equilibrium with the cooling water at all times. Also it is assumed that the cleanup system removes all of the fission products from the water passing through it. A material balance may be written for the first number of a fission product decay chain as follows:

$$\frac{dN_{iw}}{dt} + \frac{dN_{is}}{dt} = -\lambda_i N_{iw} - \lambda_i N_{is} - \beta N_{iw}$$

where

N_{iw} = quantity of isotope in the water

N_{is} = quantity of isotope on the coolant system surfaces

λ_i = decay constant

β = cleanup constant = $\frac{\text{(flow rate to the cleanup system)}}{\text{(volume of system)}}$

t = time

Letting,

$$\delta_i = \frac{N_{is}}{N_{iw}} = \frac{\text{atoms of isotope on cooling system surfaces}}{\text{atoms of isotope in cooling system water}} ,$$

therefore,

$$\frac{dN_{is}}{dt} = \delta_i \frac{dN_{iw}}{dt} ,$$

and

$$\frac{dN_{iw}}{dt} = -\mu_i N_{iw}$$

where

$$\mu_i = \lambda_i + \frac{\beta}{1 + \delta_i} \quad .$$

Writing a similar material balance for the second member of a fission product decay chain,

$$\frac{dN_{(i+1)w}}{dt} + \frac{dN_{(i+1)s}}{dt} = \lambda_i N_{iw} + \lambda_i N_{is} - \lambda_{i+1} N_{(i+1)w} - \lambda_{i+1} N_{(i+1)s} - \beta N_{(i+1)w} \quad .$$

Letting,

$$\delta_{i+1} = \frac{N_{(i+1)s}}{N_{(i+1)w}} \quad ,$$

therefore,

$$\frac{dN_{(i+1)s}}{dt} = \delta_{i+1} \frac{dN_{(i+1)w}}{dt} \quad ,$$

and

$$\frac{dN_{(i+1)w}}{dt} = \epsilon_i N_{iw} - \mu_{i+1} N_{(i+1)w}$$

where

$$\epsilon_i = \frac{1 + \delta_i}{1 + \delta_{i+1}} \lambda_i$$

$$\mu_{i+1} = \lambda_{i+1} + \frac{\beta}{1 + \delta_{i+1}} \quad .$$

Solving these equations for N_{iw} and $N_{(i+1)w}$,

$$N_{iw} = N_{iw}^{o} e^{-\mu_i t}$$

$$N_{(i+1)w} = N_{(i+1)w}^{o} e^{-\mu_{i+1} t} + \frac{\epsilon_i N_{iw}^{o}}{\mu_{i+1} - \mu_i} \left[e^{-\mu_i t} - e^{-\mu_{i+1} t} \right]$$

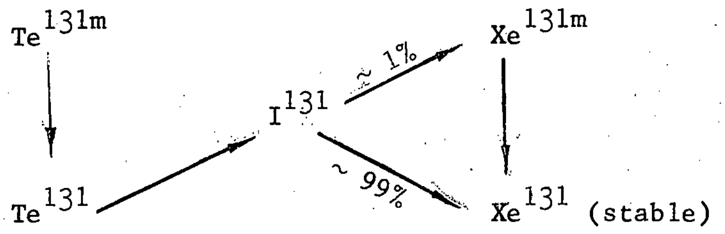
where

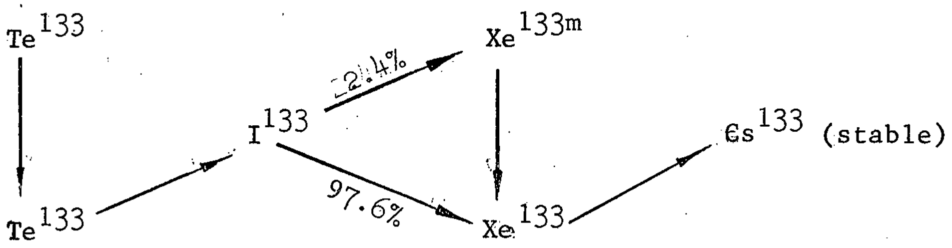
$N_{iw}^{o} = N_{iw}$ immediately after the meltdown

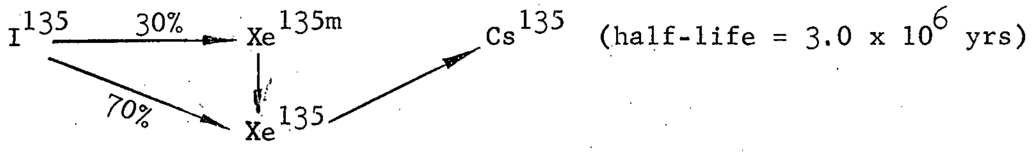
$N_{(i+1)w}^{o} = N_{(i+1)w}$ immediately after the meltdown

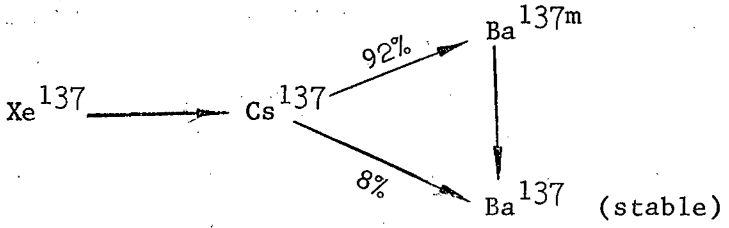
t = time after meltdown .

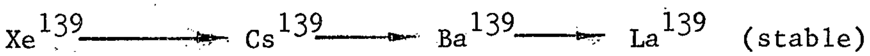
The removal of most of the isotopes released during the meltdown of the fuel from the primary coolant system can be represented by the above equations. However, there are some specific cases where the released isotope must be considered as a third or a higher number member of a decay chain. Specific decay chains considered for these special cases are as follows:











Material balances in the form of differential equations similar to those shown above can be written for each member in the above chains. These equations then can be solved for the quantity of each isotope in the system by the use of Laplace transformation methods.

The cleanup bypass stream flow rate is 400 gpm[8] which gives a value of the cleanup constant β of 400/30,000 or 0.0133 min^{-1}. Using this value and the above relations, the concentrations of the fission product activities in the water and on the surfaces 24 hours after the meltdown were calculated. These values are shown in Table I.

Gamma Sources in Coolant System

The number and energy of gamma photons given off from the disintegrating isotopes are given by Blomeke and Todd.[3] For convenience, the photons are listed in four energy ranges.[3] Table II shows the gamma sources in the HFIR primary coolant system immediately following the meltdown of the fuel element. Table III shows the gamma sources in the coolant system 24 hours after the meltdown.

Discussion

Many assumptions were made in obtaining the coolant system activity following the meltdown of the HFIR fuel. In particular, the values used for the amount of fission products deposited on the coolant system surfaces are a very rough estimate based on some semi-quantitative data obtained by Edwards, et al.[6] It was assumed that the deposition of fission products on the coolant system is uniform which probably is not actually true. The system volume to surface ratio was ignored in considering the wall deposition. Also particles of uranium oxide which contain fission products may be suspended in the water following the meltdown. These were ignored in these computations.

Inspection of Tables II and III shows that the halogens and the rare gases constribute to most of the gamma activity in the coolant system. After 24 hours, iodine appears to be the major source of activity. This occurs because iodine and its precursor, tellurium, are very readily deposited on the coolant system surfaces. These results appear to be consistent with the data obtained at the Westinghouse Testing Reactor during the period following the meltdown of a fuel element in this reactor. Binford[9] peeled the decay curves of the WTR head tank activity[10] and obtained decay constants approximately equal to those of I^{135}, Br^{84}, and Kr^{88}. These isotopes also appear to a major source of activity in the HFIR coolant following the meltdown of the fuel in the reactor.

Conclusions

An estimate has been made of the fission product activity in the HFIR primary coolant system immediately following and 24 hours following the melting of the fuel within the reactor. Many assumptions were made in making this estimate, particularly the one regarding the amount of isotopes adsorbed on the cooling system surfaces. The rare gases and the halogens appear to be the main contribution to the gamma activity in the coolant system immediately after the meltdown, and iodine appears to be the main contribution 24 hours after the meltdown. These results seem to be consistent with the data obtained at the Westinghouse Testing Reactor following the fuel element meltdown in that reactor.

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✓ Should be CF-60-4-104
Report is preliminary and not for external distribution. Superseded by WTR-49. per N. T. Bray 2/7/61

Table II

Gamma Sources in the HFIR Primary Coolant System Immediately after Meltdown

Isotope	Coolant				Surface			
	Group I $E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group II $0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group III $1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group IV $E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group I $E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group II $0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group III $1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group IV $E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$
Kr-83m	2.6×10^8							
Kr-85m	3.2×10^8	8.0×10^7						
Kr-85								
Kr-87		1.5×10^8		1.9×10^8				
Kr-88	5.0×10^8	2.8×10^8	1.8×10^8	6.9×10^8				
Kr-89								
Kr-90								
Kr-92								
Xe-131m	1.5×10^6							
Xe-133m	3.8×10^7							
Xe-133	1.2×10^9							
Xe-135m		5.0×10^8						
Xe-135	3.6×10^7	1.9×10^6						
Xe-137								
Xe-138								
Xe-139								
Xe-140								
Br-82		1.1×10	2.2×10			1.2×10^4	2.3×10^4	
Br-83	4.3×10^4				4.5×10^7			
Br-84		1.5×10^5		5.2×10^4		1.6×10^8		5.4×10^7
Br-85								
Br-87				2.2×10^5				2.2×10^5
Br-88								
I-130			8.4×10				8.7×10^4	
I-131	1.4×10^5	1.4×10^5			1.5×10^8	1.4×10^8		
I-132		8.1×10^5	6.8×10^4	2.5×10^4		8.4×10^8	7.0×10^7	2.6×10^7
I-133		5.9×10^5	6.0×10^3			6.1×10^8	6.2×10^6	
I-134		2.1×10^4	2.5×10^5	2.5×10^5		3.2×10^7	2.5×10^8	2.5×10^8
I-135			2.8×10^5	2.8×10^5			2.9×10^8	2.9×10^8
I-136								
I-138								
I-139								

Table II contd

Isotope	Coolant				Surface			
	Group I	Group II	Group III	Group IV	Group I	Group II	Group III	Group IV
	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$
Se-77m	3.8×10^{-1}				1.7×10^3			
Se-79m	3.1×10				1.4×10^5			
Se-79								
Se-81m	1.7×10				8.8×10^4			
Se-81								
Se-83	7.6×10^2	7.6×10^2			3.4×10^6	3.4×10^8		
Se-84								
Mo-99	1.1×10^4	1.2×10^3			4.8×10^7	5.3×10^6		
Mo-101	1.0×10^4	7.3×10^3			4.7×10^7	3.3×10^3		
Mo-102								
Te-125m	4.9×10^{-4}				2.5			
Te-127m	4.1				2.2×10^4			
Te-127								
Te-129m	1.2×10^2				6.2×10^5			
Te-129		2.6×10^3				1.4×10^7		
Te-131m	8.3×10^2				4.3×10^6			
Te-131	5.3×10^3	2.4×10^3			2.8×10^7	1.3×10^7		
Te-132	7.2×10^3				3.7×10^7			
Te-133m		1.1×10^4				5.8×10^7		
Te-134								
Te-135								
Tc-99m	1.2×10^3				5.4×10^6			
Tc-101		1.0×10^4				4.7×10^7		
Tc-102								
Tc-107								
Ru-103		8.7×10				3.9×10^5		
Ru-105		1.8×10^2				8.2×10^5		
Ru-106								
Ru-107								

Table II contd

Isotope	Coolant				Surface			
	Group I	Group II	Group III	Group IV	Group I	Group II	Group III	Group IV
	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$
Rb-86			2.0					
Rb-88		5.0×10^4		2.2×10^5				
Rb-89								
Rb-90								
Rb-91								
Rb-92								
Cs-134		2.6×10^{-1}	1.3×10^{-2}					
Cs-136		7.3×10^2						
Cs-137								
Cs-138		1.5×10^6	1.5×10^6					
Cs-139								
Cs-140								
Sr-89								
Sr-90								
Sr-91		2.0×10^4	1.3×10^4			3.4×10^6	2.2×10^5	
Sr-92								
Sr-93								
Sr-94								
Ba-137m		2.2×10				3.9×10^3		
Ba-139	2.2×10^4		6.3×10^3		3.8×10^6		1.1×10^6	
Ba-140	1.6×10^4	5.7×10^3			2.8×10^5	1.0×10^6		
Ba-141								
Ba-142								
Ba-143								
Total	2.4×10^9	1.0×10^9	1.8×10^8	8.8×10^8	3.8×10^8	1.9×10^9	6.2×10^8	3.0×10^9

Table III

Gamma Sources in the HFIR Primary Coolant System
24 hours after Meltdown

Isotope	Coolant				Surface			
	Group I $E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group II $0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group III $1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group IV $E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec ml}}$	Group I $E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group II $0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group III $1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	Group IV $E \geqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$
Kr-83m	2.4×10^4							
Kr-85m	3.4×10^{-2}	8.4×10^{-3}						
Kr-85								
Kr-87	1.9×10^{-6}	2.4×10^{-6}						
Kr-88	5.5×10^{-3}	3.1×10^{-3}	2.0×10^{-3}	7.6×10^{-3}				
Xe-131m	1.1×10^3							
Xe-133m	3.0×10^4							
Xe-133	5.2×10^5							
Xe-135m		3.1×10^6						
Xe-135	1.2×10^6	6.0×10^5						
Xe-137								
Br-82		6.7	1.3×10			6.9×10^3	1.4×10^4	
Br-83	4.0×10				4.1×10			
Br-84		5.0×10		1.7×10		5.1×10^4		1.7×10^4
I-130			2.1×10				2.2×10^4	
I-131		1.2×10^5				1.2×10^8		
I-132		7.9×10^4	6.6×10^3	2.5×10^3		8.4×10^7	7.0×10^6	2.6×10^6
I-133		2.5×10^5	2.5×10^3			2.6×10^8	2.6×10^6	
I-134		1.6×10^{-4}	1.8×10^{-3}	1.8×10^{-3}		1.6×10^{-1}	1.9	1.9
I-135			2.2×10^4	2.2×10^4			2.3×10^7	2.3×10^7
I-136								
Se-79								
Se-81m	3.6×10^{-6}				1.6×10^{-2}			
Mo-99	8.0×10^3	8.9×10^2			3.6×10^7	4.0×10^6		

Table III contd

Isotope	Coolant				Surface			
	Group I	Group II	Group III	Group IV	Group I	Group II	Group III	Group IV
	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \geqslant 1.71$ Mev $\frac{\text{photons}}{\text{sec ml}}$	$E \leqslant 0.25$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$0.26 \leqslant E \leqslant 1.00$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$1.01 \leqslant E \leqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$	$E \geqslant 1.70$ Mev $\frac{\text{photons}}{\text{sec cm}^2}$
Te-125	4.7×10^{-4}				2.4			
Te-127m	4.0				2.0×10^{4}			
Te-127								
Te-129m	1.1×10^{2}				5.9×10^{5}			
Te-129		2.3×10^{2}				1.2×10^{6}		
Te-131m	3.2				1.7×10^{7}			
Te-131	3.9	1.8			1.9×10^{4}	8.7×10^{3}		
Te-132	7.1×10^{3}				3.7×10^{7}			
Te-133m		1.5×10^{-3}				7.9		
Te-134								
Tc-99m	9.3×10^{3}				4.1×10^{7}			
Rb-86			9.0×10^{-9}					
Rb-88		6.3×10^{-3}		2.8×10^{-2}				
Cs-134		1.2×10^{-9}	6.0×10^{-11}					
Cs-136		3.1×10^{-6}						
Cs-137								
Sr-89								
Sr-90								
Sr-91		2.4×10^{3}	1.6×10^{3}			4.0×10^{5}	2.6×10^{5}	
Sr-92								
Ba-137m		1.3×10^{-2}				2.1		
Ba-139	6.9		2.0		1.1×10^{2}		3.3×10^{2}	
Ba-140	1.0×10^{4}	3.7×10^{3}			1.7×10^{6}	6.3×10^{5}		
Total	1.8×10^{6}	4.2×10^{6}	3.3×10^{4}	2.5×10^{4}	1.2×10^{8}	4.7×10^{8}	3.3×10^{7}	2.6×10^{7}

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