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FATALITY RISK ESTIMATION FOR REPLACEMENT TRITIUM FACILITY

by

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Fatality Risk Estimation for Replacement Tritium Facility (U)

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[Abstract]

Prompt and latent cancer fatality risks are estimated in this report for the operation of the Replacement Tritium Facility (RTF) at the Savannah River Site (SRS). The purpose of this report is to demonstrate that : 1) the calculated fatality risk for the RTF operation is well within the quantitative Nuclear Safety Goals established by the Department of Energy (DOE) and 2) a simple point estimate method can produce results comparable to those of more detailed calculation utilizing computer codes and protocols developed for Probabilistic Risk Assessment (PRA) of nuclear power reactors.

Point estimates of prompt and cancer fatality risks are performed using a simple mathematical formalism derived from the complementary cumulative distribution function (CCDF) of consequences. The protocol of establishing CCDF is based on a successive summation of event frequencies. The consequences (i.e., calculated individual radiation doses at site boundary) and associated event frequencies are available from the RTF Final Safety Analysis Report (FSAR).

The results indicate that calculated prompt fatality and cancer fatality risks due to RTF operation are 0 and $1.5 \times 10^{-9}/\text{yr}$, respectively, well below the DOE's Safety Goals of $5 \times 10^{-7}/\text{yr}$ (prompt fatality) and $2 \times 10^{-6}/\text{yr}$ (cancer fatality). The agreement between the point estimate method and the PRA method is very good considering the differences in assumptions between the two methods (i.e., additional earthquake-induced scenarios).

Introduction

The RTF is designed and constructed to replace the existing tritium loading facilities at the SRS. A detailed description of the RTF design and operation is presented in the FSAR ¹. The FSAR also presents analyses of various postulated accident scenarios in terms of radiological consequences (e.g., maximum individual doses or MIDs) and associated event frequencies as well as the consequence of normal operation. The analyses in FSAR are, in principle, deterministic analyses of selected discrete accident scenarios using computer codes AXAIR89Q ² for radiological dose calculation and CAFTA³ for frequency estimation. The results are point estimates of radiation doses and frequencies for discrete accident events. These point estimates are not directly comparable to the DOE's Nuclear Safety Goals defined in terms of *total* fatality risks from *all accidents* to an *average individual* at the site boundary and within 10 miles from that site boundary ⁴. In order to estimate the radiological risk comparable to the DOE's Nuclear Safety Goals, an additional probabilistic risk analysis using such computer codes as MACCS and FUSCRACK3 was performed recently ⁵.

The computer codes, MACCS and FUSCRACK3 have been developed for PRAs of commercial nuclear reactors and these codes require statistically distributed inputs. Therefore, the results of AXAIR89Q and CAFTA (i.e., point estimates) currently available from SARs of nonreactor facilities at SRS can not be directly used for MACCS or FUSCRACK3.

In order to utilize the results of accident analyses typically available in the SARs (i.e., point estimates based on predetermined parameters), a simple mathematical formalism and protocol were proposed in a recent report ⁶. In this report, mathematical expression for the estimate of total fatality risk was derived from a complementary cumulative distribution function, CCDF (or simply called annual exceedance probability/frequency) of consequence and its integrals. The protocol for establishing CCDF is based on a successive summation of discrete event frequencies followed by enveloping high points with a straight line (Limit Line). Further details are presented in Reference 6 as an example case analysis. It was shown that total prompt fatality and latent cancer fatality risks comparable with DOE's Nuclear Safety Goals can be calculated from exceedance probabilities of radiation dose [denoted by $P(>D)$] summarized below.

The prompt fatality risk, F_p can be expressed as

$$(1) \quad F_p = P(> D_L)$$

for the case when the dose-response function is a step function (i.e., probability of prompt fatality changes from 0 to 1.0 at $D = D_L$ where D_L is the lethal dose), or

$$(2) \quad F_p = \left(\frac{1}{D_2 - D_1} \right) \cdot \int_{D_1}^{D_2} P(> D) \cdot dD$$

for the case when dose-response function is a linear function between D_1 and D_2 (i.e., probability of prompt fatality increase linearly from 0 to 1 between D_1 and D_2).

The latent cancer fatality risk, F_c can be calculated by

$$(3) \quad F_c = K \cdot \int_0^{D_{\max}} P(> D) \cdot dD$$

where K is the cancer rate per exposure (i.e., cancer per rem).

The above simple method is used for the calculation of fatality risks due to RTF operation as shown below.

Summary of FSAR and Data Adjustment

The RTF FSAR presents various discrete accident scenarios and resulting radiation doses to various target individuals and population groups. Additional accident scenarios initiated by Design Basis Earthquakes (DBE) are analyzed recently and reported in the SAR Addendum ⁷. The individual accident scenarios and normal operation selected for this analysis are summarized in Table I, Frequency and MID columns.

Since the MID values are the maximum individual CEDE (cumulative effective dose equivalent), that is, 50-year cumulative effective dose equivalent to a hypothetical person at the worst sector of the site boundary (maximum individual), the MID values need to be adjusted to represent *average acute individual doses* at the site boundary and *average* individual CEDE within 10 miles from the site boundary.

Two factors, meteorological dispersion factor (χ/Q) and dose accumulation time factor, need to be considered for the adjustment. The adjustment due to χ/Q differences between the worst sector and average sector can be made by the following equation (m_1 denotes the adjustment factor).

$$m_1 = \frac{\sum_{i,j} [(\chi/Q)_{i,j} \times P_{i,j}]}{(\chi/Q)_{\text{MID}} \times \sum_{i,j} (P_{i,j})}$$

where $(\chi/Q)_{i,j} = \chi/Q$ at distance i and directional sector j
 $(\chi/Q)_{\text{MID}} = \chi/Q$ at worst sector of site boundary, and
 $P_{i,j} =$ population in i,j -segment.

Using the χ/Q values and population distribution listed in Table II ⁸, m_1 is calculated to be 0.6 at the site boundary and 0.005 for a 10 mile band from the site boundary.

The adjustment factor, m_2 for conversion of CEDE to acute dose can be expressed by following equation.

$$m_2 = \frac{1 - \exp(-0.17\Lambda)}{1 - \exp(-50\Lambda)},$$

where $\Lambda = (\ln 2)/T_{1/2}$, and $T_{1/2}$ is the effective half life of tritium, which is about 10 days (0.027 yr)⁹. For the purpose of this analysis, acute dose is defined as cumulative dose effect for 60 days (0.17 yr) due to a short term inhalation of tritium. Using the above values, the m_2 is calculated to be 0.99, which means that acute dose is about the same as CEDE (i.e., 99% of CEDE due to a single tritium intake is contributed during the first 60 days).

Using m_1 and m_2 , the MID values can be converted to acute dose to an average person at the site boundary, and CEDE to average person within 10 miles of the site boundary by multiplying by 0.6 (0.6×0.99) and 0.005 (m_1 only), respectively. The results are also summarized in Table I. It should be noted that the MID for Normal Operation reported in the FSAR (Event 10 of Table I) is based on annual average χ/Q , hence the adjustment factor for 10 mile average CEDE is 0.5 (ratio of annual average χ/Q at site boundary and χ/Q at 10 mile segments).

Prompt Fatality Risk

From Table I, the exceedance probability of acute dose, $P(>D)$ can be established as shown in Table III and graphically shown in Figure 1 with a Limit Line.

From Figure 1, it is apparent that the prompt fatality risk is 0 (i.e., the integral of equation 1 or 2 is 0, since the maximum acute dose of about 4 rem is much smaller than D_L or D_1 which is on the order of a few hundred rem¹⁰).

Latent Cancer Fatality

For the cancer fatality risk, the exceedance probabilities are established using the 10-mile average individual CEDE, and the result is summarized in Table IV and graphically shown in Figure 2 with Limit Line. The cancer fatality risk is calculated by integration of the Limit Line according to Equation (3). Various cancer rates per exposure have been reported in literature, but a cancer rate of $K = 8 \times 10^{-4}$ /rem¹¹ was used in this study for conservatism. In the calculation below, the normal operation includes anticipated operational occurrences (i.e., $P(>D)=0.01$ or $D < 1.4 \times 10^{-5}$ rem).

$$\begin{aligned}
F_o &= (8 \times 10^{-4}) \cdot \int_0^{0.033} P(> D) \cdot dD \\
&= (8 \times 10^{-4}) \cdot \left\{ \int_0^{1.4(-5)} P(> D) \cdot dD + \int_{1.4(-5)}^{0.033} P(> D) \cdot dD \right\} \\
&= (8 \times 10^{-4}) (7.2 \times 10^{-7} + 1.1 \times 10^{-6}) \\
&= 5.8 \times 10^{-10} / \text{yr (normal operation)} + 9.0 \times 10^{-10} / \text{yr (accident)} \\
&= 1.5 \times 10^{-9} / \text{yr (total)}
\end{aligned}$$

Uncertainty

As indicated in the previous sections, the fatality estimation in this report is a deterministic point estimate based on "*average values*" of consequences and associated frequencies available from existing FSAR. Although "average values" in the FSAR are not rigorously defined from mathematical standpoint (e.g., they varies between mean, median, nominal, and best estimates), they tend to be on the conservative side. Therefore, fatality risk estimates in this report may also be a conservative estimation for the *average* population. No attempt is made in this report to define the uncertainty associated with the calculated risk, since doing so will reduce the usefulness of the approach taken in this report, which is to make point estimates of fatality risks comparable to DOE's Safety Goals utilizing the results readily available from existing FSAR without utilizing PRA methods.

In a recent presentation by G.T. Medford, et.al. at EFGOG workshop¹², it was shown that nominal point estimates of frequencies and source terms for a fire scenario agree reasonably well with the mean risk values by MUPPET code with Monte Carlo sampling technique except for the low frequency/high source term extreme range (NOTE: Low frequency-high consequence end of the Limit Line contribute very little to total cancer risk). Several papers by Helton, et.al. ¹³ indicated that mean or 50 percentile consequence values are reasonable "average" estimates of consequences (i.e., they falls between 5-95 percentile values). Therefore, it is concluded that fatality risk estimates in this report are adequate estimates for the purpose of comparing with DOE's Safety Goals which are defined by point values.

Conclusion

Based on the preceding analysis and discussion, it is concluded that the prompt fatality risk and cancer fatality risk due to RTF operation are substantially below the DOE's Safety Goals as summarized below.

	<u>RTF</u>	<u>Safety Goal</u>
Prompt Fatality	0	5×10^{-7} /yr
Latent Cancer Fatality	1.5×10^{-9} /yr	2×10^{-6} /yr

The total cancer fatality risk is about equally contributed from normal operation including anticipated occurrences (40 % of total) and hypothetical accidents (60 % of total).

It should be noted that the analysis in this paper include additional earthquake-induced accident scenarios (events 8A through K2 in Table I), which were not included in the analysis of Reference 5. Furthermore, all the earthquake-induced events are treated as discrete independent events in this report, although the frequency value of initiating event (i.e., earthquake) is clearly an exceedance frequency. Considering the above conservatism, the result in this paper is generally in a good agreement with that of PRA methods presented in Reference 5 (i.e., 0 prompt fatality and 8.7×10^{-10} /yr total cancer fatality). Hence, it is concluded that a simple approach taken in this paper is a useful and economical alternative method to the PRA method for estimation of fatality risks comparable to DOE Safety Goals.

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TABLE I
Individual Dose Summary

	<u>Event/Sequence</u>	<u>Frequency</u> (/yr)	<u>MID-CEDE</u> (rem)	<u>Site Boundary</u> <u>Acute Dose (rem)</u>	<u>10 Mile Average</u> <u>CEDE (rem)</u>
1	Rupture/Leak	2.4 (-4)	1.7 (-3)	1.0 (-3)	8.5 (-6)
2	N2 Line Breach	5.3 (-6)	1.4 (-9)	8.4 (-10)	7.0 (-12)
3	Confinement Failure	3.0 (-2)	8.4 (-6)	5.0 (-6)	4.2 (-8)
4	Vessel Leak During Maintenance	6.0 (-4)	1.4 (-5)	8.4 (-6)	7.0 (-8)
5	Deflagration During Maintenance	3.9 (-6)	3.4 (-1)	2.0 (-1)	1.7 (-3)
6	Fire with GB Breach	5.2 (-3)	6.4 (-8)	3.8 (-8)	3.2 (-10)
7	Design Basis Tornado	1.1 (-6)	2.0 (-7)	1.2 (-7)	1.0 (-9)
8	Earthquake				
	A	2.0 (-4)	3.1 (-3)	1.9 (-3)	1.6 (-5)
	B	2.0 (-5)	2.9 (-1)	1.7 (-1)	1.5 (-3)
	C1	2.0 (-5)	8.5 (-2)	5.1 (-2)	4.3 (-4)
	C2	2.0 (-5)	1.8 (+0)	1.1 (+0)	9.0 (-3)
	D1	2.0 (-6)	2.6 (-1)	1.6 (-1)	1.3 (-3)
	D2	2.0 (-6)	1.9 (+0)	1.1 (+0)	9.5 (-3)
	D3	2.0 (-7)	1.9 (+0)	1.1 (+0)	9.5 (-3)
	E1	1.2 (-6)	4.9 (-3)	2.9 (-3)	2.5 (-5)
	E2	9.4 (-9)	4.3 (-3)	2.6 (-3)	2.2 (-5)
	F1	1.2 (-7)	1.9 (+0)	1.1 (+0)	9.5 (-3)
	F2	1.2 (-7)	3.7 (+0)	2.1 (+0)	1.9 (-2)
	F3	9.4 (-10)	1.2 (+0)	7.2 (-1)	6.0 (-3)
	G1	1.2 (-8)	2.2 (+0)	1.3 (+0)	1.1 (-2)
	G2	1.2 (-9)	3.7 (+0)	2.1 (+0)	1.9 (-2)
	G3	9.4 (-11)	1.5 (+0)	9.0 (-1)	7.5 (-3)
	H1	4.8 (-7)	7.1 (-3)	4.3 (-3)	3.6 (-5)
	H2	7.8 (-9)	9.5 (-3)	5.7 (-3)	4.8 (-5)
	I1	4.8 (-8)	4.0 (+0)	2.4 (+0)	2.0 (-2)
	I2	4.8 (-9)	5.8 (+0)	3.5 (+0)	2.9 (-2)
	I3	7.7 (-11)	6.5 (+0)	3.9 (+0)	3.3 (-2)
	J1	4.8 (-8)	7.3 (-1)	4.4 (-1)	3.7 (-3)
	J2	4.8 (-10)	4.4 (-1)	2.6 (-1)	2.2 (-3)
	J3	4.8 (-11)	2.5 (+0)	1.5 (+0)	1.3 (-2)
	K1	2.8 (-9)	4.3 (+0)	2.6 (+0)	2.2 (-2)
	K2	2.8 (-10)	5.8 (+0)	3.5 (+0)	2.9 (-2)
9	STCS Single Point Failure	2.0 (-6)	1.7 (+0)	1.0 (+0)	8.5 (-3)
10	Normal Operation	1.0	2.2 (-7)	NA	1.1 (-7)

TABLE II
Off-site Population and Meteorology Data Base

<u>SECTOR</u>	5-10 Mile <u>χ/Q</u>	5-10 Mile <u>Population</u>	10-20 Mile <u>χ/Q</u>	10-20 Mile <u>Population</u>
S	2.48	8	1.08	50
SSW	3.69	7	1.60	65
SW	5.79	6	2.50	109
WSW	4.62	7	2.04	167
W	3.73	170	1.81	145
WNW	3.17	856	1.52	683
NW	3.83	135	1.59	2329
NNW	5.77	1580	2.35	4381
N	4.62	21	2.11	1301
NNE	4.88	46	2.24	69
NE	4.76	56	2.29	299
ENE	4.67	21	2.28	779
E	4.39	5	1.93	1231
ESE	4.32	0	1.87	440
SE	2.84	0	1.23	92
SSE	2.24	0	0.97	139

NOTE: The unit of χ/Q is 10^{-8} sec/m³

TABLE III
P(>D) for Prompt Fatality

<u>Acute Dose at Site Boundary (rem)</u>	<u>Events #</u>	<u>Frequency (/yr)</u>	<u>P(>D)</u>
3.9(+0)	I3	7.7(-11)	7.7(-11)
3.5(+0)	I2+K2	5.1(-9)	5.2(-9)
2.6(+0)	K1	2.8(-9)	8.0(-9)
2.4(+0)	I1	4.8(-8)	5.6(-8)
2.1(+0)	F2+G2	1.2(-7)	1.8(-7)
1.5(+0)	J3	4.8(-11)	1.8(-7)
1.3(+0)	G1	1.2(-8)	1.9(-7)
1.1(+0)	C2+D2+D3+F1	2.2(-5)	2.2(-5)
1.0(+0)	9	2.0(-6)	2.4(-5)
9.0(-1)	G3	9.4(-11)	2.4(-5)
7.2(-1)	F3	9.4(-10)	2.4(-5)
4.4(-1)	J1	4.8(-8)	2.4(-5)
2.6(-1)	J2	4.8(-10)	2.4(-5)
2.0(-1)	5	3.9(-6)	2.8(-5)
1.7(-1)	B	2.0(-5)	4.8(-5)
1.6(-1)	D1	2.0(-6)	5.0(-5)
5.1(-2)	C1	2.0(-5)	7.0(-5)
5.7(-3)	H2	7.8(-9)	7.0(-5)
4.3(-3)	H1	4.8(-7)	7.0(-5)
2.9(-3)	E1	1.2(-6)	7.1(-5)
2.6(-3)	E2	9.4(-9)	7.1(-5)
1.9(-3)	A	2.0(-4)	2.7(-4)
1.0(-3)	1	2.4(-4)	5.1(-4)

Note: $2.0(-3) = 2.0 \times 10^{-3}$

TABLE IV
P(>D) for Cancer Fatality

<u>10 Mile Average CEDE(rem)</u>	<u>Events #</u>	<u>Frequency (/yr)</u>	<u>P(>D)</u>
3.3(-2)	I3	7.7(-11)	7.7(-11)
2.9(-2)	I2+K2	5.1(-9)	5.2(-9)
2.2(-2)	K1	2.8(-9)	8.0(-9)
2.0(-2)	I1	4.8(-8)	5.6(-8)
1.9(-2)	F2+G2	1.2(-7)	1.8(-7)
1.3(-2)	J3	4.8(-11)	1.8(-7)
1.1(-2)	G1	1.2(-8)	1.9(-7)
9.5(-3)	D2+D3+F1	2.3(-6)	2.5(-6)
9.0(-3)	C2	2.0(-5)	2.2(-5)
8.5(-3)	9	2.0(-6)	2.4(-5)
7.5(-3)	G3	9.4(-11)	2.4(-5)
6.0(-3)	F3	9.4(-10)	2.4(-5)
3.7(-3)	J1	4.8(-8)	2.4(-5)
2.2(-3)	J2	4.8(-10)	2.4(-5)
1.7(-3)	5	3.9(-6)	2.8(-5)
1.5(-3)	B	2.0(-5)	4.8(-5)
1.3(-3)	D1	2.0(-6)	5.0(-5)
4.3(-4)	C1	2.0(-5)	7.0(-5)
4.8(-5)	H2	7.8(-9)	7.0(-5)
3.6(-5)	H1	4.8(-7)	7.0(-5)
2.5(-5)	E1	1.2(-6)	7.1(-5)
2.2(-5)	E2	9.4(-9)	7.1(-5)
1.6(-5)	A	2.0(-4)	2.7(-4)
8.5(-6)	1	2.4(-4)	5.1(-4)
1.1(-7)	10	1.0(+0)	1.0(+0)

Note: 2.0(-3) = 2.0×10^{-3}

FIGURE 1
PROMPT FATALITY

FIGURE 2
CANCER FATALITY

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Bradley, R.F. 992-2W
Cappucci, A.J. 992-1W
Dickey, B.R. 992-4W
Durant, W.S. 992-1W
Ebra-Lima, O.M. 703-F
Hitchler, M.J. 992-1W
Moore, M.L. 773-A
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Paddleford, D.F. 992-1W
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