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Observations on the Use of the Consequence Model CRAC for Small Nonreactor Atmospheric Releases

David M. Ericson, Jr.

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OBSERVATIONS ON THE USE OF THE CONSEQUENCE MODEL
CRAC FOR SMALL NONREACTOR ATMOSPHERIC RELEASES

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ABSTRACT

The consequence model CRAC from the Reactor Safety Study recently has been applied to atmospheric releases of radioactive material from nonreactor sources. This study examines the effect of three model parameters, interval size, population distribution and plume thermal bouyancy, on the consequence estimates. Recommendations for the appropriate use of CRAC in such consequence studies are included.

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Introduction

As part of the Reactor Safety Study, a consequence model, CRAC, was developed to examine the public consequences of accidental releases of radioactive material from nuclear power plants.¹⁻³ Since the development of the model, several studies have been conducted to examine the sensitivity of the model to factors such as plume rise, wind shear, rain, and population evacuation.⁴⁻¹¹ All of these studies were performed assuming one or more of the potentially large accidental releases from reactor sites. At the same time, CRAC has been used to examine the consequences of sabotage-caused releases from spent fuel^{12,13} during transport. In the most recent study, the consequence estimates obtained with CRAC were compared with those obtained using METRAN, the consequence model developed for the Urban Study.¹³ In the course of this comparison it was apparent that the degree of agreement between the two consequence models was strongly influenced by the way CRAC was used, especially in regard to the size of the spatial intervals, the assumed population density and the thermal content of the released plume. Therefore, these factors were examined parametrically to establish their influence on consequence estimates. The results of these studies are reported here.*

*The computational results in the Urban Study¹³ reflect what we believe to be a judicious use of CRAC and the insights generated in this study.

Significant Features of the CRAC Model

The CRAC model has been more fully described elsewhere¹⁻³; however, it is appropriate to note here some of the features which bear upon the parameters mentioned above. CRAC operates basically on a radial computational mesh. The circular area is centered at the release point and divided into 16 segments each of $22\text{-}1/2^\circ$. Each segment has 34 radial intervals, the inner and outer radii of which can be specified by the analyst. The population distribution surrounding the site may be specified in several ways: (1) a uniform population density can be ascribed to the entire area, (2) the actual population in each discrete area can be specified, or (3) with slight code modification, a uniform population density can be specified within selected radial intervals. CRAC has provisions for including cloud rise due to thermal buoyancy, in which case the analyst specifies a heat rate which may be due to radioactive decay processes or sensible heat added by some other mechanism. The model also has provisions for using either constant weather characteristics set by the analyst or actual hourly weather records from selected sites. In the usual mode of operation, releases are assumed to move radially outward in each of the $22\text{-}1/2^\circ$ segments for 91 different sequences of weather conditions sampled from a full year of data from a site. The results of these calculations are combined and reported as frequency distributions of consequence values. Statistics on those distributions, such as mean and standard deviations, as well as the distributions

are also available in the code output. If a uniform population density is run, the mean will be for 91 calculations since each radial segment is identical. If the population distribution is fully specified (544 entries), then the mean will be computed from 1456 separate calculations ($16 \times 91 = 1456$).

Influence of Spatial Interval Size

The normal CRAC radial intervals, shown in Table 1, were established to adequately reflect atmospheric concentrations from large reactor releases over a very large geographical area. Therefore, the interval lengths were set at 0.5 mile out to a 5 mile radius, and gradually increased to 5 miles at a 20 mile radius. This provides more detail in close where conditions are changing fairly rapidly. Beyond the 85 mile radius the intervals become much larger.

When the initial consequence estimates were made for the Urban Study,¹³ the decision was made to reduce the close-in intervals to 0.5 km in length based in part on the fact that the METRAN model uses a one square kilometer calculational grid with considerable internal detail. However, because of this detail and the fact that the dispersion calculation associated with METRAN has finer resolution, the question arose as to whether or not CRAC could or should be run with smaller intervals. To explore this question, calculations were made using nominal close in interval spacings of 1.0,

0.8, 0.5, 0.25, 0.12, and 0.06 kilometer.* The results are shown on Table 3. Several points should be noted about these results. The predictions of early fatalities (EF) and early morbidities (EM) both exhibit sensitivity to interval size with the EF showing the strongest dependence. This behavior is due to the fact that EF and EM are computed in terms of individual exposures, and because there are dose response thresholds involved. That is, as the interval size is reduced, the dose in the innermost intervals rises (CRAC assigns a single value, the average, to the entire interval) and therefore individual doses rise to levels sufficient to cause an effect. It is noteworthy that there is a point at which decreasing the interval size further has no significant effect. This is expected because once the average dose in an interval is above the level required for 100% effect, further increases will make no difference. The predicted latent cancer fatalities (LCF) are insensitive to the size of the spatial interval. This is also as expected since LCF are computed based upon the total population dose (person-rem). Therefore if the intervals are smaller, the dose may be higher but there are fewer people exposed so the product is essentially constant.

*Although the Martin and Tikvart fits for the Pasquill-Gifford (PG) curves are questionable within 1/2 km of the release point they were used in the initial calculations because they are in CRAC. Subsequent calculations with other fits to the PG curves confirm the results reported here.

Influence of Assumed Population Density

Studies using CRAC are frequently conducted using uniform population densities. In fact, many analyses have been conducted assuming 38.5 persons per square kilometer (100 per square mile) which is a reasonable average figure for the continental United States. However, the recent applications of CRAC have been concerned with urban areas where the population densities are many times greater. Unfortunately, there has been a tendency on the part of some observers to simply scale estimates from one population density to another. Such scaling can lead to erroneous and at times absurd results. These problems are illustrated in the following paragraphs.

At a population density of 38.5 persons/km², there are some 4.9 million people assumed to be in the 22-1/2° sector extending out to 800 km downwind from the release point, certainly not an unreasonable number. Now if one simply scales the population density to 77000 persons/km² which is representative of a hyperurban area, then there would be 9.8 billion in the same area. Clearly, this has no relation to the real world.

An alternate view of the problems engendered by linear scaling may be achieved by examining the consistency between the predicted number of LCFs and the individual radiation dose. One estimate for a particular release from spent fuel predicted 0.6 LCF at a population density of 38.5 persons/km². Assuming a density of 77000 persons/km² and linearly scaling,

the expected result would be an estimated 1200 LCF. This number in itself may not appear unreasonable. However, using an estimate of 120 LCF per million person-rem population dose¹⁴, the population dose would have to be on the order of 1×10^7 person-rem to realize 1200 LCF. CRAC calculations show that the individual dose, as a function of distance from the point of release, falls below 0.1 rem within 2.5 km. Therefore, one would have to conclude that the bulk of the 1×10^7 person-rem required by simple linear scaling is a result of hundreds of millions (to perhaps billions) of people receiving less than 0.1 rem over 40 years, a situation which is difficult to visualize considering that the total US population is on the order of 220 million.

The influence and importance of the population distribution is further illustrated by the data in Tables 4 and 5. Table 4 shows the population distributions used in the calculations reported in Table 5. These distributions essentially model various types of distributions from a large, densely-populated city down through cities and small towns to a rural area. Actual population densities from the Urban Study were used in one case. The results in Table 5 have not been normalized but reflect the consequences (mean LCF) predicted using CRAC for the "baseline estimate release" from spent fuel as defined in the Urban Study (See footnote on Table 3). In the Urban Study it was observed that 80 percent of the LCFs occurred within

10 km of the release point for the hyper-urban population distribution (also see Figure 1). It is apparent from the data in Table 5 that a similar situation exists whenever distributions are used which model towns and cities. For Cases 2 through 6 the ratios of LCFs from one case to another approximate the population ratios close to the release point. Such scaling is not observed between the two uniform population cases (7 and 8, Tables 4 and 5) nor can one scale from the uniform to the distributed population. This behavior is attributed to several effects. In CRAC, the long term or chronic exposure calculation includes exposures from inhalation of resuspended material, groundshine from surface contamination and ingestion via food pathways. However, the model assumes that a given amount of land will only "feed" a fixed number of people regardless of the population density. Therefore, as the population density is increased to simulate cities, the exposure via the food pathway has less and less influence on the predicted consequences. For example, for one spent fuel release at 38.5 persons/km², the ingestion pathway accounts for 40 percent of the predicted LCF, but for the same release at 770 persons/km², the ingestion pathway accounts for only 3 percent of the LCF. Or stated another way, simply scaling from a few tens of persons per square kilometer to thousands per square kilometer implies that foodstuffs increase in the same proportion which is obviously unrealistic. However, scaling results for small areas

with high population densities is more accurate because the non-linear effect of the ingestion dose pathway has already been suppressed.

Another aspect of the influence of population distribution is shown on Figure 1. The cumulative fraction of LCFs is shown as a function of distance from the release point for Case 1 and Case 7 (Table 4). It is noted that for a uniform population distribution the number of LCF continually increases, as would be expected, because even though the dose is steadily declining as a function of the distance, the total number of people is increasing, the net result being significant additional LCF. In contrast, when there is a high population density close to the release point, the total number of LCF rises very rapidly and even the addition of more people at distances beyond about 15 kilometers doesn't add materially to the number of LCF predicted.

Influence of Thermal Content of Plume

Provisions have been made in CRAC for including thermal bouyancy in the released plume. This is required to adequately account for the sensible heat associated with potential reactor accidents, and for the much smaller contribution from the radioactive decay of short-lived fission products. For small releases the provision of a thermal source may or may not be necessary. A portion of the Urban Study was concerned with the potential consequences

from sabotage of shipping containers, especially spent fuel shipping casks, for which it was postulated that substantial quantities of high explosives would be involved. Based upon earlier work at Sandia, a value for the thermal source was selected.¹⁵ Again, because CRAC results were being compared with METRAN results and because METRAN has no provision for buoyancy, a decision was made to explore the effect of the thermal source on consequence estimates. The results, shown in Table 6, have been normalized to the values obtained with no heat in the release to better illustrate the behavior. The thermal content does have a strong effect upon the predicted early consequences for the "baseline estimate" release of the Urban Study. As heat is added to the release plume, the lofting reduces the expected doses close in and thus the associated EF and EM. This is as expected because the early consequences are threshold phenomena and because they are estimated on an individual dose basis. The estimate of LCF does not vary significantly with thermal content of the plume. Again this may be attributed to the total person-rem approach to predicting LCF.

Conclusions and Recommendations

Based upon the information presented here, the following conclusions may be drawn relative to using CRAC for small (compared to potential reactor accidents) atmospheric releases such as those postulated from sabotage of spent fuel in transit (~ 10,000 Ci).

1. The interval size selected for the analysis can have a significant effect upon the results, particularly the prediction of EF and EM. The prediction of LCF is not very sensitive to the interval size.
2. The choice of population distribution used can have a significant impact upon the consequence estimates. A population distribution which simulates an urban area will lead to predictions of many casualties close in with the majority of the LCFs occurring within 10-20 km of the release point.
3. Because of the non-linearities in the consequence model, linear scaling of consequence estimates with population density can, and usually does, lead to over estimates of the consequences, if scaling from low to high population densities.
4. The thermal content of the release can have a significant effect upon consequence estimates, primarily the prediction of early effects.

The following recommendations are made for using the consequence model CRAC with small releases:

1. The analyst should select the interval size with care. Areas in which there could be significant numbers of people close to the release point, and thus a potential for early consequences, should be modelled with spatial intervals of 1/4 kilometer or less near the release point. Rural areas in which the more sparse population makes latent

effects the major concern can be modelled with larger intervals.

2. Population distributions should be carefully chosen to match the situation being studied. If there are strong variations in numbers depending upon direction, these should be included.
3. Consequence results should not be scaled from one population density to another.
4. The thermal content of the plume should be chosen to duplicate the expected condition as closely as possible. This is especially true for situations in which early effects to a close in population are being considered.

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Table 1

Normal Interval Radii for CRAC

<u>Interval No.</u>	<u>Outer Radius (mi)</u>	<u>Outer Radius (km)</u>
1	0.5	0.8
2	1.0	1.6
3	1.5	2.4
4	2.0	3.2
5	2.5	4.0
6	3.0	4.8
7	3.5	5.6
8	4.0	6.4
9	4.5	7.2
10	5.0	8.0
11	6.0	9.7
12	7.0	11.0
13	8.5	14.0
14	10.0	16.0
15	12.5	20.0
16	15.0	24.0
17	17.5	28.0
18	20.0	32.0
19	25.0	40.0
20	30.0	48.0
21	35.0	56.0
22	40.0	64.0
23	45.0	72.0
24	50.0	80.0
25	55.0	89.0
26	60.0	97.0
27	65.0	104.0
28	70.0	113.0
29	85.0	137.0
30	100.0	161.0
31	150.0	241.0
32	200.0	322.0
33	350.0	563.0
34	500.0	805.0

Table 2

Modified Close-in Interval Radii for CRAC Sensitivity Study

<u>Radii Set</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
	Outer Radii (km)			
<u>Interval No.</u>				
1	0.5	0.25	0.12	0.06
2	1.0	0.5	0.25	0.12
3	1.5	0.75	0.38	0.19
4	2.0	1.0	0.5	0.26
5	2.5	1.25	0.63	0.32
6	3.0	1.5	0.76	0.37
7	3.5	2.0	1.0	0.5
8	4.0	2.5	1.2	0.8
9	4.5	3.5	1.7	1.2
10	5.0	4.4	2.2	1.6
11	5.5	5.4	2.8	2.4
12	6.0	6.4	3.2	3.2
13	7.0	7.3	3.6	3.6
14	7.5	8.5	7.2	7.2
15	11.2	11.2	11.2	11.2
16	16.0	16.0	16.0	16.0
17*	28.0	28.0	28.0	28.0

*Beyond interval 17, all cases are the same as Normal, Table 1.

Table 3

Normalized Consequence Estimates from CRAC*
 (Spatial Intervals Varied, Results Normalized to Those at 0.06 km Spacing)
 (Uniform Population Density 38.5/km²)

<u>Nominal Interval Spacing (km)</u>	<u>Early Fatalities</u>	<u>Early Morbidities</u>	<u>Latent Cancer Fatalities</u>
0.06	1.0	1.0	1.0
0.12	1.0	1.0	1.0
0.25	0.68	1.1	0.99
0.5	0.17	1.1	0.99
0.8	0	0.4	1.01
1.0	0	0	1.01

*Release was a mixed fission product release from spent fuel, 1 percent of solids and 100 percent of noble gases from 1.4 MTHM after 33000 MWD/MT at 40 kw/kg, cooled 150 days.

Table 4

Assumed Population Distributions for Consequence Estimates

<u>Case</u>	<u>Population Density (#/km²)</u>	<u>Radius (km)</u>
1	Actual population data NYC	0-5.5
Hyper-urban	16200	5.5-16
(New York	3860	16-48
City Data)	386	48-88
	38	>88
2	16200	0-16
Hyper-urban	3860	16-48
	386	48-88
	38	>88
3	2895	0-16
Large City	689	16-48
	69	48-88
	38	>88
4	1390	0-11.2
Medium-Size City	332	11.2-40
	38	>40
5	695	0-9.6
Small City	69	9.6-32
	38	>32
6	347	0-7.5
Town	38	>7.5
7	38	0-800
Rural		
8	772	0-800
Semi-Rural		

Table 5

Mean CRAC LCF Estimates for a Release from Spent Fuel*

<u>Population Distribution**</u>	<u>Latent Cancer Fatalities</u>
1	111
2	65
3	12
4	5.3
5	2.3
6	1.3
7	0.6
8	7.9

*Release was a mixed fission product release from spent fuel, 0.07 percent solids and 10 percent noble gases from 1.4 MTHM after 33000 MWD/MT at 40 kw/kg, cooled 150 days.

**See Table 4.

Table 6

Normalized Mean Consequence Estimates for Releases
from Spent Fuel* with Varying Thermal Sources

<u>Thermal Source (BTU/sec)</u>	<u>EF</u>	<u>EM</u>	<u>LCF</u>
0	1.0	1.0	1.0
1.45×10^2	0.29	0.87	1.08
1.45×10^3	0.22	0.42	1.08
1.45×10^4	0.07	0.38	1.1
1.45×10^5	0.02	0.05	1.02

*Release is described on Table 5.

Figure 1. Cumulative Fraction of Latent Cancer Fatalities as Function of Distance from Release Point.

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