8. Atmospheric Transport Results for Fukushima Daiichi Units 1, 2, and 3

Many of the BSAF participants provided source terms to be evaluated by Sandia National Laboratories[1] by applying HYSPLIT [2,3,4,5] to treat atmospheric transport and dispersion (ATD). The objective was to estimate the deposition pattern that would have resulted from the predicted source term. For the participants who provided results for all three units, the overall deposition pattern can be compared with the observed deposition pattern; for the participants who submitted source terms for one or two units, the results can only be compared with each other. Atmospheric transport calculations were performed for a single isotope, Cs-137. It is the primary isotope of concern for long-term contamination and it is relatively easy to measure the strong gamma signal produced from its short-lived decay product, Ba-137m.

All the atmospheric transport calculations used the actual location of each of the three units; the releases were not presumed to emanate from the same location. Also, when they were provided, release energies were accounted for in the analysis, so plume lofting was considered. Finally, aerosol size distribution data were considered for purposes of estimating deposition. In some cases, aerosol size distribution can significantly influence deposition patterns.

The BSAF participants who provided one or more source terms for this evaluation are listed in Table 8-1. Deposition patterns corresponding to these source terms are shown in the following subsections.

Table 8-1 Participants and codes contributing source terms for ATD calculations.

	Code	Country	Units
CIEMAT	MELCOR 2.1-4803	Spain	1
CRL	MELCOR 2.1-6342	Canada	2
CRIEPI	MAAP 5.01	Japan	2,3
IAE	SAMPSON-B 1.4 beta	Japan	1,2,3
IRSN	ASTEC V2.0 rev3 p1	France	1,2,3
KAERI (SI Kim)	MELCOR 1.8.6	South Korea	2
KAERI (TW Kim)	MELCOR 1.8.6	South Korea	1,2,3
PSI	MELCOR 2.1-4206	Switzerland	3
NRC/DOE/SNL	MELCOR 2.1-5864	U.S.A.	1,2,3

8.1. Influence of Weather Data

Four weather datasets were considered and compared for this evaluation. One of these was supplied by Hiroaki Terada at JAEA. However, this dataset was supplied in a format that could not be used directly with HYSPLIT. SNL converted this file into a format that could be used; however, this process was somewhat complicated and the resulting dataset produced an unusual deposition

[1] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

pattern, indicating that there might have been a problem in the conversion process. As a result, this weather dataset is not included with the results below.

Total deposition isopleths are compared for three weather datasets, all obtained from NOAA [6]. A short set of attributes for these datasets are listed in Table 8-2.

A set of ground deposition isopleths for Cs-137 corresponding to the three weather datasets are shown in Figures 8-1 through 8-3 using the combined source terms for the three units created by Sandia using MELCOR 2.1-5864. For comparison, Figure 8-4 shows the measured Cs-137 isopleths using the same distance scale and using similar contour shading to facilitate the comparisons. However, note that the dark red contour level shown in Figures 8-1 through 8-3 is not used in Figure 8-4. The results clearly show that the weather dataset significantly influences the predicted ground deposition pattern. This has a confounding influence on the evaluation of source terms since significant uncertainty is introduced through the weather data chosen for the analysis.

Table 8-2 Characteristics of meteorological datasets used to evaluate the influence of weather data on ground deposition pattern.

		Spatial Resolution	Frequency	Nudged with Observations
1	GDAS	0.5° (about 32 km)	3 hr	No
2	WRF 2014	4 km	20 min	No
3	WRF 2017	4 km	5 min	Yes

It is not entirely obvious, which of the weather datasets best matches the observations. Furthermore, it may not be entirely fair to judge the weather datasets based on matching the observations since it is unlikely that the source term used in this comparison matches the actual source term. The WRF 2017 dataset is expected to be the best of the three datasets, primarily because it has been nudged by observational data. It also has the best combination of spatial and temporal resolutions of the three datasets. Because of these features, it is selected to be used for all the comparisons shown in the remainder of this section.

Figure 8-1 Ground deposition pattern for Cs-137 based on GDAS weather data and SNL MELCOR source term

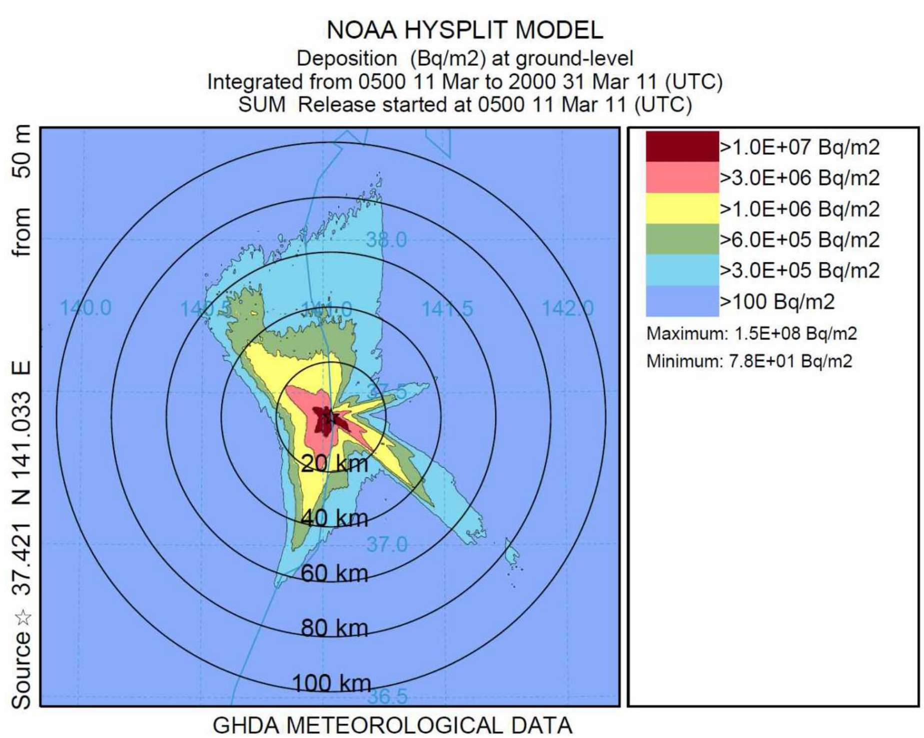


Figure 8-2 Ground deposition pattern for Cs-137 based on WRF 2014 weather data and SNL MELCOR source term

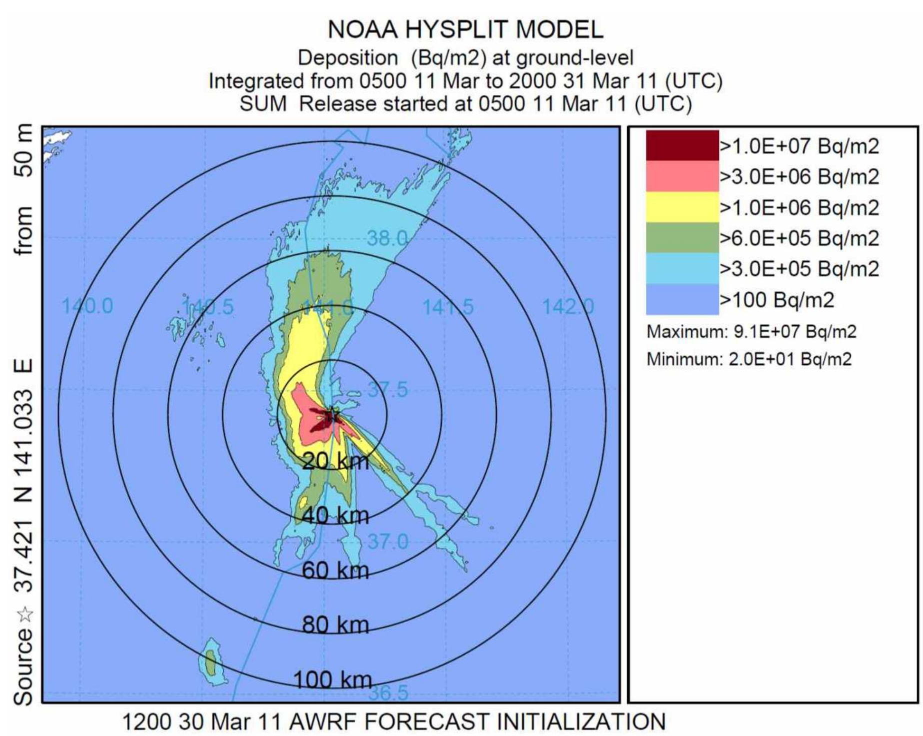


Figure 8-3 Ground deposition pattern for Cs-137 based on WRF 2018 weather data and SNL MELCOR source term

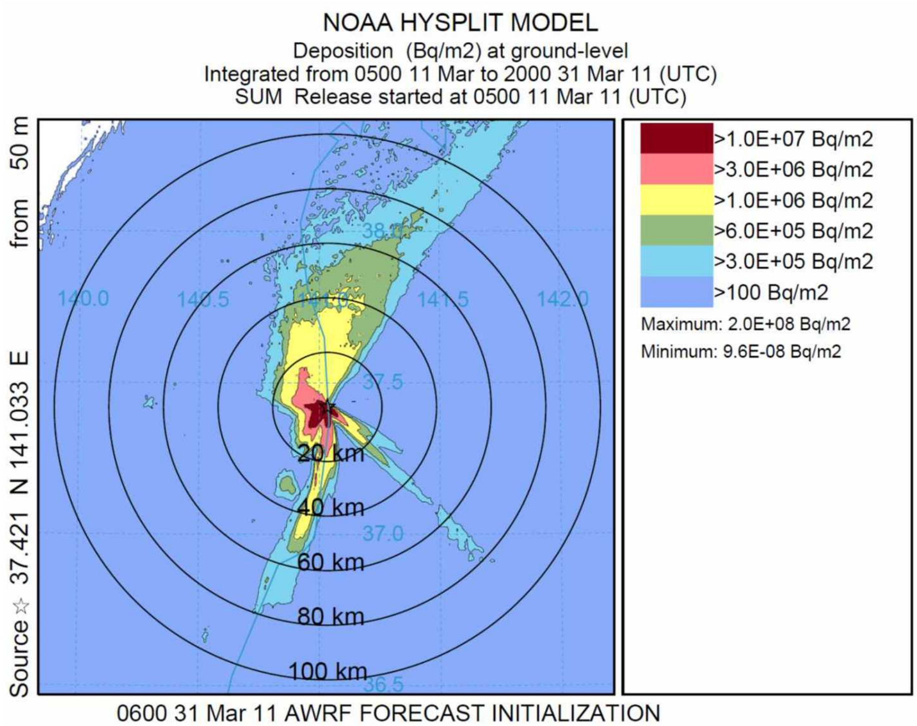
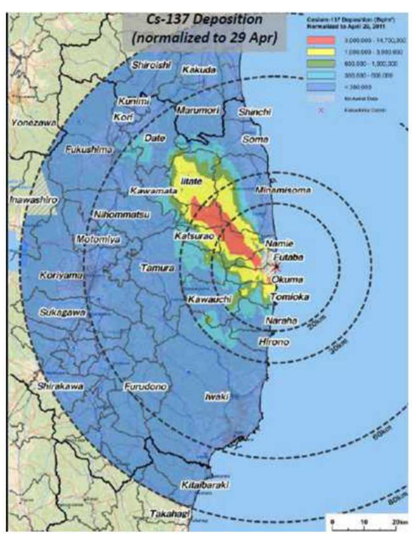


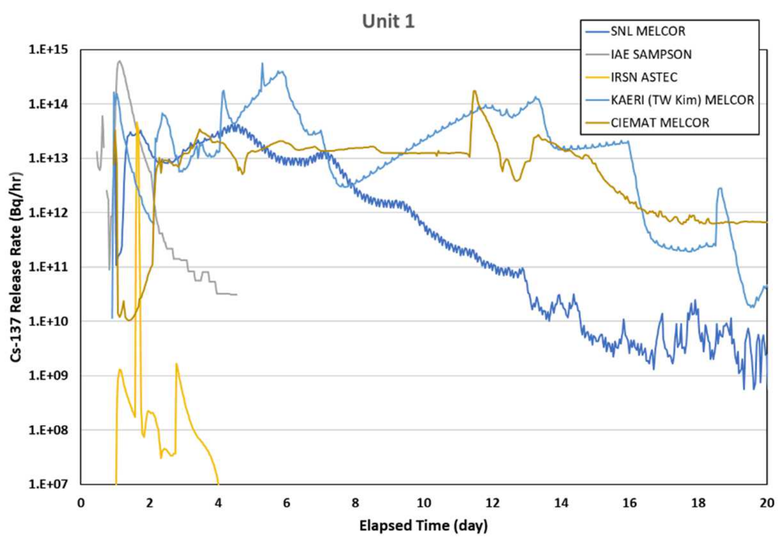
Figure 8-4 Observed ground deposition pattern for Cs-137



8.2. Comparisons for Unit 1

Five of the organizations participating in BSAF Phase 2 submitted a Unit 1 source term for atmospheric transport analysis. Those were CIEMAT, IAE, IRSN, KAERI (TW Kim), and NRC/DOE/SNL. A comparison of these five source terms is shown in Figure 8-5. Figures 8-6 through 8-10 show the deposition patterns predicted for these source terms.

Figure 8-5 Unit 1 source terms for Cs-137 predicted by five BSAF participants



Of the five source terms, three produce a significant deposition over land (CIEMAT, KAERI (TW Kim), and DOE/NRC/SNL). The other two (IAE, and IRSN), produce nearly all the deposition over the ocean. Note that that the land/ocean border is indicated by the light blue line that runs roughly north and south through the center of the isopleth plots.

Figure 8-6 Cs-137 isopleths calculated for the CIEMAT Unit 1 source term

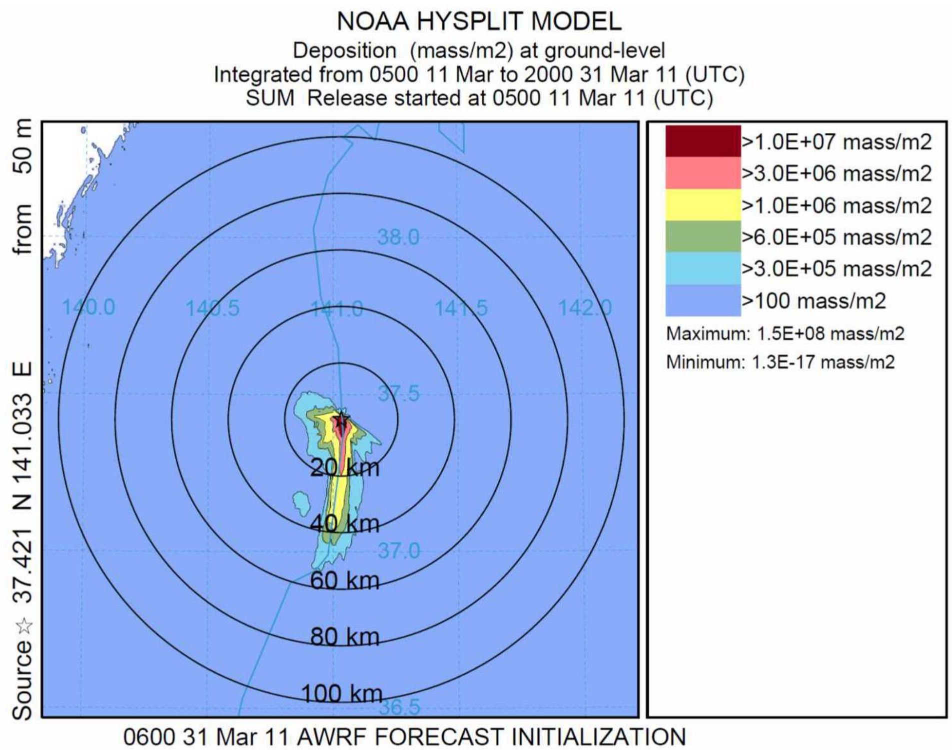


Figure 8-7 Cs-137 isopleths calculated for the IAE Unit 1 source term

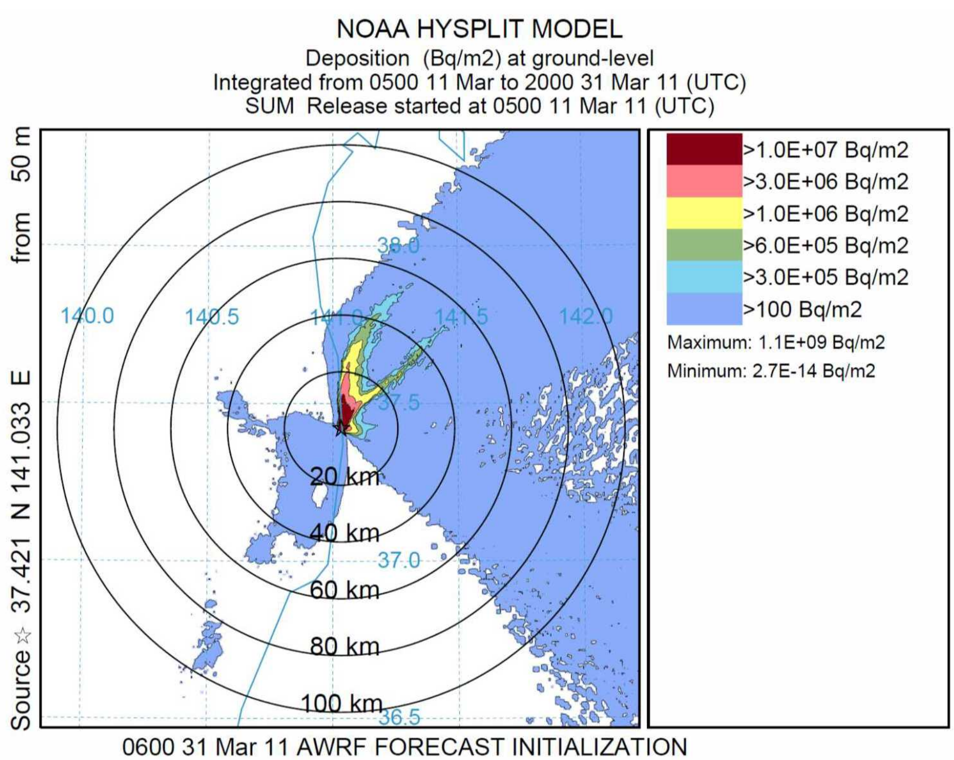


Figure 8-8 Cs-137 isopleths calculated for the IRSN Unit 1 source term

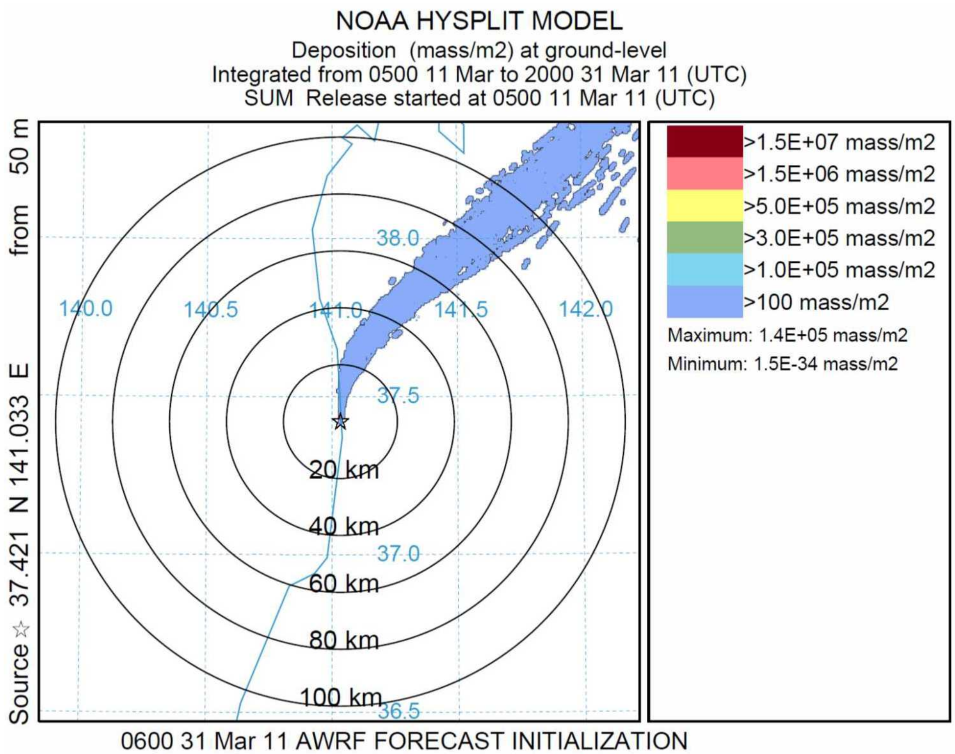


Figure 8-9 Cs-137 isopleths calculated for the KAERI (TW Kim) Unit 1 source term

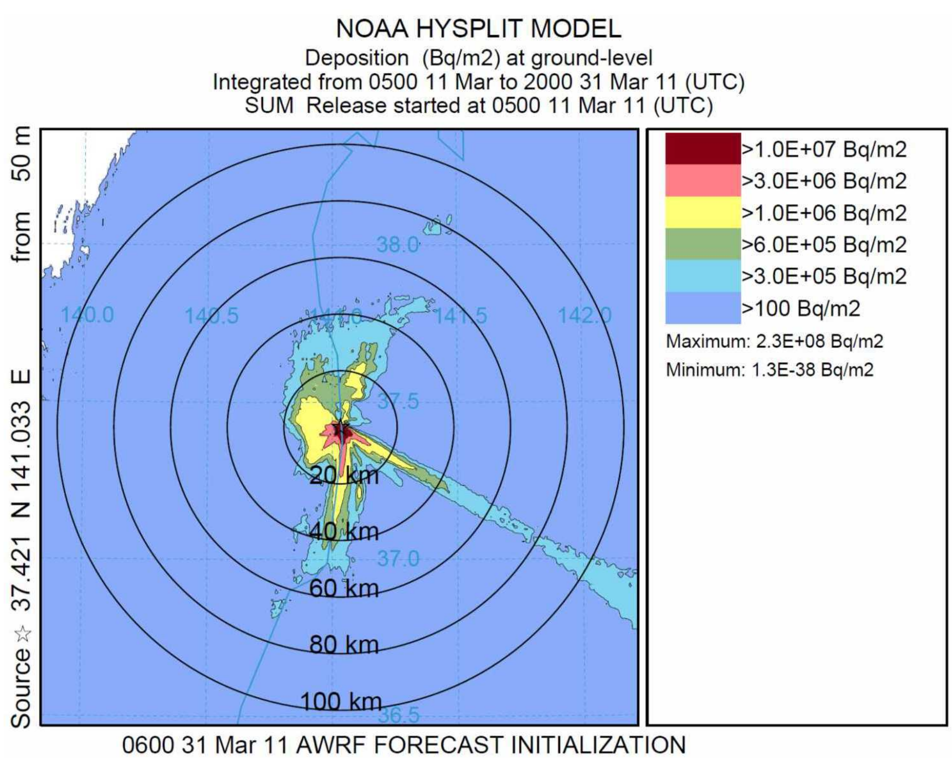
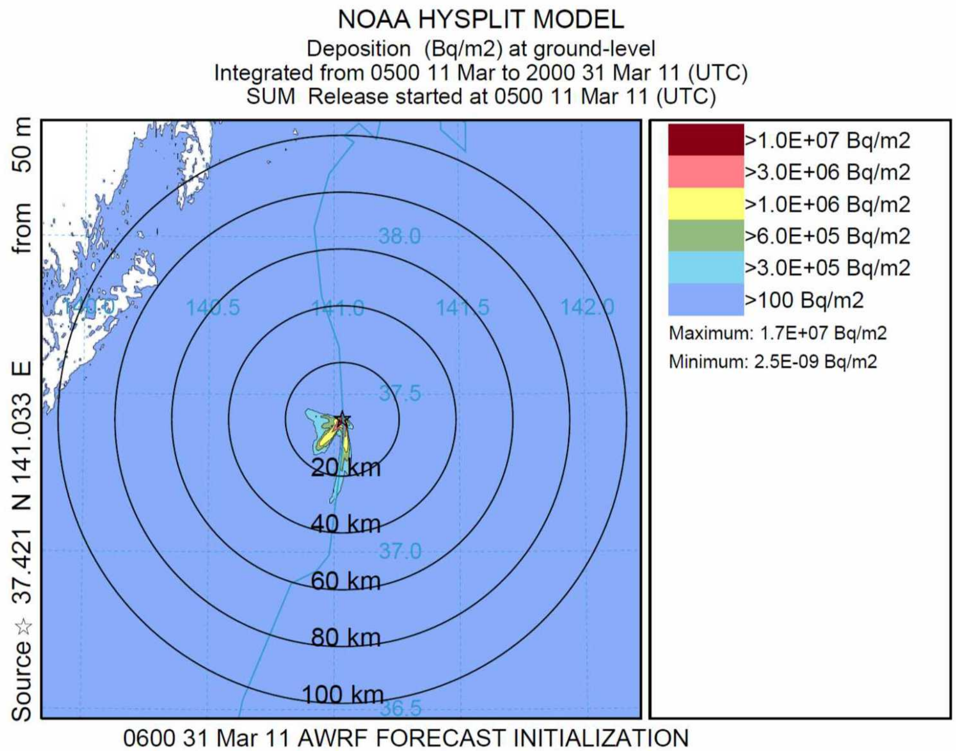


Figure 8-10 Cs-137 isopleths calculated for the NRC/DOE/SNL Unit 1 source term



8.3. Comparisons for Unit 2

Seven of the organizations participating in BSAF Phase 2 submitted a Unit 2 source term for atmospheric transport analysis. Those were CRL, CRIEPI, IAE, IRSN, KAERI (SI Kim), KAERI (TW Kim), and NRC/DOE/SNL. A comparison of these seven source terms is shown in Figure 8-11. Figures 8-12 through 8-18 show the deposition patterns predicted for these source terms. All of them except the ones from IAE and IRSN produce significant deposition over land. Very little release is predicted for Unit 2 by these two codes; in the case of IAE, it is essentially zero.

Figure 8-11 Unit 2 source terms for Cs-137 predicted by seven BSAF participants

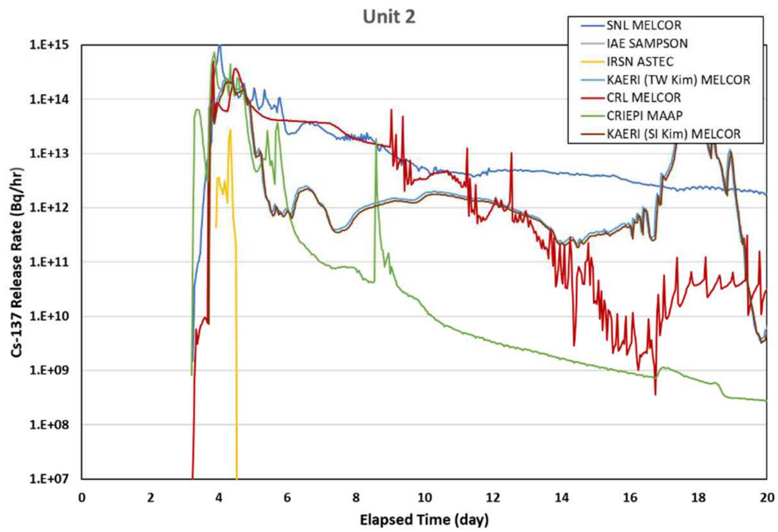


Figure 8-12 Cs-137 isopleths calculated for the CNL Unit 2 source term

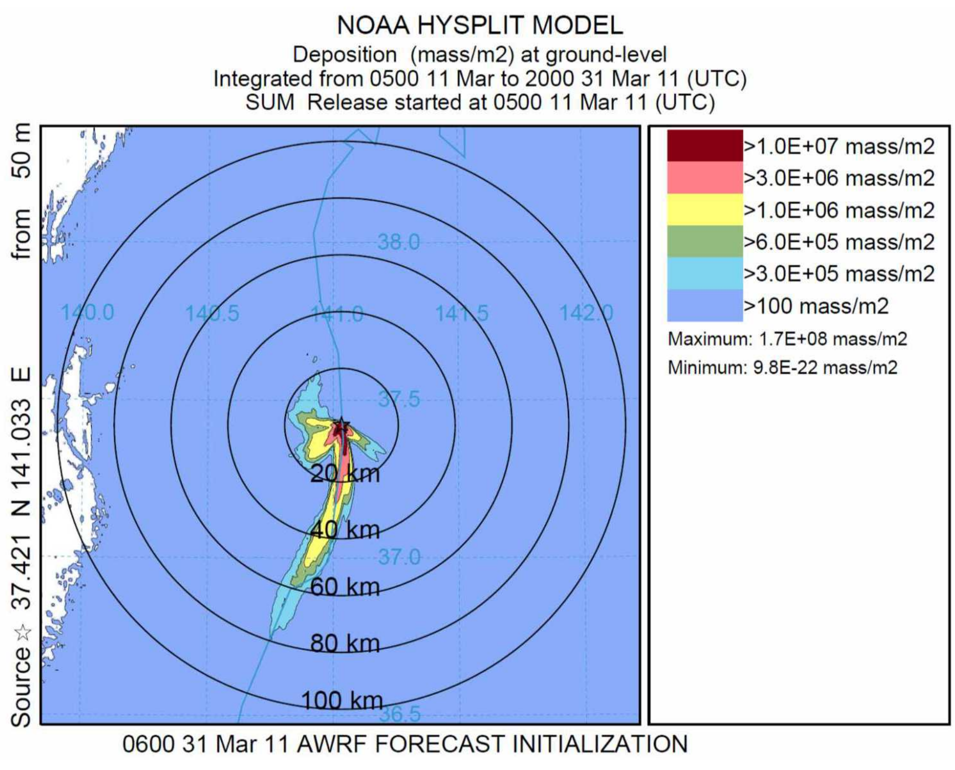


Figure 8-13 Cs-137 isopleths calculated for the CRIEPI Unit 2 source term

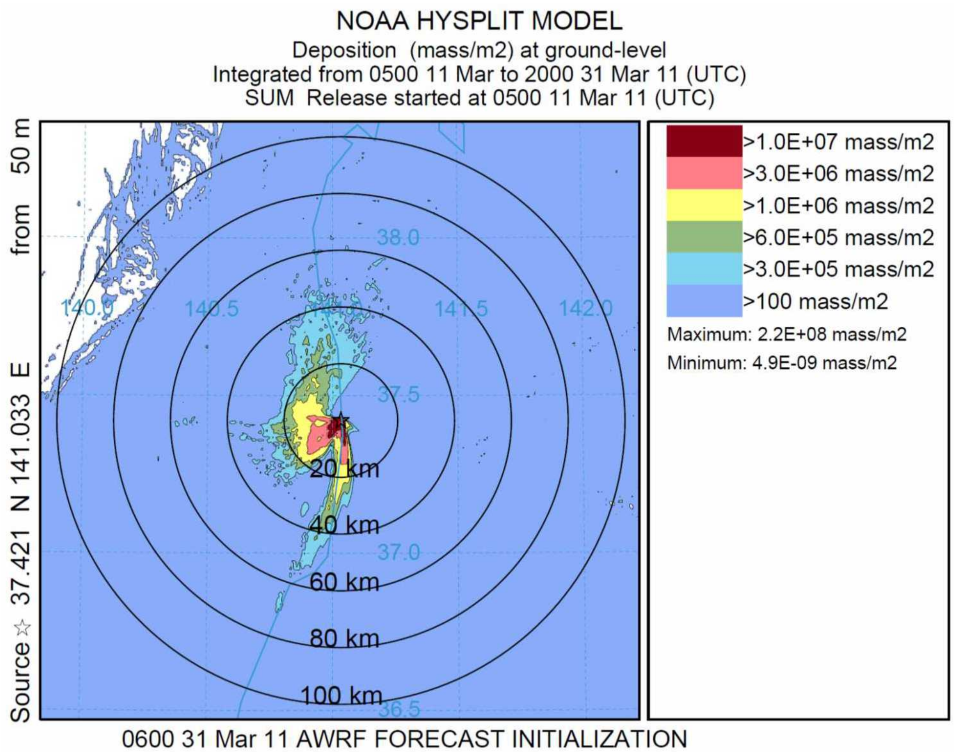


Figure 8-14 Cs-137 isopleths calculated for the IAE Unit 2 source term

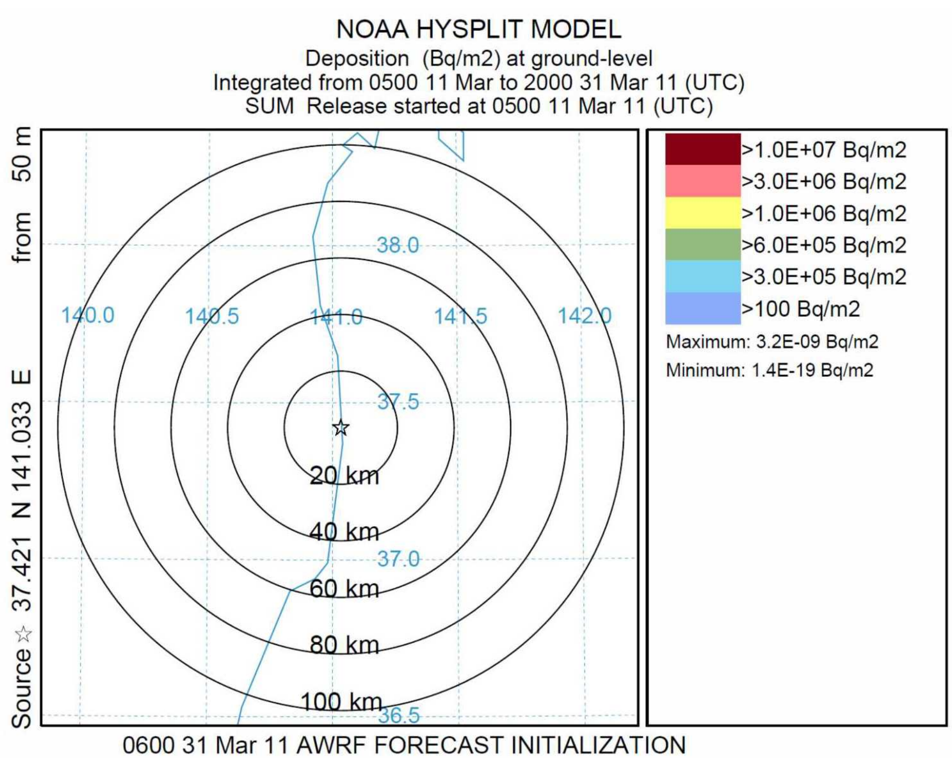


Figure 8-15 Cs-137 isopleths calculated for the IRSN Unit 2 source term

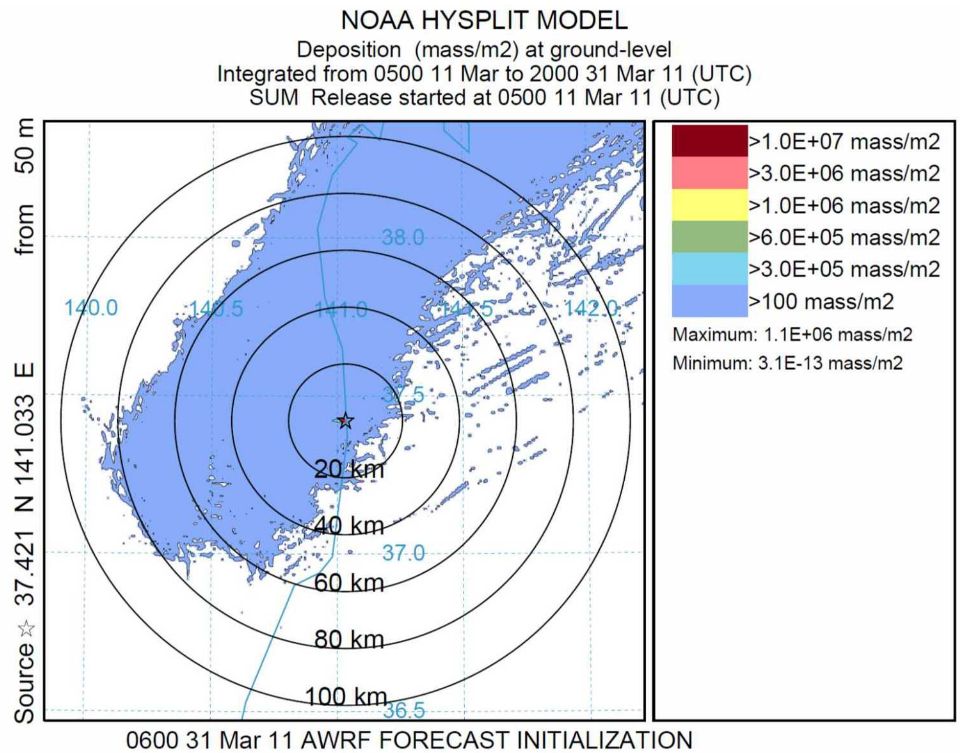


Figure 8-16 Cs-137 isopleths calculated for the KAERI (SI Kim) Unit 2 source term

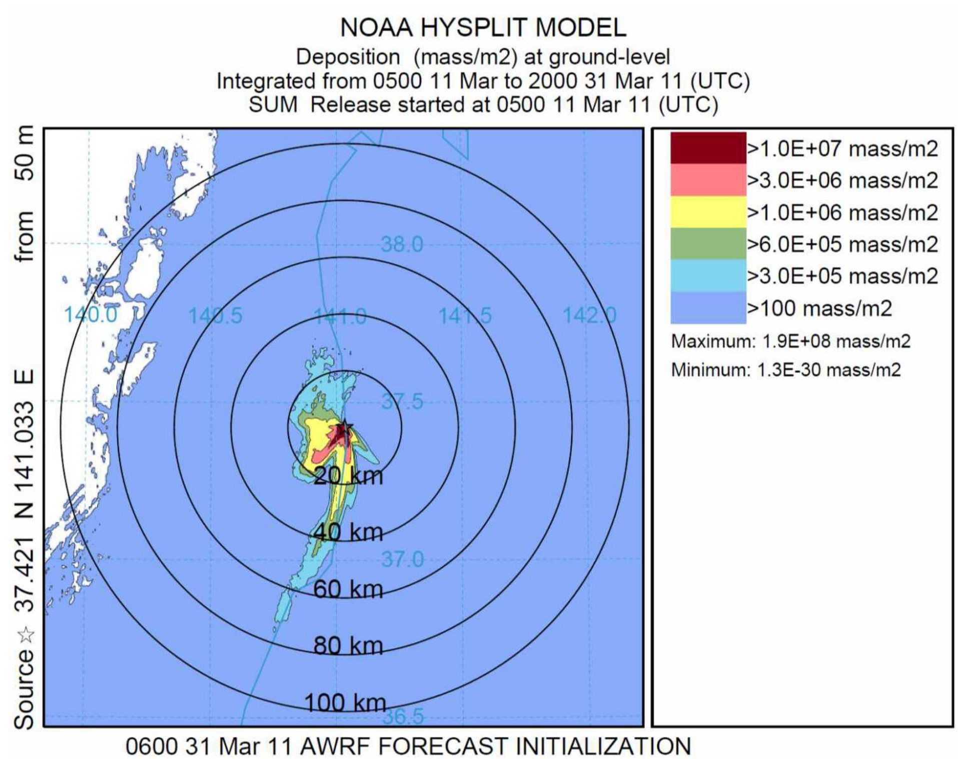


Figure 8-17 Cs-137 isopleths calculated for the KAERI (TW Kim) Unit 2 source term

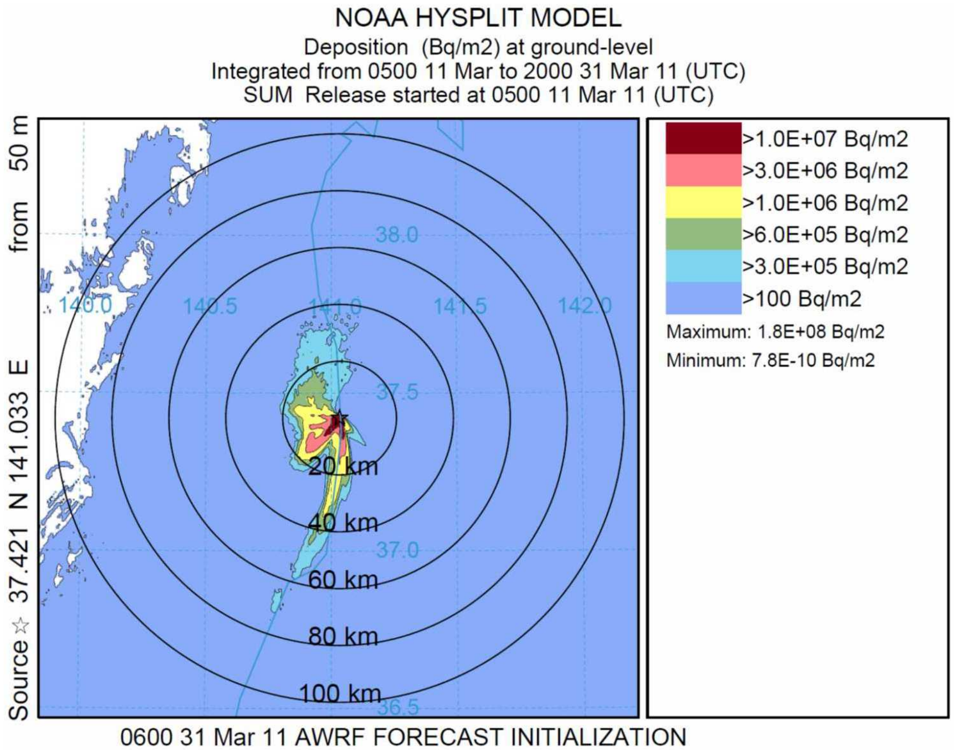
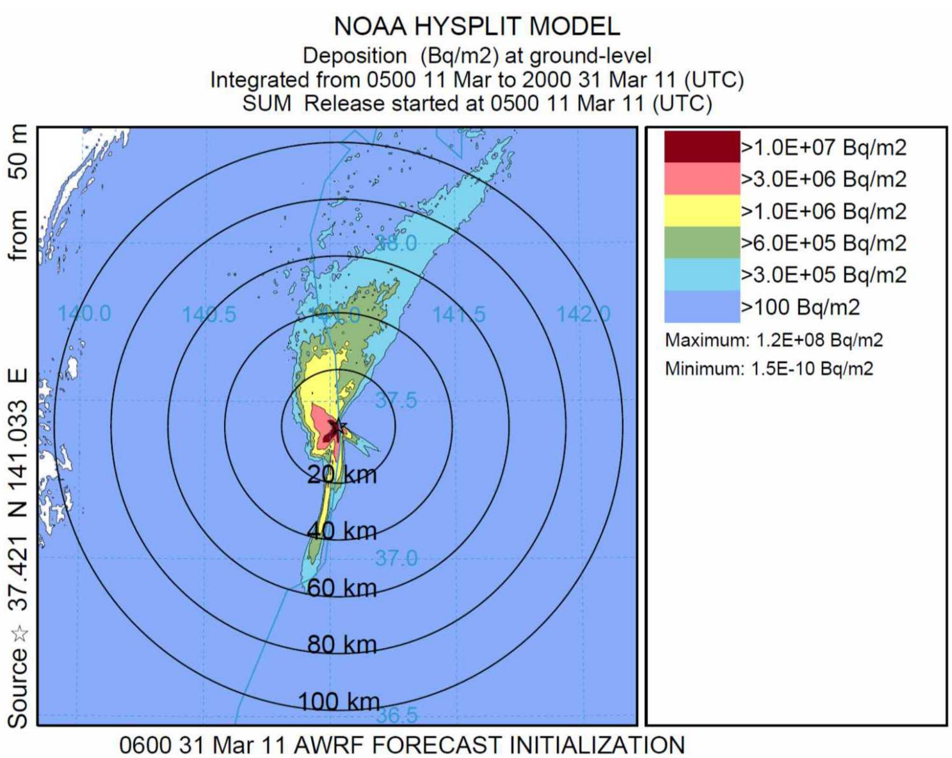


Figure 8-18 Cs-137 isopleths calculated for the NRC/DOE/SNL Unit 2 source term



8.4. Comparisons for Unit 3

Six of the organizations participating in BSAF Phase 2 submitted a Unit 3 source term for atmospheric transport analysis. Those were CRIEPI, IAE, IRSN, KAERI (TW Kim), PSI, and NRC/DOE/SNL. A comparison of these six source terms is shown in Figure 8-19. Figures 8-20 through 8-25 show the deposition patterns predicted for these source terms. Three of the source terms for Unit 3 produce significant deposition over land, which are the ones provided by IRSN, KAERI (TW Kim), and DOE/NRC/SNL. The source terms provided by CRIEPI, IAE, and PSI produce low-level deposition over land as well as over the ocean.

Figure 8-19 Unit 3 source terms for Cs-137 predicted by seven BSAF participants

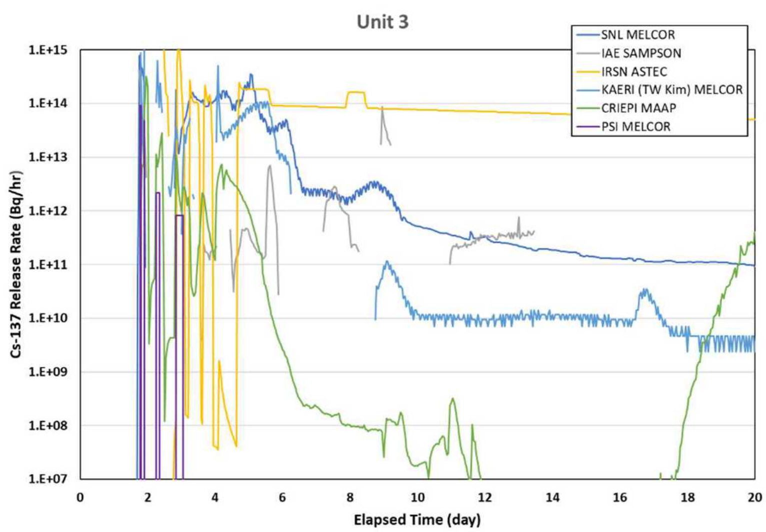


Figure 8-20 Cs-137 isopleths calculated for the CRIEPI Unit 3 source term

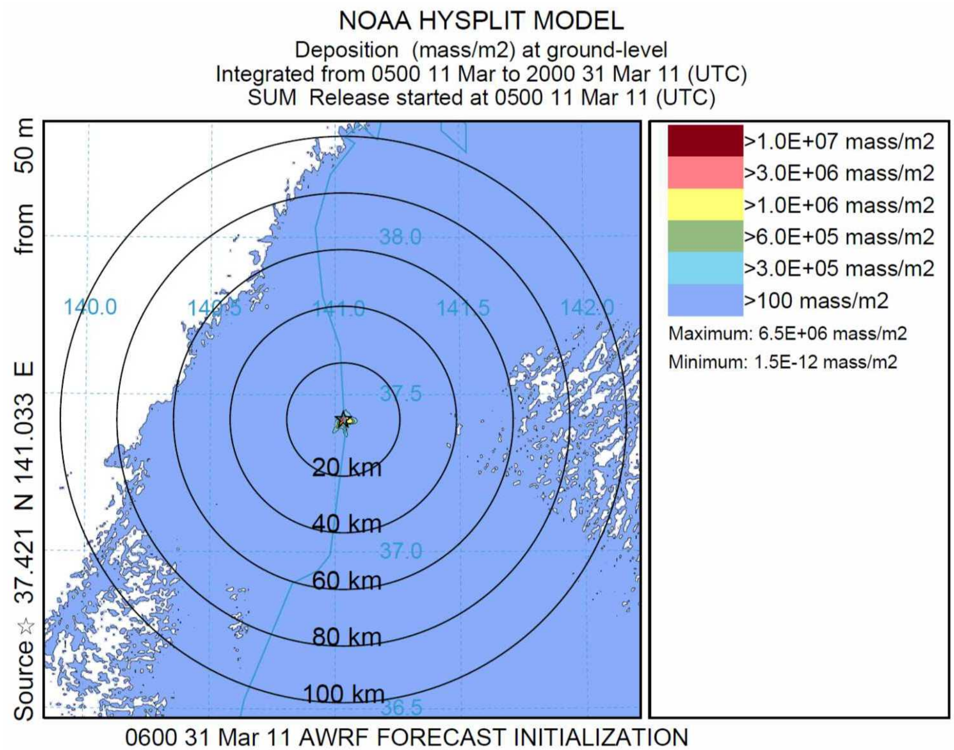


Figure 8-21 Cs-137 isopleths calculated for the IAE Unit 3 source term

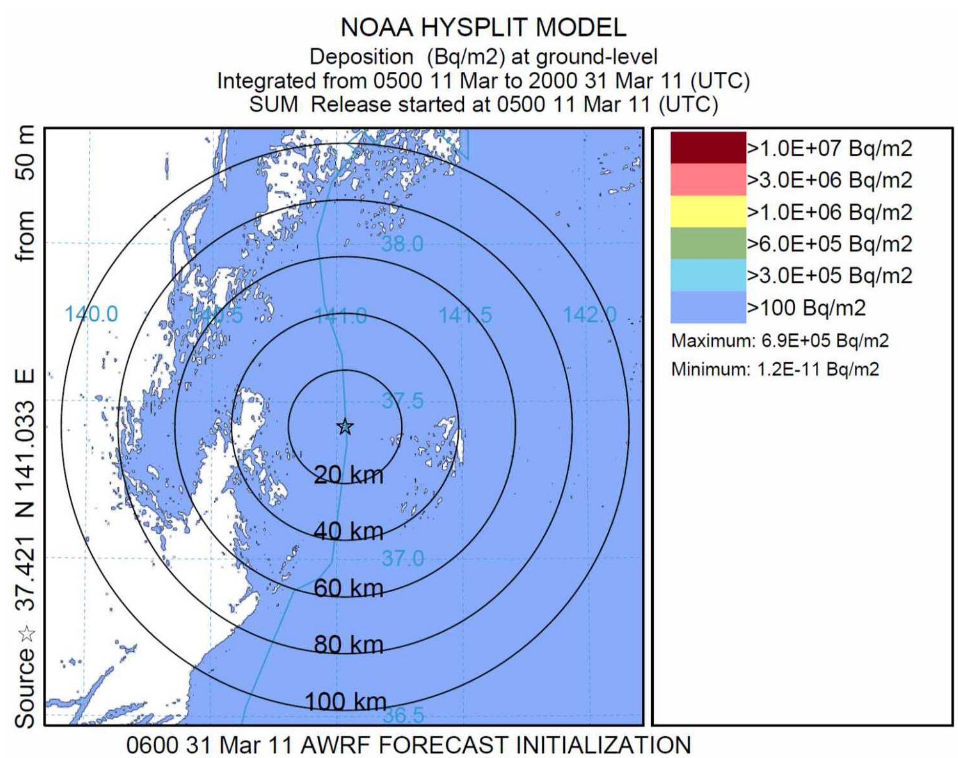


Figure 8-22 Cs-137 isopleths calculated for the IRSN Unit 3 source term

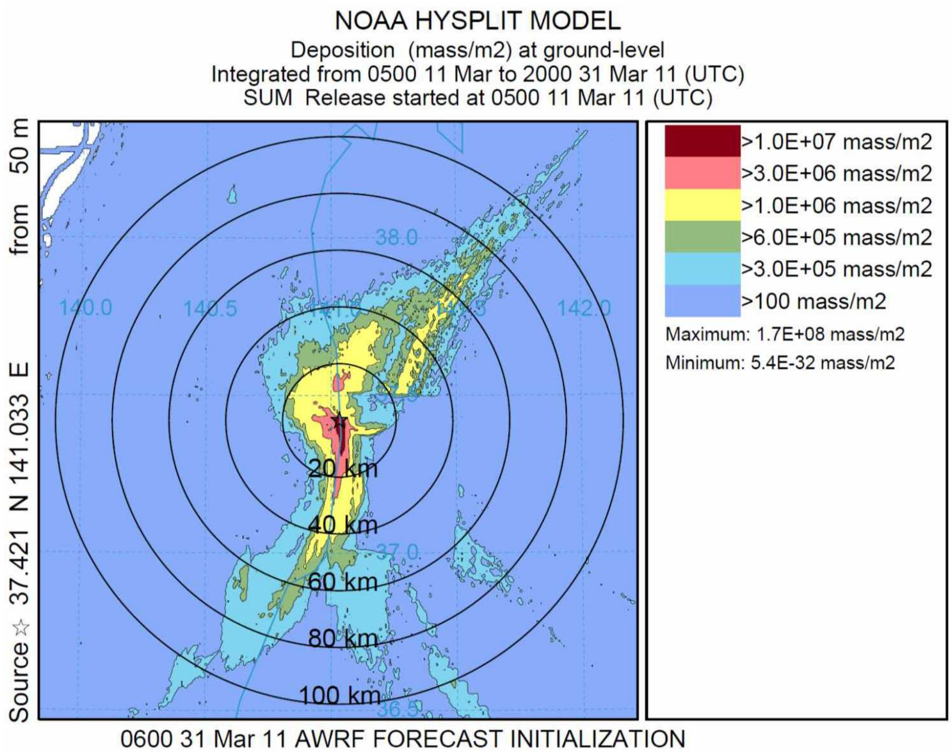


Figure 8-23 Cs-137 isopleths calculated for the KAERI (TW Kim) Unit 3 source term

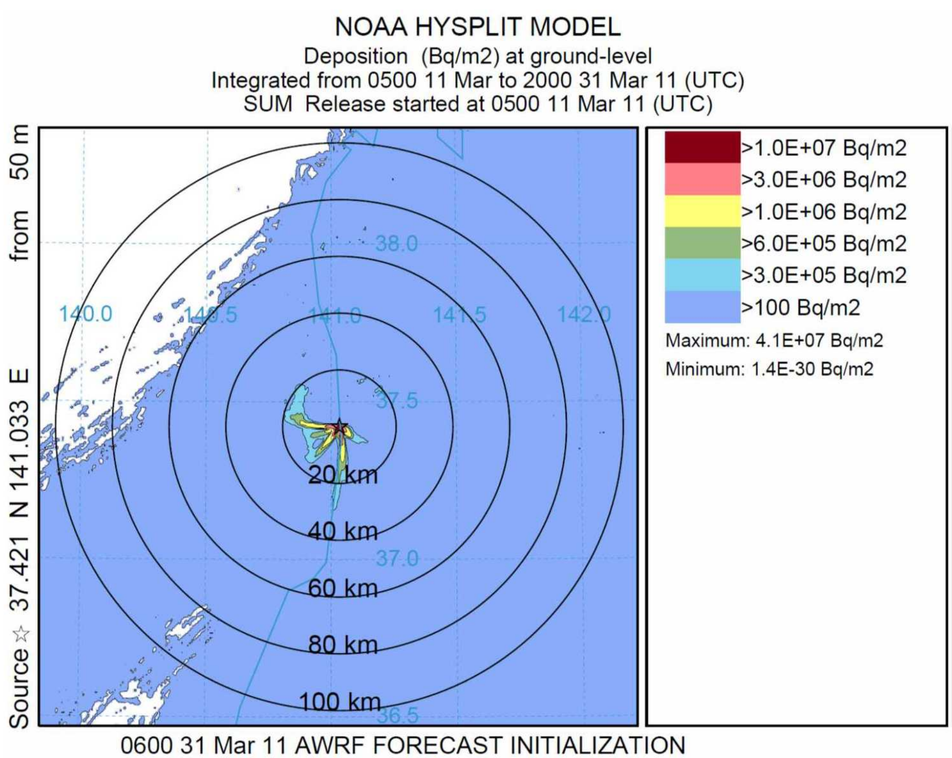


Figure 8-24 Cs-137 isopleths calculated for the PSI Unit 3 source term

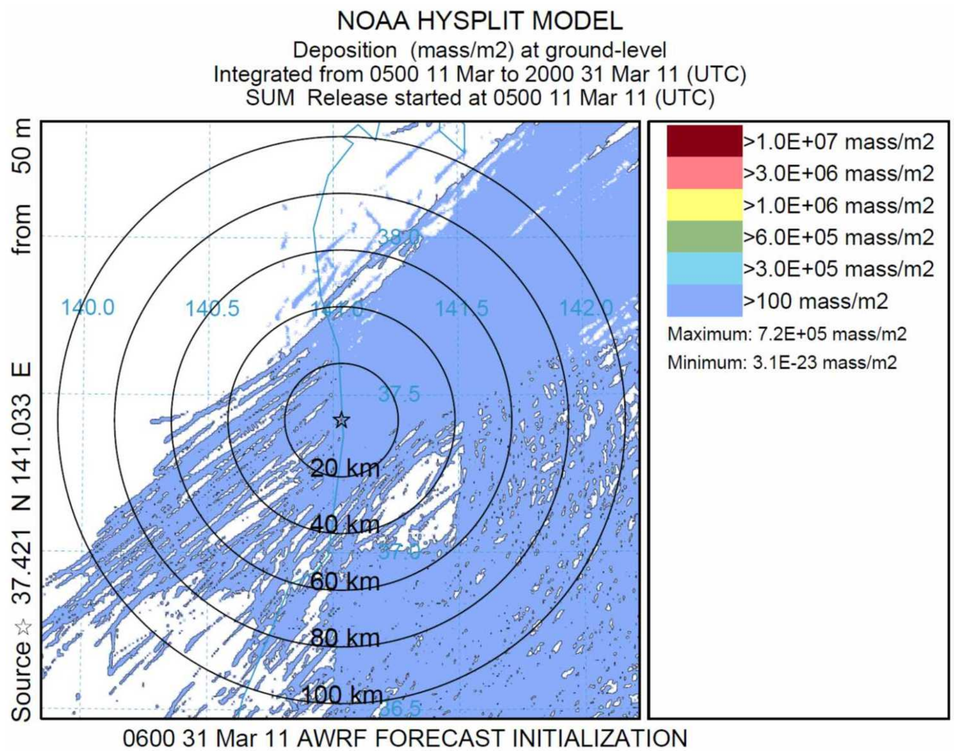
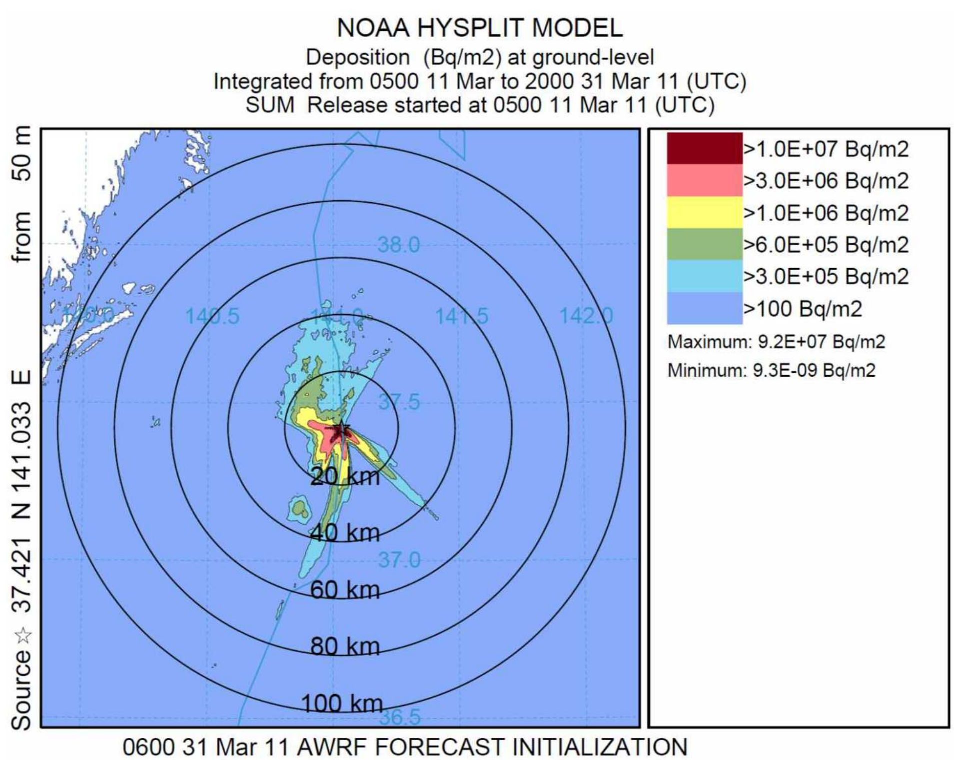


Figure 8-25 Cs-137 isopleths calculated for the NRC/DOE/SNL Unit 3 source term



8.5. Comparisons for Three Units Combined

Four of the organizations participating in BSAF Phase 2 submitted a source term for all three units for atmospheric transport analysis. Those were IAE, IRSN, KAERI (TW Kim), and NRC/DOE/SNL. A comparison of these four source terms is shown in Figure 8-26. GRS used observational data from locations near the Fukushima site to reconstruct a source term. The observational data were interpreted using an IAE tool called WSPEEDI. The GRS source term is also shown in Figure 8-26. Figures 8-27 through 8-31 show the deposition patterns predicted for these source terms.

While Figure 8-26 shows the total released Cs-137 activities for all three units for the four organizations, the actual atmospheric modeling was performed unit by unit and the resulting depositions summed to account for all three units. This allowed each unit to be analyzed at its correct location and it also allowed plume lofting due to buoyancy to be treated independently for each unit. The GRS source term is estimated for all three units and was modeled as if the entire source term was emitted from Unit 2.

The IAE source term produced significant deposition over the ocean but very little over land. The other three source terms produced significant deposition over land. Each of these has unique characteristics, but all three have some features in common. These include (1) significant deposition (>3 MBq/m^2) out to 10 to nearly 20 km towards the northwest and (2) a peninsula of deposition southward along the coastline. The deposition pattern for the GRS source term does not show the distinct peninsulas of deposition to the northwest or south along the seacoast that are observed in Figures 8-28 through 8-30.

The deposition to the northwest was observed (see Figure 8-4), but such a high level of on-shore deposition to the south was not. However, it has been noted that the sand along the seacoast to the south is heavily contaminated, which may indicate that significant deposition occurred slightly to the east (over the ocean) and resulted in contamination of the sand through wave and tidal interactions with the seashore [7]. Thus, a peninsula of deposition to the south near the seashore is entirely plausible.

Figure 8-26 Combined three-unit source terms for Cs-137 predicted by five BSAF participants

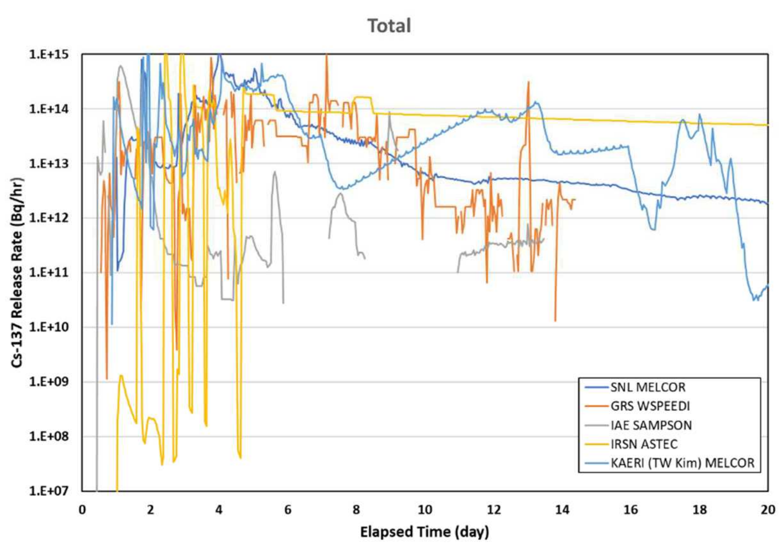


Figure 8-27 Cs-137 isopleths calculated for the IAE three-unit source term

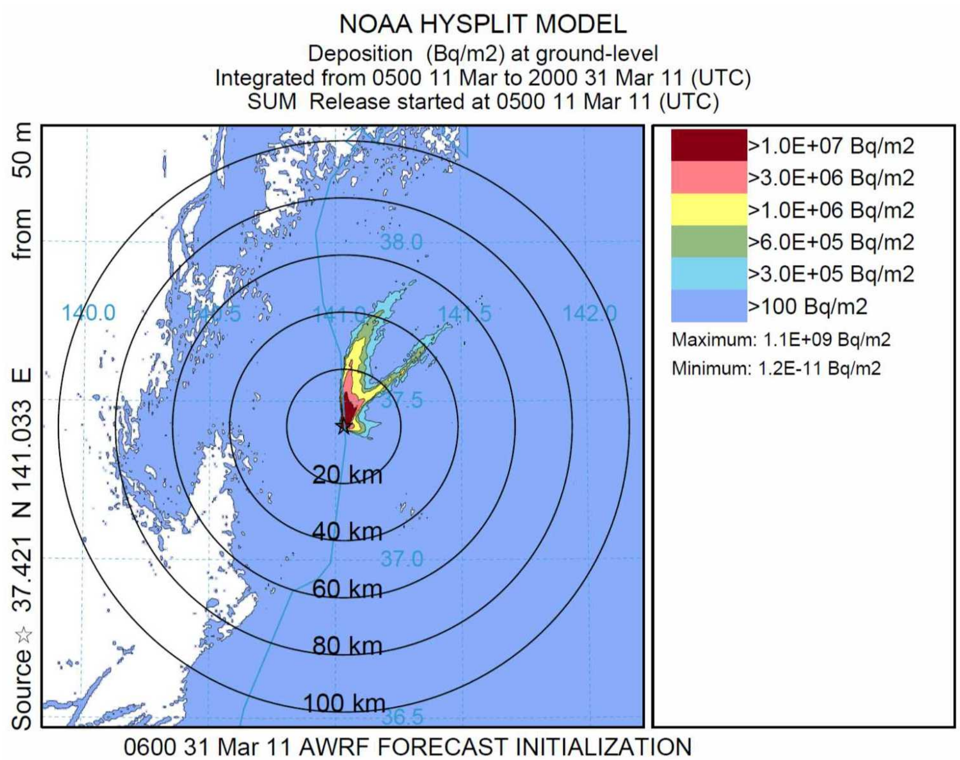


Figure 8-28 Cs-137 isopleths calculated for the IRSN three-unit source term

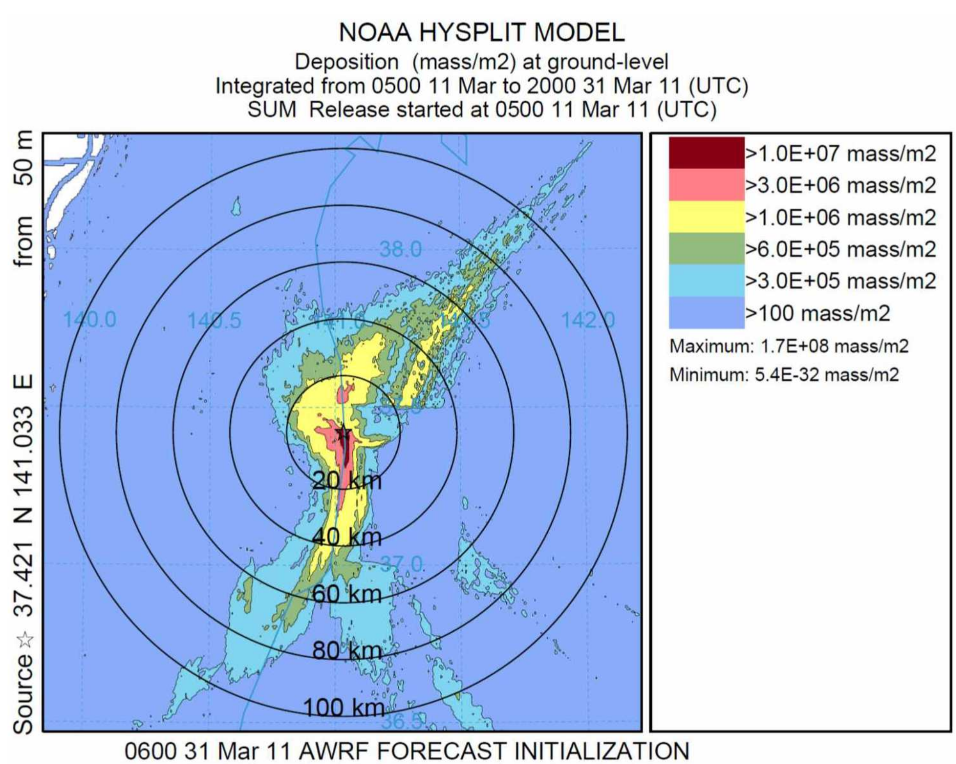


Figure 8-29 Cs-137 isopleths calculated for the KAERI (TW Kim) three-unit source term

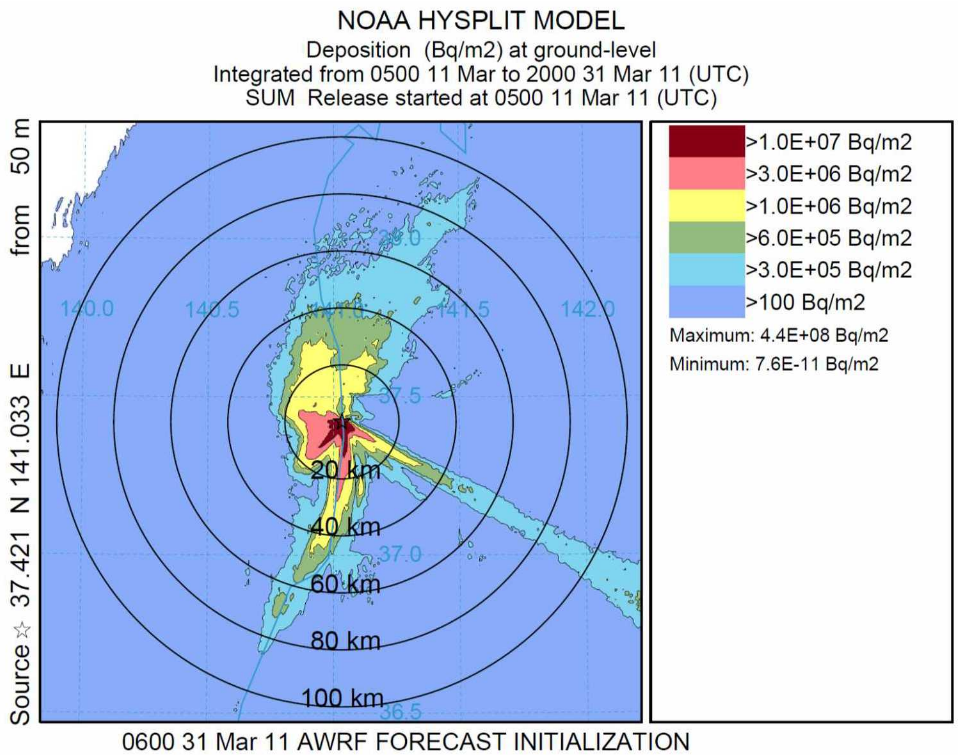


Figure 8-30 Cs-137 isopleths calculated for the NRC/DOE/SNL three-unit source term

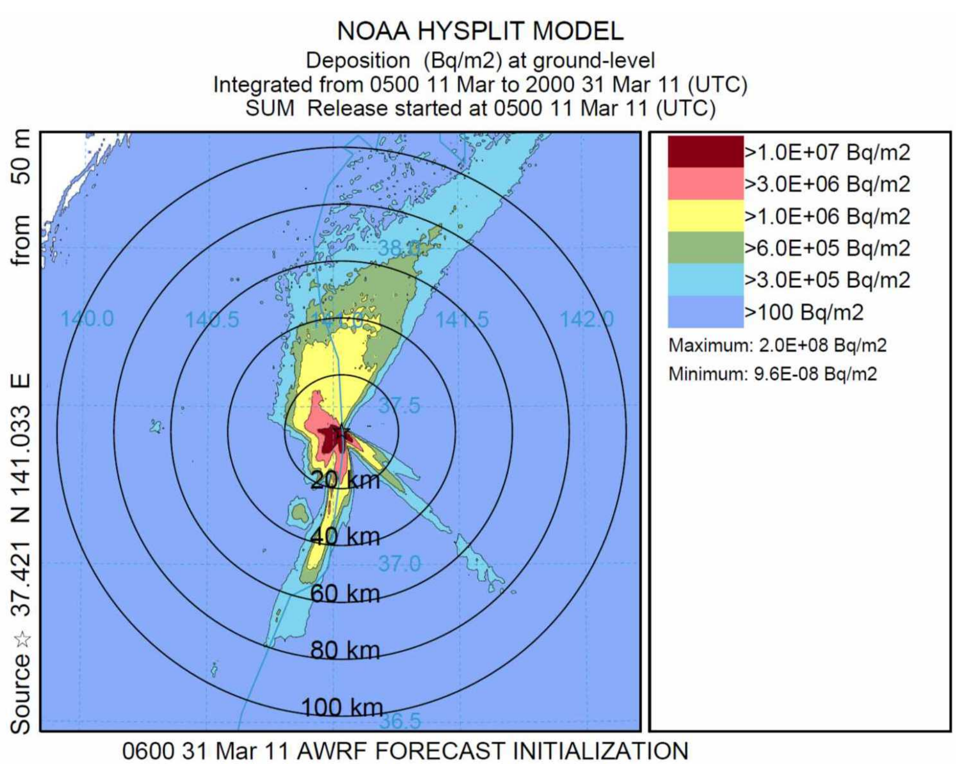
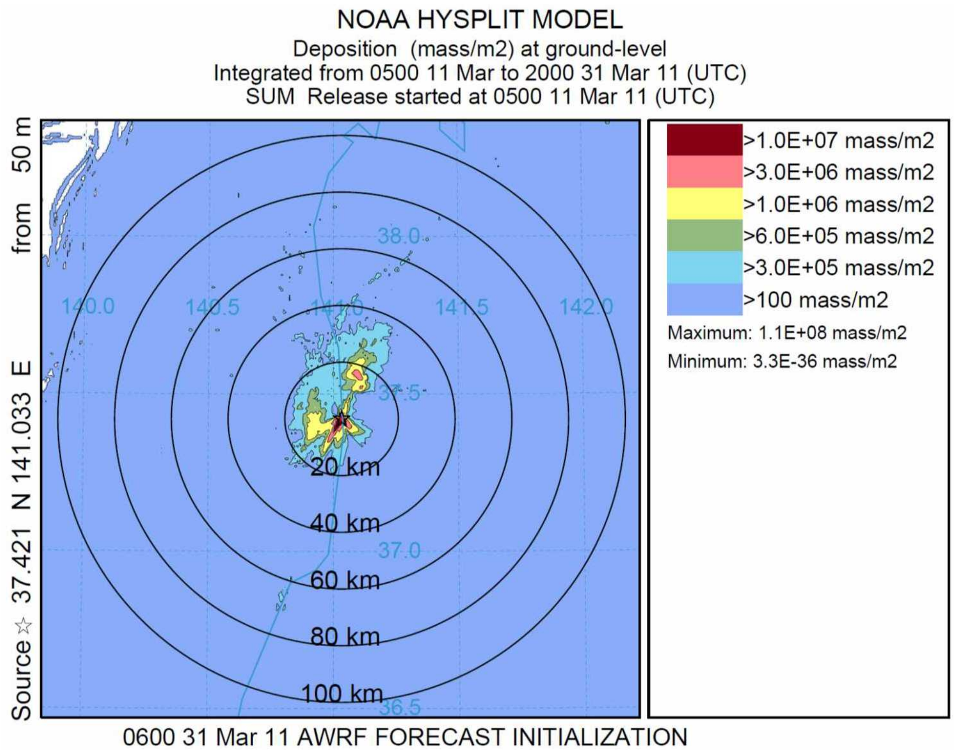


Figure 8-31 Cs-137 isopleths calculated from the GRS/WSPEEDI source term



8.6. Estimated Integral Releases

Table 8-3 shows the integral releases of Cs-137 (units are in PBq) predicted by each of the BSAF contributors to this chapter and the combined releases for all three units for organizations that evaluated all the units. In the case of GRS, individual units were not evaluated; instead, observational data were used to reconstruct a source term for the combination of the three units. Estimated releases from all three units range from 5.5 to 43.2 PBq of Cs-137. Other independent evaluations of integral release from all three units range from 9 to 37 PBq, all based on observational data.

Table 8-3 Integral releases of Cs-137 (PBq) predicted by BSAF contributors.

	Code	Country	Unit 1	Unit 2	Unit 3	Combined
CIEMAT	MELCOR 2.1-4803	Spain	5.6			
CRL	MELCOR 2.1-6342	Canada		8.1		
CRIEPI	MAAP 5.01	Japan		6.7	0.8	
IAE	SAMPSON-B 1.4 beta	Japan	4.4	0.0	1.1	5.5
IRSN	ASTEC V2.0 rev3 p1	France	0.1	0.1	43.1	43.2
KAERI (SI Kim)	MELCOR 1.8.6	South Korea		5.1		
KAERI (TW Kim)	MELCOR 1.8.6	South Korea	18.9	5.8	10.9	35.5
PSI	MELCOR 2.1-4206	Switzerland			0.2	
NRC/DOE/SNL	MELCOR 2.1-5864	U.S.A.	2.8	12.3	10.6	25.7
GRS	WSPEEDI	Germany				13.1

References

[1] Draxler, R.R., and G.D. Hess, 1997: Description of the HYSPLIT_4 modeling system. NOAA Tech. Memo. ERL ARL-224, NOAA Air Resources Laboratory, Silver Spring, MD.
[2] Draxler, R.R., and G.D. Hess, 1998: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. Aust. Meteor. Mag., 47, 295-308.
[3] Draxler, R.R., 1999: HYSPLIT4 user's guide. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring, MD.
[4] National Oceanic and Atmospheric Administration, Air Resources Laboratory, HYSPLIT User Guide retrieved from: http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf, December 22, 2016.
[5] National Oceanic and Atmospheric Administration, Air Resources Laboratory, Weather Data Archive retrieved from: ftp://arlftp.arlhq.noaa.gov/archives/, November 2017.
[6] Sanial, V., K.O. Buesseler, M.A. Charette, and S. Nagao, 2017: Unexpected source of Fukushima-derived radiocesium to the coastal ocean of Japan. Proc. of the National Academy of Sciences of the United States of America, http://www.pnas.org/content/early/2017/09/26/1708659114.