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ABSTRACT

A Radiological Dispersal Device (RDD) is a simple weapon capable of causing human harm, environmental contamination, disruption, area denial and economic cost. It can affect small, large or long areas depending on atmospheric stability. The risk of developing a radioinduced cancer depends on exposure, and an effective response depends upon available timely guidance. This paper proposes and demonstrates a convergence of three different capabilities to assess risk and support rapid safe resource efficient response. The three capabilities that are integrated are Hotspot for dispersion, RERF for epidemiological risk and RESRAD-RDD for response guidance. The combined methodology supports decisions on risk reduction and resource allocation through work schedules, the designation and composition of response teams, and siting for operations. In the illustrative RDD scenario, the contamination area for sheltering, evacuation and long term public concern was greatest for calm atmospheric conditions, whilst close quarter responders faced highest dose rates for neutral atmospheric conditions. Generally the risks to women responders were found to be significantly greater than for men, and the risks to 20 year old responders were three times that of their 60 year old counterparts for similar exposure.

Key-words: Risk Assessment, Radiation, Convergence Methodology

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INTRODUCTION

A Radiological Dispersal Device (RDD) is a relatively simple device that does not require an extensive knowledge of nuclear technology to assemble and use for harmful effect. A small amount of radioactive material may be spread over an area to cause harm, disruption and environmental contamination. The explosion of such a device is not usually intended to produce a considerable amount of debris, though it can happen in some cases in the vicinity of the explosion site(1). For this work, the spread of radiological material was achieved by a small amount of explosive.

Radiation spread by an RDD can affect large and long areas depending on the local atmospheric stability. This sort of incident can potentially paralyze a city or state, by inflincting significant economic, political and social impact. The magnitude of the impact depends on factors involving the local population, climate conditions and the estimate of the radiation doses. There has already been work that combines the radiological dispersion with population distribution to forecast long term economic impact(2, 3). The work presented here concentrates on optimizing efficiency and safety in early response.

The HotSpot code(4) uses a semi-empirical Gaussian model to provide a fast first-order approximation of radiation effects associated with the atmospheric release of radioactive materials. Other dispersion models exist such as NAMEIII(5) developed by the UK meteorological office which includes sophisticated atmospheric modelling. However, Hotspot is fast, widely accessible and suitable for early response. Hotspot conservatively evaluates contamination in an affected area and calculates the total effective dose equivalent (TEDE) by accounting for external contributions to the absorbed dose. Such data is needed to conduct effective risk assessments and optimize safety.[6]

RESRAD-RDD was developed by Argonne Laboratory and sponsored by the US Department of Energy (DOE). It is intended to support the implementation of operational guidelines for Emergency Preparedness and Response for an incident involving an RDD. A previous study using RESRAD-RDD was performed by Kamboj and colleagues, but it did not using a statistical model to perform risk assessment.[7]

Risks arising from exposure to ionizing radiation have been studied by the Radiation Effects Research Foundation (RERF)[8, 9] which provides technical data to the United Nations Scientific Committee, including the Effects of Atomic Radiation (UNSCEAR) on induced cancer risk in the population.The model estimates the relative risk (RR) of developing cancer as a result of exposure to radiation. It has been developed using the epidemiological follow-up of Japanese atomic bomb survivors, the Life Span Study (LSS) and shows the risks that males and females can develop cancer from the same radiation dose are different. The risk to an embryo from radiation is greater than to a child, which in turn is greater than to an adult. The differing risks give rise to different radiation exposure legislation and operational guidance for men, women and children.

The convergence of different capabilities was crucial to this study and has led to the proposal of two well-defined phases using the three main tools. Figure 1 shows the main outputs of the Hotspot, RERF and RESRAD-RDD tools, which together provide the data needed for risk assessment and decision support. Phase 1 of the work includes simulating a scenario by using Hotspot which is then fed into the RERF modeling to obtain a prompt risk assessment for field work. In phase 2, RESRAD-RDD is used to propose coping strategies based on the boundary conditions simulated in the first phase, and to generate risk mission tables for personnel involved in the RDD response.

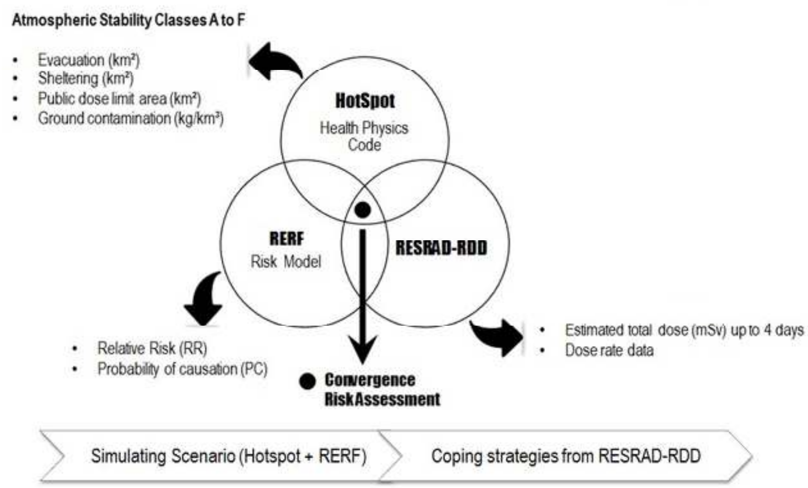

Fig. 1 – Scheme of calculations used in this work for risk assessment resources.

METHODOLOGY

Radioactive materials are ejected into the atmosphere to a height which depends on the energy of release. They are carried by the wind and dispersed by natural processes of turbulent atmospheric diffusion[10]. The turbulent state of the atmospheric boundary layer is described by stability classes, also known as diffusion categories. The Pasquill-Gifford notation[11, 12] defines atmospheric stability classes as A: Extremely Unstable ($\sigma_\theta \geq 25°$), B: Moderately Unstable ($\sigma_\theta = 20°$), C: Slightly Unstable ($\sigma_\theta = 15°$), D: Neutral ($\sigma_\theta = 10°$), E: Slightly Stable ($\sigma_\theta = 5°$) and F: Moderately Stable ($\sigma_\theta = 2.5°$) where σ_θ is the standard deviation in the horizontal wind direction. This work follows this notation and so uses an atmospheric stability classification system recommended by the Nuclear Regulatory Commission (NRC).[13]

Risk Assessment

Risk in the mission is the chance of any responder eventually developing solid cancer due to external exposure during the mission. It is a tailored parameter as it takes into account specific individual characteristics such as age and sex. It helps select the most adequate personnel for the mission in order to reduce radiation exposure to a minimum, both individually and for the group. Risk can be expressed as a relationship between threat, vulnerability and consequence described by equation 1.[14]

$$\text{Risk} = \text{Threat} \times \text{Vulnerability} \times \text{Consequence} \quad (1)$$

For this scenario, threat was associated with total effective dose (TEDE), vulnerability was associated with Relative Risk (RR, see equation 2) and consequence was associated with the probability of causation (PC)[15]. The PC is an estimative of the probability that a given radiation dose in the history of a patient was the cause, in some sense, of a subsequent malignant neoplasm that has actually occurred[15]. Because RR and PC are influenced by the variables of age and gender and the TEDE is affected by fluctuations in horizontal wind direction the mission risk can be estimated by taking into account gender, age and weather conditions. The methodology could support a decision maker to choose the most appropriate human resources to keep individual doses below gender and age specific risk thresholds and minimize collective risk.

An RDD scenario demands quick decisions on protective measures such as shelter and evacuation to minimize risk. The effectiveness of the protective measure is determined from the dose that would be received with protective measures compared to the dose that would be received without. The projected radiation dose parameter (PRD) is often used to set thresholds at which protective measures are advised.[16, 17] Typically, the response to an RDD can be divided into three phases (a) initial (b) intermediate and (c) late (see table I), regardless of the type of radioactive incident.[11, 6]

Table I – General phases of an RDD emergency response[12]

Phase	Protection Action	Protection Action Guide (PAG) thresholds
Initial	Sheltering	Projected dose of 10 to 20 mSv (in 2 days)
	Evacuation	Projected dose of 20 to 50 mSv (in one week)
Intermediate	Exposure Limit	50 mSv/year
	Public resettlement	Projected dose of 20 mSv/first year
	Ban food consumption (local goods)	Projected dose of 5 mSv/year
	Ban water consumption	Projected dose of 5 mSv/year
Late	Decontamination and disposal	PAG based on the optimization of response actions

In this work, the HotSpot code was used to determine dose distributions which were then input to the RERF model to give the relative risk of developing cancer.

RESRAD-RDD is a software tool highlighted in the Protective Actions Guide[11] (PAGs) for protecting emergency workers and the public during early response and recovery. RESRAD-RDD provides guidance for evacuation, sheltering and access control in the early phase. In the recovery phase when the plume has dissipated then RESRAD-RDD can be used to estimate the dose absorbed by individuals entering the scene from ground contamination distributions calculated by Hotspot.[4]

This study aims to test the convergence methodology which is the combination of different independent methodologies to reach a common goal. Thus, a third software tool (RERF) was included to test the risk of developing human solid tumors as the final outcome of the RDD. The mathematical model presented by RERF for the relative risk (RR) adapted for solid tumors appears in equation 2.

$$RR = R_0(a,s)[1+(\alpha_s D)\exp(\beta(e-25))] \quad (2)$$

Where α_s (Sv^{-1}) is the excess linear risk for the specific age, e is the age at exposure in years, β is the determining factor modifier effect for the age (Male: α_s = 0.45, β = -0.026; Female: α_s = 0.77, β = -0.026), a is the attained age and, D is the dose in Sv [(15)]. $R_0(a,s)$ is the local baseline mortality rate which was made unity for simplification purposes.

The convergence methodology using Hotspot, RESRAD-RDD and RERF was applied to a cesium dirty bomb scenario where decision making for safety, staffing and work rotas for two groups of people would be required. One group would conduct access control at the perimeter and the other group would conduct recovery operations closer to the detonation site. The parameters entered into the models to define the scenario appear in table II below.

Table II - The input parameters for Hotspot code and RESRAD-RDD for the scenario.

Input Data for Hotspot and RESRAD-RDD	
Hotspot	RESRAD-RDD
1. Material at Risk (MAR) - Total activity of Cs-137: 3.70 x 10^{14}Bq	1. External dose conversion factor: ICRP 60
2. Breathable Fraction (RF) (≤ 10 μm): 0.200	2. Internal dose factor: ICRP 72
3. Material Breathable: 7.40x10^{13}Bq	3. Risk factor: FGR-13 Morbidity
4. Material Non-Breathable: 2.96x10^{14}Bq	4. Radionuclide: powdered ^{137}Cs
5. Wind speed (h = 10 m - default): 2.50 m/s	5. Roughness correction factor for external radiation: 1
6. Explosive Material: 22.00 Pounds of TNT	6. Resuspension factor (m^{-1}): 1.0x10^{-6}
7. Location: Lat. 22° 53' 57.07" S, Long. 43°12' 32.79" O	7. Groups A and B for response

Meteorological data: Brazilian National Institute for Space Research (INPE – http://www.inpe.br)

RESULTS AND DISCUSSION

Contamination from Hotspot calculations

The Hotspot code was used to explore the area over which various weather conditions may spread radiological contamination to different concentrations. This is shown in figure 2.

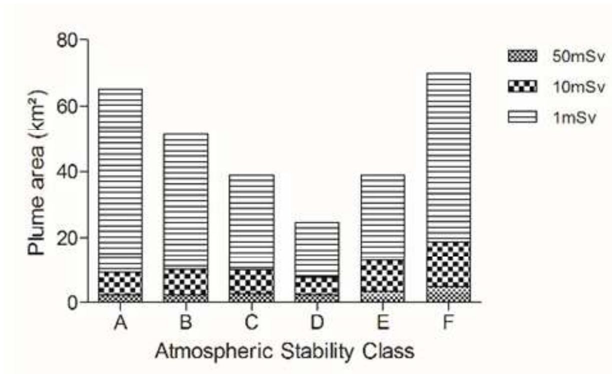

Fig. 2 – Relationship between affected area and atmospheric stability class.

The data for the 1 mSv/year outer isodose contour represents the limit for public safety recommended by ICRP[18]. The dose limits for public and responders are different from each other and follow recommendations from ICRP 103 as reviewed by Wrixon[19] where the guidance on permissible dose for an emergency responder is 50mSv in one year and 100mSv has been put forward as a threshold for life saving measures.

The area of the contamination defined by the 1mSv/yr outer perimeter is at a minimum of 25 km^2 for neutral class D conditions, greatest for moderately stable class F weather conditions at around 70 km^2, but similarly large at 65 km^2 for extremely unstable class A conditions. Authorities should consider how atmospheric conditions affect the number of citizens who will be affected psychologically and possibly physically to a level beyond what is considered safe.

The area-weather trend seen for the 1 mSv/yr public safety limit is not the same area-weather trend that Hotpot reveals for the 10 mSv exposure limit for sheltering or the 50 mSv exposure limit for evacuation and responder recovery actions (see PAG guidance, table 2). For the 10mSv sheltering threshold the area remains nearly constant around 5.3 km^2 for extremely unstable atmospheric class A to neutral class D, before increasing to approximately 15 km^2 for the moderately stable atmospheric class F. A similar trend is seen for the 50 mSv evacuation threshold which remains around 2km^2 for the less stable conditions A to D before rising to 4.4 km^2 for moderately stable atmospheric conditions.

Relative Risk (RR) – RERF

The Relative Risk calculations become important as they predict the vulnerability of public and personnel to solid tumours. The results are shown in Figure 3. The risk seems to be similar for female and male groups for atmospheric stability class A. For atmospheric classes B to F, there is a progressive increase in risk for women relative to men.

It should be noted that children of both sexes were included in the study to highlight how the risk of young people developing cancer is much greater than for older people. These results can help emergency medical staff define procedures and set priorities for initial screening. Not withstanding political and ethical considerations, the results indicate that children of both sexes should be considered first for triage, followed by women and then men in ascending order of age.

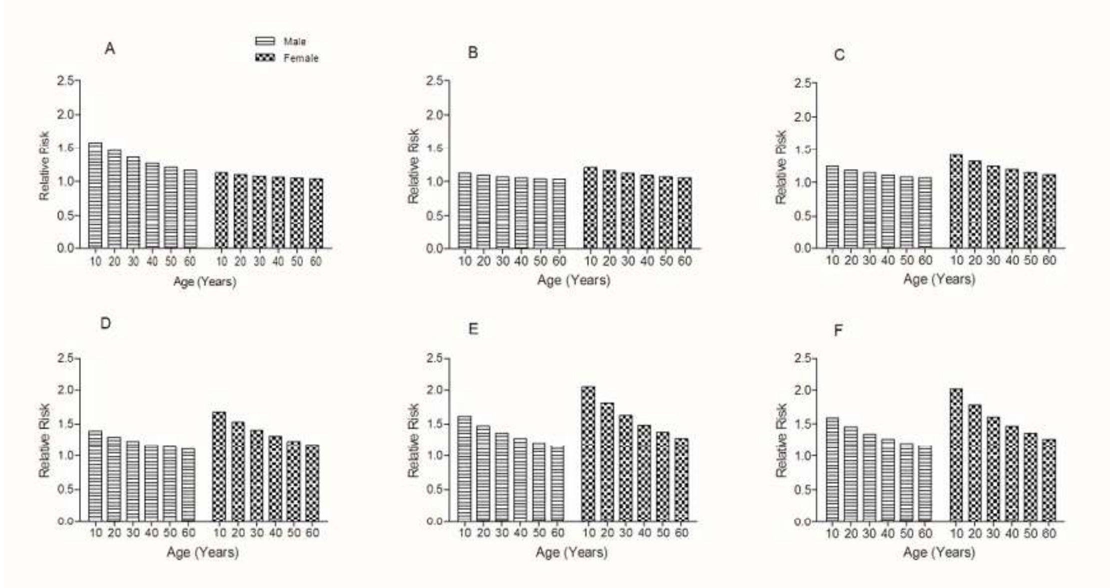

Fig. 3– Relative Risk (RR) adjusted for solid tumors. The population is considered to be homogeneously distributed within the area of interest.

Risk and Mission Level

The Operation Guide of RESRAD-RDD is characterized by seven groups of measures A to F (not to be confused with atmospheric stability classes also described A-F). Measures A to F refer to different sets of activities and phases of initial response and recovery. Measures A and B are dedicated to urgent protection in the early stages up to 4 days after the explosion. In this study, only groups A and subgroups B were considered, and the atmospheric stability class A was considered all through to calculate risk and mission level. In this scenario group B was subdivided into 3 task groups all working within 100m downind from the release site, where subgroup B1 remained inside shelter all of the time, subgroup B2 worked outside shelter for brief periods (but otherwise worked inside the shelter), and group B3 were always outside the shelter. The risk and mission level, which are the risk from equation 2 normalized to each group and subgroup in relation to the RR accounted for 4 Sv (mean LD_{50} for humans), for the special case of solid tumor development was calculated according to equation 2.

RESRAD-RDD Group A- Access control during emergency response operation

Group A are the measures designed to assist in the decision-making process for creating control zones and boundaries for the purpose of making staff safe in the initial deployment phase. The PAG's that RESRAD-RDD supports feature a 100 mSv threshold for personnel during a radiological emergency. In this scenario, responders were located 2 km downwind from the source release and are not permitted to change their roles during operations in order to comply with the PAGs.

Hotspot was used to calculate total dose for the purposes of evacuation and sheltering, and RESRAD-RDD was used to calulate doses for field operations. Marked differences were found in the duration that field operatives could work given different atmospheric conditions. Atmospheric stability class A indicated that a responder equipped with a respirator could be kept working 2,300 hours before reaching 100mSv. For the same protective equipment and permissible dose the working time directly downwind is shortened to 180 hours for moderately stable atmospheric class F (see figure 4). The typical activity profile for personnel required to remain 2 km downwind may include: (a) administration, (b) media interaction, (c) shift management and (d) risk assessment control. However, relocating these people to an off downwind-axis location would be preferable. Table III shows risk calculations for personnel aged from 20 to 60 years-old in this location. The risks for 20 year old responders are almost 3 times greater than for 60 year old responders, and the risks for women are about 70% greater for women than men.

Mission Level (ML) is a parameter which considers external whole body exposure scaled as 10 for 4Sv (mean LD_{50} for humans) and 0 for background level of radiation. ML is stated in arbitrary units and shows no differences between males and females. Risk is defined as the true chance of developing cancer because of the mission. Risk was calculated as (RR -1) x baseline x lifetime risk of cancer x 100%, even though baseline x lifetime risk of cancer were kept as unit for simplification purposes. Mission level varies from 0 to 10 providing fast risk identification. As an example, ML = 0,25 means that a responder from Group A, aged 20 (male or female) is under 100 mSv radiation field, as expected.

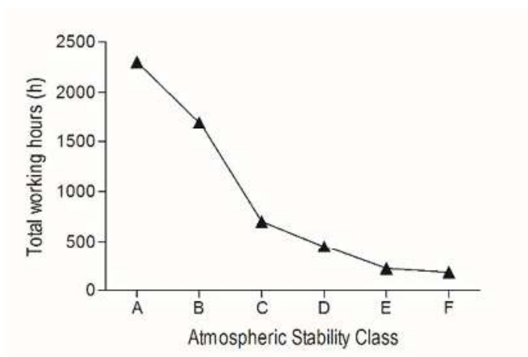

Fig. 4– Time to reach 100 mSv exposure 2 km downwind of release for different atmospheric stability classes (A to F) calculated from Hotspot.

Table III– Mission level evaluation for Group A, initial access control, for Atmospheric Stability Class A ($\sigma_\theta \geq 25$).

Group A - Individual Risk Assessment			
	Risk (%)		Mission Level (arbitrary units)
Age (years)	**Male**	**Female**	**ML**
20	5.12	8.77	0.25
30	3.95	6.76	0.19
40	3.05	5.21	0.15
50	2.35	4.02	0.11
60	1.81	3.10	0,09

RESRAD-RDD Group B- Initial response, urgent protective actions (evacuation and sheltering)

This group B represents people undertaking actions close to the release site for up to 4 days. Figure 5 reveals that atmospheric stability severely influences the total estimated dose (TEDE) that responders in subgroups B1, B2 and B3 would receive during field operations. The results in figure 5 should be compared to those in figure 2, which suggests that the atmospheric conditions giving the least overall area of concern to the public arise from finite material being concentrated where this scenario has specified type B recovery actions are conducted. For this demonstration of convergence methodology only atmospheric stability class A was taken forward to calculate mission risks for these subgroups.

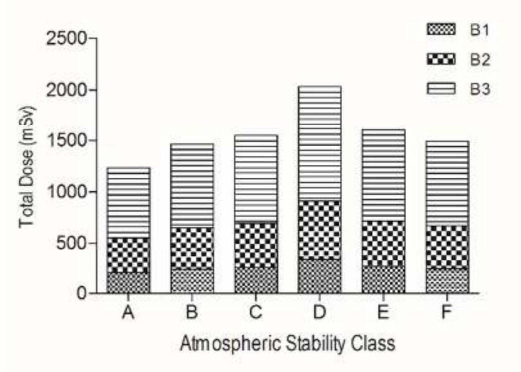

Fig. 5 – Total estimated dose (mSv) at 100 m from hotzone for all subgroups B and for different atmospheric stability classes.

Table IV shows risks and mission levels calculations for personnel aged from 20 to 60 years-old in activity subgroups B1, B2 and B3. The mean risk for subgroup B1 working under shelter 100m downwind is about twice that of group A conducting access control at the perimeter. Subgroup B2 conducting their mission under partial shelter experiences mission risk 3.6 times greater than group A, and mean risk for subgroup B3 working outside without shelter are around 6.8 times greater than group A. These results could be interpreted as being the advised reductions in the duty time of staff conducting these close quarter operations compared to those at the access point. Or the results could indicate the increased numbers of trained staff that may be required to surge into these close quarter roles on a short duty cycle rota basis.

Overall, results indicate that the mission risk for women is greater than for men, and that the risks for 20 year old responders are almost three times greater than for their 60 year old counterparts. Approximately, the risks faced by subgroup B3 are double those of subgroup B2 which are double those of subgroup B1. This information could be considered as guiding the relative number of responders needed to work in rotas in each subgroup to spread risk uniformally below some threshold. Mission levels rise up to 1.7 in subgroups B. Mission levels decrease with age and increase with subgroups duties (B1 to B3).

Table IV – Risk and Mission Level evaluation for Subgroups B (RESRAD-RDD), Atmospheric Stability Class A ($\sigma_\theta \geq 25$).

Subgroup B1 - 100% inside shelter			
	Risk (%)		Mission Level (arbitrary units)
Age (years)	Male	Female	ML
20	10.25	17.54	0.50
30	7.90	13.52	0.39
40	6.09	10.43	0.30
50	4.70	8.04	0.23
60	3.62	6.20	0.18
Subgroup B2 - hot area sometimes			
	Risk (%)		Mission Level (arbitrary units)
Age (years)	Male	Female	ML
20	17.94	30.69	0.87
30	13.83	23.66	0.67
40	10.66	18.25	0.52
50	8.22	14.07	0.40
60	6.34	10.85	0.31
Subgroup B3 - 100% outside shelter			
	Risk (%)		Mission Level (arbitrary units)
Age (years)	Male	Female	ML
20	34.85	59.63	1.70
30	26.87	45.98	1.31
40	20.72	35.45	1.01
50	15.97	27.33	0.78
60	12.32	21.08	0.60

CONCLUSION

The results from this work demonstrating convergence methodology are consistent with the literature and represent an additional tool to help decision-making during the response to an RDD incident. The findings provide additional support for (a) estimating the area extent of initial measures versus long term public concern, (b) human resource planning and training for responders, (c) scientific justification for the selection of individual responders for a specialized response team, (d) appropriate designation of a specific team to a specific scenario or task, (e) selection of schedule and shifting in the affected area, (f) determining the best location for the base of operations and (g) overall and individual risk reduction.

The study highlighted how the most stable and most turbulent atmospheric conditions yield the greatest areas of low level contamination relevant to long term public concern. The contaminated areas requiring sheltering and evacuation measures are reasonably constant for unstable atmospheric conditions, but rise significantly between neutral and stable conditions. However conducting timely measures for long thin plumes could be even more difficult than for localized ones for the further reason that any uncertainty in mean wind direction could change the whole area over which the measures are required.

Illustrative risk data shows females to be exposed to greater risks than males. Some close quarter recovery mission profiles were identified that gave eight times the exposure rate of missions for boundary access controls. This could mean a requirement for shorter work rotas and more staff trained for that role, if recovery and access control measures ran for the same duration.

Further studies are needed to define measures that would most effectively support the decision-making process in a real RDD scenario given the wide range of factors involved. However, this work has demonstrated a pragmatic functional convergence of three radiological assessment and planning tools that between them enable improved decision making for the selection, scheduling and locating of human resource in the early phases of an RDD incident.

REFERENCES

1. Saint Yves TLAC, P.A.M ; Alves, P.M.P.M ; LAURIA, D.C.; Andrade, E.R. Terrorist radiological dispersive device (rdd) scenario and cancer risk assessment. Human and Ecological Risk Assessment, 2012; 18:971-83.
2. Giesecke JA, Burns WJ, Barrett A et al. Assessment of the regional economic impacts of catastrophic events: Cge analysis of resource loss and behavioral effects of an rdd attack scenario. Risk Anal, 2012; 32 (4):583-600.
3. Dombroski MJ, Fischbeck PS. An integrated physical dispersion and behavioral response model for risk assessment of radiological dispersion device (rdd) events. Risk Anal, 2006; 26 (2):501-14.
4. S.G. H. Hotspot health physics codes version 3.0 user's guide. CA, USA.: Lawrence Livermore National Laboratory, 2013.
5. Jones A.R. TDJ, Hort M. and Devenish B. The uk met office's next-generation atmospheric dispersion model, name iii. In: BCaN A.-L, editor. Air Pollution Modeling and its Application XVII (Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application). Series The uk met office's next-generation atmospheric dispersion model, name iii. Banff Centre, Banff, Alberta, Canada; 2007; p. 580-9.
6. Shin H, Kim J. Development of realistic rdd scenarios and their radiological consequence analyses. Appl Radiat Isot, 2009; 67 (7-8):1516-20.
7. Kamboj S, Cheng JJ, Yu C et al. Modeling of the emras urban working group hypothetical scenario using the resrad-rdd methodology. J Environ Radioact, 2009; 100 (12):1012-8.
8. Thompson DE, Mabuchi K, Ron E et al. Cancer incidence in atomic bomb survivors. Part ii: Solid tumors, 1958-1987. Radiat Res, 1994; 137 (2 Suppl):S17-67.
9. Mabuchi K, Soda M, Ron E et al. Cancer incidence in atomic bomb survivors. Part i: Use of the tumor registries in hiroshima and nagasaki for incidence studies. Radiat Res, 1994; 137 (2 Suppl):S1-16.
10. Pasquill F. The estimation of dispersion of windborne material. Meteorol. Mag., 1961; 90:33-49.
11. Jeong H, Park M, Hwang W et al. Radiological risk assessment caused by rdd terrorism in an urban area. Appl Radiat Isot, 2013; 79:1-4.
12. EPA. Protective action guides and planning guidance for radiological incidents - draft for interim use and public comment. In: EPA 400-R-92-001. Series Protective

action guides and planning guidance for radiological incidents - draft for interim use and public comment. USA: United States Environmental Protection Agency's (EPA); 2013.
13. N. E. Bixler EC, and C. W. Morrow. Synthesis of distributions representing important non-site-specific parameters in off-site consequence analyses. In: NR Research, editor., Series Synthesis of distributions representing important non-site-specific parameters in off-site consequence analyses. Albuquerque, New Mexico: Office of Nuclear Regulatory Research; 2013.
14. Cox LA, Jr. Some limitations of "risk = threat x vulnerability x consequence" for risk analysis of terrorist attacks. Risk Anal, 2008; 28 (6):1749-61.
15. IAEA. Methods for estimating the probability of cancer from occupational radiation exposure. Vienna, Austria. 1996.
16. IAEA. Bss, international basic safety standards for protection against ionizing radiation and for the safety of radiation sources Vienna: IAEA. 1996.
17. IAEA. Generic procedures for assessment and response during a radiological emergency Vienna. 2000.
18. ICRP. Recommendations of the international commission on radiological protection. In: ICRP Publication 60. Ann. ICRP 21 (1-3). Series Recommendations of the international commission on radiological protection. 1991.
19. Wrixon AD. New icrp recommendations. J Radiol Prot, 2008; 28 (2):161-8.