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NATO LETTER OF PROMULGATION

20 September 2017

1. The enclosed Allied Engineering Publication AEP-72, Volume V, Edition A, Version 1 RADIOLOGICAL CHALLENGE LEVELS, which has been approved by the nations in the NATO ARMY ARMAMENTS GROUP, is promulgated herewith. The recommendation of nations to use this publication is recorded in STANREC 4790.

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RECORD OF SPECIFIC RESERVATIONS

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1 AIM

The purpose of Volume V of this Allied Engineering Publication (AEP) is to recommend deposition and dosage levels of radiological materials to which protective equipment and procedures for NATO forces should be designed to allow unaffected operations. These challenge levels are intended to provide design guidelines and are not to be used for "risk assessment".

2 AEP-72 STRUCTURE

Volume I of AEP-72 presents a NATO Unclassified, Releasable to PfP, challenge level summary of the other AEP-72 volumes.

Volume II covers chemical agent challenge levels. Volume III covers TIC challenge levels. Volume IV covers biological warfare agent challenge levels. Volume V covers radiological material challenge levels.

3 APPLICATIONS AND LIMITATIONS

General applications and limitations are given in Volume I, Chapter 4.

The recommended radiological challenge levels are in terms of deposition and dosage at operationally relevant downwind distances and exposure durations. The dosage challenge levels are most useful for designers of physical protective equipment and for medical care. Information on radiological material deposition and reaerosolisation (resuspension) is also useful for these same applications. Deposition values are most useful for designers of surface contamination detection and identification equipment and methods, as well as decontamination equipment, solutions, and methods.

Limitations for the radiological challenge levels in this AEP include:

- The vignettes considered are intended to provide a reasonable cross-section of the expected intentional incident types for the radiological materials of most concern. The vignettes include attacks that would be conducted by non-state actors. The set of vignettes includes a limited set of release and environmental conditions intended to be favourable to generation of large hazard areas; the set of vignettes is by no means comprehensive.
- This volume focuses on inhalational exposure and does not address in depth radiation exposure through other means, such as cloud shine and ground shine. Deposition is only reflected in inhalation from reaerosolisation of deposited particles. The vignettes were defined to result in worst-case inhalation hazards and may not reflect similar dosage levels for other types of

radiological hazards. These processes may be addressed in future editions of this AEP.

- Deposition challenge levels included in this volume are for horizontal surfaces, which have limited applicability to skin deposition.
- The current challenge levels may be of limited use to groups concerned with operations and doctrine.
- Large variations in the efficiency of dispersion devices and material in the device could lead to a great range of possible variations in the particle size distribution and the effective mass released.
- Due to the complex mix of radioisotopes from reactor incidents, all challenge levels are expressed as effective dose in units of Sievert (Sv). Conversion from activity concentrations to effective dose includes factors such as breathing rate and dose conversion factors, among others.
- Vignettes addressed are based on the threat considered relevant prior to 2006 and have not been revised for AEP-72 Volume 5. New threats may be addressed in future editions of this AEP.
- Challenge levels from nuclear weapons were considered but are not addressed in this AEP. The hazard from ground shine and cloud shine resulting from a nuclear weapon attack are known to be significant; however, only inhalation challenge levels are considered in this AEP.
- Inhalation challenge levels from the primary source document, AC/225(LG/7)D(2006)0003 [1], used for this AEP, include vignettes where the same radiological material is released indoors and inhaled for the following 15 minutes as for outdoor simulations. More realistic indoor vignettes may be considered in future editions of this AEP.
- The legacy document on which this document is based refers to ICRP 26 [11], ICRP 68 [8], and STANAG 2473 [3], which have been superseded by more recent documents. This has also led to the use of units of measure in this document that are no longer used in the community. In future editions of this AEP the units will be updated to current standards.

4 INTRODUCTION

The deliberate release of radiological materials against North Atlantic Treaty Organization (NATO) forces could result in both large hazard areas and operational risks.

The concept of radiological challenge levels was developed by the Nuclear Protection Sub Group (NPSG), later the Joint Radiological and Nuclear Defence Sub-Group (RNDSG), under Land Group 7 (LG/7) on Joint NBC Defence as AC/225(LG/7)D(2006)0003 [1]. That report followed previous work documented in AC/225(LG/7)D(2004)2(INV) [2]. The challenge level part of the 2006 RNDSG document is published in this volume of AEP-72. This volume builds on and aligns this work with other AEP-72 volumes to provide updated radiological challenge levels.

NATO LG/7 initiated the project to fully delineate the threat from non-article 5 scenarios and, from an investigation of this threat, to develop radiological challenge levels. The resulting document, published in 2006, deals exclusively with the challenge posed by the inhalation of aerosolised radioactive material, not external radiological threats. The results of that document were intended for use in developing requirements for defensive capabilities, especially personal protective equipment.

The 2006 document considered the following scenarios:

- The residual effects of a tactical nuclear weapon strike
- A nuclear weapon incident involving dispersal of ^{239}Pu
- A radiological weapon involving the deliberate dispersal of radiological material
- A damaged nuclear reactor facility, resulting in the release of radioactive material containing multiple radioisotopes
- The inhalational threat to personnel involved in vehicle decontamination activities following an incident involving radioactive material

These scenarios cover the three main types of radiological material (α, β and γ emitters), and involve the specific isotopes believed, at the time of the study, to represent the greatest hazard to living organisms, based on availability, typical activities, ease of aerosolisation and the biological damage that the specific isotopes can inflict.

In 2014, the Joint Chemical, Biological, Radiological and Nuclear Defence Capability Development Group (JCBRND-CDG) tasked the Chemical, Biological and Radiological Challenge Levels Team of Experts (CBRCL TOE) to develop AEP-72 Volume 5 with radiological challenge levels.

5 METHODOLOGY

Three main types of radiation are emitted from radioactive material, which have very different physical characteristics and therefore different biological effects. Gamma (γ) radiation is very penetrating, requiring a large amount of shielding to stop, and therefore poses a significant external radiation threat. Alpha (α) and beta (β) radiations are less penetrating and are therefore less of a threat when external to the body (with the exception of high-energy β radiation) but pose a very significant threat when internalised. It is important to address all three of these types of radiation when assessing the challenge posed by radiological aerosols.

For radiological material inhalation challenges, the quantity of biological significance is the committed effective dose (CED). This dose is related to the type of material that is inhaled, the size of the particles, the specific activity, the type of radiation that they emit, organ uptake and of course, the quantity that is inhaled. Because of this complexity in the determination of the dose, inhaling the same mass of two different radiological materials could result in vastly different levels of committed effective dose. The activity and type of the radiological material in question are the important factors in assessing its biological impact (these factors are given by full isotopic specification of the material). In that light, the radiological challenge levels should be defined in terms of integrated *activity* concentration rather than mass concentration (as is appropriate for chemical challenges). To do this, typical specific activities will be assumed for each of the scenarios under consideration.

The outdoor radiological inhalation challenge level is defined as the airborne respirable concentration of the radiological material multiplied by the expected exposure time for a person standing 100 meters downwind of a radiological dispersion device (RDD) when it is detonated. The same parameters apply for these RDDs when they are detonated in a confined space [1]. The confined space challenge levels assume that personnel will be working in a 10-meter radius hemispherical area for a 15 minute duration. These definitions were set by the LG/7 NPSG to represent reasonable distances from, and operating times in, the event of a RDD attack. In order to compare RDD inhalation challenge levels to those from nuclear reactor facility incidents/accidents, challenge levels are expressed in terms of integrated activity concentrations in units of Bq min m^{-3} and committed effective dose (CED) in Sieverts (Sv). The assumptions required to calculate the CED from the integrated activity concentration are specified where necessary.

Radiological inhalation challenge levels are also provided for a nuclear reactor facility incident/accident, resulting in the release of radioactive material containing multiple radionuclides. This incident is assumed to occur during NATO non-article 5 crisis response operations, not general nuclear war, and is therefore covered by commander's guidance specified in STANAG 2473, "Commander's Guide to Radiation Exposure in Non-Article 5 Crisis Response Operations" [3]. NATO forces responding to this incident are assumed to complete missions requiring both occupancy in an area affected by the radioactive plume and also entrance into the plume itself for various mission-critical activities, such as emergency or lifesaving activities. Inhalation committed effective dose was calculated at a location and time in which the external dose approached a given Radiation Exposure State (RES) upper limit as defined in STANAG 2473. For inhalation exposure involving multiple radionuclides, contributions from each component cannot be determined from the reported committed effective dose. Challenge levels from the nuclear reactor vignettes will be expressed in terms of committed effective dose equivalent (CEDE) in Sv. A breathing rate of 25 litres per minute was assumed for the study. Doubling breathing rate to 50 litres per minute will result in twice the inhaled mass and twice the resulting dose.

Inhalation challenges from fallout from a nuclear weapon strike were also considered in the study. Despite the fact that a greater amount of radiological material is released, the threat from these scenarios is predominantly from external radiation. A significant fraction of this material is released in particle sizes that are too large to be inhaled, and those particles that are respirable are often released with such energy that they are carried to high altitudes where they disperse to low concentrations before they return to near ground level, where they can be inhaled.

The risk of inhalation of radiological aerosols must include consideration for personnel conducting decontamination operations. The radionuclide surface contamination reaerosolised during vehicle decontamination operations can only be estimated by operational tests. An experimental study using ^{140}La, which has a short half-life, was done on light armoured vehicles, and resulting challenge levels were measured. As with the RDD study, challenge levels are expressed in terms of integrated activity concentrations in units of Bq min m^{-3} and in terms of the CED in Sv.

6 INCIDENT TYPES AND VIGNETTES

This chapter outlines the vignettes that were considered in this study, based on the scenarios outlined in chapter 4. Five radiological dispersion device vignettes were considered which cover both radiological weapon threats and plutonium dispersion from an undetonated nuclear weapon; calculations on resuspension of radioactive material from a contaminated vehicle, during a decontamination operation, used the same source parameters as in the five vignettes. In addition, five nuclear reactor release vignettes were evaluated. The radiological challenge from a tactical nuclear weapon was considered, but is not included in this AEP, following the findings of the Radiological Aerosol Challenge Level report from 2006 [1].

6.1 Radiological dispersion devices

Five different radiological weapon vignettes were chosen for the calculation of aerosol challenge levels from radiological dispersal devices. The original Radiological Challenge Level [1] report by the RNDSG considered a sixth vignette using a uniquely large plutonium thermoelectric generator source created for the Cassini space probe. This vignette was excluded from this document as it was considered to be unrealistic as a threat to NATO forces.

The five vignettes cover the three main types of radiation, and the quantities and types of radioactive material were chosen to represent plausible worst-case scenarios. They were not chosen to represent the most likely scenarios, but rather those that would have the largest radiological health effects. The vignettes are summarised in Table 1.

Table 1: Summary of the radiological weapon vignettes

Isotope	Form	Origin of Source	Activity (Bq)	Radiation
^{90}Sr	$SrTiO_3$	Radioisotope Thermoelectric Generator	1.1×10^{16}	β
^{90}Sr	$Sr(NO_3)_2$	Radioisotope Thermoelectric Generator	1.1×10^{16}	β
^{137}Cs	CsCl	Industrial Irradiator	1.85×10^{15}	γ
^{60}Co	Metal	Industrial Irradiator	1.1×10^{16}	γ
^{239}Pu	Pu metal	Nuclear Weapon	2.3×10^{12}	α

The first two vignettes involve the dispersal of a ^{90}Sr source from a radioisotope thermoelectric generator (RTG). The different forms of ^{90}Sr result in different particle size distributions (see Table 3). RTGs use the heat produced by the decay of a radioactive source to generate electricity through a thermocouple device. The United States and Russia have both used RTGs as power sources in remote locations such as: the arctic, offshore oil platforms and space. RTGs generally contain either ^{90}Sr or ^{238}Pu in quantities up to approximately 1.1×10^{16} Bq (300 kCi). Russia had thousands of RTGs that were used to power lights in ocean buoys and lighthouses. Of these approximately 80% were strontium titanate ($SrTiO_3$) and 20% strontium nitrate [$Sr(NO_3)_2$]. RTGs are no longer in general use and are now mainly thought to be secured, but the possibility exists some of these sources remain unsecured and available for malicious use against NATO troops.

The next two vignettes involve high-energy gamma emitting isotopes from industrial irradiators. The two most widely used high energy gamma sources are ^{137}Cs and ^{60}Co. These isotopes are used extensively for medical, industrial and research applications. The activity of ^{137}Cs chosen was 1.85×10^{15} Bq (50 kCi), corresponding to the activity of a caesium capsule from an industrial irradiator. For ^{60}Co, 1.1×10^{16} Bq (300 kCi) was chosen to allow direct comparison between the effects of ^{60}Co and the ^{90}Sr RTG vignettes. This activity of cobalt corresponds to approximately 20 new MDS Nordion C-188 “pencil” sources that are used in their industrial irradiators.

The final vignette involves the dispersal of ^{239}Pu metal and was designed to address the possibility of the production of a radiological weapon using fissile material normally used for the production of nuclear weapons. This vignette could also arise either from a group obtaining a nuclear weapon and being unable to achieve criticality or from an accident in the transportation of a nuclear weapon, such as the incident that occurred on January 17, 1966 in Palomares, Spain. The activity of ^{239}Pu in this vignette, 2.3×10^{12} Bq (62 Ci), corresponds to a mass of 1 kg of plutonium.

6.2 Nuclear reactor incidents

For the nuclear reactor incidents, it was assumed that the nuclear facility uses a pressurised water reactor (PWR), approximately 3000 MW(t). It has been operating at full power long enough for the fission products with short half-lives to have reached equilibrium and contains a significant inventory of fission products with long half-lives such as ^{137}Cs and ^{90}Sr. The PWR was chosen since it is a very common type of nuclear power plant, and 3000 MW(t) has the potential to produce worst-case inhalation hazards. Sensitivity calculations were completed [4] for different types of reactors (i.e. RBMK, CANDU, etc.) to assess differences in the source terms between the various types of reactors and were shown to yield broadly similar results. The different conditions of the reactor used in this report are outlined in reports HRP/LLR/96/P6 [5] and PFP(NAAG-LG/7)D(2000)4 [6] from Land Group 7 on NBC Defence, Working Group 2 on Low Level Radiation, as summarised in Table 2. These reports classified reactor incident scenarios into five source term categories (STC) 1 to 5, with STC-5 having the most severe effects.

Table 2: Nuclear facility release categories

Release Category	Class of Severity	Summary of Release Characteristics
STC-5	Major	Widespread health and environmental effects
STC-4	Large	Significant release, likely to require full implementation of planned countermeasures
STC-3	Moderate	Limited release, likely to require partial implementation of planned countermeasures
STC-2	Small	Small release
STC-1	Minor	Minor release

This AEP examines STC-3, STC-4, and STC-5 type events only. The STC-1 and STC-2 categories would involve negligible particulate release to the environment. The incidents consist of damage to the reactor followed by detonation of an explosive device, which produces a large hole within the containment. A damage type of 25% cladding failure was chosen to approximate a STC-3 level event, a 10% core melt was chosen to approximate a STC-4 level event, and a vessel melt through was chosen to approximate a STC-5 level event. For each of the three reactor scenarios above, the NATO forces execute two types of missions:

1. The forces are stationed downwind of the reactor at a specified distance and require six hours after the release to complete their mission before evacuation.
2. The forces enter the release plume to conduct (emergency, lifesaving, etc.) operations for one hour and then exit the area.

The time durations for these missions were chosen as the most realistic based on current NATO CBRN incident response capabilities and concepts of operation.

6.3 Radiological hazard from vehicle decontamination

In order to determine the challenge posed by the performance of vehicle decontamination operations, surface contamination concentrations were derived from the five radiological dispersal device vignettes outlined in section 6.1 and detailed in Table 1.

7 ANALYSIS AND RESULTS

7.1 Radiological dispersion devices

Methodology

In the NATO Radiological and Nuclear Defence Sub group's report "Radiological Aerosol Challenge Levels" [1], the outdoor radiological aerosol challenge level was defined to be the integrated activity concentration of radioactive material at a location 100 m downwind of the detonation of an optimized radiological dispersal weapon. The radiological weapon parameters were chosen to maximise the concentration of radioactive aerosol close to the ground with a moderate wind speed to ensure dispersion in the area immediately surrounding the device. To calculate the associated CED, a breathing rate of 25 L min^{-1} was assumed for the duration of the plume passage. This breathing rate was chosen to be consistent with the NATO document "Field Methodology for Estimating Total Effective Dose Equivalent from Internal and External Irradiation" [6].

The indoor radiological challenge level was defined as the activity of radioactive material that a person would be exposed to if they were to be in a confined space, unprotected, following the indoor detonation of a radiological dispersal weapon. The assumptions that were used to calculate the indoor challenge level were: 1) to simulate the confined space, the aerosolised radiological material was assumed to be isotropically distributed within a hemisphere of 10 m radius, and 2) the exposed person would stay for 15 min within the hemisphere of 10 m radius.

The other factors required in order to determine properly the challenge levels are the specific activity of the source, the respirable fraction after dispersal, and the particle size distribution. Plausible specific activities were assumed for each of the scenarios. The respirable fraction of the source and the particle size distributions for each scenario were set based on unpublished experimental work carried out at Sandia National Laboratories[1]. The aerosol parameters for the different scenarios are summarised in Table 3. With these definitions and aerosol parameters, it is possible to calculate the challenge levels. The specific activities were chosen to represent plausible values for available sources and physical forms. The respirable fractions and particle sizes are from experimental work carried out at Sandia National Laboratories [7]. CsCl has two approximately equal peaks in the particle size distribution.

Table 3: Summary of aerosol input parameters relevant to the challenge level calculations.

Source	Specific Activity (Bq g^{-1})	Respirable Fraction	Particle Physical Diameter (µm)	Particle Aerodynamic Diameter (µm)
$^{90}SrTiO_3$	1.05×10^{12}	0.1	1.05	2.3
$^{90}Sr(NO_3)_2$	6.90×10^{11}	0.5	1.33	2.3
$^{137}CsCl$	7.40×10^{11}	0.5	0.35, 1.15	0.7, 2.3
^{60}Co metal	4.18×10^{13}	0.001	0.77	2.3
^{239}Pu metal[2]	2.30×10^{9}	0.8	0.18	0.7

The indoor challenge level in Bq min m^{-3} is straightforward to calculate, according to:

$$CL_{indoor} = \frac{A_s \cdot F_r}{V} \cdot t$$

Where: A_s is the total activity of the source (from Table 1), F_r is the respirable fraction (from Table 3), V is the indoor volume (the 10 m radius hemisphere), and t is the time of exposure (15 min). The indoor challenge level is then converted to CED in Sv using the breathing rate (25 L min^{-1}) and ICRP 68[3] dose conversion factors.

1 Private communication, Dr. F. Harper, Sandia National Laboratories,
2 The Pu metal is assumed to be oxidised after aerosolisation
3 ICRP 68 has been superseded by ICRP 103

The outdoor challenge level is more complicated to calculate, in that it requires a dispersion model to determine airborne concentrations and plume duration at the location specified (100 m downwind). These calculations are dependent on the particle size of the aerosol, the assumed atmospheric conditions and the model itself. In the 2006 report, the NATO RNDSG ruled out the use of a standard atmospheric dispersion code, such as the Hazard Prediction and Assessment Capability (HPAC) software, after obtaining inconsistent results with dispersion code versions at the time and noting that they were designed to model the large-scale dispersion and deposition of material, not to calculate accurate concentrations at the short distance scales required here.

The NATO RNDSG instead chose an alternate approach[4] to this calculation using a simple Gaussian dispersion model combined with some assumptions about the dispersion mechanism and atmospheric conditions that would maximise the concentration of radioactive aerosol close to the ground. The approach used an initial Gaussian distribution of aerosolised radiological material based on experimental results obtained at Sandia National Laboratories[5] [7]. This initial plume would then be carried by the wind using a non-buoyant, unstable atmospheric model with a mean wind speed of 3 m s^{-1} over the location specified in the definition of the outdoor challenge level, 100 m downwind from the detonation. The weapon parameters were chosen to maximise the concentration of radioactive aerosol close to the ground with a moderate wind speed to ensure dispersion in the area immediately surrounding the device. The outdoor challenge level $CL_{outdoor}$ was then set by the integrated activity concentration $C(t)$ at that location, with the duration t of the plume determined by the dynamics of the atmospheric model.

Analysis

Radiological aerosol challenge levels were calculated according to the above described methods. These challenge levels define the activity of radioactive material that could be inhaled by an unprotected person in two different radiological dispersal weapon scenarios (indoors and outdoors), and for the various radioactive sources specified in the vignettes. Combining these activities with the chemical forms and aerodynamic particle sizes from Table 3, and using dose conversion factors (in Sv/Bq) derived from ICRP 68 [8], the health effect (in Sv), in terms of the 50-year committed effective dose, can also be calculated.

4 This approach was suggested by members of the US delegation, specifically experts in radiological aerosol dispersion from Sandia National Laboratories

5 The measured aerosol parameters are assumed to be applicable to these vignettes, despite the fact that the conditions are not identical.

Results

The challenge levels and corresponding doses for the radiological weapon vignettes are summarised in Table 4. The committed effective doses are included in Table 4 to illustrate that significant radiation doses are possible from optimized radiological dispersal weapons, especially for the case where the dispersal occurs in a confined space. For comparison, the NATO Radiation Exposure States (RES), as defined in STANAG 2473 [3], are given in Table 5.

Table 4: Summary of the aerosol challenge levels and associated radiation dose for the radiological dispersal weapon vignettes.

Source	Challenge Level ($Bq \cdot min \cdot m^{-3}$)		Committed Effective Dose (mSv)	
	Outdoor	Indoor	Outdoor	Indoor
$^{90}SrTiO_3$	2.2×10^{9}	8.0×10^{12}	7900	2.8×10^{7}
$^{90}Sr(NO_3)_2$	1.1×10^{10}	4.0×10^{13}	8000	2.8×10^{7}
$^{137}CsCl$	1.9×10^{9}	6.6×10^{12}	230	8.2×10^{5}
^{60}Co metal	2.2×10^{7}	8.0×10^{10}	16	5.5×10^{4}
^{239}Pu metal	3.7×10^{6}	1.3×10^{10}	1700	6.0×10^{6}

Table 5: Upper limits for RES categories. Each RES category consists of a range of doses, however, only the upper limit in each category is shown here.

RES State	RES 0	RES 1A	RES 1B	RES 1C	RES 1D	RES 1E
Total cumulative dose (mSv)	0.5	5	50	100	250	750

7.2 Nuclear reactor incidents

Methodology

For the calculation of the radiological inhalation challenge resulting from three different nuclear incidents a dose projection model was used called Radiological Assessment System for Consequence Analysis (RASCAL) 3.0. Rascal is a US national level emergency response code developed by the US nuclear regulatory commission. The dose projection model calculates the radioactive material release and resulting radiation dose using the following steps:

- It defines the source term for the damage category, in units of Bq, for each of the radioisotopes released.
- It then calculates the expected release fraction (the fraction of the source term released) for each of the various categories of fission products.
- It then identifies the pathway for release and adjusts the released activity based on the release conditions and any mitigating effects
- It finally calculates the atmospheric transport based on the assumed meteorological conditions and uses the resulting airborne and deposition concentrations to calculate the internal and external radiation dose.

Three specific damage-estimate source terms were used, which define the amounts (in Bq) of each radionuclide released for a 25% cladding failure (STC-3), a 10% core melt (STC-4), and a vessel melt through (STC-5). Additional details on the exact composition of the computed source can be found in appendix A of the original NATO Radiological Aerosol Challenge Level Report [1].

The release fractions for the three vignettes are summarised in Table 6. The release for the STC-3 vignette is calculated for a 25% cladding failure, with release duration of 0.5 hours. The STC-4 case assumes the cladding failure release is followed by a 10% core melt, with release duration of 1.3 hours. The worst-case scenario, STC-5, consists of cladding failure for 0.5 hours, followed by core melt for 1.3 hours, and finally the vessel melts for two hours. So, 3.8 hours of damage occur followed by an explosion, which opens a 1 m^2 hole in the containment.

Table 6: Release fractions for the different fission product groups and for each release category.

Elements	**Release Fraction**		
	STC-3	**STC-4**	**STC-5**
Xe, Kr	0.05	1.00	1.00
I, Br	0.05	0.40	0.65
Cs, Rb	0.05	0.30	0.65
Te, Sb, Se	0	0.05	0.30
Ba, Sr	0	0.02	0.12
Ru, Rh, Pd, Mo, Tc, Co	0	0.0025	0.0050
La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	0	0.0005	0.0055
Ce, Pu, Np	0	0.0002	0.0052

The model subsequently identifies the path by which the radioactive material was released into the atmosphere. Safety-system sprays (for the core and containment) were assumed not to function and the pressure inside the containment was assumed to be greater than atmosphere. For purpose of calculation, 1.02 atmospheres was used as the pressure inside the containment.

The final step before calculation of projected doses was to choose the meteorological conditions that affect the atmospheric transport of the radioactive materials. This report used a standardised meteorology of 6 kilometres per hour wind, 50% relative humidity, 21.1 degrees Celsius, neutral stability (Stability Class D), and no precipitation. The code uses Gaussian plume and puff models to describe the atmospheric dispersion of radioactive effluents from the reactor facility. A straight line Gaussian plume model, TADPLUME, was used near the release point where travel times are short and plume depletion associated with dry deposition was small. A Lagrangian-trajectory Gaussian puff model, TADPUFF, was used at longer distances where temporal or spatial variations in meteorological conditions or depletion of the plume due to dry deposition may be significant.

Atmospheric dispersion consisted of calculation of an airborne concentration in Bq m^{-3} using a given release rate in units of Bq s^{-1} and wind speed plus horizontal and vertical dispersion equations. Addition of an appropriate deposition velocity to this airborne concentration resulted in the ground deposition in units of Bq m^{-2}. These airborne and ground concentrations were used to calculate the external and internal doses for personnel immersed in the radioactive plume using ICRP methodology and factors summarised in Federal Guidance Report No. 12 [9], and Federal Guidance Report No. 11 [10], respectively.

Analysis

The calculation of radiation doses during the reactor incident included both the external dose and internal dose. The RES 1D and 1E categories for the external radiation dose, as outlined in Table 5, were used to determine the downwind distances at which the aerosol challenge levels were calculated. To determine the downwind distance only gamma radiation was used as it was assumed that the contributing factor resulting from beta radiation was much lower. The RES category upper limits for external dose were used to set a downwind distance at which a specific mission could be carried out and have the external radiation exposure remain within the RES category. That location was then used as the point at which the aerosol challenge was calculated. The lower-dose RES category locations are significantly farther from the release, and are dominated by external exposure, and thus do not guide the challenge level recommendations.

External radiation exposure was considered from both cloud shine and ground shine. Cloud shine was the external dose received by personnel from gamma radiation as a result of direct immersion in the plume of radioactive material. Ground shine was the external dose received from gamma radiation produced by radioactive material deposited on the ground. Resuspension of ground contamination was assumed to be negligible.

Internal dose is due primarily by inhalation of radionuclides released by the reactor incident and involves the transport of each radionuclide inside the body. Internal dose is defined in a term called 50 year Committed Dose Equivalent (CDE) for each of the primary internal organs. Each dose to an individual organ is multiplied by a respective tissue weighting factor and then summarized to the 50 year CEDE. This CEDE, as defined in ICRP 26[6] [11], is the weighted sum of selected organ doses. This internal dose or CEDE thus defines a radiological challenge level.

Unlike the radiological weapon scenario, a reactor release involves a large mix of radionuclides; therefore, the external dose close to the release point is expected to be severe. The challenge levels were calculated at a location where personnel will reach RES category upper limits from external dose. The challenge level is then the inhalation CEDE, which includes the contribution from the thyroid CDE. The thyroid dose from ^{131}I dominates thyroid dose over all other radionuclides. This report also considered the use of stable iodine as a blocking agent before exposure, which was assumed to be 100% effective in blocking the uptake of radioactive iodine into the thyroid gland[7]. For the case where a blocking agent was used, the challenge level was calculated by subtracting the thyroid CDE from the inhalation CEDE, i.e. it is the CEDE from radioisotopes other than iodine.

Example 1: Mission Type 1 – Six Hour Exposure.

For this example, a troop-occupancy location 1.1 km from the release point after a 10% core melt was chosen where the external dose (cloud shine + period ground shine) is approximately the RES 1E category upper limit. Relevant external dose values for this location are 460 mSv for the cloud shine, and 300 mSv for the ground shine for a total external dose of 760 mSv.

The inhalation dose 1.1 km from the release point is 4300 mSv. The challenge level, if a blocking agent is not used, is this value, the “Inhalation CEDE”. Or, if a blocking agent is used, the challenge level is the “Particulate CEDE other than iodine” calculated by subtracting the committed effective dose from the thyroid from the total inhalation CEDE. So, a 3000 mSv committed effective dose from the thyroid is obtained by multiplication of the Thyroid CDE (100,000 mSv) times the ICRP 26 thyroid-weighting factor (0.03) resulting in 3000 mSv committed effective dose. The

6 CEDE is no longer used within NATO. ICRP 26 has been superseded by ICRP 103 which defines the term CED.
7 Iodine is only at its most effective if taken before inhalation occurs. The optimal time is 24 hours before inhalation,although some reduced benefit can be obtained within 2 hours after inhalation.

challenge level then if a blocking agent is used is 1300 mSv (3000 mSv subtracted from the total inhalation dose of 4300 mSv).

Example 2: Mission Type 2 – One-Hour Exposure.

For this example, personnel were exposed for one hour immediately after vessel melt through before the cloud had settled to the ground, so cloud shine was the largest contributor to their total dose. Therefore, 9 km from the release point was selected as the location where external dose (691 mSv) was nearest to the 750 mSv RES 1E limit. A receptor at that location along the centre line of the plume was then simulated to produce a graph of the rate at which the cloud shine dose was accumulated (Sv h^{-1}) and cumulative cloud shine dose (Sv) versus time since release (in hours). These graphs show the highest cloud shine dose occurred from 0130 hours to 0230 hours after the release started at 0000 hours. This specific time period was chosen as a worst case of airborne contamination.

The dose projection model was then run again using that specific time interval after release and location to list cloud shine, Inhalation CEDE, and Thyroid CDE. Specifically, personnel received 558 mSv from cloud shine, and 8910 mSv from Inhalation CEDE, and 4890 mSv (163,000 × 0.03) from Thyroid CDE. The challenge level (if a blocking agent was used) was 4000 mSv i.e. 4900 mSv subtracted from 8900 mSv.

Results

Mission Type 1-personnel occupancy for six hours:

Table 7 and Table 8 present the results for the maximum inhalation, thyroid CDE and particulate CEDE received by personnel at distances from the release point, which produce RES 1E and RES 1D external dose-equivalents.

Table 7: Summary of Mission Type 1 Challenge Levels (Dose-equivalent Values) for RES 1E (750 mSv).

Core Damage State	Distance (km)	Inhalation CEDE (mSv)	Thyroid CDE (mSv)	Particulate CEDE(-)[8] (mSv)
Vessel melt through (STC-5)	14	8700	4700	4000
10% core melt (STC-4)	1.1	4300	3000	1300
25% cladding failure (STC-3)	0.3	4100	3400	700

Table 8: Summary of Mission Type 1 Challenge Levels (Dose-equivalent Values) for RES 1D (250 mSv)

Core Damage State	Distance (km)	Inhalation CEDE (mSv)	Thyroid CDE (mSv)	Particulate CEDE(-) (mSv)
Vessel melt through (STC-5)	24	3800	2100	1700
10% core melt (STC-4)	4.8	1500	1100	400
25% cladding failure (STC-3)	0.8	1500	1200	300

Mission Type 2-personnel immersion in cloud for one hour:

Table 9 and Table 10 present the results for the maximum inhalation, thyroid CDE and particulate CEDE received by personnel at distances from the release point, which produce RES 1E and RES 1D external dose-equivalents. All table values were calculated for only the worst-case scenario, vessel melt through (STC-5).

Table 9: Summary of Mission Type 2 Challenge Levels (Dose-equivalent Values) for RES 1E (750 mSv).

Core Damage State	Distance (km)	Inhalation CEDE (mSv)	Thyroid CDE (mSv)	Particulate CED(-) (mSv)
Vessel melt through (STC-5)	9.0	8900	4900	4000

8 Particulate CEDE(-) is the particulate CEDE other than from iodine (appropriate when a blocking agent is used)

Table 10: Summary of Mission Type 2 Challenge Levels (Dose-equivalent Values) for RES 1D (250 mSv).

Core Damage State	Distance (km)	Inhalation CEDE (mSv)	Thyroid CDE (mSv)	Particulate CEDE(-) (mSv)
Vessel melt through (STC-5)	18	4500	2500	2000

For this mission type, although the mission duration is six times less than for Mission Type 1, the immersion of troops inside the cloud results in similar inhalation doses.

7.3 Radiological hazard from vehicle decontamination

Methodology

The fraction of material reaerosolised during decontamination operations was estimated based on a set of field decontamination experiments conducted at the Decontamination and Protection Centre at Bourges (ETBS/DEP - France), and scaled according to the expected surface contamination concentrations from the RDD vignettes.

The surface contamination concentrations for the RDD vignettes were derived using the aerosolised fraction of radioactive material and the deposition velocity corresponding to the particle aerodynamic diameter detailed in Table 3. The resulting surface activity concentrations for the vignettes are given in Table 11.

Table 11: Surface activity concentrations for the RDD vignettes. These correspond to contamination levels on vehicles in the immediate area during a radiological weapon attack; vehicles driven through the area post-attack will have significantly less contamination.

Source	Surface Activity Concentration (Bq m^{-2})
$^{90}SrTiO_3$	1.3×10^9
$^{90}Sr(NO_3)_2$	6.6×10^9
$^{137}CsCl$	1.1×10^9
^{60}Co metal	1.3×10^7
^{239}Pu metal	2.2×10^6

During the trials at Bourges, a French light armoured vehicle (VAB) was contaminated by radioactive fallout consisting of $^{140}LaCO_3$. The vehicle contamination was performed in the “Fallout Room” at ETBS/DEP. The $^{140}LaCO_3$ was deposited on the vehicle from above. First, the amount of deposited contamination was measured and then the VAB was decontaminated using the standard French operational procedure:

1. First, the operator spreads the decontamination solution in foam form on the vehicle using a high pressure cleaner, with the front of the vehicle in a down-wind position,
2. Second, the foam and the contamination are removed by high pressure and high temperature water cleaning. The operation begins by decontaminating the top, from the front to the back, continues on the front of the body, then the sides, and finally the bottom and the back. The duration of the decontamination operation is about 45 minutes.

During the decontamination operation, a contaminated aerosol is generated, with 100 µm average droplet size, blown by the wind. To obtain an estimate of the maximum inhalational risk to the operator, air sampling was done down-wind of the operation. The maximum risk for the operator was measured as follows:

- The quantity of contaminated aerosol inhaled by the operator was evaluated using air samplers throughout the decontamination site; 8 air samplers pumping ~50 L min^{-1} were placed around the vehicle at 1.5 meters height,
- The contamination of the mask canister as well as the clothes of the operator were measured as well as the dose rate resulting from this contamination,
- The gamma absorbed dose was measured with an individual gamma electronic dosimeter.

Analysis

The results showed that 90% of the contamination is removed by the decontamination procedure. Part of this contamination corresponding to the breathable airborne contamination is aerosolised and can be collected by the air samplers. The other part is deposited on the soil in liquid form. By taking the average air sample activity and dividing by two, to account for the difference between the sampling rate and the standard breathing rate, it was determined that the average operator is potentially exposed to 120 Bq of internalised radioactive material during a single 45 min decontamination operation. This figure is used as a plausible upper limit to the exposure to an operator during a single decontamination operation of a large vehicle contaminated by a deposition of 100 MBq m^{-2}. During the decontamination operation, the gamma effective dose absorbed by the operator was measured to be ~20 µSv. This dose is mainly absorbed during spreading of the decontamination solution.

On the basis of these experimental results, the challenge levels were extrapolated from the RDD vignette surface contamination levels in Table 11. The specific activity of $^{140}LaCO_3$ is taken to be 8.3 x 10^{17} Bq g^{-1} and the breathing rate as 25 L min^{-1}. The corresponding challenge levels for an inhaled activity of 120 Bq were calculated from the experimental data for $^{140}LaCO_3$. Additionally, the CED for the extrapolated inhaled activity for each RDD vignette was calculated using the Euratom 96/29 Policy [12] using a mean lung clearance factor[9].

Results

The challenge levels for decontamination procedures using these other radioactive materials have been estimated by using the ratio between the radionuclide surface contamination in the scenarios and ^{140}La surface contamination in the tests at Bourges. The results are listed in
Table 12.

Table 12: Summary of the challenge levels and corresponding CED for the RDD vignettes. "Ratio" is the ratio between the radionuclide surface contamination in the scenarios and ^{140}La surface contamination in the tests at Bourges. The values for the $^{140}LaCO_3$ used in the Bourges are shown in **bold** for comparison.

Source	Surface Activity Concentration (Bq m^{-2})	Ratio	Inhaled Activity (Bq)	Challenge Level (Bq·min m^{-3})	CED (mSv)
$^{140}LaCO_3$	**1.0×10^8**	**1**	**120**	**4800**	**0.0001**
$^{90}SrTiO_3$	1.3×10^9	13	1550	62000	0.056
$^{90}Sr(NO_3)_2$	6.6×10^9	66	7920	320000	0.29
$^{137}CsCl$	1.1×10^9	11	1320	53000	0.013
^{60}Co metal	1.3×10^7	0.13	15.6	620	0.00016
^{239}Pu metal	2.2×10^6	0.022	2.6	100	0.13

For the radionuclides that emit gamma radiation, such as ^{60}Co or ^{137}Cs, the external absorbed dose to the operator is mainly due to gamma-ray exposure during the decontamination operation. The effective dose can be estimated by multiplying the experimental effective dose of ~20 µSv by the contamination ratio. This would indicate about 0.22 mSv for $^{137}CsCl$ and 0.003 mSv for ^{60}Co metal.

9 The mean lung clearance factors that were used for this calculation were: 1.1×10^{-9} Sv Bq^{-1} for $^{140}LaCO_3$, 3.6×10^{-8} Sv Bq^{-1} for $^{90}SrTiO_3$ and $^{90}Sr(NO_3)_2$, 9.7×10^{-9} Sv Bq^{-1} for $^{137}CsCl$, 1.0×10^{-8} Sv Bq^{-1} for ^{60}Co, and 5.0×10^{-5} Sv Bq^{-1} for ^{239}Pu metal

For the ^{90}Sr vignettes, the external dose rate is predominantly due to Bremsstrahlung radiation (assuming that the operator is wearing appropriate individual protective equipment to absorb the beta radiation). The Bremsstrahlung dose rate is very dependent on the scenario under consideration.

The external dose from alpha emitters (^{239}Pu) is assumed to be negligible.

8 RECOMMENDED RADIOLOGICAL CHALLENGE LEVELS

Radiological dispersal device challenge levels

The CBRCL ToE takes the original recommendation from the RNDSG of using the worst case $^{90}Sr(NO_3)_2$ vignette[10].

- The recommended challenge level for an outdoor radiological dispersion device is 1.1×10^{10} Bq·min·m^{-3} (~8000 mSv for $^{90}Sr(NO_3)_2$).
- The recommended challenge level for an indoor radiological dispersion device is 4.0×10^{13} Bq·min·m^{-3} (~2.8 x 10^7 mSv for $^{90}Sr(NO_3)_2$).

Nuclear reactor incidents challenge levels

The CBRCL ToE takes the original recommendation from the RNDSG of using the worst case STC-5 release.

- The recommended challenge level for 6-hour personnel occupancy mission (mission type #1) is 4000 mSv with thyroid blocking agent or 8700 mSv without thyroid blocking agent.
- The recommended challenge level for the 1-hour cloud immersion duration mission (mission type #2) is 4000 mSv with thyroid blocking agent or 8900 mSv without thyroid blocking agents.

Vehicle decontamination challenge levels

The CBRCL ToE takes the original recommendation from the RNDSG of using the worst case $^{90}Sr(NO_3)_2$ vignette.

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10 The RNDSG included a safety factor of 2 to account for uncertainties in calculations which is not incorporated here.

- The recommended challenge level for a decontamination operation is 3.2×10^5 Bq min m^{-3} (~0.29 mSv for $^{90}Sr(NO_3)_2$).

9 CONCLUSION

In general, the greatest inhalational threat arises from the deliberate dispersal of radioactive material from a radiological weapon or nuclear weapon incident. It is possible for these types of scenarios to present hazards that are predominantly inhalational in nature. Nuclear weapon strikes and reactor incidents produce a wide variety of radioisotopes, and consequently result in a radiation hazard that is predominantly external in nature. Because of these differences in the nature of the hazard, different approaches were taken for different incident types.

Additional precautions are recommended when facing radiological challenges for the inhalation vignettes. For gamma emitting materials, account must be taken of external radiation exposure, which dominates the total hazard and cannot be mitigated by adoption of respiratory protection.

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11 GLOSSARY

AEP	Allied Engineering Publication
ATP	Allied Tactical Publication
CANDU	CANada Deuterium Uranium
CBRCL	Chemical, Biological and Radiological Challenge Levels
CBRN	Chemical, Biological, Radiological and Nuclear
CDE	Committed Dose Equivalent
CDG	Capability Development Group
CED	Committed Effective Dose
CEDE	Committed Effective Dose Equivalent
CsCl	Caesium Chloride
DEP	Decontamination and Protection Studies Centre
ETBS	Etablissement Technique de Bourges
GBR	Great Britain
HPAC	Hazard Prediction and Assessment Capability
HRP	Hazardous Response Program
ICRP	International Commission on Radiological Protection
JCBRND-CDG	Joint Chemical Biological Radiological and Nuclear Defence Capability Development Group
kCi	kilocurie
LG	Land Group
LLR	Low-Level Radiation
LTUAF	Lithuanian Air Force
MBq	Megabequerel
MCi	Megacurie
MW	Megawatt
NAAG	NATO Army Armaments Group
NATO	North Atlantic Treaty Organization
NBC	Nuclear, Biological, Chemical
NPSG	Nuclear Protection Sub Group
NSO	NATO Standardization Office
OTAN	Organisation du Traité de l'Atlantique Nord
PFP	Partnership for Peace
PWR	pressurised water reactor
RASCAL	Radiological Assessment System for Consequence AnaLysis
RBMK	Reaktor Bolshoy Moshchnosti Kanalnyy
RDD	Radiological Dispersal Device
RES	NATO radiation exposure state
RNDSG	Radiological and Nuclear Defence Sub Group
RTG	Radioisotope Thermoelectric Generator
STANAG	Standardization Agreement

STANREC	Standardization Recommendation
STC	source term categories
TADPLUME	Transport and Diffusion Plume (RASCAL)
TADPUFF	Transport and Diffusion Puff (RASCAL)
TIC	Toxic Industrial Chemical
TOE	Team of Experts
VAB	Vehicule de l'Avant Blinde

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