Radiological Nuclear Defence R&D Priorities: Proposal for a Long Range Plan for DRDC

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Preface

This document was written at the request of Dr. Pierre Lavoie, Director General Science and Technology Force Employment (DGSTFE). As requested, the purpose of this document is to propose areas of radiological/nuclear (RN) defence research and development (R&D) which would benefit the Canadian Armed Forces (CAF). Not all the R&D conducted for the CAF has to be carried out by DRDC; if sufficient expertise exists in industry, academia or other government departments, ADM(S&T) could provide funding for some of the R&D to be carried out external to DRDC. The scientific staff of DRDC Ottawa Research Centre's RNAD Group provided their expert opinions to generate the prioritized RN defence R&D list at the end of this document. We hope that this document, in addition to CAF client feedback, will inform ADM(S&T)'s future program investments in RN defence R&D.

Introduction

The CAF must be able to conduct operations in the presence of many threats, including radiological and nuclear. In addition, the CAF has a key role to play in preventing nuclear and radiological attacks. A single nuclear weapon has the capacity to kill hundreds of thousands of people, destroy a Canadian city, and have a profound effect on the entire nation. Radiological weapons and attacks on nuclear facilities could also cause severe consequences in a domestic event or an international incident involving the Canadian Armed Forces (CAF). For these reasons, the CAF requires a robust RN defence capability. A useful categorization of RN defence capabilities is provided by considering the five "typical" CBRN defence enabling components [CONPLAN RUBICON], plus "planning and preparation":

1. planning and preparation;
2. detection, identification and monitoring;
3. information management;
4. physical protection;
5. hazard management; and,
6. medical countermeasures and support.

Studying the details of these capabilities (i.e. looking at a more granular level), reveals that there are a large number of CAF RN defence capabilities which would be improved (in some cases dramatically) if progress were made in various aspects of RN defence research and development (R&D). The impact of improving these capabilities depends on the RN threats faced by Canada and the CAF, now and in the future.

This document begins by outlining the current RN threat picture and its possible evolution over time. The CAF RN defence capabilities required to reduce the risk posed by these threats are then presented. Subsequently, possible RN defence R&D areas are ranked by their likely impact on CAF capabilities. The link between these R&D areas and the "hard problems" of RN defence is made afterward. This takes us to the focus of this document: we consider in which R&D areas ADM(S&T) should invest to improve CAF RN defence capability. We conclude by considering RN S&T direct client support that has historically been provided to the CAF by DRDC (in addition to the RN R&D work).

RN Threat Picture

The CAF must be able to operate through and reduce the risk posed by a wide range of nuclear and radiological threats and hazards. These threats and hazards include:

- Nuclear warfare – nuclear strikes during force-on-force warfare
- Nuclear proliferation – nuclear weapons (NW) spreading to new states
- Improvised and acquired nuclear weapons – non-state entities acquiring or improvising NWs
- Radiological weapons – dispersal or exposure devices and deliberate contamination
- Nuclear facility releases – malicious or accidental release of radioactive material from a reactor or facility (e.g. Fukushima)
- Orphaned sources – lost or abandoned radioactive sources
- Operations near compromised industrial or medical sources (i.e. near bombed-out factories)
- Military equipment that utilizes radioactive material – general radiation safety

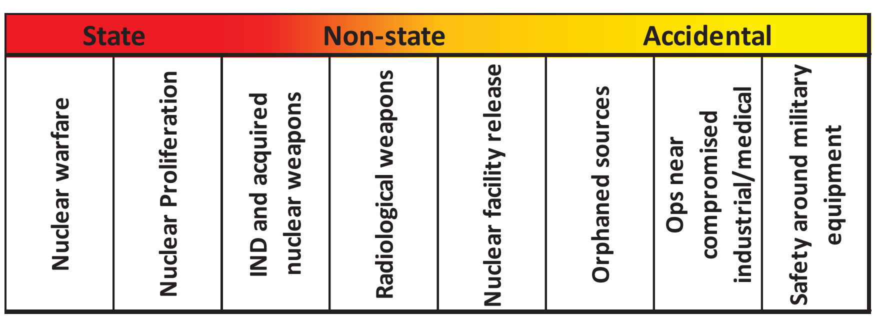

Figure 1: Spectrum of RN threats.

These threats and hazards (see Figure 1) are enduring, but changes to the world's political landscape, the rise and fall of extremist organizations, and technological advances could have a large effect on the likelihood of the CAF having to face specific RN threats from state or non-state actors in the future. Facing hazards from accidental releases and exposures is always a possibility for the CAF, and have been encountered in past military operations (e.g. CAF encountering industrial sources in Kosovo).

Political instability could lead to a rapid change in the threats posed by nuclear weapons in particular. Several countries possess nuclear arsenals, the means to produce nuclear weapons, or host nuclear weapons from nuclear states. Some of these countries have governments that could be considered unstable due to the internal state of the country. Others are involved with conflicts with neighbouring countries. A rapid change in security conditions in one of these countries could lead to the availability of a nuclear weapon or nuclear material to a non-state actor or to a belligerent, but previously non-nuclear, state. Several past and present violent extremist organizations (VEOs) have expressed interest in obtaining nuclear weapons to conduct catastrophic terrorist attacks, and it is likely that future VEOs will have similar ambitions.

Future technological advances could also lead to an increase in the number of states (and even non-state actors) capable of producing nuclear material with sufficient isotopic enrichment to produce viable nuclear weapons. An example of an enrichment technology that is currently in its infancy, but has the possibility to make enrichment much easier in the future, is laser excitation enrichment. It was developed in the early 1990's in Australia and is considered classified information by the US federal government, but if (or when) the technology is acquired by less friendly countries; it could pose a nuclear proliferation threat. The first "test loop" laser enrichment facility was completed in the US in 2012.

Of all the RN threats and hazards, by far the most severe consequences to the CAF and our nation are posed by nuclear weapons (NWs). The scale of the potential impact of a NW is so great, that even though the probability of an attack in the near future may be low, the CAF must strive to obtain the capabilities required to prevent, prepare, respond and recover from a NW attack, with particular emphasis on "prevent" (which is a CANSOFCOM mission). The other RN threats and hazards also pose significant risks to the CAF and Canada, so they must be addressed as well.

Desired RN Defence Capabilities

As mentioned in the introduction of this document, the capabilities required for a robust RN defence can be categorized by dividing them into six enabling components. Another popular categorization analyzes an RN event's timeline and divides it into event "phases" [cite CONPLAN RUBICON]. The relationship between the RN defence enabling components and the RN event phases is shown in Appendix A.

We have taken each of the six enabling components of RN defence and broken them down into multiple sub-components in order to have a more granular view of RN defence capabilities. Table 1 lists this breakdown. Definitions for each of these sub-components are provided in Appendix B.

Table1 : RN Defence enabling components and sub-components.

RN Defence Enabling Component	RN Defence Sub-component
Planning and Preparation	RN threat assessment
	RN proliferation detection
	RN capability assessment
	RN response planning
Detection, Identification and Monitoring	Nuclear material detection
	Radiological material detection
	RN material localization and imaging
	RN material identification
	RN material quantification
	RN weapon triage
	RN material sampling and analysis
	RN hazard monitoring
Information Management	RN hazard modelling and simulation
	RN sensor fusion for situational awareness
	RN warning and reporting
	RN decision support
Physical Protection	RN individual protective equipment
	RN collective protection
Hazard Management	RN equipment and personnel decontamination
	RN contamination avoidance
	Radiation dosimetry
Medical Countermeasures and Support	Retrospective radiation dosimetry
	RN medical triage/diagnostics
	RN medical treatment

Ranking of RN defence R&D areas

Each of the RN defence enabling sub-components is associated with an RN defence capability or activity. We have ranked these capabilities and activities in terms of the importance of doing R&D in these areas to improve CAF capabilities. In other words, we have attempted to answer the question: "What R&D *should* be done to improve the RN defence capability of the CAF?" To do this, we assessed (1) the likelihood that R&D in each area would lead to a successful outcome, and (2) the impact that successful R&D would have on the CAF's ability to reduce the risks posed by the spectrum of RN threats. This was done considering not just the current RN threats, but what the future RN threat space might look like. We also considered how relevant technologies may change in the future. This included both (a) RN-defence-specific technologies (e.g. compact accelerators; low power, low cost single-photon detectors; sensitive, high-resolution scintillator and semi-conductor materials) and (b) rapidly advancing non-RN-defence-specific technologies that could improve RN defence capabilities:

- Artificial intelligence (e.g. machine learning, deep learning),
- Big data/data mining,
- Parallel computing (e.g. GPUs, quantum computing),
- Autonomous vehicles,
- Smartphones,
- Wearables,
- Energy harvesting,
- Augmented reality,
- Advanced and/or adaptive materials, and
- Other possibilities.

The overall ranking of the RN sub-components (or "RN defence R&D areas") was performed by having RN defence SMEs at Ottawa Research Centre individually rank the sub-components. The SMEs' rankings were combined using a consensus voting algorithm [CONDORCET]. There was a clear consensus on the top three areas for RN defence R&D: (1) Nuclear material detection, (2) RN material localization and imaging, and (3) RN weapon triage, with "Nuclear material detection" unequivocally the top priority. The high rank of these areas is due to the transformational effect that R&D could have for these capabilities. As described in the "Hard Problems" section below, the current capability to detect (special) nuclear material is extremely limited; in addition, the consequence of not preventing a nuclear weapon attack would be catastrophic. R&D success in "RN material localization and imaging" could provide a solution to the hard problem of "stand-off detection of RN material" and success in "RN weapon triage" R&D could provide a way to predict and mitigate the consequences of a nuclear and radiological weapon attacks.

The assigned priorities for the RN Defence R&D Areas are:

- A priority of "Very High" was assigned to the top three ranked RN defence R&D areas, for reasons described above.

- The RN defence R&D areas ranked 4 through 7 were all ranked highly with similar levels of importance as determined by most of the SMEs. We assign these a priority of “High”.
- The RN defence R&D areas ranked 8 through 12 received mixed support from the SMEs. We assign these a priority of “Medium”.
- The RN defence R&D areas ranked 13 through 17 received marginal support from a minority of the SMEs. We assign these a priority of “Low”.
- The RN defence R&D areas ranked at 18 (tied) received no support from any of the SMEs. We assign these a priority of “Very Low”.

The ranking and prioritization of the RN defence R&D topics is provided in Table 2 and the detailed SME rankings and results are presented in Appendix C.

Table 2: Ranking and prioritization of RN defence R&D areas.

Ranking	RN defence R&D area	Priority
1	Nuclear material detection	**Very High**
2	RN material localization and imaging	
3	RN weapon triage	
4	RN sensor fusion for situational awareness	**High**
5	RN material quantification	
6	RN threat assessment	
7	RN decision support	
8	Radiological material detection	**Medium**
9	RN proliferation detection	
10	RN hazard modelling and simulation	
11	RN equipment and personnel decontamination	
12	RN material identification	
13	RN warning and reporting	**Low**
14	RN material sampling and analysis	
15	RN capability assessment	
	RN response planning	
17	RN contamination avoidance	
18	RN hazard monitoring	**Very Low**
	RN individual protective equipment	
	RN collective protection	
	Radiation dosimetry	
	Retrospective radiation dosimetry	
	RN medical triage/diagnostics	
	RN medical treatment	

Hard Problems

There are significant hard problems that endure within the realm of radiological and nuclear defence.

Detection of special nuclear materials (SNM) is a hard problem because the radiation emissions from these materials are weak, easy to shield, and often difficult to distinguish from background radiation. Detection of these materials is highly desirable in order to prevent their use in a nuclear weapon, which would have catastrophic consequences. This hard problem is represented by “Nuclear material detection” in Table 2, and is widely regarded as the most pressing and challenging problem in RN defence [ITF-53].

Detection of shielded or masked RN materials is a hard problem because the radiation emissions from threat materials can be shielded with and/or masked with emissions from non-threat radioactive materials. For example a high activity source that could be used in an RDD could be undetectable with traditional radiation detectors if placed in an appropriately engineered shield. Some commodity materials (e.g. kitty litter, granite) are naturally radioactive and their emissions can overwhelm the emissions from many RN threat materials, making them effectively undetectable. Multiple RN R&D areas from Table 2 are related to this hard problem: “ Nuclear material detection”, “R material detection”, “RN material localization and imaging”, and “RN material identification”.

Stand-off detection of RN material is a hard problem because existing detection systems have limited ranges at which they can detect RN threat and hazard materials. Some threat materials are only detectable at a range of a few centimeters and may be completely undetectable by traditional means when shielded. Even threat materials that are potentially detectable at significant distances (~100 m) are a challenge to detect over large areas with limited detection resources. Multiple RN R&D areas from Table 2 are related to this hard problem: “N material detection”, “R material detection”, “RN material localization and imaging”, and “RN sensor fusion for situational awareness”.

Decontamination of equipment and materials is a hard problem because it can be extremely challenging, if not impossible, to perform radiological decontamination down to levels that allow for unrestricted use under national and international regulations. Contaminated equipment and infrastructure may, therefore, be unusable after contamination. This hard problem is covered in Table 2 by “RN equipment decontamination”.

RN defence R&D thru ADM(S&T)

Table 2 provides a ranking and prioritization of RN defence R&D areas after considering the question: “What R&D should be done to improve the CAF’s RN defence capabilities?”. At least some R&D is ongoing in most of these areas at government labs, private companies and academic institutions in Canada and allied countries. In light of this, a critical question to answer is “What R&D should be done thru ADM(S&T)?”. There is limited value in duplicating work done elsewhere, so the most productive niches must be identified. Which R&D niches should be filled by DRDC depends on the nature of the R&D work: DRDC must focus on R&D that is (a) sensitive, (b) classified and/or (c) strategic (SCS).

We have taken the top ten RN defence R&D areas listed in Table 2 and identified (1) which topics are not adequately covered by our allies, industry, academia or other government labs, and (2) which topics are sensitive, classified and/or strategic. As part of this analysis, we looked at the next-level down in R&D granularity: we considered specific technologies and techniques that are pertinent to the different RN defence R&D areas. Specific, relevant technologies and techniques for the entire range of potential RN defence were identified during structured brainstorming sessions with DRDC SMEs, and were categorized as follows:

- **Traditional radiation detection:** gamma imaging, advanced algorithms for spectral analysis, networked detectors, air deployable detectors, neutron imaging, directional detection, directional + spectroscopic detectors, anti-neutrino detection, detector materials, neutron spectroscopy, medical Imaging techniques, improved beta detection and ID, portable low energy beta detection, improved branching ratio knowledge, multi-sensor mobile imaging systems, fast neutron detection, large area neutron detection, large area gamma + neutron detection, directional neutron detectors.
- **Alternate detection techniques:** active interrogation (with neutrons and/or high energy photons, possibly from compact accelerators), muon tomography, gravity gradiometry, air fluorescence, surrounding material excitation techniques, chemical signatures (LIBS, FTIR, etc.), .
- **Modelling:** Radiation transport, atmospheric dispersion, hydrocode, computational fluid dynamics, operational modelling.
- **Situational awareness and decision support:** RN data sensor fusion, RN + non-RN data sensor fusion, RN decision support, wearables and augmented reality for SA.
- **Threat analysis:** field trials of threat devices (TERES), risk assessment (PRA), shielding + enrichment analysis, source term experiments, dispersion experiments.
- **Laboratory analysis:** radiological screening (α, β, γ, n), physical characterization, isotopic analysis (α, β, γ spectrometry), isotopic/chemical analysis (mass spec), analysis of contaminated evidence, whole-air sampling and analysis.
- **Radiation hardness:** gamma dose, neutron dose, dose rate.
- **Decontamination:** peelable coatings, self peeling coatings, omniphobic/repellancy materials, self-encapsulating, reactive coatings, nano-machines.
- **Dosimetry:** Optically stimulated luminescence, novel materials, no-power colour-metric materials, dose reconstruction modeling, self-contained passive dosimeters.

Table 3 shows a shortened list of the specific technologies and techniques that are considered relevant to research in the RN defence R&D areas that were prioritized as “very high” and “high”.

Table 3: Relevance of specific research topics to the "very high" and "high" priority R&D Areas. Green represents high relevance, yellow is moderate relevance, and no colour (white) indicates no relevance.

	Sub-component:	**Very High Priority**			**High Priority**			
	Specific Research Topic	1: Nuclear material detection	2: RN material localization and imaging	3: RN weapon triage	4: RN sensor fusion for situational awareness	5: RN material quantification	6: RN threat assessment	7: RN decision support
Traditional Detection	Gamma Imaging	Green	Green	Green	Yellow	Yellow		
	Advanced Algorithms for isotope ID	Yellow		Green		Green		Yellow
	Networked Detectors	Yellow	Green		Green	Yellow		Green
	Air deployable detectors	Yellow	Green		Green			Green
	Neutron Imaging	Green	Green	Green	Yellow			
	Directional Detection	Yellow	Green	Yellow	Green			
	Directional + Spectroscopic	Yellow	Green	Green	Green	Green		
	Anti-neutrino Detection	Green						
	Detector Materials	Green		Green		Yellow		
	Neutron Spectrocopy	Green		Green				
	Medical Imaging Techniques	Green	Green	Green	Yellow			
	Improved Branching ratio Knowledge	Yellow		Yellow		Green		
	Multi-sensor mobile imaging systems	Green	Green		Green			Green
	fast neutron detection	Green		Green	Yellow	Yellow		
	large area neutron detection	Green	Yellow	Green	Green	Green		
	dual, large area gamma-n detection	Green	Yellow	Green	Green	Green		
	directional neutron detectors	Green	Green	Green	Green			
Alternate Detection	Active Interrogation	Green		Green		Green		Yellow
	Muon Tomography	Green		Green		Yellow		Yellow
	Gravity Gradiometry	Green		Yellow		Yellow		
	Air fluorescence	Green	Green		Yellow			
	Surrounding material excitation techniques	Green	Green		Yellow			
	Chemical Signatures (LIBS, FTIR, etc.)	Green			Yellow			
Modelling	Radiation Transport			Green		Green	Green	
	Atmospheric Dispersion						Green	Green
	Hydrocode			Green			Green	
	Computational Fluid Dynamics			Yellow			Green	
	Operational Modelling						Green	Green
SA and DS	RN data sensor fusion				Green			Green
	RN + non-RN data sensor fusion				Green			Green
	RN Decision support				Green			Green
	Wearables and augmented reality for SA				Green			Green
Threat Analysis	Field Trials of Threat Devices - TERES			Green			Green	Green
	Risk Assessment (PRA)						Green	Green
	Shielding + Enrichment Analysis			Green		Green		Green
	Source Term Experiments			Green			Green	Yellow
	Dispersion Experiments			Green			Green	Yellow
Laboratory Analysis	Radiological screening (α, β, γ, n)	Yellow		Yellow		Green	Green	
	Physical characterization			Yellow		Yellow	Yellow	
	Isotopic analysis (α, β, γ spectrometry)			Yellow		Yellow	Green	
	Isotopic/chemical analysis (mass spec)					Yellow	Yellow	
	Whole-air sampling and analysis						Yellow	

These technologies and techniques were then considered for whether or not they are appropriate and attractive research topics in which ADM(S&T) should invest. This analysis involved three considerations: (1) the "Impact Potential" for the research, (2) whether the research is DRDC Appropriate, and (3) whether or not there is a "Niche for ADM(S&T)" in the research area.

- **Impact Potential:** In this we answered the question: "Will research in this area be useful to the CAF?" Three considerations made up this metric: (1) the chance for success in this research area; (2) if successful, is uptake by the CAF likely; (3) if successful, is this likely to reduce the risk to the CAF significantly?. These questions were answered "yes" (green), "maybe" (yellow) or "no" (red). If the answer to any one of these questions is "no", then ADM(S&T) should not invest in this area, as research in the area is unlikely to have a significant impact for the CAF. A majority of "yes" answers means that it is *likely to be useful* to the CAF and a majority "maybe" means that it *might be useful* to the CAF. Both cases are considered further.
- **DRDC Appropriate:** To evaluate the appropriateness of each research topic we looked at whether or not the research topic contained elements that are: sensitive, classified, strategic, or addressed a hard problem. If the research topic contains none of these elements, then we deemed it inappropriate for DRDC to pursue. If one or more of these elements are present , then the topic was categorized as green (appropriate); otherwise the rating is yellow (possibly appropriate).
- **Niche for ADM(S&T):** Lastly, we wanted to determine whether or not each research area was adequately covered by academia, industry OGD or allies' research programs. If the area is not adequately covered, then there is a "niche for ADM(S&T)" to pursue a research program in the area. The existence of a niche in each area was categorized as "yes", "maybe" or "no". If the answer is "no", then ADM(S&T) should not invest in this area.

Each of the specific research topics listed in Table 3 (those relevant to the "very high" or "high" priority research areas in Table 2) were evaluated against the three above criteria to make a recommendation regarding whether or not ADM(S&T) should invest in research in the specific RN topics. A summary of the evaluation is presented in Table 4, and the details of the evaluation going into the summary are presented in Appendix D. If all three criteria were rated "green" then the overall rating is green, meaning ADM(S&T) *should* invest in this topic. If any criterion is "red", the overall rating is red, meaning ADM(S&T) *should not* consider investment at this time. For the remaining cases, the overall rating is yellow, meaning we recommend that ADM(S&T) *could* consider investment.

Recommendations for Specific RN Defence Research Topics

The authors recommend that ADM(S&T) should invest in RN research in a number of specific research topics, categorized here under priorities 1 through 3.

Priority 1 – Topics applicable to multiple "very high" priority research areas (see Table 3)

- Gamma Imaging[1]
- Networked Detectors
- Shielding and Enrichment Analysis[2]

Priority 2 – Topics applicable to a single very high priority research area (see Table 3)

- Field Trials of Threat Devices – TERES
- Dispersion Experiments

Priority 3 – Topics applicable to high priority research areas (see Table 3)

- RN data sensor fusion
- RN decision support

The authors recommend that, given adequate resources, ADM(S&T) could also consider investing in RN research in some of the following specific research topics, categorized here as priority 4:

Priority 4 – Other topics relevant to high priority research areas

- Air deployable detectors
- Neutron Imaging
- Directional Detection
- Directional + Spectroscopic
- Anti-neutrino Detection
- Applications of medical imaging techniques
- Dual large area gamma-n detection
- Directional neutron detectors
- Active Interrogation
- Muon Tomography[3]
- Air fluorescence
- Atmospheric Dispersion[4]
- Operational Modelling[5]
- RN + non-RN data sensor fusion
- Wearables and augmented reality for SA
- Risk Assessment (PRA)
- Source Term Experiment
- Isotopic analysis (α, β, γ spectrometry)
- Isotopic/chemical analysis (mass spec)
- Whole-air sampling and analysis

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[1] The potential niche is development of image reconstruction algorithms and software for gamma imaging systems
[2] This area may be adequately covered by allies, but the results are not shared
[3] The niche in muon tomography is in adapting existing techniques for military applications
[4] The potential niche in dispersion modelling is in developing and validating fast running urban dispersion codes
[5] The potential niche is in incorporating RN threats and hazards into operational models

Table 4: Evaluation of specific RN topic areas.

Category	Research Topic	Impact Potential	DRDC Appropriate?	Niche for DRDC?	Should DRDC pursue?
Traditional Detection	Gamma Imaging	Green	Green	Green	Green
	Advanced Algorithms for isotope ID	Green	Green	Red	Red
	Networked Detectors	Green	Green	Green	Green
	Air deployable detectors	Green	Green	Yellow	Yellow
	Neutron Imaging	Yellow	Green	Yellow	Yellow
	Directional Detection	Green	Green	Yellow	Yellow
	Directional + Spectroscopic	Green	Green	Yellow	Yellow
	Anti-neutrino Detection	Yellow	Green	Green	Yellow
	Detector Materials	Red	Red	Red	Red
	Neutron Spectrocopy	Yellow	Green	Red	Red
	Applications of medical imaging techniques	Yellow	Green	Yellow	Yellow
	Improved Branching ratio Knowledge	Red	Red	Yellow	Red
	Multi-sensor mobile imaging systems	Yellow	Green	Red	Red
	fast neutron detection	Yellow	Green	Red	Red
	large area neutron detection	Yellow	Green	Red	Red
	dual, large area gamma-n detection	Yellow	Green	Yellow	Yellow
	directional neutron detectors	Yellow	Green	Yellow	Yellow
Alternate Detection	Active Interrogation	Yellow	Green	Yellow	Yellow
	Muon Tomography	Yellow	Green	Green	Yellow
	Gravity Gradiometry	Red	Green	Green	Red
	Air fluorescence	Yellow	Green	Green	Yellow
	Surrounding material excitation techniques	Red	Green	Green	Red
	Chemical Signatures (LIBS, FTIR, etc.)	Red	Green	Green	Red
Modelling	Radiation Transport	Red	Green	Red	Red
	Atmospheric Dispersion	Yellow	Green	Yellow	Yellow
	Hydrocode	Red	Green	Red	Red
	CFD	Red	Green	Red	Red
	Operational Modelling	Yellow	Green	Yellow	Yellow
SA and DS	RN data sensor fusion	Green	Green	Green	Green
	RN + non-RN data sensor fusion	Yellow	Green	Green	Yellow
	RN decision support	Green	Green	Green	Green
	Wearables and augmented reality for SA	Yellow	Yellow	Green	Yellow
Threat Analysis	Field Trials of Threat Devices - TERES	Green	Green	Green	Green
	Risk Assessment (PRA)	Yellow	Green	Green	Yellow
	Shielding and Enrichment Analysis	Green	Green	Green	Green
	Source Term Experiments	Yellow	Green	Yellow	Yellow
	Dispersion Experiments	Green	Green	Green	Green
Laboratory Analysis	Radiological screening (α, β, γ, n)	Red	Red	Red	Red
	Physical characterization	Red	Yellow	Yellow	Red
	Isotopic analysis (α, β, γ spectrometry)	Yellow	Yellow	Yellow	Yellow
	Isotopic/chemical analysis (mass spec)	Yellow	Yellow	Yellow	Yellow
	Whole-air sampling and analysis	Yellow	Yellow	Yellow	Yellow

Direct Client Support

In addition to DRDC's research program, DRDC scientists are often called upon to provide direct support to our military clients. In the recent past, this activity has included a number of different types of tasks:

- **On-site scientific support during security operations:** During recent, major events in Canada (2016 North America Leaders' Summit, 2010 Winter Olympics, 2010 G8/G20 Summits, 2008 Francophonie Summit) DRDC's RNAD Group has provided on-site scientific support in the form of scientists and/or technologists, plus, sometimes, specialized radiation detection and identification equipment. The scope of support has varied from up to six staff deployed with DRDC's Mobile Nuclear Laboratory over a six week period (e.g. 2010 Winter Olympics in Vancouver), to a single scientist or technologist for a few days (e.g. 2008 Francophonie Summit). In addition to the time spent at the actual event, substantial effort can also been required in the planning and training involved in the lead-up to these events.
- **Remote RN S&T reach-back during operations and exercises:** DRDC's RNAD group frequently provides RN S&T reach-back for CAF operations and exercises (e.g. Op IMPACT, Op PODIUM, Ex Midnight Archer, Ex VA17). This ensures that the CAF receives the best possible scientific advice when dealing with possible RN threats. The RNAD's expertise in performing R&D to defend against RN threats allows us to provide unique advice to the CAF.
- **Specialized training for advanced response and analysis techniques:** The RNAD Group has been involved with the RN defence training of members of the CAF for many years. The largest training commitment is the provision of the week-long Advanced Radiation Response (ARR) Course, primarily for CJIRU operators. This course is taught once or twice a year and is the final RN defence course required for the CBRN Operator trade in the CAF. It has also been taken or audited by a small number of members of D CBRN D and the RCMP. The ARR course transfers as much as possible of the group's cutting edge knowledge of RN threats and defence to CJIRU operators so that the need for RN S&T reach-back is reduced as much as possible. In addition to the ARR Course, RNAD group members have taught the RN portions of the Advanced CBRN Defence course run by CFFCA at CFB Borden, and the Senior Officers' CBRN Advisor course taught in Ottawa. We have also provided one-off training in highly specialized topics, as required; a recent example is the RN MAC training provided to CJIRU.
- **Conceptual and operational assessments of equipment for procurement projects:** DRDC's RNAD Group has supported several CAF RN procurement projects in the last few years, and has done so, further in the past as well. This support has included performing measurements of the performance of radiation detectors in different scenarios, and simulating their performance when the scenarios are too difficult or expensive to create in the laboratory. The most recent procurement projects we have supported include
    - **Radioisotope Identification System (RadIS):** the RNAD Group helped to determine the requirements for this D CBRN D project through literature reviews, client consultations and laboratory measurements with commercial-off-the-shelf (COTS) equipment. The performance of the systems submitted by vendors for the Request For Proposal (RFP) were measured by DRDC as well.

    - **Sensitive Mobile Radiation Detection (SMRD):** similar work was performed for CANSOFCOM's SMRD project, including field measurements of the system that was ultimately procured for the CAF.
    - **Radiation Detection System (RDS) project:** DRDC has advised D CBRN D on this procurement project by participating in the Testing and Evaluation Working Integrated Project Team (T&E WIPT) for the equivalent US RDS project. This work will include high-energy gamma-ray testing of the US RDS system at Canadian Nuclear Laboratories (CNL) in Chalk River, Ontario (February 2018), and operational assessment (OA) testing (May 2018). The OA testing was originally planned to be done at DRDC Ottawa Research Centre, but with the RN program's move to Suffield, the OA testing must take place there instead.
- **S&T advice on Tactics, Techniques and Procedures (TTPs):** CJIRU has requested DRDC for assistance with developing and validating new TTPs for RN defence (e.g. sampling procedures for measuring radioactive material).
- **Laboratory reach-back:** DRDC has provided laboratory reach-back for the CAF by analyzing radiological samples obtained on operations abroad at DRDC laboratories in Ottawa. DRDC's RN sample analysis capability supports CJIRU's MAC and DRDC's commitments under CONPLAN RUBICON [1].

All of these activities have provided immediate benefits for our CAF clients. The RNAD Group has been able to provide this direct client support with a relatively small amount of effort due to our years of expertise in RN defence R&D, and our RN laboratory infrastructure and equipment. Areas of R&D that are most frequently relevant in terms of preparing us to provide effective direct client support are

- Nuclear material detection,
- RN weapon triage,
- RN material quantification,
- RN threat assessment,
- Radiological material detection,
- RN hazard modelling and simulation,
- RN material identification, and
- RN material sampling and analysis.

Conclusion

A thorough analysis of 24 different areas of RN defence R&D, and, at a more granular level, specific R&D topics within those areas, leads us to recommend that ADM(S&T) invest in a number of areas of RN defence R&D. Successful R&D in these areas should significantly improve upon the CAF's current capabilities. Bearing in mind that the resources to carry out RN defence R&D are currently very limited, only a small number of research topics should be addressed at any given time. For this reason we have produced a list of R&D topics that is divided into three high priority groups (with two or three topics per group), and a fourth group of lower priority topics. The remaining topics are not recommended for investment at this time. Previous expertise gained from working in many of these R&D areas was excellent preparation, and in some cases vital, for DRDC providing direct client support in RN S&T.

Summary

We have recommended priorities for future ADM(S&T) investment in RN defence R&D. The recommendation is based on the "appropriateness" for ADM(S&T) investment (Table 4) and the potential impact on RN defence for the CAF (Table 2). In the past, our R&D program has been complementary to our provision of direct client support. It is expected that this symbiosis will continue in the future.

References

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Appendix A

This graphic shows a mapping of the applicability of the RN Defence Enabling Components and potential research areas to the different phases of response.

	ConPlan RUBICON Response Phases:	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4: Employment			Phase 5
RN Enabling Component	**RN Subcomponent**	**Shaping**	**Warning**	**Preparation**	**Deployment**	**Crisis Response**	**Consequence Management**	**Recovery Operations**	**Redeployment**
Planning/Preparation	RN threat assessment	■							
	RN proliferation detection	■							
	RN capability assessment	■							
	RN response planning	■							
Detection, Identification and Monitoring	Nuclear material detection		■						
	Radiological material detection		■						
	RN material localization and imaging		■			■			
	RN material identification					■			
	RN material quantification					■			
	RN weapon triage					■			
	RN material sampling and analysis						■	■	
	RN hazard monitoring						■		
Information Management	RN hazard modelling and simulation		■	■	■	■	■		
	RN sensor fusion for situational awareness		■	■	■	■	■		
	RN warning and reporting		■						
	RN decision support		■	■	■	■	■		
Physical Protection	RN individual protective equipment					■	■	■	
	RN collective protection					■	■		
Hazard Management	RN equipment and personnel decontamination						■	■	■
	RN contamination avoidance						■		
	Radiation dosimetry						■	■	
Medical Countermeasures and Support	Retrospective radiation dosimetry							■	
	RN medical triage/diagnostics							■	■
	RN medical treatment							■	■

Appendix B

The following definitions of the RN Defence Sub-components (and potential RN Defence R&D Areas) were used:

Planning/Preparation

- **RN threat assessment** is the process of understanding the threats, risks, and hazards posed to the CAF by radiological and nuclear weapons and materials.
- **RN proliferation detection** is the process of gathering information that could indicate proliferation activities (e.g. refinement, enrichment, weapons testing).
- **RN capability assessment** is the process of understanding the CAF's capabilities, including personnel, equipment, etc., for responding to RN threats and hazards.
- **RN response planning** is the process of developing high level plans and specific tactics, techniques and procedures (TTPs) for responding to RN threats and hazards.

Detection, Identification and Monitoring

- **Nuclear material detection** involves the detection of nuclear weapons or special nuclear material (SNM) by exploiting the weak radiation signature emitted by these materials and/or other signatures such as their density or induced emissions from active interrogation with a radiation beam.
- **Radiological material detection** involves detecting the radiation signatures emitted from radiological weapons or materials, including short-range radiation and shielded, dispersed, and moving sources.
- **RN material localization and imaging** involves the determination of the location(s) and distribution of nuclear or radiological material.
- **RN material identification** involves the exploitation of the energy signature of radiation to aid in the detection and identification of the threat isotope.
- **RN material quantification** involves detailed measurements of radiation emissions from a threat material, and modifications of those emissions due to the surrounding material, in order to quantify the amount of different radioisotopes (this includes fissile material enrichment calculations).
- **RN weapon triage** combines imaging, identification and quantification of RN weapon materials with additional information such as x-ray images and visual inspection, to determine the viability and potential consequences of a radiological or nuclear weapon.
- **RN material sampling and analysis** involves taking samples of radiological and nuclear materials and analyzing them for their radiation emissions, chemical makeup and other properties in order to determine detailed information of the hazard they pose, the material origin, etc. This includes forensic analysis of samples and associated materials.
- **RN hazard monitoring** involves utilizing radiation detection techniques to monitor radiation hazards for long-term situational awareness.

Information Management

- **RN hazard modelling and simulation** involves using computer codes to simulate processes such as radiation interactions with matter and atmospheric dispersion of materials, for purposes such as detector development, hazard prediction and threat assessment.
- **RN sensor fusion and situational awareness** involves the combination and analysis of information from multiple sensors and/or sensor types (including non-RN sensors), and presenting this combined information in a coherent way to aid situational awareness of RN threats and hazards.
- **RN warning and reporting** involves using sensor data, models and expert inputs to generate warning messages for RN hazards (e.g. using the NATO ATP-45 standard).
- **RN decision support** involves the synthesis of RN data with other data types, in a way that allows informed decisions about RN threats and hazards within a greater operational context.

Physical Protection

- **RN individual protective equipment** includes clothing, respirators and other equipment designed to protect the wearer from nuclear and radiological hazards.
- **RN collective protection** includes air filtration systems, shielding and other equipment designed to protect groups of personnel from nuclear and radiological hazards.

Hazard Management

- **RN equipment and personnel decontamination** involves the removal of radioactive contamination from equipment and/or people.
- **RN contamination avoidance** involves the use of RN sensor data to demark areas of possible radiological contamination to be avoided, reducing requirements for later decontamination.
- **Radiation dosimetry** involves the measurement of radiation exposure to individuals.

Medical Countermeasures and Support

- **Retrospective radiation dosimetry** involves the reconstruction/estimate of radiation doses to individuals not wearing a radiation dosimeter, but exposed to a radiation hazard.
- **RN medical triage/diagnostics** is the determination of which personnel require medical treatment, and what type of treatment, following exposure to a radiological or nuclear hazard.
- **RN medical treatment** involves the use of countermeasures, prophylaxis, decorporation, supportive care, or other medical treatments prior to, or after, exposure to a radiological or nuclear hazard.

Appendix C

Nine RN subject matter experts (SMEs) were asked to rank the possible R&D areas corresponding to the RN Defence Enabling Components from Table 1. Ranking of the R&D areas was done in terms of importance to improve CAF capabilities. (i.e. "What R&D *should* be done to improve the RN defence capability of the CAF?"). SMEs were asked to assess (1) the likelihood that R&D in each area would lead to a successful outcome, and (2) the impact that successful R&D would have on the CAF's ability to reduce the risks posed by the spectrum of RN threats. The SMEs were asked to rank their top 10 R&D areas in order, with all other R&D areas assigned a rank of 11. Consensus ranking was performed using an online software tool, The Condorcet Internet Voting Service (CIVS). The web site is available at: http://civs.cs.cornell.edu/. The individual SME rankings are shown in table C2, and the detailed results (using the Schulze/Beatpath/CSSD tie-breaking algorithm from the CIVS web site) are shown in table C2.

Table C1: Detailed SME rankings of the RN defence R&D Areas. SME names have been anonymized.

RN Enabling Component	RN Subcomponent	SME Rankings								
		A	B	C	D	E	F	G	H	I
Planning/ Preparation	RN threat assessment	11	11	4	4	9	8	3	5	9
	RN proliferation detection	4	11	10	7	6	9	11	11	7
	RN capability assessment	11	11	11	8	11	11	4	11	11
	RN response planning	11	6	11	11	11	11	5	11	11
Detection, Identification and Monitoring	Nuclear material detection	1	2	1	3	1	1	1	1	1
	Radiological material detection	8	11	9	6	2	11	11	11	4
	RN material localization and imaging	7	4	2	5	3	5	2	3	2
	RN material identification	11	8	11	9	5	11	11	11	3
	RN material quantification	3	3	6	10	7	3	11	4	11
	RN weapon triage	2	1	3	11	8	4	6	2	6
	RN material sampling and analysis	9	11	11	11	11	11	11	9	5
	RN hazard monitoring	11	11	11	11	11	11	11	11	11
Information Management	RN hazard modelling and simulation	11	5	11	11	10	10	9	7	10
	RN sensor fusion for situational awareness	6	11	5	2	4	6	7	11	8
	RN warning and reporting	11	9	11	11	11	11	8	8	11
	RN decision support	5	11	7	1	11	7	11	6	11
Physical Protection	RN individual protective equipment	11	11	11	11	11	11	11	11	11
	RN collective protection	11	11	11	11	11	11	11	11	11
Hazard Management	RN equipment and personnel decontamination	10	7	8	11	11	2	11	10	11
	RN contamination avoidance	11	11	11	11	11	11	10	11	11
	Radiation dosimetry	11	11	11	11	11	11	11	11	11
Medical Countermeasures and Support	Retrospective radiation dosimetry	11	11	11	11	11	11	11	11	11
	RN medical triage/diagnostics	11	11	11	11	11	11	11	11	11
	RN medical treatment	11	11	11	11	11	11	11	11	11

Table C2: Detailed results of the consensus voting.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. Nuclear material detection	–	9	8	8	9	9	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
2. RN material localization and imaging	0	–	5	7	6	8	7	8	8	9	8	9	9	9	9	9	9	9	9	9	9	9	9	9
3. RN weapon triage	1	4	–	7	6	7	8	6	7	8	7	6	8	7	7	7	8	8	8	8	8	8	8	8
4. RN sensor fusion for situational awareness	1	2	2	–	5	5	5	5	5	7	6	6	7	6	6	6	7	7	7	7	7	7	7	7
5. RN material quantification	0	3	3	4	–	5	6	5	5	7	6	5	7	7	6	7	7	7	7	7	7	7	7	7
6. RN threat assessment	0	1	2	3	4	–	5	5	5	7	6	5	7	6	7	7	7	7	7	7	7	7	7	7
7. RN decision support	1	2	1	3	1	3	–	5	4	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5
8. Radiological material detection	0	1	3	2	3	3	2	–	4	5	4	4	5	5	5	5	5	5	5	5	5	5	5	5
9. RN proliferation detection	0	1	2	2	3	3	3	2	–	6	4	4	6	5	6	6	6	6	6	6	6	6	6	6
10. RN hazard modelling and simulation	0	0	0	2	2	1	4	4	3	–	5	4	5	5	5	5	6	6	6	6	6	6	6	6
11. RN equipment and personnel decontamination	0	1	1	3	1	3	2	4	4	3	–	5	4	3	5	4	5	5	5	5	5	5	5	5
12. RN material identification	0	0	3	2	3	3	3	2	3	3	3	–	4	4	3	3	4	4	4	4	4	4	4	4
13. RN warning and reporting	0	0	0	2	1	1	2	3	3	1	2	2	–	3	2	1	3	3	3	3	3	3	3	3
14. RN material sampling and analysis	0	0	1	2	1	2	1	1	2	2	3	2	2	–	3	3	3	3	3	3	3	3	3	3
15. RN capability assessment	0	0	2	1	2	0	1	1	1	2	2	2	2	2	–	2	2	2	2	2	2	2	2	2
16. RN response planning	0	0	1	2	1	1	2	2	2	1	2	2	2	2	1	–	2	2	2	2	2	2	2	2
17. RN contamination avoidance	0	0	0	0	1	0	1	1	1	0	1	1	0	1	0	0	–	1	1	1	1	1	1	1
18. RN hazard monitoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0	0	0	0	0	0
19. RN individual protective equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0	0	0	0	0
20. RN collective protection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0	0	0	0
21. Radiation dosimetry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0	0	0
22. Retrospective radiation dosimetry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0	0
23. RN medical triage/diagnostics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	0
24. RN medical treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–

Appendix D

Full evaluation used to recommend whether or not DRDC should pursue research in the specific RN topic areas, from Table 3, relevant to the "Very High" and "High" priority research areas from Table 2. Everything to the right of the vertical dashed line are the inputs into the summary presented to the left of the vertical dashed line.

							Impact Potential			DRDC Appropriate?				
Category	Research Topic	Impact Potential	DRDC Appropriate?	Niche for DRDC?	Should DRDC pursue?		Likely to succeed	Uptake by CAF	Risk Reduction to CAF	Sensitive	Classified	Strategic	Hard Problem	Niche for DRDC?
Traditional Detection	Gamma Imaging	Green	Green	Green	Green		Green	Green	Yellow	Green	Green	Yellow	Green	Green
	Advanced Algorithms for isotope ID	Green	Green	Red	Red		Green	Green	Yellow	Green	Green	Yellow	Red	Red
	Networked Detectors	Green	Green	Green	Green		Green	Green	Yellow	Green	Green	Red	Green	Green
	Air deployable detectors	Green	Green	Yellow	Yellow		Green	Green	Yellow	Green	Green	Red	Green	Yellow
	Neutron Imaging	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Yellow	Green	Green	Yellow	Green	Yellow
	Directional Detection	Green	Green	Yellow	Yellow		Green	Green	Yellow	Green	Green	Red	Red	Yellow
	Directional + Spectroscopic	Green	Green	Yellow	Yellow		Green	Green	Yellow	Green	Green	Red	Red	Yellow
	Anti-neutrino Detection	Yellow	Green	Green	Yellow		Yellow	Yellow	Green	Green	Yellow	Green	Green	Green
	Detector Materials	Red	Red	Red	Red		Red	Yellow	Yellow	Red	Red	Red	Red	Red
	Neutron Spectrocopy	Yellow	Green	Red	Red		Yellow	Yellow	Yellow	Green	Green	Red	Green	Red
	Applications of medical imaging techniques	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Yellow	Green	Green	Yellow	Green	Yellow
	Improved Branching ratio Knowledge	Red	Red	Yellow	Red		Yellow	Green	Red	Red	Red	Red	Red	Yellow
	Multi-sensor mobile imaging systems	Yellow	Green	Red	Red		Yellow	Green	Yellow	Green	Green	Red	Green	Red
	fast neutron detection	Yellow	Green	Red	Red		Yellow	Yellow	Yellow	Green	Green	Red	Green	Red
	large area neutron detection	Yellow	Green	Red	Red		Green	Yellow	Yellow	Green	Green	Red	Green	Red
	dual, large area gamma-n detection	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Yellow	Green	Green	Red	Green	Yellow
	directional neutron detectors	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Yellow	Green	Green	Red	Green	Yellow
Alternate Detection	Active Interrogation	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Green	Green	Green	Yellow	Green	Yellow
	Muon Tomography	Yellow	Green	Green	Yellow		Green	Yellow	Yellow	Green	Green	Yellow	Green	Green
	Gravity Gradiometry	Red	Green	Green	Red		Red	Yellow	Green	Green	Yellow	Yellow	Green	Green
	Air fluorescence	Yellow	Green	Green	Yellow		Green	Yellow	Yellow	Green	Yellow	Red	Yellow	Green
	Surrounding material excitation techniques	Red	Green	Green	Red		Red	Yellow	Yellow	Green	Yellow	Red	Yellow	Green
	Chemical Signatures (LIBS, FTIR, etc.)	Red	Green	Green	Red		Red	Yellow	Yellow	Green	Yellow	Red	Yellow	Green
Modelling	Radiation Transport	Red	Green	Red	Red		Green	Yellow	Red	Green	Yellow	Yellow	Green	Red
	Atmospheric Dispersion	Yellow	Green	Yellow	Yellow		Green	Yellow	Yellow	Green	Yellow	Red	Green	Yellow
	Hydrocode	Red	Green	Red	Red		Red	Yellow	Yellow	Green	Green	Green	Green	Red
	CFD	Red	Green	Red	Red		Red	Yellow	Red	Green	Yellow	Red	Green	Red
	Operational Modelling	Yellow	Green	Yellow	Yellow		Yellow	Yellow	Yellow	Green	Yellow	Yellow	Green	Yellow
SA and DS	RN data sensor fusion	Green	Green	Green	Green		Green	Green	Yellow	Yellow	Green	Yellow	Green	Green
	RN + non-RN data sensor fusion	Yellow	Green	Green	Yellow		Yellow	Green	Yellow	Yellow	Green	Yellow	Green	Green
	RN decision support	Green	Green	Green	Green		Green	Green	Green	Yellow	Green	Green	Green	Green
	Wearables and augmented reality for SA	Yellow	Yellow	Green	Yellow		Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red	Green
Threat Analysis	Field Trials of Threat Devices - TERES	Green	Green	Green	Green		Yellow	Green	Green	Green	Green	Green	Green	Green
	Risk Assessment (PRA)	Yellow	Green	Green	Yellow		Green	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Green
	Shielding and Enrichment Analysis	Green	Green	Green	Green		Green	Yellow	Green	Yellow	Yellow	Green	Green	Green
	Source Term Experiments	Yellow	Green	Yellow	Yellow		Green	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Yellow
	Dispersion Experiments	Green	Green	Green	Green		Green	Yellow	Green	Yellow	Green	Yellow	Green	Green
Laboratory Analysis	Radiological screening (α, β, γ, n)	Red	Red	Red	Red		Red	Green	Red	Red	Red	Red	Red	Red
	Physical characterization	Red	Yellow	Yellow	Red		Red	Yellow	Red	Red	Red	Yellow	Red	Yellow
	Isotopic analysis (α, β, γ spectrometry)	Yellow	Yellow	Yellow	Yellow		Yellow	Green	Yellow	Yellow	Red	Yellow	Yellow	Yellow
	Isotopic/chemical analysis (mass spec)	Yellow	Yellow	Yellow	Yellow		Yellow	Green	Yellow	Yellow	Red	Yellow	Yellow	Yellow
	Whole-air sampling and analysis	Yellow	Yellow	Yellow	Yellow		Green	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Yellow

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radiological nuclear defence, radiological, nuclear, radiological/nuclear, research and development, stragetic plan