Contaminant Stabilization Technology Gap Report

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Acronyms

AFFF	aqueous film-forming foam
ANL	Argonne National Laboratory
APP	ammonium polyphosphate
AS	ammonium sulfate
$CaCl_2$	calcium chloride
CASCAD	Canadian Aqueous System for Chemical / Biological Agent Decontamination
cP	centi-Poise
Cs	cesium
CsCl	cesium chloride
DAP	diammonium phosphate
EAI	Environmental Alternatives, Inc
FFFP	film-forming fluoroprotein foams
gal	gallon
IND	improvised nuclear device
lb	pound
LLNL	Lawrence Livermore National Laboratory
MAP	monoammonium phosphate
$MgCl_2$	magnesium chloride
mPa.s	milli-Pascal second
PFA	pulverized fly (fuel) ash
QAPP	Quality Assurance Project Plan
RDD	radiological dispersal device
REEco	Reynolds Electrical and Engineering Co.
RH	relative humidity
SDF	Surface Decon Foam
SNL	Sandia National Laboratories
US EPA	United States Environmental Protection Agency

1.0 Introduction

After an intentional radiological release or nuclear power plant (NPP) accidental release, there may be a large area that is contaminated. Re-suspension and tracking of contamination may create issues with containing the contaminated area and create additional exposure to responders. There is a need for technologies/methodologies to reduce resuspension and tracking. Current radiological particle containment relies on securing the area, setting up a single egress and ingress route, and minimizing the amount of contaminated equipment and vehicles leaving the contaminated zone. The re-suspension and tracking of contamination greatly hampers the ability to conduct first response activities in that zone therefore technologies that can reduce these spreading mechanisms are needed.

In the NPP decommissioning industry, coatings are employed to reduce the spread of contamination. These coatings may not be readily available in the quantities needed for early response. Responders need containment methodologies that can be employed with existing equipment and materials on site using techniques such as fire hosing, street sweepers, and painting. A review by Parra et al. (2009) provided a good overview of fixative/stabilization materials, which formed the basis (in addition to a literature search) for a list of potential technologies presented to stakeholders in the initial stages of this work. Advantages and disadvantages were identified for each of the technologies, which were grouped into tiers based on the time-frame they would be available following a radiological release, Figure 1. Stakeholders then ranked containment technologies in terms of their preference and interest in use and availability. The final part of this task is to gather more information on the stakeholder-selected technologies and identify technical gaps that need to be filled with experimental research before technical procedures can be developed for containment technology use in the field.
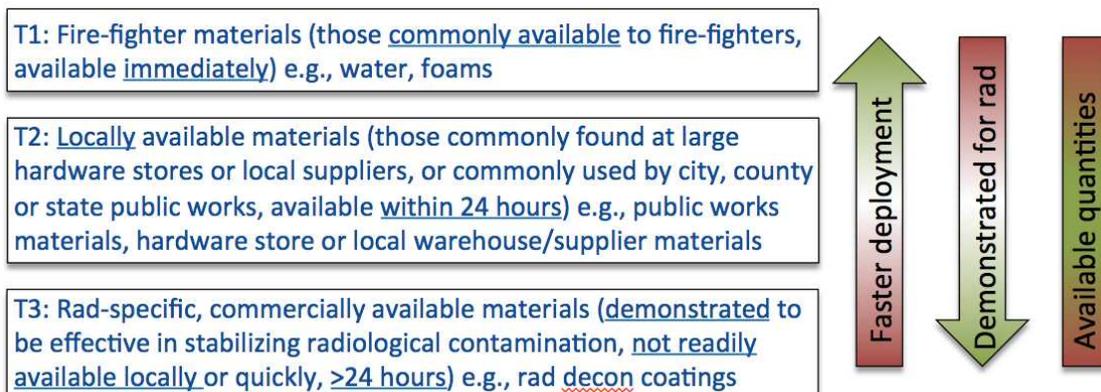

Figure 1. Stabilization technology tiers (T1, T2, and T3) based on availability timeframe

Successful containment technologies should have the following desirable properties in regard to implementation following an uncontained radiological release:

- Suppression of particle resuspension and reduction in the spread of contamination

- Reduction in dose to responders and public

- Minimization of waste consequences

- Stability over time

For some technologies, one or more of the desirable characteristics are known. A literature review will highlight areas of known properties of interest, while identifying technical gaps that need to be filled. This approach will utilize prior work while making laboratory and field experiments focused and cost-effective.

A list of containment technologies together with pros and cons for potential use after a radiological release was developed in the initial part of Phase I of this work. The list was reviewed by stakeholders, who subsequently ranked the containment technologies, Table 1. Median and average scores were calculated from the stakeholder feedback (n=11). For the purpose of the detailed literature review, technologies with an average score greater than 3.00 were be evaluated. A dotted line in Table 1 separates technologies for review from those to be excluded. Additionally, epoxy and acrylic type coatings were included and grouped with gels.

A literature search was conducted to collect information on proven and potential particle resuspension suppression technologies identified in Table 1 with an average stakeholder score of 3.00. Specific information to be garnered includes:

- Demonstrated ability to prevent resuspension (Cs-137 contained particulates)

- Impact on ultimate decontamination and waste processes

- Reduction in dose with thickness (dose attenuation)

In some cases, technologies are known to prevent particle migration (e.g., specialized gels and polymers designed to trap and remove contamination). In addition, more specialized technologies may require long production lead times and delivery times, or may not be available in enough quantity to provide wide area stabilization. For this work, the term "wide area" may be considered to be a city block (buildings, streets, grass etc.) "Low-tech" containment technologies such as water fogging or fire-fighting foams will be readily and rapidly available, but their ability to prevent resuspension of contaminants is not well understood and they may dissolve and spread contamination rather than serving as containment. Technical gaps needs to be assessed before technologies can be proposed in response to a radiological event.

Table 1. Stakeholder Ranked Containment Technologies

Median Value	Average	Technology
4.00	3.73	Water application/ fogging nozzle
4.00	3.55	Fire-fighting foam: Wet foam (protein, fluroprotein, aqueous film-forming)
4.00	3.40	Gels/polymers/coatings (e.g., *DeconGel, ANL Supergel, Westinghouse WES Strip*)
3.50	3.50	Decon foams (e.g., *InstaCote Autofroth, Global Matrechs, Inc. NuCap, SNL AFC-380, Allen Vanguard CASCAD and SDF, Dow FrothPak*)
3.00	3.27	Clays (e.g., montmorillonite, kaolinite, illite, bentonite)
3.00	3.18	Chloride salts ($CaCl_2$, $MgCl_2$ with or without road salt)
3.00	3.00	Dry firefighting foam (high expansion)
3.00	3.00	Dust wetting agents (e.g., propylene glycol products)
3.00	2.80	Rad-Specific Epoxys (e.g., Master Lee *InstaCote CC Epoxy SP InstaCote M-25*)
2.50	2.90	Rad-Specific Acrylics (e.g., Master Lee *InstaCote CC Strip, CC Wet and CC Fix; Bartlett Stripcoat TLC and Polymeric Barrier System, Isotron RADblock, ALARA and IsoFix*)
2.00	2.27	Commercial Paint
2.00	2.09	Dust Surface Crusting Agents (e.g., acrylics)
2.00	2.00	Fire-extinguishers: CO_2; Purple K (potassium bicarbonate)
2.00	2.00	Mulch
2.00	2.00	Gravel
2.00	2.00	Dust Binding Agents (e.g., lignin, emulsions)
2.00	1.73	Sand
1.50	2.10	Cakes (e.g., *AGUA A3000*)
1.50	2.00	Lignin
1.00	1.73	Imported Soil (non-local, non-contaminated)
1.00	1.73	Straw
1.00	1.64	Road oil
1.00	1.55	Emulsified Petroleum Resins

Note: high-ranking technologies from stakeholders shown above the dotted line, technologies not selected for further evaluation shown with gray shading.

2.0 Top Stakeholder Technologies

2.1 Water Application

The application of water, either through a regular hose or a misting nozzle offers rapid deployment by fire-fighters. During the response to the Chernobyl incident about 200-300 tonnes of water per hour was injected into the intact half of the reactor using the auxiliary feedwater pumps but this was stopped after half a day owing to the danger of it flowing into and flooding units 1 and 2 (World Nuclear http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/). Water is readily available in most areas in a large amount, is the fastest to deploy and is the cheapest technology considered in this evaluation. Water is widely used in dust suppression, from underground mining applications to construction sites and has demonstrated ability to prevent resuspension by increasing the weight or density of particulates (either through temporary adhesion to surfaces or clumping), or dissolution.

In the case of radionuclide contamination (and those technologies that contain significant quantities of water), we consider two types of particles, namely highly soluble Cs-137 and less soluble IND debris. For Cs-137, while the use of water spray will significantly reduce the amount of particulate contamination available for resuspension, it will also solubilize the contamination. This may increase difficulty of decontamination with porous materials/surfaces in contact with contaminated water (which subsequently adheres within pores), and clean areas including sewer/drainage systems becoming contaminated. While the problem may be less pronounced for IND debris, soluble components will behave similar to Cs, while insoluble components will be washed to sewers and drainage systems. Subsequent treatment of large volumes of contaminated water would be required. An alternative would be to deploy absorbent material to collect contamination prior to runoff into the sewer or drainage system or treatment/filtering of sewer water. Absorbent materials may include clay booms. There are no technology gaps associated with understanding the application of water as a particulate suppression technology other than site-specific fate/transport and the combination of water and sorbent materials. The technology does not address dose reduction.

2.2 Fire-Fighting Foams and Retardants

Traditionally, fire-fighting foams are designed to starve a fire of oxygen and subsequently dissipate with quick, minimal cleanup. Fire-fighting technologies can be divided between short-term (wet or dry fire-fighting foam) and long-term (fire retardants). Fire retardants were not included in the original evaluation sent to stakeholders, but were recommended by a stakeholder for consideration based on large quantity application and high viscosity. Gross and Hiltz (1980) evaluated

foams for mitigating air pollution from hazardous spills, however the chemicals treated were gases and vapors from solvents rather than particulates.

Foam sprays were used at Chernobyl, although mainly applied to rooms and areas containing flammable materials (World Nuclear http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Chernobyl-Accident---Appendix-1--Sequence-of-Events/). Wet, low expansion foam such as aqueous film-forming foam (AFFF), protein-based foams and film-forming fluoroprotein foams (FFFP) are more widely used and carried by fire departments. Their high water content is not amenable to stabilization of soluble contaminants such as Cs-137, which would result in dissolution followed by migration into porous materials and contamination of sewer/drainage systems similar to plain water application (section 2.1). There may be some interesting behavior to be studied with regard to dissolved cesium cations interacting with anionic surfactants in the foam, but since foam lifetime is designed to be minimal (AFFF dissipation $\sim$ 30 mins, FFFP dissipation $\sim$ 1 hour), the application of such wet foams in the stabilization of Cs-137 is fairly impractical. The nature of foam offers no reduction in whole body ground-shine dose beyond movement of contamination to drainage areas and away from wide spread surfaces.

High-expansion foams (e.g., Hi-Ex, Ultra Foam, Jet X) typically consist of 25-60% water and have an expansion ratio above 200. While the water content is lower than that of low-expansion foams, the likelihood of Cs-137 dissolution and subsequent migration may still be considered problematic. Furthermore, Hi-Ex foam is most commonly used in enclosed locations. The foam can be affected greatly by weather and transit and so outdoor use is limited. It is unlikely the foam offers any dose attenuation from ground-shine.

Long-term fire retardants are most commonly known for their use in wildland/forest fires, often dropped from the air. The retardants are typically dropped in-front of the fire to create a control line or fire break as well as to extinguish fire and can provide protection from days to months. Most commonly available as a powder that can be mixed in water, the current retardant technologies contain some mixture of monoammonium phosphate (MAP), diammonium phosphate (DAP), ammonium sulfate (AS) and ammonium polyphosphate (APP). A range of viscosities can be achieved by the addition of clay or (more commonly) guar gum as a thickening agent. Examples of Phos-Chek and Fire-Trol products are given in Table 2. An excellent review by Gimenez et al. (2004) discusses the quality, effectiveness, application and environmental considerations of long-term fire retardants.

Aquatic toxicity due to high ammonium concentrations may present a problem for areas with bodies of water. Toxicity to humans related to sodium dichromate or sodium fluorosilicate typically added as corrosion inhibitors. The environmental implications of fire-retardant chemicals (including PhosChek and Fire-Trol reagents) has been evaluated by Little and Calfee (2002) showing that the presence of ferrocyanide increased the toxicity amongst other factors.

Table 2. Examples of long-term fire retardant products, gum thickened, containing corrosion-inhibitors

Product	Type	Yield	Viscosity, cP (or mPa.s)	Specific Weight, lb/gal
Phos-Chek D75-R and D75-F (no longer produced)	MAP/AS high viscosity, air application only,	1 t = 1,786 gal	1,000 – 1,600	8.91
Phos-Chek P100-F	MAP/AP, high viscosity	1t = 2,150 gal	801 – 1,500	8.74
Phos-Chek MVP-F	MAP/AS medium viscosity, contains flow conditioner	1t = 2,225 gal	401 - 800	8.79
Phos-Chek LC-95A-R	APP low viscosity	1t = 1,054 gal	75 - 225	8.97
Phos-Chek 259-F	DAP low viscosity non-corrosive to Mg	1t = 1,869 gal	75 - 250	8.90
Phos-Chek G75-F and G75-W (no longer produced)	MAP/AS low-viscosity, contains bactericide	1t = 1,907 gal	60 - 250	8.85
Phos-Chek LV-R and MV-R	MAP/AS, low/medium viscosity, contains stabilizers	1t = 860 gal	75 - 225 / 450 - 750	8.93
Phos-Chek HV -R and -F	MAP/AS high viscosity, contains stabilizer	1t = 775 - 860 gal	1,000 - 1,600	8.93
Fire-Trol GTS-R	DAP/AS high viscosity	1t = 1325 gal	1,200 - 1,800	9.07
Fire-Trol LCA-R, LCG-R, LCA-F	APP low viscosity	1t = 923 - 989 gal	<50	9.07 - 9.13
Fire-Trol 931 (Canada only)	APP low viscosity	1t = 962 gal	<50	9.00
Fire-Trol 300F	DAP/AS high viscosity	1t = 1250 gal	1,200 - 1,800	9.12

Sources: http://www.fs.fed.us/rm/fire/wfcs/products/index.htm and
http://www.fs.fed.us/rm/fire/retardants/current/laqa/psi.htm
Note: For comparison, approximate viscosities of common liquids are: water: 1 cP, ethylene glycol 15 cP, vegetable oil 40-50 cP, tomato juice 180 cP, maple syrup 400-500 cP, glycerine 650-800 cP, caster oil 1,000 cP, glycerol 1500 cP, honey >2,000 cP, molasses >5,000 cP. 1 cp = 1 mPa.s

The interaction with contamination (particularly soluble Cs-137) and the ability of long-term fire retardants such as Phos-Chek and Fire-Trol to stabilize contamination has not been investigated and represents a technical gap before determining whether such technologies are appropriate for application following a RDD/IND. Additionally, the effect of dose attenuation with retardant thickness should be evaluated. The application of fire retardants in a short timeframe may

only be feasible in States that have such wildfire resources, or where retardants could be flown to the area from other States in a rapid timeframe.

2.3 Specialized Decon Gels, Polymers and Foams

Gels, polymers and coatings have been designed specifically for use in remediating radiological contamination. In some cases, gels and polymer barriers act as permanent isolation, whereas others are designed to permanently encapsulate the contamination. Some coatings are "strippable" such as Bartlett's Stripcoat TLC (US EPA, 2008a), Sherwin Williams Alara 1146 (Archibald et al., 1999a/b), Isotron Corp Orion SC (US EPA 2008b), Pentek 604 (Archibald et al. 1999a/b), Westinghouse WES Strip (NEI, 1996) and DeconGel (US EPA, 2011), designed to peel away to remove contamination. Strippable coatings offer stabilization plus a single solid waste stream. An assessment of strippable coatings was performed by Ebadian (1998). Such materials have been widely demonstrated and proven successful on porous and non-porous surfaces for a variety of contaminants. Recently, Bratskaya et al. (2014) provided evidence of a nanosized selective dust suppression coating containing transition metal ferrocyanides that actively bind Cs in carboxylic latex.

Similarly, specialized foams and chemical treatments for use in decontaminating surfaces containing radiological contamination such as Allen Vanguard's CASCAD and SDF-200 (US EPA, 2013a) and EAI Rad-Release (US EPA, 2013b) have been tested on both horizontal and vertical surfaces. Designed for quick decontamination rather than stabilization for longer periods, such foams are generally accepted to be good and removing surface contamination and even removing sub-surface contamination from porous materials.

Logistically, it may be difficult to obtain and mobilize enough specialized foam, gel or coating depending on the area of outdoor contamination. Shelf-life, cure-time, application lifetime, weathering, and effectiveness for particulate contamination are generally well known for these products and are available from the manufacturers and suppliers.

2.4 Clays and Zeolites

Clay and zeolite materials are well known as strong adsorbers, particularly for Cs-137. Clays are routinely used for stabilizing radioactive and hazardous waste. Lacy (1954) treated a mixed fission product solution with montmorillonite. Biotite, zeolite, heavy clay, sepiolite, kaolinite and bentonite uptake of Cs-137 and other radionuclides have been widely researched and demonstrated by Dyer and Mikhail (1985), Passikallio (1999), Said and Hafez (1999) and Bayulken et al. (2010) for example. The ability of clay to sorb and seal when hydrated has led to their preference as a designed engineered barrier in many nuclear waste disposal concepts. The role of reactive clay barriers in soil for Cs-137 retention and limiting

bioavailability was evaluated by Krumhansl et al. (2000). Some 5,000 tons of boron, dolomite, sand, clay and lead were dropped on to the burning core by helicopter in an effort to extinguish the blaze and limit the release of radioactive particles (World Nuclear http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/). 1,800 tons of sand and clay (World Nuclear http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Chernobyl-Accident---Appendix-1--Sequence-of-Events/). Vovk et al. (1993) and Ahn et al. (1995) demonstrated decontamination of building surfaces (including those in urban areas affected by Chernobyl) using naturally occurring clays from Korea and Ukraine.

Since clays and zeolites have been well demonstrated both in the laboratory and in contaminated areas including Chernobyl, little technical gaps exist. The major questions associated with fielding clays and zeolites as a rapid stabilization technology following a radiological release are whether enough material could be deployed in time and whether radionuclides bound to clay dust could resuspend. Nevertheless, clay should be considered a prime candidate for stabilization, especially since it also serves as a decontamination technology.

2.5 Chloride Salts

Calcium and magnesium chloride salts are widely used for dust control on non-paved roads, hence their availability, rapid deployment and easy of use are preferential. In fact, calcium chloride has been used to treat roads since the 19th century. Both chemicals are hygroscopic, which helps bind dust/particles to the surface. Performance depends on temperature, relative humidity and traffic, with effectiveness generally lasting 6-12 months (Wisconsin Transportation Information Center, 1997 and Han, 1992). Both technologies can well withstand average daily traffic of <250 and offer fair protection above 250 (Han, 1992). Sanders and Addo (1993) report 55% aggregate retention compared to a control for $CaCl_2$ and 77% retention for $MgCl_2$.   Satterfield and Ono (1996) observed a 92% dust reduction using a 26% $MgCl_2$ solution applied during street sweeping (US EPA, 2004). Both salts are highly soluble, so rain will disturb the surface and reduce effectiveness. There are operational issues associated with chloride salt use, including corrosion and the generation of slippery surfaces. Surfaces must be graded well and therefore the technology cannot be applied to sloped roofing or vertical surfaces. Magnesium chloride requires temperatures above 70°F, RH above 32% and more material compared to calcium chloride to be effective, but creates a harder surface (Wisconsin Transportation Information Center, 1997).

A report by the US EPA on the ecological impact of land restoration and cleanup (US EPA) chlorides can be applied to large affected areas using standard agricultural or construction equipment, restricted to areas where there is space for the equipment to be used effectively. In addition, the EPA report notes that chlorides offer intermediate durability lasting between 1 to 5 years. In practice however,

reapplication is needed after rain or after 6 months. Vegetation recovery requires removal of chloride material and the technology is classified as acceptable as an alternative stabilization method for suburban and coastal regions, but a last resort method for agricultural land (US EPA, 1978).

The application of such salts to address radiological contamination is not new; Tawil and Bold (1983) included chloride salts in their guide to radiation fixatives stating that it has been successfully used by the Reynolds Electrical and Engineering Co. (REECo) at the Nevada Test Site to reduce dust and prevent migration of particulate contamination. However, in the urban environments considered for the current evaluation, the aqueous nature of the chloride application may solubilize Cs-137. The high concentration of chloride may depress CsCl solubility, but experiments should be performed to evaluate the effect of $MgCl_2$ and $CaCl_2$ on the mobility of Cs-137 in porous materials. The effectiveness to bind or incorporate Cs-137 (thereby preventing migration or resuspension) has not been investigated and represents a technology gap that should be addressed in determining applicability for RDD and IND response. It is anticipated that dose attenuation will be minimal for chloride salt stabilization. The chloride cake will dissolve under rain, but some researchers have studied additives such as CaO, MgO, sodium silicate (REF Chao Wu et al. 2007), pulverized fly ash (PFA) (Salyak et al., 2008) with successful results. The use of such additives to chloride salts is recommended for future stabilization experiments.

2.6 Dust Wetting Agents

Dust wetting agents were originally developed for coal mine dust suppression, down-mine, on road and prevent loss from pile (Glanville and Wightman, 1979; Glanville and Haley, 1982 and Zeller, 1983). Dust wetting agents are typically surfactants or organic compounds based on alcohols and diols (e.g., propylene glycol) that alter the interaction of particles and surfaces. Dust wetting agents suffer from the same inherent technical problem when considering Cs-137 stabilization, namely the solubility of Cs in the wetting agent and subsequent implications on the management of containment and waste. In the liquid phase, Cs-137 is likely to migrate into porous materials and enter sewer/drainage systems. However, the role of dust wetting agents on the agglomeration of particulates resulting in the encapsulation of Cs-137 has not been investigated. It is assumed that no dose attenuation can be achieved by using dust wetting agents beyond removal of contaminants from the respirable range. Additionally, Instacote provides a wetting agent (CC Wet - http://instacote.com/cc-wet.htm) specifically for stabilizes radiological, beryllium, asbestos and other hazardous contamination, to be applied prior to Instacote CC Fix. A similar product (CC Demo 100 - http://instacote.com/cc-demolition.htm) penetrates rubble and soil to form a penetrating protective layer over contaminated demolition debris and may be useful in providing some level of protection from reaerosolization of contaminants outdoors. However, a potential disadvantage of these two products is availability at

the incident scene in a short period of time in large enough amounts to treat a wide area.

3.0 Summary and Recommendations

The advantages and disadvantages of traditional and non-traditional stabilization technologies have been examined. In some cases, the high water content of some technologies will lead to the dissolution and migration of Cs-137 contamination, likely resulting in remediation that is more difficult, destructive and time-consuming as well as potentially increasing the waste residuals. Examples in this case would be water spraying/misting and fire-fighting foams (which are designed to blanket the fuel of a fire and then collapse/dissipate quickly).

The use of non-traditional radiological stabilization technologies such a fire retardants, wetting agents and chloride salts may provide quicker access on a larger scale than more traditional nuclear-facility designed products such as specialized coatings, foams and gels. While these are water-based, there exists the potential to bind contamination (including soluble Cs-137) to prevent resuspension.

The high viscosity (similar to honey) of some fire retardants such as Fire-Trol and Phos-Chek may be advantageous on non-horizontal surfaces such as roofs and walls, as well as treating agricultural or forest lands, where resuspension from plants/leaves is a concern. Additionally, the thickening agents used in some fire retardants (guar gum and attapulgus clay) are known to bind contaminants, and in the case of clay (which can also be included in fire retardants as a colorant), specifically binding Cs-137 and other radionuclides (Belfiore et al, 1984). Additional information on practical application should be obtained from the US Forest Service or CalFire.

The formation of a chloride cake after applying $CaCl_2$ and/or $MgCl_2$ has been demonstrated to prevent dust resuspension. It is likely that Cs-137 would be trapped under the cake once the cake-layer forms, but the aqueous nature of the chloride spray may dissolve soluble Cs. Additional information is needed to understand the behavior of Cs in the presence of $CaCl_2/MgCl_2$ On porous surfaces. Similarly, the application of wetting agents (e.g., diols) may dissolve Cs-137 contamination, but the agglomeration of particles during the normal use of wetting agents may provide a binding site for Cs-137. Additional information is needed to understand the behavior of Cs-137 particles with wetting agents over time.

To evaluate the effectiveness of such non-traditional technologies, laboratory and field tests are required to address technical knowledge gaps. The following evaluations are proposed:

- Fire Retardants
  - Laboratory-scale sorption of Cs-137 to high viscosity fire retardants containing clay and guar gum;
  - Laboratory-scale dose attenuation of Cs-137 through high viscosity retardants studying the effect of thickness;
  - Field-scale time-phased evaluation of retardant effectiveness for reducing particulates mimicking contamination by natural weathering and traffic; and
  - Evaluation of impacts to decontamination and waste management.

- Chlorides
  - Laboratory-scale sorption changes on coupons contaminated with Cs-137 using chloride salt deposits, specifically examining the role of high chloride concentration on the depression of CsCl solubility
  - Field-scale time-phased evaluation of chloride effectiveness for reducing particulates mimicking contamination by natural weathering and traffic

- Wetting Agents
  - Laboratory-scale sorption changes on coupons contaminated with Cs-137 using wetting agents
  - Field-scale time-phased evaluation of retardant effectiveness for reducing particulates mimicking contamination by natural weathering and traffic.

A Quality Assurance Project Plan (QAPP) will be written to define the quality objectives and parameters necessary to perform laboratory and field-scale testing to address these technology gaps.

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