

# **Environmental Effects of Radio Frequency (RF) Chaff Released during Military Training Exercises: A Review of the Literature**



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## Executive Summary

Chaff is a radiofrequency countermeasure released by military aircraft (ships and ground vehicles) to confuse enemy radar. As with most acquired skills, the effective use of chaff can be maintained only by practicing in-flight deployments during training issues. The release of chaff into the environment during these exercises has raised concerns among both public-interest groups and the government regarding the fate and environmental impact of chaff particles.

A review of the available literature has shown that chaff is generally resistant to chemical weathering (much like naturally occurring aluminosilicate minerals) and probably remains in the environment for long periods of time; i.e., at least on the order of years. However, chaff recovery studies conducted within chaff release areas within several U.S. military operating areas (MOAs) have shown that the concentrations of chaff dipoles (fibers) in the environment are very small. Consequently, even though chaff dipoles contain aluminum and other trace metals that can ultimately be leached from the chaff, the amount of chaff needed to raise environmental concentrations of these metals above background levels far exceeds the number than can be realistically deposited in a given area of land or body of water. As such, chaff releases are not expected to have any significant effect on ecosystem functioning in either terrestrial or aquatic environments.

From the limited data available, it appears that chaff dipoles remain intact after deployment. And, because they are too large to be inhaled by humans or livestock, it is unlikely that exposure to airborne chaff will result in respiratory dysfunction. However, additional data is necessary to better define the extent to which chaff breaks up during deployment and whether it can be reduced to respirable sizes ( $PM_{10}$  or  $PM_{2.5}$ ) during weathering in the environment. Likewise, because there is no data on the effects of respirable chaff particulates on lung tissue, Hullar et al. (1999) suggested that additional studies be conducted to provide the type and quality of information required to better determine the risks associated with human exposure to chaff. Given the extremely low concentrations of chaff encountered in the environment, there is only a remote possibility that chaff could be ingested by humans, livestock, or wildlife—thus, health hazards associated with this exposure pathway are deemed to be negligible.

There is some speculation that the ingestion of large quantities of chaff could harm waterfowl, though there are no data to support this hypothesis. Furthermore, toxicity tests using a variety of marine organisms demonstrated that exposure to environmentally relevant concentrations of chaff produced no significant adverse effects. Likewise, it was reported that 25 years of chaff operations at Chesapeake Bay, Maryland, failed to produce a significant increase in total-, inorganic-, or organic-Al concentrations in sediments or soils collected from directly under the chaff release area (and compared to samples collected upwind of the release area).

In summary, the overwhelming majority of the available data indicate that it is highly unlikely

that chaff releases during training exercises will have a significant adverse impact on either ecosystem functioning or human and wildlife health within the Goose Bay Military Training Area.

## **Introduction**

Radio frequency (RF) chaff is an electronic, defensive countermeasure designed to reflect radar waves and, thus, obscure aircraft (ships and other military equipment) from radar-tracking sources. The chaff packets are ejected from an aircraft in cartridges or projectiles that contain millions of individual fibers. Once released into the aircraft slipstream, the chaff packages burst open and a diffuse cloud of dipoles is formed to produce a radar-reflective cloud called a “chaff corridor”. Each chaff package is designed to simulate an aircraft. Several aircraft can create a chaff curtain, consisting of thousands of false targets, which confuse the radar guidance package on a missile so they are unable to locate the real targets within the chaff cloud.

The chaff then falls to the earth at a settling velocity of approximately 30 cm per second. Atmospheric residence times range from 10 minutes for the majority of chaff released at 100 m to approximately 10 hours for chaff released at 10,000 feet. Thus, depending on prevailing atmospheric conditions, chaff particles can travel a considerable distance from their release point (Hullar et al., 1999). Not surprisingly, therefore, concerns regarding the impact of chaff releases on the environment have been raised by individuals and both public and government agencies during the 50+ years that RF chaff has been employed in training exercises by U.S. and NATO forces.

In response to these concerns, the U.S. Department of Defense (DOD) has either sponsored or conducted research to address a number of chaff-related issues (Hullar et al., 1999; USAF, 1997; Cataldo et al., 1992; Haley & Kurnas, 1992; National Guard Bureau, 1990, USAF, 1978; Systems Consultants, 1977). Most of these studies, however, were not peer-reviewed for scientific content, did not address issues associated with “cold climate” sites (such as Goose Bay), and are not easily accessible to the public. Hence, concerns regarding the environmental impact of chaff releases continue to this day.

In Canada, the use of chaff in training is currently restricted to designated areas within the confines of the Cold Lake Air Weapons Range (CLAWR) in Alberta. However, due to changing needs, NATO forces training at the Goose Bay Military Training Area (GBMTA) in Labrador are expected to request permission to incorporate defensive countermeasures (i.e., RF chaff) into future pilot training programs. Indeed, to effectively deploy this electronic countermeasure, training in the use of chaff is considered to be an essential component of pilot training. It is assumed that there will be *ca.* 5,000 training sorties per year (for the short-term future), and that about half of these sorties will include the use of RR-188 training chaff. Thus, assuming that each sortie releases 30 bundles of chaff and that the average weight of a chaff in a bundle is 95-g, the release of chaff fibers into the environment will total 7.12 tones per year. Furthermore, by

assuming that chaff deposition will be confined to the “practice target area” (PTA; with an area of *ca.* 2,000 km<sup>2</sup>) it is estimated that this will result in a chaff deposition rate of 3.56 kg km<sup>-2</sup> yr<sup>-1</sup>.

Issues associated with the release of chaff fibers into the Canadian, and more specifically, the Labrador environment mirror those associated with its use in the United States. Thus, what follows is a brief summary and assessment of the available information regarding the persistence and fate of chaff fibers in the environment and the impact of chaff releases on human and wildlife health. In addition, computer modeling was used to estimate the environmental partitioning of chaff components in the environment under conditions characteristic of Labrador.

## **Environmental Issues**

Once deployed, chaff fibers remain suspended in the atmosphere for a period of time, raising issues regarding air quality, safety from unintended interference with FAA or other radar systems, risks to other aircraft engines, and impacts on birds and bats. The time the chaff remains airborne depends on the combination of local meteorological conditions and the altitude of deployment. Eventually, however, the chaff settles to the earth’s surface where it may be deposited on land or water.

Issues associated with chaff deposited on land focus primarily on the chemical and physical impacts of chaff on soil functioning and human and wildlife health. Chemical impacts are related to the basic toxicity of chaff and its constituent materials. The impact of chaff deposited on water depend in part on whether the water body is an ocean or an inland water body, and then on whether it is enclosed (i.e., a lake or pond) or a running stream or river. Again, the primary areas of concern revolve around chemical and physical effects.

## **Chaff Composition**

RF chaff was first used as a radar countermeasure in December 1943 by U.S. bombers flying over Bremen, Germany (USGAO, 1998). At that time, the chaff consisted of solid pieces of aluminum (of a non-specific size) that were dropped or tossed from the bombers. Since then, chaff technology has evolved considerably and modern chaff is composed of very thin glass monofilaments coated with an even thinner layer of metallic aluminum. Modern RF chaff is made as small and light as possible, so as to remain airborne long enough to confuse enemy radar, and the chaff fibers are cut to one-half the wavelength of specified radar bands<sup>1</sup>. Moreover, whereas lead was used to add weight to the chaff in early versions, this metal is no longer incorporated into chaff (USGAO, 1998, USAF, 1997).

Today’s chaff is made of type E glass fibers coated with a 3- $\mu$ m layer of high-purity (>99%)

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<sup>1</sup>Chaff used for training purposes (e.g., RR-188 training chaff) consists of fibers 1.8-cm in length. This chaff reflects the *I*-band frequency only and, hence, does not interfere with Federal Aviation Administration (FAA) radar.

aluminum, which provides the fiber with its radar reflective properties. The chaff fibers are about the thickness of a human hair (*ca.* 25 $\mu$ m in diameter) and range in length from about 0.8 to 7.5 cm. The fibers are ~60% silicate glass and ~40% aluminum, and contain trace amounts (< 1%) of silicon, iron, copper, manganese, magnesium, zinc, vanadium, and titanium (Table 1). In addition, the fibers are coated with a lipid [either stearic acid or *Neofat 18*, a 90:10 (w/w) mixture of stearic and palmitic acids] which acts as a lubricant to prevent clumping during deployment.

**Table 1. Composition of RR-188 chaff\***

Component	Chemical symbol	Percent (w:w)
----- Silica core -----		
Silica dioxide	SiO <sub>2</sub>	52–56
Aluminum oxide	Al <sub>2</sub> O <sub>3</sub>	12–16
Calcium + Magnesium oxide	CaO & MgO	16–25
Boron oxide	B <sub>2</sub> O <sub>3</sub>	8–13
Sodium + Potassium oxide	Na <sub>2</sub> O & K <sub>2</sub> O	1–4
Iron oxide	Fe <sub>2</sub> O <sub>3</sub>	≤1
----- Aluminum coating -----		
Aluminum	Al	99.45 <sup>†</sup>
Silicon & Iron	Si & Fe	0.55 <sup>‡</sup>
Copper	Cu	0.05 <sup>‡</sup>
Manganese	Mn	0.05 <sup>‡</sup>
Magnesium	Mg	0.05 <sup>‡</sup>
Zinc	Zn	0.05 <sup>‡</sup>
Vanadium	V	0.05 <sup>‡</sup>
Titanium	Ti	0.03 <sup>‡</sup>
Miscellaneous trace elements	---	0.03 <sup>‡</sup>
----- Neofat coating -----		
Stearic acid	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>16</sub> COOH	90
Palmitic acid	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>14</sub> COOH	10

\* USAF (1997).

<sup>†</sup> Minimum allowable concentration.

<sup>‡</sup> Maximum allowable concentration.

Chaff fibers are dispensed in cartridges or projectiles, thus some “chaff debris” also is released into the environment during deployment. This debris typically consists of paper, cardboard, and assorted styrene plastic caps, pistons and miscellaneous parts. Although this debris can have a nuisance effect, particularly in areas where ground cover is sparse, its release is not considered a safety issue. That is, under normal circumstances, the weight of the debris is so little or they create so much drag in comparison to their weight that “no injury would be anticipated even if a person were impacted” (USAF, 1997). Indeed, there has never been a recorded instance of an

injury from falling chaff debris. Moreover, the U.S. Air Force also estimated that the probability of a person on the ground being hit by an unopened box of non-pyrotechnic chaff is between 1:63,000 and 1:185,000 (USAF, 1997).

## **Deposition and Distribution of Chaff in the Environment**

In their report “*Environmental Effects of RF Chaff: A Select Panel Report to the Undersecretary of Defense for Environmental Security*”, Hullar et al. (1999) estimated that the yearly distribution of chaff in the U.S. (based on 1996–1997 amounts and averaged over all MOAs<sup>2</sup>) is *ca.* 0.010 kg km<sup>-2</sup> yr<sup>-1</sup> (or 1.0 g ha<sup>-1</sup> yr<sup>-1</sup>). Estimates also were generated for one “high” chaff use (Fallon Navel Air Station, Nevada) and one “low” chaff use (Patuxent Navel Air Station, Maryland) MOA. Chaff use at the Fallon NAS in 1997-1998 totaled 5,964 kg dispersed over an estimated area of 16,093 km<sup>2</sup>—yielding a distribution rate of 0.37 kg km<sup>-2</sup> yr<sup>-1</sup> (or 3.7 g ha<sup>-1</sup> yr<sup>-1</sup>). During the same period, chaff use at the Patuxent NAS totaled 136 kg dispersed over an estimated area of 3,862 km<sup>2</sup>—yielding a distribution rate of 0.035 kg km<sup>-2</sup> yr<sup>-1</sup> (or 0.35 g ha<sup>-1</sup> yr<sup>-1</sup>). In all cases, these estimates assume that all chaff released during training exercises landed within the respective MOAs and, thus, should be considered worst-case (upper limit) scenarios.

**Chaff in terrestrial environments:** Despite the relatively long history of chaff usage at training facilities (or MOAs, military operating areas) in the United States, there is only a very limited amount of data on the actual amounts of chaff present in the environment. During the early 1990s, surveys were conducted at Nellis AFB in Nevada and the Townsend Air to Ground Gunnery Range (AGGR) in Georgia. These sites were chosen as representative of arid (Nevada) and temperate (Georgia) environments and because they were considered to be “high chaff use” sites (USAF, 1997; 1994).

Glass fiber chaff was found in 54 of 75 soil samples (10-cm × 10-cm × 2-cm) collected from within the training range at Nellis AFB, but was recovered from only three of 28 samples collected outside the training range—but still within the Nellis MOA. Chaff fiber concentrations in the soil ranged from 0.02 to 251 mg of dipoles kg<sup>-1</sup> soil, with most of the samples containing <0.5 mg of dipoles kg<sup>-1</sup> soil. At the Townsend AGGR, glass fiber chaff was recovered from only six of 96 soil samples—with chaff concentrations ranging from 0.03 to 0.9 mg of dipoles kg<sup>-1</sup> soil.

Microscopic analysis of a subset of samples from each site indicated that weathering of the chaff fibers was greatest in the “temperate” environment characteristic of the Townsend site. That is, four of the five samples examined showed evidence of weathering—including extensive surface pitting and dissolution of the aluminum coating. Although the silica core of the fibers was exposed in some places, there was no evidence to suggest weathering of the core itself. Chaff fibers from three of the five Nellis samples examined exhibited some surface alteration—namely a

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<sup>2</sup> Assumes that the U.S. Air Force and Navy are responsible for all chaff releases and that these releases are confined to MOAs, which encompass about 4.345 million km<sup>2</sup>.

roughening of the surface—though exposure of the silica core was rare. This irregular surface morphology of the fibers was thought to result from the partial dissolution of the aluminum coating and subsequent formation of aluminum oxyhydroxides, sulfates and carbonates on the surface of the fibers.

Analysis of chaff fibers exposed to synthetic seawater and aqueous solutions at pH 4, 7, and 10 also were conducted, and were found to be consistent with the field results. That is, samples exposed at pH 4 (similar to that of the soils at the Townsend AGGR) exhibited extensive pitting of the aluminum coating—a result consistent with those observed for chaff samples recovered at the Townsend site. Likewise, chaff fibers exposed to solutions at pH 10 exhibited partial dissolution of the aluminum coating and the formation of crystals on the coating. These crystals were thought to be synthetic gibbsite or bayerite [ $\text{Al}(\text{OH})_3$  polymorphs]. This assumption was supported by the work of Hsu (1989), who demonstrated the formation of gibbsite in solutions with OH:Al ratios  $> 3:1$ .

**Chaff in aquatic environments:** Aquatic environments are potentially more sensitive to chemicals released from chaff than are terrestrial environments. This reflects the fact that (i) the dissolution of materials is faster in water than on land, (ii) the released chemicals are more mobile and more bioavailable in aquatic ecosystems, and (iii) toxicity thresholds are generally lower for sensitive aquatic organisms. Wilson et al. (as cited in Arfsten et al., 2002) reported that 25 years of chaff operations at Chesapeake Bay, Maryland, did not result in a significant increase in total-, inorganic-, or organic-Al concentrations in sediments or soils collected from directly under the chaff release area and compared to samples collected 3.7 km upwind of the release area. The data also indicated that differences in Al concentration were not being masked by ion sequestration. Although plant analyses were not conducted, the authors postulated that because Al partitioning between aquatic macrophytes and the environment occurs at a 1:1 ratio (Jackson, 1998), plants from the chaff release area would not be expected to accumulate Al at concentrations greater than those found in plants growing outside the release area.

In a report prepared by Systems Consultants, Inc. (1977) it was reported that direct exposure of six marine organisms from Chesapeake Bay to chaff fibers had no significant impact on the mortality of any of the species. Blue crab (*Callinectes sapidus*), menhaden (*Brevoortia tyrannus*), and killfish (*Fundulus heteroclitus*) were force fed whole and broken fibers for several weeks at concentrations up to 1000-times greater than those in the Bay itself<sup>3</sup>, with no effect. Oyster larvae (*Crassostrea virginica*) exposed at 10- and 100-times the environmental exposure showed no effect, though there was a small decrease in the size of 10-day-old larvae at 1000-times the environmental exposure. The polychaete worm (*Nereis succinea*) was exposed to chaff at 10-times the environmental exposure with no effect.

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<sup>3</sup>Calculated environmental exposure rates were estimated as being equivalent to the amount of chaff present following a single release event (i.e., a surface exposure of 0.042 g of dipoles  $\text{m}^{-2}$ ).

**Chaff and air quality:** Intact chaff fibers are not considered to pose an inhalation risk to humans (Arfsten et al., 2001). That is, typically, only particles less than 10  $\mu\text{m}$  in diameter ( $\text{PM}_{10}$ ) or 2.5  $\mu\text{m}$  in diameter ( $\text{PM}_{2.5}$ ) are considered hazardous because they can enter into mammalian airways where they may pose a toxic or abrasive risk. However, chaff fibers have a relatively large diameter relative to other air contaminants and, thus, are not expected to contribute significantly to  $\text{PM}_{10}$  or  $\text{PM}_{2.5}$  emissions. Indeed, previous chaff reviews (Hullar et al., 1999; USAF, 1997) have explicitly considered this point and found that post-deployment chaff is normally not of this particle size and is thus unlikely to have a significant negative impact on air quality.

Hullar et al. (1999) also estimated that if all the chaff released over Fallon NAS (a “high” chaff use area located in Churchill County, NV) abraded to a size of 10- $\mu\text{m}$ , this would constitute only about 0.05% of “normal” background releases of  $\text{PM}_{10}$  (Figure 1). Similarly, if all the chaff abraded to a 2.5- $\mu\text{m}$  size it would constitute only about 0.25% of “normal”  $\text{PM}_{2.5}$  releases (Figure 2). This is supported by preliminary data from a U.S. Navy sponsored study at Fallon NAS, which indicate that chaff plumes contribute <0.5% of the total  $\text{PM}_{10}$  at ground level in the training range (Arfsten et al., 2002). Under similar conditions, however we would expect that these upper-bound calculations are an underestimation of the overall contribution of chaff fibers to atmospheric particulate concentrations in areas such as Goose Bay. That is, the largest contributors to  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  (from largest to smallest) are: unpaved road dust, wind erosion dust, crop dust, construction dust, paved road dust, managed burning, ‘other dust’, industrial processes, fuel combustion and non-road engine exhaust. Thus, in areas such as Goose Bay, which is more isolated, ambient particulate matter concentrations are presumably lower and the overall contribution of chaff may be higher than that estimated by Hullar et al. (1999). Indeed, this is not an unrealistic conclusion, given the relatively high chaff release rate ( $3.56 \text{ kg km}^{-2} \text{ yr}^{-1}$ ) anticipated at the Goose Bay LLTA. Nevertheless, the contribution of chaff to small particulate matter in the atmosphere is considered to be negligible and even the “worst-case” scenario-based on the assumptions that all the chaff remains within the LLTA and abrades to  $\text{PM}_{10}$  or  $\text{PM}_{2.5}$ —is unlikely to result in a significant deterioration of air quality in the Goose Bay area.

### **Toxicity of Chaff and its Constituents**

Based on a review of numerous toxicological studies, Hullar et al. (1999) concluded that the primary constituents of chaff (aluminum, silica glass, and stearic acid) will have no “adverse impact (on) human and environmental health”. This conclusion was based on the general toxicity of the components, dispersion patterns, deposition rates, and the unlikely occurrence of synergistic toxic effects resulting from interactions between chaff components and naturally occurring substances in the environment. The primary source of this toxicological data was the comprehensive *TOMES* database established and maintained by the U.S. EPA.



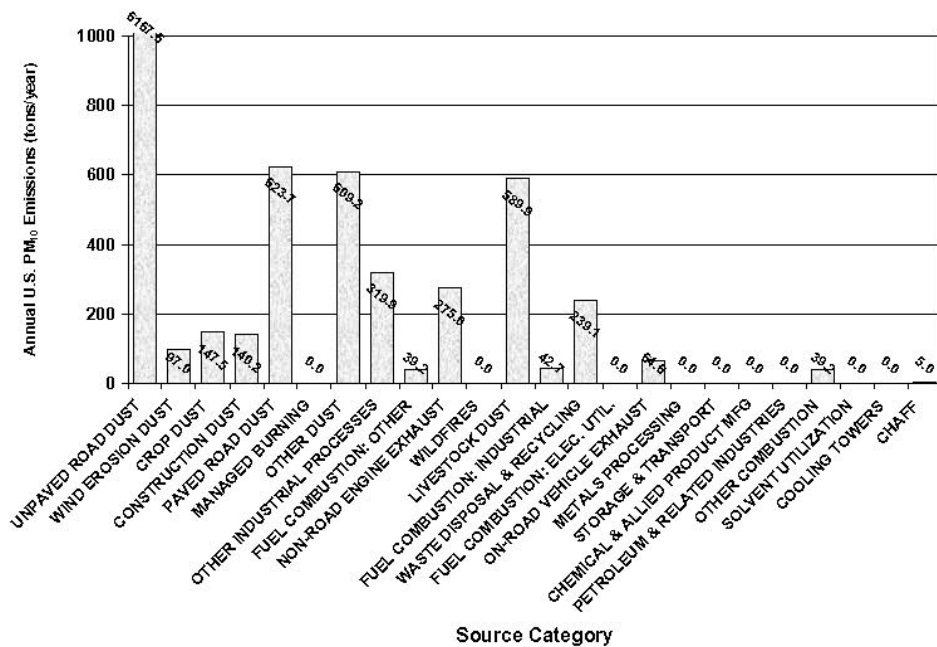


Figure 1. PM<sub>10</sub> emission estimates for 1997 in Churchill County, Nevada. Data from USEPA (1998); figure adapted from Hullar et al. (1999).

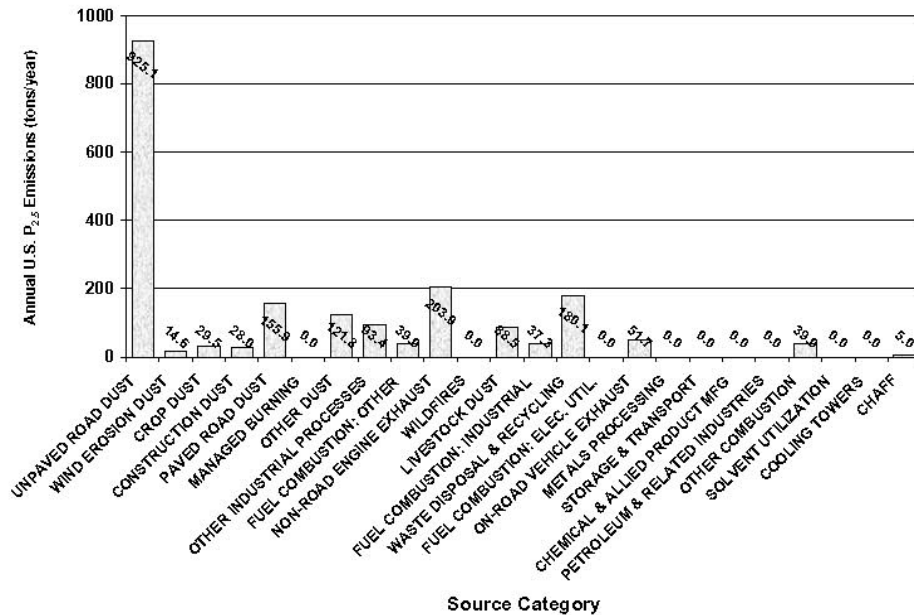


Figure 2. PM<sub>10</sub> emission estimates for 1997 in Churchill County, Nevada. Data from USEPA (1998); figure adapted from Hullar et al. (1999).

## **Environmental Fate of Chaff (a review of the literature)**

The primary elements of concern with chaff entering the environment are: aluminum, magnesium, copper, manganese, titanium, vanadium, zinc, boron, and silicon. The geochemical significance of chaff fibers deposited in the environment following aerial deployment are generally not thought to be important (Hullar et al., 1999). For example, windblown dusts typically contain 50–60% SiO<sub>2</sub> (Pye, 1987), which is similar to that of the Type E fiberglass used to produce RF chaffs. As well, the amounts of these elements introduced into the environment as chaff fibers are in the range of 375 to 10,000 times lower than annual depositions from other natural and anthropogenic sources. Similarly, the contribution of chaff to background ultrafine particulate emissions is negligible, ranging from 0.036 to 0.061 µg m<sup>-3</sup> which is far below the background levels of 6.4 to 20 µg m<sup>-3</sup> observed in the continental U.S. (Once again, these atmospheric impact calculations assume that all chaff will degrade to ultrafine particles, which is a very conservative assumption.)

The impact of chaff on humans is generally thought to be negligible, largely because several epidemiological studies comparing lung pathologies in workers at factories producing fibrous glass or vitreous fibers to those in comparable control (non-exposed) groups of workers found no evidence that the exposed workers had a significant increase in lung diseases (Hullar et al., 1999). The authors chose glass and man made vitreous fibers as surrogates for chaff because of the similarity between these substances. The authors also considered risk from exposure to aluminum (the primary element found in chaff) and concluded that the likelihood of harmful exposure is extremely small.

Unlike the inhalation route of exposure, ingestion of chaff is a likely route of exposure for animals living in areas impacted by chaff releases. The predominant metal in chaff is aluminum, which has a maximum tolerable level in cattle and sheep feed of 1000 mg kg<sup>-1</sup>. Similar research on non-ruminants such as turkeys and chicks suggested 200 mg kg<sup>-1</sup> as the maximum tolerable level. Aluminum will likely only be bioaccessible for uptake if the pH of the stomach is below 5. The authors concluded that, because rumen pH rarely drops below 5 and because transit through the hindgut and abomasum (where the pH is <5) is relatively rapid, little of the aluminum in chaff will become bioaccessible. The authors of the *Select Panel Report* (Hullar et al., 1999) did note that chaff fibers may have the potential to form ‘hair-balls’ inside the digestive track, but did not consider it a problem as this typically occurs in ruminants in any case. Negative effects of aluminum on ruminants would not be expected to occur at below ingestion rates of 11-g per day. The authors concluded that since worst-case exposure rates estimated an exposure of only 0.066 g of aluminum per day, that it was unlikely that livestock would be negatively effected by chaff deposition. It also was concluded that physical exposure to chaff particles was unlikely to cause damage to the gut mucosa—this conclusion was based on the results of two studies in which chaff

was fed to livestock and no physical damage to the mucosa was observed (CDA, 1972; USAF, 1978).

As indicated in the previous section, analysis of the risk of chaff fibers to aquatic organisms found that there were no observed effects on freshwater fleas, blue crabs, menhaden and killifish, oysters and polychaetes at elevated doses of chaff. Furthermore, if one considers that chaff like particles (e.g., sponge spicules) are normally found in freshwater and marine systems, it was concluded that there is no evidence—and no reason to believe—that aquatic ecosystems will be harmed by chaff deposition (Systems Consultants, 1972).

Although the ingestion of chaff may represent a potential hazard to waterfowl feeding/nesting in aquatic ecosystems impacted by chaff (USAF, 1997), there have been no peer-reviewed studies examining either this possibility, or the impact of chaff on wildlife in general. However, during the chaff recovery surveys conducted at Nellis AFB and the Townsend AGGR, animal abundance and nesting activities in the survey area were considered normal (USAF, 1997)—prompting the authors to conclude that chaff interference with wildlife activities was expected to be negligible.

Whereas it can be concluded from the existing literature that there is little risk from chaff as it is currently used, there is no data on the re-suspension of chaff fibers and little is known about the breakdown of chaff under relevant conditions. Thus, to address these and other gaps in our knowledge, Hullar et al. (1999) recommended in the *Select Panel Report* that seven questions be addressed:

1. What fraction of emitted chaff breaks up in atmospheric turbulence into inhalable particles?
2. How much chaff is abraded and resuspended after it is deposited on a surface?
3. What are the shapes of chaff particles after abrasion?
4. What is the empirical terminal deposition velocity of chaff?
5. What is the spatial distribution of chaff clouds under different release and meteorological conditions?
6. How do chaff emissions and expected concentrations compare to emissions and concentration from other particle emitters over the time periods and areas where chaff is released?
7. What quantities of inhalable chaff are found in communities near training facilities where chaff is released.

These questions are designed to address the primary risk from chaff release, inhalation and exposure to fibers. The composition of the fibers themselves does not pose a hazard but exposure either oral or inhalatory to small fibrous particles could potentially pose a risk to an exposed

population. There is currently no information on the long term fate and atmospheric fate of chaff in regard to it's physical attributes.

### **Environmental Fate of Chaff (modeling of the Labrador environment)**

Because virtually all of the available data regarding the fate of RF chaff comes from areas where the climate and general environment are quite different from that of Labrador, we modeled the environmental partitioning of the component elements of chaff using the ChemCAN Level III Fugacity Model of Regional Fate of Chemicals Version 6.0 © Trent University 2003 (Webster et al., *In press*). The geographical region chosen was that of Labrador, but with user defined properties of a reduced surface area (2,000 km<sup>2</sup>) and no coastal water. All the evaluated compounds fit the Type 2 profile with little or no vapor pressure and thus equivalent concentrations (Mackay, 2001).

Our approach in this section was to assume that all material in the chaff enters the PTA ecosystem and then assess the steady state concentrations of these compounds in the PTA system. This information was then compared against regional background values when available and published toxicity thresholds.

Compound properties were calculated with EPI (Estimation Programs Interface) Suite version 3.11© EPA. This program suite was developed by the EPA's Office of Pollution Prevention Toxics and Syracuse Research Corporation and contains:

AOPWIN	– estimates atmospheric oxidation rates,
BCFWIN	– estimates bioconcentration factors,
BIOWIN	– estimates biodegradation probability,
ECOSAR	– estimates aquatic toxicity,
HENRYWIN	– estimates Henry's law constant,
HYDROWIN	– estimates aqueous hydrolysis rates
KOWWIN	– estimates octanol-water partition coefficients
MPBPWIN	– estimates melting point, boil point and vapor pressure,
PCDOCWIN	– estimates soil sorption coefficient, and
WSKOWWIN	– estimates water solubility.

In our case, we used PCDOCWIN to estimate soil sorption coefficients and used this same value for water-sediment, water-suspended particles coefficients. The fish-water partitioning coefficient was estimated using BCFWIN. The aerosol-water and air-water coefficients were set to a default value of 0.0001 since there is effectively no partitioning for the compounds under consideration. The reaction half lives were set at negligible for the air reactions and for the remaining environmental compartments were the half lives provided by the Fugacity Level III model output included in EPI Suite.

Emission amounts were calculated by assuming 2,500 flights dropping 30 bundles with each bundle having an average weight of 0.095 kg for a total yearly input of 7,125 kg of chaff. Using data from Table 1, we assigned the glass fibers a composition of 56% (w/w) silica dioxide, 16% aluminum oxide and 2% potassium oxide. In addition, 40% of chaff weight is the aluminum coating comprised of 99.45% aluminum; for modeling purposes, we assumed that the aluminum in this coating would be present in the environment as aluminum oxide. We used results from ICP-MS analysis of RR-188 chaff fibers (conducted in-house) for the remaining elements and ranked these elements in terms of the amount released (Table 2).

Background concentrations for these elements in the PTA were not available, thus global averages were used wherever possible. It should be noted that for many elements, the models predict a decrease from the background inflow. This is the result of the model assuming that there are no elements already present in the sediments or soils and thus, these newly deposited elements will partition into these compartments. We also performed a third calculation assuming that there is no element in solution, which provided us with an estimate of the relative increase in environmental concentrations we could expect due to chaff deposition.

We then compared the estimated exposure values to aquatic toxicity reference values. Sediment toxicity reference values are in the mg/kg range (Division, 1999) which is significantly greater than the levels predicted for all elements except silica dioxide, which in any case is a major component of the soil itself. Thus, sediment toxicity reference values are not included in the discussion.

Aluminum oxide is the most prevalent compound in the chaff material with 40% (w/w) of the chaff being aluminum and 16% of the glass fibers being aluminum oxide. This corresponds to a yearly input of 5,357 kg of aluminum oxide in the PTA. In all environmental compartments, aluminum oxide concentrations are expected to be minimal, only  $79 \mu\text{g L}^{-1}$  in the water,  $1.4 \text{ ng g}^{-1}$  in the soil and  $0.62 \text{ ng g}^{-1}$  in the sediment with an average background concentration of  $2250 \mu\text{g L}^{-1}$  in the incoming surface water. With zero background inflows, chaff deposition is expected to only increase aluminum concentrations in water by  $8.7 \text{ ng L}^{-1}$ . Given that the aquatic reference toxicity value for aluminum in water is  $87 \mu\text{g L}^{-1}$  (Division, 1999), which is 10% higher than the worst case analysis, there is relatively little risk due to aluminum toxicity in the waters of the PTA. It should be noted that this worst-case analysis actually predicts a decrease in water aluminum concentrations because the inflowing water was assumed to be at  $2,250 \mu\text{g L}^{-1}$ . A more realistic assessment is that chaff deposition will increase the amount of aluminum in water by 0.01% of the value thought to be protective for aquatic organisms. Similarly, the increase in soil is  $1.4 \text{ ng g}^{-1}$  and soils typically contain  $71 \text{ g kg}^{-1}$  (Sparks, 2003), which is ten million times more than that deposited.

The second most prevalent deposited element is silica dioxide, which is the major component (56% w/w) of the glass core of the fibers and is deposited at 3,630 kg per year. Silica is a major

component of surface waters, ranging between 5 and 100 mg L<sup>-1</sup> (Sparks, 2003). Using these limits for inflow into the PTA one can see that there is a negligible increase in environmental silica levels (Table 2). Even assuming no background inflows, there is only an increase of 5.8 ng L<sup>-1</sup> in the surface water the PTA, or a 0.001% increase in silica levels if the waters of the PTA are exceptionally low in silica dioxide, 5 mg L<sup>-1</sup>.

Approximately 130 kg of potassium oxide will be deposited each year into the PTA because of its prevalence in the glass fibers, 2% (w/w). Assuming no background inflows results in a net increase of 0.22 ng L<sup>-1</sup> in the surface waters or less than one millionth of a typical background concentration, whereas assuming a 10 mg L<sup>-1</sup> background inflow results in a concentration of 0.35 mg L<sup>-1</sup> in the PTA. Similarly, 10.8 kg of Fe will be deposited in the PTA each year. Assuming that this is iron oxide, and there is no iron oxide in the inflow waters, there will be a 0.016 ng L<sup>-1</sup> increase or 0.00016% of background.

**Table 2. Estimated Elemental Deposition onto the PTA.**

<b>Compound</b>	<b>Content</b>	<b>Amount Release (kg)</b>
Aluminum coating	40% (w:w)	4320
Silicate glass	60% (w:w)	6480
Al <sub>2</sub> O <sub>3</sub>	16% (w:w)	1036.8
SiO <sub>2</sub>	56% (w:w)	3628.8
K <sub>2</sub> O	2% (w:w)	129.6

<b>Trace Elements*</b>	<b>Concentration (ppm)</b>	<b>Total Release (kg)</b>
Fe	995	10.75
B	162	1.75
Zn	50.44	0.54
Ti	47	0.51
Zr	32.20	0.35
V	19.69	0.21
Mn	14	0.15
Ni	5.85	0.06
Cu	4.17	0.04
Pb	3.82	0.04
Ba	1.98	0.02
Ce	1.39	0.01
Mo	1.06	0.01
Ca	1.00	0.01
Sr	0.89	0.01
Sn	0.86	0.01
As	0.73	0.01
Y	0.72	0.01
Hf	0.67	0.01
Sb	0.62	0.01
Nd	0.56	0.01
La	0.51	0.01
Th	0.46	0.00
U	0.41	0.00
Co	0.26	0.00
Gd	0.18	0.00
Nb	0.16	0.00
Pr	0.15	0.00
Sm	0.14	0.00
Dy	0.13	0.00
Ag	0.11	0.00
Ta	0.09	0.00
W	0.09	0.00
Er	0.08	0.00
Tl	0.08	0.00
Yb	0.07	0.00
Rb	0.07	0.00
Eu	0.03	0.00
Ho	0.02	0.00
Tm	0.01	0.00
Lu	0.01	0.00
Tb	0.01	0.00
Sc	0.01	0.00
Cd	0.01	0.00

\* Based on ICP-MS analysis of triplicate sub-samples of RR-188 chaff fibers. Analyses were conducted at the University of Saskatchewan.

**Table 3. Estimated environmental concentrations of chaff compounds deposited at greater than 1 kg per year in the PTA**

Compound	Background Inflows (ng/L)	Water (ng/L)	Soil (ng/g)	Sediment (ng/g)
Al <sub>2</sub> O <sub>3</sub>	2250000*	79433	1.39	562
1344-28-1	12000*	432	1.39	3.06
SiO <sub>2</sub>	100 × 10 <sup>6</sup> †	3.53 × 10 <sup>6</sup>	0.879	457300
7631-86-9	5 × 10 <sup>6</sup> †	1.77 × 10 <sup>5</sup>	0.879	2287
K <sub>2</sub> O	10 × 10 <sup>6</sup> †	3.54 × 10 <sup>5</sup>	0.031	3324
12136-45-7	1 × 10 <sup>6</sup> †	3.54 × 10 <sup>4</sup>	0.0311	332
FeO	1 × 10 <sup>6</sup> †	3.53 × 10 <sup>5</sup>	2.64 × 10 <sup>-3</sup>	7915
1309-37-1	0.01 × 10 <sup>6</sup> †	353	2.64 × 10 <sup>-3</sup>	7.92
B <sub>2</sub> O <sub>3</sub>	1 × 10 <sup>6</sup> †	35337	4.26 × 10 <sup>-4</sup>	562
1303-86-2	20 × 10 <sup>3</sup> †	707	4.26 × 10 <sup>-4</sup>	11.2

\* From: Jones & Bennett (1986).

† From: Sparks (2003).

Each year, 1.75 kg of boron will be deposited on the PTA. Assuming that this is boric oxide, and there are no background inflows, there will be approximately 2.7 µg L<sup>-1</sup> increase in the surface water concentration. Worst case scenario, assuming a background inflow of 1000 µg L<sup>-1</sup> results in a water concentration of 35 which compares favorably to the toxicity reference value of 750 µg L<sup>-1</sup> (Division, 1999).

There are a variety of compounds such as zinc, zirconium, vanadium and manganese that are deposited at rates varying between 0.54 and 0.15 kg yr<sup>-1</sup>. The deposition of these compounds results in an increase in the surface concentration of approximately 1 µg L<sup>-1</sup>. The toxicity reference values for these compounds are 120, 17, 20 and 120 µg L<sup>-1</sup> (Division, 1999), respectively. Thus, the deposition of these trace elements into the PTA will result in a cumulative increase in the concentration of these elements of approximately 0.0001%. The likely increase in risk is negligible. Similarly, other trace elements in chaff are present at even lower concentrations and those elements also have toxicity reference values greater than 0.5 µg L<sup>-1</sup> which results in a similar 0.0001% increase.



It is important to note that our analysis makes several assumptions: first, and most importantly, it assumes that all the environmental compartments are well mixed. While this may be the case for surface and groundwater, it is not the case for soil and is limited for sediment. However, the values for sediments and soils are miniscule and thus, this assumption while not strictly true, does not invalidate the analysis.

Secondly, this analysis assumes that there the assessed compounds are not already present in the environment. This allows us to assess the incremental risk associated with chaff use in the PTA. This also avoids complications due to high backgrounds in the area, which may or may not exist.

Finally, this analysis assumes that the released compounds do not catalyze any further reactions in the environment or change into more toxic species.

## **Summary**

To reduce the risk of pollution and protect civilian airways, the United States Joint Chiefs of Staff issued a directive that placed restrictions on the use of chaff for training purposes in the United States (CJCSM, 1998). As a result there are now only about 50 sites where the use of chaff is permitted in defensive training. Moreover, flight rules have been changed to restrict chaff releases to higher altitudes that ensure the chaff plumes are widely dispersed and ground concentrations are very low. Despite these changes, concerns regarding the impacts of chaff released into the environment continue to be raised by both the public action and government groups.

In response, the U.S. Department of Defense (DOD) has either sponsored or conducted research to address a number of environmental and health issues associated with the release of RF chaff during training flights. Recently, a select panel of university-based research scientists, each with published expertise in a relevant field of study, conducted an extensive review of this research (Hullar et al., 1999)—concluding that “widespread environmental, human, and agricultural impacts of RF chaff as currently used in training are negligible, and (are) far less than those from other man-made emissions”. It was noted that this conclusion was based on “available data, analyses, estimations, and related information”.

In the current report, we reviewed much of the same information available to the Select Panel and conducted a modeling exercise to assess the environmental and ecotoxicological impact of RF chaff at the Goose Bay Military Training Area. The user-defined parameters used in the model included geographical region (Labrador), but with a reduced surface area (i.e., that of the practice target area, or PTA; 2,000 km<sup>2</sup>), and exclusion of coastal waters. It also was assumed that all the chaff released in a given year (ca. 7,125 kg) would settle over the PTA and would degrade to release its individual constituents into the environment. Consequently, our results should be viewed as being representative of the most extreme, or worst-case, scenario.

Together with the information gleaned from the available literature, the model results indicate that—at the anticipated release/deposition rate of  $3.56 \text{ mg m}^{-2} \text{ yr}^{-1}$ —the occurrence of an adverse environmental or health impact associated with chaff deployments during flight training exercises is negligible.

Whereas conditions conducive to chaff degradation (low soil pH, moist & warm conditions) are likely to occur during the summer months, the effects of an extended winter period on the environmental degradability of chaff is unknown. Regardless, from a chemical toxicity standpoint, it is highly unlikely that chaff releases will have any impact on ecosystem functioning. Likewise, human health issues associated with the inhalation or ingestion of chaff fibers are considered to be negligible because the chaff fibers are too large to pass through the nose or mouth, and because concentrations of suspended chaff are well below known toxic thresholds. There is some evidence to suggest that exposure to airborne chaff could cause dermal irritation; however, it is unlikely that concentrations of airborne chaff at ground level would ever reach the level needed to bring about this effect.

The effects of chaff on the species of greatest concern in the Goose Bay region (woodland caribou, moose, sport fish, waterfowl, bald eagles, and osprey) have not been considered in previous studies. Having said that, however, it is worth noting that the available data does indicate that there is little or no threat to livestock and non-domestic grazers associated with the inhalation and ingestion of chaff fibers. As well, it is expected that there will be no toxicological effects associated with the ingestion of chaff by wildlife; i.e., deposition rates of chaff are much too low to yield toxic concentrations of elements such as aluminum, boron, zinc, vanadium, or manganese.

Issues remaining to be addressed include determining (i) the half-life of chaff dipoles (fibers) in various soil and environmental conditions and (ii) the extent to which these dipoles can break down or be abraded to respirable sizes (i.e.,  $\text{PM}_{10}$  or  $\text{PM}_{2.5}$ ). Whereas issues surrounding the break-up of chaff dipoles are currently being investigated by the U.S. Navy (Arfsten et al., 2002), we do not know of any studies addressing the weathering of chaff dipoles under the cold climate conditions characteristic of the Labrador (Goose Bay) environment.

### **Disclaimer**

The opinions and assertions presented in this document are strictly those of the authors, and should not be construed as being official or reflecting the views of the Canadian Department of National Defense.

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