ioMosaic®
Minimizing risk. Maximizing potential.®

Overlooked Inherent Hazards of Commonly Used Pool and Water Treatment Chemicals

An ioMosaic® Publication

G. A. Melhem, Ph.D., FAIChE, E. Shaaban, Ph.D., and A. Iskandar, Ph.D.

This page is intentionally left empty

IOMOSAIC® CORPORATION

Overlooked Inherent Hazards of Commonly Used Pool and Water Treatment Chemicals

Process Safety and Risk Management Practices

authored by

G. A. Melhem, Ph.D., FAIChE, E. Shaaban, Ph.D., and A. Iskandar, Ph.D.

Printed July 22, 2026

This page is intentionally left empty

Notice:

This document was prepared by ioMosaic® Corporation (**ioMosaic**) for Public Release. This document represents ioMosaic's best judgment in light of information available and researched prior to the time of publication.

Opinions in this document are based in part upon data and information available in the open literature, data developed or measured by ioMosaic, and/or information obtained from ioMosaic's advisors and affiliates. The reader is advised that ioMosaic has not independently verified all the data or the information contained therein. This document must be read in its entirety. The reader understands that no assurances can be made that all liabilities have been identified. This document does not constitute a legal opinion.

No person has been authorized by ioMosaic to provide any information or make any representation not contained in this document. Any use the reader makes of this document, or any reliance upon or decisions to be made based upon this document are the responsibility of the reader. ioMosaic does not accept any responsibility for damages, if any, suffered by the reader based upon this document.

Revision Log:

Revision 1: July 22, 2026

...

Table of Contents

List of Figures 3

List of Tables 4

1 Introduction 5

2 Recent Incidents 6
2.1 Bio-Lab, 2024 . . . 7
2.2 Optima Belle, 2020 . . . 7

3 Hydrolysis and Decomposition Reactions 8
3.1 Trichlorocyanuric Acid (TCCA, CDB-90) . . . 9
3.2 Sodium Dichloroisocyanate (NaDCC) . . . 12
3.3 Bromochlorodimethylhydantoin, BCDMH . . . 20

4 GC-MS and FTIR Gas Analysis After The Runaway 25
4.1 TCCA . . . 26
4.2 Anhydrous NaDCC . . . 26
4.3 NaDCC dihydrate . . . 27
4.4 BCDMH . . . 27

5 NFPA Water Reactivity Classification 28

6 Pool Chemicals Water Reactivity Classification 28

7 Should Pool Chemicals be Designated as Water Reactive ? 29

8 NFPA-704 vs. NFPA-400, Tactics vs. Prevention 30

9 Should Pool Chemicals be Designated as Class 1 Explosives ? 31

10 Conclusions 32

11 References 33

Index 35

List of Figures

1 Warehouse storage racks . . . 5
2 Chemical structures of common pool chemicals and related compounds . . . 6
3 Nitrogen trichloride thermochemistry . . . 9
4 ARC Measured TCCA decomposition rate $\frac{dT}{dt}$ using different water to TCCA ratios 11
5 ARC Measured TCCA decomposition rate $\frac{dP}{dt}$ using different water to TCCA ratios 12
6 TCCA/CDB-90 measured runaway decomposition behavior using DSC under open and confined conditions . . . 13
7 NaDCC measured runaway decomposition behavior using DSC under open and confined conditions . . . 16
8 ARC Measured NaDCC decomposition rate $\frac{dT}{dt}$ using different water to NaDCC ratios . . . 17
9 ARC Measured NaDCC decomposition rate $\frac{dP}{dt}$ using different water to NaDCC ratios . . . 18
10 CDB-56 measured runaway decomposition behavior using DSC under open and confined conditions . . . 19
11 ARC Measured NaDCC dihydrate decomposition rate $\frac{dT}{dt}$ using different water to NaDCC dihydrate ratios . . . 20
12 ARC Measured NaDCC dihydrate decomposition rate $\frac{dP}{dt}$ using different water to NaDCC dihydrate ratios . . . 21
13 Nitrogen tribromide thermochemistry . . . 21
14 ARC Measured BCDMH decomposition rate $\frac{dT}{dt}$ using different water to BCDMH ratios . . . 23
15 ARC Measured BCDMH decomposition rate $\frac{dP}{dt}$ using different water to BCDMH ratios . . . 24
16 BCDMH measured runaway decomposition behavior using DSC under confined conditions . . . 25
17 Example of FTIR of ARC headspace gases after thermal runaway of TCCA with water . . . 26
18 Example of GC-MS peaks versus retention time of ARC headspace gases after thermal runaway of TCCA with water . . . 27

List of Tables

1 NFPA 704 Rating for degree of water reactivity hazards 30

1 Introduction

Common pool chemicals are not classified as water reactive chemicals and are not considered by the general public to be hazardous. Why should they be? They are widely used to treat and disinfect pools and spas all over the world. When used to disinfect large quantities of water (dissolved in large amounts of water) and/or when stored or transported dry and without confinement, their reactivity hazards are negligible.

This paper will show that when common pool chemicals are confined and heated [1] they decompose violently and generate large quantities of gaseous products. Decomposition may also initiate without added heat for some formulations under certain conditions. Adiabatic calorimetry measurements show that decomposition rates are exceedingly fast and rival the decomposition of propellants and some explosives. The decomposition products can be both flammable and/or toxic.

When partially wet and confined, for example during processing, storage, or transportation, the same water reaction that is intended to disinfect large amounts of water can trigger the decomposition of these materials, potentially leading to severe fires and explosions.

Figure 1: Warehouse storage racks

Source: CSB [1]

Confinement can be exhibited when wet pool chemicals (small granules and/or powder) are stored in a sealed container or when stored in bulk in large quantities [2]. A three to four feet of powder over a crusted wet cake of pool chemicals can form a sufficient sealant to permit the formation of highly unstable nitrogen trichloride (NCl_3) or nitrogen tribromide (NBr_3). If the concentration of NCl_3 or NBr_3 gets high enough, the spontaneous decomposition of these unstable chemicals acts as a trigger for the decomposition of the pool chemical itself, which can lead to severe fires and explosions. It is important to note that pool chemicals powders are also poor conductors of heat.

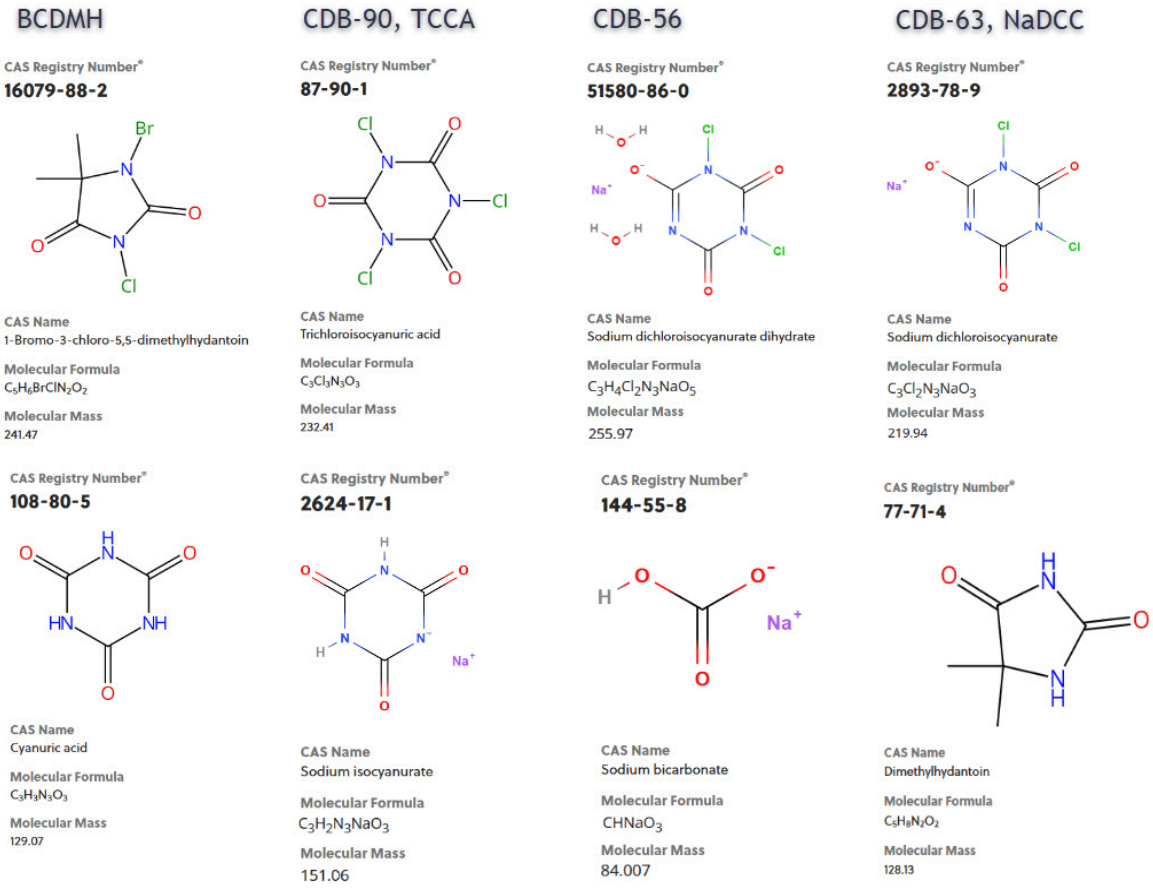
This paper provides irrefutable evidence and learnings from more than forty measured calorimetry and analytical tests data sets as well as thermochemical evaluations that demonstrate the mechanism of how partially wet and confined pool chemicals can cause severe fires and explosions.

Pool chemicals [2] considered in this study (see Figure 2) included trichloroisocyanuric acid (CDB-90 or TCCA), sodium dichloroisocyanurate (CDB-63, NaDCC), sodium dichloroisocyanurate dihydrate (CDB-56, NaDCC.$2H_2O$), bromochlorodimethylhydantoin (BCDMH), and related compounds.

[1] Heating can occur due to reaction with water or with other materials as pool chemicals are strong oxidizers. Heating can also occur due an external fire, or use of heating jackets, or use of heating elements.

[2] CDB-90/63/56 are "Chlorinated Dry Bleach" where the numbers denote percent by weight of available chlorine (as Cl_2): $\simeq$ 90 % for TCCA, $\simeq$ 63 % for anhydrous NaDCC, and $\simeq$ 56 % for NaDCC.$2H_2O$.

Figure 2: Chemical structures of common pool chemicals and related compounds



Source: ioMosaic®

Different ratios of water to pool chemical were tested using adiabatic and differential scanning calorimetry highlighting the critical water to chemical ratio required to cause the most severe decomposition outcomes. Reaction products were identified and quantified by Gas Chromatography and Mass Spectrometry (GC/MS) and Fourier Transform Infrared Spectroscopy (FTIR). Additional properties such as thermal effusivities and heats of combustion were are also measured and are provided in this paper.

2 Recent Incidents

Some selected recent incidents highlight several overlooked inherent hazards of common pool chemicals during processing and storage.

2.1 Bio-Lab, 2024

On September 29, 2024, the Bio-Lab, Inc. (BioLab) facility located in Conyers, Georgia, experienced multiple fires, extensive off-gassing, and a massive plume of potentially toxic smoke [1, 3].

As a result of the incident, local officials reported that about 17,000 people were evacuated. The facility stored TCCA, BCDMH, CDB-56, and CDB-63 in a warehouse in large quantities (see Figure 1).

Due to heavy rain fall [3] from hurricane Helene and warehouse roof leaks some stored materials may have been exposed to rain and became partially wet. However, the Chemical Safety Board [3] considered this rain scenario as well as other scenarios that could have led to the partial wetting of some stored materials and concluded that the water leaks were caused by corrosion of sprinkler system components that started leaking shortly after the facility began storing chlorinated isocyanurates in 2019. Employees assigned to fire watch heard popping sounds. These popping sounds were most likely attributed to the formation of highly unstable nitrogen trichloride and/or nitrogen tribromide from wet materials.

2.2 Optima Belle, 2020

At approximately 10:00 PM on December 8, 2020, a pressure rated rotary double cone dryer containing CDB-56 exploded, causing a subsequent fire and toxic release at the Optima Belle LLC. facility (Optima) in Belle, West Virginia. In addition to shelter in place impacts on the surrounding communities, Optima experienced significant property damage, and one Optima employee was fatally injured [4].

The explosion occurred while Optima, a toll manufacturer [4, 5], was drying CDB-56 to remove water and to make CDB-63 on behalf of Clearon Corporation (Clearon). Optima′s estimated property damage from the incident was in excess of thirty million dollars. A violent decomposition of partially wet CBD-56 occurred and caused the vessel failure [6, 7]. The partially wet CDB-56 caused the formation of nitrogen trichloride which accumulated in the dryer. The nitrogen trichloride spontaneously decomposed and caused the violent decomposition of the NaDCC.

A technology transfer package (TTP) [5] was provided by Clearon to Optima. The TTP contained adequate and critical information about the potential reaction hazards of NaDCC with water and the impact of confinement. Unfortunately, Optima personnel did not possess the necessary skills and chemical reactivity experience required to properly use the TTP information for equipment selection, process hazards analysis, and the development of safe operating limits.

Selected excerpts from the TTP [5] provide insight into the hydrolysis chemistry and dangers of partial wetting of TCCA and NaDCC. These excepts are just but a few examples of some of the important and relevant process safety information (PSI) provided by the TTP.

In this excerpt, FMC points out with clarity that “inertial or mass or overburden confinement” can

[3] Approximately 10 inches of rain fell between September 26 and 27
[4] Employee was critically injured and died later due to intoxication from inhaled fumes
[5] FMC Corporation, Thermal Decomposition Studies of CDB-63, FMC-RR-68-5251-R, December, 1968.

prevent NCl_3 vapors from escaping and cause the NCl_3 vapors to accumulate as if the system was a closed system [6]. Stopping the dryer rotation can create the type of confinement the Clearon TTP warned about: *"The thermal decomposition of sodium dichloroisocyanurate (CDB-63) was initiated at temperatures as low as 60 to 90 °C by the presence of water in sufficient quantity to form a wet cake of the material. The CDB's must be in a container which will hold the NCl_3 vapors, produced by the hydrolysis reaction, until an explosive concentration is reached. The spontaneous decomposition of NCl_3 generates sufficient heat to initiate decomposition in the CDB mass.* **A 3 to 4 ft height of CDB powder over a crusted wet cake is sufficient sealant to permit this concentration build up**. *In a tightly sealed system NCl_3 build up is rapid enough to cause a detonation."*

In the following excerpt, the TTP draws a clear distinction between **open** and **closed** systems: *"The effect of water on the decomposition of CDB-63 was studied in* **open and closed systems** *with the amount of CDB-63 ranging from test tube samples to 4 foot columns in 2-inch pipes."* The operating limits provided by the TTP were for an open system and have been verified as accurate and representative by ioMosaic®. When dryer rotation is stopped for long periods of time, the bottom contents of the dryer become inertially confined by the mass on top or overburden of the CDB material.

This excerpt describes the equivalence of CDB-63 and CDB-56: *"CDB-63 forms a dihydrate at ambient temperature which becomes a monohydrate at 80 °C, and an anhydrous salt at 110 °C"*. CDB-56 is CDB-63 with two water molecules (a dihydrate). CDB-56 becomes a CDB-63 monohydrate at 80 °C and an anhydrous CDB-63 at 110 °C , well below the the 140 °C upper temperature drying limit provided by Clearon. CDB-56 did not have to be called out specifically by the TTP [5] as it is a CDB-63 dihydrate. Water did not have to be added to the CDB-56 to cause a self-sustaining runaway decomposition, the CDB-63 dihydrate (CDB-56) has its own stoichiometric water content which is released when heated and needed to be continuously removed by having an open and rotating double cone dryer system that is under vacuum and/or nitrogen purge.

The TTP warns about the potential hazards in a closed system: *"In the presence of sufficient water to give a wet of CDB-63, spontaneous decomposition will take place with detonation at 55-60 °C in a completely enclosed system. In a system closed only by a column of CDB-63 powder, the detonation occurs at 90 to 100 °C"*. Pulling a vacuum on the dryer and/or continuous purging with nitrogen, as long as the dryer is rotating, ensures that the dryer is behaving like an open system. Stopping the dryer for long periods of time turns it into a closed system by inertial or mass or overburden confinement.

3 Hydrolysis and Decomposition Reactions

Pool chemicals such as TCCA, Anhydrous NaDCC, NaDCC dihydrate, and BCDMH possess dual hazards as they are Class 2 Oxidizers and contain an organic fuel source (their ring structure) within the same molecule. This makes pool chemicals susceptible to self-accelerating decomposition and combustion without the need for air, similar to organic peroxides.

[6] The terms "closed", "sealed", and/or "confined" are used interchangeably

However, due to their apparent stability under ambient conditions in dry forms and when added to a large open body of water, their water reactivity is typically overlooked. Test data and multiple incidents indicate that wetting the powder under confinement (in a closed vessel or under self-confinement by bulk mass) causes reactions that initiate energetic decomposition and self-combustion reactions.

In such types of pool chemicals, the organic ring structure (e.g., isocyanuric acid or dimethylhydantoin) is engineered to ensure the controlled, sustained release of the active sanitizers, hypochlorous acid (HOCl) or hypobromous acid (HOBr), into the pool water. This slow release mechanism in a large body of water maintains a consistent residual sanitizer level over time, allowing the chemical to effectively decompose pathogens without requiring constant reapplication or reaching overly high concentrations that could irritate swimmers.

The opposite scenario, adding a small amount of water to a large amount of pool chemicals under confinement, however, can initiate the decomposition and combustion under a far lower onset temperature, in comparison to pure form, causing a serious chemical hazard. As these chemicals normally hydrolyze to form HOCl or HOBr or both, the wetted area of the powder becomes concentrated enough in HOCl or HOBr or both to initiate the exothermic decomposition and combustion of the organics in the material. Such decomposition can form hazardous gases, including the explosive NCl_3 and/or NBr_3, and a hot spot that can initiate self-accelerating decomposition and combustion of the rest of the powder, leading to thermal runaway, overpressure/explosion, and toxic-gas release.

3.1 Trichlorocyanuric Acid (TCCA, CDB-90)

The TCCA hydrolysis reaction leads to the formation of cyanuric acid (CA) and hypochlorus acid (HOCl):

$$\underbrace{C_3Cl_3N_3O_3}_{\text{TCCA}} + \underbrace{3\ H_2O}_{\text{Water}} \xrightarrow{\text{endothermic}} \underbrace{C_3H_3N_3O_3}_{\text{cyanuric acid}} + \underbrace{3\ HOCl}_{\text{hypochlorus acid}}$$

When water is well in excess of TCCA, HOCl will react in the water and there will be no free HOCl for further reaction with the TCCA or CA. HOCl will react with pathogens and disinfect the water, but will be too diluted for further reaction with TCCA or CA.

However, when TCCA is well in excess of water, water becomes highly concentrated with HOCl and the following reaction leads to the formation of nitrogen trichloride:

Figure 3: Nitrogen trichloride thermochemistry

** Melhem Index			
Hazard Rating	Heat of reaction	CART	Effective CART
High	-456.63 cal/g	3371.86 K	4248.27 K
	-54.96 kcal/gmol; 1 gmol basis		

Chemical Name	Formula	Phase	Initial Moles	Change	Final Moles
NITROGEN TRICHLORIDE	Cl3N	Vapor	1.0000	-1.0000	0.0000
NITROGEN	N2	Vapor	0.0000	0.5000	0.5000
CHLORINE	Cl2	Vapor	0.0000	1.5000	1.5000
Other. < 0.0001 moles			0.0000	0.0000	0.0000
Totals			1.0000	1.0000	2.0000

Source: SuperChems® Expert

$$\underbrace{C_3Cl_3N_3O_3}_{\text{TCCA}} + \underbrace{6\ HOCl}_{\text{hypochlorus acid}} \xrightarrow{\text{exothermic}} \underbrace{3\ NCl_3}_{\text{nitrogen trichloride}} + \underbrace{3\ H_2O}_{\text{Water}} + \underbrace{3\ CO_2}_{\text{carbon dioxide}}$$

Nitrogen trichloride, which can also be formed by the decomposition of TCCA, is highly unstable and can spontaneously decompose exothermically if it is allowed to accumulate:

$$\underbrace{NCl_3}_{\text{nitrogen trichloride}} \xrightarrow{\text{exothermic}} \underbrace{\frac{1}{2}\ N_2}_{\text{nitrogen}} + \underbrace{\frac{3}{2}\ Cl_2}_{\text{chlorine}}$$

The nitrogen trichloride calculated adiabatic reaction (decomposition) temperature (CART [8, 9, 10, 11]) is very high (see Figure 3) which is why it serves as a strong trigger for the decomposition of TCCA. Nitrogen trichloride formation is favored by acidic conditions [12] or a low water to TCCA mass ratio. Under acidic conditions (low pH < 4), nitrogen trichloride formation is favored. Under alkaline conditions (pH > 7), monochloramine formation is favored.

Cyanuric acid will also react with HOCl exothermically via one of the following stoichiometries:

$$\underbrace{C_3H_3N_3O_3}_{\text{cyanuric acid}} + \underbrace{4.5\ HOCl}_{\text{hypochlorus acid}} \xrightarrow{\text{exothermic}} \underbrace{3\ CO_2}_{\text{carbon dioxide}} + \underbrace{1.5\ H_2O}_{\text{Water}} + \underbrace{1.5\ N_2}_{\text{nitrogen}} + \underbrace{4.5\ HCl}_{\text{hydrogen chloride}}$$

$$\underbrace{C_3H_3N_3O_3}_{\text{cyanuric acid}} + \underbrace{9.0\ HOCl}_{\text{hypochlorus acid}} \xrightarrow{\text{exothermic}} \underbrace{3\ CO_2}_{\text{carbon dioxide}} + \underbrace{6\ H_2O}_{\text{Water}} + \underbrace{1.5\ N_2}_{\text{nitrogen}} + \underbrace{4.5\ Cl_2}_{\text{chlorine}}$$

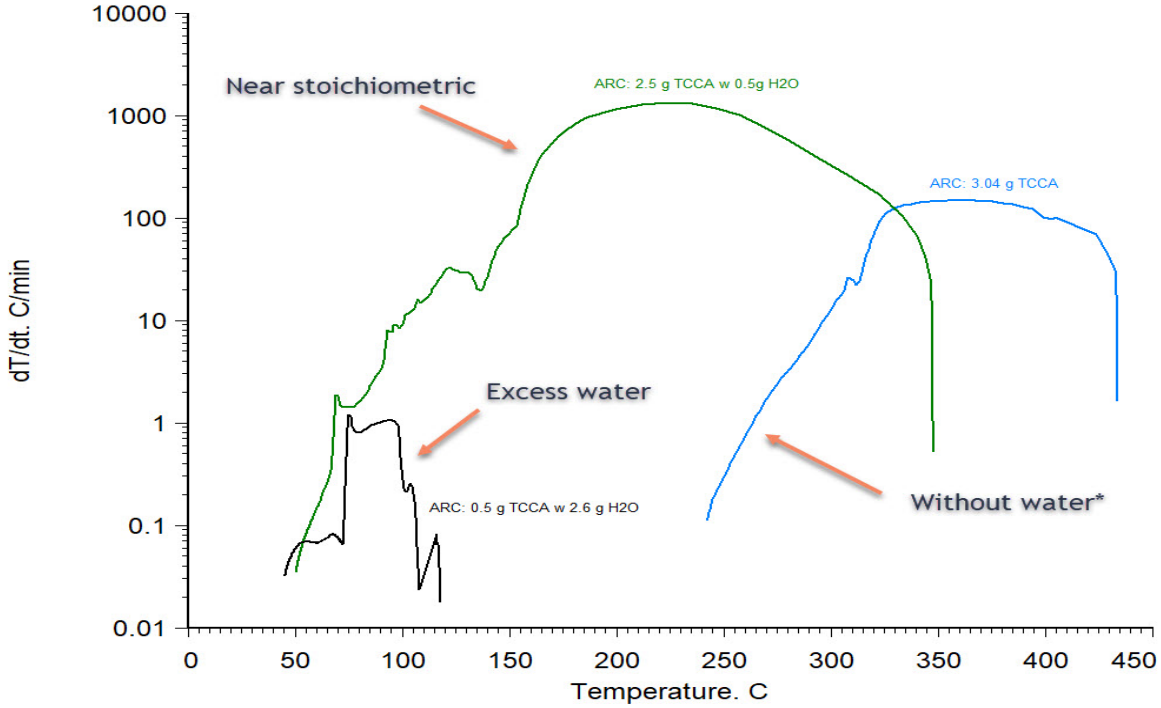
The worst case water to TCCA molar ratio, is 3 to 1 (or 18.86 % water mass fraction or 23.23 % water to TCCA mass ratio), or stoichiometric. Numerous calorimetry tests were conducted with varying water to TCCA mass fractions ranging from 0 % water (100 %TCCA) to 91.5 % water (141.9 to 1 water to TCCA molar ratio).

Differential scanning calorimetry tests were also conducted using sealed high pressure test cells and also open test cells. The measured heat of fusion by DSC ranged from 54 to 88 J/g while the measured heat of decomposition ranged from -1050 to -1060 J/g TCCA or -251 to -253 cal/g of TCCA.

Heat of combustion testing for TCCA results ranged from -1487 BTU/lb (-3459 kJ/kg) to -1572 BTU/lb (-3654 kJ/kg). The combustion tests resulted in a solid white-yellow residue remaining after the tests, which indicated that the TCCA was not fully combusted. The remaining TCCA powder was approximately 45 % of the initial amount of TCCA powder. The heat of combustion of TCCA may also include contributions from the decomposition of TCCA.

Figures 4 and 5 show the impact of water to TCCA ratio on the stability and reaction rates of TCCA and TCCA with water. When water is well in excess of TCCA, the overall rates of reactions (dissolution, mixing, and decomposition) are low and would be what is expected when treating large volumes of water with small amounts of TCCA. When TCCA is heated without water, its decomposition temperature is well in excess of 200 °C. The data shown in Figures 4

Figure 4: ARC Measured TCCA decomposition rate $\frac{dT}{dt}$ using different water to TCCA ratios



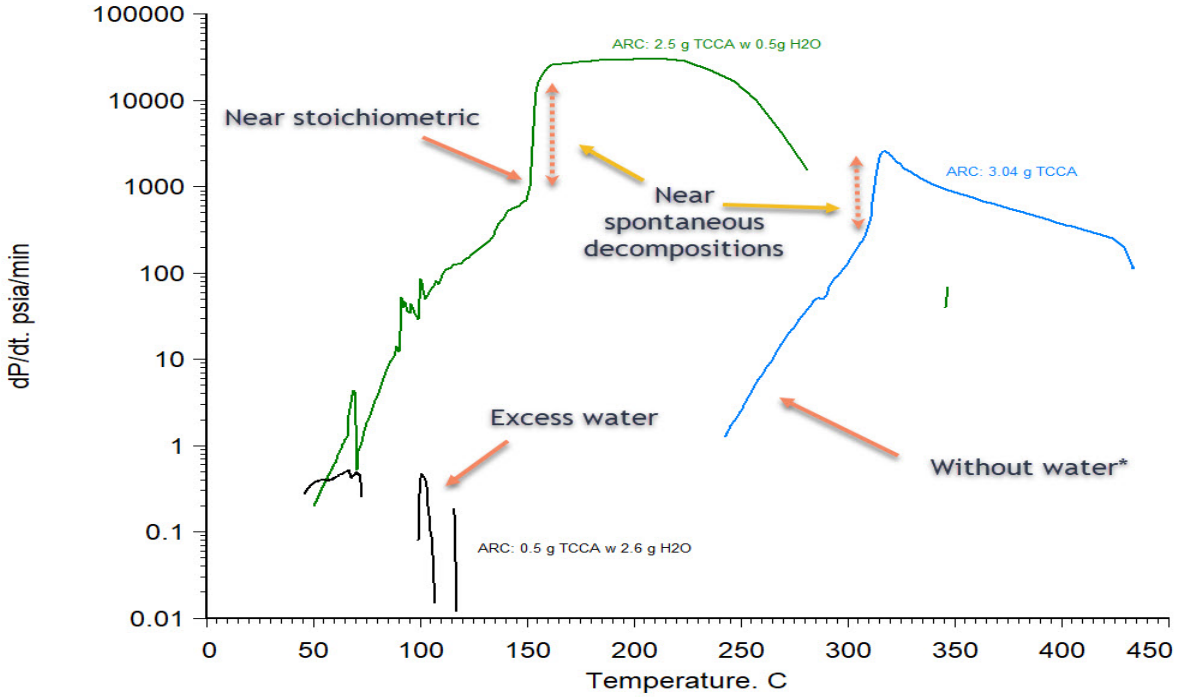
Source: ioMosaic®; *: Test terminated due to instrument temperature limit

and 5 does not capture the entire decomposition exotherm of TCCA because the decomposition reaction temperature either exceeded the temperature limit or the pressure rise rate tracking limit of the ARC. The estimated partial heat of decomposition of TCCA ranges from -175 to -218 cal/g TCCA. The decomposition of TCCA can form nitrogen trichloride which in turn can decompose spontaneously and exothermically to chlorine and nitrogen.

The near stoichiometric test shows a low detected onset temperature of approximately 50 °C. We also note the magnitude of the exotherm and the measured heat of reaction ranging from -420 to -520 cal/g of TCCA. As mentioned earlier [2], when TCCA is wet and stored in a sealed container or when stored in bulk in large quantities, severe fires and/or explosions can occur. A three to four feet of TCCA powder over a crusted wet cake of TCCA can form a sufficient sealant to permit the formation and accumulation of highly unstable nitrogen trichloride (NCl_3). If the concentration of NCl_3 gets high enough, the spontaneous decomposition of NCl_3 acts as a trigger for the decomposition of TCCA which can lead to severe fires and/or explosions. It is important to note that TCCA powders are also poor conductors of heat.

When confined, the formation and accumulation of nitrogen trichloride or the formation of hypochlorous acid (followed by formation and accumulation of nitrogen trichloride) have a profound impact on the hazard potential of TCCA (CDB-90). This is shown in Figure 6. As Figure 6 shows, when heated in an open system and decomposition products are allowed to escape, the hazard potential of TCCA is much less than when it is confined.

Figure 5: ARC Measured TCCA decomposition rate $\frac{dP}{dt}$ using different water to TCCA ratios



Source: ioMosaic®; *: Test terminated due to instrument temperature limit

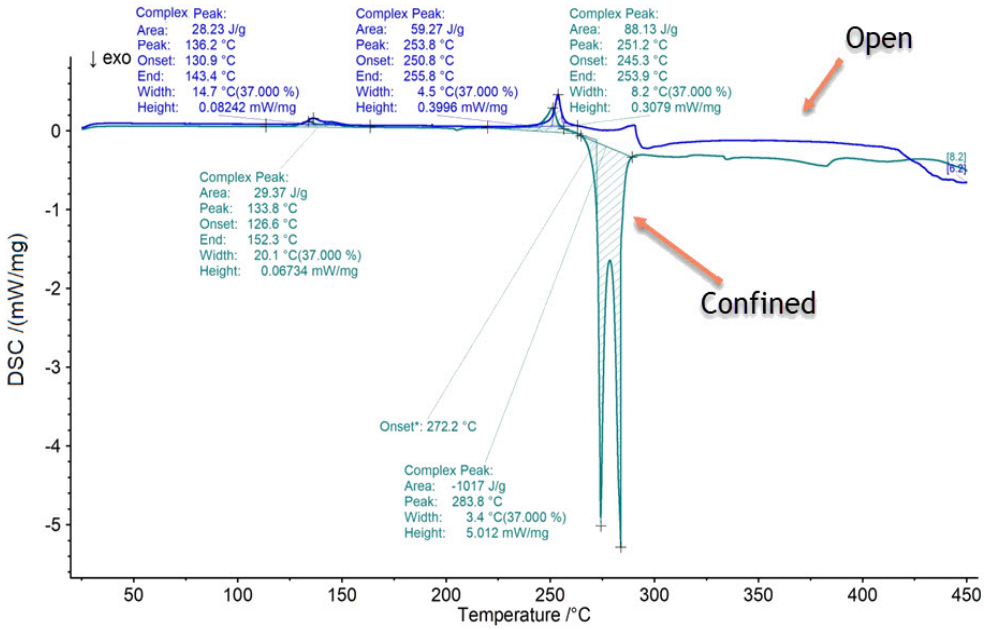
3.2 Sodium Dichloroisocyanate (NaDCC)

Anhydrous NaDCC (Dichlor-60 or CDB-63) and NaDCC dihydrate (Dichlor-56 or CDB-56) are essentially the same molecule. The $\simeq$ 14 % by mass water of crystallization in the dihydrate (NaDCC.$2H_2O$) can be released by two endothermic reaction steps (see section 3.2.2) starting at 47 °C and 86 °C respectively. Although the release of water from NaDCC dihydrate crystal is endothermic, once the water is free, it initiates a hydrolysis reaction to form HOCl, which in turn starts an energetic isocyanurate ring exothermic decomposition ($\simeq$ 75 °C as observed from adiabatic calorimetry tests as described later in this document) to produce NCl_3. Calorimetry tests also show that increasing water beyond the stoichiometric amount in NaDCC systems, by injecting water, lowered the detected decomposition onset temperature, reaching $\simeq$ 46 °C at 50% water by mass.

Anhydrous NaDCC does not contain crystallization water. Adiabatic calorimetry testing shows that the detected onset temperature for decomposition, without added water, was $\simeq$ 111 °C. However, once anhydrous NaDCC contacts water, it exothermically rehydrates to the NaDCC dihydrate or completely dissolves. In ARC testing, injecting 0.5 g of water into 2.5 g of anhydrous NaDCC at 30 °C produced a rapid hydration heat release (exotherm), with the temperature rise rate reaching $\simeq$ 80 °C/min four minutes after the water addition, and the released heat was estimated to be $\simeq$ 44 calories per gram of mixture. The exotherm persisted and ultimately initiated the explosive decomposition.

The NaDCC dihydrate effectively carries its own trigger, two molecules of water bound to the

Figure 6: TCCA/CDB-90 measured runaway decomposition behavior using DSC under open and confined conditions



Source: ioKinetic®

NaDCC molecule and held in the lattice. When the bound water molecules are released and re-wet the solid, local hot spots are created, accelerate hydrolysis, and drive decomposition. Although heat is required to release the lattice water, adding a small amount of external water can lower the onset temperature to $\simeq 46\ ^{\circ}\mathrm{C}$. Anhydrous NaDCC requires external water. However, once the right amount of water is added, the exothermic hydration can drive the hydrolysis, and the decomposition proceeds more readily starting at room temperature.

To fully understand the hazard and risks for any process involving anhydrous or NaDCC dihydrate, three main reactions should be evaluated:

1. Hydration and dehydration dynamics (reversible conversion between dihydrate and anhydrous) with heat release on contact of anhydrous NaDCC with liquid water and heat absorption on thermal dehydration.
2. Hydrolysis to release HOCl in the presence of free water (small amount, added or liberated from the crystal). Hydrolysis is endothermic but it generates HOCl that can be concentrated enough to initiate an energetic exothermic decomposition.
3. The explosive decomposition of the isocyanurate ring; based on the two above reactions and the conditions that control them, the onset temperature of the exothermic explosive decomposition of the isocyanurate ring becomes a moving target.

The Optima Belle double cone dryer explosion [6] occurred during drying of CDB-56 to CDB-63. The CSB concluded that the explosion was due to self accelerating decomposition of heated NaDCC dihydrate. The CSB attributed the incident to the unsafe setup, the repeated unplanned

dryer rotation pauses, and the disregard of shutdown instructions that left the dryer without rotation, nitrogen purge, or jacket cooling, which trapped heat, caused vapor to condense and re-wet the solids, lowered the decomposition onset temperature, and ultimately triggered the runaway decomposition reaction. The CSB findings are summarized in the Conclusion Section 5.1 of the published investigation final report [6]. These findings cover 1) process knowledge management, 2) thermal hazard assessment, 3) equipment selection and process design, 4) tolling of hazardous materials, and 5) regulatory coverage of reactive hazards.

Another subtle factor that has not been considered in the CSB investigation is that the rewetting of some of the dried powder (once the recondensation happens during the operation pauses on the day of the incident) will cause fast exothermic rehydration. Local hot spots from the hydration exotherm formed wherever water touches the dried powder, will increase the likelihood of decomposition. To put this into perspective, about 125 gallons of water must be removed from 8,820 lb of the CDB-56 [7], so assuming a 10-hour run, that is 12.5 gal per hour. If 1 % of the total water condenses back when the dryer rotation is stopped without cooling and nitrogen purge, $\simeq$ 1.25 gallons could recondense into the CDB powder to reform the dihydrate. For this 1.25 gallons of water, $\simeq$ 63.7 lb of CDB-63 powder would become CDB-56. This will cause a fast increase in the temperature in this area by $\simeq$ 125 °C above the operating temperature [8].

3.2.1 Anhydrous Sodium Dichloroisocyanurate (NaDCC, CDB-63)

The NaDCC hydrolysis reaction leads to the formation of sodium isocyanurate (NaCA) and hypochlorus acid (HOCl):

$$\underbrace{C_3Cl_2N_3O_3Na}_{\text{NaDCC}} + \underbrace{2\ H_2O}_{\text{Water}} \xrightarrow{\text{endothermic}} \underbrace{C_3H_2N_3O_3Na}_{\text{sodium isocyanurate}} + \underbrace{2\ HOCl}_{\text{hypochlorus acid}}$$

When water is well in excess of NaDCC, HOCl will react in the water and there will be no free HOCl for further reaction with the NaDCC or NaCA. HOCl will react with pathogens to disinfect the water, but will be too diluted for further reaction with NaDCC and NaCA. However, when NaDCC is well in excess of water, water becomes highly concentrated with HOCl and the following reaction leads to the formation of nitrogen trichloride:

$$\underbrace{C_3Cl_2N_3O_3Na}_{\text{NaDCC}} + \underbrace{7\ HOCl}_{\text{hypochlorus acid}} \xrightarrow{\text{exothermic}} \underbrace{NaHCO_3}_{\text{sodium bicarbonate}} + \underbrace{3\ NCl_3}_{\text{nitrogen trichloride}} + \underbrace{3\ H_2O}_{\text{Water}} + \underbrace{2\ CO_2}_{\text{carbon dioxide}}$$

As mentioned earlier, nitrogen trichloride is highly unstable. When enough nitrogen trichloride is accumulated, its exothermic spontaneous decomposition (see Figure 3) acts as a trigger and causes

[7] The CSB published report [6] does not state 125 gallons of water must be removed. The CSB performed a theoretical calculation and the report states, "The CSB calculated that approximately 125 gallons of water could be removed from 8,820 lbs of CDB-56 during dehydration". The CSB report also states the dehydration process was capable of releasing approximately 125 gallon of water.

[8] Assuming a heat capacity of water of 1.0 cal/g/K, a heat capacity of NaDCC of 0.25 cal/g/K, and that hydration or dissolution releases 44 cal per gram of mixture.

the decomposition of NaDCC.

$$\underbrace{NCl_3}_{\text{nitrogen trichloride}} \xrightarrow{\text{exothermic}} \underbrace{\frac{1}{2}\,N_2}_{\text{nitrogen}} + \underbrace{\frac{3}{2}\,Cl_2}_{\text{chlorine}}$$

Even when the concentration of nitrogen trichloride is not high enough to trigger a decomposition of NaDCC, the chlorine that is formed further reacts with sodium bicarbonate and also with water to make additional HOCl:

$$\underbrace{Cl_2}_{\text{chlorine}} + \underbrace{NaHCO_3}_{\text{sodium bicarbonate}} \xrightarrow{\text{endothermic}} \underbrace{NaCl}_{\text{sodium chloride}} + \underbrace{CO_2}_{\text{carbon dioxide}} + \underbrace{HOCl}_{\text{hypochlorus acid}}$$

$$\underbrace{Cl_2}_{\text{chlorine}} + \underbrace{H_2O}_{\text{Water}} \xrightarrow{\text{endothermic}} \underbrace{HCl}_{\text{hydrogen chloride}} + \underbrace{HOCl}_{\text{hypochlorus acid}} \tag{1}$$

$$\underbrace{Cl_2}_{\text{chlorine}} + \underbrace{C_3Cl_2N_3O_3Na}_{\text{NaDCC}} \xrightarrow{\text{exothermic}} \underbrace{C_3Cl_3N_3O_3}_{\text{TCCA}} + \underbrace{NaCl}_{\text{sodium chloride}} \tag{2}$$

Any TCCA that is formed as a reaction product will also react with water as outlined in section 3.1. The worst case water to NaDCC molar ratio, is 2 to 1 (or 14 % water mass fraction or 16.3 % water to NaDCC mass ratio), or stoichiometric. Numerous calorimetry tests were conducted with varying water to NaDCC mass fractions ranging from 0 % water (100 % NaDCC) to 96 % water (61 to 1 water to NaDCC molar ratio).

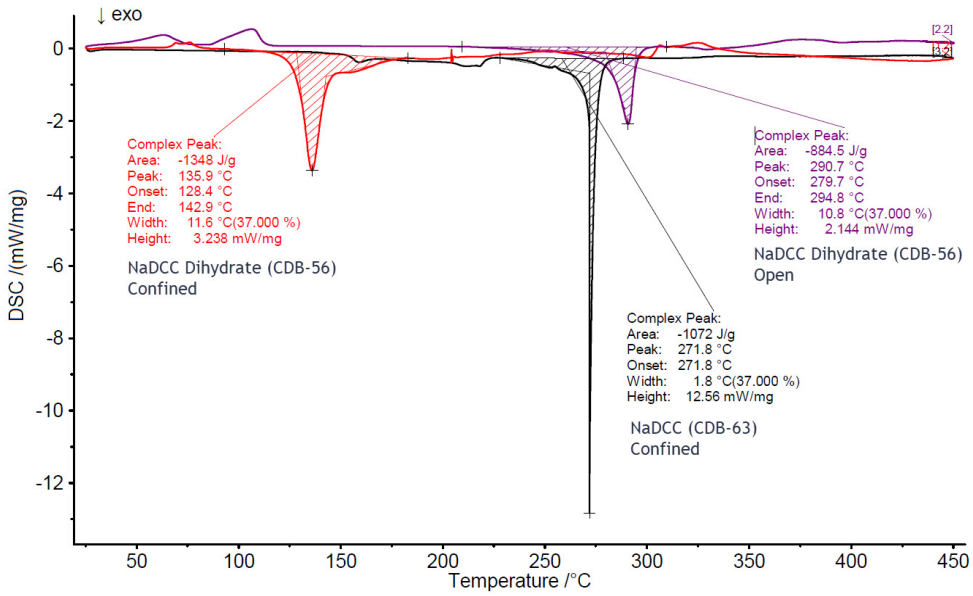
Differential scanning calorimetry tests were also conducted using sealed high pressure test cells and also open test cell for and anhydrous NaDCC and NaDCC dihydare. The measured heat of decomposition under confinement by DSC is -1072 J/g NaDCC (-256 cal/g NaDCC) (see Figure 7).

When confined, the formation and accumulation of nitrogen trichloride or the formation of hypochlorous acid (followed by formation and accumulation of nitrogen trichloride) have a profound impact on the hazard potential of NaDCC. This is shown in Figure 7. As Figure 7 shows, when heated in an open system and decomposition products are allowed to escape, the hazard potential of NaDCC is much less than when it is confined.

Heat of combustion testing for NaDCC (CDB-63) results ranged from -1642 BTU/lb (-3816 kJ/kg) to -1700 BTU/lb (-3952 kJ/kg). The combustion tests resulted in a solid white-yellow residue remaining after the tests, which indicated that the NaDCC was not fully combusted and/or formation of solid ionic combustion products such as sodium salts. The heat of combustion measurement may also include contributions from the decomposition of NaDCC.

Figures 8 and 9 show the impact of water to NaDCC ratio on the stability and reaction rates of NaDCC and NaDCC with water. When water is well in excess of NaDCC, the overall rates of reactions (dissolution, mixing, and decomposition) are low and would be what is expected when treating large volumes of water with small amounts of NaDCC. When NaDCC is heated without water, its ARC detected decomposition temperature is approximately 100 °C. The data shown

Figure 7: NaDCC measured runaway decomposition behavior using DSC under open and confined conditions



Source: ioKinetic®

in Figures 8 and 9 does not capture the entire decomposition exotherm of NaDCC because the decomposition reaction pressure rise rate exceeded the pressure limit of the ARC. The estimated partial heat of decomposition of NaDCC is -263 cal/g NaDCC. The decomposition of NaDCC can form nitrogen trichloride which in turn can decompose spontaneously and exothermically to chlorine and nitrogen.

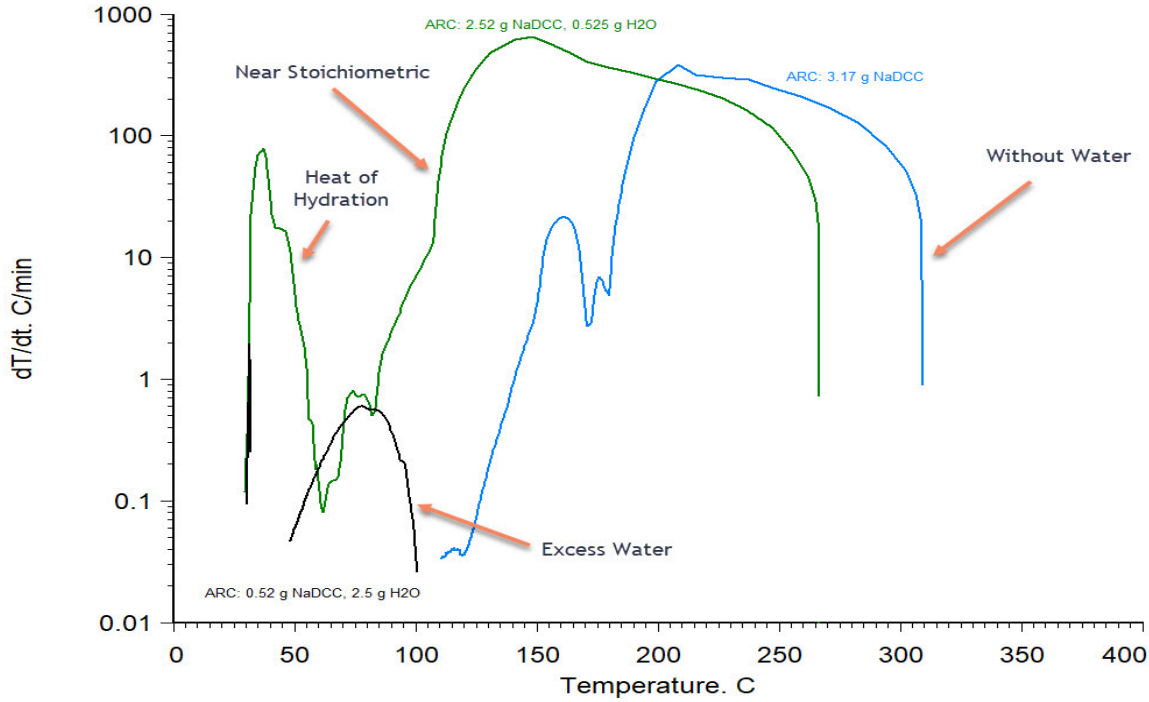
The near stoichiometric test shows that the exothermic reaction starts once the water is injected into the NaDCC at 30 °C. We also note the magnitude of the exotherm and the measured partial heat of reaction of -730 cal/g of NaDCC. The entire exotherm was not captured as the pressure rise rate exceeded the limit of the ARC.

As mentioned earlier [2], when NaDCC is wet and stored in a sealed container or when stored in bulk in large quantities, severe fires and/or explosions can occur. A three to four feet of NaDCC powder over a crusted wet cake of NaDCC can form a sufficient sealant to permit the formation and accumulation of highly unstable nitrogen trichloride (NCl_3). If the concentration of NCl_3 gets high enough, the spontaneous decomposition of NCl_3 acts as a trigger for the decomposition of NaDCC which can lead to severe fires and/or explosions.

The confinement impact on water reactivity of NaDCC is often ignored or discounted because water is added to NaDCC in an open system [13]. Carpenter and Ogle [13] conducted moisture testing in the open to determine the cause of an industrial accident involving NaDCC. They also conducted ARC testing and their results are consistent with our findings for dry NaDCC under confinement. However, their water testing with 4 g of water added to 30 grams of NaDCC product mixture only caused a momentary temperature rise [9] to 115 °C but failed to initiate an NaDCC

[9] Most likely due to heat of hydration

Figure 8: ARC Measured NaDCC decomposition rate $\frac{dT}{dt}$ using different water to NaDCC ratios



Source: ioMosaic®; Tests of dry near stoichiometric NaDCC terminated before completion due to ARC maximum temperature and/or pressure rise rate limits.

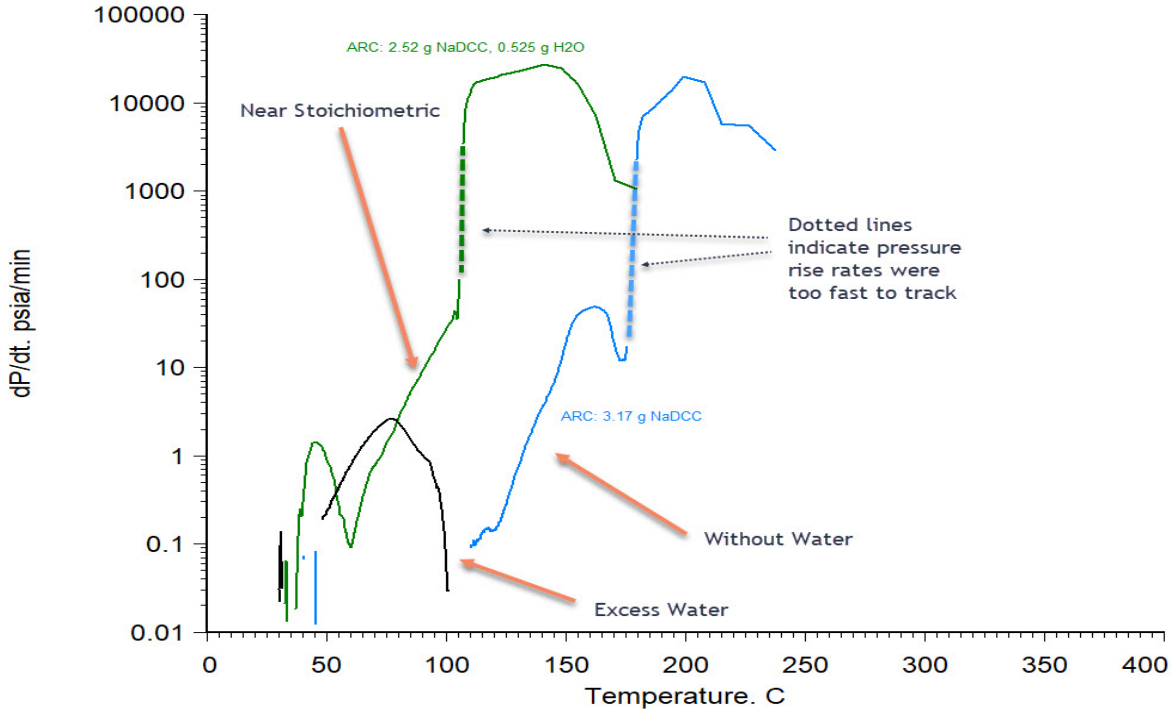
decomposition because the system was open. Had they injected water to NaDCC using the ARC , they would have come to similar findings regarding the profound impact of small amounts of water on potential NaDCC decomposition hazards. Because of this oversight, their incident investigation finding (that friction caused the decomposition of 500 kg of material in a ribbon blender) was most likely in error and may not have been the actual cause of the incident.

It is important to note that NaDCC powders are also poor conductors of heat. FMC [2] reports a heat capacity of 0.24 cal/g NaDCC, a bulk density of 801 $\mathrm{kg/m3}$, and a thermal conductivity of 0.072 $\mathrm{W/m/K}$.

3.2.2 NaDCC Dihydrate, CDB-56

The NaDCC Dihydrate (NaDCC.$2H_2O$) is the same as NaDCC but it has two molecules of water chemically bound to it. These two water molecules can react with NaDCC at elevated temperatures if they are freed by heating the NaDCC dihydrate by either oxidizing other materials or contaminants, using an external heating source, or by adding more water. The dehydration of NaDCC dihydrate proceeds via two reactions, the formation of NaDCC monohydrate, and the formation of dry NaDCC.

Figure 9: ARC Measured NaDCC decomposition rate $\frac{dP}{dt}$ using different water to NaDCC ratios



Source: ioMosaic®; Tests of dry near stoichiometric NaDCC terminated before completion due to ARC maximum temperature and/or pressure rise rate limits.

$$\underbrace{C_3Cl_2N_3O_3Na.2H_2O}_{\text{NaDCC dihydrate}} \xrightarrow{\text{endothermic}} \underbrace{C_3Cl_2N_3O_3Na.H_2O}_{\text{NaDCC monohydrate}} + \underbrace{H_2O}_{\text{Water}}$$

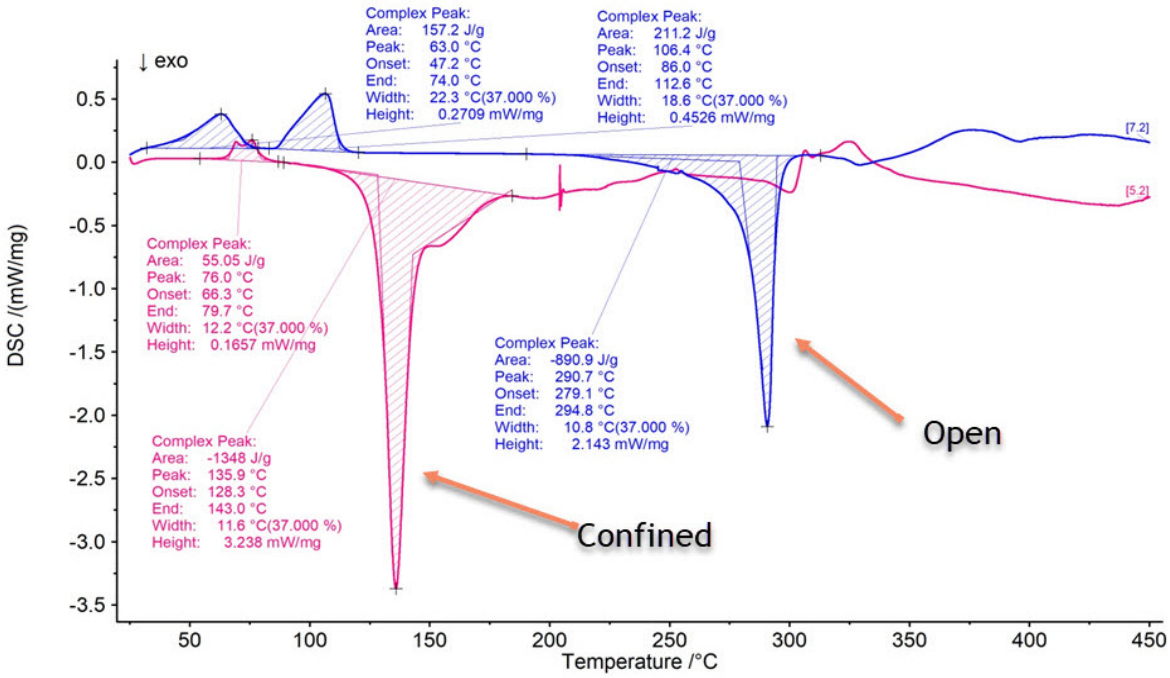
$$\underbrace{C_3Cl_2N_3O_3Na.H_2O}_{\text{NaDCC monohydrate}} \xrightarrow{\text{endothermic}} \underbrace{C_3Cl_2N_3O_3Na}_{\text{NaDCC}} + \underbrace{H_2O}_{\text{Water}}$$

Both reactions are endothermic based on DSC measurements as shown in Figure 10. The production of NaDCC monohydrate starts at 47 °C and is endothermic with a heat of reaction of 157 J/g (37.5 cal/g) of NaDCC Dihydrate. The production of dry NaDCC from the monohydrate is also endothermic. It starts at 86 °C with a heat of reaction of 211 J/g (50 cal/g) of NaDCC monohydrate.

We also note from Figure 10 that the decomposition of NaDCC Dihydrate is more energetic and occurs at lower temperatures when confined. The heat of reaction when confined is -1348 J/g (-322 cal/g) of NaDCC Dihydrate. The heat of reaction for an open system is -890 J/g (-212 cal/g) of NaDCC Dihydrate.

Figures 11 and 12 show the impact of water to NaDCC dihydrate water ratio on the stability and reaction rates of NaDCC dihydrate and NaDCC dihydrate with water. When water is well in excess of NaDCC dihydrate, the overall rates of reactions (dissolution, mixing, and decomposition) are low and would be what is expected when treating large volumes of water with small amounts of

Figure 10: CDB-56 measured runaway decomposition behavior using DSC under open and confined conditions



Source: ioMosaic®.

NaDCC dihydrate.

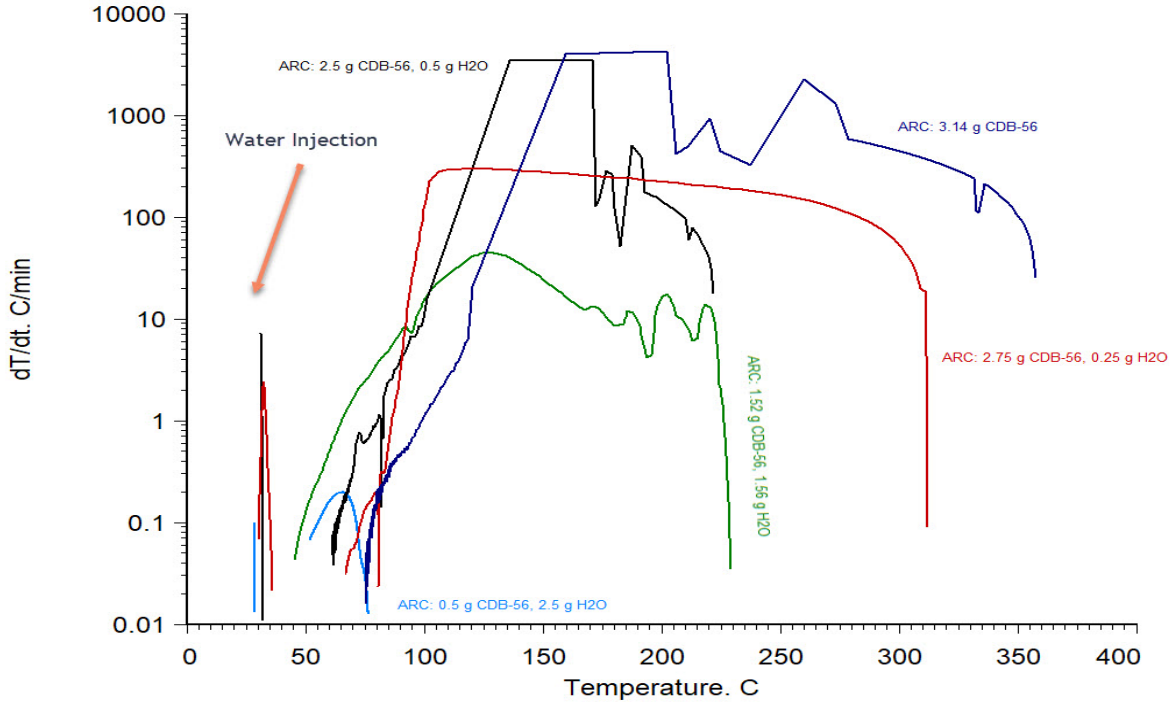
When NaDCC dihydrate is heated without water, its ARC detected decomposition temperature is approximately 75 °C. The data shown in Figures 11 and 12 does not capture the entire decomposition exotherm of NaDCC dihydrate because the decomposition reaction temperature rise rate exceeded the preset limit of the ARC. The estimated partial heat of decomposition of NaDCC dihydrate ranges from -300 to -373 cal/g NaDCC dihydrate (vs. a DSC value of -322 cal/g). When mixed with water, the detected onset temperature is approximately 45 °C [10]. However, an exotherm due to mixing is detected at 30 °C as soon as water is injected into the test cells. The decomposition of NaDCC dihydrate can form nitrogen trichloride which in turn can decompose spontaneously and exothermically to chlorine and nitrogen.

Heat of combustion testing for NaDCC dihydrate (CDB-56) results ranged from -1581 BTU/lb (-3675 kJ/kg) to -1735 BTU/lb (-4033 kJ/kg). The combustion tests resulted in a solid white-yellow residue remaining after the tests, which indicated that the NaDCC dihydrate was not fully combusted. The heat of combustion measurement may also include contributions from the decomposition of NaDCC dihydrate.

It is important to note that NaDCC dihydrate powders are also poor conductors of heat. ioKinetic® measured a thermal conductivity of 0.0946 $\mathrm{W/m/K}$ and an average thermal effusivity of 300

[10] When corrected for the thermal inertia of the ARC (Φ), the corrected onset temperature, $T_{d,c}$, can be 5 to 10 degrees lower than the detected/measured onset temperature, $T_{d,m}$: $\frac{1}{T_{d,c}} = \frac{1}{T_{d,m}} + \frac{R_g}{E} \ln(\Phi)$ where R_g is the universal gas constant, E is the activation energy, and T is absolute temperature.

Figure 11: ARC Measured NaDCC dihydrate decomposition rate $\frac{dT}{dt}$ using different water to NaDCC dihydrate ratios



Source: ioMosaic®; All tests were terminated before completion due to ARC preset limits

$\mathrm{Ws}^{0.5}/\mathrm{K}/\mathrm{m}^2$ at room temperature.

3.3 Bromochlorodimethylhydantoin, BCDMH

The hydrolysis of BCDMH releases bromine and chlorine as hypobromous acid (HOBr) and hypochlorous acid (HOCl). The bromine is released rapidly while the chlorine is released slowly. Analysis of the hydrolysis reactions indicates that HOBr formation is thermodynamically favored:

$$\underbrace{C_5H_6BrClN_2O_2}_{\text{bromochlorodimethylhydantoin}} + \underbrace{H_2O}_{\text{Water}} \xrightarrow{\text{exothermic}} \underbrace{HOBr}_{\text{hypobromus acid}} + \underbrace{C_5H_7ClN_2O_2}_{\text{monochloro dimethylhydantoin}}$$

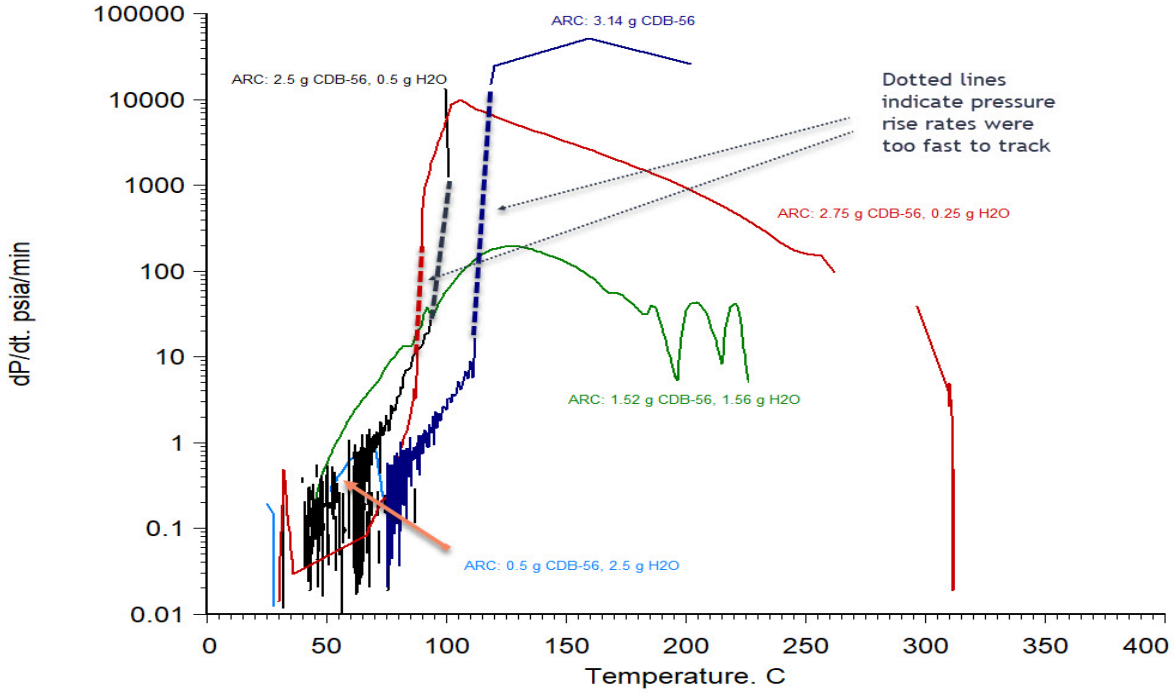
$$\underbrace{C_5H_7ClN_2O_2}_{\text{monochloro dimethylhydantoin}} + \underbrace{H_2O}_{\text{Water}} \xrightarrow{\text{endothermic}} \underbrace{HOCl}_{\text{hypochlorus acid}} + \underbrace{C_5H_8N_2O_2}_{\text{dimethylhydantoin}}$$

$$\underbrace{C_5H_6BrClN_2O_2}_{\text{bromochlorodimethylhydantoin}} + \underbrace{H_2O}_{\text{Water}} \xrightarrow{\text{exothermic}} \underbrace{HOCl}_{\text{hypochlorus acid}} + \underbrace{C_5H_7BrN_2O_2}_{\text{monobromo dimethylhydantoin}}$$

$$\underbrace{C_5H_7BrN_2O_2}_{\text{monobromo dimethylhydantoin}} + \underbrace{H_2O}_{\text{Water}} \xrightarrow{\text{endothermic}} \underbrace{HOBr}_{\text{hypobromus acid}} + \underbrace{C_5H_8N_2O_2}_{\text{dimethylhydantoin}}$$

This leads to the following overall hydrolysis reaction:

Figure 12: ARC Measured NaDCC dihydrate decomposition rate $\frac{dP}{dt}$ using different water to NaDCC dihydrate ratios



Source: ioMosaic®; All tests were terminated before completion due to ARC preset limits

$$\underbrace{C_5H_6BrClN_2O_2}_{\text{bromochlorodimethylhydantoin}} + \underbrace{2\ H_2O}_{\text{Water}} \xrightarrow{\text{exothermic}} \underbrace{HOBr}_{\text{hypobromus acid}} + \underbrace{HOCl}_{\text{hypochlorus acid}} + \underbrace{C_5H_8N_2O_2}_{\text{dimethylhydantoin}}$$

When water is well in excess of BCDMH, HOCl and HOBr will react in the water and there will be no free HOCl or HOBr for further reaction with the BCDMH or dimethylhydantoin (DMH). HOCl and HOBr will react with pathogens and disinfect the water, but will be too diluted for further reaction with BCDMH or DMH. ioKinetic® testing for the excess water reaction with BCDMH (67 to 1 water to BCDMH molar ratio) using the ARC, yields a heat of reaction of -27 cal/g of mixture or -162 cal/g of BCDMH. This value is also confirmed by thermochemical estimates using SuperChems® Expert with formation energies independently calculated using quantum chemistry and heat of combustion measurements. Thermochemical estimates in the ideal gas phase using SuperChems® Expert

Figure 13: Nitrogen tribromide thermochemistry

** Melhem Index				
Hazard Rating	Heat of reaction		CART	Effective CART
High	-216.66 cal/g		3310.59 K	4171.08 K
	-54.97 kcal/gmol; 1 gmol basis			
Chemical Name	Formula	Phase	Initial Moles	Change	Final Moles
NITROGEN TRIBROMIDE	NBr3	Vapor	1.0000	-1.0000	0.0000
NITROGEN	N2	Vapor	0.0000	0.5000	0.5000
BROMINE-REF	Br2	Vapor	0.0000	1.5000	1.5000
Other. < 0.0001 moles			0.0000	0.0000	0.0000
Totals			1.0000	1.0000	2.0000

Source: SuperChems® Expert

show a heat of reaction of -51 cal/g of mixture. We note that the ideal gas estimate does not include heat of mixing and/or solution effects. The hydantoin ring in BCDMH and DMH is less stable than the triazine ring in TCCA and cyanuric acid, as confirmed by quantum chemical and heat of combustion estimates of the formation energies.

When BCDMH is well in excess of water, water becomes highly concentrated with HOCl and HOBr and the following reaction leads to the formation of nitrogen trichloride and nitrogen tribromide:

$$\underbrace{C_5H_6BrClN_2O_2}_{\text{bromochlorodimethylhydantoin}} + \underbrace{2\ HOCl}_{\text{hypochlorus acid}} + \underbrace{2\ HOBr}_{\text{hypobromus acid}} \xrightarrow{\text{exothermic}} \underbrace{NCl_3}_{\text{nitrogen trichloride}} + \underbrace{NBr_3}_{\text{nitrogen tribromide}} + \underbrace{2\ H_2O}_{\text{Water}} + \underbrace{CO_2}_{\text{carbon dioxide}} + \underbrace{CO}_{\text{carbon monoxide}} + \underbrace{C_3H_6O}_{\text{acetone}}$$

Nitrogen tribromide and nitrogen trichloride, that can also be formed by the decomposition of BCDMH, are highly unstable and can spontaneously decompose exothermically if allowed to accumulate:

$$\underbrace{NCl_3}_{\text{nitrogen trichloride}} \xrightarrow{\text{exothermic}} \underbrace{\frac{1}{2}\ N_2}_{\text{nitrogen}} + \underbrace{\frac{3}{2}\ Cl_2}_{\text{chlorine}}$$

$$\underbrace{NBr_3}_{\text{nitrogen tribromide}} \xrightarrow{\text{exothermic}} \underbrace{\frac{1}{2}\ N_2}_{\text{nitrogen}} + \underbrace{\frac{3}{2}\ Br_2}_{\text{bromine}}$$

Nitrogen trichloride (and possibly nitrogen tribromide) formation is favored by acidic conditions [12] or a low water to BCDMH mass ratio. Under acidic conditions (low pH < 4), nitrogen trichloride (and possibly nitrogen tribromide) formation is favored. Under alkaline conditions (pH > 7), monochloramine formation (or monobromoamine) is favored.

The Calculated Adiabatic Reaction (decomposition) Temperatures (CART) [8, 9, 10, 11]) for nitrogen trichloride and nitrogen tribromide are very high (see Figures 3 and 13 which is why they are strong triggers for the decomposition of BCDMH.

DMH will also react with HOCl and HOBr exothermically via one of many potential reaction stoichiometries or pathways. A thermodynamically favorable stoichiometry leading to maximum energy release and minimum Gibbs free energy (equilibrium state) using ideal gas formation energies is:

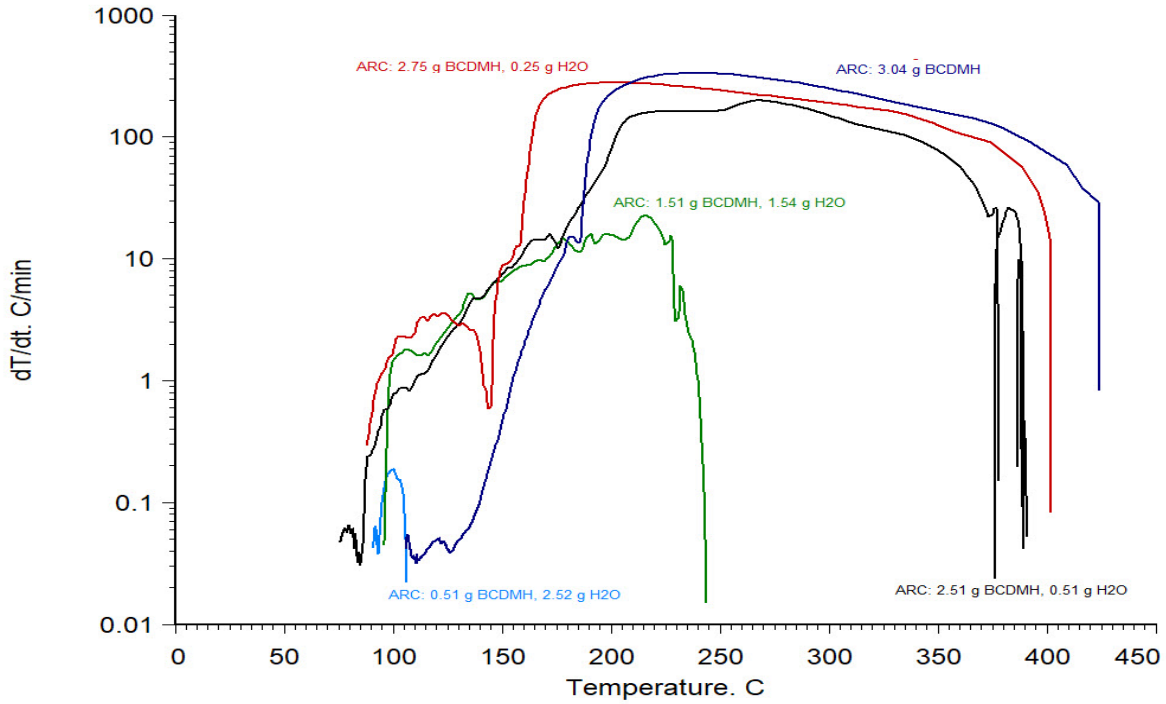
$$\underbrace{C_5H_8N_2O_2}_{\text{dimethylhydantoin}} + \underbrace{6\ HOCl}_{\text{hypochlorus acid}} + \underbrace{6\ HOBr}_{\text{hypobromus acid}} \xrightarrow{\text{exothermic}} \underbrace{5\ CO_2}_{\text{carbon dioxide}} + \underbrace{4\ H_2O}_{\text{Water}} + \underbrace{1\ N_2}_{\text{nitrogen}} + \underbrace{6\ HCl}_{\text{hydrogen chloride}} + \underbrace{6\ HBr}_{\text{hydrogen bromide}}$$

The worst case water to BCDMH molar ratio, is 2 to 1 (or 13 % water mass fraction or 15 %

water to BCDMH mass ratio), or stoichiometric. Numerous calorimetry tests were conducted with varying water to BCDMH mass fractions ranging from 0 % water (100 %BCDMH) to 98.5 % water (67 to 1 water to BCDMH molar ratio).

Heat of combustion testing for BCDMH results ranged from -5042 BTU/lb (-11720 kJ/kg) to -5100 BTU/lb (-11855 kJ/kg). These values are considerably higher than measured heat of combustion values of TCCA and NaDCC. The BCDMH combustion tests resulted in an oily residue. The heat of combustion of BCDMH may also include contributions from the decomposition of BCDMH.

Figure 14: ARC Measured BCDMH decomposition rate $\frac{dT}{dt}$ using different water to BCDMH ratios



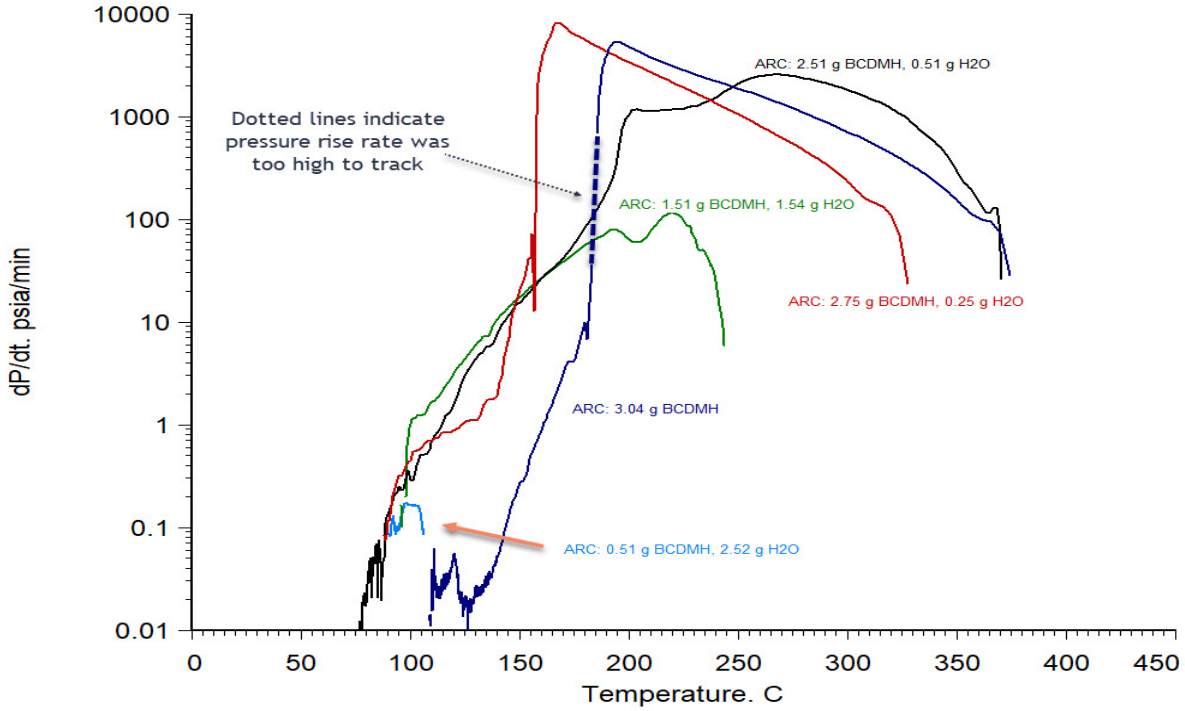
Source: ioMosaic®; Tests terminated due to instrument preset temperature and/or pressure limits

Figures 14 and 15 show the impact of water to BCDMH ratio on the stability and reaction rates of BCDMH and BCDMH with water. When water is well in excess of BCDMH, the overall rates of reactions (dissolution, mixing, and decomposition) are low and would be what is expected when treating large volumes of water with small amounts of BCDMH.

When BCDMH is heated without water, its decomposition temperature is in excess of 100 °C. The data shown in Figures 14 and 15 does not capture the entire decomposition exotherm of BCDMH because the decomposition reaction temperature exceeded the preset ARC temperature limit . The estimated partial heat of decomposition of BCDMH is approximately -191 cal/g BCDMH using a BCDMH heat capacity of 0.25 cal/g. The decomposition of BCDMH can form nitrogen trichloride and nitrogen tribromide that in turn can decompose spontaneously and exothermically to chlorine, bromine, and nitrogen. The heat of decomposition of BCDMH was also measured using DSC (as shown in Figure 16) to be -948 J/g of BCDMH or -227 cal/g of BCDMH.

The near stoichiometric test shows a low detected onset temperature of approximately 76 °C. When

Figure 15: ARC Measured BCDMH decomposition rate $\frac{dP}{dt}$ using different water to BCDMH ratios



Source: ioMosaic®; Tests terminated due to instrument preset temperature and/or pressure limits

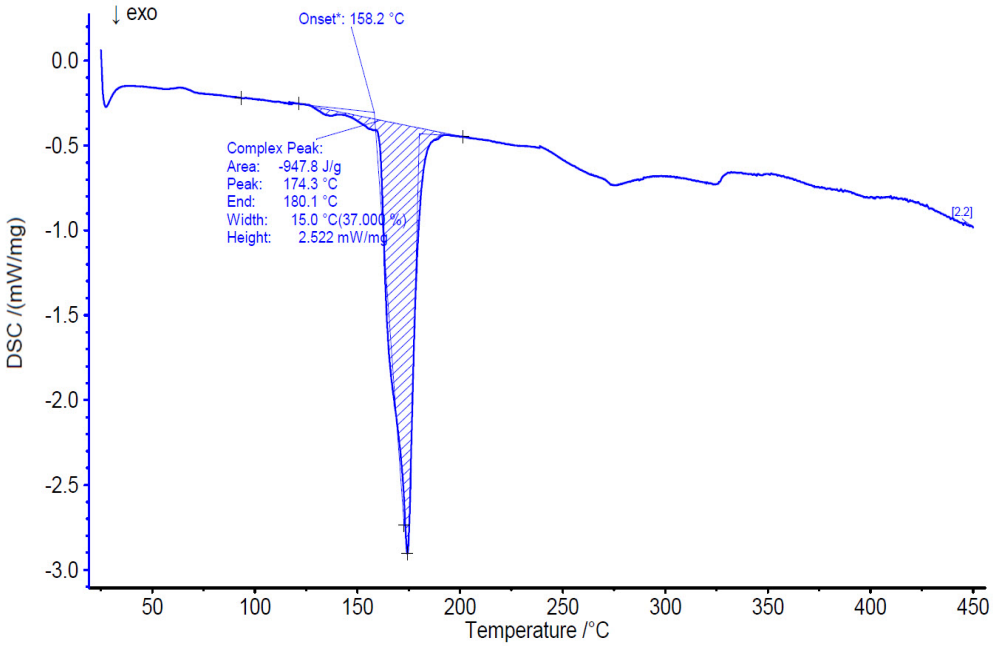
BCDMH is wet and stored in a sealed container, or when stored in bulk in large quantities, severe fires and/or explosions can occur. A three to four feet of BCDMH powder over a crusted wet cake of BCDMH can form [2] a sufficient sealant to permit the formation and accumulation of highly unstable nitrogen trichloride (NCl_3) and nitrogen tribromide (NBr_3). If the concentrations of NCl_3 and/or (NBr_3) get high enough, the spontaneous decomposition of NCl_3 and/or NBr_3 acts as a trigger for the decomposition of BCDMH which can lead to severe fires and/or explosions. It is important to note that BCDMH powders may also be poor conductors of heat.

When confined, the formation and accumulation of nitrogen trichloride or nitrogen tribromide, or the formation of hypochlorous acid or hypobromous acid (followed by formation and accumulation of nitrogen trichloride or nitrogen tribromide) have a profound impact on the hazard potential of BCDMH.

This finding was also reported by Arthur D. Little Inc. (ADL) internal studies [11] on the stability of BCDMH and BCDMH with water in the mid 1990s. The ADL study used the ARC as well as additional testing using heated copper blocks and glass tubes to not only demonstrate the confinement impact on BCDMH potential decomposition/explosion hazards, but also to demonstrate and to visually confirm the impact of having an open system to show the substantial reduction of such hazards.

[11] These studies were conducted by G. A. Melhem and E. Shanley

Figure 16: BCDMH measured runaway decomposition behavior using DSC under confined conditions



Source: ioKinetic®

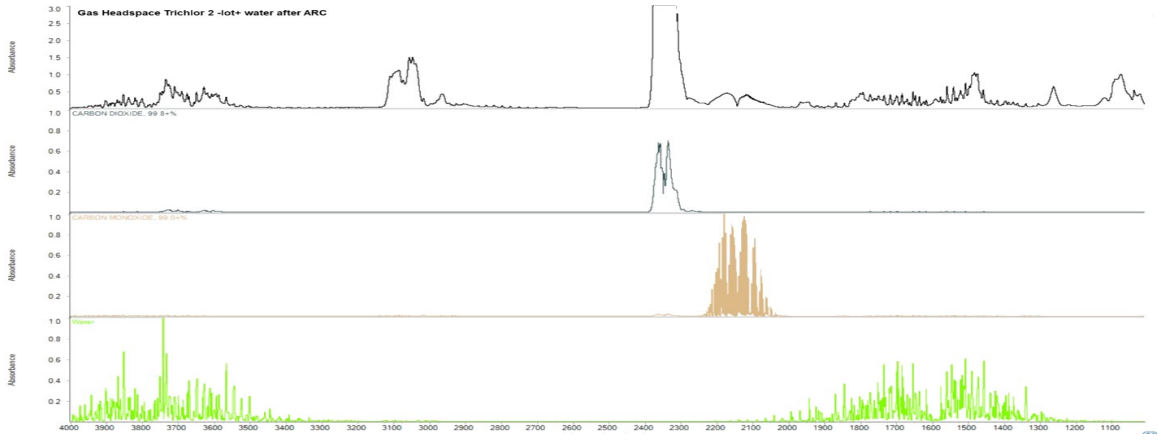
4 GC-MS and FTIR Gas Analysis After The Runaway

Gas Chromatography-Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR) gas analysis was performed for the headspace gases following ARC testing. Testing was conducted to evaluate the chemical reactivity of TCCA, Anhydrous NaDCC, NaDCC dihydrate, and BCDMH samples with water. The gas analysis was performed after the ARC test (near stoichiometric ratio of water to pool chemical) was completed. It should be noted that the headspace gas was sampled after the ARC run (up to 400 °C) and after cooling, so some reactive species that evolved earlier as the reaction progressed may have already been transformed. Also, the GC-MS can under-report heavier or highly reactive gases due to column retention or surface reactions. The gases were collected in a 500 ml Swagelok® stainless steel sample cylinder.

For the GC-MS analysis, a sample from the cylinder was injected into the GC-MS using a 250 μl gas-tight syringe. The analysis was performed using a GC-MS system (Agilent 6890N coupled with 5973 MS) equipped with a PLOT column (Agilent J&W PoraBOND Q for volatile solvents and hydrocarbons, 25 m x 0.25 mm x 3 μm, -100 °C to 300/320 °C). Helium was used as the carrier gas at a 1.5 ml/min flow rate. The oven temperature program started at 40°C (held for 10 minutes), increased at 10 °C/min to 200°C, and was then held at the final temperature for 5 minutes. The injector was operated in splitless mode at 200°C.

For the FTIR analysis, the gas cell was first evacuated, and a background spectrum was recorded. A spectrum of the empty gas cell was then measured to confirm the absence of any residual peaks. Subsequently, the sample cylinder was briefly opened to fill the FTIR gas cell, and the sample

Figure 17: Example of FTIR of ARC headspace gases after thermal runaway of TCCA with water



Source: ioKinetic®

spectrum was acquired.

4.1 TCCA

The headspace after thermal runaway of TCCA with water is dominated by hydrogen chloride, carbon dioxide, and carbon monoxide. All three species are confirmed by FTIR (see Figure 17). HCl shows a band near 2600-3100 cm^{-1}, CO_2 has bands near 2400-2200 and 3740-3540 cm^{-1}, and CO appears near 2250-2050 cm^{-1}. Water is detected by FTIR (broad bands at 4000-3500 and 2000-1250 cm^{-1}).

Other compounds observed by GC-MS (see Figure 18) at lower relative abundance include nitrous oxide and several chlorinated $C_1 - C_3$ species and related oxygenates, such as chloromethane, chloroacetic acid, chloroacetaldehyde, 2-chloro-2-nitropropane, chloroform, dichloromethane, chloroacetyl chloride, and 1,2-dichloro-2-methylpropane.

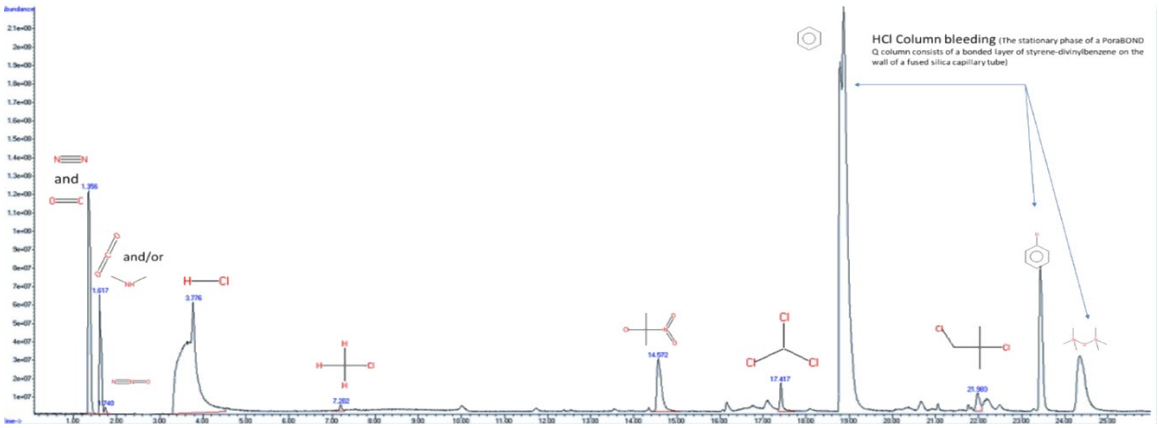
Several GC-MS peaks in the analysis reflected simultaneous elution of two or more compounds, causing mixed spectra and reduced match factors. For example, at 1.4 min the peak contains nitrogen, carbon monoxide, and/or ethylene; at 1.6 min the peak contains carbon dioxide with minor amounts of 2-hydroxy-propanamide and dimethylamine; at 17.4 min the peak comprises chloroform, with co-eluting dichloronitromethane and dichloroacetyl chloride.

4.2 Anhydrous NaDCC

The headspace after thermal runaway of anhydrous NaDCC with water is dominated by carbon dioxide and carbon monoxide. FTIR confirms CO_2 (2400-2200, 3740-3540 cm^{-1}) and CO (2250-2050 cm^{-1}), and also detects water (4000-3500, 2000-1250 cm^{-1}) and hydrogen chloride (2600-3100 cm^{-1}).

Lower-abundance GC-MS species include cyanogen chloride (3.2% at 9.2 min) and acetone (2.5% at 14.6 min). Several GC-MS peaks show co-elution that can depress match factors: at 1.4 min

Figure 18: Example of GC-MS peaks versus retention time of ARC headspace gases after thermal runaway of TCCA with water



Source: ioKinetic® Agilent MS5973N GC 6890

carbon monoxide co-elutes with nitrogen and/or ethylene; at 1.6 min carbon dioxide overlaps with ethanolamine and methylhydrazine.

4.3 NaDCC dihydrate

The headspace after thermal runaway of NaDCC dihydrate with water is dominated by carbon dioxide, carbon monoxide, and nitrous oxide, with acetone also present at notable levels. FTIR confirms CO_2 (2400-2200, 3740-3540 cm^{-1}) and CO (2250-2050 cm^{-1}), and also detects methane (2850-3170, 1350-1200 cm^{-1}), water (4000-3500, 2000-1250 cm^{-1}), acetone (1250-1150, 1450-1350, 1700-1800, 3100-2850 cm^{-1}), and ethylene (3200-2900 cm^{-1}).

Other GC-MS components at lower abundance include nitrogen, methylhydrazine, cyanogen chloride, acetonitrile, methyl isocyanide, methylene chloride (dichloromethane), and trichloromethane (chloroform). Several GC-MS peaks show simultaneous elution, at 1.4 min: nitrogen, carbon monoxide, and ethylene co-elute; at 1.6 min nitrous oxide, carbon dioxide, and methylhydrazine overlap; at 13.1 min acetonitrile and methyl isocyanide co-elute.

4.4 BCDMH

The headspace after thermal runaway of BCDMH with water is dominated by both propane and acetone, each approximately 28% by area in the GC-MS results, followed by significant carbon dioxide at around 9.6%. FTIR confirms carbon dioxide (2400-2200, 3740-3540 cm^{-1}) and carbon monoxide (2250-2050 cm^{-1}), and also detects methane (2850-3170, 1350-1200 cm^{-1}), water (4000-3500, 2000-1250 cm^{-1}), acetone (1250-1150, 1450-1350, 1700-1800, 3100-2850 cm^{-1}), and propane (3000-2850, 1550-1425, 1425-1300 cm^{-1}).

Lower-abundance GC-MS species include isobutane, cyclopropane, butane, several C_3-C_4 alkenes (including 2-methylpropene (isobutene) and 2-butene), acetonitrile, and traces of halogenated com-

pounds such as chloroform and dichloromethane/bromodichloromethane.

Multiple GC-MS peaks reflect co-elution, leading to mixed spectra and sometimes lower match factors. For instance, at 1.6 minutes, the carbon dioxide peak overlaps with 2-hydroxy-propanamide, methylhydrazine, and dimethylamine. At 2.4 minutes, acetonitrile co-elutes with ethane/ethylene, and at 7.4 minutes, propane overlaps with cyclopropylcarbinol and pentanal.

5 NFPA Water Reactivity Classification

The National Fire Protection Association (NFPA) addresses water reactivity in two standards: NFPA-704 and NFPA-400. The purpose of water-reactivity classification in NFPA-704 is to warn of situations where using water in non-flooding quantities during emergency response could increase or change the hazard posed by a chemical, whereas NFPA-400 sets general facility controls for water-reactive materials.

NFPA 704 Annex F classifies water reactivity by how much heat a material releases on contact with water and whether that reaction drives hazardous gas evolution. When the expected heat release is substantial (Class W2 for heat of mixing between 100 and 600 cal/g and Class W3 for more than 600 cal/g), the barred "W" is required to warn responders against using water in non-flooding quantities. According to Annex F, in fires involving class W2 materials, water "should be used only where it can be applied in flooding quantities (which can be impractical for large piles of solids)" so that water can absorb the heat, quench the reaction, and help control any gases produced. The standard calls for considerable judgment when applying the W because even with low measured heat release, conditions that produce toxic gas or localized boiling when small amounts of water contact large piles can justify assigning W2 to enforce a flooding-only response.

Water reactivity classification also warrants regulations for storage controls per NFPA 400. Class 1 materials are treated more leniently through managing lower maximum allowable quantities (MAQs) and general incompatibility segregation without costly structural modifications. Class 2 and 3 materials, however, trigger prescriptive building exclusions-water-resistant (waterproof) rooms [12], no floor drains, and no non-fire-protection water piping routed over/through the area unless isolated.

6 Pool Chemicals Water Reactivity Classification

ARC tests showed that partial wetting of TCCA, NaDCC (as dihydrate or anhydrous), or BCDMH in closed systems causes the violent decompositions to start at far less temperature (in some cases at ambient temperature) compared to the dry powder. In all cases, the heat of reactions exceeded the 100 cal/g threshold for W2 classification and was accompanied by rapid pressure build-up from toxic gases.

Except in the case of anhydrous NaDCC, it should be noted that the amount of heat released is

[12] NFPA does not distinguish "water-resistant" from "waterproof". "water-resistant" and "waterproof" may have different meanings for some specific industrial applications.

not instantaneous or rapid upon contact with water; in fact, the initial contact of these chemicals with water causes an endothermic hydrolysis reaction to produce HOCl and/or HOBr. High concentrations of these acids in small amounts of water and confinement are necessary to trigger the dangerous exothermic decomposition reactions that will follow.

As demonstrated by calorimetry testing earlier, lack of confinement will slow the decomposition or shifts it to higher temperatures as the Cl_2 (gaseous form of HOCl in water) and NCl_3 gases escape the reaction mixture. On this basis, it can be argued that the W2 classification may be overstating the risk and thereby unnecessarily restricting the use of water (the most effective and readily available firefighting agent), which could actually dissipate heat, dilute HOCl, and dissolve toxic gases such as HCl. However, it should be noted that W is a precautionary warning, not an absolute ban on water. It mandates that emergency responders avoid using non-flooding quantities (like hose streams or fog) because limited water could initiate a violent, dangerous reaction.

Water reactivity classification also warrants regulations for storage controls per NFPA 400. Given the severity of the exothermic decomposition and its probable initiation upon wetting, TCCA, NaDCC (as dihydrate or anhydrous), or BCDMH should be classified as W2. As mentioned earlier, W triggers prescriptive building exclusions to prevent unintended water contact and keep spills/runoff out of plumbing and the environment. It should be noted that the CSB investigation updates on the 2024 Bio-Lab (Conyers, GA) fire note recurrent corrosion in the facility fire-protection system, including corroded sprinkler components; investigators also observed corrosion on a sprinkler pipe near the suspected incident origin area. The evidence points to chlorine-driven corrosion of sprinkler pipes, which can breach the system, introduce water, and escalate toward catastrophic outcomes.

7 Should Pool Chemicals be Designated as Water Reactive ?

As mentioned earlier, NFPA-704 proposes a thermal stability indicator for water reactivity, W, in Appendix F [14, 15] for informational purposes only. Where a material shows unusual reactivity with water, the symbol W is to be displayed on the NFPA hazard rating diamond. NFPA-704 water reactivity ratings are shown in Table 1.

The heat of reaction with water is best determined using an adiabatic calorimeter such as the ARC or other screening tools such as the two drop calorimeter [16] using an equal mass ratio of chemical to water (1:1).

NFPA-704 indicates that considerable judgment is required when classifying the water reactivity of chemicals and also warns of cases where use of water in non-flooding quantities during emergency response can increase increase the hazard. We have demonstrated through calorimetry testing that the most severe water reactivity hazard occurs at stoichiometric water to pool chemical ratios, significantly less than 1:1 water to chemical ratio by weight.

Furthermore, NFPA-704 does not consider the impact of mass confinement on water reactivity classification. As indicated earlier, confinement can be exhibited when wet pool chemicals (small granules and/or powder) are stored in a sealed container or when stored in bulk in large quantities [2] where three to four feet of powder over a crusted wet cake of pool chemicals can form

Table 1: NFPA 704 Rating for degree of water reactivity hazards

Rating	ΔH_{rxn}, cal/g	Description
0	< 30	Non-reactive, below 30 cal/g. Does not require a W to be displayed in the special hazards quadrant.
1	≥ 30 & < 100	Materials that react vigorously with water, but not violently†. Materials whose heat of mixing is at or above 30 cal/g and less than 100 cal/g. Materials that react with water, producing either heat or gas leading to pressurization or toxic or flammable gas hazards.
2	≥ 100 & < 600	Materials that react violently with water, including the ability to boil water, or that evolve flammable or toxic gas at a sufficient rate to create hazards under emergency response conditions††. Materials whose heat of mixing is at or above 100 cal/g and less than 600 cal/g.
3	≥ 600	Materials that react explosively with water without requiring heat or confinement††. Materials whose heat of mixing is greater or equal to 600 cal/g.
4		Not Applicable

†: Criterion most applicable when assigning water reactivity rating to solids because the heat of mixing is determined by physical characteristics and the degree to which the material has dissolved).

††:Qualitative description most applicable when assigning water reactivity ratings to solids because the heat of mixing is determined by physical characteristics and the degree to which the material has dissolved)

a sufficient sealant to permit the formation of highly unstable nitrogen trichloride (NCl_3) and/or nitrogen tribromide (NBr_3). If the concentration of NCl_3 or NBr_3 gets high enough, the spontaneous decomposition of these unstable chemicals acts as a trigger for the decomposition of the pool chemical itself which can lead to severe fires and explosions hazards. As also noted earlier, pool chemicals powders are also poor conductors of heat.

As a result, pool chemicals shipped, stored, or processed in bulk, should carry the NFPA classification of W2. Pool chemicals shipped in sealed containers where sufficient pressure can be built up, regardless of quantity, should also carry the NFPA classification of W2.

8 NFPA-704 vs. NFPA-400, Tactics vs. Prevention

NFPA-704 and NFPA-400 use essentially the same qualitative criteria for water reactivity, but focus on different stages of hazard management. NFPA-704 provides firefighters with information on whether water in use in non-flooding amounts will make a fire worse. NFPA-400 focuses on preventive measures (storage design, separations, MAQs, and operating safeguards).

The case of pool chemicals shows how we should separate firefighters needs (NFPA 704), which tend to be more effective in choosing between two bad scenarios, while NFPA 400 is focused on

risk prevention. For example, relinquishing the W symbol and classifying the material as water-reactive class 1 might aid early fire suppression, but it would also relax NFPA 400 safeguards, likely increasing the frequency of incidents.

9 Should Pool Chemicals be Designated as Class 1 Explosives ?

Pool chemicals are not manufactured to have a pyrotechnic or explosive affects. However, numerous ARC tests (under confinement) show exceedingly high decomposition rates at elevated temperatures for dry pool chemicals and for partially wet pool chemicals. The pressure rise rates are shown in Figures 5, 9, 12, and 15. These pressure rise rates are high enough to be fast deflagration rates and will most likely fail the UN Series Test 2(c)(i) Time/Pressure Test criteria [17] of an overpressure rise from 100 psig to 300 psig in less than 30 ms.

We believe these ARC test results strongly indicate that it is also highly likely that pool chemicals will fail UN Series Test 2(b) Koenen test. The UN Series Test 2(b) Koenen test determines the sensitivity of solid and liquid substances to intense heat under high confinement where the confinement is a steel tube with a specified orifice plate size. The substance is heated within this tube, and the size of the orifice controls the pressure build-up. The violence of the reaction is assessed based on the resulting damage.

The goal of UN Series 2 testing is to determine if a substance is too insensitive to be classified as a Class 1 explosive (see [17] Section 25 and Figures 20.1 (a), 10.2 and 10.3). The use of "defined confinement" ensures the test results are repeatable and provides a standardized method for assessing the substance′s hazardous properties. According to UN Series 2 testing, "defined confinement" is the condition of testing a substance within a specific, rigid enclosure to determine its explosive behavior when subjected to shock, heat, or ignition under pressure. The specific test equipment and conditions define the level of confinement. The tests in this series are designed to evaluate if a substance is too insensitive to be included in the UN Class 1 for explosives. If pool chemicals are designated as Class 1 explosives, there maybe limits on packaging weight or sizes for transportation.

10 Conclusions

This paper conclusively demonstrates that pool chemicals can decompose at elevated temperatures when dry, and can violently decompose when partially wet and confined, or dry and confined. Confinement may be provided by the vessel or by the inertial loading of pool chemical powders/solids overburden or mass.

Pool chemicals fire and explosion hazards are exacerbated when pool chemicals are partially wetted (see Figures 4, 8, 11, and 14), and/or confined as shown by the test data presented in this paper.

The onset of decomposition for partially wet and confined pool chemicals can be as low as ambient temperature. We have provided conclusive measurements indicating that pool chemicals (when confined and/or partially wetted) should be classified as water reactive (~~W~~2) and possibly as Class 1 explosives [13].

[13] Further testing is needed to confirm or refute this proposed classification

11 References

[1] The Chemical Safety Board. Investigation update on the chemical decomposition, fire, and toxic gas release at Bio-Lab, Inc. Investigation Report 2024-04-I-GA, CSB, May 2025.

[2] FMC Corporation. Thermal decomposition studies of CDB-63, FMC-RR-68-5251-R, December 1968.

[3] The Chemical Safety Board. Chemical decomposition, fires, and toxic gas release at KIK consumer products / Bio-Lab, Conyers facility. Investigation Report 2024-04-I-GA, CSB, July 2026.

[4] G. A. Melhem. Managing chemical reactivity hazards in multipurpose equipment. In *AIChE/DIERS Virtual Spring Meeting*. AIChE, April 2024.

[5] G. A. Melhem. Managing chemical reactivity hazards in multipurpose equipment. *ioMosaic Corporation Publication*, October 2023.

[6] The Chemical Safety Board. Fatal chemical decomposition reaction and explosion at Optima Belle LLC. Investigation Report 2021-02-I-WV, CSB, July 2023.

[7] G. A. Melhem. A review of the Optima Belle runaway and explosion. In *AIChE/DIERS Virtual Spring Meeting*. AIChE, May 2025.

[8] G. A. Melhem. Reactivity screening made easy. *Process Safety Progress*, 23(2):99–107, 2004.

[9] G. A. Melhem. Systematic evaluation of chemical reaction hazards. In *2nd International Symposium on Runaway reactions, Pressure Relief Design and Effluent Handling*, pages 399–443. DIERS, AIChE, 1998.

[10] G. A. Melhem and E. S. Shanley. On the estimation of hazard potential for chemical substances. *Process Safety Progress*, 15(3):168–172, 1996.

[11] G. A. Melhem. A detailed method for the estimation of mixture flammability limits using chemical equilibrium. *Process Safety Progress*, 16(4), 1997.

[12] Jean-Michel Paul, Gerard Hecquet, and Jean-Luc Mieloszynski. Chloroisocyanurics - study of their ability to generate chloramines on their own or in the presence of nitrogenous species. *L'actualite' 10 chimique*, (274):10–15, 2004.

[13] A. R. Carpenter and R. A. Ogle. Toxic gas release caused by the thermal decomposition of a bulk powder blend containing sodium dichloroisocyanurate. *Process Safety Progress*, 22(2):75–83, 2003.

[14] NFPA 704. Standard system for the indentification of the hazards of materials for emergency response, 2007.

[15] NFPA 704. Standard system for the indentification of the hazards of materials for emergency response, 2022.

[16] T. Hofelich, D. Frurip, and J. Powers. The determination of compatibility via thermal analysis and mathematical modeling. *Process Safety Progress*, 13(4):227–233, 1994.

[17] United Nations. Manual of tests and criteria, Seventh revised edition, Amendment 1, 2021.

....

Index

ARC, 11, 12, 15–21, 23–29, 31

BCDMH, 25

CSB, 5, 13, 14, 29
Chemical reactivity, 37
CDB-56, 19
TCCA/CDB-90, 13

DSC, 10, 13, 15, 16, 18, 19, 23, 25
Decomposition, 13, 16, 19, 25
Dust, 37

Flammability, 37

ioKinetic®, 37
ioMosaic®, 36, 37
ISO certified, 37

NFPA, 28–30
NaDCC, 16

Process Safety Enterprise, 38
Process Safety Learning, 38
Process Safety Office, 38
Process Safety tv, 38

SuperChems® Expert, 9, 21

About the Authors

Dr. Melhem is an internationally known pressure relief and flare systems, chemical reaction systems, process safety, and risk analysis expert. In this regard he has provided consulting, design services, expert testimony, incident investigation, and incident reconstruction for a large number of clients. Since 1988, he has conducted and participated in numerous studies focused on the risks associated with process industries fixed facilities, facility siting, business interruption, and transportation.

Prior to founding ioMosaic® Corporation, Dr. Melhem was president of Pyxsys Corporation; a technology subsidiary of Arthur D. Little Inc. Prior to Pyxsys and during his twelve years tenure at Arthur D. Little, Dr. Melhem was a vice president of Arthur D. Little and managing director of its Global Safety and Risk Management Practice and Process Safety and Reaction Engineering Laboratories.

Dr. Melhem holds a Ph.D. and an M.S. in Chemical Engineering, as well as a B.S. in Chemical Engineering with a minor in Industrial Engineering, all from Northeastern University. In addition, he has completed executive training in the areas of Finance and Strategic Sales Management at the Harvard Business School. Dr. Melhem is a Fellow of the American Institute of Chemical Engineers (AIChE) and Chair of the AIChE Design Institute for Emergency Relief Systems (DiERS).

Contact Information

Georges. A. Melhem, Ph.D., FAIChE
E-mail. melhem@iomosaic.com

ioMosaic Corporation
93 Stiles Road
Salem, New Hampshire 03079
Tel. 603.893.7009, x 1001
Fax. 603.251.8384
web. www.iomosaic.com

How can we help?

Please visit www.iomosaic.com and www.iokinetic.com to preview numerous publications on process safety management, chemical reactivity and dust hazards characterization, safety moments, video papers, software solutions, and online training.

In addition to our deep experience in process safety management (PSM), chemical reaction systems, and the conduct of large-scale site wide relief systems evaluations by both static and dynamic methods, we understand the many non-technical and subtle aspects of regulatory compliance and legal requirements. When you work with ioMosaic® you have a trusted ISO certified partner that you can rely on for assistance and support with the lifecycle costs of relief systems to achieve optimal risk reduction and PSM compliance that you can evergreen. We invite you to connect the dots with ioMosaic®.

We also offer laboratory testing services through ioKinetic® for the characterization of chemical reactivity and dust/flammability hazards. ioKinetic® is an ISO accredited, ultramodern testing facility that can assist in minimizing operational risks. Our experienced professionals will help you define what you need, conduct the testing, interpret the data, and conduct detailed analysis. All with the goal of helping you identify your hazards, define and control your risk.

ioMosaic®
Minimizing risk. Maximizing potential.®

About ioMosaic Corporation

Our mission is to help you protect your people, plant, stakeholder value, and our planet.

Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of disciplines, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training, and software development.

As a certified ISO 9001:2015 Quality Management System (QMS) company, ioMosaic offers integrated process safety and risk management services to help you manage and reduce episodic risk. Because when safety, efficiency, and compliance are improved, you can sleep better at night. Our extensive expertise allows us the flexibility, resources, and capabilities to determine what you need to reduce and manage episodic risk, maintain compliance, and prevent injuries and catastrophic incidents.

Consulting Services

- Asset Integrity
- Auditing
- Due Diligence
- Facility Siting
- Fault Tree/SIL Analysis
- Fire & Explosion Dynamics
- Incident Investigation, Litigation Support, and Expert Testimony
- Hydrogen Safety
- LNG Safety
- LPG Safety
- Pipeline Safety
- Process Hazard Analysis
- Process Engineering Design and Support
- Process Safety Management
- Relief and Flare Systems Design and Evaluation
- Risk Management Program Development
- Quantitative Risk Assessment
- Software Solutions
- Structural Dynamics
- Sustainability Reporting Support
- Technology Transfer Package Development
- Process Safety Training

Laboratory Testing Services (ISO Accredited)

- Battery Safety Testing
- Chemical Reactivity Testing
- Combustible Dust Hazard Analysis and Testing
- Flammability Testing
- Physical Properties Testing
- Process Safety Services
- Specialized Testing

US Offices

Salem, New Hampshire
Houston, Texas
Minneapolis, Minnesota
Berkeley, California

International Offices

Al Seef, Kingdom of Bahrain
Bath, United Kingdom

Software Solutions

Process Safety Office®: A suite of integrated tools for process safety professionals and risk analysts.

Process Safety Enterprise®: Process Safety Management compliance made easy with enterprise workflows, dynamic forms, document management, key performance indicators and metrics, and more.

Process Safety Learning®: Build your process safety competencies incrementally using learning modules.

Process Safety tv®: The worldś first video streaming platform dedicated to process safety.

Contact us

www.ioMosaic.com
sales@ioMosaic.com
1.844.ioMosaic