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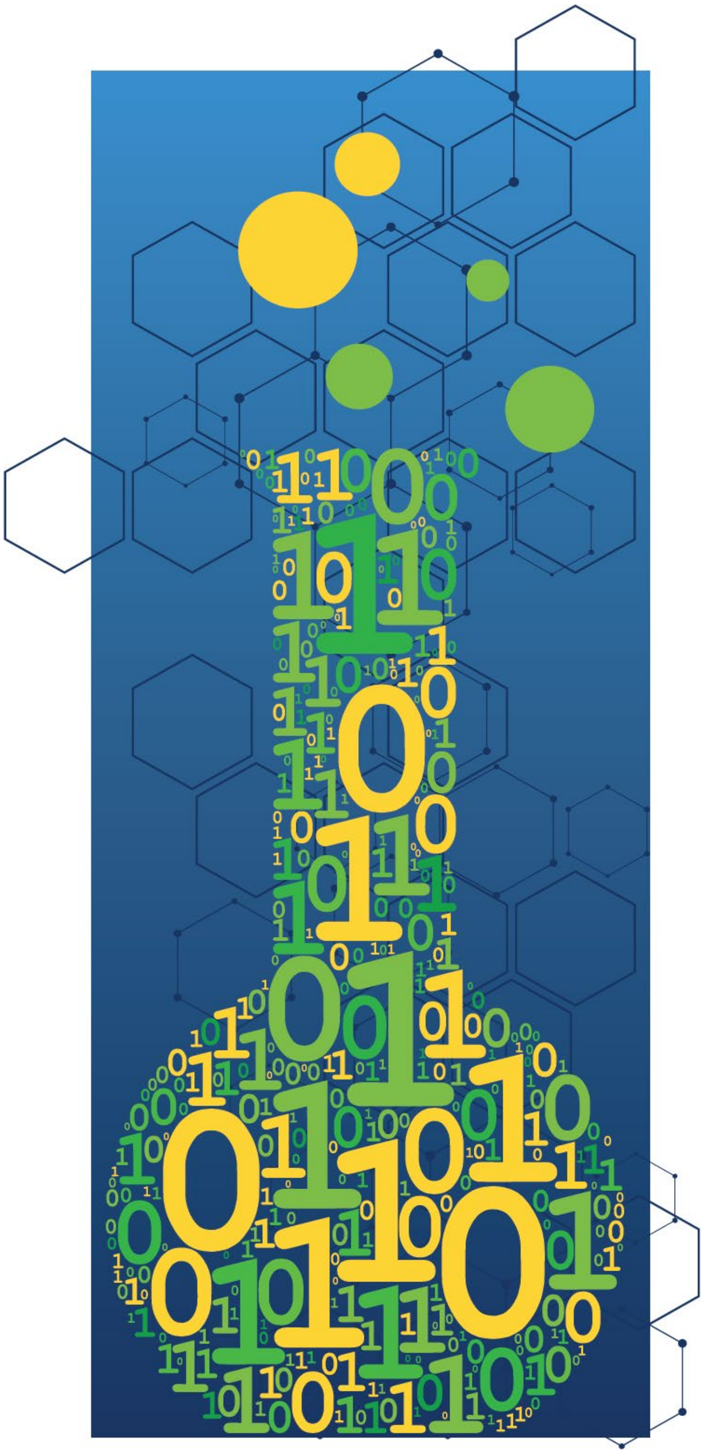

Managing Chemical Reactivity Hazards in Multipurpose Equipment

An ioMosaic Corporation White Paper

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Managing Chemical Reactivity Hazards in Multipurpose Equipment

Process Safety and Risk Management Practices

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Runaway reactions leading to catastrophic events continue to occur in multipurpose equipment [3]. Examples of causes that can lead to such catastrophic events include but are not limited to: (a) failure to identify and quantify runaway reactions hazards, (b) undersized pressure relief systems for unintended chemical reactions, (c) improper equipment selection and design, (d) cooling systems that are susceptible to single point failure, (e) process knowledge management, (f) management of organizational change and succession planning, and (g) deficient process safety information.

Many bench scale chemists developing new processes do not fully understand scaleup. Scaling up from a flask where heat exchange or loss is excellent and sufficient at laboratory scale can lead to near adiabatic conditions in large scale equipment and runaway reactions. A small exotherm at laboratory scale can yield a significant runaway reaction at pilot or plant scale. Because of the focus on process development of intended chemistries, unintended chemistries are often not quantified properly or overlooked. Research and development organizations need to collaborate with production facilities to understand what are the "unintended reactions" that could occur at pilot or plant scale.

It is not uncommon to have multiple raw materials, for a variety of products, all to be hard piped to the same vessel. Understanding the likelihood and potential for each of those raw materials to interact unintentionally in multipurpose equipment is key for process safety risk identification and management efforts. A simple skipped water charge, may be the worst case scenario resulting in an unintended runaway chemical reaction.

In addition, organizations are also challenged to properly manage their knowledge for high hazard chemistries. With organizational change happening much more frequently nowadays, it is even more essential that once a hazard is identified, the knowhow is properly managed and available independent of current staffing. Knowledge Management is a huge gap in numerous organizations, especially small and medium size enterprises.

Although many organizations can be vulnerable to such catastrophic events, they have not taken sufficient and proper steps to identify and truly understand chemical reactivity hazards.

> *"We cannot manage chemical reactivity hazards if we cannot first identify them"*

This paper provides guidance that can help you to better understand your organization's potential vulnerabilities that are related to chemical reactivity hazards.

2 Reducing Runaway Reactions Risks

Many chemical companies, toll manufacturers, and certified contract, development, and manufacturing organizations (CDMO) often use the same process equipment for the production of different chemistries or recipes.

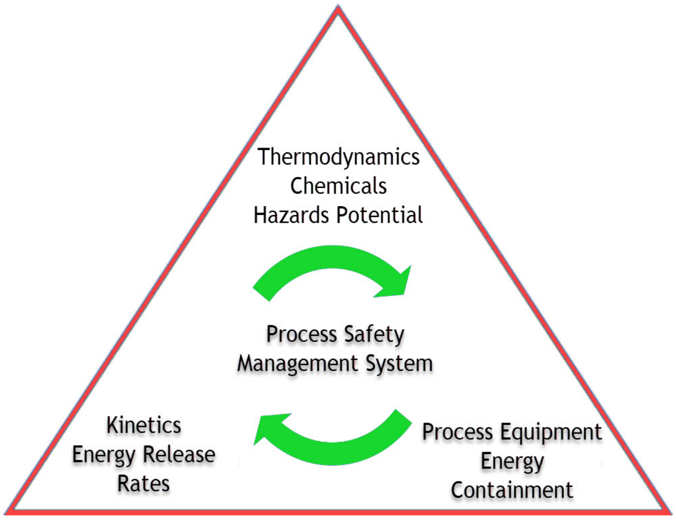
These companies face a significant challenge to properly and safely adapt the processing of the many different chemicals that they manufacture to their equipment. Typical multipurpose process equipments include chemical reactors, blenders, storage vessels, dryers, mixers, etc.

A thorough understanding is needed of (a) the hazard potential of the different chemicals and chemistries, (b) the chemical reaction rates for both desired and undesired reactions, and (c) the suitability of the process equipment to handle the scaleup with different process conditions and chemicals.

A robust process safety management system is also essential. Critical elements of an effective process safety management system include but are not limited to process safety information (PSI), management of change (MOC), asset or mechanical integrity (AI/MI), safe work permit, prestartup safety reviews, operating discipline, process hazards analysis (PHA), safety culture, and operator training.

Multiple disciplines are often involved in chemical hazards evaluation and scaleup. Proper scaleup and hazard management is enhanced by having people (or outside support) with a good understanding of reactive chemicals as well as people skilled in process design, operations, and risk management.

Figure 1: Chemical Reactivity Management Key Elements



The availability of an adequate reactive chemicals technology transfer package that enables safe processing and scaleup is paramount. For facilities regulated under OSHA's process safety management (PSM) standard, a technology transfer package for chemical reactivity also provides critical PSI for PSM compliance.

3 Chemical Energy and Hazards Potential

Given a sufficiently long duration and/or favorable process conditions, a chemical reaction can reach an equilibrium state (reactants $\leftarrow \frac{k_f}{k_r} \rightarrow$ products) where the forward rate of creation of reaction products, k_f, is equal to the reverse rate of destruction of reaction products, k_r:

$$\frac{dM_i}{dt} = \text{Rate of product } i \text{ creation} - \text{Rate of product } i \text{ destruction} = 0 \tag{1}$$

Where M_i is the mass of chemical species i. The use of a catalyst can speed the approach to equilibrium but does not change the equilibrium point [4].

A reaction rate can be expressed using an Arrhenius form with constant parameters that are typically suitable for a temperature range of approximately 100 to 500 K:

$$k = A \exp\left(-\frac{E}{R_g T}\right) \tag{2}$$

where k is the reaction rate (/s for a first order reaction), A is the pre-exponential factor, T is absolute reaction temperature, R_g is the universal gas constant, and E/R_g is the activation energy in Kelvin:

$$\frac{E}{R_g} = T^2 \frac{\partial \ln k}{\partial T} \tag{3}$$

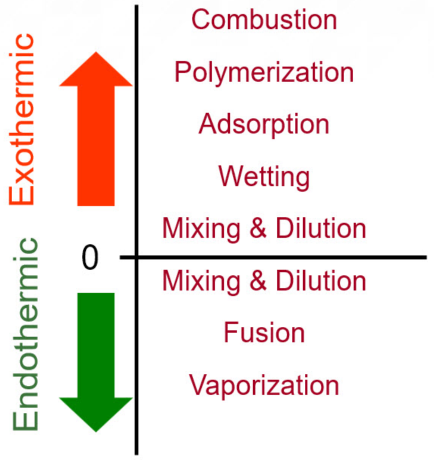
The impact of temperature on reaction rates is highly nonlinear. Higher temperatures lead to an exponential increase in reaction rates.

Although we can only establish the time required to reach equilibrium from kinetic rates, thermodynamics provides a constraint on kinetics because the kinetic ratio of k_f to k_r must be equal to the thermodynamic equilibrium constant, K_P:

$$K_P = \frac{k_f}{k_r} = \frac{A_f \exp\left(-\frac{E_f}{R_g T}\right)}{A_r \exp\left(-\frac{E_r}{R_g T}\right)} \text{ or} \tag{4}$$

$$\ln K_p = \ln\left(\frac{A_f}{A_r}\right) + \frac{E_r - E_f}{R_g T} \tag{5}$$

Figure 2: Typical Heats of Reactions



where K_P is the thermodynamic equilibrium constant in pressure units. K_P can be related to a concentration equilibrium constant K_c. Any parameter that does not effect K_P but that does effect kinetic behavior must effect k_f and k_r equally [4]. K_P is a function of temperature only. The thermodynamic equilibrium constant can be expressed as a function of the Gibbs free energy of reaction, the enthalpy of reaction, and/or the entropy of reaction:

$$\Delta G_{rxn} = -R_g T \ln K_P = \Delta H_{rxn} - T \Delta S_{rxn} \tag{6}$$

or

$$\ln K_P = \frac{\Delta S_{rxn}}{R_g} - \frac{\Delta H_{rxn}}{R_g T} \tag{7}$$

where G is the Gibbs free energy, S is entropy, and H is enthalpy. We note from Equations 5 and 7 that the entropy of reaction is related to the pre-exponential factor and the heat of reaction is related to the activation energy:

$$\Delta S_{rxn} = R_g \ln\left(\frac{A_f}{A_r}\right) \tag{8}$$

$$\Delta H_{rxn} = E_f - E_r \tag{9}$$

Measurement of equilibrium compositions can lead to accurate measurement of K_P and ΔG_{rxn}. We can also show that ΔH_{rxn} and ΔS_{rxn} can be obtained from two equilibrium constant values:

$$\Delta H_{rxn} = -R_g \frac{T_1 T_2}{T_2 - T_1} \ln\left(\frac{K_{P_1}}{K_{P_2}}\right) \tag{10}$$

where T_1 and T_2 are two different absolute temperatures such that $T_2 - T_1 \simeq 100$ K.

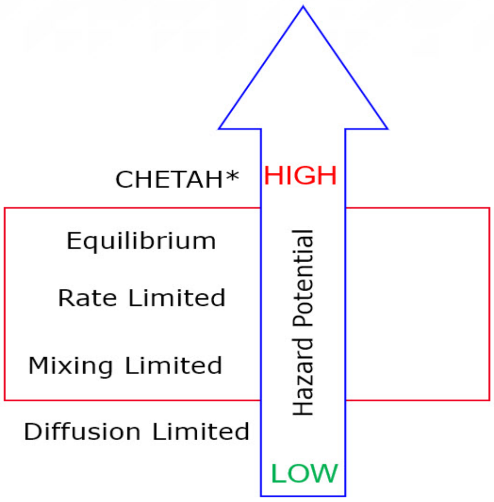
3.1 Chemical Hazards Potential

As discussed above and because of the strong dependence of kinetic rates on temperature and also the dependence of the thermodynamic equilibrium constant K_P on temperature, it is reasonable to screen and rank potential reaction hazards using the computed adiabatic reaction temperature (CART) obtained from direct minimization of the Gibbs free energy.

It is reasonable to estimate the potential hazards of chemical reactions using the gas phase state because reactions in condensed phases between nonpolar and slightly polar molecules do not differ greatly from gas phase reactions [4]. CART values should only be calculated using an equilibrium final state [5].

CART values calculated using maximization of the heat of reaction based on a stoichiometric balance that yields the most stable potential reaction products is not a good indicator of relative hazards potential for different chemicals or chemical mixtures (see [6, 7, 8]). CART values can be easily calculated using Process Safety Office® SuperChems Expert or the NASA chemical equilibrium code which can be accessed using CHETAH version 11 [9].

Figure 3: Hazard Potential Ranking



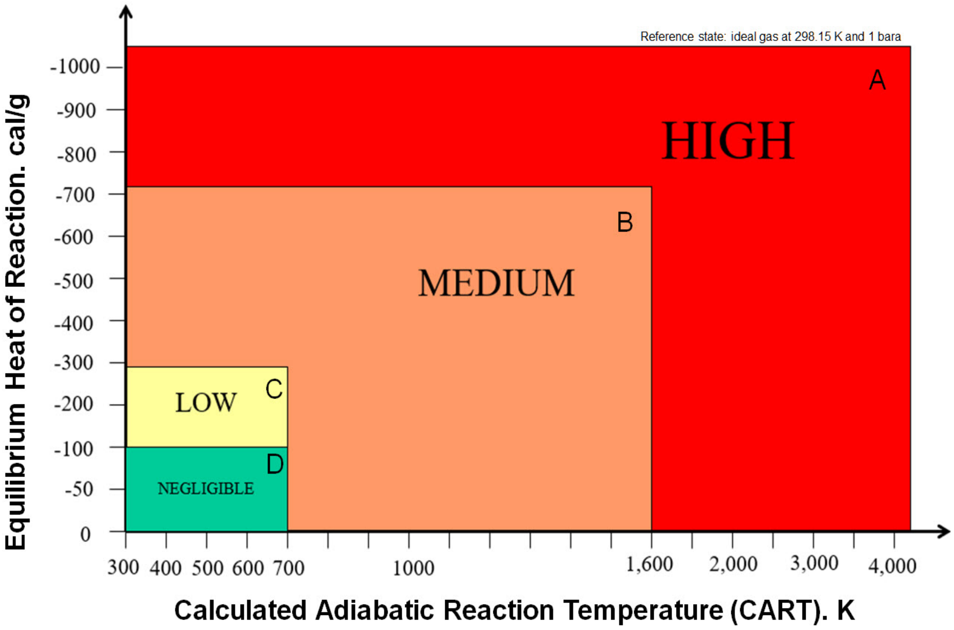
3.2 The Melhem Hazard Index

Since 1995 we have been conducting experimental and theoretical work to develop reliable chemical reaction hazard prediction methods [1, 10, 11, 12, 13, 14, 6, 7, 15, 16, 17, 18, 19, 2]. The Melhem index is based on the heat of reaction and the computed equilibrium adiabatic reaction temperature as illustrated in Figure 4 and summarized below:

A: HIGH hazard group Heat of reaction more negative than -717 cal/g (-3.0 kJ/g), or CART higher than 1,600 K.

B: MEDIUM hazard group Heat of reaction between -287 cal/g and -717 cal/g (-1.2 and -3.0 kJ/g), or CART greater than 700 K and less than 1,600 K.

Figure 4: The Melhem Chemical Reactivity Hazard Index [1]



C: LOW hazard group Heat of reaction between -100 cal/g and -287 cal/g (-0.42 and -1.2 kJ/g) and CART no more than 700 K.

D: NEGLIGIBLE or NO hazard group Heat of reaction no more negative than -100 cal/g (-0.42 kJ/g) and CART no more than 700 K.

This Melhem hazard index can be applied easily to a wide variety of reactions including condensed phase reactions such as decompositions, polymerizations, reactions of two or more species, gas phase reactions such as combustion reactions, deflagrations, and detonations, as well as reactions involving solids and dusts.

Reactions with a Melhem hazard index of A represent a high hazard and a strong potential for being explosive. Such reactions often involve the use of a very active/explosive ingredient and should only be carried out using a sufficient quantity of a diluent/solvent with a boiling point that is higher than the reaction onset temperature. These reactions may not be safe to undertake without substantial care and risk management.

A hazard index of B or C indicates a reaction system that may be energetic but that is not likely to result in an explosion hazard. These reactions can be conducted safely with proper safeguards that may include active temperature and pressure sensing and monitoring, relief devices, quench systems, etc. Reactions with a hazard index of D represent little or no reactivity hazard.

The Melhem index is supported by fundamental and experimental measurements [1]. It has been tested and validated over the past two decades using a variety of means including:

- Comparison of hazard prediction with compounds and reactions known to exhibit or known not to exhibit explosive behavior,

- Quantum mechanical validations using advanced computational tools,
- Blasting cap experimental studies, and
- Comparison of hazard prediction with compounds known to be flammable and/or detonate.

The Melhem index requires the calculation of the equilibrium heat of reaction and CART. This information can be obtained from chemical equilibrium programs such as SuperChems Expert. SuperChems Expert provides the ability to estimate CART for multiphase systems with non-ideal effects caused by pressure, heats of solution, etc. SuperChems Expert also has built-in routines that enable the user to trace CART isotherms as a function of mixture composition.

3.3 How to Calculate the Melhem Hazard Index

A starting number of moles for a single chemical or a chemical mixture is defined first. Automatic or user selection of potential reaction products is performed based on the chemical structure of the starting chemical(s). The equilibrium heat of reaction estimate is calculated at 25 $^\circ$C and 1 bara using a gas phase and also a solids phase when solids potential products are selected. A constant pressure adiabatic reaction temperature is then calculated at 1 bara to yield the value of CART. The two values are then placed on Figure 4 to determine the Melhem hazard potential index.

Chemical reactions that produce more moles of products than the starting number of moles of reactants can generate more mechanical energy or PV energy. Therefore we scale the CART value by the number of moles ratio obtained from direct minimization of the Gibbs free energy to yield an effective computed adiabatic reaction temperature, eCART:

$$\text{eCART} = \text{CART} \times \left(\frac{Np}{Nr}\right)^{1/3} \tag{11}$$

where N_p is the reaction products equilibrium number of moles, and N_r is the starting number of moles of reactants. Chemicals and/or mixtures of chemicals are ranked within hazard index groups A, B, C, and D according to their eCART values.

Although equilibrium estimates are easy to obtain using SuperChems Expert, thermodynamically consistent ideal gas formation energies and heat capacities are required. Fortunately, SuperChems Expert includes a large database of chemical species of more than 2800 records and methods for the estimation of thermodynamic and transport properties.

These thermodynamic quantities can also be obtained from measurements, additional group contribution methods, computational chemistry, chemical similarity, heats of combustion, NIST JANAF Tables, etc. Even with molecules containing atomic constituents other than C, H, N, and O, recent advances in computational chemistry [20, 21, 22, 23] have made it possible to augment missing groups in popular group contributions methods such as Benson's [4] method. Experimental measurements of heats of combustion can be used to determine reliable values of the formation energies.

In addition to the required Gibbs free energy minimization atom matrix constraints, user defined and other measurements constraints can be specified using SuperChems Expert to extract rate limited stoichiometries from calorimetry data [5].

3.4 Chemical Interaction Matrices

Prior to the calculation of the Melhem index to assess the relative hazard potential of chemicals and/or mixtures of chemicals, the development of a chemical interaction matrix can provide insight into which mixture of chemicals may have a higher reactivity potential [24] before detailed chemical equilibrium calculations.

The SuperChems Expert chemical interaction matrix tool is included with the SuperChems Reactivity Expert [25] and is based on known interactions of 147 chemical groups. New chemicals can be added to the SuperChems hazards database and associated with one or more of the 147 chemical groups based on chemical structure. Instructions on how to quickly develop a chemical interaction matrix with SuperChems Expert are provided in reference [24].

Additional tools are available in the public domain for the creation of chemical interaction matrices. The Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) provides a Chemical Reactivity Worksheet tool (CRW) based on known interactions of 68 chemical groups [26, 27]. CRW is available as a free download from the CCPS website.

Another useful tool that is available on the web is the CAMEO Chemicals: Chemical Response Data sheets and Reactivity Prediction Tool. CAMEO is provided by EPA.

CAMEO Chemicals is an extensive chemical database with critical response information for thousands of chemicals. CAMEO includes chemical data sheets that provide physical properties, health hazards, information about air and water hazards, and recommendations for firefighting, first aid, and spill response. UN/NA data sheets provide response information from the Pipeline and Hazardous Materials Safety Administration's Emergency Response Guidebook and shipping information from the Hazardous Materials Table [49 CFR 172.101].

In addition to the information on the CAMEO data sheets, a user can add chemicals to the "MyChemicals" collection to see what hazards might occur if the chemicals in the collection were mixed together. Another useful online resource that reference CAMEO Chemicals is PubChem.

3.5 Hazard Potential Screening of Multiple Recipes

When dealing with the processing of multiple chemicals and/or different chemical recipes or reaction steps in the same equipment, first develop a chemical interaction matrix to determine the mixture reactivity potential of each recipe or mixture.

The chemical interaction matrix should include expected contaminants such as water, rust, heat transfer fluids, chlorides, etc. An overall chemical interaction matrix should also be developed for the entire process or unit or site. Include any cleaning solvent/solution that may be used in between products. Also consider materials of construction issues.

For those mixtures that are predicted to be reactive based on their reactive groups classifications and interactions, calculate their Melhem hazard index. Also calculate the Melhem hazard index for the decomposition of each of the reactants.

"In general, safety data sheets (SDS) are not sufficient as they do not always contain accurate physical properties and/or thermal stability and reactivity data about either pure chemicals, mixtures of chemicals, or combustible dusts."

The mixture(s) or chemical(s) that yield the highest value of the Melhem Index can then be subjected to further reactivity screening testing and calorimetry testing to determine the potential energy release rates at storage, packaging, transportation, and processing conditions of interest. Chemical energy release rates or reaction rates are best established using testing and measurement (see Figure 5).

4 Chemical Energy Release Rates

The theoretical screening methods outlined earlier are not intended to replace testing. They are intended to refine and focus testing as it is often impractical to test hundreds of possible mixtures and chemicals. Furthermore, at early stages of development there may not be enough chemical samples that can be used for testing. Theoretical screening can help to prioritize testing after risk ranking the hazard potential of chemicals and chemical mixtures.

4.1 Overview of Common Testing Methods

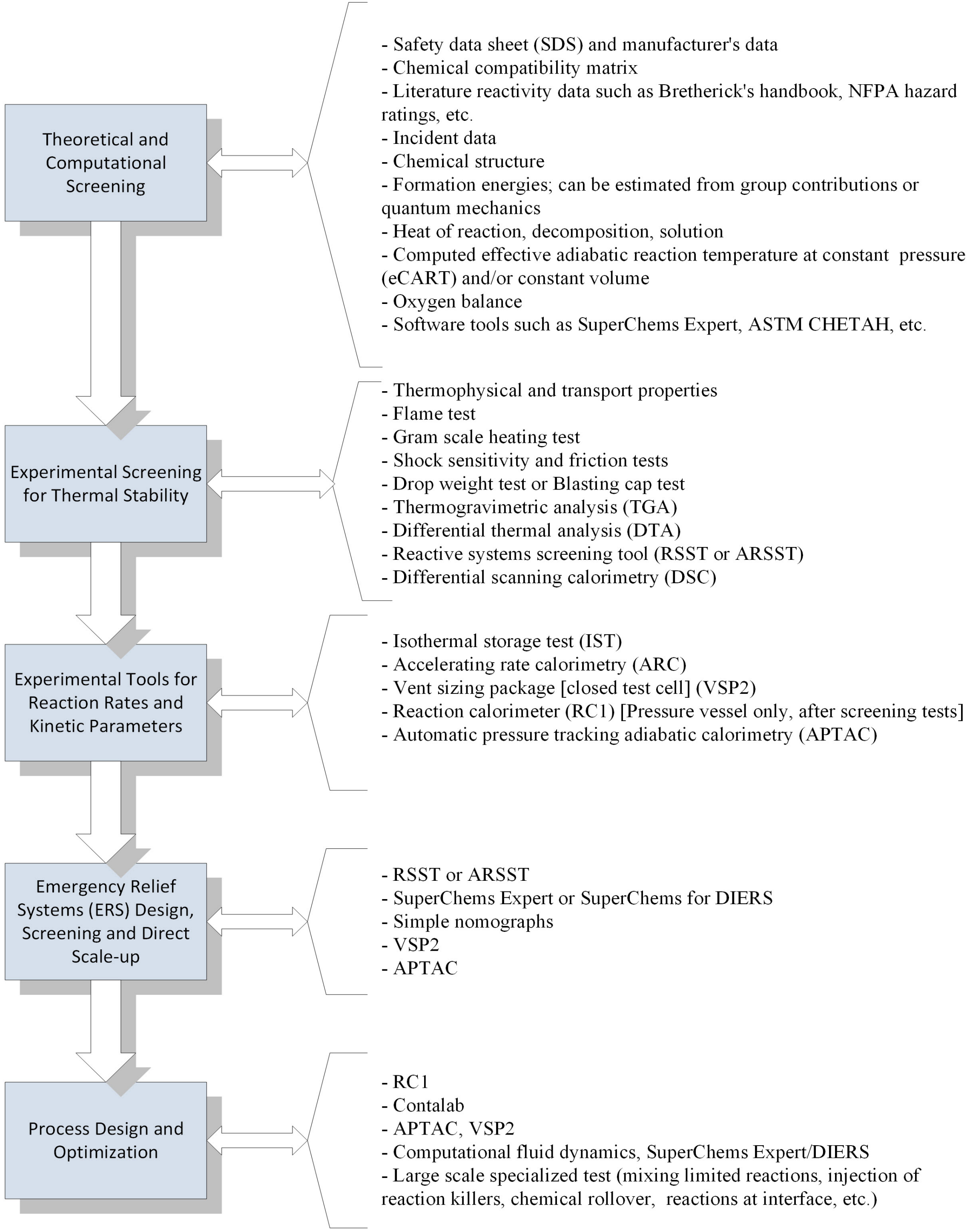
There is no such thing as a standard "tell me all I need to know" test for chemical reactivity (see Figure 5). Chemical reactions can behave differently when tested under confinement (closed test cell) or without confinement (open test cell). Test data can be apparatus dependent. The thermal inertia and detection sensitivity of the test equipment should be well understood. Corrections or reduction of test data are often required to ensure the data is appropriate for plant scale. Some reaction systems may exhibit autocatalytic behavior, while other reaction systems can be influenced by viscosity, inhibitor depletion, peroxide formation, catalyst deactivation, and/or vessel surface area. Some reactions can form highly unstable and detonable intermediates.

Expert interpretation of test data can be extremely useful in determining if the measured data is reliable or not. Not every measured data set is a good data set. Critical tests should be repeated. ISO certified testing laboratories should be used if testing is to be contracted to 3rd party testing laboratories.

4.2 Useful Testing Data

In general the following information can be obtained from the chemical reactivity testing methods outlined in Figure 5 for both desired and undesired chemical reactions:

Figure 5: A Typical Chemical Reaction Hazards Systematic Evaluation Process [2]



- Heat release rates, or $\frac{dT}{dt}$ where T is temperature and t is time
- Pressure rise rates, or $\frac{dP}{dt}$ where P is pressure
- Detected onset temperature
- Overall adiabatic heat of reaction
- Overall adiabatic temperature rise
- Shock sensitivity
- Friction sensitivity
- Time to maximum rate temperature for 8 hours, 24 hours, and 48 hours
- Thermal diffusivity
- Thermal effusivity
- Final ratio of non-condensible components after reaction completion
- Chemical identity of reaction products and/or intermediates

We note that the detected onset temperature is instrument specific and depends on the sensitivity and thermal inertia of the instrument. The detected onset temperature cannot be directly used at plant scale without correction for thermal inertia and the heat loss characteristics of the vessel or system where storage, transportation, or processing is taking place.

Test data can be used to develop kinetic models for thermal stability [28] and for pressure relief and vent containment design as well as process optimization [29].

5 Process Equipment and Containment

Process equipments provide the first layer of protection and first level of containment in case of loss of control during a chemical reaction. Loss of control occurs when the heat generation rate by the reaction system exceeds the heat loss or cooling rate by the equipment system. Total containment is not practical in most situations.

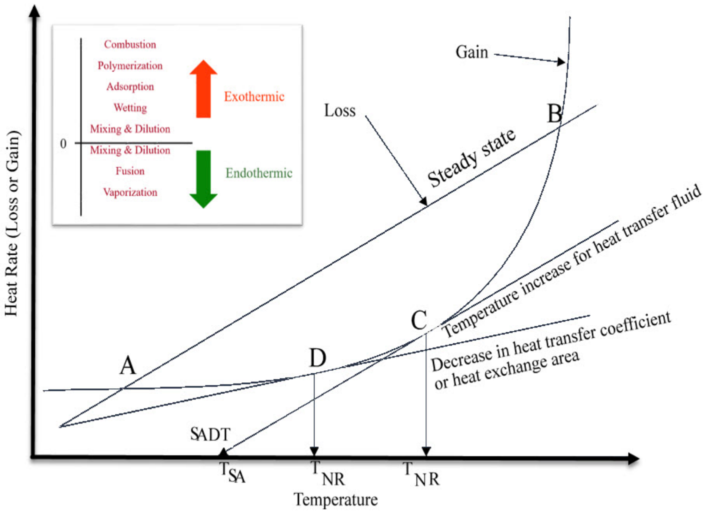
5.1 Runaway Reactions Conditions

Complete loss of control leading to runaway conditions occurs when the reacting system temperature exceeds the temperature of no return, T_{NR}. It is not possible to bring the reaction back under control if the temperature exceeds T_{NR}. T_{NR} depends on reaction rates, the geometry of the equipment, thermal capacity of the equipment, heat transfer rates, and transport properties of the reacting mixture. T_{NR} is different than the self accelerating reaction temperature T_{SA} or self accelerating decomposition temperature, T_{SADT} (see [30]). A critical aspect of managing chemical reaction hazards is temperature control as shown to the right in Figure 6.

Understanding and quantification of acceptable temperature safe operating limits are necessary. The safe temperature operating limits have to be documented as critical PSI. T_{NR}, is an important indicator and a maximum safe operating limit. It is the temperature beyond which the reaction heat generation exceeds the cooling capacity of the system.

A variety of scenarios leading to loss of reaction control that can challenge the mechanical integrity of the equipment should be considered [1] when qualifying equipment for the required chemical service and production rates. Normally these scenarios are considered in a process hazards analysis or a risk assessment before startup.

Figure 6: Loss of Temperature Control Leading to Runaway Reaction Conditions



5.2 Scenarios Leading to Runaway Reactions

The following list of scenarios is by no means exhaustive. It is intended to illustrate that reactive chemicals hazard assessments have to consider scenarios that otherwise may not be considered for non-reactive chemicals:

Operational Error:

Erroneous introduction, overcharge, undercharge, or omission of reactant and/or catalyst/initiator which causes the reaction to accelerate at its normal operating temperature or the introduction of an incompatible reactant to the vessel contents such that the reaction is immediately fast at the existing contents temperature.

Hot Spots:

Hot spots are usually caused by the failure of agitation where the system fails to maintain a homogeneous temperature below certain onset limits. High local temperatures can initiate fast propagating reactions. This is especially important for high viscosity systems.

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[1] In addition to non-reactive chemicals scenarios such as regulator failure, blocked discharge, etc.

Reactant Accumulation:

This can occur in a semi-batch process where the reaction is controlled by the slow introduction of a specified reactant. At low reaction temperatures, the consumption rate of reactant is less than the feed rate. As a result, the reactant accumulates in the reactor vessel. Later, a small increase in temperature and/or the higher concentration of reactant can cause runaway conditions. Reactant accumulation can also occur in co-feed systems when reactant ratio is not properly controlled.

Phase Separation:

Here, the reaction mixture splits into separate phases, where one or more phases are unstable. For example, liquid phases can split due to loss of mixing or poor mixing. Solid phases, for example crystallization, can occur due to cooling and can lead to deposits of unstable solids on the reactor walls.

Heating/Fire:

Internal, external, or fire heating can lead to runaway conditions. This can lead to highly accelerated reaction rates because the onset temperature is reached with less reactant consumption and also because of additional vapor generation and the thermal expansion of vessel contents. A fire allows the vessel pressure to reach a set point of the relief device with less reactant consumption. A fire can cause an inhibitor to be depleted at elevated temperatures causing spontaneous reactions. The effect of fire on reaction rates in highly nonlinear, involves complex analysis, and requires kinetic rate expressions and dynamic modeling.

Extended Residence Time:

This occurs most frequently with autocatalytic reactions after an extended reaction/cycle time. An autocatalytic reaction produces its own catalyst or one of its controlling reactants after some induction time at constant temperature. The logarithm of the induction time is usually a linear function of the inverse temperature. Thermal cycling can also lead to the increase of autocatalytic behavior because each successive thermal heating and cooling cycle creates additional catalyst and/or additional controlling reactants.

Chemical Rollover:

The slow addition of an incompatible material with limited solubility and without mixing can create two reactive immiscible liquid layers. A slow chemical reaction occurs at the interface between the two layers over a long period of time generating small amounts of heat and gas. The gas may be absorbed by one or both of the liquid layers. After some time (delay), the two layers invert or flip over due to density change and mix vigorously to generate large amounts of gas from both the superheated liquid and/or the spontaneous reaction of the two layers.

Inhibitor Depletion:

Inhibitor depletion can occur due to extended residence time, inadequate mixing in large tanks, and condensation in the vapor space. For example, when inhibited styrene monomer condenses on the vapor walls of a storage tank, the condensed styrene liquid will be without inhibitor.

Preferential Depletion of Reactants:

This is a classic scenario often encountered is batch or semi-batch operations. A highly reactive ingredient is mixed with a solvent to temper and slow down the reaction rates and to dilute the concentration of the reactive ingredient. Depending on the amount of solvent used and the boiling point of the solvent, additional heating or fire heating can cause the solvent to be preferentially depleted leading to a highly concentrated active ingredient which can explode or spontaneously decompose.

Agitator Failure:

Many reaction systems rely on agitation to ensure uniform temperature profiles and reaction rates. When an agitator fails, phase separation can occur which can lead to runaway conditions. When an agitator start is delayed due to human or control system errors after heating had started, faster reactions can occur due to elevated temperatures and stratification which can lead to runaway conditions. When an agitator is erroneously left running for extended periods of time, heat is added to the system. Depending on the vessel contents and the overall system heat loss capabilities, the heat addition can lead to runaway conditions.

An agitator shaft can become misaligned during operation or the agitator blades can detach causing friction and hot spots from contacting the vessel metal walls or bottom plates or screens. The heating created by friction can cause decomposition of materials since friction heating can create very high localized temperatures (hot spots). Agitator seal leaks can introduce incompatible materials into a reactor.

Other Scenarios:

There are numerous other scenarios that can lead to runaway conditions such as (a) fast closure of valves causing substantial compression heating of materials like ethylene or ethylene oxide that can decompose, (b) deadheading of a pump, (c) cooling coil or heating coil failure leading to leaks of incompatible materials, (d) contamination causing an unexpected decomposition (i.e. peroxide decomposition), etc. A thorough understanding of the thermal stability of individual reaction components and the overall mixture is necessary.

5.3 Heating and Cooling

Temperature control is critical for reactive chemicals safety. Many reactions involve multiple steps where heating is applied first to be later followed by cooling when the reaction is complete. Many reactors or process equipment rely on jacket cooling and heating, internal coil heating or cooling, evaporative cooling, or reflux condensing. The heating and cooling capacities of the equipment used must be verified prior to use of the equipment. The achievable rate of cooling or heating depends on many factors including but not limited to the rate of reaction, the geometry of the vessel, the degree of mixing within the vessel, the viscosity of the reacting mixture, the vessel wall thickness and the presence of insulation, the thermal diffusivity and effusivity of the reacting mixture, etc.

5.4 Equipment Materials Selection and compatibility

Materials of construction should be confirmed to be compatible with the intended chemical service. The selected material of construction cannot chemically interact with the contents and should be corrosion resistant. Changes in pH during the batch reaction steps should be considered when selecting materials of construction.

Instrumentation, valves, fittings, and piping components have to be confirmed to be compatible for the chemical service. Carbon steel or even stainless steel components may corrode quickly when in contact with some chemicals or when in contact with reacting mixtures intermediates or products during the reaction. Materials of construction thickness, pressure, and temperature ratings have to be checked and confirmed suitable. A glass lined reactor may lose its glass lining integrity if it is heated or cooled too fast. In some cases where deflagrations are possible in the vapor space of a reactor, blender, or storage vessel, pressure ratings in excess of 75 psig may be required.

5.5 Pressure Relief and Safe Discharge Location

For reactive chemicals a pressure relief systems may be the last line of defense, but it should not be the only line of defense [31]. Although temperature control and monitoring is very important for reactive systems, additional and independent layers of protection are needed. When combined, all the independent layers of protection should have a sufficient safety integrity level to reduce risk to a tolerable level.

There are two widely used methods for pressure relief design for reactive chemicals: (a) dynamic computer simulation [32, 16] and (b) direct scaleup [33, 34]. It is highly recommended to use the dynamic simulation method because direct scaleup methods do not provide sufficient information for the design and/or evaluation of any downstream interconnected equipment. In addition, safe discharge location considerations require additional information for dispersion, thermal radiation, and overpressure estimation. Direct scaleup methods can validate if an existing vent will be adequate for a specific chemical recipe using one test for each specific set of conditions for fill level, chemical composition, and initial process conditions.

Venting from chemical runaway reactions usually results in multiphase flow. Because of the different types of reactions (tempered, gassy, hybrid) [34], single phase venting might result in worst credible case estimates for relief requirement and/or reaction forces. It is possible to scale down the size of a chemical batch in fixed equipment with fixed relief capacities to ensure the vessel design limits are not exceeded if a runaway reaction occurs during processing. Safe discharge consideration might necessitate the installation of effluent handling and vent containment systems [35].

6 Chemical Process Safety Management Systems

Proper chemical reactivity management requires a coherent and forever green process safety management system. The need for such a management system (as well as a knowledge management system) was recognized long ago by industry, industry associations, labor unions, and government agencies.

6.1 OSHA's Process Safety Management Standard

Fourteen important process safety management elements (see Figure 7) were established in 1992 when OSHA developed the process safety management standard. Much later, AIChE/CCPS recommended additional PSM elements and developed useful leading and lagging metrics for the management of chemical process safety. In addition CCPS published guidelines for process safety in outsourced manufacturing operations [36] as well a numerous other guidelines dealing with different aspects of process safety management.

Process safety information (PSI) and asset/mechanical integrity (AI/MI) data are typically deficient in chemical processing facilities. Note that the OSHA PSM standard is a performance based standard and not a prescriptive standard.

6.2 Process Safety Management System Automation

Even for small chemical processing facilities, keeping PSM data forever green is a daunting task. Process safety management is a long term and drawn out process that is integral to the safe operation of an entire facility over its lifetime. PSM data is highly interconnected, especially for PSI and AI/MI.

Most PSM data is not structured data. For example, pressure relief systems design basis documentations can include photographs, spreadsheets, legacy scanned data sheets, inspection records, etc. Management of change (MOC) and safe work permits require varying levels of approval, delegation, and notification. Doing all this with paper systems or disjointed systems where different PSM elements reside on different platforms can increase the likelihood of errors and omissions and can substantially increase risk for an operating facility instead of reducing risk.

ioMosaic's Process Safety Enterprise® management system offers automation and interconnectivity for all fourteen PSM elements using visual workflows, intelligent dynamic forms, knowledge

Figure 7: Essential Elements of a Chemical Process Safety Management System

management, and document management. The ioMosaic system is an enterprise subscription system that is cloud based. Process Safety Enterprise can be setup easily and can handle single or multiple sites.

7 The Technology Transfer Package

A chemical reactivity technology transfer package should be prepared and transmitted to the manufacturing site or CDMO. The package should have sufficient information about the properties of the chemicals, as well as energy release rates for both intended/desired chemistries and unintended chemistries. Recommended safe operating limits should be included. Properties should include relevant thermodynamic, flammability, toxicity, environmental, and transport properties. A variety of thermal stability indicators [30] can be included to improve the safety of storage, transportation, and processing of reactive chemicals at the manufacturing sites and elsewhere. A well developed technology transfer package will contain most if not all the required chemical reactivity process safety information for PSM regulated facilities.

When scaling up from laboratory scale or pilot scale to plant or larger scales, a CDMO should be able to use the technology transfer package to establish requirements for product quality management, heating and cooling rates, safe drying temperatures, pressure relief and vent containment, safe discharge location, regulatory and process safety management compliance, waste treatment, equipment sizing, and equipment materials selection and compatibility. ioMosaic can assist with the preparation and maintenance of technology transfer packages and knowledge management.

8 Conclusions

Balancing safety, compliance, and productivity can be achieved for facilities using multipurpose chemical processing and storage equipment. If chemical reaction hazards are not identified early on, they cannot be properly managed later on. There are numerous existing, proven, and efficient tools and systematic processes than can be used to identify and manage chemical reactions hazards.

The creation and formal transmittal of a chemical reactivity technology transfer package to the manufacturing site or CDMO is essential for plant and worker safety.

9 Acknowledgments

The author would like to recognize the review contributions and recommendations of Judy Perry.

10 Additional ioMosaic White Papers Resources

It is not possible to cover all the various aspects and facets of chemical reactivity management in one white paper. The resources provided below address in more detail several key topics and can be requested from sales@iomosaic.com or melhem@iomosaic.com:

Chemical Reactivity Management

1. Systematic Evaluation of Chemical Reaction Hazards
2. Quickly Develop Chemical Interaction Matrices with SuperChems
3. Thermal Stability Indicators
4. Calculate Phase and Chemical Equilibria Using Process Safety Office SuperChems Expert
5. An Advanced Method for the Estimation of Reaction Stoichiometry and Rates from ARC Data
6. Development of Kinetic Models - Part I. Thermal Stability
7. Development of Kinetic Models - Part II. Pressure Relief Systems
8. Forget Direct Scaleup Vent Sizing and Master Kinetic Modeling Instead
9. Polymerization Modeling for Emergency Relief Systems
10. Polymerization Reactions Inhibitor Modeling - Styrene and Butyl Acrylate Incidents Case Studies
11. Polymerization Models for Butadiene, Vinyl Acetate, Acrylates, Acrylonitrile, and Isoprene

Pressure Relief and Vent Containment Design

1. Two-phase Flow Onset and Disengagement Methods
2. Vent Containment Design For Emergency Relief Systems
3. Forget the Omega Method and Master vdP Integration Instead
4. Advanced Pressure Relief Design Using Computer Simulation
5. Beware of Temperature Increase During Rapid Vessel Charging
6. Heat of Vaporization Considerations for Relief Systems Applications
7. Properly Calculate Relief Systems Reaction Forces

8. Realize Better Risk Characterization of STHE Tube Failure Scenarios Through Relief Systems Dynamics Modeling
9. Relief and Flare Systems Statics vs Dynamics
10. Relief Requirements for Distillation Columns
11. Retrograde and Phase Change (RPC) Flow Considerations for Relief and Depressuring Systems
12. Retrograde and Phase Change (RPC) Flow Considerations for Relief and Flare Systems
13. Single and Multiphase Control Valve Flow
14. The Anatomy of Liquid Displacement and High Pressure Fluid Breakthrough
15. Thermal Expansion Relief Requirements for Liquids, Vapors, and Supercritical Fluids
16. Quantify Non-Equilibrium Flow and Rapid Phase Transitions

PRV Stability

1. Analysis of PRV Stability In Relief Systems - Detailed Dynamics - Part I
2. Analysis of PRV Stability In Relief Systems - Screening - Part II
3. Analysis of PRV Stability In Relief Systems - How to Avoid the Singing PRV Problem - Part III
4. Analysis of PRV Stability In Relief Systems - On the Estimation of Speed of Sound - Part IV
5. Analysis of PRV Stability In Relief Systems - Get a Handle on PRV Stability - Part V
6. PRV Stability Inlet Line Critical Length
7. PRV Stability - Bridging the 3 Percent Pressure Loss Rule Gap

Fire and Explosion Modeling

1. Fire Exposure Modeling Considerations
2. RAGAGEP Considerations for Overtemperature Protection in Relief Systems
3. Calculate Flammability Limits Using Process Safety Office ®SuperChems Expert
4. How Flame Arresters Work
5. Development of Reduced Analytical Models for Explosion Dynamics
6. Quantify Explosion Venting Dynamics in Vessels Enclosures and Energy Storage Systems

Process Safety Management and Automation

1. Effectively Manage Mechanical Integrity in Process Safety Enterprise®
2. Effectively Manage Changes to Processes, Chemicals, Equipment, and Personnel Using Process Safety Enterprise®
3. Properly Evaluate Building and Facility Siting Risks
4. Emergency Response and Process Hazard Analysis Charts
5. Usage of AEGL Dosage in Safety and Risk Studies
6. Driving Safety and Business Performance Through Data Mining

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11 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 Vice Chair of the AIChE Design Institute for Emergency Relief Systems (DiERS).

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12 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) 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.

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About ioMosaic Corporation

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 areas, 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.

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