Managing Chemical Reactivity - Minimum Best Practice

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ABSTRACT

A minimum best practice (MBP) is proposed to provide enough information to process, store and transport chemicals safely. The primary objective of the MBP is to reduce the frequency and consequences of runaway reaction-generated accidents, particularly those occurring within companies with limited technical and financial resources.

1. INTRODUCTION

Cost-effective approaches to chemical reactivity management regulation are needed that promote effective management of chemical reactivity hazards by small and medium-sized companies, as well as major producers. While many large companies adequately manage chemical reactivity using available best practice (ABP), a minimum best practice (MBP) is needed in forms conducive for use by small and medium-sized companies with limited resources. The problem is one of getting everyone to do what is the minimum necessary.

ABP provides the greatest reduction in risk (frequency x consequences), while MBP provides an acceptable level of risk, taking into consideration the economic aspect.[1] Here we note that the most effective way to reduce risk associated with runaway incidents is to provide simple, easy to use, and well-verified affordable methods that can give employees of resource-limited firms the skill and knowledge to decide for themselves what is adequately safe which is the best way to promote safety awareness and make safety second nature.

2. MINIMUM BEST PRACTICE (MBP)

The key components of the MBP include acquisition of adequate reaction rate data ($\dot{T}$ and $\dot{P}$)[2] allowing assessment of either prevention or accommodation of uncontrolled reactivity that satisfies the following desired attributes:

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[1] Costs of implementation as well as benefits on direct losses, insurance costs, etc.

[2] Here we note that various proposed methods such as Literature Review for Potential Hazards (material safety data sheets - MSDS), Bretherick, Lees, etc., NFPA ratings, Functional Groups, ΔH_F, ΔH_R, ΔT_{ad}, CART, etc., CCPS materials (Safety Alerts; Reactive Materials Hazards; Essential Practices for Managing Chemical Reactivity Hazards), are not specific enough, i.e., the need for rate data (rate of temperature rise, $\dot{T}$, and rate of pressure rise, $\dot{P}$) is essential to reduce the risk from runaway reactions.

- Inexpensive
- Quick
- Minimal reactive hazard expertise needed
- Can apply to individual species and mixtures
- Compatibility (acid/base etc.)
- Contamination (water, metal, etc.)
- Provide activation energy, pre-exponential factor
- Few or no properties required
- Provides clear direction - prevention or accommodation
- No "false-negatives" (reliable)

As such, the common misconception that acquisition of rate data and interpretation require significant reactive hazard expertise,[3] is very time consuming and costly[4] can be corrected by adopting the Reactive System Screening Tool (RSST) [1], or the Advanced Reactive System Screening Tool (ARSST) [2], as a MBP standard as illustrated in Table 1.

Table 1. Reactivity Hazard Evaluation Tools

Available Best Practice (ABP)	**Minimum Best Practice (MBP)**
Large Companies[5]	Limited Resources
- Initial Screen Literature Calculation/Prediction	- Initial Screen Literature
- Analytical Screen Mixing calorimetry DSC	- Analytical Screen RSST/ARSST
- Quantitative ARC Specialized calorimetry	- Quantitative RSST/ARSST
- Scale VSP Reaction calorimetry Modeling	- Scale RSST/ARSST Calculations

[3] Quoting Reactive Materials Hazards – What You Need to Know, CCPS, October 1, 2001: A number of sophisticated tools can be of assistance in these areas. Two of the more common tools are the Differential Scanning Calorimeter (DSC) and the Accelerating Rate Calorimeter (ARC). The resulting data can then be used to properly size heat transfer equipment and relief devices, as well as establish safe limits of operation. You may need to get professional assistance to gather the data you require.

[4] Quoting U.S. Chemical Safety and Hazard Investigation Board, Hazard Investigation, Improving Reactive Hazard Management, December 2002: Compared to DSC screening calorimetry, adiabatic calorimetry (ARC and PHI-TEC are noted) is more costly and time intrusive.

[5] Kenan Stevick and Tim Overton, CSB/OSHA/EPA Roundtable, June 10, 2003.

Screening using differential scanning calorimetry (DSC) is more expensive and is generally not capable of providing information required for assessing thermal or chemical stability. More advanced calorimetry such as Accelerating Rate Calorimetry (ARC™) and Vent Sizing Package (VSP™) require more reactive hazard expertise, are more time consuming and much more expensive than the RSST/ARSST™ calorimeter concept. As such, it is more appropriate to consider tools like ARC and VSP, as part of available best practice (ABP).

The inexpensive and easy to use RSST/ARSST is ideally suited for use by small and medium-sized companies with limited resources. Minimal reactive hazard expertise is needed as best illustrated by the extensive use of the RSST/ARSST as an undergraduate unit operation laboratory tool (Purdue University, Carnegie Mellon University, University of Michigan, University of Costa Rica, Northwestern University, Wayne State University, Michigan Technological University, Texas A&M, University of Iowa, University of Minnesota, University of Malibor, Slovenia, Unversidad de Zaragoza, Spain, University of Yokohama, Japan, and Memorial University, Canada). Currently about 200 units are used worldwide, and no serious incidents are known by the author to have occurred at companies making use of the RSST/ARSST as part of their chemical hazard safety assessment.

Rate data from the RSST/ARSST can be used directly to assess prevention and accommodation of uncontrolled chemical reactivity. Its capabilities are illustrated by the recent DIERS Users Group Round-Robin Testing of the Styrene-MMA-AIBN System [3]. Figure 1 illustrates ARC data for this system. Note that these data cannot be used directly for scale-up. Peak rates are only about 10°C/min with a peak temperature of about 210°C. The number of exotherms are not clearly defined by these data.

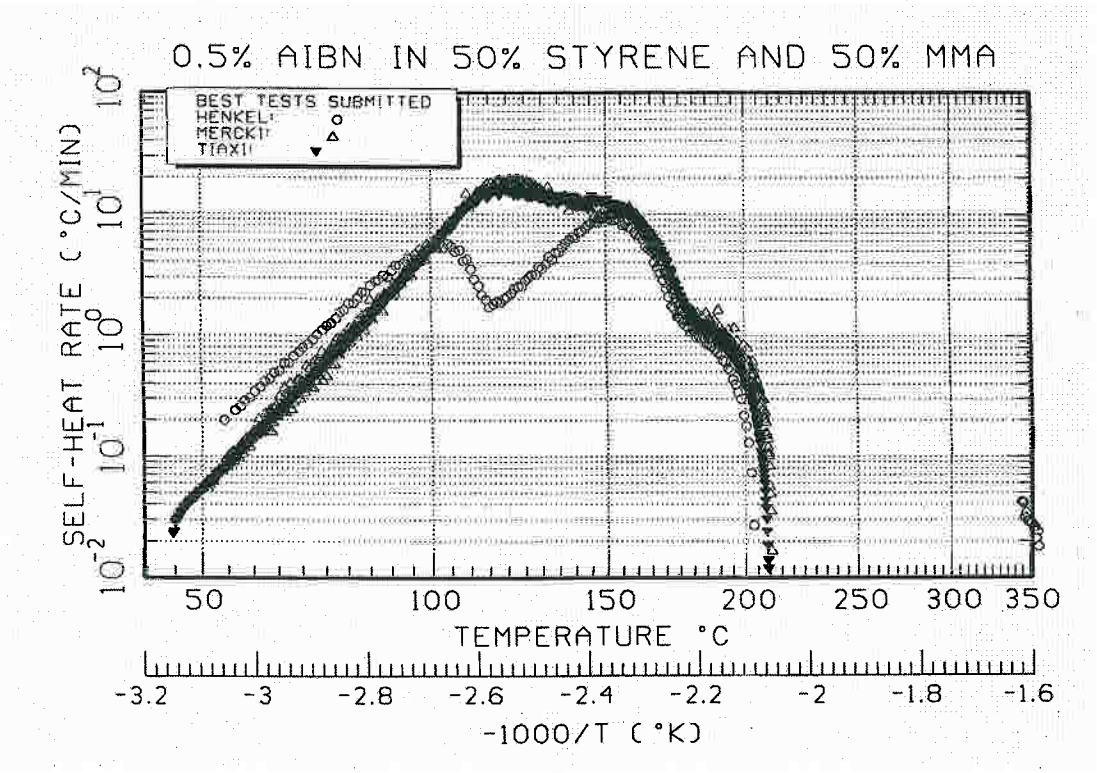

Figure 1. Illustration of ARC Data

Figure 2 illustrates low Phi-factor calorimetry data provided by the VSP2, APTAC, etc. Excellent agreement is noted and the data can be used directly for scale-up. Peak heating rates of about 100°C/min are noted (about 10 times larger than the ARC data) and peak temperatures of about 300°C are noted. In contrast to the ARC data, three exotherms are clearly noticeable.

Figure 3 compares the data obtained with the ARSST and the VSP2 calorimeter (same data as shown in Figure 2). The agreement between the two sets of data is very good. The ARSST data can be scaled directly, with peak rates of about 100°C/min and a peak temperature of about 300°C. Again the presence of three exotherms is clearly indicated.

In summary, the ARSST calorimeter can be effectively used as a screening tool as well as a best estimate tool. As such, it provides the necessary rate data for the MBP. More detailed applications of the ARSST for chemical reactivity screening are provided by Burelbach and Theis [4].

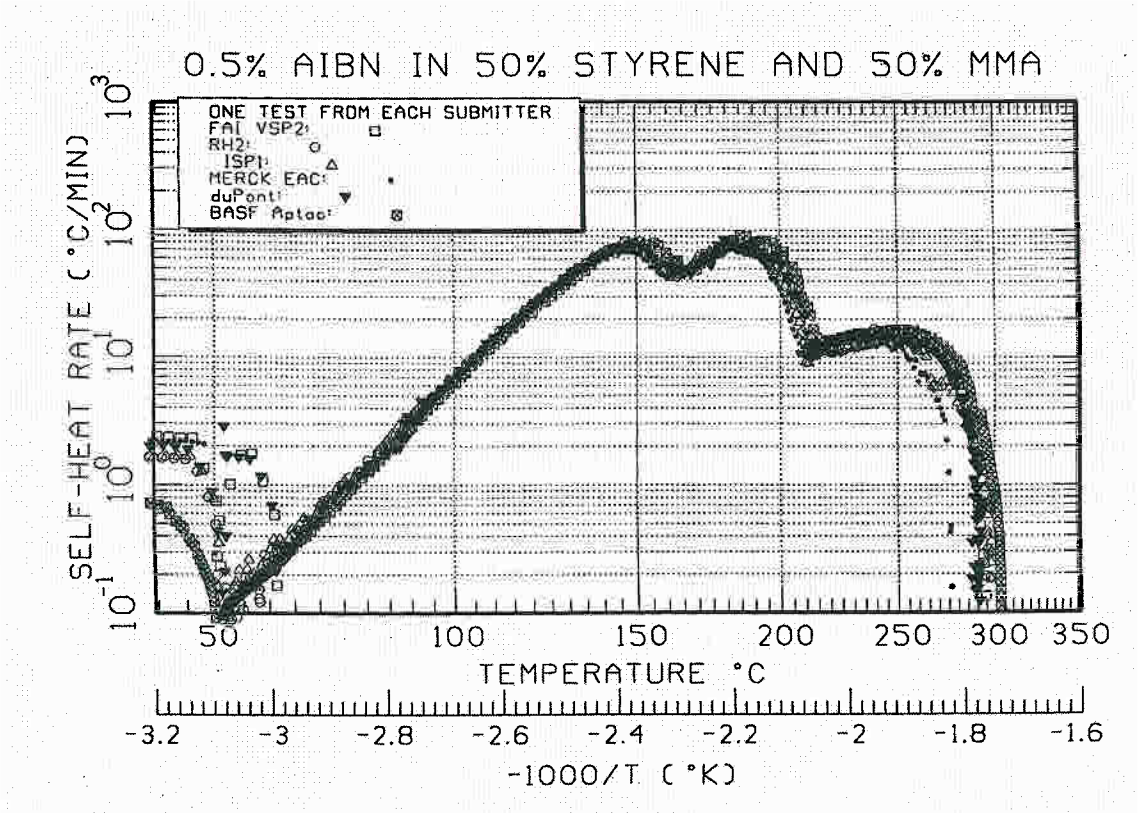

Figure 2. Comparison of VSP2 and APTAC Like Data

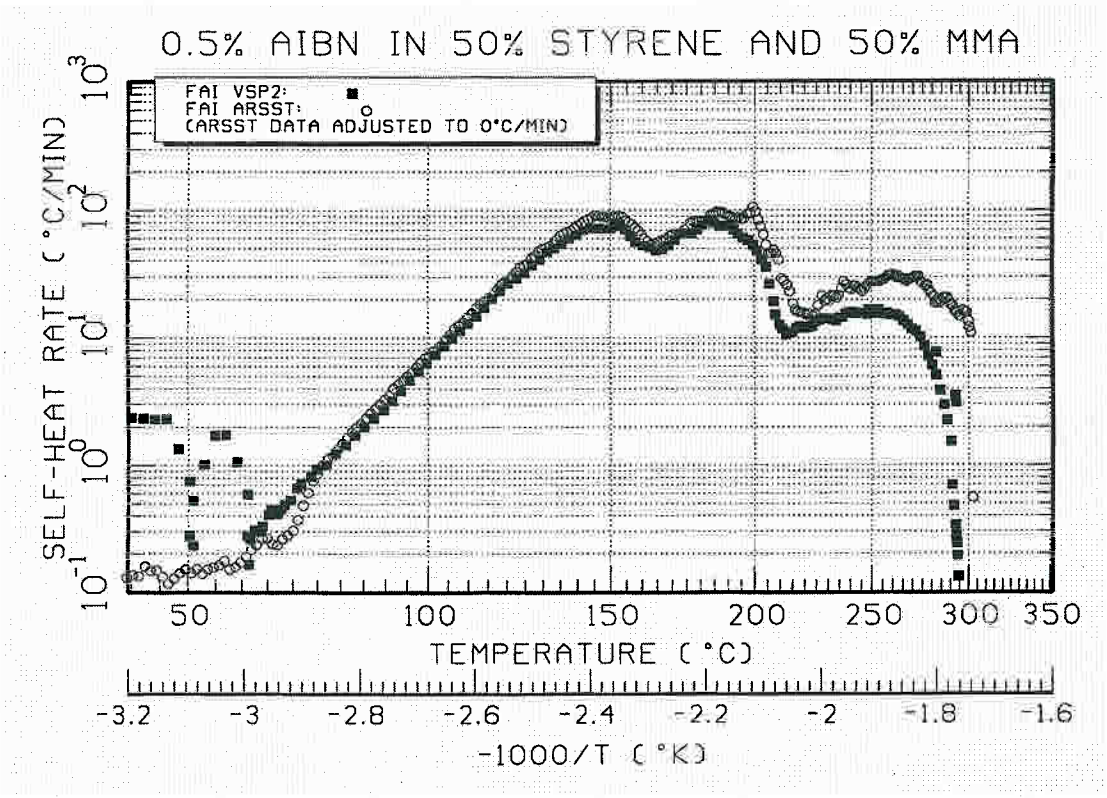

Figure 3. Comparison Between ARSST and VSP2 Data

2.1 Runaway Prevention

Effective management of reactive chemical hazards would benefit from always recognizing that thermal or chemical stability in contrast to classical safety data such as flash points, explosion limits, etc., is not an absolute quantity that can be assigned to a given chemical - therefore the need for rate data.

Runaway times are of immediate interest to both storage and transportation. The characteristic time of adiabatic runaway, t (s), can be estimated from Gygax [5]

$$t = \frac{T^2}{\dot{T}\,B} \qquad (1)$$

where T (K) is the temperature, $\dot{T}$ (K s^{-1}) is the corresponding self-heat rate and B (K) is the activation temperature.

If the runaway times are much larger than the exposure times even assuming adiabatic conditions, the situation can be judged to be immediately safe. However, in many practical cases it is of interest to consider non-adiabatic conditions.

As an example chemical stability or the absence of a hazardous reaction runaway condition can be described in terms of the so-called self-accelerating decomposition temperature (SADT) which varies depending upon the heat dissipation rate [6]. This means that even a very weak initial chemical heat evolution rate may lead to a hazard if it takes place in an environment prone to heat accumulation.

For viscous and solid materials (non-convective) T_{SADT} can be estimated from (Frank-Kamenetskii model [7])

$$T_{SADT}^2 = \frac{R^2 B}{\delta_c \alpha} A e^{-B/T_{SADT}} \quad (2)$$

where R (m) is the radius of the material, α ($m^2 s^{-1}$) is the thermal diffusitiviy of the material, δ_c = 3.32 for sphere; = 2.37 for cylinder with H = 3 R; = 2.00 for an infinite cylinder; = 0.88 for an infinite slab with diameter = 2R, A ($K s^{-1}$) is the pre-exponential factor, B (K) is the activation temperature, and for non-viscous or convective liquids (Semenov model [7])

$$T_{SADT}^2 = \frac{V \rho c B}{h S} A e^{1-B/T_{SADT}} \quad (3)$$

where V (m^3) is the volume of the material, ρ ($kg m^{-3}$) is the density of material, c ($J kg^{-1} K^{-1}$) is the specific heat of material, h ($W m^{-2} K^{-1}$) is the effective heat transfer coefficient, and S (m^2) is the surface area.

In the absence of physical properties, the following approximate inequalities can be used to assess the characteristic dimension or diameter, d (m), to prevent runaway conditions

$$d < 6 \times 10^{-5} \frac{T_o}{\sqrt{\dot{T}(T_o)}} \quad (4)$$

for non-convective systems and

$$d < 2 \times 10^{-8} \frac{T_o^2}{\dot{T}(T_o)} \quad (5)$$

for convective systems where $\dot{T}$ ($°C min^{-1}$) is the self-heat rate at temperature T_o (K).

The above stability criteria are of key importance in establishing safe storage sizes and transportation times of self-reactive chemicals. The MBP should include establishing a stability map for each chemical or mixture that may be considered for storage, transportation and processing.[6] The RSST/ARSST concept can be used to generate such maps [8]. An example is illustrated in Figures 4 and 5. Figure 4 illustrates kinetic information obtained for t-Butyl Peroxybenzoate using the RSST. This information is used together with Eq. 3 to develop the stability map shown in Figure 5. The 10 gm RSST sample shows excellent agreement with the full-scale United Nations Test (25 kg package) and readily explains a damaging runaway incident involving a pallet of 48 forty pound containers of t-Butyl Peroxybenzoate stored in a non-refrigerated trailer subjected

[6] If applicable, it is recommended that the MSDS should include stability information of this type.

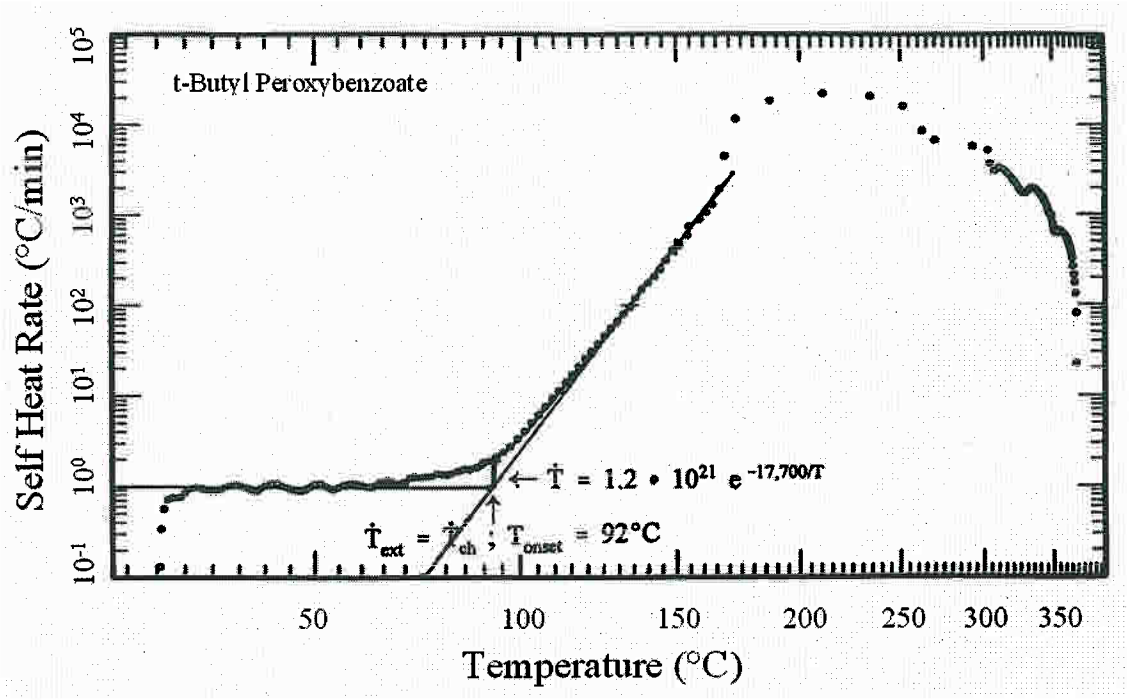

Figure 4. Kinetic Information, from RSST

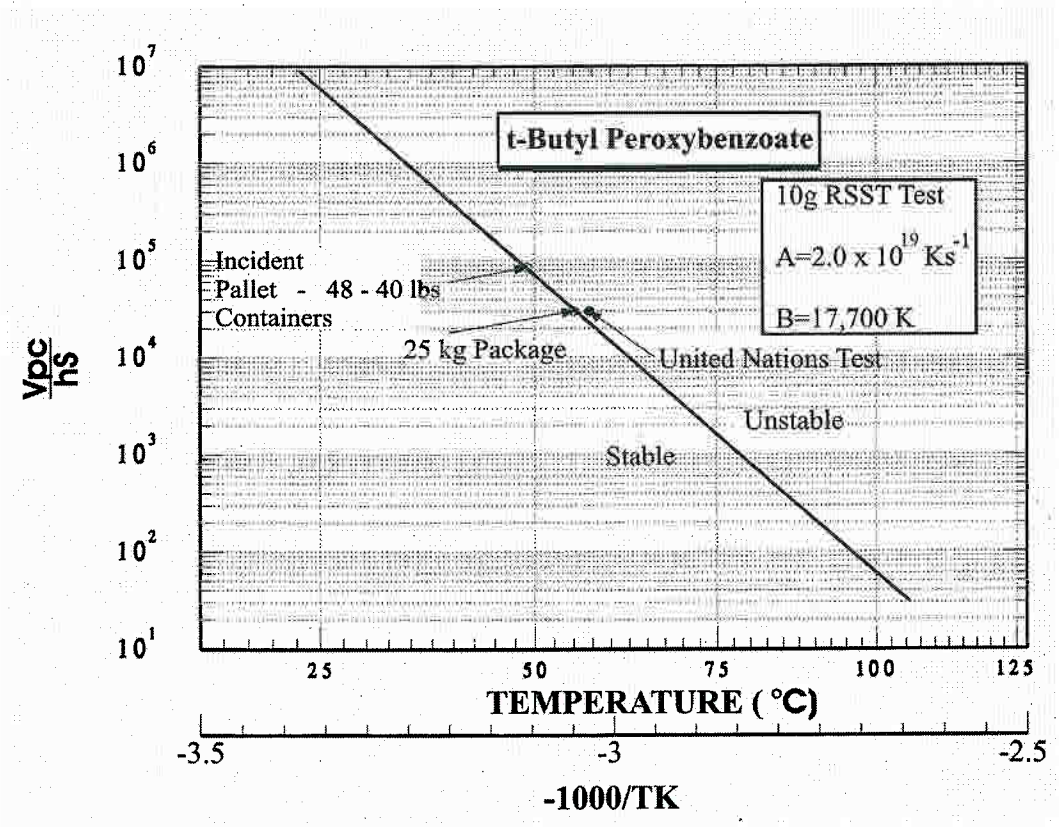

Figure 5. Example of MBP Stability Map

to sunny 100°F weather for 2-3 days.[7] These observations support the validity of extrapolating RSST data downwards by several decades providing low heating rates of the order of 10^{-3} °C min^{-1} or about 100 μW/g. Furthermore, since the RSST/ARSST data (such as illustrated in Figure 3) can be safely scaled directly the calorimeter concept provides an easy means for assessing cooling requirements to assure desirable exothermic process conditions.

Safe storage and transportation of large quantities of self-reactive materials also needs to consider product control in terms of potential contamination. Slowly decomposing gassy systems are particularly sensitive to small contaminates such as metals and moisture and can require frequent measurements of thermal activity (TA) of the order of one μW/g at low temperature. Again, recognizing the need for inexpensive and quick measurements requiring no special expertise, a fast thermal activity interpreter (FTAI) has been developed [9]. A simple measurement of the pressure change under isothermal conditions (T ± 0.01°C) for a one hour duration can provide a measure of the thermal activity.

$$T\ A\ (\mu W/g) \approx \dot{P}\ (Pa\ min^{-1}) \tag{6}$$

where $\dot{P}$ (Pa min^{-1}) is the measured rate of pressure rise at the isothermal condition T (K). Given the ability to accurately measure pressure changes of the order of 100 Pa, TA values of the order of 1 μW/g can be inferred with an isothermal test duration of only one hour.

Using such measurements a first order assessment of the stability for self-reacting gaseous chemicals is provided by

$$d < 10^{-3} \frac{T_o^2}{\dot{P}(T_o)} \tag{7}$$

for non-viscous fluids, and

$$d < 10^{-2} \frac{T_o}{\sqrt{\dot{P}(T_o)}} \tag{8}$$

for viscous and solid materials, where d (m) is the characteristic dimension or diameter, T_o (K) is the ambient temperature, and $\dot{P}$ (Pa min^{-1}) is the measured rate of pressure rise provided by the FTAI at the isothermal condition T_o.

The hydrogen peroxide system is an example of a self-reactive chemical which is highly sensitive to contamination

$$H_2O_2 \rightarrow H_2O + 1/2\ O_2 \tag{9}$$

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[7] Using the following values in Eq. 3, h = 300 J m^{-2} min^{-1} K^{-1}, B = 17,700 K, A = 1.2 • 10^{21} K min^{-1}, S = 5.53 m^2, V = 0.87 m^3, ρ = 1000 kg m^{-3}, results in T_{SADT} = 322.5 K or 49.5°C. Note that for a single 40 lbs container T_{SADT} = 331 K or 58°C.

For commercial grades of hydrogen peroxide even in the hottest climate storage stability is not a concern. Two one hour data sets obtained with the FTAI glass test cell half-full with commercial grade 50% H_2O_2 solution at a 40°C isothermal operation are shown in Figure 6, illustrating an average slope of $1.2 \cdot 10^{-3}$ psi/min or 8.2 Pa min^{-1}. Using this information in Eq. 7 suggests a stable condition for $d < 12$ m or quantities up to 1000 tonnes, which is consistent with the hydrogen peroxide Bulk Storage Guidelines [10].

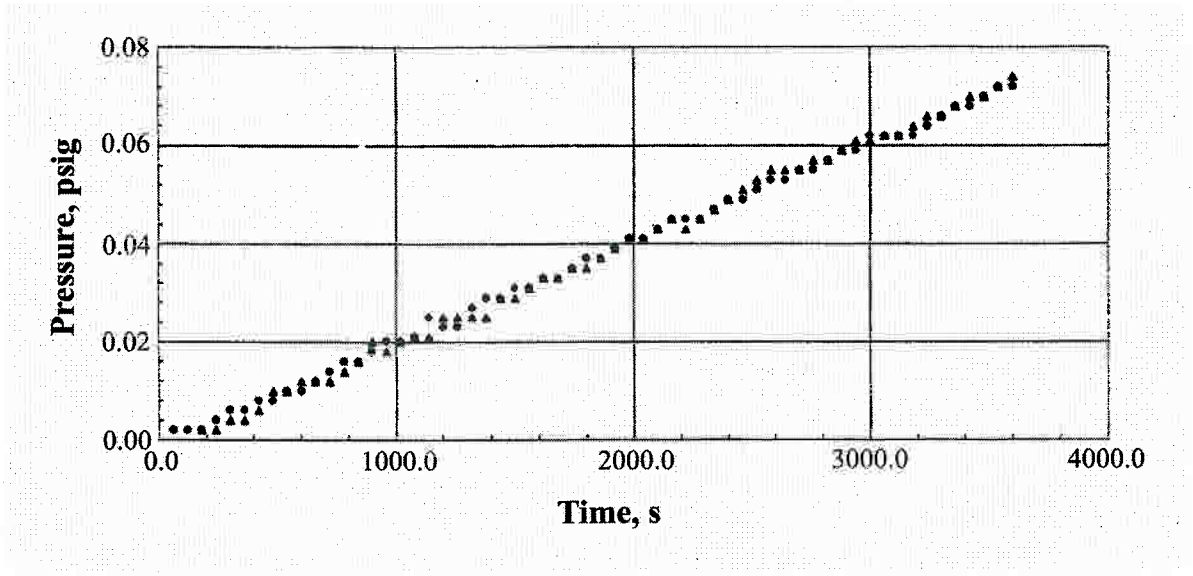

Figure 6. FTAI 50% H_2O_2 Test Data at 40°C Isothermal Operation

In contrast, consider a metal contamination of only about 15 ppm, the thermal activity at 10°C is about 150 μW/g. According to Eq. 7, this suggests that a hydrogen peroxide quantity in excess of about 100 kg will experience runaway at an ambient temperature of 10°C. This observation is consistent with the Wilberforce experiments [11], where 200 kg of 50% hydrogen peroxide with a metal contamination of 15 ppm ran away at an ambient temperature of 12°C. Due to adequate venting (see later discussion) the reaction tempered at about 105°C. Note that according to Eq. 7, a thermal activity of less than 120 μW/g at 12°C would have prevented the 200 kg hydrogen peroxide batch from experiencing runaway. As such, effective product and contamination control limiting the thermal activity to a safe limit, i.e., ruling out a runaway reaction hazard at temperatures of interest can be assured by frequent sampling using the FTAI concept.

2.2 Runaway Accommodation

A second key part of the MBP relates to accommodation of runaway reactions in terms of adequate pressure protection.[8] Information on rates of temperature and pressure

[8] The MBP must also consider effluent control. Here we note that both Seveso and Bhopal incidents had adequate relief or pressure protection but did not provide adequate effluent control measures.

rise obtained from the RSST/ARSST can also be used to estimate the required vent size from (note that no physical properties are required) [12,13]

$$A_v = \frac{3.5 \cdot 10^{-3}}{P\left[1 + \frac{1.98 \cdot 10^3}{P^{1.75}}\right]^{0.286}} \frac{V(\dot{T} + \dot{P})}{C_D} \qquad (10)$$

where

A_v (m^2) = vent area,
P (psig) = relief set pressure or peak relief pressure,
V (m^3) = volume of reactant,
C_D = discharge coefficient,
$\dot{T}$ (°C/min) = rate of temperature rise,
$\dot{P}$ (psi/min) = rate of pressure rise resulting from 10 g test sample in the RSST/ARSST 350 ml vessel.

and depending on the system

System	$\dot{T}$	$\dot{P}$
Vapor[9]	$\dot{T}$ (P)	0
Gassy	0	$\dot{P}_{max}$
Hybrid	$\dot{T}$ (P)	$\dot{P}$ (P)

Eq. 10 has been subjected to extensive benchmarking against vapor, gassy and hybrid system data including incidents resulting from pressure relief undersizing (Figure 7).

An example of a "vapor" system is the foamy-like phenol-formaldehyde system where the reaction is controlled or tempered by latent heat of evaporation. Howard [14] recommended the following correlation for safe prediction of vent sizes based upon large-scale experience

$$D = 0.26\sqrt{V} \qquad (11)$$

where D is the vent diameter given in inches and V is the volume of reactants given in gallons. Eq. 11 is noted to be valid for a set pressure of about 1.5 psig and a self-heat rate of about 6.5°C min^{-1}. Eq. 11 can be restated as

$$A/V = 9.0 \times 10^{-3}\ m^{-1} \qquad (12)$$

where A (m^2) is the vent area and V (m^3) is the volume of the reactant. Given the conditions applicable to Eq. 12 of P = 1.5 psig and $\dot{T}$ = 6.5°C min^{-1}, Eq. 10 gives

[9] In case of "foamy" vapor systems, estimated vent area is multiplied by a factor of two.

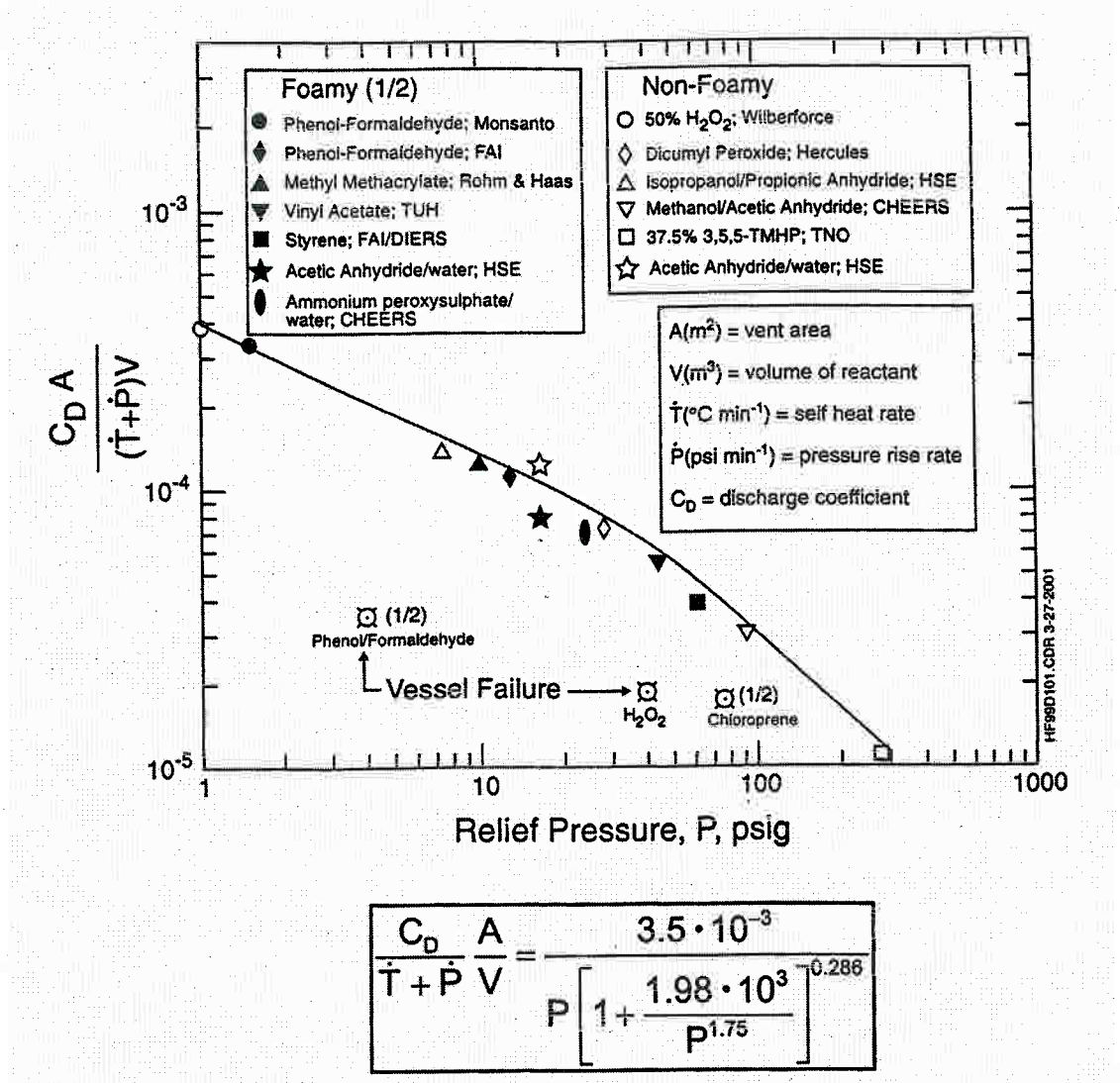

Figure 7. Generalized Vent Sizing Guideline and Comparison with Benchmark Data

$$A/V = \frac{7.0 \times 10^{-3}}{1.5\left[1+\frac{1.98 \times 10^3}{1.5^{1.75}}\right]^{0.5}} \frac{6.5}{} \qquad (13)$$

$$= 8.5 \times 10^{-3}\ m^{-1}$$

which compares to $9.0 \cdot 10^{-3}$ m^{-1} (Eq. 12). Eq. 10 is also consistent with a recent industrial incident case, where a phenol-formaldehyde runaway reaction resulted in catastrophic failure of the reactor vessel and associated facility damage. The incident vessel was fitted with two 12-inch rupture disks with tailpipes ($C_D \sim 0.5$) and contained about 21.2 m^3 of reactants, which translates to a value of $A/V = 6.90 \cdot 10^{-3}$ m^{-1}. The relief set pressure was four psig and based upon calorimetry simulation test results which

agreed with early limited incident data, indicated a self-heat rate $\dot{T}$ = 50°C min^{-1} at a relief set pressure of four psig. Using this information with Eq. 10 results in a required value of A/V = $4 \cdot 10^{-2}$ m^{-1}, which translates to two 28-inch rupture disks. It is therefore not surprising that the reaction vessel experienced a catastrophic failure.

Figures 8 and 9 illustrate the case of readily obtainable RSST data for sizing pressure relief requirements for gassy systems. The measured peak rate of pressure rise of 100,000 psi/min from a 10 gm sample (Figure 8) used together with Eq. 10 is illustrated to be in good agreement with large scale data (Figure 9)[10]

Finally, the hybrid system (the reaction is tempered by latent heat of evaporation, but includes noncondensable gases such as the hydrogen peroxide system) is considered which represents the most critical test of Eq. 10. Excluding contamination from alkaline products (e.g. caustic soda), the following totally empirical approach, based on the analysis of past hydrogen peroxide incidents, is recommended by the hydrogen peroxide Bulk Storage Guidelines [10]

$$200 \text{ cm}^2 / \text{tonne } H_2O_2 \text{ 100\%} \tag{14}$$

This approach is commonly used for the design of the relief vent by the users of hydrogen peroxide, and is considered adequate for contamination factors as high as of the order of 1000. Setting the density of 100% H_2O_2 equal to 1400 kg m^{-3} condition (14) can be restated as

$$A/V = 2.8 \times 10^{-2} \text{ m}^{-1} \tag{15}$$

where A (m^2) is the vent area and V (m^3) is the volume of 100% hydrogen peroxide.

The above vent requirement can be compared to Eq. 10 considering the following example of 1000 kg 25% wt H_2O_2 with a relief pressure of five psig and corresponding RSST measurements of $\dot{T}$ = 23°C min^{-1} (contamination factor of the order of 1000) and $\dot{P}$ = 6 psi min^{-1} (10 g RSST sample). Applying Eq. 15 to this example results in

$$\begin{aligned} A &= \left(2.8 \times 10^{-2}\right)\left(1000 \times 0.25\right)/1400 \\ &= 5 \times 10^{-3} \text{ m}^2 \text{ or } 50 \text{ cm}^2 \end{aligned} \tag{16}$$

Applying Eq. 10 to the same hybrid example

$$\begin{aligned} A/V &= \frac{3.5 \times 10^{-3}}{5\left[1 + \frac{1.98 \times 10^3}{5^{1.75}}\right]^{0.286}}[23 + 6] \\ &= 5.2 \times 10^{-3} \text{ m}^{-1} \end{aligned} \tag{17}$$

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[10] Note that the rate of pressure rise data illustrated in Figure 8 corresponds to the rate of temperature rise data shown in Figure 4. Also note that the venting requirement for this material becomes impractical (Figure 9) indicating a need for emphasizing runaway prevention.

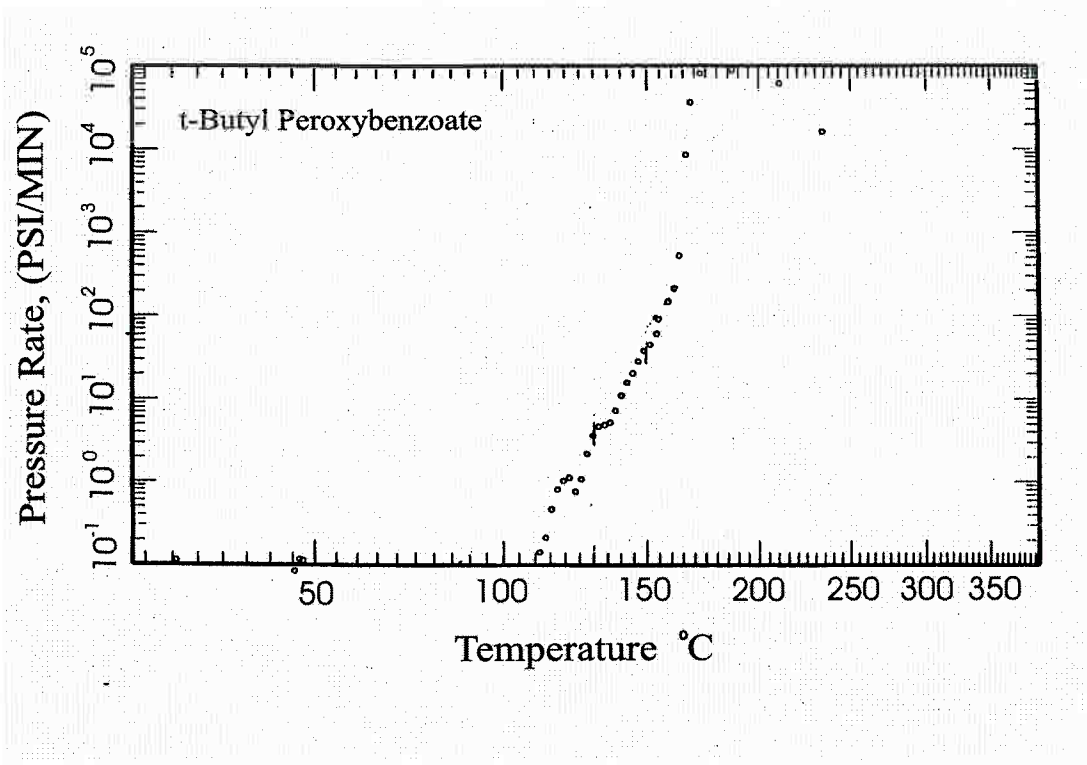


Figure 8. RSST Pressure Rate ($\dot{P}$) Data

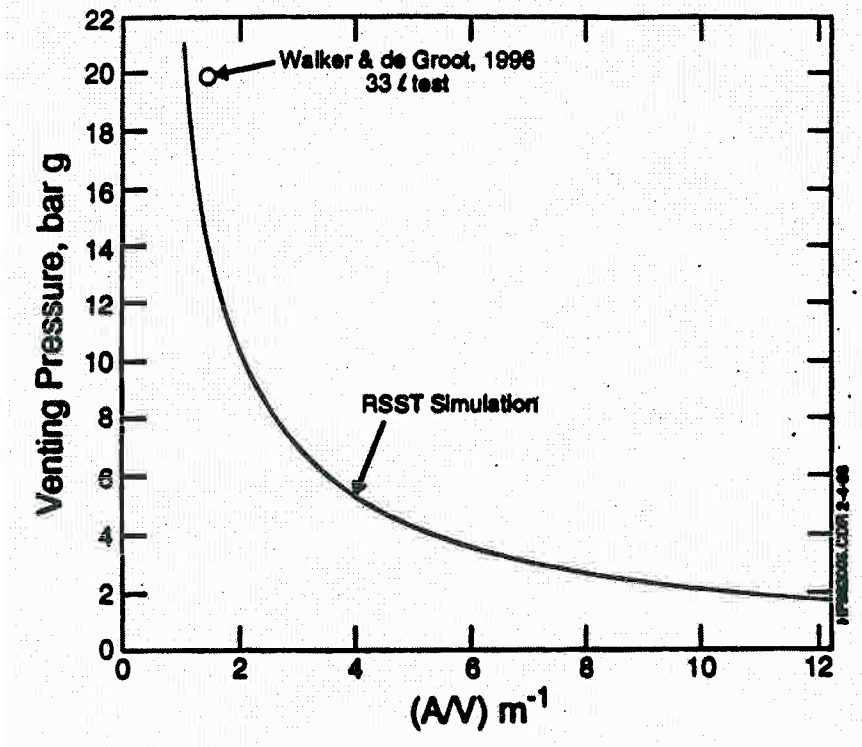


Figure 9. Comparison of Large-Scale Data with Pure t-Butyl Peroxybenzoate and RSST Simulation

Setting the density of 25% H_2O_2 solution equal to 1010 kg m^{-3} results in

$$A = \left(5.2 \times 10^{-3}\right)(1000/1010) \\ = 5.15 \times 10^{-3}\ m^2 \ \text{ or } \ 51.5\ cm^2 \tag{18}$$

which is consistent with the Bulk Storage Guideline value of 50 cm^2. These values are in stark contrast to the value obtained applying the DIERS two-phase methodology with a 20% overpressure which results in an order of magnitude larger vent area. The noted large difference results from the all gas-vapor venting approach used to develop Eq. 10 which is consistent with experimental observations by Wilberforce [11].

A further test of Eq. 10 for higher contamination is provided by Trial 3 reported by Wilberforce with a 200 kg 50% H_2O_2 solution with a contamination factor of about 3500. The runaway reaction tempered and vented safely with a value of $A/V = 2.6 \cdot 10^{-2}$ m^{-1} and a resulting relief pressure of about one psig. The self-heat rate at tempering equaled 55°C min^{-1} and the inferred rate of pressure rise was 14 psi min^{-1} (corresponding to a 10 g sample in the RSST). The above conditions with Eq. 10 result in $A/V = 2.75 \cdot 10^{-2}$ m^{-1} which compares to the experimental value of $2.6 \cdot 10^{-2}$ m^{-1}. Not surprising, due to the high contamination, the hydrogen peroxide Bulk Storage Guideline (condition 14) underestimates the vent size resulting in $A/V = 1.4 \cdot 10^{-2}$ m^{-1}.

3. CONCLUDING REMARKS

A MBP is proposed (Figure 10) that is

- affordable
- easy to practice
- understandable,
- reliable, and

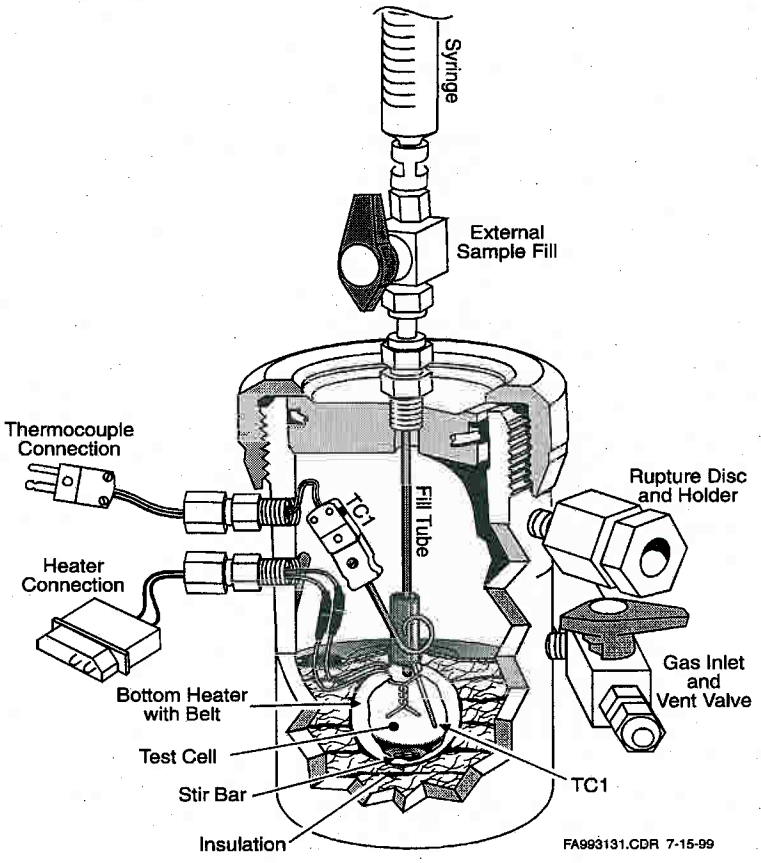
that would likely have prevented a majority of past documented accidents, particularly those that have occurred within companies with limited technical and financial resources. Therefore, in order to get everyone to do what is the minimum necessary, it is recommended that the necessary permitting to handle significant quantities of reactive chemicals (storing, transporting or processing) include as a minimum prerequisite documented use of applicable tools equivalent to the MBP concept summarized in Figure 10.

4. REFERENCES

1. Fauske, Hans K., 1993, System Screening Tool, United States Patent Number 5, 229, 075, July 20, 1993.
2. Fauske, Hans K. et al., 2000, Advanced Reactive System Screening Tool, United States Patent Number 6, 157,009, December 9, 2000.
3. Leung, Joseph C. et al., 2005, "Runaway Reaction Characterization: Further Round-Robin Study on Four More Systems," see these proceedings.
4. Burelbach, James P., and Theis, Amy E., "Thermal Hazards Evaluation Using the ARSST," see these proceedings.

Minimum Best Practice Tool Box
(Controlling Chemical Reactivity)

RSST/ARSST



$$\Downarrow$$

$$\dot{T} \; ; \; \dot{P}$$

Prevention	Accommodation (Pressure Relief)
$d < 2 \times 10^{-8} \dfrac{T_o^2}{\dot{T}(T_o)}$ (convective systems)	$A/V = \dfrac{C}{P\left[1 + \dfrac{1.98 \times 10^3}{P^{1.75}}\right]^{0.286}} \dfrac{\dot{T} + \dot{P}}{C_D}$
$d < 6 \times 10^{-5} \dfrac{T_o}{\sqrt{\dot{T}(T_o)}}$ (non-convective systems)	Vapor, Gassy and Hybrid Systems

Figure 10. Summary Illustration of Proposed MBP

5. Gygax, R. W., 1990, Scaleup Principles for Assessing Thermal Runaway Risks, Chem. Eng. Progress, pp. 53-60, February 1990.
6. Fisher, H. G. and Goetz, D. D., 1993, "Determination of Self-Accelerating Decomposition Temperatures for Self Reactive Substances," J. Loss Prev. Process Ind., Vol. 6, No. 3, 1993.
7. Jones, J. C., 1993, Combustion Science, Principles and Practice, Millennium Books, Australia, 1993.
8. Fauske, Hans K., 2000, Easily Determine Self-Accelerating Decomposition Temperature (T_{SADT}), FAI Process Safety News, Spring 2000.
9. Fauske, Hans K., 2004, A Fast Thermal Activity Interpreter for Controlling Chemical Reaction Hazards, Process Safety Progress, Vol. 23, No. 2, June 2004, United States Patent pending.
10. Bulk Storage Guide, 2001, Peroxygens' Hydrogen Peroxide Subgroup, European Chemical Industry Council, Brussels, Belgium, September, 2001.
11. Wilberforce, J. K., 1988, "Emergency Venting of Hydrogen Peroxide Tanks," CEFIC Hydrogen Peroxide Safety Conference, Gothenburg, Sweden, September 22, 1988.
12. Fauske, Hans K., 2000, Properly Size Vents for Nonreactive and Reactive Chemicals, Chemical Engineering Progress, February 2000.
13. Fauske, Hans K., 2003, "Generalized Vent Sizing Equation for Reactive Systems," FAI Process Safety News, Summer 2003.
14. Howard, W. B., 1973, "Reactor Relief Systems for Phenolic Resins," Monsanto Company, June 1973.
15. Walker, J. P. and deGroot, J. J., 1996, "Venting of Decompositions of Energetic Liquids Using a Bottom Vent," Proc. of Process Plant Safety Symposium, Vol. 2, pp. 55-71, Houston, TX.