Promoting a Safe Laboratory Environment Using the Reactive Hazard Evaluation and Analysis Compilation Tool

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ABSTRACT: In the past several years, the U.S. Chemical Safety Board has found an increase in the frequency of laboratory accidents and injuries. An independent survey of industrial and academic laboratories by the authors indicated the shortage of documentation on best practices and lack of free and user-friendly risk assessment tools to be some of the key reasons for the occurrence of safety incidents. Thus, development of a framework to document, assess, and mitigate hazards is a critical starting point for ensuring safe laboratory practices. To address this requirement, Reactive Hazards Evaluation Analysis and Compilation Tool (RHEACT), an online platform to compile and scrutinize hazards-related information, was developed. When planning an experiment, the researchers provide RHEACT: (1) information about the chemicals involved in the reaction, in the form of Safety Data Sheets (SDS), and (2) operating parameters of the reaction. Through the user-supplied SDS, an operational hazard matrix and a chemical compatibility matrix are generated. In addition, adiabatic temperature rise of the reaction is estimated to ensure that the chemistry is within user-controlled bounds. The user is provided with a broad initial evaluation of potential hazards and is notified of safety concerns associated with the reaction before conducting the experiment. We believe that this user-friendly online tool will help engender a safer laboratory working environment.

KEYWORDS: *laboratory safety, risk assessment, process hazard analysis (PHA), online tool, chemical compatibility, adiabatic temperature*
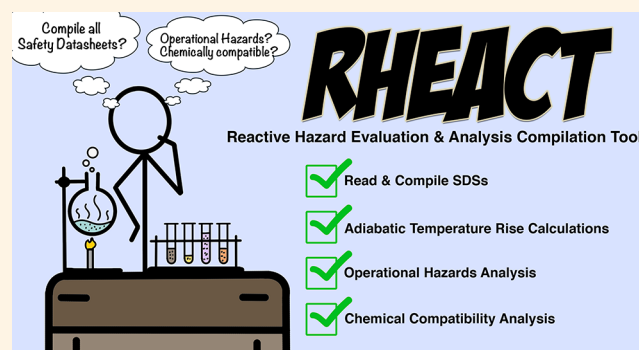
1. INTRODUCTION

Recent statistics from the U.S. Chemical Safety Board (CSB) suggests that incidents leading to loss of productivity, personnel injuries, and fatalities have continued to rise in the government and private sector laboratories, including universities and high school laboratories. Figure 1 shows the reported frequency of laboratory safety incidents with the associated number of injuries and fatalities that were identified by the U.S. Chemical Safety Board (CSB) between January 2001 and July 2018. These trends suggest the need for a broad and systematic change in laboratories that goes beyond mere safety compliance and toward promoting safer practices and building a strong safety culture.[1,2]

To address this gap, the National Science Foundation (NSF) encouraged and funded a joint effort between two research centers, Center for Innovative and Strategic Transformation of Alkane Resources (CISTAR) and Purdue Process Safety & Assurance Center (P2SAC), to investigate ways to improve safety practices in research laboratories and develop a tool that will assist with the hazard analysis process. An independent survey of safety practices, conducted with the help of industrial and academic laboratories involved with CISTAR and P2SAC, suggested that the continued occurrence of incidents is potentially linked to the lack of adequate documentation of best practices and the scarcity of tools that can help research laboratories quickly analyze and address safety risks.[5] Equally important, from the Texas Tech laboratory explosion case study, the CSB cited the researchers'
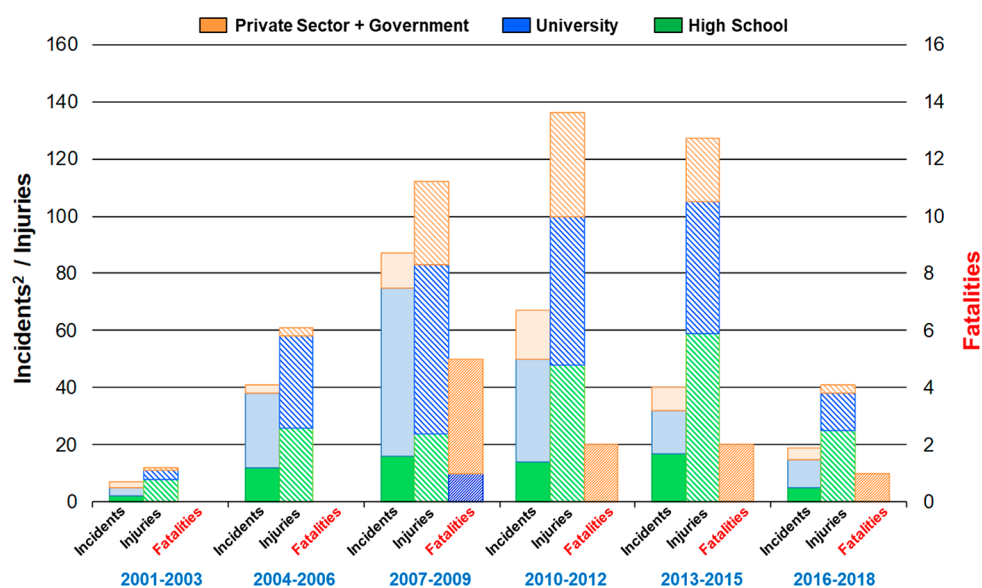
[1]Laboratory incident dataset from January 2001 through July 2018
[2]Excludes incidents that may have occurred but not identified by CSB

Source – U.S. Chemical Safety Board, Dataset on Incidents in Public and Private Laboratories, August 2018

Figure 1. Number of reported incidents, injuries, and fatalities identified by the CSB in public and private laboratories between January 2001 and July 2018.[3,4]

ineffective assessment of the physical hazards and limited analysis of the issues arising during scale-up that contributed to the incident.[6,7] In so doing, the researchers' assumptions concerning the relative safety of the small-scale reaction batch did not directly translate to the larger-scale setup. This disparity resulted in the explosion of the reaction mixture causing personnel injuries. Thus, because of this lack of risk assessment, as well as other broader managerial deficiencies, the CSB determined that the physical hazards in the laboratory could have been better managed through effective hazard evaluation guidance, research-specific risk training, and the presence of formal documentation such as standard operating procedures (SOPs).[4,6] Furthermore, on revisiting the lessons learned from some of the other recent academic laboratory safety incidents,[7−10] we observed that these incidents could have been prevented if a more thorough hazard evaluation process was undertaken. Moreover, the CSB case study mentioned that there seem to exist different levels of hazard evaluation between industry and academic laboratories and have called for a guidance on hazard evaluation methodologies within academic laboratories.[4,6]

The American Chemical Society (ACS) Committee on Chemical Safety has taken commendable steps toward developing guidelines for identifying and evaluating hazards in research laboratories.[11] Through the principles of RAMP (Recognize Hazards, Assess the risks of hazards, Minimize the risks of hazards, Prepare for emergencies), ACS assists researchers with the steps in building a strong safety culture in the academic laboratories.[12] On a related front, there exist a wide variety of hazard evaluation tools (CHETAH, CAMEO, DYNOCHEM, CRW, RAST) and property databases (Bretherick's Handbook, NIOSH, NIST, Scifinder) widely used in industry[13−20] which allow researchers to evaluate hazards and safety concerns for their reaction setup. For instance, Risk Analysis Screening Tool (RAST), developed at Dow Chemical and now available through the CCPS (Center

for Chemical Process Safety), can be used to predict thermal runaway events and gas generation potentials and generate worst-case scenarios for a specific reaction system done in the lab, pilot, or plant scale. Similarly, Chemical Reactivity Worksheet (CRW) or CAMEO Chemicals can be used to predict the chemical compatibility matrix for the components involved in a system and avoid inadvertent mixing of incompatible materials.

The property databases mentioned earlier can be used to understand the inherent hazards associated with the type of reaction system being studied. Despite access to these tools, our independent industrial survey noted certain challenges when using these tools to assess the risks involved in a specific experimental system.[5] Some of these challenges include the inconvenience of accessing multiple tools and databases during hazard evaluation, the lack of a streamlined procedure for hazard evaluation, and the limited functionalities in major tools for chemical compatibility checks or PPE (personal protective equipment) guidance. Therefore, there is a need for the development of a convenient and accessible platform that can (a) collect critical information about a planned experiment, (b) conduct necessary operational hazard analysis, and (c) summarize potential red flags and recommend best practices.

In that context, a web-based tool called RHEACT (Reactive Hazards Evaluation Analysis and Compilation Tool) was developed that aids in providing a convenient platform to compile and analyze hazard-related information before conducting laboratory experiments. Some of the capabilities provided in the tool involve (1) parsing multiple Safety Data Sheets (SDSs) for chemical and safety information, (2) creating an operational chemical hazard matrix, (3) generating a pairwise chemical compatibility matrix, and (4) calculating adiabatic temperature changes. Thus, this open-source web-based tool is positioned as a first layer of protection that can enable researchers to assess and prioritize safety concerns when planning experiments.

2. TOOL DESCRIPTION

RHEACT was developed to serve as an initial risk assessment tool for new and existing chemistries employed by academic and industrial laboratory researchers. The block diagram in Figure 2 explains the high-level structure and function of the tool.
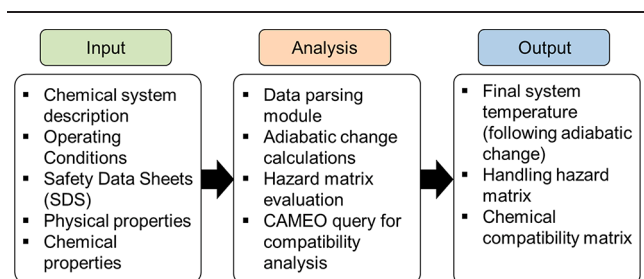

Figure 2. Process block diagram for RHEACT.

The tool workflow can be divided into three main process blocks: inputs, analysis, and outputs. The input block is the first step in the workflow wherein critical process information about the user-defined reaction mixture and setup is obtained. The major source of this information is the Safety Data Sheets (SDSs), uploaded by the user. Also, the user can manually add inputs wherever necessary or when a particular reagent does not have a corresponding SDS (usually the case for proprietary chemicals). The input block sends the parsed and user-input data to the analysis block where the software framework

evaluates the hazard matrix, generates a chemical compatibility matrix, and estimates the temperature change considering adiabatic conditions. Following this analysis, the information is passed to the output block, which displays the matrices and calculations as a hazard summary report to the user. Detailed functioning of the individual blocks is described in the sections to follow.

The tool is designed to retrieve the property and hazard-specific data from the SDS. The overall tool architecture can be classified into front-end/graphical user interface (GUI) and back-end (software framework). The GUI (Figure 3) serves as the primary interface between the user and the analysis block in the back-end, collecting relevant information from the user and dispatching it to the back-end for further analysis. The GUI is implemented using React.JS,[21] an open-source javascript library for building user interfaces. The back-end of the software is built using Flask,[22] a python-based web framework.

Figure 3 shows a part of the graphical user interface (GUI). Researchers have the provision to enter unique identifiers for their project such as information on the researcher's name, name of the PI (Principal Investigator), and project title. This meta-data can be retrieved during final reporting for future reference. To initiate the calculation, users have to provide operational parameters in the section defined as "Operating Parameters". These parameters are crucial when determining the adiabatic temperature rise and serve as the basis for defining the nature of the mixture being analyzed. Next, the balanced chemical reaction scheme and potential side reactions

Figure 3. User interface for RHEACT.

can be added in the fields provided for additional documentation purposes. This can be done by selecting the number of side reactions and adding onset temperature and pressure conditions for these reactions. The tool uses the information on side reactions to generate alerts in situations where the final system temperature exceeds the onset temperature for the user-defined side reaction(s).

Figure S1 (in the Supporting Information, Section S1) shows the remaining portion of the input GUI where the user can upload the SDSs and parse the necessary information. As per the current implementation of the tool, the uploaded SDSs are required to be from Sigma Aldrich (approximately 300 000 chemical SDSs are available from Sigma Aldrich). Once the user adds the reaction mixture operational parameters and uploads the appropriate SDS to the front-end, the data parsing module, located in the tool's back-end, parses and extracts the relevant physical—chemical and hazard-related information and sends it back to the GUI for the user to review (an example of this process is shown in the Supporting Information, Section S2, Figure S2). Among all the inputs to the tool, operating parameters like system temperature, pressure, and heat of reaction and reagent properties like the specific heat capacity and the component mole fraction (all highlighted in red) are required inputs to the tool for further analysis. The "?" symbol is provided beside certain tags in the tool to provide an additional explanation regarding the input. For example, in the case of initial weight fraction, it alerts the user to ensure that the total reactant and product weight fractions add to 1. The tool provides the user with an option to save progress by clicking "Save Reaction". This generates a downloadable .json file that can be studied later using the "Load Reaction" tab on the tool. That being said, the tool itself does not save any data or hazard summary reports (in its database) to ensure user privacy.

Once the user hits "Calculate", the parsed information, along with the operational parameters (operating conditions, specific heat capacities), is transferred to the back-end into the calculation block. As a part of the calculation block, adiabatic temperature rises for the system of reagents are estimated; information pertaining to the H-phrases (to be defined shortly), CAS number, and the chemical name is used to generate the operational hazard matrix and the chemical compatibility matrix. The data flow is summarized using the flowchart shown in Figure 4.

The tool can currently perform the following tasks:

(1) Set up a reaction comprising a maximum of 4 reactants, 4 products, and 2 diluents.

(2) Extract and display the values from the SDS (user-input) using the data parsing module.

(3) Calculate the adiabatic temperature rise associated with the reaction system. Generate reactant, product, diluent, and system alerts for deviation of the material/system properties from the calculated final temperature.

(4) Generate a chemical hazard matrix from the H-phrase values parsed from the SDS and provide guidelines for PPE selection.

(5) Submit a CAMEO query and generate a pairwise chemical compatibility matrix for all the components involved in the reaction system.

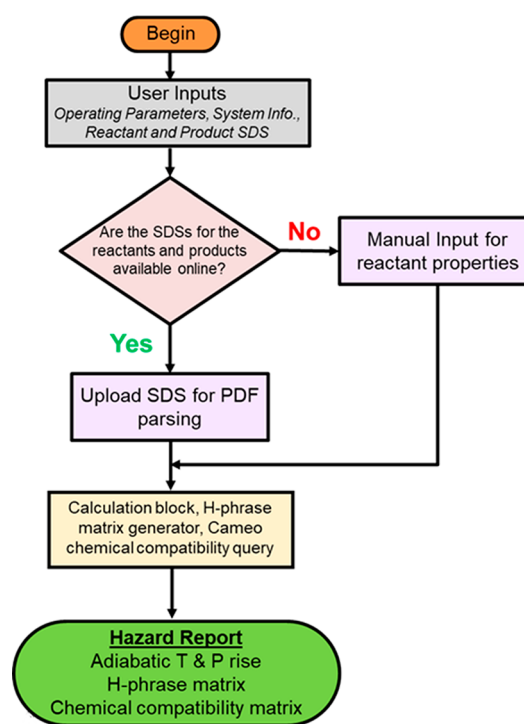(6) Provide the option to save progress and reports for future reference.

Figure 4. Data flowchart for RHEACT.

The sections below describe the specific functions of the sub-blocks in the analysis block.

2.1. Data Parsing Module. To parse the user-supplied SDS and extract necessary operational information, a python module, pdftotext,[23] is used to parse through the supplied SDSs using regular expressions (regex). This information is sent back to the front-end to be displayed. An illustration of this parsing operation is presented using the Sigma Aldrich SDS for ammonia (shown in Figure S2, in the Supporting Information, Section S2). The key properties such as CAS number and the chemical name are used as unique identifiers for the CAMEO Chemicals tool to generate the chemical compatibility matrix. The physical and chemical properties parsed from the SDS are used in the calculation block module of the tool. The H-phrases extracted by the data parser are used to generate the hazard matrix to aid PPE selection.

2.2. Calculation Block. As mentioned earlier, the user information (operating conditions, heat of reaction) combined with the data parsed from the SDS (specific heat capacity) is used to predict the adiabatic temperature rise associated with the reaction system. The values entered by the user for the heat of reaction and specific heat capacity are expected to be at the operating conditions. The tool cannot extrapolate these values from standard conditions. Also, the changes due to the adiabatic operation are calculated by assuming the contributions from the heat of the reaction alone. These calculations are carried out using the following formulas:

$$\Delta T_{ad} = -\frac{\Delta H_{rxn}(T)}{C_{p,mix}(T)}$$

$$T_f = T + \Delta T_{ad}$$

where T_{ad} = adiabatic temperature change due to heat of reaction alone (°C), $\Delta H_{rxn}(T)$ = heat of reaction at the operating temperature (cal/g), $C_{p,mix}$ = specific heat capacity of

Hazard Matrix ⓘ

Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Other	Ingestion
Ethyl acetate	✕	✓	✓	✓	◯	△	✓	✓	✓	✓	✓
Hexane	✕	✓	✓	△	✓	◯	✓	◯	✓	◯	✕
Diethyl ether	✕	✓	✓	✓	✓	△	✓	✓	✓	✓	◯

Legend: ✓ Safe   △ Caution   ◯ Warning   ✕ Danger

Figure 5. Hazard matrix generated by RHEACT

the mixture at the operating temperature (cal/(g °C)), T = operating temperature (°C), and T_f = final system temperature (°C). $C_{p,mix}$ is calculated as the weighted average of the specific heat capacity of all the components in the mixture by using the component mole fraction and the specific heat capacity which are necessary inputs to the GUI. RHEACT has a database of about 300 chemicals with their physical and chemical properties located in the back-end (imported from RAST). This database is used to autofill inputs that are not available from the SDS. However, it is recommended that the user verify these values. For example, the specific heat capacity of a component may not be at the operating temperature, required as an input for the adiabatic change calculations. In such a case, the user needs to correct these values. The adiabatic changes can be used to deduce the final system temperature, which can be compared to the physical properties for the reactants and products (like the autoignition and decomposition temperatures), parsed from the SDS, or available as a manual entry from the user. Deviations from the parsed/input values can be used to alert the user. For example, if the final system temperature exceeds the autoignition/decomposition temperature for any component involved in the system, there is a likelihood of a hazardous event to occur (depending on the nature of the components). In such cases, the tool displays an alert highlighting these deviations. Additionally, the user can provide information on the secondary reactions associated with the reaction system (as shown in Figure 3). This can be used to create alerts in case the final system temperature (following adiabatic changes) exceeds the onset temperature for the secondary reactions. Through this analysis, the tool can be used to predict potential thermal runaway events.

2.3. Chemical Hazard Chart. Hazards associated with each chemical are encoded as H-phrases. H-phrases are standardized hazard statements as defined in the Globally Harmonized System of Classification and Labeling of Chemicals system.[24] These hazards usually pertain to the chemical's effect on the user and communicate precautions pertaining to the chemical's storage and handling. Each hazard statement is designated a code, starting with the letter "H" followed by three digits. To express the operational hazards about a particular H-phrase succinctly, all the H-phrases are systematically categorized according to 11 hazard categories— flammability, reactivity, skin absorption, skin contact, eye contact, respiratory, carcinogen, reproductive hazard, sanitizer, ingestion, and other. Next, for every category, a severity is assigned, which is later expressed as a color code in the RHEACT's final output. This information is tabulated in the tool's back-end and is referred to when generating the chemical hazard chart for the total mixture. The logic for categorizing the H-phrase information into relevant hazards was formulated in collaboration with our industry partners. Through this logic,

the web tool tabulates the code associated with each H-phrase, for a given reagent, using the parsed SDS information.

A hazard matrix is created for every reagent with each H-phrase and its corresponding hazard category and severity listed. Every hazard category as identified before has a corresponding severity of the hazard expressed as Safe (green), Caution (yellow), Warning (orange), or Dangerous (red). Besides the color-coding, each severity level is also assigned a distinct symbol for additional visibility. Developing such a hazard chart allows the user to determine the types of operational hazards and their corresponding severity and thereby help select the appropriate PPE to be used (additional links provided by RHEACT to guide the PPE selection process). This gives the user the ability to tabulate necessary safety risks each chemical might pose. An example of the chemical hazard matrix is shown in Figure 5. It is important to note that the hazard chart displayed specifically addresses hazards for a given chemical and does not account for interactions between the chemicals. The implications of pairwise mixing of chemicals are explained through the compatibility matrix analysis as described in the previous section, and as shown in the example in Figure 7.

2.4. Chemical Compatibility Chart. When combining two or more chemicals, it is important to understand the possible consequences of the mixing. Combining two or more chemicals often results in a chemical change that could produce toxic gas or excessive heat which might pose a threat to the researcher. The RHEACT web tool provides a convenient way to obtain a preliminary understanding of the possible reactions between the chemicals involved in the user-defined mixture. Using CAMEO's chemical reactivity assessment tool,[15] RHEACT can estimate the tendency of the participating reactants to undergo a chemical change and comment on the implications of the change. The web tool uses Selenium's python bindings which provides an interface for the Selenium WebDriver,[25] a remote-control interface to automate web browser interaction to query the chemicals defined in the reaction mixture on the CAMEO chemical data set website.

The compatibility matrix generated using CAMEO's resources is extracted using Selenium and displayed on the web tool interface. For the purposes of predicting the reactivity, each chemical in the CAMEO data set is assigned to one or more reactivity groups (68 reactive groups are defined in total[15]). The reactivity groups are predetermined in the CAMEO data set based on the chemical structure of the reagent. Using reactivity group classifications, reactivity predictions are shown in the form of a pairwise compatibility chart wherein each interaction is marked either as Incompatible, Caution, or Compatible. An example of the compatibility chart is shown in Figure 7. Exothermic chemical reactions producing excess heat (more than 100 calories per gram) or reactions that result in the production of hazardous products

Product Name	Ethyl acetate	Hexane	Diethyl ether
Initial Weight Fraction ⑦			
Mol. Weight (g/mol)	88.11	86.18	74.12
CAS-No.	141-78-6	110-54-3	60-29-7
Physical and Chemical Properties			
pH at 20°C (g/l)	No data available	7.0	No data available
Initial boiling point (°C)	76.5	69	34.6
Flash point (°C)	-4	22	40
Upper explosion limit (% V)	2	8.1	36
Lower explosion limit (% V)	No data available	1.0	1.7

Figure 6. Parsing SDS data for ethyl acetate, hexane, and diethyl ether.

are labeled as "Incompatible". Currently, the analysis is limited to pairwise interaction between each chemical at a given time. Additional interactions (ternary and above) are not predicted by CAMEO Chemicals. Also, RHEACT generates the chemical compatibility matrix based on the database available within CAMEO Chemicals. For reagents not available on CAMEO, the tool returns the compatibility matrix for all the reagents except the ones unavailable. More details about the prediction and estimation of the compatibility can be found on the CAMEO website.[15]

3. EXAMPLES

RHEACT can be used to perform an initial hazard analysis on the systems studied on various scales: lab, pilot, or plant scale. RHEACT is an appropriate tool for initial risk assessment in academic and small-scale laboratories where the level of hazard analysis and access to databases/online tools are often limited. That being said, the user may also choose to undertake additional hazard analyses (inherent safety review, Hazard Operability (HazOP) study, etc.) when studying these reactions at any scale. Additionally, pilot-scale and plant-scale operations need to account for the hazards associated with the scale (reactant and product feed amounts) of these systems. The examples listed below are actual industrial and academic laboratory accidents. These cases are evaluated using RHEACT to analyze and predict potential reactive hazards associated with the setup. The highlighted examples elucidate how the various functionalities within the tool could aid the hazard analysis procedure. Subsequently, the alerts generated through the tool when analyzing these cases showcase its utility for the experimentalists for designing safer laboratory protocols.

3.1. Identifying Potentially Explosive Reagents/Mixtures. The case studies highlighted in this section involve systems consisting of flammable reagents and/or systems involving a mixture of potentially explosive reagents. The hazard matrix and the chemical compatibility matrix functionality within RHEACT can be used to understand the hazards associated with these systems.

3.1.1. University of Pennsylvania Chemistry Building Incident. In August 2020, the Chemistry department at the University of Pennsylvania reported an explosion of the vacuum pump connected to a rotary evaporator assembly used by the researcher to evaporate solutions containing ethyl acetate and hexane.[26] The researcher decided to reboot the pump due to a lack of vacuum, resulting in an explosion. The most likely cause of the explosion was the ignition of the explosive concentration of diethyl ether (accumulated from previous experiments) vapor expelled from the vacuum pump. The possible ignition source could have been a spark from the pump motor, or the cooling fan housed in the same cabinet with the vacuum pump.[26] Although there could have been additional process controls (like proper venting, additional cold traps) employed to avoid the incident, RHEACT was used to understand the hazards associated with the chemicals in the system. Figure 5 shows the hazard matrix generated by the tool for this incident. The matrix indicates that all the reagents are flammable. The flammable nature of the chemicals warrants additional hazard review procedures.

Parsing physical and chemical property data from the SDS for the components using RHEACT can be used to make decisions on selecting the appropriate pressure and temperature desired for the rotary evaporator. For example, Figure 6 shows the temperature data parsed from the SDS for ethyl acetate, hexane, and diethyl ether. The researcher can use this

(A)

Hazard Matrix ⓘ

Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Other	Ingestion
Hydrogen	✖	△	✔	✔	✔	✔	✔	✔	✔	✔	✔
Oxygen	✔	✖	✔	✔	✔	✔	✔	✔	✔	✔	✔
Carbon dioxide	✔	△	✔	✔	✔	✔	✔	✔	✔	✔	✔

Legend: ✔ Safe   △ Caution   ⭘ Warning   ✖ Danger

(B)

Cameo Matrix ⓘ

	Hydrogen	
Oxygen	**Incompatible** ✖ Explosive Flammable Generates gas Generates heat Intense or explosive reaction Unstable when heated	Oxygen
Carbon dioxide	**Compatible** ✔	**Compatible** ✔

Figure 7. (A) Hazard matrix and (B) chemical compatibility matrix generated by RHEACT for the UH incident.

information to select the operating temperature to be used for the rotary evaporator and avoid any process hazards (for example, avoiding solvent flashing at high concentrations). The ability to parse and tabulate the SDS data in a concise, systematic format through RHEACT helps in performing an initial hazard analysis.

3.1.2. University of Hawaii Incident. A laboratory incident at the University of Hawaii, in March 2016, resulted in a postdoctoral researcher being severely injured when a tank containing a mixture of hydrogen, oxygen, and carbon dioxide ignited.[27−30] This gas mixture was used as feedstock for a bacterial culture inside a low-pressure tank. A spark from the electronic pressure gauge used inside the gas mixing vessel was identified as the ignition source. The investigation report from the University of California Center for Laboratory Safety (UCCLS) stated the failure to recognize the hazards of an explosive gas mixture as the underlying cause of the accident.

RHEACT can be used to study the nature of the chemicals used in this study and understand the compatibility of these chemicals. Figure 7A shows the hazard matrix generated by the tool indicating the flammable nature of hydrogen and the reactive hazards associated with all the components. Figure 7B shows the chemical compatibility matrix generated using the CAMEO chemical data set. The compatibility matrix, analyzing the pairwise chemical interaction, highlights the incompatibility between hydrogen and oxygen used in the study. The mixture is expected to be explosive and flammable when mixed. Alerts like this can help the researchers when designing additional safety controls for the system.

3.1.3. Azide Explosions. Several incidences involving the explosion of sodium azide in the presence of water or acid have been reported to cause serious bodily injuries.[31,32] Hydrolysis

of sodium azide in water and acids forms hydrazoic acid (HN_3), a highly toxic and volatile liquid solution that poses a serious inhalation hazard. Also, sodium azide or concentrated azide solutions in contact with metal surfaces such as lead, copper, zinc, silver, or brass produce heavy metal azides, which are highly shock-sensitive explosives. Even dilute azide solutions can accumulate enough azide salts over time to cause a serious explosion.[33,34] Using RHEACT, one can use the chemical compatibility matrix functionality to understand the reactive hazards on mixing these components.

The operational hazard matrix generated by the tool, shown in Figure 8A, indicates no issues with the flammability or reactivity of the individual compounds (sodium azide, hydrochloric acid, and water) used in this study. However, the chemical compatibility matrix generated by the tool, highlighted in Figure 8B, clearly indicates the reactive hazards arising from mixing the reagents. These results can be used to perform additional safety reviews for the system and eventually help design safer reaction procedures.

Additional incidents involving a combination of potentially explosive reagents have been studied using RHEACT and are presented in Section S3 of the Supporting Information.

3.2. Identifying Potential Hazards from Adiabatic Operations. In 2007, an explosion occurred at T2 Laboratories during the production of methylcyclopentadienyl manganese tricarbonyl (MCMT), a gasoline additive.[35,36] The primary reason for this explosion, as identified by CSB, was a thermal runaway due to the nature of the reactions involved. The thermal runaway was initiated by a failure in the reactor cooling control system and inappropriate size of the relief system employed to address excessive pressure buildup. The report published by CSB states that the relief system employed

(A)

Hazard Matrix �

Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Other	Ingestion
Sodium azide	✔	✔	✔	✖	✖	✖	✔	✔	✔	◯	✖
Hydrochloric acid	✔	△	✔	✖	✖	◯	✔	✔	✔	✔	✖
Water	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔

Legend: ✔ Safe   △ Caution   ◯ Warning   ✖ Danger

(B)

Cameo Matrix ⊙

	Sodium azide	
Hydrochloric acid	**Incompatible** ✖ Explosive Flammable Generates gas Generates heat Toxic	Hydrochloric acid
Water	**Incompatible** ✖ Generates gas Generates heat	**Caution** △ Corrosive Generates gas Generates heat

Figure 8. (A) Hazard matrix and (B) chemical compatibility matrix generated by the RHEACT tool for the system involving sodium azide, hydrochloric acid, and water.

for the reactor was incapable of relieving the pressure generated by the runaway reaction.[36] Furthermore, it was postulated that the thermal runaway might have been initiated by the decomposition of the solvent (diglyme) involved in the reaction (secondary reaction onset). The exothermic decomposition of the diglyme solvent in the presence of sodium or possibly sodium methylcyclopentadiene was unknown to the T2 owners.[35,37] This resulted in high heat of reaction and elevated reaction rates (due to high temperature), resulting in the ineffectiveness of the normal hydrogen vent, cooling capability, and the relief device.

When the reaction mixture, operated by T2 Laboratories, is simulated with RHEACT, the incompatibility between the components is captured, as depicted by the compatibility matrix in Figure 9. Next, performing the adiabatic temperature change calculations (data imported from the case study report presented by the Center for Chemical Process Safety)[35,37] reveals that the final system temperature following the adiabatic change exceeds the secondary reaction (diglyme solvent decomposition) onset temperature, the proposed initiating event for the thermal runaway. Such an analysis is contingent on the researchers providing information on the possible side reactions associated with the reaction under the operating conditions. The adiabatic change calculations using RHEACT can provide an initial hazard analysis on the system and urge the user to undertake additional hazard review

procedures to be taken during equipment design and process planning.

4. CONCLUSIONS AND FUTURE WORK

An increasing number of safety-related incidents in academic research laboratories warrant the need for a comprehensive hazard assessment tool alongside a compilation of best laboratory practices. Through analyzing wide-ranging, real-life safety accidents, it is shown that RHEACT can help in the initial hazard assessment of reaction systems. The tool provides a convenient platform to analyze, compile, and predict the hazards associated with the handling and storage of individual components and mixtures. These results enable the researcher to make informed decisions on the choice of PPE required for handling the reagents and resulting reaction products. It also provides information on the reactive hazards resulting from the mixing of incompatible materials and the potential for thermal runaway events. These alerts can be used for the safer design of reaction systems.

The tool can estimate the adiabatic temperature change associated with the reaction system considering the contributions from the heat of reaction alone. Reaction heat gain or loss due to events involving the reaction plus fire, pooling, and misloading is not available with RHEACT but can be studied in further detail using the Risk Analysis Screening Tool (RAST) available online. Currently, additional links to guide the researchers in the PPE selection process are provided. In

Calculation ⍰

Adiabatic temperature change: 52.000 °C
Calculated final temperature: 202.000 °C
Calculated final pressure: 4.606 bar

Alerts

Final temp exceeds reactant 1 boiling point
Final temp exceeds reactant 1 flash point
Final temp exceeds reactant 2 boiling point
Final temp exceeds reactant 2 flash point
Final temp exceeds product 1 boiling point
Final temp exceeds product 1 flash point
Final temp exceeds product 2 flash point
Final temp exceeds side reaction 1 temperature onset

Cameo Matrix ⍰

	Methylcyclopentadiene dimer		
Diethylene glycol diethyl ether	**Caution** ⚠ Potentially hazardous	Diethylene glycol diethyl ether	
Sodium	**Incompatible** ❌ Generates heat Polymerization hazard	**Incompatible** ❌ Corrosive Flammable Generates heat	Sodium
Hydrogen	**Caution** ⚠ Generates heat Potentially hazardous	**Compatible** ✅	**Incompatible** ❌ Explosive Generates heat Intense or explosive reaction

Figure 9. Calculation block and the chemical compatibility matrix generated by the RHEACT tool for the T2 laboratories case study.

the future, the tool will use data from the chemical hazard matrix to predict appropriate PPE for the user based on the handling hazards. In addition, the tool will also provide a compilation of laboratory best practices and complementary safety resources (videos, documents, guides, etc.). We believe a free and online risk-assessment tool such as RHEACT would help democratize and encourage a culture of safety and due diligence when planning experiments.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.chas.1c00006.

Additional examples of reaction systems studied for hazard analysis using RHEACT and information on the data acquisition and data parsing module available within RHEACT (PDF)

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