Demonstration of Reactive Hazards Evaluation & Analysis Compilation Tool (RHEACT)

Sopuru Ezenwa,[1] Jeremy Arvay,[1] Abhijit D. Talpade,[1] Pushkar Ghanekar,[1] Ravi Joshi,[1] Samuel Kravitz,[2] Anirudh Tunga,[3] Vikrant Gajria,[2] Jay Devaraj,[4] Fabio H. Ribeiro,[1] Ray Mentzer[1,5]

[1]Davidson School of Chemical Engineering, Purdue University, West Lafayette, IN, USA
[2]Department of Computer Science, Purdue University, West Lafayette, IN, USA
[3]School of Industrial Engineering, Purdue University, West Lafayette, IN, USA
[4]Corteva Agriscience, Indianapolis, IN, USA
[5]Purdue Process Safety and Assurance Center (P2SAC), West Lafayette, IN, USA

Purdue Process Safety and Assurance Center (P2SAC) Spring 2022 Conference – Day 1 (Tutorials)
May 9, 2022
Virtual Meeting

Safety incidents are still prevalent in chemical research laboratories

PROBLEM

Prevalence of lab safety incidents & Need for convenient tool for preliminary hazard evaluation

CSB Releases Laboratory Incident Data (Jan. 2001 - Jul. 2018) https://www.csb.gov/csb-releases-laboratory-incident-data-jan-2001---jul-2018/
Kaufman, J. A. Memorial Wall - Killed in Lab Accident; Laboratory Safety Institute https://www.labsafety.org/memorial-wall
Vidal, S. Safety First: A Recent Case of a Dichloromethane Injection Injury. *ACS Cent. Sci.* **2020**, *6*, 83–86.
Juba, B. W. et al. Lessons Learned—Fluoride Exposure and Response. *ACS Chem. Health Saf.* **2021**, *28*, 129
https://www.jconline.com/story/news/local/lafayette/2020/08/20/two-injured-purdue-university-explosion-chemistry-building/3401596001/
https://ehrs.upenn.edu/health-safety/lab-safety/safety-alerts-and-faqs/vacuum-pump-explosion-chemistry-building

CISTAR/P2SAC initiative aims to improve lab safety practices

PROBLEM

Prevalence of lab safety incidents & Need for convenient tool for preliminary hazard evaluation

SOLUTION & APPROACH

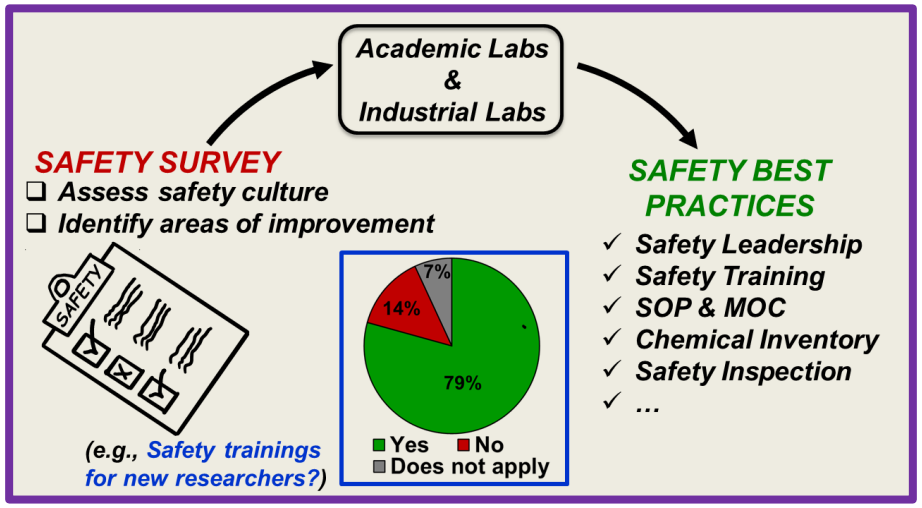
LAB SAFETY INITIATIVE

Assess safety practices in academic & industrial labs

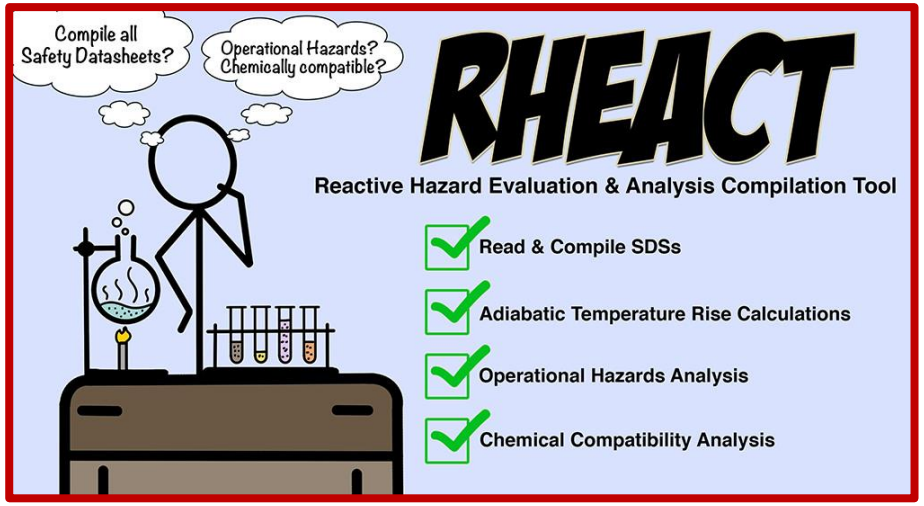
Develop tools and compile best practices for safety evaluation

IMPACT

Reduction of the occurrence and severity of safety incidents and losses



Ezenwa, S.;[#] Talpade, A. D.;[#] Ghanekar, P.; Joshi, R.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. Toward Improved Safety Cultures in Academic and Industrial Chemical Laboratories: An Assessment and Recommendation of Best Practices, *ACS Chem. Health Saf.* **2022,** *29*, 202



Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. Promoting a Safe Laboratory Environment Using the Reactive Hazard Evaluation and Analysis Compilation Tool. *ACS Chem. Health Saf.* **2021**, *28*, 134

P2SAC Purdue Process Safety & Assurance Center

CISTAR NSF Engineering Research Center Center for Innovative and Strategic Transformation of Alkane Resources

NSF

Brief history of RHEACT

- **Summer 2018:** Purdue ChE Professional Masters Project with Dow AgroSciences (now Corteva Agriscience)
  - *"A Systems Engineering Approach for Managing Changes in Chemical Process R&D Labs"*
- **October 2018:** P2SAC/CISTAR Lab Safety Project formally initiated with funds from NSF
  - *Project Title: Safety in Academic & Industrial Laboratories*
  - *Initial team: 2 Purdue ChE Profs., 1 industrial collaborator, 4 ChE PhD students*
- **May 2019:** Tool development begins after addition of software programmer
- **March 2021:** RHEACT Alpha version (1.0) developed and made available for testing
- **May 2022:** RHEACT Beta version (2.0) developed

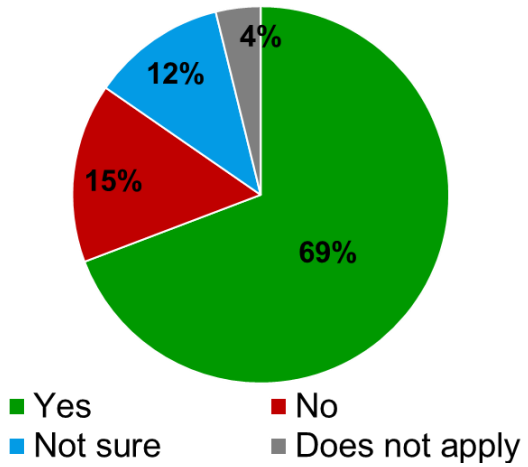
Excerpt from email soliciting Purdue CISTAR grad student participation (October 2018):

***University and R&D laboratory safety has been identified as an area of national concern that needs attention, following various well publicized mishaps and fatalities**. In light of conditions and hazardous materials encountered by universities engaged in CISTAR, safety-related materials and training will be required to ensure consistent expectations and application. A set of best practices and tools will be identified and developed based on a survey of the practices in the five universities associated with CISTAR, as well as a broader look at other universities and CISTAR and P2SAC member company labs. An Internet accessible App or Excel macro will be developed to compile a host of safety-related information to evaluate and understand all hazards before performing lab experiments.*

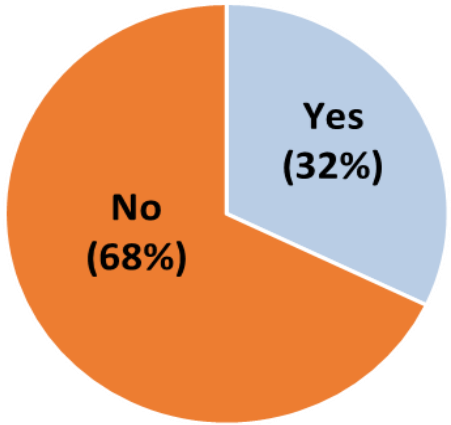
Surveys highlight hazard evaluation practices at academic and industrial labs

- Demographics of respondents:
  - ***Academic survey:*** Lab experience > 10 yr. (55%; mostly PI/faculty) or >4 yr. (90%; including grad students/postdocs)
  - ***Industrial survey:*** *pharmaceuticals, (petro)chemicals, oil & gas, engineering, polymers, energy; members or leaders of process safety groups or technical R&D groups*

Review of new or modified experimental setup (26 responses)

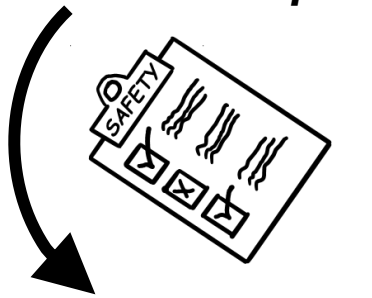


Use of proprietary software tools



SAFETY SURVEY

- ❑ ***Assess safety culture***
- ❑ ***Identify areas for improvement***



Academic Labs & Industrial Labs

- **Survey results further suggest that continued occurrence of lab incidents is potentially linked to:**
  - **Inadequate documentation of best practices**
  - **Limited tools for rapid preliminary analysis of safety risks in research labs**

Ezenwa, S.;[#] Talpade, A. D.;[#] Ghanekar, P.; Joshi, R.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2022**

Industrial survey: Data, databases and tools used for hazard evaluation

- Common Hazards evaluated
  - Chemical reactivity
  - Toxicity and Flammability
  - Loss of containment
  - Thermal runaway

- Data collected for hazard evaluation
  - Thermal stability and heat of reaction
  - flammability limit, toxic levels of concern
  - Physical and chemical properties, Operating conditions (temperature, pressure, flow)

- **Databases consulted:** Safety Data Sheets (SDS), Bretherick's Handbook, NIOSH, NIST, Scifinder, Internal databases

- **Software tools used:** **CAMEO** Chemicals, Chemical Reactivity Worksheet (**CRW**), Risk Analysis and Screening tool (**RAST**), Chemical Thermodynamic and Energy Release Evaluation Program (**CHETAH**), **DYNOCHEM**, in-house tools

- **Some identified challenges during hazard evaluation:**
  - Inconvenience of accessing multiple tools and databases
  - Lack of streamlined procedure
  - Limited functionalities in major tools for chemical compatibility checks or PPE guidance

Ezenwa, S.;[#] Talpade, A. D.;[#] Ghanekar, P.; Joshi, R.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2022**

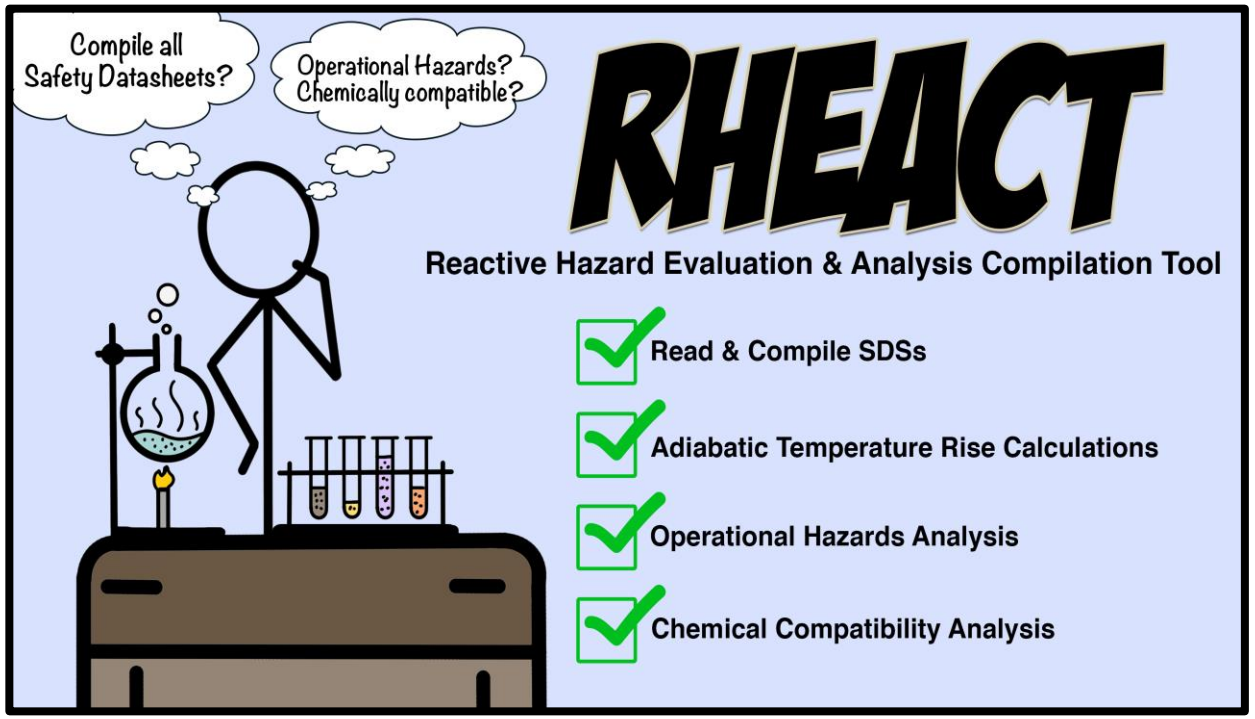
Development of a convenient hazard evaluation tool for research labs

- Common software tools: *CRW, RAST, CHETAH, CAMEO, CHEF*

- Need for development of a convenient web tool that can:
  - Collect critical information about planned experiment
  - Conduct preliminary operational hazard analysis
  - Summarize potential safety issues and best practices

- Target users:
  - Academic chemical research and teaching labs
  - Small and mid-size enterprises' (SME) R&D labs

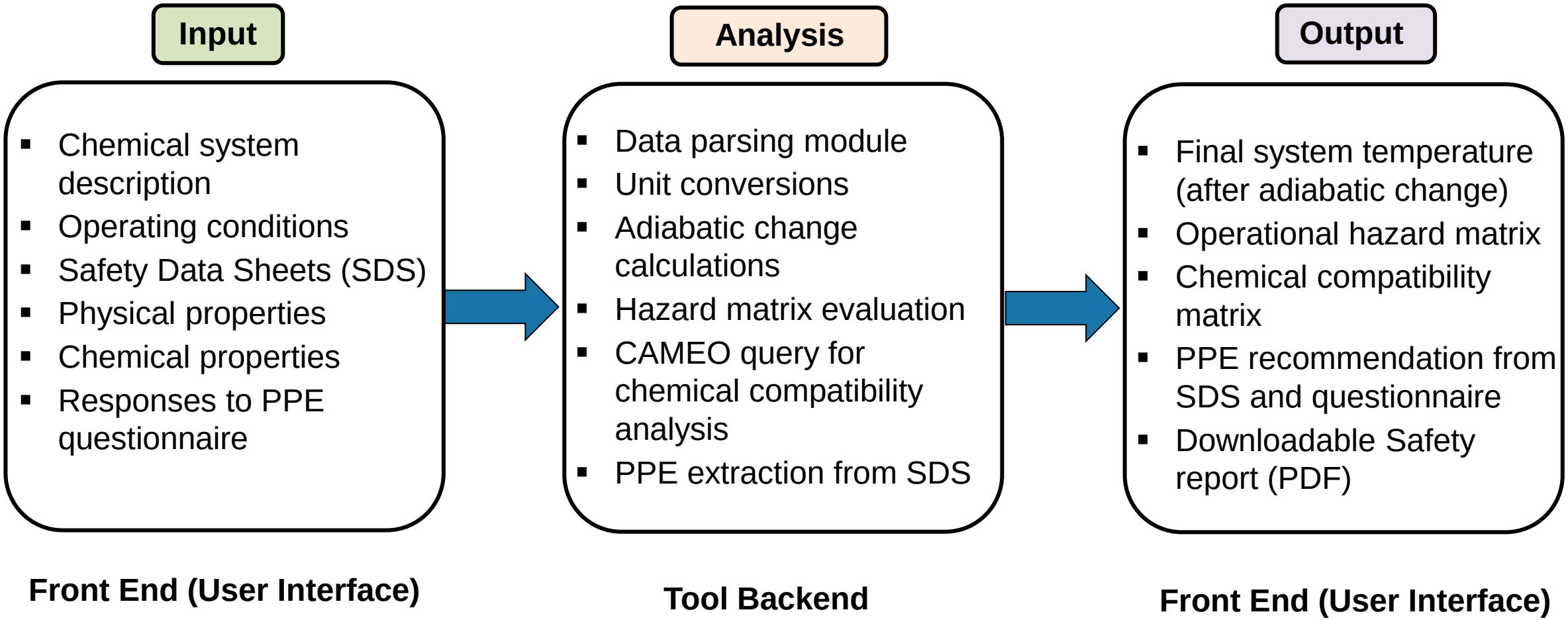
We aim for RHEACT to be a quick preliminary screening tool that alerts users about hazards and pushes them to perform further analysis.



Talpade, A. D.;# Ghanekar, P.;# Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. Promoting a Safe Laboratory Environment Using the Reactive Hazard Evaluation and Analysis Compilation Tool. *ACS Chem. Health Saf.* **2021**, *28*, 134

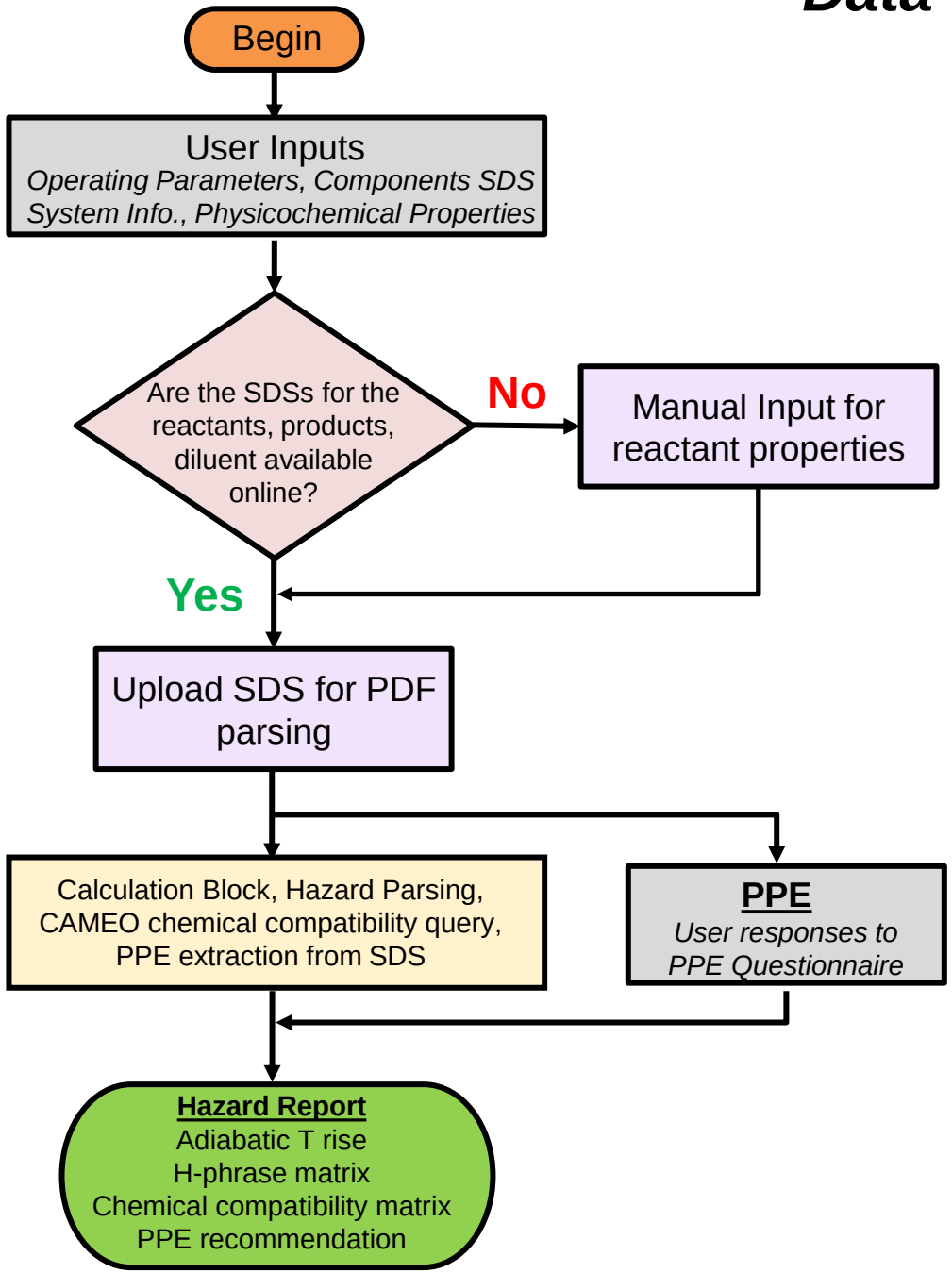
RHEACT overall workflow

Process Block Diagram for RHEACT

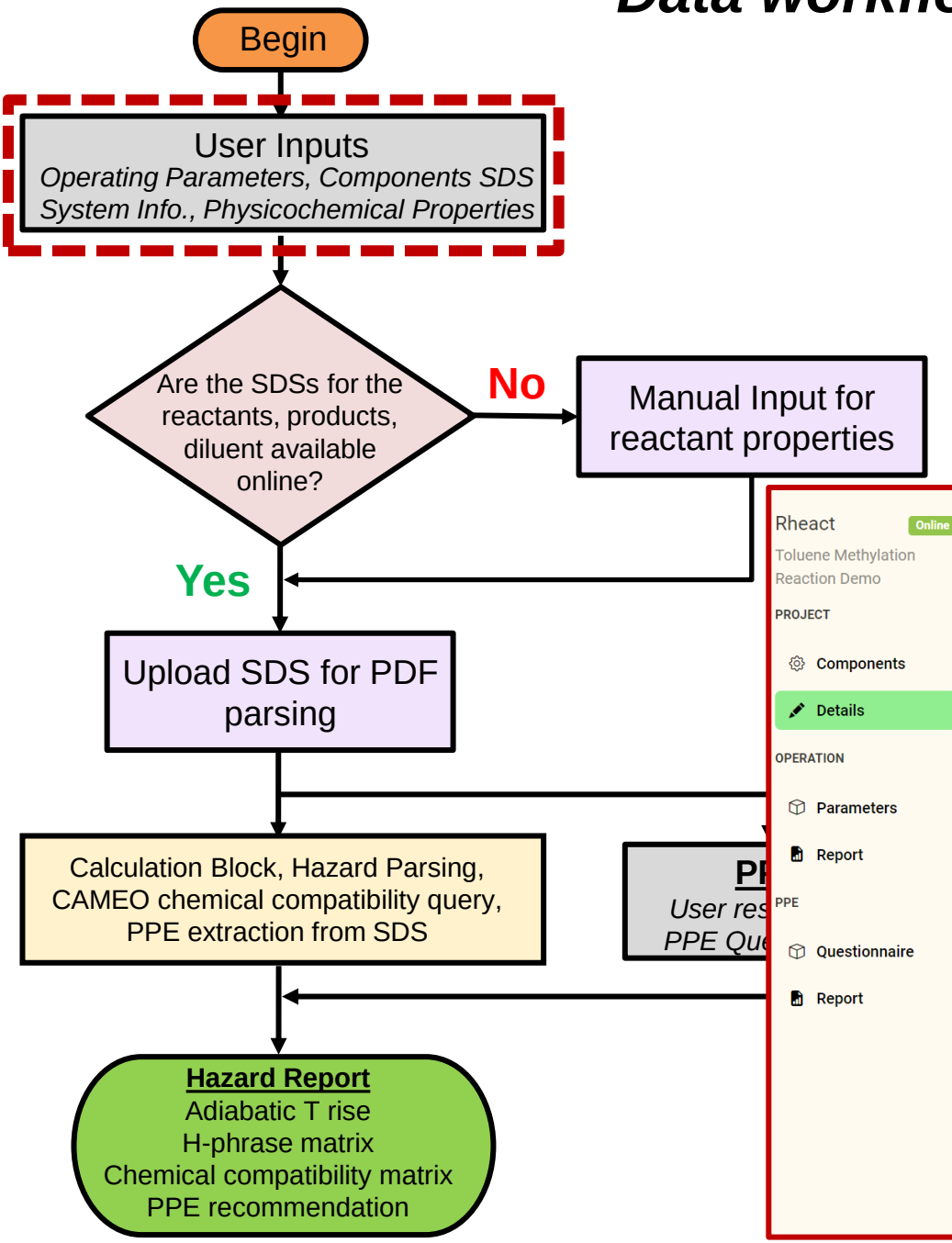


Talpade, A. D.;[#] Ghanekar, P.;[#] **Ezenwa, S.**; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Data workflow for RHEACT

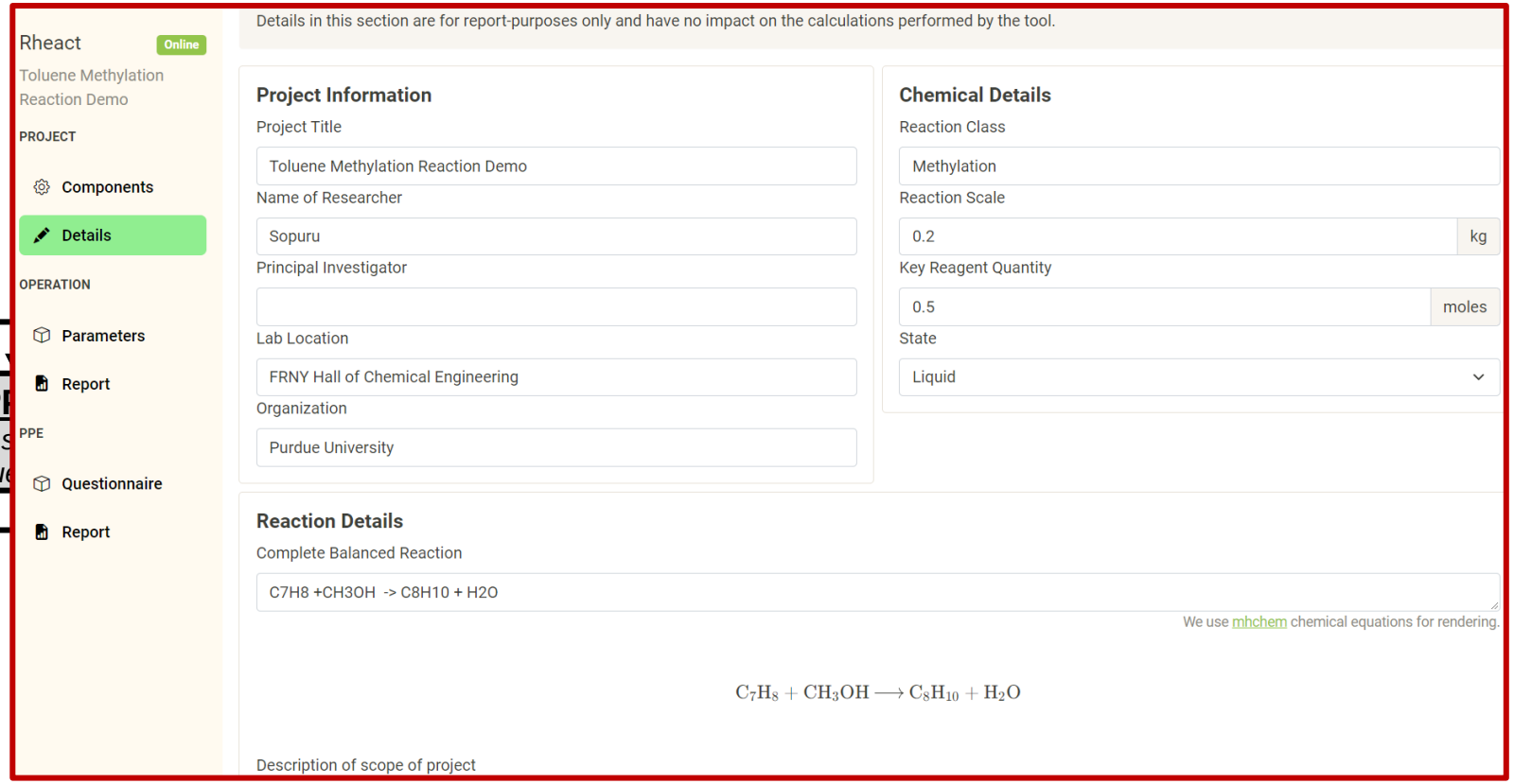


Data workflow for RHEACT: User Inputs

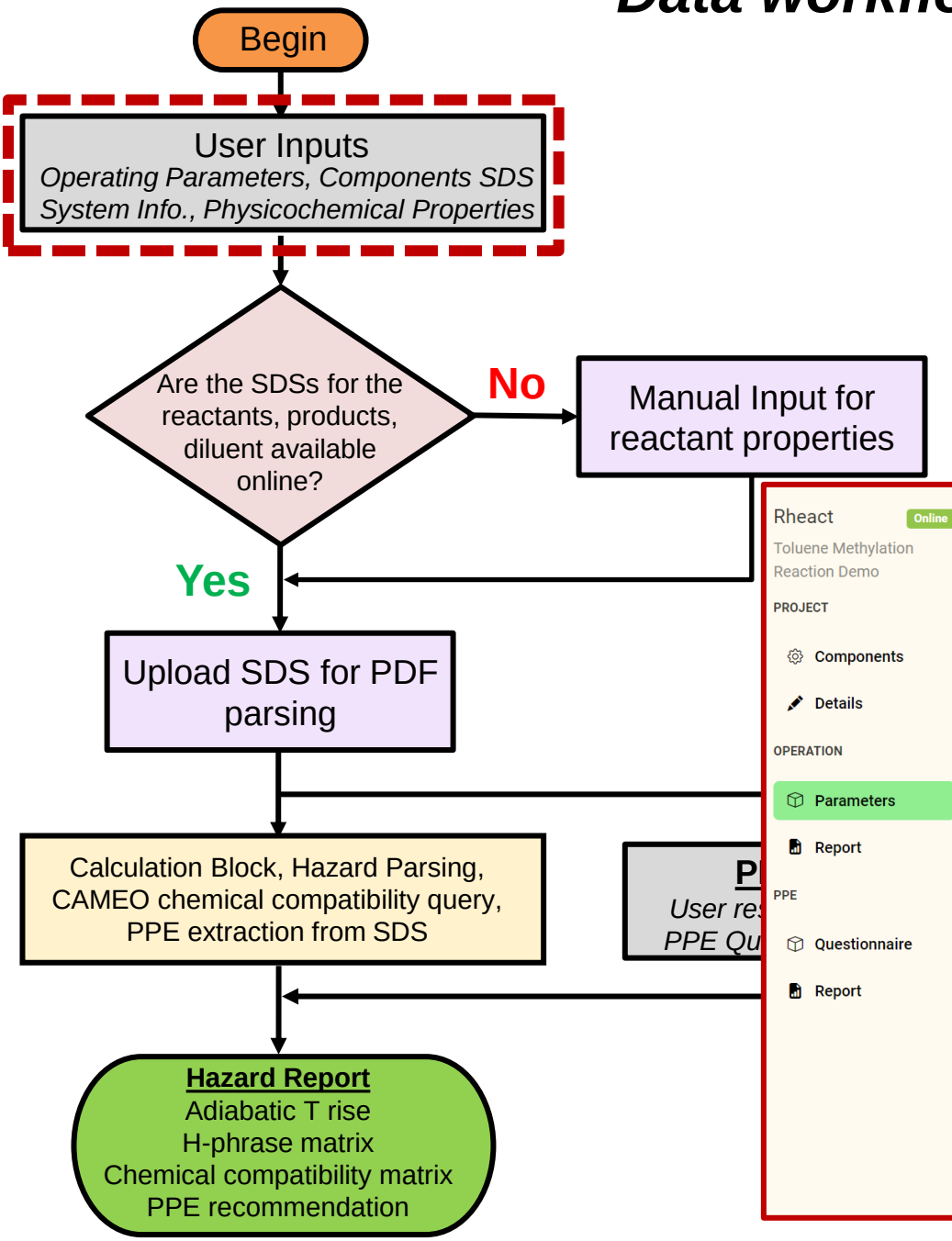


- Project information, chemical reaction details (reaction class, scale, phase, chemical equation)

Screenshot of Project Details Page

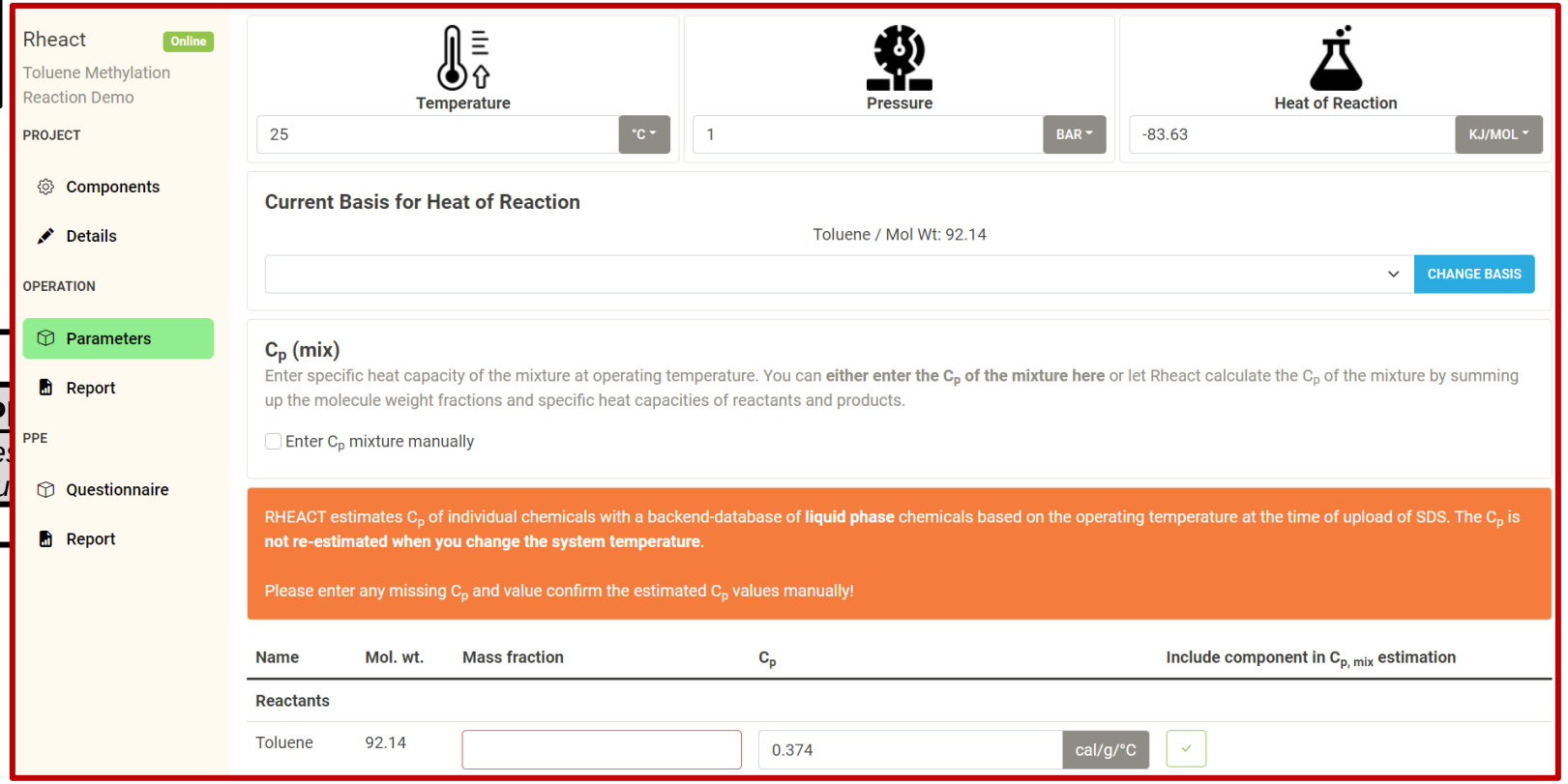


Data workflow for RHEACT: User Inputs

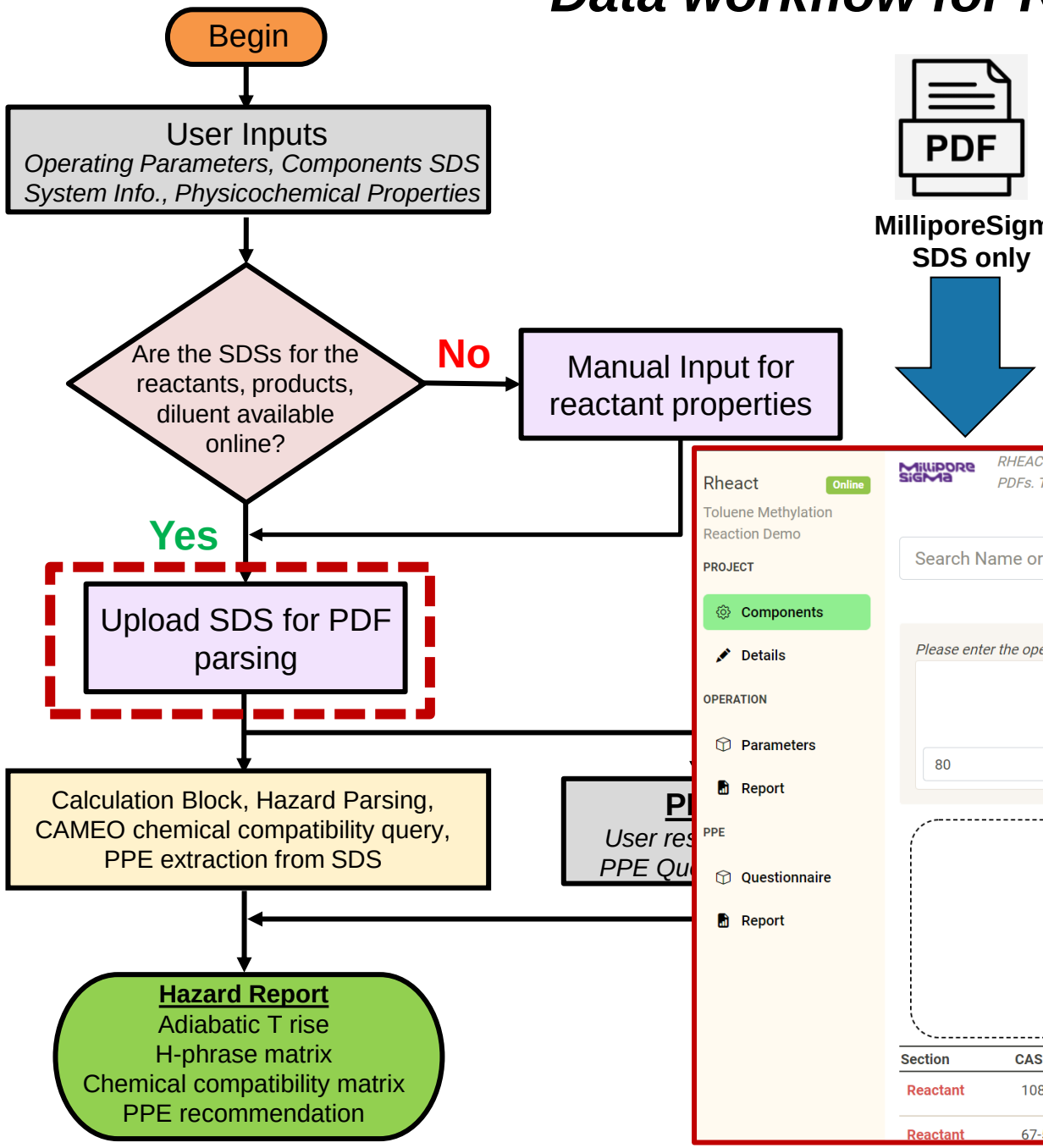


- Project information, chemical reaction details (reaction class, scale, phase, chemical equation)
- Temperature, Pressure, ΔH_{rxn} (with basis), $C_{p,j}$ or $C_{p,mix}$

Screenshot of Operation Parameters



Data workflow for RHEACT: SDS Upload

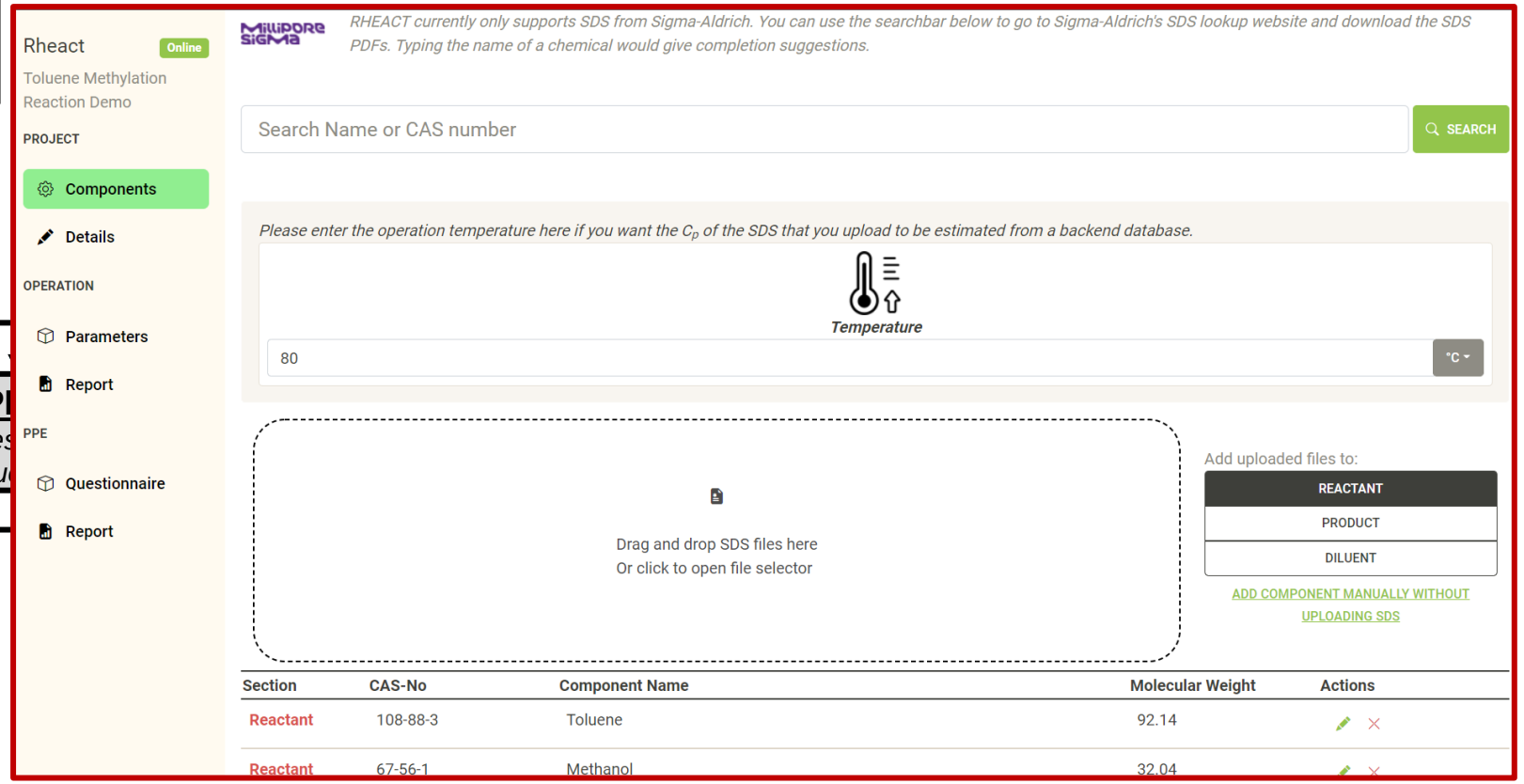


PDF

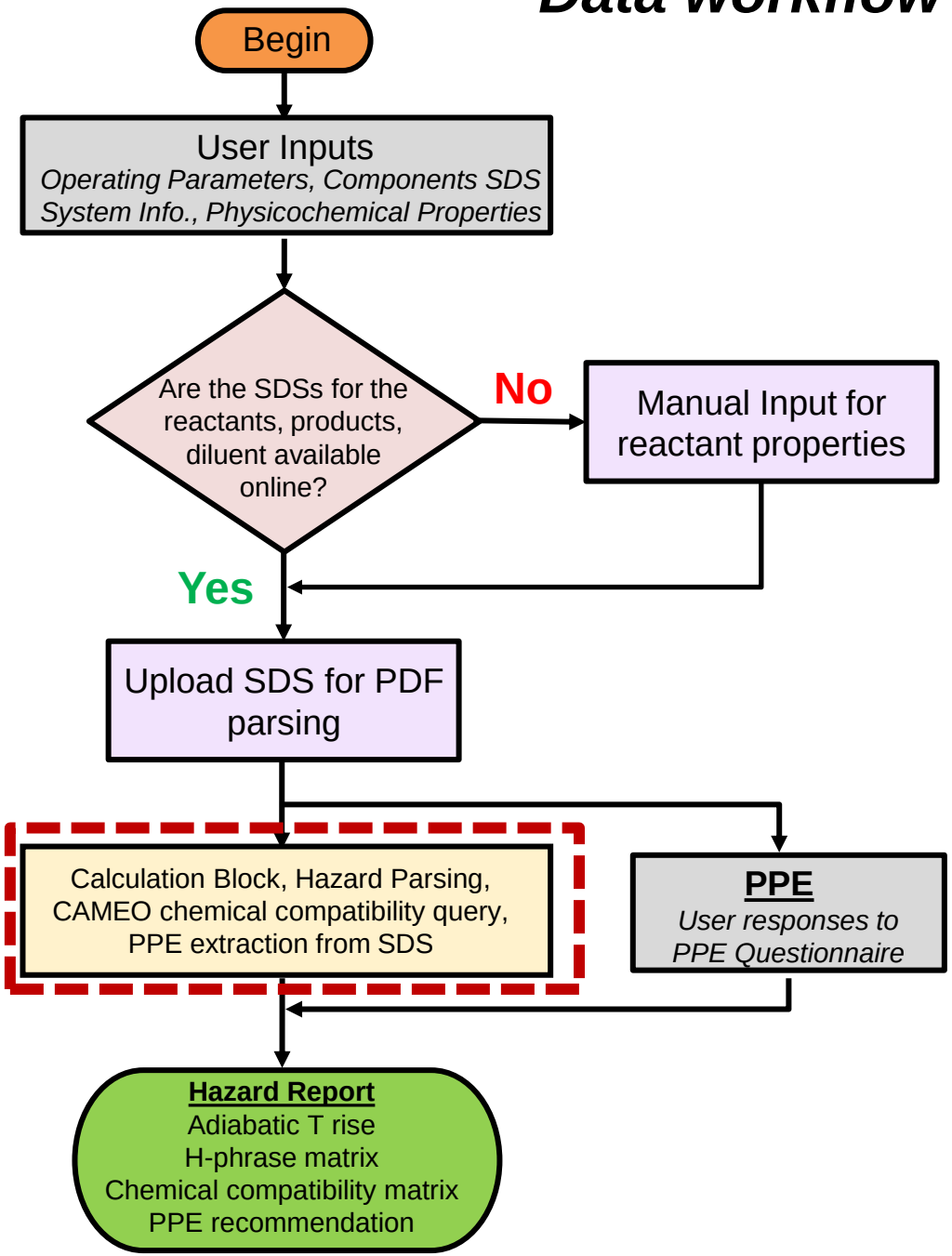
MilliporeSigma SDS only

- SDS upload automatically adds component to system
- Pdftotext module used to parse the supplied SDS(s)
- Information sent back to the front-end display

Screenshot of SDS Upload Page



Data workflow for RHEACT: Calculation Block



- Database of ~300 chemicals with physical and chemical properties
- Autofill inputs (e.g., $C_{p,liquid}$) that are unavailable from user/SDS
- Unit conversions from user desired units to base calculation units

Adiabatic temperature rise (ΔT_{ad})

User provided

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

$$\mathcal{C}[=] \frac{cal}{g_i} * \frac{g_{total}\,^{\circ}\mathrm{C}}{cal} * \frac{g_i}{g_{total}}$$

Estimated or User provided

Final temperature, $T_{final} = T_{initial} + \Delta T_{ad}$

Mixture heat capacity ($C_{p,mix}$)

$$C_{p,mix} = \sum_{j}^{\#\ components} X_j * C_{p,j}$$

$$C_{p,mix,\ rescaled} = \sum_{j \neq m}^{\#\ components} \frac{X_j}{\sum_{k \neq m}^{\#components} X_k} * C_{p,j}$$

X_i : mass fraction of ΔH_{rxn} basis (= 1 if total reaction mixture)

$C_{p,j}$: *Component heat capacity (user-provided or estimated)*

$C_{p,mix,rescaled}$: *Rescaled mass fractions if component (m) is neglected from* $C_{p,mix}$ calculations

Data workflow for RHEACT: Operational hazard matrix

- Parse H-phrases (Hazard statements) from uploaded SDS

Hazard Statements

Name	H-Number	H-Statement
Water		
Chloroform	H302 H331 H315 H319 H351 H361 H336 H372 H402 H412	Acute toxicity, Oral (Category 4) Acute toxicity, Inhalation (Category 3) Skin irritation (Category 2) Eye irritation (Category 2A) Carcinogenicity (Category 2) Reproductive toxicity (Category 2) Specific target organ toxicity - single exposure (Category 3), Central nervous system Specific target organ toxicity - repeated exposure (Category 1), Liver, Kidney Short-term (acute) aquatic hazard (Category 3) Long-term (chronic) aquatic hazard (Category 3)
Acetone	H225 H319 H336	Flammable liquids (Category 2) Eye irritation (Category 2A) Specific target organ toxicity - single exposure (Category 3), Central nervous system
Sodium hydroxide	H290 H314 H318 H402	Corrosive to Metals (Category 1) Skin corrosion (Category 1A) Serious eye damage (Category 1) Short-term (acute) aquatic hazard (Category 3)

Data workflow for RHEACT: Operational hazard matrix

- Parse H-phrases (Hazard statements) from uploaded SDS
- Implemented a logic for categorizing each H-phrase into operational hazards
- Severity assigned for each operational hazard expressed as a color code

Hazard Matrix

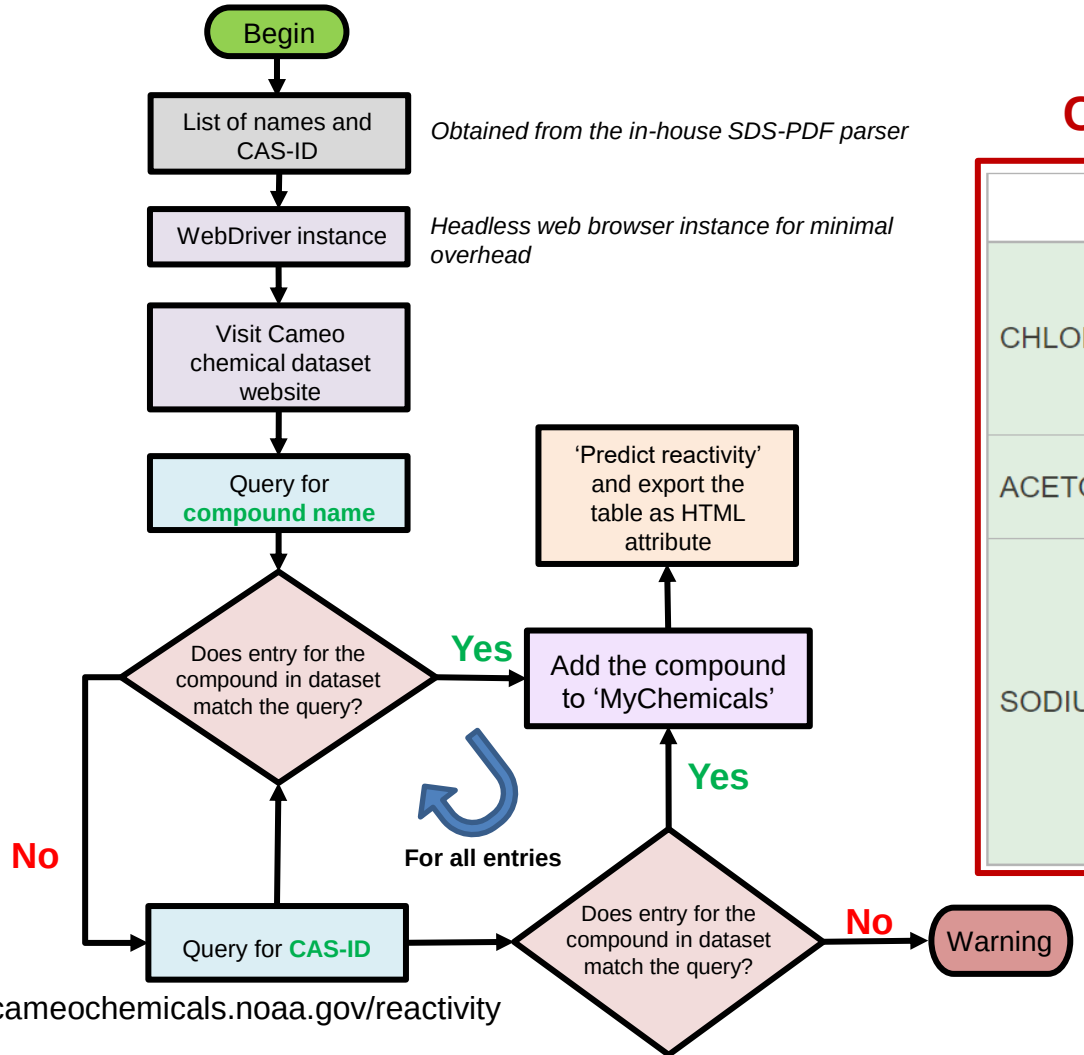
Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Ingestion	Other
Water	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Chloroform	✓	✓	✓	△	○	✕	✕	○	✓	○	✕
Acetone	✕	✓	✓	✓	○	△	✓	✓	✓	✓	✓
Sodium hydroxide	✓	△	✓	✕	✕	○	✓	✓	✓	✕	✓

Legend: ✓ Safe △ Caution ○ Warning ✕ Danger

Compile and visualize all the Hazards in a condensed format

Data workflow for RHEACT: Chemical Compatibility matrix

- Queries CAMEO chemical reactivity assessment tool to simulate pair-wise interactions of chemicals
- Selenium WebDriver automates web browser interaction between RHEACT and CAMEO website
- The generated matrix is imported into RHEACT



https://cameochemicals.noaa.gov/reactivity

Compatibility chart for compounds available in CAMEO

	WATER		
CHLOROFORM	Caution Corrosive Generates gas	CHLOROFORM	
ACETONE	Compatible	Compatible	ACETONE
SODIUM HYDROXIDE SOLUTION	Caution Corrosive Generates gas Generates heat Toxic	Incompatible Corrosive Flammable Generates gas Intense or explosive reaction Toxic	Incompatible Generates heat

Data workflow for RHEACT: PPE recommendation

- PPE extracted from MilliporeSigma SDS (Section 8.2)

PPE Extraction from SDS

Water (7732-18-5)

SECTION 7: Handling and storage

7.1 Precautions for safe handling
For precautions see section 2.2.

7.2 Conditions for safe storage, including any incompatibilities

Storage conditions
No special storage conditions required.
Storage class (TRGS 510): 10: Combustible liquids

7.3 Specific end use(s)
Apart from the uses mentioned in section 1.2 no other specific uses are stipulated

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Ingredients with workplace control parameters
Contains no substances with occupational exposure limit values.

8.2 Exposure controls

Appropriate engineering controls
not required

Personal protective equipment

Eye/face protection
not required

Skin protection
not required

Acetone (67-64-1)

8.2 Exposure controls

Appropriate engineering controls
Change contaminated clothing. Preventive skin protection recommended. Wash hands after working with substance.

Personal protective equipment

Eye/face protection
Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU). Safety glasses

SIGALD - 179124 Page 5 of 12

The life science business of Merck KGaA, Darmstadt, Germany operates as MilliporeSigma in the US and Canada

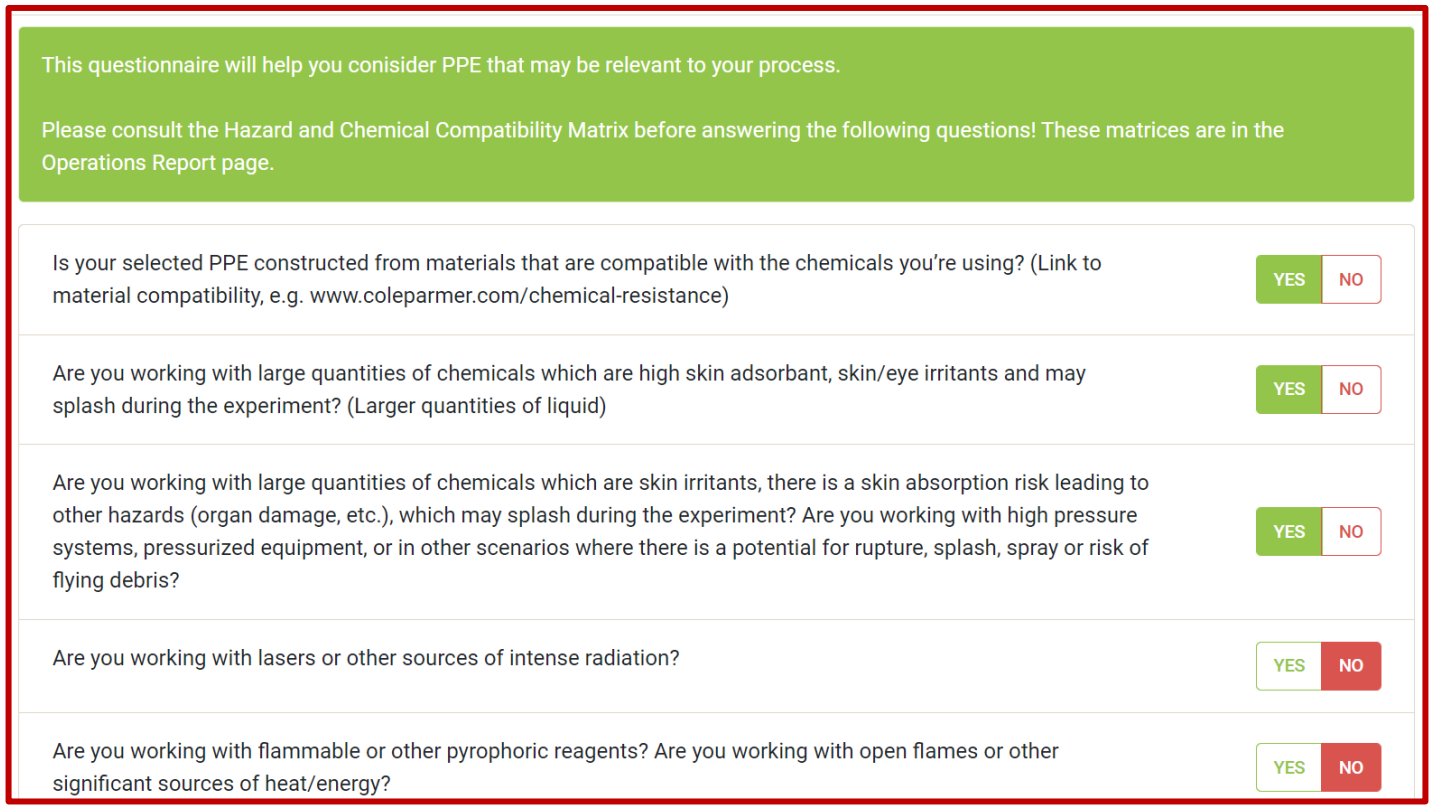
Skin protection
This recommendation applies only to the product stated in the safety data sheet, supplied by us and for the designated use. When dissolving in or mixing with other substances and under conditions deviating from those stated in EN374 please contact the supplier of CE-approved gloves (e.g. KCL GmbH, D-36124 Eichenzell, Internet: www.kcl.de).
Full contact
Material: butyl-rubber
Minimum layer thickness: 0.7 mm
Break through time: 480 min
Material tested:Butoject® (KCL 898)

This recommendation applies only to the product stated in the safety data sheet,

Data workflow for RHEACT: PPE recommendation

- PPE questionnaire (20 questions) provides additional application-specific PPE suggestions

PPE Questionnaire



This questionnaire will help you conisider PPE that may be relevant to your process.

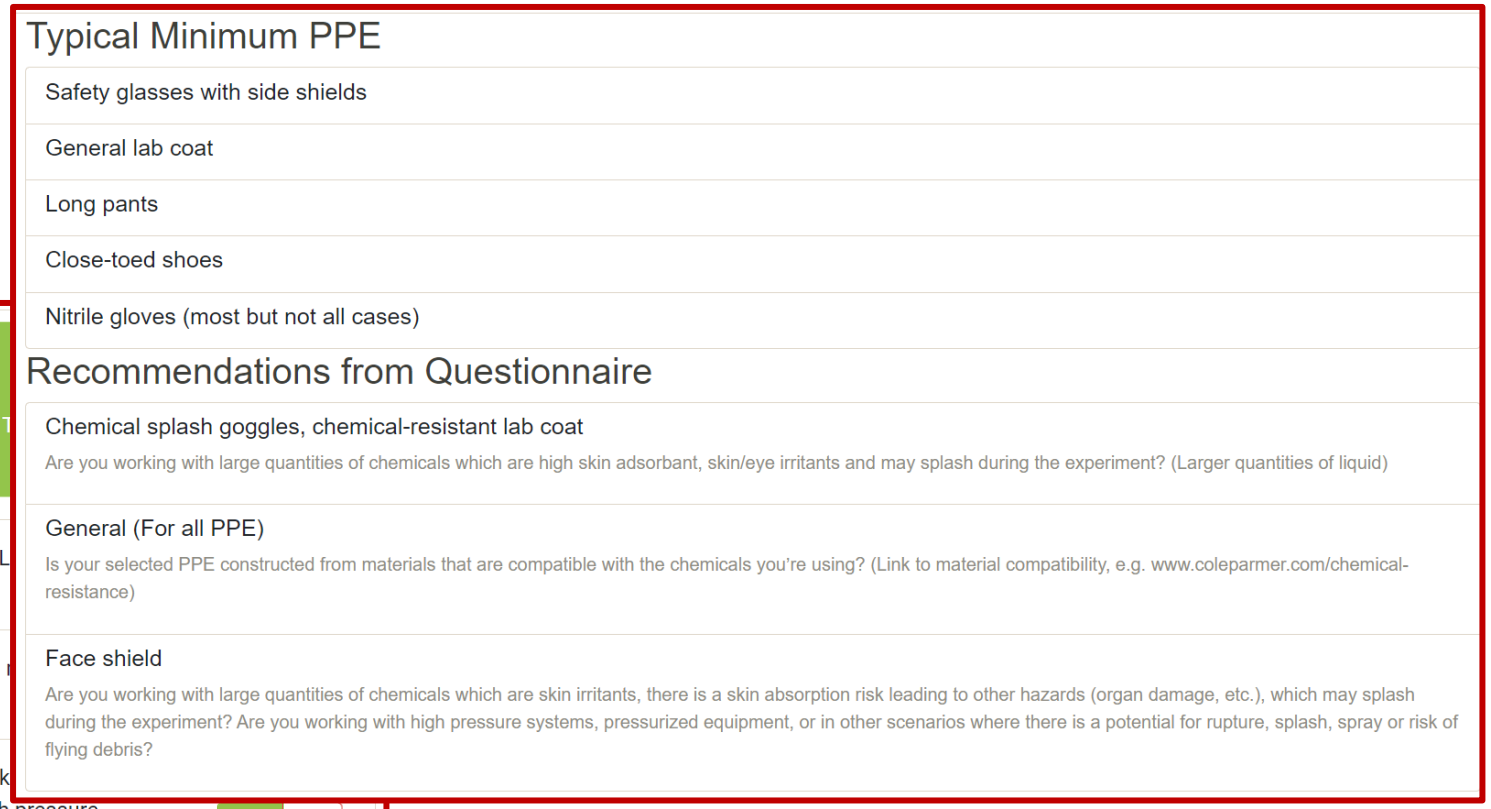
Please consult the Hazard and Chemical Compatibility Matrix before answering the following questions! These matrices are in the Operations Report page.

Is your selected PPE constructed from materials that are compatible with the chemicals you're using? (Link to material compatibility, e.g. www.coleparmer.com/chemical-resistance)	YES / NO
Are you working with large quantities of chemicals which are high skin adsorbant, skin/eye irritants and may splash during the experiment? (Larger quantities of liquid)	YES / NO
Are you working with large quantities of chemicals which are skin irritants, there is a skin absorption risk leading to other hazards (organ damage, etc.), which may splash during the experiment? Are you working with high pressure systems, pressurized equipment, or in other scenarios where there is a potential for rupture, splash, spray or risk of flying debris?	YES / NO
Are you working with lasers or other sources of intense radiation?	YES / NO
Are you working with flammable or other pyrophoric reagents? Are you working with open flames or other significant sources of heat/energy?	YES / NO

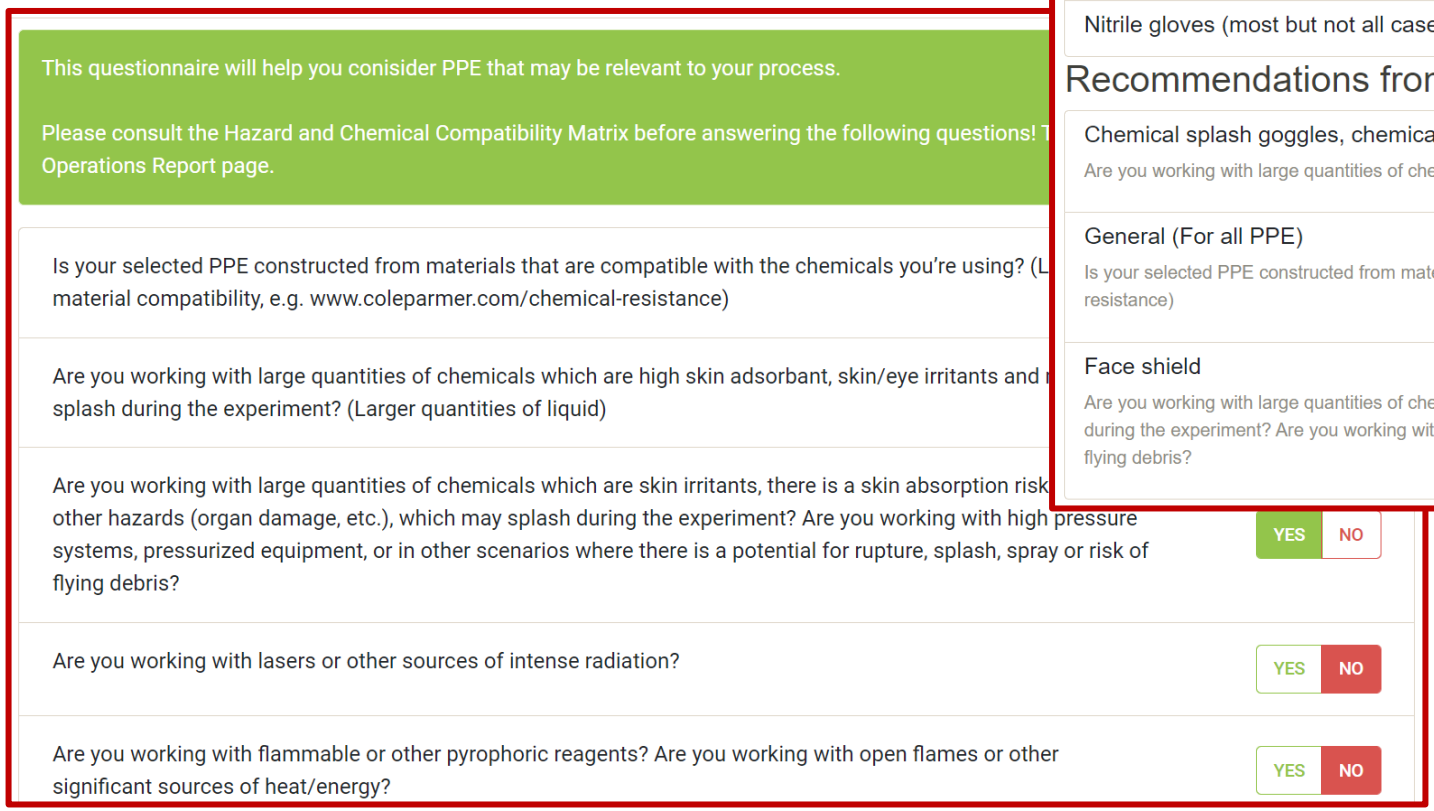
Data workflow for RHEACT: PPE recommendation

- PPE questionnaire (20 questions) provides additional application-specific PPE suggestions

PPE Suggestions



PPE Questionnaire



Some case studies to validate and demonstrate RHEACT capabilities

- University of Hawaii Incident (March 2016)
- Sodium Azide Explosions
- University of Pennsylvania Chemistry Building Incident (August 2020)
- **T2 Laboratories incident (December 2007) :** killed 4, injured 32, and destroyed multiple businesses
  - demonstrates RHEACT utility beyond lab & pilot plant
  - studied as a case study for RAST (Risk Analysis Screening Tool)[2]

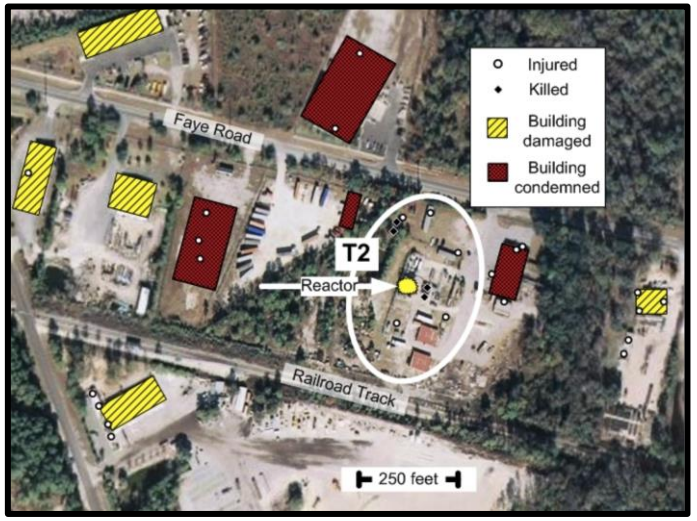
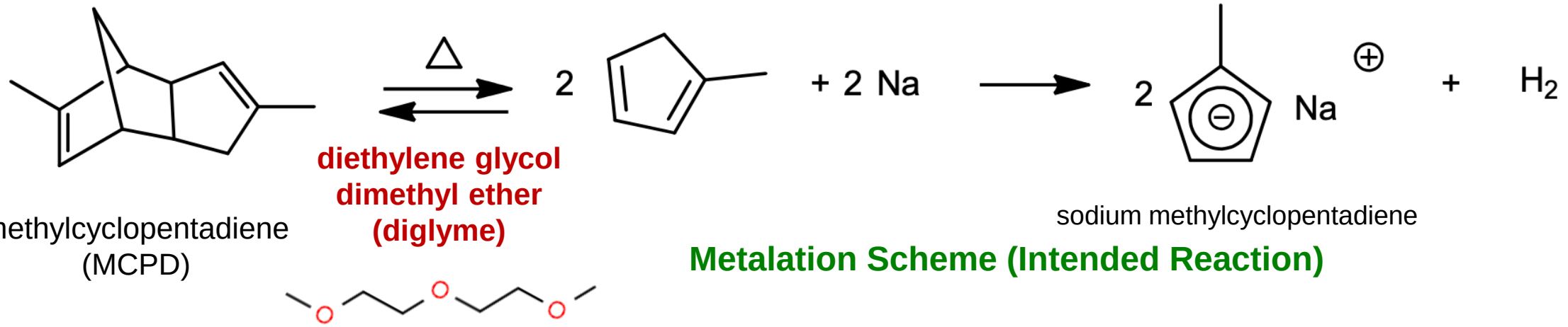


Photo courtesy: The U.S. Chemical Safety Board. T2 Laboratories Inc. Reactive Chemical Explosion.

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134
The U.S. Chemical Safety Board Investigation Report (2009). T2 Laboratories Inc. Runaway Reaction. https://www.csb.gov/t2-laboratories-inc-reactive-chemical-explosion/
https://www.aiche.org/ccps/resources/tools/risk-analysis-screening-tool-rast-and-chemical-hazard-engineering-fundamentals-chef/case-studies

Case Study: T2 Laboratories explosion and fire (Jacksonville, FL; Dec. 2007)

- MCMT (gasoline additive) produced in a batch reactor in three steps
- The first step of the reaction (metalation reaction) requires heating to initiate the reaction
- All other steps are exothermic (heat-producing) and required cooling



Metalation Scheme (Intended Reaction)

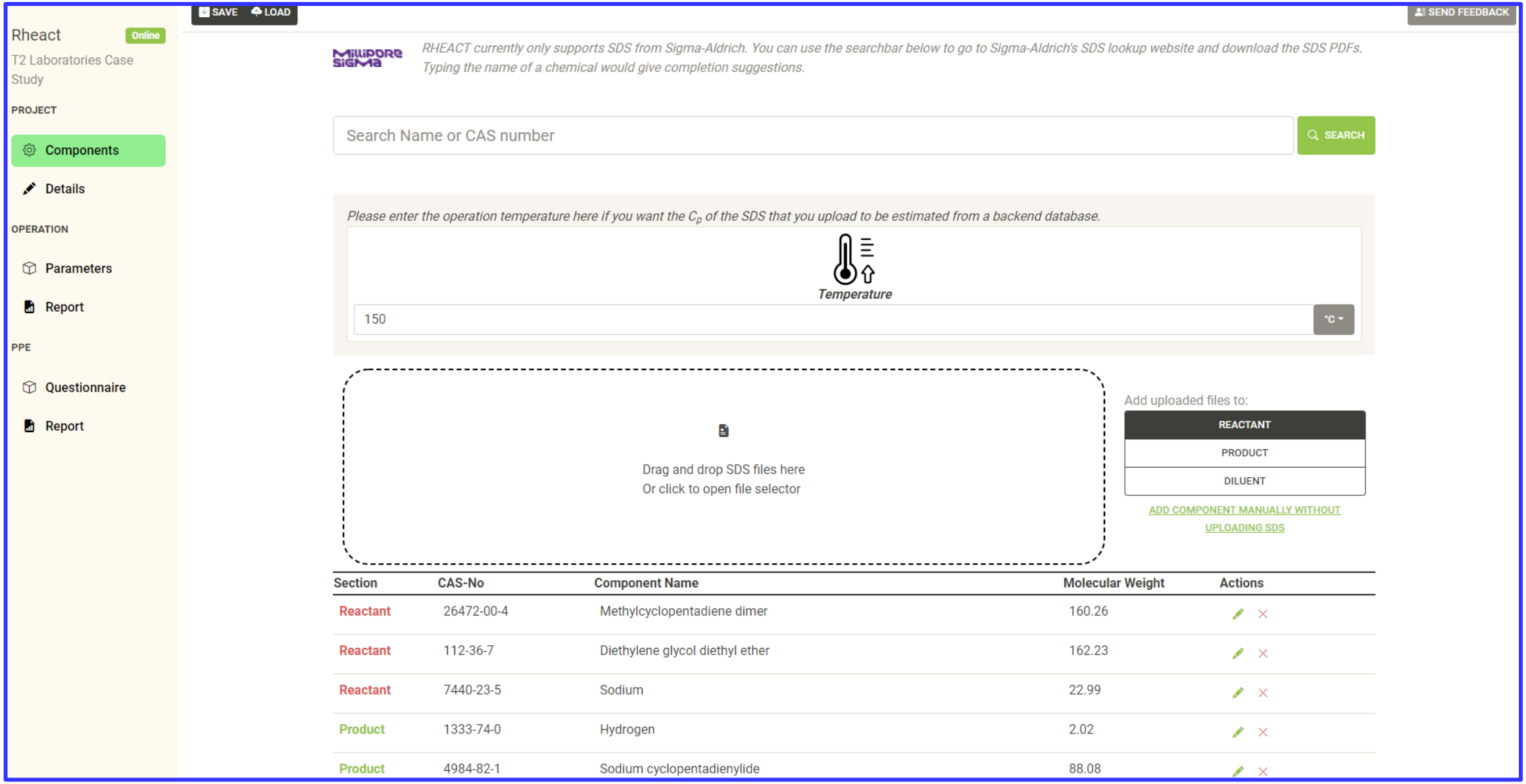
Some key findings (CSB Final report. 2009) :

1. Desired exothermic reaction in the metalation step ran away due to a cooling system failure, leading to undesired exothermic decomposition of diglyme solvent.
2. Pressure relief system designed only for normal operating conditions
3. Personnel likely unaware of the solvent decomposition that occurred in the batch recipe at high temperatures.

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134
https://www.aiche.org/ccps/resources/tools/risk-analysis-screening-tool-rast-and-chemical-hazard-engineering-fundamentals-chef/case-studies
The U.S. Chemical Safety Board Investigation Report (2009). T2 Laboratories Inc. Runaway Reaction. https://www.csb.gov/t2-laboratories-inc-reactive-chemical-explosion/

Case Study: T2 Laboratories explosion and fire (Dec. 2007)

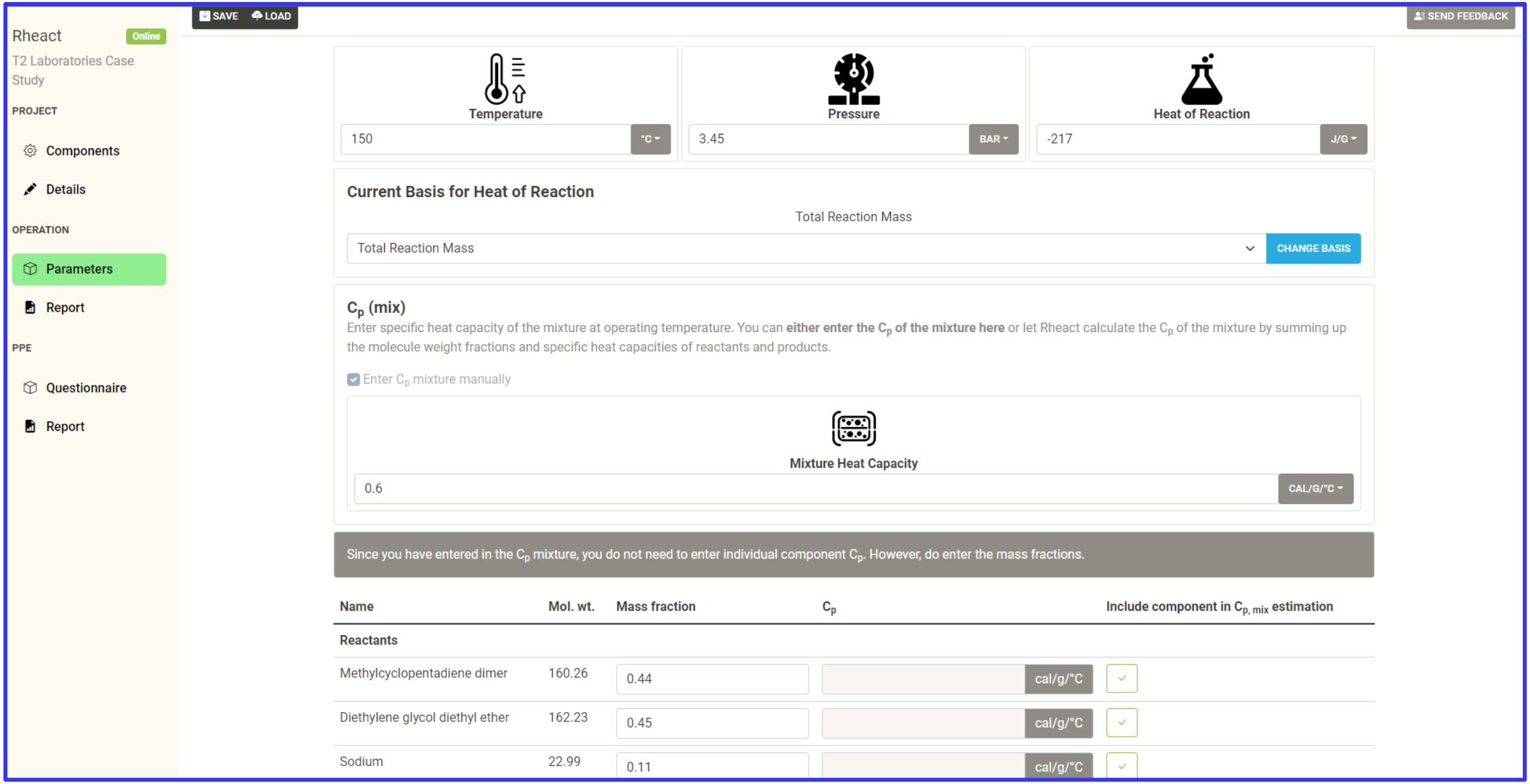
1. Upload SDS and Setup metalation reaction conditions in RHEACT



Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Case Study: T2 Laboratories explosion and fire (Dec. 2007)

1. Upload SDS and Setup metalation reaction conditions in RHEACT



Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

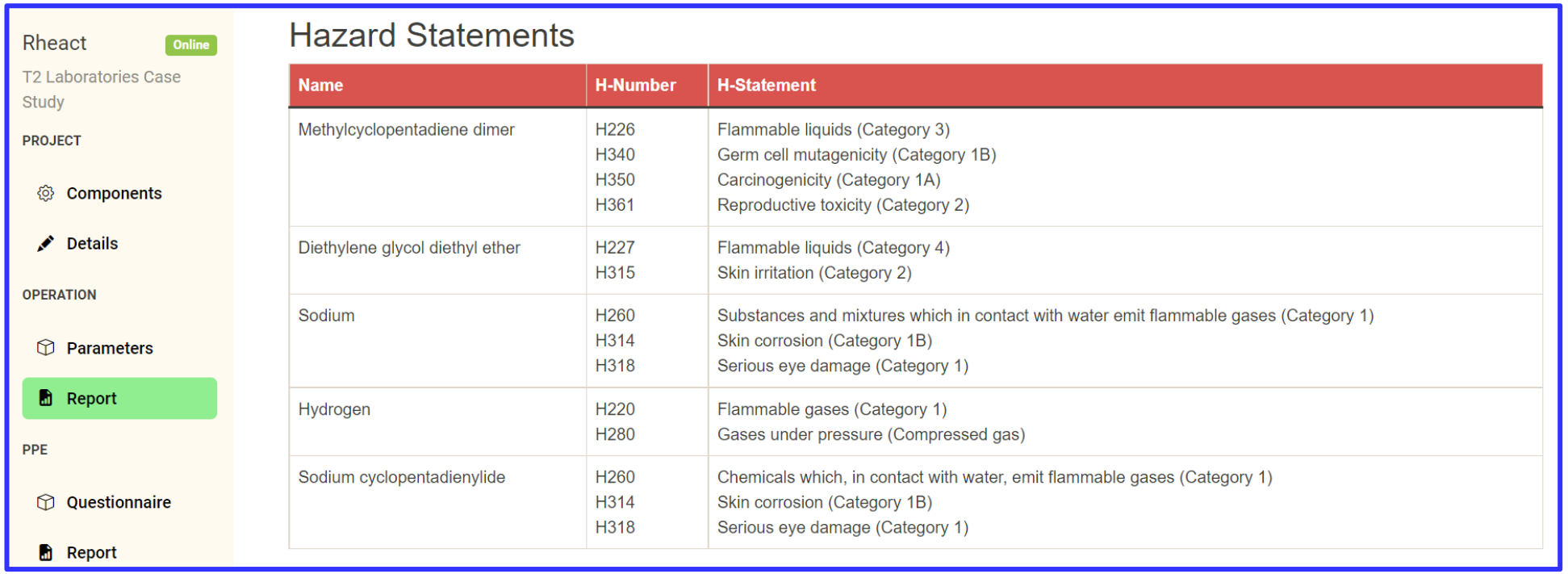
Case Study: T2 Laboratories explosion and fire (Dec. 2007)

1. Upload SDS and Setup metalation reaction conditions in RHEACT

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Case Study: T2 Laboratories explosion and fire (Dec. 2007)

2. H-phrase parsing and generation of Hazard Matrix



Hazard Statements

Name	H-Number	H-Statement
Methylcyclopentadiene dimer	H226 H340 H350 H361	Flammable liquids (Category 3) Germ cell mutagenicity (Category 1B) Carcinogenicity (Category 1A) Reproductive toxicity (Category 2)
Diethylene glycol diethyl ether	H227 H315	Flammable liquids (Category 4) Skin irritation (Category 2)
Sodium	H260 H314 H318	Substances and mixtures which in contact with water emit flammable gases (Category 1) Skin corrosion (Category 1B) Serious eye damage (Category 1)
Hydrogen	H220 H280	Flammable gases (Category 1) Gases under pressure (Compressed gas)
Sodium cyclopentadienylide	H260 H314 H318	Chemicals which, in contact with water, emit flammable gases (Category 1) Skin corrosion (Category 1B) Serious eye damage (Category 1)

- RHEACT highlights significant flammability and reactivity hazards
- H-matrix can guide PPE selection, engineering and administrative controls

Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Ingestion	Other
Methylcyclopentadiene dimer	○	✓	✓	✓	✓	✗	✗	✗	✓	✓	✓
Diethylene glycol diethyl ether	△	✓	✓	△	✓	✓	✓	✓	✓	✓	✓
Sodium	✓	✗	✓	✗	✗	○	✓	✓	✓	✗	✓
Hydrogen	✗	△	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sodium cyclopentadienylide	✓	✗	✓	✗	✗	○	✓	✓	✓	✗	✓

Legend: ✓ Safe △ Caution ○ Warning ✗ Danger

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Case Study: T2 Laboratories explosion and fire (Dec. 2007)

3. Pairwise Chemical Compatibility

	METHYLCYCLOPENTADIENE DIMER, [LIQUID]		
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

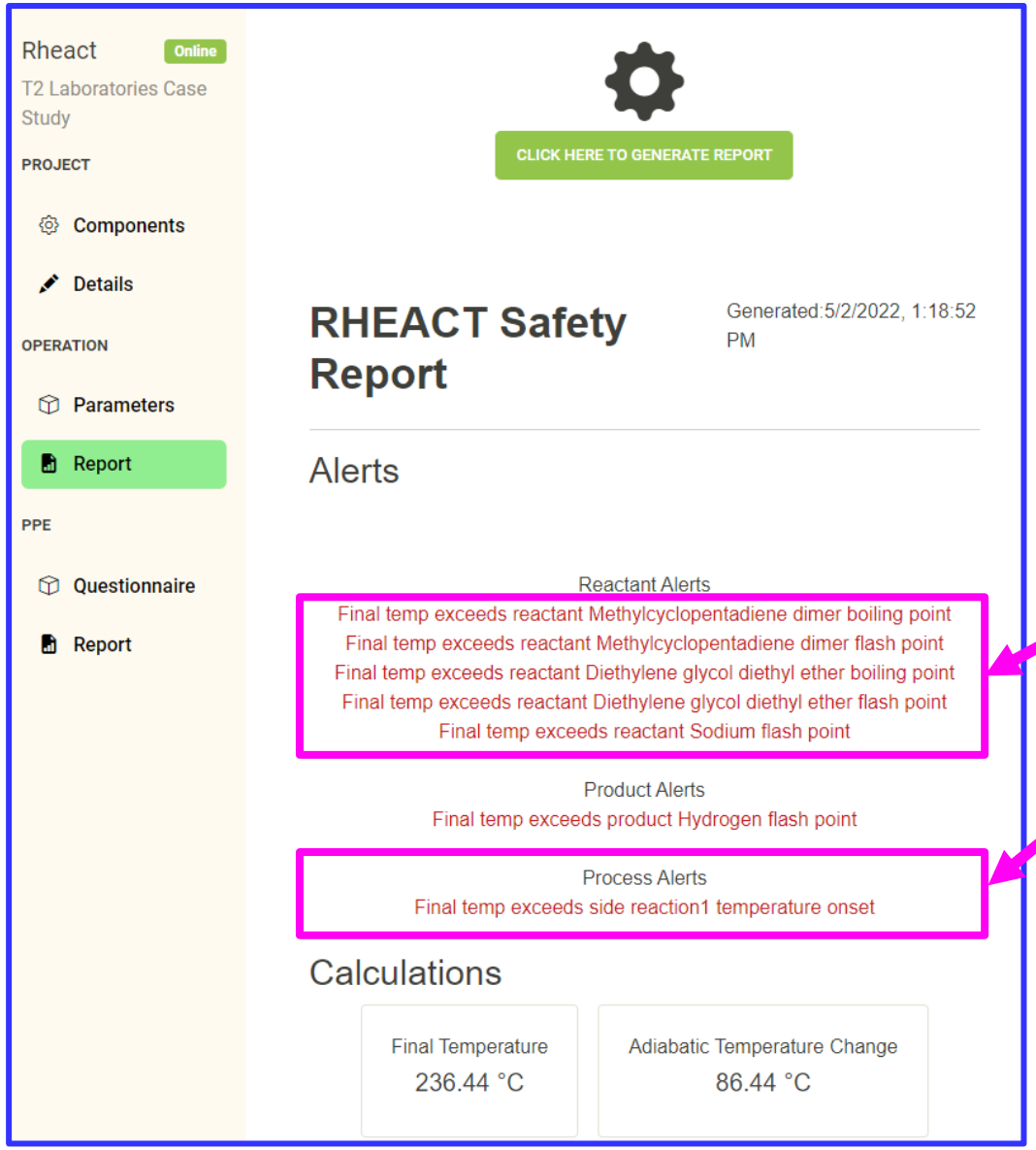
Generated using the CAMEO chemicals tool available online. For more information, check https://cameochemicals.noaa.gov/

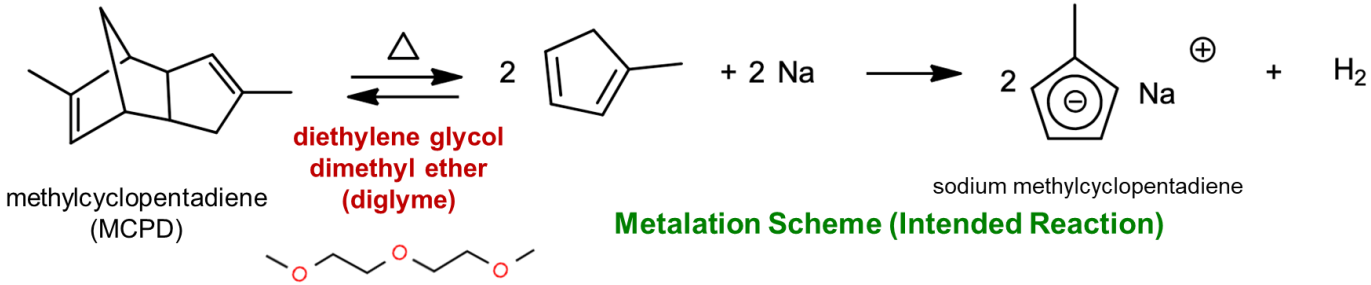
- Incompatibility of sodium and diethylene glycol dimethyl ether (diglyme) is evident from compatibility analysis
- Similar preliminary analysis could help researchers identify key risk areas
- Users are directed to go to CAMEO Chemicals to learn more about the safety of the mixture system

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Case Study: T2 Laboratories explosion and fire (Dec. 2007)

4. Adiabatic temperature change calculations and Safety Alerts





Metalation Scheme (Intended Reaction)

Operating temperature: 150°C

T_{final} following adiabatic change exceeds b.p. of certain reactants and products

T_{final} following adiabatic change exceeds secondary reaction onset **(diglyme solvent decomposition @ 190°C)**

ΔT_{ad} calculations using RHEACT provide preliminary caution and urge the user to undertake additional hazard review

Users must know the process chemistry

Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. *ACS Chem. Health Saf.* **2021**, *28*, 134

Case Study: Preparation of Aqua Regia

- **Aqua regia:** mixture of HNO_3 and HCl in 1:3 molar ratio

Chemical reactions during Aqua regia preparation

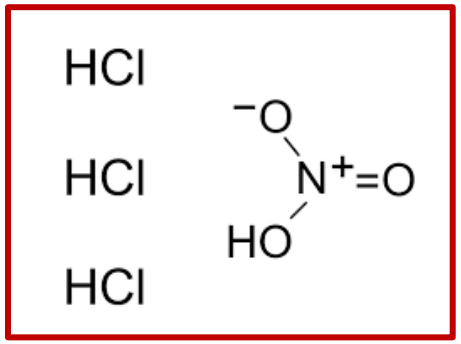
$$HNO_3 + 3\ HCl \rightarrow NOCl\ (g) + Cl_2\ (g) + 2\ H_2O$$

$$2\ NOCl\ (g) \rightarrow 2\ NO\ (g) + Cl_2\ (g)$$

$$2\ NO\ (g) + O_2\ (g) \rightarrow 2\ NO_2\ (g)$$

Photo courtesy: Enyclopaedia Britannica (*@thejohnnler)*

- Used in various academic and industrial applications
  - Refining gold
  - Etching in microfabrication and microelectronics
  - Cleaning lab glassware of organic compounds and metal residues

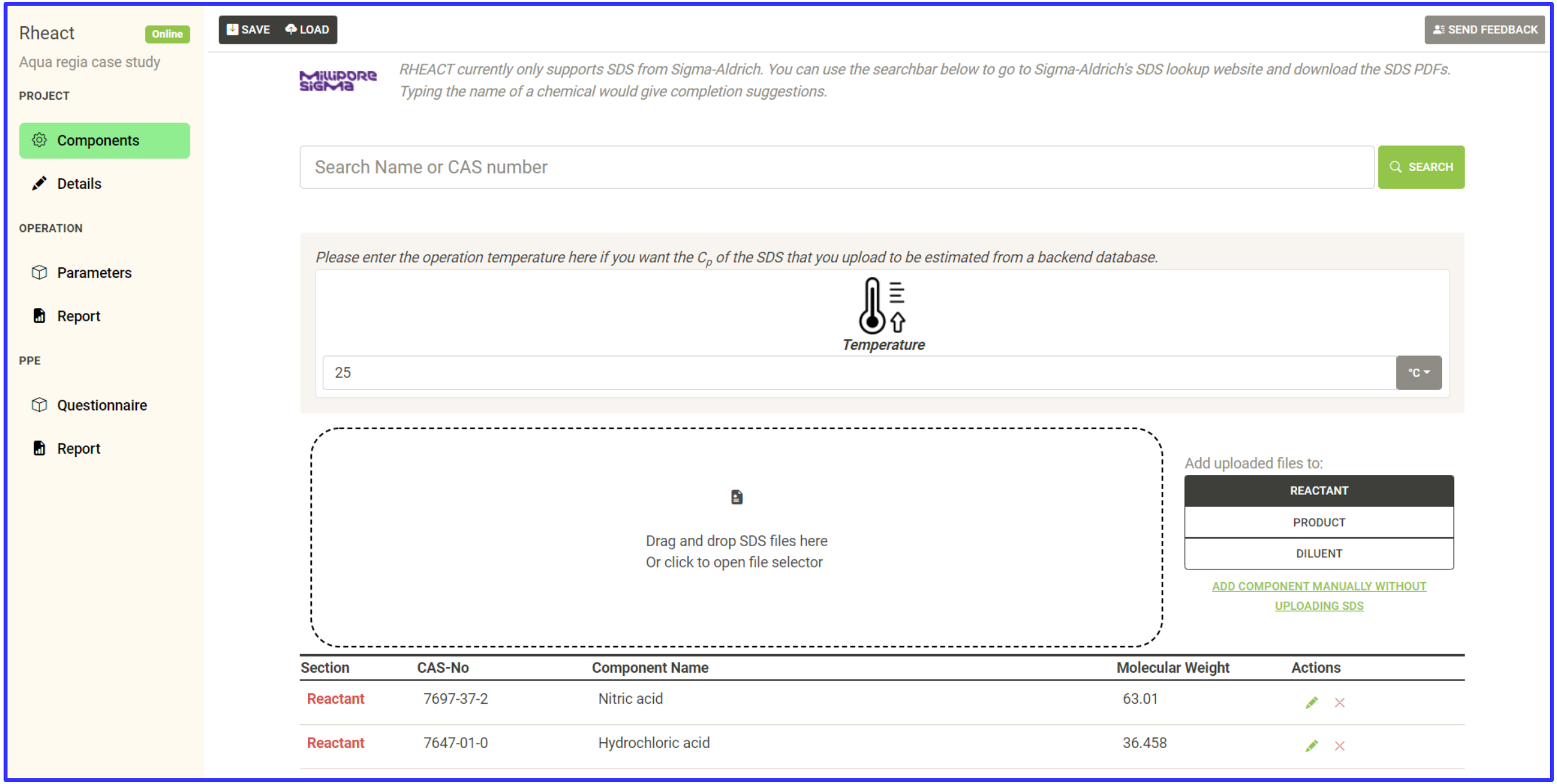


- Implicated in several accidents due to mishandling
- Many (but not all) institutions have safety protocols for handling aqua regia
- RHEACT will be used to simulate preliminary hazard analysis in an academic lab
  - **Assumption:** User has limited knowledge of the dangers of working with Aqua Regia

https://www.energy.gov/ehss/downloads/type-b-accident-investigation-june-7-2005-acid-vapor-inhalation-ta-48-building-rc-1
https://llis.nasa.gov/lesson/945
https://umanitoba.ca/admin/vp_admin/risk_management/ehso/media/Concentratedacidmixtures.pdf

Case Study: Preparation of Aqua Regia

1. Upload SDS and Setup reaction conditions in RHEACT



Case Study: Preparation of Aqua Regia

2. H-phrase parsing and generation of Hazard Matrix

Name	H-Number	H-Statement
Nitric acid	H272 H290 H331 H314 H318	Oxidizing liquids (Category 3) Corrosive to Metals (Category 1) Acute toxicity, Inhalation (Category 3) Skin corrosion (Category 1A) Serious eye damage (Category 1)
Hydrochloric acid	H290 H314 H318 H335	Corrosive to Metals (Category 1) Skin corrosion (Category 1B) Serious eye damage (Category 1) Specific target organ toxicity - single exposure (Category 3), Respiratory system

Name	Flammability	Reactivity	Skin absorption	Skin contact	Eye contact	Respiratory	Carcinogen	Reproductive hazard	Sensitizer	Ingestion	Other
Nitric acid	✓	○	✓	✗	✗	✗	✓	✓	✓	✗	✓
Hydrochloric acid	✓	△	✓	✗	✗	○	✓	✓	✓	✗	✓

Legend: ✓ Safe △ Caution ○ Warning ✗ Danger

The user is quickly alerted to handling hazards associated with aqua regia preparation

Case Study: Preparation of Aqua Regia

3. Pairwise Chemical Compatibility

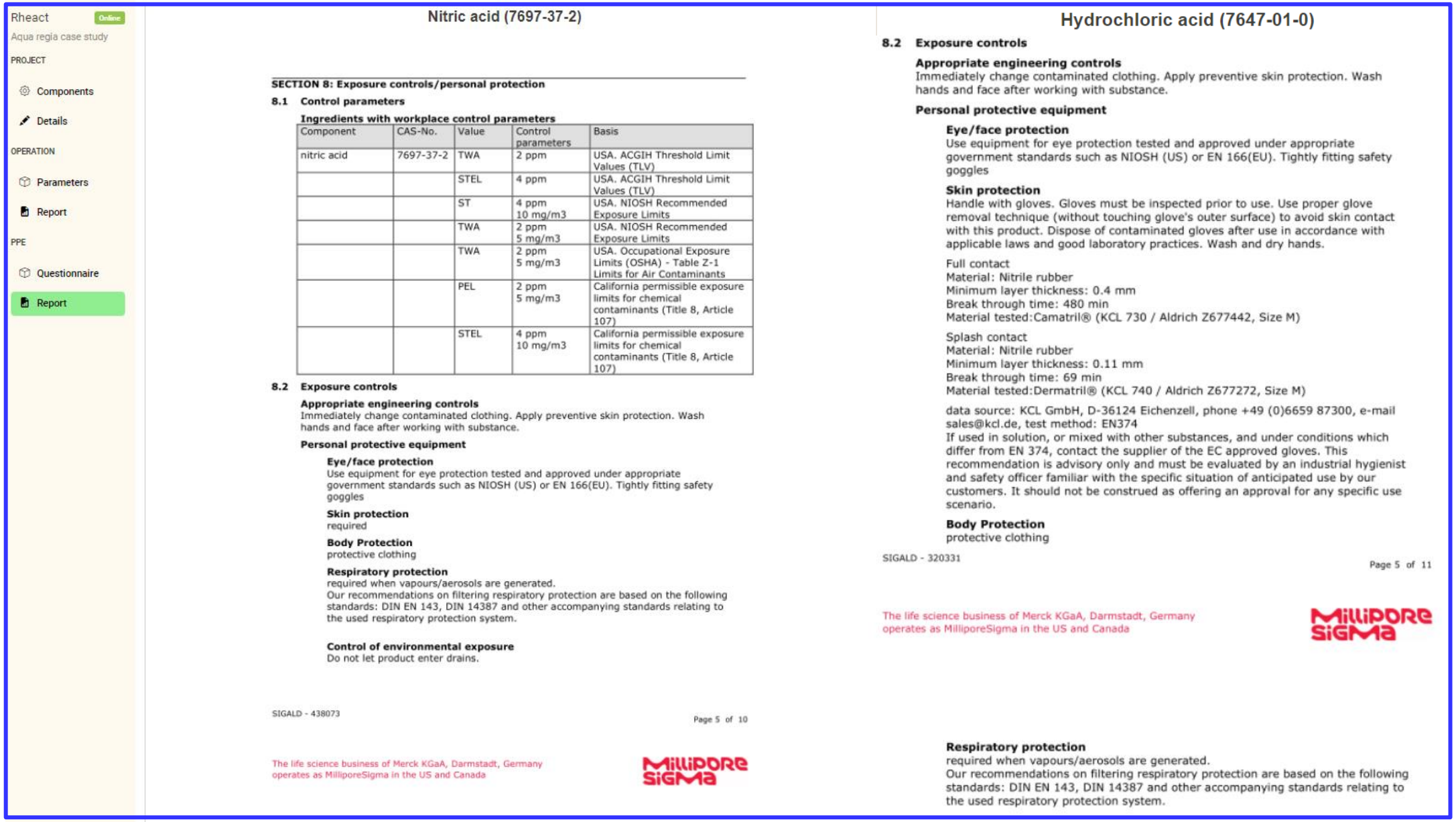
	NITRIC ACID, RED FUMING
HYDROCHLORIC ACID, SOLUTION	**Incompatible** ☒ Corrosive Explosive Flammable Generates gas Generates heat Intense or explosive reaction Toxic

Generated using the CAMEO chemicals tool available online. For more information, check https://cameochemicals.noaa.gov/

RHEACT further leverages CAMEO to alert user to gas generation potential during process

Case Study: Preparation of Aqua Regia

4. PPE suggestion from extracted SDS pages



Nitric acid (7697-37-2)

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Ingredients with workplace control parameters

Component	CAS-No.	Value	Control parameters	Basis
nitric acid	7697-37-2	TWA	2 ppm	USA. ACGIH Threshold Limit Values (TLV)
		STEL	4 ppm	USA. ACGIH Threshold Limit Values (TLV)
		ST	4 ppm 10 mg/m3	USA. NIOSH Recommended Exposure Limits
		TWA	2 ppm 5 mg/m3	USA. NIOSH Recommended Exposure Limits
		TWA	2 ppm 5 mg/m3	USA. Occupational Exposure Limits (OSHA) - Table Z-1 Limits for Air Contaminants
		PEL	2 ppm 5 mg/m3	California permissible exposure limits for chemical contaminants (Title 8, Article 107)
		STEL	4 ppm 10 mg/m3	California permissible exposure limits for chemical contaminants (Title 8, Article 107)

8.2 Exposure controls

Appropriate engineering controls
Immediately change contaminated clothing. Apply preventive skin protection. Wash hands and face after working with substance.

Personal protective equipment

Eye/face protection
Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU). Tightly fitting safety goggles

Skin protection
required

Body Protection
protective clothing

Respiratory protection
required when vapours/aerosols are generated.
Our recommendations on filtering respiratory protection are based on the following standards: DIN EN 143, DIN 14387 and other accompanying standards relating to the used respiratory protection system.

Control of environmental exposure
Do not let product enter drains.

Hydrochloric acid (7647-01-0)

8.2 Exposure controls

Appropriate engineering controls
Immediately change contaminated clothing. Apply preventive skin protection. Wash hands and face after working with substance.

Personal protective equipment

Eye/face protection
Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU). Tightly fitting safety goggles

Skin protection
Handle with gloves. Gloves must be inspected prior to use. Use proper glove removal technique (without touching glove's outer surface) to avoid skin contact with this product. Dispose of contaminated gloves after use in accordance with applicable laws and good laboratory practices. Wash and dry hands.

Full contact
Material: Nitrile rubber
Minimum layer thickness: 0.4 mm
Break through time: 480 min
Material tested:Camatril® (KCL 730 / Aldrich Z677442, Size M)

Splash contact
Material: Nitrile rubber
Minimum layer thickness: 0.11 mm
Break through time: 69 min
Material tested:Dermatril® (KCL 740 / Aldrich Z677272, Size M)

data source: KCL GmbH, D-36124 Eichenzell, phone +49 (0)6659 87300, e-mail sales@kcl.de, test method: EN374
If used in solution, or mixed with other substances, and under conditions which differ from EN 374, contact the supplier of the EC approved gloves. This recommendation is advisory only and must be evaluated by an industrial hygienist and safety officer familiar with the specific situation of anticipated use by our customers. It should not be construed as offering an approval for any specific use scenario.

Body Protection
protective clothing

Respiratory protection
required when vapours/aerosols are generated.
Our recommendations on filtering respiratory protection are based on the following standards: DIN EN 143, DIN 14387 and other accompanying standards relating to the used respiratory protection system.

Case Study: Preparation of Aqua Regia

4. PPE suggestion from questionnaire

Typical Minimum PPE

- Safety glasses with side shields
- General lab coat
- Long pants
- Close-toed shoes
- Nitrile gloves (most but not all cases)

Recommendations from Questionnaire

Chemical splash goggles, chemical-resistant lab coat

Are you working with large quantities of chemicals which are high skin adsorbant, skin/eye irritants and may splash during the experiment? (Larger quantities of liquid)

Face shield

Are you working with large quantities of chemicals which are skin irritants, there is a skin absorption risk leading to other hazards (organ damage, etc.), which may splash during the experiment? Are you working with high pressure systems, pressurized equipment, or in other scenarios where there is a potential for rupture, splash, spray or risk of flying debris?

Chemical resistant apron (over lab coat), shoe covers, gloves for heavy chemical protection

Are you working with larger quantities of extremely hazardous chemicals which may spill or splash? (e.g., acid digestion procedures)

Heavy chemical protection gloves (e.g. thicker nitrile, rubber, SilverShield)

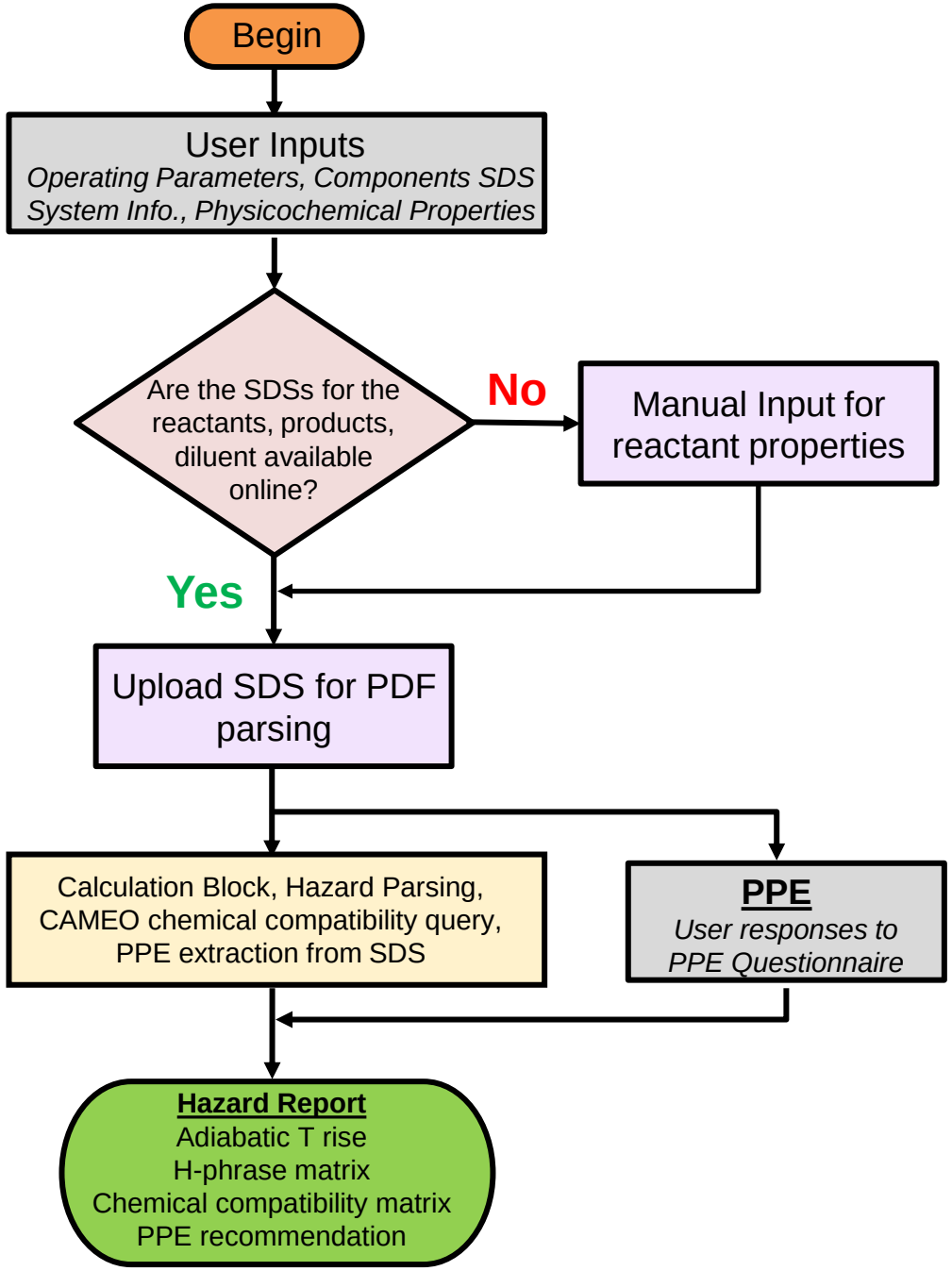
Are you working with large volumes of chemicals that have significant corrosive, reactive, skin contact, carcinogenic or reproductive hazards with the potential of splash or spill?

Full-face or half-face respirators

Are you working with potentially airborne pathogens, hazardous gases, or volatile/aerosolized chemicals that may pose a serious toxicity or other inhalation hazard?

PPE suggestion from questionnaire reinforces and supplements SDS PPE recommendations

Final takeaways



- RHEACT aims to be a convenient web tool that can:
  - Collect critical information about planned experiment
  - Conduct preliminary operational hazard analysis
  - Summarize potential safety issues and best practices

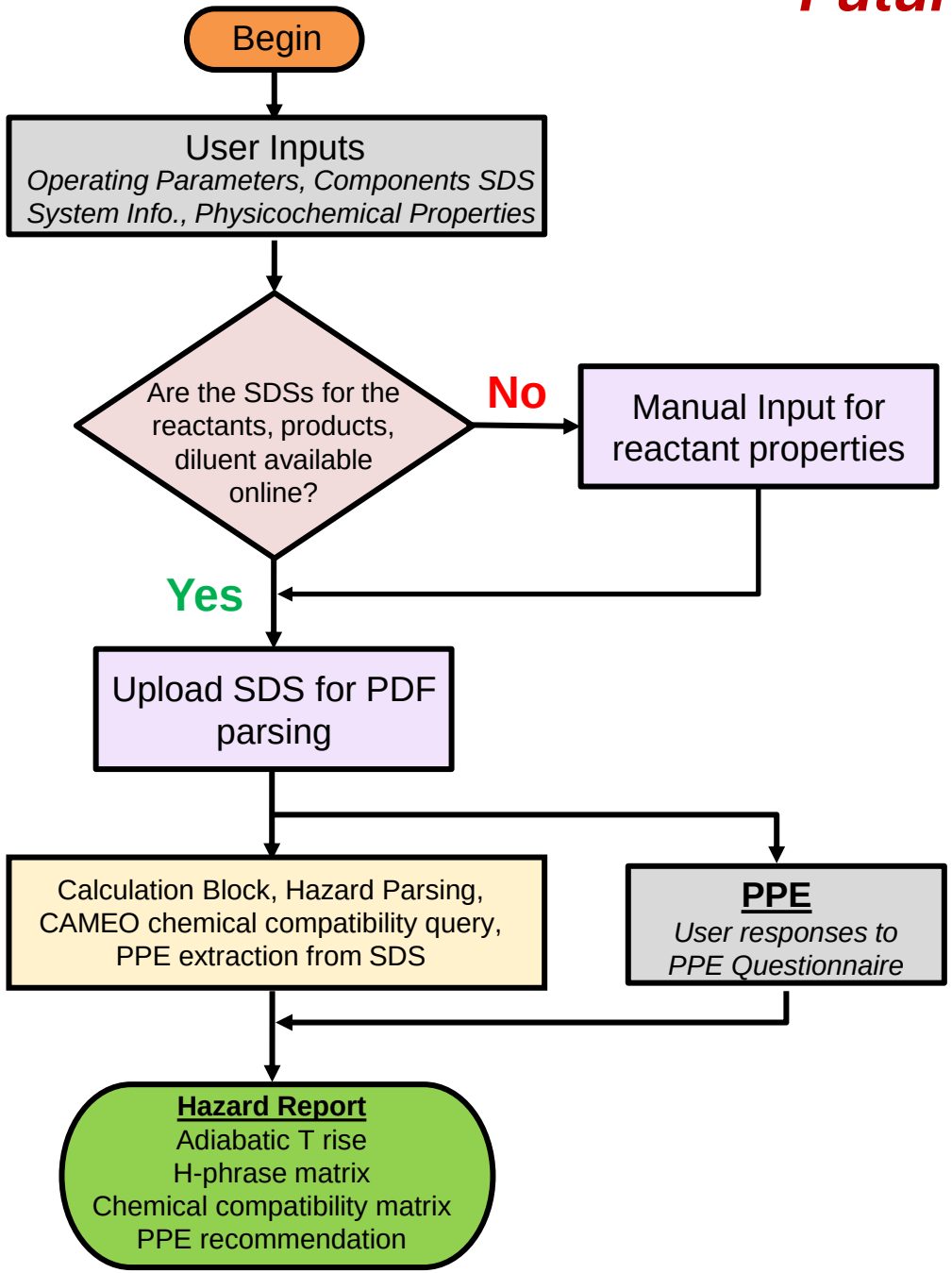
- Target users:
  - Academic chemical research and teaching labs
  - Small and mid-size enterprises' (SME) R&D labs

We aim for RHEACT to be a quick preliminary screening tool that alerts users about hazards and pushes them to perform further analysis.

Output

- Final system temperature (ΔT_{ad})
- Operational hazard matrix
- Chemical compatibility matrix
- PPE recommendation
- Downloadable Safety report

Future outlook on RHEACT



- Make Beta version available for external testing in summer 2022
- Incorporating additional features
  - Protection Action Criteria (PAC) Rating for Chemicals
  - Safety Trigger Grid for Management of Change (MOC)
- Addition of safety resource links
  - Standard Operating Procedure (SOP) development guide
  - PPE selection guides for specific hazards
  - Safety training videos
  - Summaries and reports from popular safety case studies
  - Links to other tools/databases for further hazard analysis

https://edms.energy.gov/Content.aspx/STARS-ChemPACsTEELs

CISTAR/P2SAC initiative aims to improve lab safety practices

PROBLEM

Prevalence of lab safety incidents & Need for convenient tool for preliminary hazard evaluation

SOLUTION & APPROACH

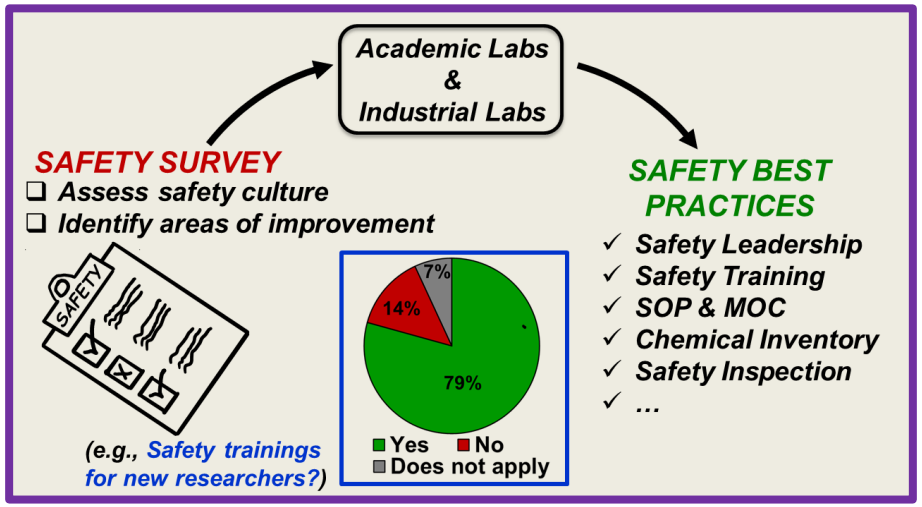
LAB SAFETY INITIATIVE

Assess safety practices in academic & industrial labs

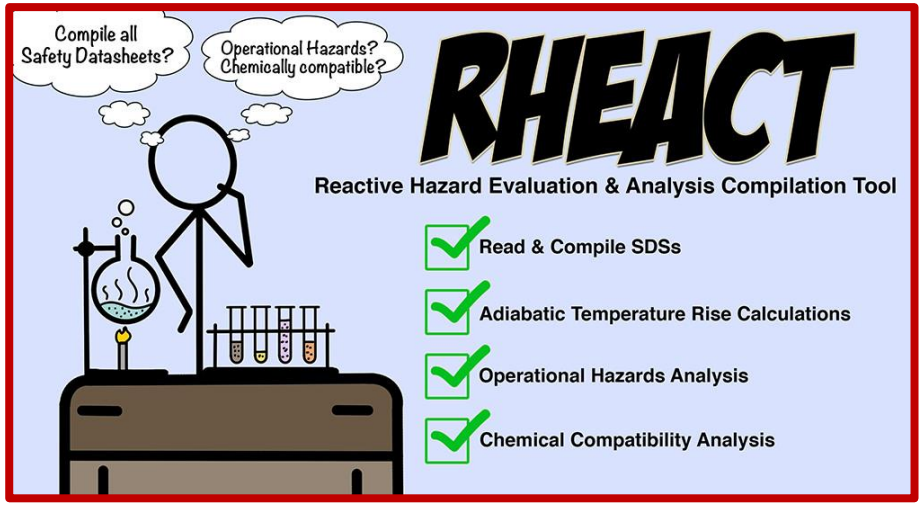
Develop tools and compile best practices for safety evaluation

IMPACT

Reduction of the occurrence and severity of safety incidents and losses



Ezenwa, S.;[#] Talpade, A. D.;[#] Ghanekar, P.; Joshi, R.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. Toward Improved Safety Cultures in Academic and Industrial Chemical Laboratories: An Assessment and Recommendation of Best Practices, *ACS Chem. Health Saf.* **2022,** *29*, 202



Talpade, A. D.;[#] Ghanekar, P.;[#] Ezenwa, S.; Joshi, R.; Kravitz, S.; Tunga, A.; Devaraj, J.; Ribeiro, F. H.; Mentzer, R. Promoting a Safe Laboratory Environment Using the Reactive Hazard Evaluation and Analysis Compilation Tool. *ACS Chem. Health Saf.* **2021**, *28*, 134

P2SAC Purdue Process Safety & Assurance Center

CISTAR NSF Engineering Research Center Center for Innovative and Strategic Transformation of Alkane Resources

NSF

Acknowledgements

Prof. Ray Mentzer, ***Purdue ChE, P2SAC***

Prof. Fabio H. Ribeiro, ***Purdue ChE, CISTAR***

Dr. Jay Devaraj, ***Corteva***



Present & Past student team members:





Sopuru Ezenwa (ChE)

Dr. Jeremy Arvay (ChE)

Vikrant Gajria (CS)

Dr. Abhijit D. Talpade (ChE)

Dr. Pushkar Ghanekar (ChE)

Dr. Ravi Joshi (ChE)

Samuel Kravitz (CS)

Anirudh Tunga (IE)

P2SAC Purdue Process Safety & Assurance Center

CISTAR™ NSF Engineering Research Center Center for Innovative and Strategic Transformation of Alkane Resources

CISTAR Universities: ***Purdue, Notre Dame, Northwestern, New Mexico, UT Austin***

CISTAR Industry Partners: *https://cistar.us/industry-innovation*

P2SAC Industry Partners: *https://engineering.purdue.edu/P2SAC/people/partners*

Contact: sezenwa@purdue.edu,

Funding: NSF

This presentation is based upon work supported **primarily OR in part** by the National Science Foundation under Cooperative Agreement No. EEC-1647722. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.