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The 2017 April issue of *Chemical Engineering*[†] has a great article on safety and on a number of critical thinking and creative thinking questions that should be asked. Socratic questioning is at the heart of critical thing and we shall use R.W. Paul's Six Types of Socratic Questions shown in Table 11-4 as a basis for our discussion.[‡] A critical aspect of process safety is "anticipating" what could go wrong in a chemical process and ensuring it won't go wrong. We are going to use an actual life example to discuss critical thinking.

Actual Case History: A large tank containing ethylene oxide has been insulated and is out in the plant. There is uncertainty as to whether or not corrosion has taken place under the insulation. To strip of the insulation and check for corrosion would require shutting the plant down for 3 weeks. Because such a shutdown would affect the supply chain and many customers, the shutdown would be very costly, ca. 5 million dollars. Let's apply R. W. Paul's Six Types of Critical Thinking questions to this situation to help us decide whether or not to strip the insulation.

TABLE 15-3 R.W. PAUL'S SIX TYPES OF CRITICAL THINKING QUESTIONS (CTQS) AND EXAMPLES[*]

Type of CTQ	Example Phrases of CTQ	CTQ Safety Examples
1. Questions about the question or problem statement: *The purpose of this question is to determine why the question was asked, who asked it, and why the question or problem needs to be solved.*	• What is the main question you want to answer? • What is the point of this question? • Why do you think I ask this question? • Why is it important you learn the answer to that question? • How does this question relate to our discussion?	Why do you think I questioned you about corrosion under the insulation, considering the storage tank is only 10 years old?
2. Questions for clarification: *The purpose of this question is to identify missing or unclear information in the problem statement question.*	• What do you mean by that? • What information do we need to answer this question? • How does that relate to our discussion? • What do we already know about that?	Are there industry identified case histories about corrosion occurring under insulation?
3. Questions that probe assumptions: *The purpose of this question is to identify any misleading or false assumptions.*	• What could we assume instead? • How does one verify or disapprove that assumption? • Explain why. . . (Explain how. . .) • What would happen if. . . ? • What is the basis of this assumption?	How did you assume stripping the insulation is the only method to check for corrosion?

[†] *https://www.chemengonline.com/key-questions-guide-effective-selection-personal-protective-equipment-PPE-safety-chemicalsafety/?s=april+2017*

[‡] Paul, R. W., Critical Thinking, Foundation for Critical Thinking, Santa Rosa, CA, 1992.

[*] See page 58-59, Fogler, H. S., LeBlanc, S. E. and Rizzo, B. R., *Strategies for Creative Problem Solving*, 3rd Ed., Pearson Publishers: Boston MA, 2014.

4. Questions that probe reasons and evidence: *The purpose of this question is to explore whether facts and observations support an assertion.*	• What would be an example? • Why is . . . happening? • What is analogous to. . . ? • What do you think causes. . . ? Why? • What evidence is there to support your answer?	What evidence do you have that corrosion may have occurred in this tank in the last 10 years?
5. Questions that probe viewpoints and perspectives: *The purpose of this question is to learn how things are viewed or judged and consider things not only in a relative perspective but also as a whole.*	• What is a counterargument for ____? • What are the strengths and weaknesses of that viewpoint? • What are the similarities and differences between your point of view and compare the other person's point of view? • Compare _____ and _____ with regard to _____. • What is your perspective on why it happened?	What are counter arguments for taking all the insulation off and inspecting the tank?
6. Questions that probe implications and consequences: *The purpose of this question is to help understand the inferences or deductions and the end result if the inferred action is carried out.*	• What are the consequences if that assumption turns out to be false? • What will happen if the trend continues? • Is there a more logical inference we might make in this situation? • Could you explain how you reached that conclusion? • Given all the facts, is that really the best possible conclusion?	What are consequences of ethylene oxide leaking into the atmosphere on people, equipment and the environment?

HSF favorite questions are (1) Why do you think I asked this question? (2) What information do we need to answer this question? (3) Could you explain your reasoning for making that choice? (4) Can you give me an example? (5) What is a counter argument for your suggestion? (6) What are the consequences if your assumption is false?

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In addition to critical thinking questions discussed in Table 15-3 in Chapter 15, we also have Rubenfeld and Scheffer† seven Critical Thinking Actions (CTAs) shown in Table 16-1. We will use Example 13-2 to hypothesize the CTAs for each of type of action.*

TABLE 16-1 TYPES OF CRITICAL THINKING ACTIONS (CTAS) AND EXAMPLES**

Types of CTA	Examples Phrases of CTA	CTA Safety Examples
1. Predicting: envisioning a plan and its consequences	• I could imagine that happening if I … • I anticipated … • I was prepared for … • I made provisions for … • I envisioned the outcome to be … • My prognosis was … • I figured the probability of … • I tried to go beyond the here and now …	I knew that if the cooling system were to fail for more than 9 minutes [cf. Example 13-2], the reaction would runaway.
2. Analyzing: separating or breaking a whole into parts to discover their nature, function, and relationships	• I dissected the situation … • I tried to reduce things to manageable units … • I detailed a schematic picture of … • I sorted things out by … • I looked for the parts that … • I looked at each piece individually …	I dissected the energy balance to find the parameters that were the most sensitive to down time and temperature increases and would cause the reaction to runaway.
3. Information seeking: searching for evidence, facts, or knowledge by identifying relevant sources and gathering objective, subjective, historical, and current data from those sources	• I made sure I had all the pieces of the picture … • I knew I needed to look up, or study … • I wondered how I could find out … • I asked myself if I knew the whole story … • I kept searching for more data … • I looked for evidence of … • I needed to have all the facts …	I looked up the heat of reaction to calculate the heat generated Q_g in the reactor at the start of the reaction to see if it would be greater than the heat removed, Q_r.
4. Applying standards: judging according to established personal, professional, or social rules or criteria	• I judged that according to … • I compared this situation to what I knew to be the rule … • I thought of/studied the policy for … • I knew I had to … • There are certain things you just have to account for … • I thought of the bottom line that is always … • I knew it was unethical to …	I measured the corrosion inside the reactor tubes and determined the tube wall thickness was insufficient to withstand 1,000 psi according to established standards for the pipe material.
5. Discriminating: recognizing differences and similarities among things or situations and distinguishing carefully as to category or rank	• I grouped things together … • I put things in categories … • I tried to consider what was the priority of … • I stood back and tried to see how those things were related … • I wondered if this was as important as …	I made a list of all the things that could go wrong when we restart the reaction system.

† Rubenfeld, M. G., and B. Scheffer, Critical Thinking TACTICS for Nurses: Achieving the IOM Competencies, Second Edition, Jones & Bartlett Publishers, Sudbury, MA, 2010.

*Fogler, H. S., *Elements of Chemical Reaction Engineering*, 6th Ed, Pearson Publishers: Boston MA, 2020.

**See page 58-59, Fogler, H. S., LeBlanc, S. E. and Rizzo, B. R., *Strategies for Creative Problem Solving*, 3rd Ed., Pearson Publishers: Boston MA, 2014.

	• I listed the discrepancies in the study and found that … • What I heard and what I saw were consistent/ inconsistent with … • This situation was different from/the same as …	
6. Transforming knowledge: changing or converting the condition, nature, form, or function of concepts among contexts	• I wondered if that would fit in this situation … • I took what I knew and asked myself if it would work … • I improved on the basics by adding … • At first I was puzzled; then I saw that there were similarities to … • I figured if this were true, then that would also be true.	I was puzzled at first because I did not understand why the reactor took so long to explode after the cooling system failed [cf. Example 13-2]. Then I calculated and determined the rate of temperature increase (dT/dt) was so small that it took a long time, 2h, to reach a point where the Arrhenius dependence dominated the heat generated term.
7. Logical reasoning: drawing inferences or conclusions that are supported in or justified by evidence	• I deduced from the information that … • I could trace my conclusion back to the data … • My diagnosis was grounded in the evidence … • I considered all the information and then inferred that … • I could justify my conclusion by … • I moved down a straight path from the initial data to the final conclusion … • I had a strong argument for … • My rationale for the conclusion was …	I justified my conclusion that the reaction would not have runaway for the increased feed charge by carrying out a number of computer simulations to show that the heat generated, Q_g, was less than the heat removed, Q_r, for a downtime less that 5 minutes.

HSF favorite actions (1) I envisioned the outcome would be… (2) I dissected the situation… (3) I know I had to look up or study… (4) I judged that according to… (5) I grouped things together… (6) At first I was puzzled; then I saw that there were similarities to… (7) I justified my conclusion with the evidence that…