Plant Expansion Phase
An Illustration of the Relative Ranking and HAZOP Analysis Methods for a Batch Process

18.1 Problem Definition

Background

The VCM plant has proved to be a successful enterprise. Five years into its operation, ABC's marketing group has recommended expanding the product line by making polyvinyl chloride (PVC) from vinyl chloride monomer (VCM). After ABC's business team reviews this recommendation, they decide to move forward with this venture. To expedite this expansion, ABC has chosen to buy the PVC technology from American Industrial Chemical Enterprises, Inc. (AICE), a major developer and licensor of PVC manufacturing technology. They are also recognized as a safety leader in the industry, and, after preliminary review of the PVC reactor design, ABC believes AICE's design and safety standards are as good as or better than ABC's.

As with all the other units at the VCM plant, the business team and company management require that a hazard evaluation be performed on this new unit. ABC is particularly concerned because PVC production is a batch process, rather than a continuous one like most of ABC's other processes, and evidence has shown that batch processes are more prone to safety incidents. The business team asks ABC's process hazards analysis group to perform the HE study.

ABC is considering two locations for the PVC reactor (Figure 18.1). Location #1 is near the VCM storage area. It is the preferred location because its proximity to the VCM supply would reduce piping and pumping costs. A negative aspect of site #1 is its proximity to the local highway: catastrophic accidents in the PVC reactor may threaten passing motorists. Also, the unit would be outdoors, which may pose a problem with freezing and plugging, since the PVC process uses water as a carrier.

The second site being considered is near the VCM purification area. This location is an ample distance from the public. Also, the reactor could be located in an existing heated building, thus reducing the likelihood of freezing and plugging problems. However, PVC reactor accidents may threaten personnel in the plant's administrative offices.
Figure 18.1 VCM plant layout—PVC siting alternatives.
In addition to the two locations, ABC is also considering using a decommissioned reactor vessel it has in storage. This vessel, while only designed to a 150-psig pressure, is adequate for use as the PVC reactor (the operating pressure of the PVC reactor is 75 psig). However, AICE has recommended a reactor with a 250-psig design pressure.

**Available Resources**

While ABC has some experience producing VCM, they have no experience producing PVC. AICE, however, has a wealth of experience in this area. In particular, they can provide the following information for ABC's HE study:

- Typical P&IDs (Figure 18.2)
- Design specifications
- PFDs
- Operating experience
- HE studies on PVC technology
- Operating procedures
- Alarm setpoints and interlock descriptions
- MSDSs of all materials in the PVC process
- Emergency response plan

In addition, AICE offers to supply ABC with one of its PVC process designers for the hazard evaluation.

**Selection of Hazard Evaluation Techniques**

Mr. Dennis, of ABC's process hazards analysis group, is assigned to supervise the HE study of the new PVC production process. After an initial review of the PVC reactor design, Mr. Dennis determines that two studies are needed: one HE study to help determine where the PVC reactor should be sited, and another to examine the process safety hazards associated with the unit. Only the PVC reactor poses a significant siting concern because of its large VCM inventory; after the VCM is converted to PVC, the material presents a minimal hazard.

For the siting issue, Mr. Dennis quickly narrows his choices of HE methods to PHA and relative ranking. These techniques are selected because they focus on both the equipment at hand and on other equipment and buildings in the area. To select from among the siting alternatives, Mr. Dennis decides he needs a more definitive result than the qualitative ranking that a PHA normally provides. With this in mind, he chooses the Relative Ranking method, which gives a "hazard score" for each siting location.

The detailed HE study of the PVC unit should cover a broad range of hazards. Thus, Mr. Dennis decides that What-If Analysis, FMEA, HAZOP Analysis, and Checklist Analysis methods may be applicable. Not having a good checklist for this new technology, Mr. Dennis rules out this method. (Mr. Dennis has some generalized process hazard checklists, but he is not comfortable using them on a technology unknown to him.) Of the remaining choices, Mr. Dennis believes the HAZOP Analysis method will work best because the guide word technique can easily be applied to batch procedures. Thus, he chooses the HAZOP Analysis method.
Figure 18.2 PVC batch reactor P&ID.
Study Preparation

Relative Ranking. Mr. Dennis chooses to use the *Dow Fire and Explosion Index (F&EI) Hazard Classification Guide* in his relative ranking HE study. To perform the ranking, he needs a plot plan of the site, a PFD of the new unit, and Dow’s F&EI Guide. He also needs an inventory of the flammable and/or toxic materials in the new unit. Mr. Dennis obtains a plot plan with the proposed new unit locations from the Anywhere VCM plant. The remaining information is obtained from AICE. Mr. Dennis reviews this information and the Dow Guide to see if any additional data are needed. He notes that the credit factors require information on process control features and fire protection, information that he does not have. He will obtain this information through telephone interviews with AICE and Anywhere plant personnel.

HAZOP Analysis. As with other HAZOP Analyses he has led, Mr. Dennis selects appropriately, skilled personnel to participate in the review. Since most of the ABC personnel who will participate have little or no PVC production experience, Mr. Dennis focuses on obtaining people with related experience (polymer production, batch operations, etc.). He also decides that it is critical that an experienced AICE employee participate in the study. The following skilled personnel are selected for the review:

- **Leader** — A person experienced in leading a HAZOP Analysis. Mr. Dennis will be the leader.
- **Scribe** — A person with a good understanding of technical terminology and the ability to quickly and accurately record information. Ms. Selda Slough will fill this position.
- **Process Engineer** — A person who is thoroughly familiar with the design of the process and how it responds to process transients. Mr. Thurman Plastic of AICE, who helped design the PVC reactor, will fill this position.
- **Operator** — An experienced person who knows how operators detect and respond to reactor upsets. ABC has no experienced operators for this reactor system. Mr. Jim Smith, who has worked as a VCM plant operator for the past four years, will fill this position. Jim formerly worked for AICE on some of their batch reactors.
- **Safety Expert** — A person familiar with the safety features at the VCM plant. Mr. Fred Scott, a chemical engineer with over 15 years of experience at the Anywhere site (both at the chlorine and at the VCM plant), will fill this position.

In preparation for the HAZOP meeting, Mr. Dennis, working with Mr. Plastic, divides the unit into sections. For each section, he defines a design intention: the function performed by that section and its normal operating parameters. Since it is a batch operation, the design intention of the sections may change throughout the batch. To address this, Mr. Dennis leads the HAZOP Analysis of the batch procedure and of the process equipment.
Next, Mr. Dennis notifies the team of the schedule and place for the HAZOP Analysis. Mr. Dennis chooses the Anywhere plant site for the meeting, thus allowing him to review the site for the new unit. (Mr. Dennis plans to complete the relative ranking before the HAZOP Analysis; the HAZOP Analysis visit will allow him to double-check the siting and protection information he used in the relative ranking.) Included in the notification is a set of information provided by AICE (P&ID's, operating procedures, etc.) and the sections and intentions developed by Mr. Dennis and Mr. Plastic.

As a last step, Mr. Dennis asks Ms. Slough to prepare a blank HAZOP table to use in the review. Ms. Slough records the HAZOP Analysis minutes in pencil on a blank HAZOP table.

### 18.2 Analysis Description

#### Relative Ranking

Mr. Dennis performs the relative ranking alone and then has his work reviewed by another member of the process hazards analysis group. Since the PVC reactor is the only major unit with a significant inventory of flammable material, he selects this vessel for the HE study. The batch reaction used to make PVC requires large volumes of VCM and water. For simplicity (and to be conservative), he only considers the VCM in the batch reactor’s mixture when performing the relative ranking (i.e., he does not take into account the lower ranking that may occur if water is in the mixture).

Having reviewed the Dow F&EI Guide, Mr. Dennis summarizes much of the information needed for the ranking (Table 18.1). He also calls Mr. Scott (to discuss the safety features in place at the two proposed sites) and Mr. Plastic (to discuss

<table>
<thead>
<tr>
<th><strong>Table 18.1 PVC Reactor/Site Information</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume:</strong> 5,000 gal</td>
</tr>
<tr>
<td><strong>Normal Fill:</strong> 80%</td>
</tr>
<tr>
<td><strong>Mixture:</strong> ~43% VCM, 56% Water, 1% Other</td>
</tr>
<tr>
<td><strong>Operating Pressure:</strong> 75 psig</td>
</tr>
<tr>
<td><strong>Rupture Disk Setting:</strong> 200 psig (New Vessel) 100 psig (Used Vessel)</td>
</tr>
<tr>
<td><strong>Outdoor Unit (Site #1)</strong></td>
</tr>
<tr>
<td><strong>Site #1 (ft)</strong></td>
</tr>
<tr>
<td>Administrative Offices: 1500</td>
</tr>
<tr>
<td>Maintenance Shops: 1200</td>
</tr>
<tr>
<td>Highway: 800</td>
</tr>
<tr>
<td>VCM Storage: 180</td>
</tr>
<tr>
<td>Furnaces: 500</td>
</tr>
<tr>
<td>Ethylene Feed Area: 150</td>
</tr>
<tr>
<td>OHC Reactors: 300</td>
</tr>
<tr>
<td>Direct Chlorination Reactors: 200</td>
</tr>
<tr>
<td>VCM Purification Columns: 350</td>
</tr>
<tr>
<td><strong>Site #2 (ft)</strong></td>
</tr>
<tr>
<td>Administrative Offices: 800</td>
</tr>
<tr>
<td>Maintenance Shops: 850</td>
</tr>
<tr>
<td>Highway: 1500</td>
</tr>
<tr>
<td>VCM Storage: 800</td>
</tr>
<tr>
<td>Furnaces: 200</td>
</tr>
<tr>
<td>Ethylene Feed Area: 900</td>
</tr>
<tr>
<td>OHC Reactors: 600</td>
</tr>
<tr>
<td>Direct Chlorination Reactors: 450</td>
</tr>
<tr>
<td>VCM Purification Columns: 100</td>
</tr>
</tbody>
</table>
shutdown interlocks on the reactor). Based on these discussions, Mr. Dennis determines that the loss control credit factors that are part of the Dow Guide will be about the same for both locations. He chooses to estimate these factors because they affect the damage estimate for an accident, and thus are a factor in the site selection.

The Dow Guide describes a step-by-step procedure for estimating an F&E index and, subsequently, a radius of exposure for the different reactors. In calculating the factors, Mr. Dennis:

1. Estimates the material factor (MF) for VCM. (VCM is listed in the Guide and Mr. Dennis locates its factor in the appropriate table.)

2. Estimates the general process hazard factor ($F_1$). Following the instructions in the Guide, Mr. Dennis determines penalties for exothermic chemical reactions, material handling, enclosed process unit, access, and drainage. Because site #2 is indoors and has fair-to-poor drainage, Mr. Dennis penalizes this PVC reactor more heavily than the reactor at site #1.

3. Estimates the special process hazard factor ($F_2$). Again, Mr. Dennis follows the Guide's instructions. He notes that the pressure component of this factor changes slightly, depending on which reactor vessel is used. He also penalizes site #2 for its proximity to the cracking furnaces.

4. Estimates the unit hazard factor ($F_3$), fire and explosion index, and radius of exposure. These calculations involve simple multiplication and addition of MF, $F_1$, and $F_2$. Note that Mr. Dennis calculates the F&EI twice for the site #2 cases because the unit hazard factor exceeds the recommended cutoff of 8.0. Since Mr. Dennis only wants to compare causes rather than use the specific values, he calculates the F&EI using his estimated unit hazard factor and the cutoff value of 8.0.

5. Estimates the loss control credit factor. Mr. Dennis gives additional credit to site #1 for drainage and to site #2 for the building sprinkler system. Otherwise, both sites have the same credits. Credit values are selected in accordance with guide instructions.

Figures 18.3-18.10 at the end of this chapter summarize Mr. Dennis's calculations for the two proposed PVC sites and the different reactors. Table 18.2 summarizes his findings. Using the estimated radius of exposure and the Anywhere VCM plant plot plan, Mr. Dennis then identifies the equipment and personnel most likely to suffer impact should a fire or explosion occur in the PVC unit.

**HAZOP Analysis**

As the HAZOP Analysis begins, Mr. Dennis introduces the team members and their areas of expertise. He then reviews the analysis schedule. Normally, Mr. Dennis would also review the HAZOP Analysis method with the team; however, all
Table 18.2 Relative Ranking Results for the Plant Expansion Phase

<table>
<thead>
<tr>
<th>Option</th>
<th>F&amp;E Index</th>
<th>Loss Control Credit Factor</th>
<th>Radius of Exposure (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site #1, 150 psig</td>
<td>164</td>
<td>0.74</td>
<td>137</td>
</tr>
<tr>
<td>Site #1, 250 psig</td>
<td>159</td>
<td>0.74</td>
<td>134</td>
</tr>
<tr>
<td>Site #2, 150 psig</td>
<td>168</td>
<td>0.69</td>
<td>141</td>
</tr>
<tr>
<td>(218)*</td>
<td></td>
<td></td>
<td>(183)*</td>
</tr>
<tr>
<td>Site #2, 250 psig</td>
<td>168</td>
<td>0.69</td>
<td>141</td>
</tr>
<tr>
<td>(212)*</td>
<td></td>
<td></td>
<td>(178)*</td>
</tr>
</tbody>
</table>

*Value assuming the unit hazard factor is not truncated at 8.0. The actual calculated value is used.

of the team members, including Mr. Plastic, have previously participated in HAZOP Analyses. After discussing the objectives of the HAZOP Analysis, Mr. Dennis asks Mr. Plastic to explain the PVC production process.

Mr. Plastic — The PVC production process is relatively straightforward (see Figure 18.11, at the end of this chapter). To begin, we prepare the PVC reactor for feeds according to procedure. Once the reactor is ready, we add process water, the dispersants, the monomer, and the initiator. The reactor is heated to 50°C to initiate the reaction. The pressure at the beginning of PVC production is about 75 psig, but it falls to around 7 psig when the conversion is complete. We then heat the reactor to drive off excess monomer, and follow this step by dropping the reactor contents into the centrifuge. In the centrifuge we remove excess water from the PVC. The PVC pellets are then conveyed by air to a hot air dryer, sieved to remove oversized particles, and finally stored.

Mr. Dennis — Thanks. To start the review, we have agreed to HAZOP the batch procedure. Mr. Plastic, could you walk us through the details of the batch?

Mr. Plastic — Sure. Each of you has a copy of the batch procedure (see Table 18.3), so I will just explain the reasoning behind each step. First, we verify that all feed valves are closed to help ensure that we start with an empty reactor. Then we pull a vacuum on the reactor to minimize the oxygen concentration in it, thus reducing the potential for creating a flammable concentration in the gas phase. Next we fill the reactor approximately half full with water, which acts as the suspension phase for the polymerization. After that
### Table 18.3 PVC Batch Reactor Operating Procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Verify that all feed line valves to the PVC reactor are closed and reactor is empty</td>
</tr>
<tr>
<td>2</td>
<td>Open the vacuum line valve and reduce reactor pressure to 10 psi</td>
</tr>
<tr>
<td>3</td>
<td>Open the water line valve and add 2250 gal of water to the reactor (set water flow totalizer)</td>
</tr>
<tr>
<td>4</td>
<td>Start the agitator</td>
</tr>
<tr>
<td>5</td>
<td>Close the vacuum line valve</td>
</tr>
<tr>
<td>6</td>
<td>Open the poly (vinyl alcohol) line valve and add 7 gal of poly (vinyl alcohol). Open the sodium isobutyl napthalene sulfonate line valve and add 1 gal</td>
</tr>
<tr>
<td>7</td>
<td>Open the lauryl peroxide line valve and add 7 gal</td>
</tr>
<tr>
<td>8</td>
<td>Open the VCM line valve and add 1700 gal of monomer</td>
</tr>
<tr>
<td>9</td>
<td>Set the reactor temperature controller to 50°C and heat up the reactor for about eight hr. Maintain reactor temperature at 50°C for eight hr</td>
</tr>
<tr>
<td>10</td>
<td>When the reactor pressure drops to 7.5 psig, open the vacuum line valve for 15 minutes</td>
</tr>
<tr>
<td>11</td>
<td>Cool the reactor to 16°C (about six hr)</td>
</tr>
<tr>
<td>12</td>
<td>Open the nitrogen supply line valve and vent to atmospheric pressure</td>
</tr>
<tr>
<td>13</td>
<td>Open the discharge valve and drop the reactor contents into the centrifuge</td>
</tr>
</tbody>
</table>


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**Mr. Plastic**

(cont’d) The agitator is started, the reactor is bottled up, and dispersants are added. Finally, we add lauryl peroxide, an initiator, to the batch and then add the monomer. With all the ingredients present, we raise the reactor temperature to 50°C (the reactor pressure will be about 75 psig initially) with steam heating on the jacket, and maintain the temperature until about 90% conversion is reached. It takes about eight hours. At that point the pressure is about 7.5 psig. The vacuum line is opened and the excess monomer is vented off and recovered. Usually 5 minutes is all that is needed for this step, but we recommend 15 minutes for a margin of safety. After recovering excess monomer, the reactor is cooled; then the reactor is padded with nitrogen, vented, and the PVC/water mixture is dropped into the centrifuge to begin the drying process.
Mr. Dennis — Okay. The first guide word is No. Applying this to the first batch step gives the deviation No Verification. What is the consequence of no verification of closed feed valves?

Mr. Smith — If you ran the previous batch correctly, I wouldn't think anything would happen. But, if you didn't dump the previous batch, you'll eventually overfill the reactor with water. The reactor will be solid with PVC and water, which you back up into one of the chemical feed lines, the vacuum line, or the nitrogen line. That would be a terrible clean-up problem, but I don't see any safety consequences.

Mr. Plastic — I agree. However, that error would probably only force you to take longer in centrifuging and restarting the batch. On the other hand, if one of the chemical feed valves is open, then you may add too much dispersant, which lowers product quality, or too much monomer, which could be a fire hazard. This problem exists even if the last batch went through okay.

Ms. Slough — I don't understand. Where is the fire hazard?

Mr. Plastic — If you have too much monomer, then you could have monomer left in the batch after the recovery step. The problem arises when this monomer gets to the hot air dryer.

Mr. Dennis — What are causes for skipping step 1?

Mr. Smith — Well, I'll point the finger at myself. An operator could forget this step.

Mr. Dennis — Others? [None suggested.] Safeguards?

Mr. Scott — I'm sure we'll have extensive operator training before starting this process. Also, we'll require written procedures for the batch.

Mr. Dennis — Any more safeguards? [None suggested.] Actions?

Mr. Scott — We should develop a checklist for the operator — a simple one-page checkoff like this list you gave us. I also don't see any load cells or a level indicator on the reactor P&ID. Perhaps we should add (1) a level indicator so the operator can catch a valve being open at the wrong time and (2) a high level alarm.

Mr. Dennis — Ms. Slough, do you have that recommendation? [Nods yes.]

Mr. Plastic — The water and monomer lines are the only big lines to the reactor. A level indicator and alarm may catch a problem with these lines, but I doubt it will help with the other feeds.
Mr. Dennis — Wait a minute. We are already designing solutions. Let's just note that the operators need a way to positively verify and acknowledge that the valves are closed and the reactor is empty. If there are no more ideas, let's move on.

Mr. Scott — The flow meters on the feed lines would be a better way to catch an open valve. That's what you should alarm.

Mr. Dennis — I get the idea. Again, let's not attempt to design the solution. Another possible No deviation is No Step; that is, a written step prior to verification is needed. Is this the case here? [Heads shake no.] Okay, do you think the High and Low guide words apply to step 1? [Team says no.] How about Reversing the step sequence, doing something Other Than this step, or doing only Part Of this step?

Mr. Plastic — Reversing this Step would be checking the reactor first and the valves second. That should be no problem. Doing only Part Of the step or something Other Than this step is the same as not doing step 1. You may have too much dispersant, initiator, or monomer that could lead to poor product quality or a fire hazard in the dryer.

Mr. Dennis — What are the causes?

Mr. Plastic — I think the causes, safeguards, and actions we just suggested apply again. [Others agree.]

Ms. Slough — Let me read them back to you to be sure. [She reads them and team agrees they are okay.]

Mr. Dennis — I plan to cover the As Well As deviation as we cover the later steps in the process. The next step is to reduce the reactor pressure to about 10 psi. Is there a step missing between steps 1 and 2? [Team agrees no.] What happens if this step is skipped?

Mr. Plastic — Then you will have air in the head space during the batch. That is a potential fire and explosion hazard.

Mr. Dennis — Causes?

Mr. Smith — Operator error.

Mr. Dennis — What else? [Period of silence.] What about a failed vacuum system or a stuck valve on the vacuum line?

Mr. Scott — Those make sense, although it seems as if that would be alarmed.

Mr. Plastic — The failure of the vacuum system would trigger an alarm, and the vacuum valve position is indicated in the control room. I guess you count those as safeguards. Another possible cause is a faulty reactor pressure gauge.
Mr. Dennis — Safeguards?

Mr. Plastic — You've got the alarms and indicators I've just mentioned, and you've got the operator training mentioned earlier.

Mr. Dennis — Others? [None suggested.] Actions? [None suggested.]
Okay, let's look at the High deviation. What's the consequence of pulling too much vacuum?

Mr. Plastic — I don't think the vacuum system can pull the reactor down much lower than 4 psi.

Mr. Dennis — So, the potential exists to collapse the reactor. Ms. Slough, make a note in the recommendations to determine the maximum vacuum capability of the vacuum system.

Mr. Plastic — Wait a minute. Although not rated for full vacuum, the 250-psig reactor is large enough and has sufficient wall thickness to withstand full vacuum. I'm not sure about the 150-psig reactor.

Mr. Scott — It probably can take full vacuum, but we should check it out. By the way, that 10 psi, is it gauge or absolute?

Mr. Plastic — It's absolute. But I see your point. An operator could get it wrong. I guess an action is to update the procedure to fix this.

Mr. Dennis — Come on now — let's slow down or we'll get lost. Before making recommendations, what are the causes of too much vacuum?

Mr. Smith — Operator error.

Mr. Dennis — Okay, but it's not always operator error. Jim, what else?

Mr. Smith — Well, a bad pressure gauge on the reactor would possibly mislead an operator. Also, plugging is a common problem.

Mr. Dennis — Other causes? [None suggested.] Safeguards?

Mr. Scott — Operator training. Once this reactor is up and running, I'm sure operators will know the amount of time it takes to get to 10 psia.

Mr. Dennis — Recommendations?

Mr. Smith — Besides the things you have already said, it seems like another pressure gauge would help since pressure seems pretty important in this process. Plus, the second gauge may reveal a plugging problem.

Ms. Slough — Just a minute so I can catch up on these recommendations.

Mr. Dennis — Okay. Other recommendations? [Quiet.] What about Too Little Vacuum?
Well, I think you have the same things as with skipping this step, only maybe not as bad.

— Do all of you agree? [Others nod approval.] What if you Reverse steps 1 and 2?

— If the last batch went through okay, no problem. Otherwise, if you have material left in the reactor, a leaky or open feed valve, or a leaky agitator seal, then you won't reach your 10 psia and you'll end up throwing away some materials through the vacuum line. Since we pull excess monomer out this way anyway, I don't see much more than an economic penalty.

— What about removing the air from the reactor? Won't we have the same consequence as the No Vacuum?

— Maybe. I don't know if we remove enough air in this case to be okay or not. Maybe we should take a closer look at this!

— Any other causes besides operational error for the deviation? [None suggested.] Some safeguards are, again, operator training and the pressure gauge on the reactor. Others? [Nothing said.] Recommendations?

— Why doesn't this batch reactor have a PLC (programmable logic controller) to sequence through the steps?

— That can certainly be done. I can only guess that ABC didn't want the cost.

— I think we should recommend a PLC. We are barely into this and it looks like there is plenty of room for operator error.

— Any more recommendations? [None.] Ms. Slough, are you keeping up? [Nods yes.] Let's see. Part Of would be the same as Low Vacuum. Is there anything an operator might do Other Than open the vacuum line?

— There's no incentive for an operator to take any other action here, and there are no parallel reactors that might be evacuated by mistake.

— Okay. Let's look at As Well As. What if we do step 2 As Well As one of the next steps?

— Pulling a vacuum As Well As feeding materials will result in not evacuating the air as planned, and thus we have the fire hazard. If the vacuum line is open during the batch, you'll lose a lot of monomer and will probably lift the relief valve on the condenser for monomer recovery. Also, the reactor pressure will drop.
Mr. Dennis — Causes besides operator error? [None suggested.]
Safeguards?

Mr. Plastic — You've got the same operator training factors as before, as well as the pressure gauge on the reactor. There's no reason for the operator to take a shortcut like that.

Mr. Dennis — Recommendations?

Mr. Scott — I'll reiterate my PLC recommendation.

This review continues until all the steps of the batch are examined. The team then evaluates each section of equipment in the new unit during normal operation to identify and evaluate any additional hazards. At the conclusion of the HAZOP Analysis, Mr. Dennis thanks all the participants and reminds them that he will send them a HAZOP report for their review and comment in a few weeks.

18.3 Discussion of Results

**Relative Ranking**

The Relative Ranking method was used to estimate a radius of exposure for each of the two proposed PVC unit sites. The F&EI calculations Mr. Dennis performed showed an exposure radius of about 135 feet for site #1 and 140 feet (or 180 feet using Mr. Dennis's unit hazard factor instead of the cutoff value) for site #2, regardless of which reactor vessel (the low pressure or the high pressure) was used. According to the plant's plot plan, the site #2 exposure zone encompasses other major equipment: the VCM purification columns. More importantly, the exposure zone for site #1 does not involve the VCM storage tanks. Large populations of people are not affected at either site. The safety factors at either location are about equal. Thus, site #1 appears to be the better choice.

**HAZOP Analysis**

Table 18.4 at the end of this chapter illustrates some of the HAZOP Analysis results. Ms. Slough generates the HAZOP table, transcribing her notes into a typed table. Because the PVC reactor design had not previously been examined and because it was not designed to ABC's standards, the HAZOP team suggests a number of improvements. Table 18.5 at the end of this chapter lists some of the more important recommendations.

18.4 Follow-Up

**Relative Ranking**

The Relative Ranking portion of the HE study was completed entirely by Mr. Dennis and reviewed by Ms. Deal (also with ABC's process hazards analysis group). The results, along with Mr. Dennis' recommendations, were transmitted to the VCM business team for evaluation. The business team used these results to help them select site #1 for the new PVC reactor.
HAZOP Analysis

Some unresolved issues remained following the HAZOP Analysis. These issues were assigned to various team members to resolve. Mr. Dennis checked with these members weekly until every issue was resolved. The recommendation for the PLC was accepted and the team was later reassembled to perform an FMEA on the PLC.

Mr. Dennis, along with Ms. Slough, prepared a report of the HAZOP Analysis. The report described the scope of the review, who participated, what information (drawings, procedures, etc.) was used, and the findings of the team. This report was circulated among team members for comment, updated by Mr. Dennis, and then sent to the VCM business team for evaluation. The business team was made responsible for following up on each recommendation. Using ABC's computerized tracking system, Mr. Chemist (of the business team) checked monthly on the implementation of the recommendations until all recommendations were completed.

18.5 Conclusions and Observations

Relative Ranking

The relative ranking HE was performed to determine which site should be used for the new PVC reactor. While the fire and explosion indexes for the two sites produced nearly the same results, the analysis still proved to be quite useful. Site #1 was the business team's preference of the two sites; however, they were concerned with putting the high pressure reactor near the VCM storage, the ethylene supply system, and the highway. Site #2, while more distant from large fuel supplies and the highway, had the drawback of being close to the furnaces and the administration building. The relative ranking analysis showed, however, that a major fire and explosion in the PVC reactor at site #1 should not significantly threaten the equipment, buildings, and roadways near the site. This was not true for site #2. Thus, the business team recommends site #1. The business team also notes that, provided it is adequately inspected and tested, the lower pressure reactor vessel should be adequate for this service. The time required to perform the Relative Ranking is summarized in Table 18.6 at the end of this chapter.

HAZOP Analysis

The HAZOP Analysis proved to be a very important part of the HE study because the new technology, not designed or previously evaluated by ABC, was found to have a number of safety deficiencies. The review team identified a number of recommendations that the business team should carefully consider with the acquisition of the new technology.

The HAZOP Analysis meetings went quite smoothly, both because Mr. Dennis is a highly experienced leader and because all the team members were experienced and cooperative HAZOP participants. It is important to note that Mr. Plastic was key to the success of the review. Without his depth of experience with the PVC process ABC was acquiring, the team would have struggled to understand the design. The time required to perform the HAZOP Analysis is summarized in Table 18.7 at the end of this chapter.
Table 18.4 Sample HAZOP Analysis Results for the PVC Reactor

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Deviation</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 PVC REACTOR BATCH — STEP 1: VERIFY ALL FEED LINE VALVES ARE CLOSED AND REACTOR IS EMPTY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>No verification Operator error — skips step</td>
<td>Increased potential for material to leak into reactor when air is present. Potential fire hazard (monomer and air)</td>
<td>Operator training</td>
<td>Develop a batch checklist</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Written procedures</td>
<td>Provide instruments to verify valve positions and reactor status</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Add a reactor level indicator and high level alarm</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Part of verification Operator error — skips step</td>
<td>Increased potential for material to leak into reactor when air is present. Potential fire hazard (monomer and air)</td>
<td>Operator training</td>
<td>Develop a batch checklist</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Written procedures</td>
<td>Provide instruments to verify valve positions and reactor status</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Add a reactor level indicator and high level alarm</td>
<td></td>
</tr>
</tbody>
</table>
Table 18.4 (cont'd)

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Deviation</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 PVC REACTOR BATCH — STEP 2: OPEN THE VACUUM LINE VALVE AND REDUCE REACTOR PRESSURE TO 10 PSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1 No evacuation

- Operator error — skips step
- Vacuum system failure
- Vacuum valve sticks closed
- Reactor pressure gauge fails — false low

Potential flammable/explosive mixture in reactor head space

Operator training

Written procedures

Vacuum system alarm

Pressure indicated in control room

Vacuum valve position indicated in control room

2.2 High evacuation (high vacuum)

- Operator error
- Reactor pressure gauge fails — false high

Potential reactor damage (assuming lower pressure reactor is used)

Operator training

Reactor pressure indicated in control room

Evaluate the capability of the vacuum system to damage the reactor

Revise the batch procedure to make the units clear (psia vs psig)

Install a second pressure gauge on the reactor
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2.3</strong></td>
<td><strong>Low</strong> evacuation</td>
<td>Operator error — skips step</td>
<td>Potential flammable/explosive mixture in reactor head space</td>
<td>Operator training</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum system failure</td>
<td></td>
<td>Written procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum valve sticks closed</td>
<td></td>
<td>Vacuum system alarm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reactor pressure gauge fails — false low</td>
<td></td>
<td>Pressure indicated in control room</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vacuum valve position indicated in control room</td>
<td></td>
</tr>
<tr>
<td><strong>2.4</strong></td>
<td><strong>Reverse steps 1 and 2</strong></td>
<td>Operator error</td>
<td>Potential flammable/explosive mixture in reactor head space</td>
<td>Operator training</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Written procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consider using a PLC to sequence the batch</td>
</tr>
<tr>
<td><strong>2.5</strong></td>
<td><strong>Step 2 as well as another step</strong></td>
<td>Operator error</td>
<td>Potential large release of hot monomer to the atmosphere through the overhead condenser relief valve</td>
<td>Operator training</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential fire hazard</td>
<td>Written procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consider using a PLC to sequence the batch</td>
</tr>
</tbody>
</table>
Table 18.5 Sample Recommendations from the HAZOP Analysis of the PVC Batch Reactor

- Run the batch reactor with a programmable logic controller; program interlocks into the PLC to verify proper reactor conditions before proceeding to the next batch step
- Install a redundant pressure gauge and redundant temperature indicator on the reactor
- Install an oxygen analyzer and alarm on the reactor
- Rewrite the batch procedure to clearly state valve positions and process conditions at each batch step
- Develop a checklist for operators to use when making a batch
- Define procedures for safe entry into the reactor to clear a plug in the discharge line
- Install a redundant vibration detector and shutdown interlock on the centrifuge
- Locate the centrifuge in an unoccupied room with reinforced walls (to protect against shrapnel in the event of a wreck)
- Examine the materials onsite to see if VCM reactive materials could inadvertently be added to the reactor
- Evaluate capability of vacuum system to damage reactor
- Add reactor level indicator and alarm
- Provide instruments to verify valve position and reactor status

Table 18.6 Relative Ranking Staff Requirements for the Plant Expansion Phase

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Preparation (hr)</th>
<th>Evaluation (hr)</th>
<th>Documentation (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyst(^a)</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^a\) Analyst has used the F&E Index.

Table 18.7 PVC Batch Reactor HAZOP Analysis Staff Requirements for the Plant Expansion Phase

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Preparation (hr)</th>
<th>Evaluation (hr)</th>
<th>Documentation (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader</td>
<td>8</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Scribe</td>
<td>4</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>Team Member(^d)</td>
<td>2</td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^d\) Average per team member.
EXHIBIT A
FIRE AND EXPLOSION INDEX

<table>
<thead>
<tr>
<th>PLANT</th>
<th>PROCESS UNIT</th>
<th>EVALUATED BY</th>
<th>REVIEWED BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCM PLANT - SITE #1</td>
<td>150 PSIG PVC</td>
<td>DD</td>
<td>AD</td>
</tr>
</tbody>
</table>

MATERIALS AND PROCESS UNIT:
VCM PLANTS WATER DISPERSANTS INITIATOR

<table>
<thead>
<tr>
<th>STATE OF OPERATION</th>
<th>MATERIALS AND PROCESS</th>
<th>MATERIALS IN PROCESS UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>START-UP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHUTDOWN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NORMAL OPERATION</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MATERIAL FACTOR (SEE TABLE I OR APPENDICES A OR B) Note requirements when unit temperature over 140 F:

1. GENERAL PROCESS HAZARDS

<table>
<thead>
<tr>
<th>BASE FACTOR</th>
<th>PENALTY</th>
<th>PENALTY USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. EXOTHERMIC CHEMICAL REACTIONS (FACTOR 0.20 to 0.80)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>B. ENDOTHERMIC PROCESSES (FACTOR 0.20 to 0.40)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>C. MATERIAL HANDLING &amp; TRANSFER (FACTOR 0.25 to 1.00)</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>D. ENCLOSED OR INDOOR PROCESS UNITS (FACTOR 0.25 to 0.90)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>E. ACCESS</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>F. DRAINAGE AND SPILL CONTROL (FACTOR 0.25 to 0.50)</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

GENERAL PROCESS HAZARDS FACTOR (F_1) 2.45

2. SPECIAL PROCESS HAZARDS

<table>
<thead>
<tr>
<th>BASE FACTOR</th>
<th>PENALTY</th>
<th>PENALTY USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. TOXIC MATERIAL(S) (FACTOR 0.20 to 0.80)</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>B. SUB-ATMOSPHERIC PRESSURE ( 500 mm Hg)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>C. OPERATION IN OR NEAR FLAMMABLE RANGE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. TANK FARMS STORAGE FLAMMABLE LIQUIDS</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2. PROCESS UPSET OR PULSE FAILURE</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3. ALWAYS IN FLAMMABLE RANGE</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>D. DUST EXPLOSION (FACTOR 0.25 to 2.00) (SEE TABLE II)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. PRESSURE (SEE FIGURE 2) OPERATING PRESSURE 70 psig RELIEF SETTING 100 psig</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>F. LOW TEMPERATURE (FACTOR 0.20 to 0.30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G. QUANTITY OF FLAMMABLE/UNSTABLE MATERIAL QUANTITY 13,000 lb. H2 8,000 BTU/lb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS (SEE FIG. 3)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>2. LIQUIDS OR GASES IN STORAGE (SEE FIG. 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. COMBUSTIBLE SOLIDS IN STORAGE, DUST IN PROCESS (SEE FIG. 5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. CORROSION AND EROSION (FACTOR 0.10 to 0.75)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>I. LEAKAGE - JOINTS AND PACKING (FACTOR 0.10 to 1.50)</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>J. USE OF FIRED HEATERS (SEE FIG. 6)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>K. HOT OIL HEAT EXCHANGE SYSTEM (FACTOR 0.15 to 1.15) (SEE TABLE III)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. ROTATING EQUIPMENT</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

SPECIAL PROCESS HAZARDS FACTOR (F_2) 2.18

UNIT HAZARD FACTOR (F_1 x F_2) 7.79

FIRE AND EXPLOSION INDEX (F_1 x MF x F_2 x EI) 164

Figure 18.3 Fire and explosion index calculations for low-pressure PVC reactor site #1.
## EXHIBIT B

### LOSS CONTROL CREDIT FACTORS

1. **Process Control (C₁)**
   - a) Emergency Power 0.98
   - b) Cooling 0.97 to 0.99
   - c) Explosion Control 0.84 to 0.98
   - d) Emergency Shutdown 0.96 to 0.99
   - e) Computer Control 0.93 to 0.99

   **C₁ Total 0.87**

2. **Material Isolation (C₂)**
   - a) Remote Control Valves 0.96 to 0.98
   - b) Dump/Blowdown 0.96 to 0.98
   - c) Drainage 0.91 to 0.97
   - d) Interlock 0.98

   **C₂ Total 0.91**

3. **Fire Protection (C₃)**
   - a) Leak Detection 0.94 to 0.98
   - b) Structural Steel 0.95 to 0.98
   - c) Buried Tanks 0.84 to 0.91
   - d) Water Supply 0.94 to 0.97
   - e) Special Systems 0.91
   - f) Sprinkler Systems 0.74 to 0.97
   - g) Water Curtains 0.97 to 0.98
   - h) Foam 0.92 to 0.97
   - i) Hand Extinguishers/Monitors 0.95 to 0.98
   - j) Cable Protection 0.94 to 0.98

   **C₃ Value 0.94**

**Credit Factor = C₁ X C₂ X C₃ = 0.74** Enter on Line D Below

### UNIT ANALYSIS SUMMARY

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$MM</td>
<td></td>
<td>$MM</td>
<td></td>
<td>$MM</td>
<td>days.</td>
<td>$MM</td>
</tr>
</tbody>
</table>

*Product of all factors used.

BACK OF FORM C-22360 R-4-87 (471-036)

**Figure 18.4** Radius of exposure calculations for low-pressure PVC reactor site #1.
EXHIBIT A
FIRE AND EXPLOSION INDEX

<table>
<thead>
<tr>
<th>MATERIALS IN PROCESS UNIT</th>
<th>VCM PLANT - SITE #1</th>
<th>PROCESS UNIT EVALUATED BY</th>
<th>REVIEWED BY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>550 PSIG PVC</td>
<td>DD</td>
<td>AD</td>
</tr>
</tbody>
</table>

**MATERIAL FACTOR**

1. **GENERAL PROCESS HAZARDS**

<table>
<thead>
<tr>
<th>BASE FACTOR</th>
<th>PEnalty</th>
<th>PENALTY USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. EXOTHERMIC CHEMICAL REACTIONS (FACTOR 0.30 to 1.25)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>B. ENOTHERMIC PROCESSES (FACTOR 0.20 to 0.40)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>C. MATERIAL HANDLING &amp; TRANSFER (FACTOR 0.25 to 1.05)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>D. ENCLOSURE OR ENDOOR PROCESS UNITS (FACTOR 0.25 to 0.90)</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>E. ACCESS</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>F. DRAINAGE AND SPILL CONTROL (FACTOR 0.25 to 1.00)</td>
<td>2.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

**GENERAL PROCESS HAZARDS FACTOR**

- NH = a

2. **SPECIAL PROCESS HAZARDS**

<table>
<thead>
<tr>
<th>BASE FACTOR</th>
<th>PEnalty</th>
<th>PENALTY USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. TOXIC MATERIALS (FACTOR 0.20 to 0.80)</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>B. SUB-ATMOSPHERIC PRESSURE (500 mm Hg)</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>C. OPERATION IN OR NEAR FLAMMABLE RANGE</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>1. TANK FARMS STORAGE FLAMMABLE LIQUIDS</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>2. PROCESS UPSET OR PURGE FAILURE</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>3. ALWAYS IN FLAMMABLE RANGE</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>D. DUST EXPLOSION (FACTOR 0.25 to 2.00)</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>E. PRESSURE (SEE FIGURE 2)</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>F. LOW TEMPERATURE (FACTOR 0.20 to 0.30)</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>G. QUANTITY OF FLAMMABLE/UNSTABLE MATERIAL QUANTITY 18,000 bbl, H = 8,000 BTU/lb</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>1. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS (SEE FIG. 3)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>2. LIQUIDS OR GASES IN STORAGE (SEE FIG. 4)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>3. COMBUSTIBLE SOLIDS IN STORAGE, DUST IN PROCESS (SEE FIG. 5)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>H. CORROSION AND EROSION (FACTOR 0.20 to 0.75)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>I. LEAKAGE - JOINTS AND PACKING (FACTOR 0.10 to 1.00)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>J. USE OF FIRED HEATERS (SEE FIG. 6)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>K. HOT OIL HEAT EXCHANGE SYSTEM (FACTOR 0.15 to 1.15) (SEE TABLE III)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>L. ROTATING EQUIPMENT</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

**SPECIAL PROCESS HAZARDS FACTOR**

- 3.08

**UNIT HAZARD FACTOR**

- 7.55

**FIRE AND EXPLOSION INDEX**

- 159

Figure 18.5 Fire and explosion index calculations for high-pressure PVC reactor site #1.
EXHIBIT B

LOSS CONTROL CREDIT FACTORS

1. Process Control (C1)
   a) Emergency Power .98
   b) Cooling .97 to .99
   c) Explosion Control .84 to .98
   d) Emergency Shutdown .96 to .99
   e) Computer Control .93 to .99
   C1 Total .87

2. Material Isolation (C2)
   a) Remote Control Valves .96 to .98
   b) Dump/Blowdown .96 to .98
   C2 Total .91

3. Fire Protection (C3)
   a) Leak Detection .94 to .98
   b) Structural Steel .95 to .98
   c) Buried Tanks .84 to .91
   d) Water Supply .94 to .97
   e) Special Systems .91
   C3 Value .94
   Credit Factor = C1 X C2 X C3 = .74

UNIT ANALYSIS SUMMARY

A-1. F & EI
A-2. Radius of Exposure 159 ft
A-3. Value of Area of Exposure $MM
B. Damage Factor $MM
C. Base MMPD (A-3 X B) $MM
D. Credit Factor $MM
E. Actual MMPD (C X D) $MM
F. Days Outage (MPDO) days
G. Business Interruption Loss (Bl) $MM

* Product of all factors used.

BACK OF FORM C-22380 R-4-87 (471-026)

Figure 18.6 Radius of exposure calculations for high-pressure PVC reactor site #1.
EXHIBIT A

FIRE AND EXPLOSION INDEX

**VCM PLANT - SITE #2**

- **PLANT:** VCM PLANT - SITE #2
- **PROCESS UNIT:** ISO PVC
- **EVALUATED BY:** DD
- **REVIEWED BY:** AD

**MATERIALS AND PROCESS**

**VCM WATER DISPERGANTS INITIATOR**

<table>
<thead>
<tr>
<th>MATERIAL FACTOR (SEE TABLE I OR APPENDIX A or B)</th>
<th>Note requirements when unit temperature over 140°F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BASE FACTOR</strong></td>
<td>PENALTY</td>
</tr>
<tr>
<td><strong>A</strong> EXOTHERMIC CHEMICAL REACTIONS (FACTOR .30 to 1.25)</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>B</strong> ENDOThERMIC PROCESSES (FACTOR .20 to .40)</td>
<td>-</td>
</tr>
<tr>
<td><strong>C</strong> MATERIAL HANDLING &amp; TRANSFER (FACTOR .25 to 1.05)</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>D</strong> ENCLOSED OR INDOOR PROCESS UNITS (FACTOR .25 to .90)</td>
<td>0.48</td>
</tr>
<tr>
<td><strong>E</strong> ACCESS</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>F</strong> DRAINAGE AND SPILL CONTROL (FACTOR 25 to 50)</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>G</strong> General Process Hazards Factor (F,g)</td>
<td>3.25</td>
</tr>
</tbody>
</table>

**2. SPECIAL PROCESS HAZARDS**

<table>
<thead>
<tr>
<th>BASE FACTOR</th>
<th>PENALTY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> TOXIC MATERIALS (FACTOR 0.20 to 0.80)</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>B</strong> SUB-ATMOSPHERIC PRESSURE (750 mm Hg)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>C</strong> OPERATION IN OR NEAR FLAMMABLE RANGE</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**UNIT HAZARD FACTOR:**

- **BASE FACTOR:** 1.00
- **FIRE AND EXPLOSION INDEX (F&EI):** 168

*The Dow Guide recommends a maximum unit hazard factor of 8. The F&EI is calculated twice, using 8.0 unit hazard factor (F&EI = 168) and the estimated 10.4 unit hazard factor (F&EI = 218).

**Figure 18.7** Fire and explosion index calculations for low-pressure PVC reactor site #2.
EXHIBIT B

LOSS CONTROL CREDIT FACTORS

1. Process Control ($C_1$)
   a) Emergency Power  .96 to .98
   b) Cooling .97 to .99
   c) Explosion Control .84 to .98
   d) Emergency Shutdown .96 to .99
   e) Computer Control .93 to .99
   $C_1$ Total .87

2. Material Isolation ($C_2$)
   a) Remote Control Valves .96 to .98
   b) Dump/Blowdown .96 to .98
   $C_2$ Total .96

3. Fire Protection ($C_3$)
   a) Leak Detection .94 to .98
   b) Structural Steel .95 to .98
   c) Buried Tanks .84 to .91
   d) Water Supply .94 to .97
   e) Special Systems .91
   $C_3$ Value .83

Credit Factor = $C_1 \times C_2 \times C_3 = .249$ Enter on Line D Below

UNIT ANALYSIS SUMMARY

A-1. F & EI
A-2. Radius of Exposure
A-3. Value of Area of Exposure
B. Damage Factor
C. Base MMPD (A-3 X B)
D. Credit Factor
E. Actual MMPD (C X D)
F. Days Outage (MPDO)
G. Business Interruption Loss (BI)

$\text{MMPD} = \frac{162 (212)^*}{141 (183)^*}$ $\text{ft}$

\begin{tabular}{ll}
\hline
A-2. & $162 (212)^*$ \\
A-3. & $141 (183)^*$ \\
B. & $\text{MMPD}$ \\
C. Base MMPD (A-3 X B) & $\text{MMPD}$ \\
D. Credit Factor & $\text{MMPD}$ \\
E. Actual MMPD (C X D) & $\text{MMPD}$ \\
F. Days Outage (MPDO) & $\text{MMPD}$, $\text{days}$ \\
G. Business Interruption Loss (BI) & $\text{MMPD}$ \\
\hline
\end{tabular}

* Product of all factors used.

* Depending on F&EI used.

Figure 18.8 Radius of exposure calculations for low-pressure PVC reactor site #2.
**EXHIBIT A**

**FIRE AND EXPLOSION INDEX**

**PLANT**: VCM PLANT - SITE #2  
**PRESSURE UNIT**: 250 PSIG PVC  
**EVALUATED BY**: DD  
**REVISED BY**: AD  
**WARNING**: ANYWHERE USA  
**DATE**: 2/10/94

### MATERIALS IN PROCESS UNIT

<table>
<thead>
<tr>
<th>MATERIALS AND PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCM WATER DISPERGANTS</td>
</tr>
<tr>
<td>INITIATOR</td>
</tr>
</tbody>
</table>

### STATE OF OPERATION

- **UP**: SHUT-DOWN
- **V**: NORMAL OPERATION

### MATERIAL FACTOR (SEE TABLE 1 OR APPENDICES A OR B)

#### BASE FACTOR

<table>
<thead>
<tr>
<th>PROCESS HAZARDS</th>
<th>PENALTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. EXOTHERMIC CHEMICAL REACTIONS (FACTOR 0.30 to 1.25)</td>
<td>0.5</td>
</tr>
<tr>
<td>B. ENDOThERMIC PROCESSES (FACTOR 20 to 40)</td>
<td>0.5</td>
</tr>
<tr>
<td>C. MATERIAL HANDLING &amp; TRANSFER (FACTOR 25 to 1.25)</td>
<td>0.45</td>
</tr>
<tr>
<td>D. ENCLOSED OR INDOOR PROCESS UNITS (FACTOR 25 to 90)</td>
<td>3.0</td>
</tr>
<tr>
<td>E. ACCESS</td>
<td>0.3</td>
</tr>
<tr>
<td>F. DRAINAGE AND SPILL CONTROL (FACTOR 25 to 50)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

#### GENERAL PROCESS HAZARDS FACTOR (F1)

- **G. TOXIC MATERIALS (FACTOR 0.20 to 0.80)**
- **H. SUB-ATMOSPHERIC PRESSURE (< 500 mm Hg)**
- **I. OPERATION IN OR NEAR FLAMMABLE RANGE**
  - **INERTED**
  - **NOT INERTED**
- **J. TANK FARMS STORAGE FLAMMABLE LIQUIDS**
- **K. PROCESS UPSET OR PURGE FAILURE**
- **L. ALWAYS IN FLAMMABLE RANGE**
- **M. DUST EXPLOSION (FACTOR 25 to 2.000) (SEE TABLE II)**
- **N. PRESSURE (SEE FIGURE 2) OPERATING PRESSURE 75 psig RELIEF SETTING 200 psig**
- **O. LOW TEMPERATURE (FACTOR 20 to 30)**
- **P. QUANTITY OF FLAMMABLE, UNSTABLE MATERIAL, QUANTITY 13000 lbs. H<sup>2</sup> 8000 BTU/10**
- **Q. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS (SEE FIG. 3)**
- **R. LIQUIDS OR GASES IN STORAGE (SEE FIG. 4)**
- **S. COMBUSTIBLE SOLIDS IN STORAGE DUST IN PROCESS (SEE FIG. 5)**
- **T. CORROSION AND EROSION (FACTOR 10 to 75)**
- **U. LEAKAGE - JOINTS AND PACKING (FACTOR 0.10 to 1.50)**
- **V. USE OF FIRED HEATERS (SEE FIG. 6)**
- **W. HOT OIL HEAT EXCHANGE SYSTEM (FACTOR 15 to 1.15) (SEE TABLE III)**
- **X. ROTATING DEQUIPMENT**
- **Y. SPECIAL PROCESS HAZARDS FACTOR (F2)**

#### UNIT HAZARD FACTOR (F2)

- **Z. FIRE AND EXPLOSION INDEX (F1 x MF x F & EI)**

### GENERAL PROCESS HAZARDS FACTOR (F1)

- **G. TOXIC MATERIALS (FACTOR 0.20 to 0.80)**
- **H. SUB-ATMOSPHERIC PRESSURE (< 500 mm Hg)**
- **I. OPERATION IN OR NEAR FLAMMABLE RANGE**
  - **INERTED**
  - **NOT INERTED**
- **J. TANK FARMS STORAGE FLAMMABLE LIQUIDS**
- **K. PROCESS UPSET OR PURGE FAILURE**
- **L. ALWAYS IN FLAMMABLE RANGE**
- **M. DUST EXPLOSION (FACTOR 25 to 2.000) (SEE TABLE II)**
- **N. PRESSURE (SEE FIGURE 2) OPERATING PRESSURE 75 psig RELIEF SETTING 200 psig**
- **O. LOW TEMPERATURE (FACTOR 20 to 30)**
- **P. QUANTITY OF FLAMMABLE, UNSTABLE MATERIAL, QUANTITY 13000 lbs. H<sup>2</sup> 8000 BTU/10**
- **Q. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS (SEE FIG. 3)**
- **R. LIQUIDS OR GASES IN STORAGE (SEE FIG. 4)**
- **S. COMBUSTIBLE SOLIDS IN STORAGE DUST IN PROCESS (SEE FIG. 5)**
- **T. CORROSION AND EROSION (FACTOR 10 to 75)**
- **U. LEAKAGE - JOINTS AND PACKING (FACTOR 0.10 to 1.50)**
- **V. USE OF FIRED HEATERS (SEE FIG. 6)**
- **W. HOT OIL HEAT EXCHANGE SYSTEM (FACTOR 15 to 1.15) (SEE TABLE III)**
- **X. ROTATING DEQUIPMENT**
- **Y. SPECIAL PROCESS HAZARDS FACTOR (F2)**

### UNIT HAZARD FACTOR (F2)

- **Z. FIRE AND EXPLOSION INDEX (F1 x MF x F & EI)**

*The Dow Guide recommends a maximum unit hazard factor of 8. The F&EI is calculated twice, using 8.0 unit hazard factor (F&EI = 168) and the estimated 10.08 unit hazard factor (F&EI = 212).*

**Figure 18.9** Fire and explosion index calculations for high pressure PVC reactor site #2.
EXHIBIT B

LOSS CONTROL CREDIT FACTORS

1. Process Control (C₁)

- Emergency Power: .98 to .96
- Cooling: .97 to .99
- Explosion Control: .84 to .98
- Emergency Shutdown: .96 to .99
- Computer Control: .93 to .99

C₁ Total: .87

2. Material Isolation (C₂)

- Remote Control Valves: .96 to .98
- Dump/Blowdown: .96 to .98

C₂ Total: .76

3. Fire Protection (C₃)

- Leak Detection: .94 to .98
- Structural Steel: .95 to .98
- Buried Tanks: .84 to .91
- Water Supply: .94 to .97

C₃ Value: .83

Credit Factor = C₁ X C₂ X C₃ = .0269

UNIT ANALYSIS SUMMARY

A-1. F & E
A-2. Radius of Exposure
A-3. Value of Area of Exposure
B. Damage Factor
C. Base MMPD (A-3 X B)
D. Credit Factor
E. Actual MMPD (C X D)
F. Days Outage (MPDO)
G. Business Interruption Loss (Bl)

$MM

* Product of all factors used.

BACK OF FORM C-22560 R-4-87 (471-036)

* Depending on F&El used.

Figure 18.10 Radius of exposure calculations for low-pressure PVC reactor site #1.
Figure 18.11 PVC unit block diagram.