Steps in Hazard Evaluation Process	Hazard Evaluation Procedures										
	Process/ System Checklists	Safety Review	Relative Ranking Dow & Mond	Preliminary Hazard Analysis	"What If" Method	Hazard and Operability Study	Failure Modes Effects and Criticality Analysis	Fault Tree Analysis	Event Tree Analysis	Cause Consequence Analysis	Human Error Analysis
Identify Deviations From Good Practice	Primary Purpose	Primary Purpose	Primary Purpose								
Identify Hazards	Primary Purpose*	Primary Purpose*	Primary Purpose*	Primary Purpose	Primary Purpose	Primary Purpose	Primary Purpose	Provides Context Only			
Estimate "Worst Case" Consequences			Primary Purpose		Primary Purpose	Provides Context Only	Primary Purpose				
Identify Opportunities to Reduce Consequences			Primary Purpose	Secondary Purpose		Provides Context Only	Provides Context Only				
Identify Accident Initiating Events					Primary Purpose	Primary Purpose	Primary Purpose	Primary Purpose			Primary Purpose
Estimate Probabilities of Initiating Events						Provides Context Only	Provides Context Only	Primary Purpose		Primary Purpose	Primary Purpose
Identify Opportunities to Reduce Probabilities of Initiating Events								Primary Purpose		Primary Purpose	Primary Purpose
Identify Accident Event Sequences and Consequences					Primary Purpose			Primary Purpose	Primary Purpose	Primary Purpose	
Estimate Probabilities of Event Sequences								Primary Purpose	Primary Purpose	Primary Purpose	
Estimate Magnitude of Consequences of Event Sequences									Provides Context Only	Provides Context Only	
Identify Opportunities to Reduce Probabilities and/or Consequences of Event Sequences									Primary Purpose	Primary Purpose	Primary Purpose
Quantitative Hazard Evaluation								Primary Purpose	Primary Purpose	Primary Purpose	Primary Purpose

* Previously Recognized Hazards Only.

FIGURE 3-1. MATRIX RELATING HAZARD EVALUATION PROCEDURES TO HAZARD EVALUATION PROCESS STEPS

Esempio di check list

- E’ stato previsto un bacino di contenimento?
- E’ stata calcolata la portata della perdita?
- E’ stata verificata la portata dell’acqua antincendio rispetto all’incdente?
- ...

ALLEGATI:

CHECK LIST PER:
- COSTRUZIONI CIVILI
- LAY-OUT UNITA' DI PROCESSO
- PRESCRIZIONI DI PROCESSO
- PROCESSO
- APPARECCHI DI PROCESSO
- PIPING
- MACCHINE
- SISTEMA ELETTRICO
- STRUMENTAZIONE
- UTILITIES

ATTIVITA'	DESCRIZIONE	CHECK	NOTE
LAY OUT UNITA' DI PROCESSO	1) E' assicurata l'accessibilità negli impianti ai mezzi di manutenzione e a quelli di emergenza ?		
	2) Sono state valutate le distanze di sicurezza fra le varie unità o fra i sistemi ?		
	3) Sono state previste barriere protettive o muri antiscoppio a protezione delle installazioni adiacenti a sistemi estremamente pericolosi ?		
	4) Sono stati considerati i criteri di sicurezza nel posizionare gli scarichi atmosferici ? (valvole di sicurezza, dischi di rottura, blow out etc.)		
	5) Sono state previste le vie di fuga dai punti pericolosi ?		
	6) E' stata considerata dovutamente l'accessibilità a quelle apparecchiature che devono, per ragioni di esercizio essere manipolate frequentemente ?		

Unità produttiva:	**Rilievo effettuato il:**
Impianto:	**Rilievo effettuato da:**
Area:	**in qualità di:**

Sigla macchina: **Manutenzione meccanica**

I punti di regolazione , lubrificazione e manutenzione sono distanti dalle zone pericolose delle macchine ?	SI	NO	16.01
La manutenzione ordinaria è eseguita da:			
operatore stesso	SI	NO	16.02
tecnico specializzato	SI	NO	16.03
entrambi a seconda dei casi	SI	NO	16.04
Esiste sempre una verifica dell'operato del manutentore ?	SI	NO	16.05
Esistono zone di manutenzione di difficile accesso ?	SI	NO	16.06
se SI, sono previsti sistemi di accesso (scale, passarelle, ecc.) ?	SI	NO	16.07
La manutenzione della macchina è svolto anche da personale esterno ?	SI	NO	16.08
Chi può autorizzare variazioni sostanziali della macchine (specificare) ?			16.09
La macchina è corredata da un libretto di istruzione ?	SI	NO	16.10
se SI, esso è fornito agli operatori ?	SI	NO	16.16
se SI, esso in genere contiene informazioni su:			
condizioni di utilizzazione previste	SI	NO	16.12
descrizione dei posti di lavoro	SI	NO	16.13
istruzioni per	SI	NO	16.14
messa in funzione	SI	NO	16.15
utilizzazione	SI	NO	16.16
installazione	SI	NO	16.17
montaggio	SI	NO	16.18
regolazione	SI	NO	16.19
manutenzione	SI	NO	16.20
La macchina è stata costruita su progetto inetrno allo stabilimento ?	SI	NO	16.21
La macchina è stata adattata a specifiche funzioni ?	SI	NO	16.22

TABLE 4-1. TYPICAL INFORMATION NEEDED FOR "WHAT IF" TECHNIQUE

- I. Process Flow Sheets
  - 1. Operating Conditions
    - a. Process materials used, including physical properties
    - b. Process chemistry and thermodynamics
  - 2. Equipment Description
- II. Plot Plan
- III. Process and Instrumentation Drawings
  - 1. Controls
    - a. Continuous monitoring devices
    - b. Alarms and their function
  - 2. Instrumentation
    - a. Charts
    - b. Gauges
    - c. Monitors
- IV. Operations
  - 1. Responsibilities and duties of operating personnel
  - 2. Communications systems
  - 3. Procedures
    - a. Preventive maintenance
    - b. Hot work permits
    - c. Vessel entry
    - d. Lock-out/Tag out
    - e. Emergency

3. Define the Team

Teams of two or three members are defined for each identified investigation area. The team should include:

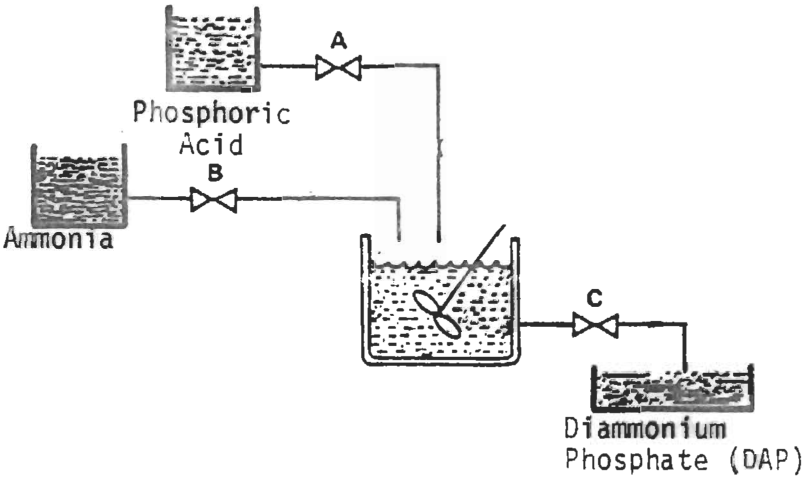


FIGURE 4-2. CONTINUOUS PROCESS EXAMPLE FOR "WHAT IF" TECHNIQUE

TABLE 4-2. "WHAT IF" QUESTIONS

"What If"
1. Wrong product is delivered instead of phosphoric acid
2. Phosphoric acid is wrong concentration
3. Phosphoric acid is contaminated
4. Valve A is closed or plugged
5. Too high a proportion of ammonia is supplied to reactor
6. Vessel agitation stops
7. Valve C is closed

What If	Consequence/Hazard	Recommendation
Wrong product is delivered instead of phosphoric acid	None likely	
Phosphoric acid is wrong concentration	Ammonia is not used up and is released to work area	Verify phosphoric acid concentration after filling vat prior to operation.
Phosphoric acid is contaminated	None likely	
Valve A is closed or plugged	Ammonia unreacted, released to work area	Alarm/shutoff of ammonia (valve B) on low flow from valve A into reactor.
Too high a proportion of ammonia is supplied to reactor	Excess ammonia released to work area	Alarm/shutoff of ammonia (valve B) on high flow from valve B into reactor
. . .	. . .	. . .

FIGURE 4-3. SAMPLE "WHAT IF" WORKSHEET FOR DAP PLANT

APPENDIX D

Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is a tool to systematically analyze all contributing component failure modes and identify the resulting effects on the system. It is frequently used for nuclear power applications whenever a detailed analysis involving fault trees (see Chapter 8) and event trees (see Chapter 9) is not required. Many times an FMEA will be performed as a preliminary system reliability analysis to assist development of a more quantitative event tree/fault tree analysis.

Several slightly different formats are used for an FMEA, but all require that the failure or malfunction of each component of the system, including the mode of failure, be considered. Then the effects of the failure are traced through the system in order to assess the ultimate effect on the system performance.

Successful development of an FMEA requires that the analyst know all the significant failure modes, such as failure to start, stop, open, close, or continue to operate, and the scheduled periods between service and the design lifetime. It also requires the analyst to assess the effect of any failure mode on the overall performance of the system according to the following hazard classification [1]:

Criticality category	Effect
I. Safe	Negligible; no effect on system.
II. Marginal	Failure will degrade system to some extent but will not cause major system damage or injury to personnel.
III. Critical	Failure will degrade system's performance and/or cause personnel injury, and if immediate action is not taken, serious injuries or deaths to personnel and/or loss of system will occur.
IV. Catastrophic	Failure will produce severe system degradation causing loss of system and/or multiple deaths or injuries.

Example D-1 Construct an FMEA for the domestic hot water system as shown in Fig. D-1. The water system works as follows: the gas valve is operated by the controller, which, in turn, is operated by a temperature measuring and comparing device. The gas valve operates the main burner in full-on/full-off modes. The check valve in the water inlet line prevents reverse flow due to overpressure in the hot water system. The pressure relief valve opens when pressure in the system exceeds 100 psi.

When the temperature of water is below the desired range (140° to 180°F), the temperature measuring and comparing device signals the controller to open the gas valve and turn on the gas burner, which is lit by a pilot burner. When the water temperature reaches the desired level, the temperature measuring and comparing device signals the controller to turn off the gas valve and thus turn off the main gas burner.

The FMEA is shown in Table D-1. ◇

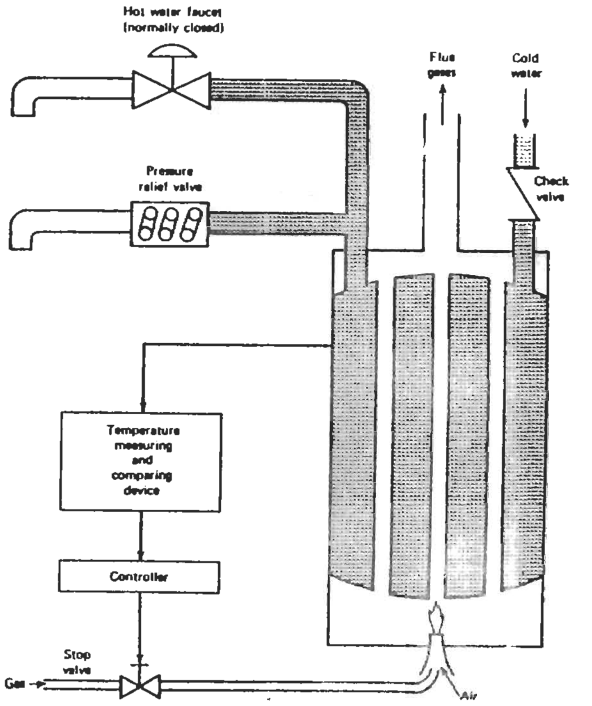


Fig. D-1 *Schematic of domestic hot water system.* [*From H. E. Lambert, Lawrence Livermore Laboratory Report* UCID-*16238 (1973).*]

Table D-1 *Failure Mode and Effects Analysis of a Domestic Hot Water System*[a]

Component	Failure or error mode	Effects on other components	Effects on whole system	Class I	Class II	Class III	Class IV	Failure frequency	Detection methods	Compensating provisions and remarks
Pressure relief valve	Jammed open	Increased operation of temperature sensing controller; gas flow due to hot water loss	Loss of hot water; greater cold water input; greater gas consumption	X				Reasonably probable	Observe at pressure relief valve	Shut off water supply, reseal or replace relief valve
	Jammed closed	None	None	X				Probable	Manual testing	Unless combined w/other component failure, this failure has no consequence
Gas valve	Jammed open	Burner continues to operate, pressure relief valve opens	Water temperature and pressure increase; water → steam			X		Reasonably probable	Water at faucet too hot; pressure relief valve open (observation)	Open hot water faucet to relieve pressure. Shut off gas supply. Pressure relief valve compensates.
	Jammed closed	Burner ceases to operate	System fails to produce hot water	X				Remote	Observe at output (water temperature too low)	
Temperature measuring and comparing device	Fails to react to temperature rise above preset level	Controller, gas valve, burner continue to function "on." Pressure relief valve opens	Water temperature too high; water → steam			X		Remote	Observe at output (faucet)	Pressure relief valve compensates. Open hot water faucet to relieve pressure. Shut off gas supply.
	Fails to react to temperature drop below preset level	Controller, gas valve, burner continue to function "off"	Water temperature too low	X				Remote	Observe at output (faucet)	

[a] From H. E. Lambert, Lawrence Livermore Laboratory Rep UCID-16238 (1973).

The process is systematic and it is helpful to define the terms that are used:

a. STUDY NODES- The locations (on piping and instrumentation drawings and procedures) at which the process parameters are investigated for deviations.

b. INTENTION- The intention defines how the plant is expected to operate in the absence of deviations at the study nodes. This can take a number of forms and can either be descriptive or diagrammatic; e.g., flowsheets, line diagrams, P&IDs.

c. DEVIATIONS- These are departures from the intention which are discovered by systematically applying the guide words (e.g., "more pressure").

d. CAUSES- These are the reasons why deviations might occur. Once a deviation has been shown to have a credible cause, it can be treated as a meaningful deviation. These causes can be hardware failures, human errors, an unanticipated process state (e.g., change of composition), external disruptions (e.g., loss of power), etc.

e. CONSEQUENCES- These are the results of the deviations should they occur (e.g., release of toxic materials). Trivial consequences, relative to the study objective, are dropped.

f. GUIDE WORDS- These are simple words which are used to qualify or quantify the intention in order to guide and stimulate the brainstorming process and so discover deviations. The guide words shown in Table 4-3 are the ones most often used in a HazOp; some organizations have made this list specific to their operations, to guide the team more quickly to the areas where they have previously found problems. Each guide word is applied to the process variables at the point in the plant (study node) which is being examined. For example:

Guide Words		Parameter	Deviation
NO	&	FLOW---------	NO FLOW
MORE	&	PRESSURE-----	HIGH PRESSURE
AS WELL AS	&	ONE PHASE----	TWO PHASE
OTHER THAN	&	OPERATION----	MAINTENANCE

These guide words are applicable to both the more general parameters (e.g., react, transfer) and the more specific parameters (e.g., pressure,

TABLE 4-3. HAZOP GUIDE WORDS AND MEANINGS

Guide Words	Meaning
No	Negation of the Design Intent
Less	Quantitative Decrease
More	Quantitative Increase
Part Of	Qualitative Decrease
As Well As	Qualitative Increase
Reverse	Logical Opposite of the Intent
Other Than	Complete Substitution

temperature). With the general parameters, meaningful deviations are usually generated for each guide word. Moreover, it is not unusual to have more than one deviation from the application of one guide word. For example, "more reaction" could mean either than a reaction takes place at a faster rate, or that a greater quantity of product results.

With the specific parameters, some modification of the guide words may be necessary. In addition, it is not unusual to find that some potential deviations are eliminated by physical limitation. For example, if the design intention of a pressure or temperature is being considered, the guide words "more" or "less" may be the only possibilities.

There are other useful modifications to guide words such as:

- SOONER or LATER for OTHER THAN when considering time
- WHERE ELSE for OTHER THAN when considering position, sources, or destination
- HIGHER and LOWER for MORE and LESS when considering elevations, temperatures, or pressures.

provide the proper authority to the study and to ensure that the study is focused. Also, even though the general objective is to identify hazards and operability problems, the team should focus on the underlying purpose or reason for the study. Examples of reasons for a study might be to:

- Check the safety of a design
- Decide whether and where to build
- Develop a list of questions to ask a supplier
- Check operating/safety procedures
- Improve the safety of an existing facility
- Verify that safety instrumentation is reacting to best parameters.

It is also important to define what specific consequences are to be considered:

- Employee safety (in plant or neighboring research center)
- Loss of plant or equipment
- Loss of production (lose competitive edge in market)
- Liability
- Insurability
- Public safety
- Environmental impacts.

For example, a HazOp might be conducted to determine where to build a plant to have the minimal impact on public safety. In this case, the HazOp should focus on deviations which result in off-site hazards.

2. Select the Team. Ideally, the team consists of five to seven members, although a smaller team could be sufficient for a smaller plant. If the team is too large, the group approach fails. On the other hand, if the group is too small, it may lack the breadth of knowledge needed to assure completeness. The team leader should have experience in leading a HazOp. The [illegible] of the team should be experts in areas [illegible] to the plant operation. [illegible] example, a team might include:

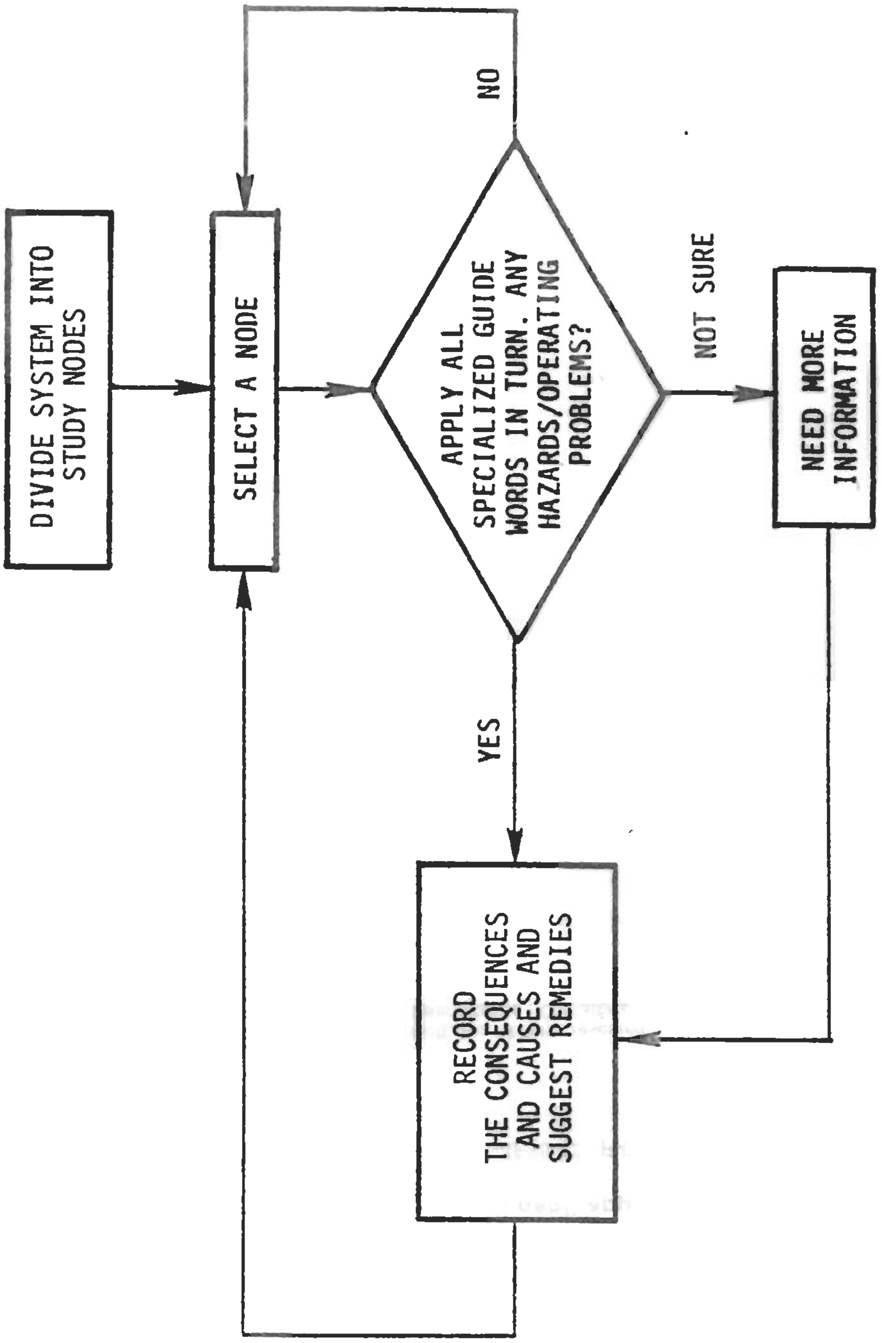


FIGURE 4-4. HAZOP METHOD FLOW DIAGRAM

only complete record of the discussions and the reasoning behind the recorded findings, and it can be invaluable later in the plant life when the plant is modified, or if an event occurs which is the result of a deviation.

Example

Consider, as a simple example, the continuous process shown in Figure 4-6. In this process, the phosphoric acid and ammonia are mixed, and a non-hazardous product, diammonium phosphate (DAP), results if the reaction of ammonia is complete. If too little phosphoric acid is added, the reaction is incomplete, and ammonia is produced. Too little ammonia available to the reactor results in a safe but undesirable product. The HazOp team is assigned to investigate "Personnel Hazards from the Reaction".

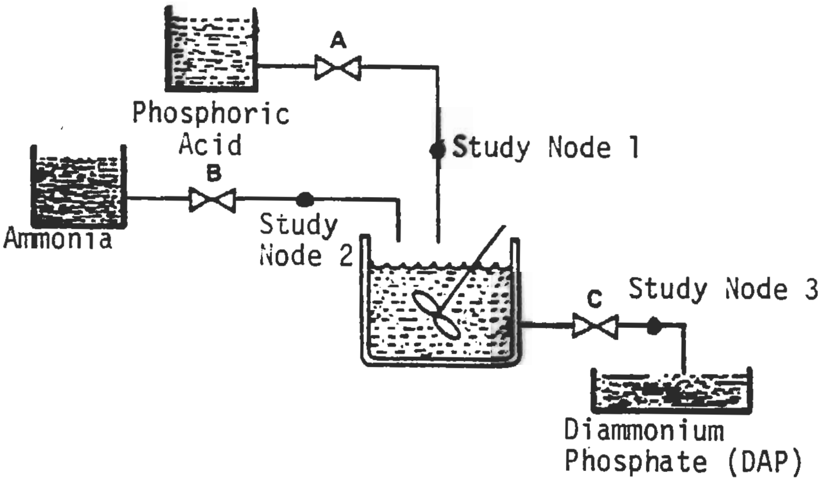


FIGURE 4-6. CONTINUOUS PROCESS EXAMPLE FOR HAZOP TECHNIQUE

The team leader starts with a study node and applies the guide words to the process parameters. Thus, for study node 1:

I. NO
  a. NO & FLOW --- no flow at study node 1
  b. Consequences: excess ammonia in reactor and release to work area

c. Causes
   - -- valve A fails closed
   - -- phosphoric acid supply exhausted
   - -- plug in pipe, pipe ruptures

d. Suggested action: automatic closure of valve B on loss of flow from phosphoric acid supply.

II. LESS

a. LESS & FLOW --- reduced flow at study node 1

b. Consequences: excess ammonia in reactor and release to work area. Amount released is related to quantitative reduction in supply. Team member assigned to calculate toxicity level versus flow reduction.

c. Causes:
   - -- valve A partially closed
   - -- partial plug or leak in pipe

d. Suggested action: automatic closure of valve B based on reduced flow in pipe from phosphoric acid supply. Set point dependent on toxicity versus reduced flow calculations.

III. MORE

a. MORE & FLOW --- increased flow at study node 1

b. Consequences: excess phosphoric acid degrades product but presents no hazard to workplace.

IV. PART OF

a. PART OF & FLOW --- decreased concentration of phosphoric acid at study node 1

b. Consequences: see II.b (low flow consequences)

c. Causes
   - -- vendor delivers wrong material or concentration
   - -- error in charging phosphoric acid supply tank

d. Suggested Action: Add check of phosphoric acid supply tank concentration after charging procedures.

V. AS WELL AS

a. AS WELL AS & FLOW --- increase concentration of phosphoric acid (not a realistic consideration since highest available concentration used to charge supply).

VI. REVERSE

a. REVERSE & FLOW --- reverse flow at study node 1

b. Consequences

c. Causes: no reasonable mechanism for reverse flow.

VII. OTHER THAN

a. OTHER THAN & FLOW --- material other than phosphoric acid in line A

b. Consequences: Depends on substitution; team member assigned to test potential substitutions based on availability of other materials at site and similarity in appearance

c. Causes:
- wrong delivery from vendor
- wrong material chosen from plant warehouse

d. Recommended Action: Plant procedures to provide check on material chosen before charging phosphoric acid supply tank.

This process then continues by choosing other process parameters and combining them with the guide words.

HazOp Variations

1. Knowledge-Based HazOp

The knowledge-based HazOp is a specialization of the Guide-Word HazOp in which the guide words are replaced by the team's and leader's knowledge

Process Unit: DAP Production

Node: 1 Process Parameter: Flow

GUIDE WORD	DEVIATION	CONSEQUENCES	CAUSES	SUGGESTED ACTION
No	No Flow	Excess ammonia in reactor. Release to work area.	(1) Valve A fails closed	Automatic closure of valve B on loss of flow from phosphoric acid supply
			(2) Phosphoric acid supply exhausted	
			(3) Plug in pipe; pipe ruptures	
Less	Less Flow	Excess ammonia in reactor. Release to work area, with amount released related to quantitative reduction in supply. Team member to calculate toxicity vs. flow reduction.	(1) Valve A partially closed	Automatic closure of valve B on reduced flow from phosphoric acid supply. Set point determined by toxicity vs. flow calculation
			(2) Partial plug or leak in pipe	
More	More Flow	Excess phosphoric acid degrades product. No hazard to work area.	--	--
Part of	Normal flow of decreased concentration of phosphoric acid	Excess ammonia in reactor. Release to work area, with amount released related to quantitative reduction in supply.	(1) Vendor delivers wrong material or concentration	Check phosphoric acid supply tank concentration after charging
			(2) Error in charging phosphoric acid supply tank	

FIGURE 4-5. SAMPLE OF HAZOP WORKSHEET

Hazard Identification Analysis (HAZID)
Example Worksheet

Scenario	Domain	Cause	Hazard Latency Time	Effect / Consequence	C	F	RPN

1	2	3	4	5
EXTREMELY UNLIKELY	VERY UNLIKELY	UNLIKELY	POSSIBLE	PROBABLE

1	2	3	4	6
SIGNIFICANT	SERIOUS	SEVERE	MAJOR	SERIOUS

Hazard Domains to consider during HAZID

Hazard Domain	**Cause**
Energy	Electricity
	Heat
	Mechanical force
	Electromagnetic fields
	Moving parts
	Suspended masses
	Pressure and vessel rupture
	Vibration
Chemical	Spills
	Toxic substances or by-products
Fire / Explosion	Inflammable gases
	Liquid or solid fuels
	Oxygen enriched environment

Analisi funzionale

In questa analisi si identificano le principali funzioni realizzate dall'impianto e più in generale sul sito. Ciascuna funzione principale sarà poi scomposta in funzioni elementari necessarie al fine di assolvere quella principale.

L'identificazione dei pericoli esaminerà le funzioni elementari al fine di evidenziarne le possibili deviazioni.

Tabella 1: Esempio di analisi funzionale

CODICE	FUNZIONE
1.	Produzione calore
1.1	Fornitura combustibile
1.1.1	Controllo pressione combustibile
...	
1.2	Combustione
1.3	Servizi ausiliari alle macchine
...	...
2.	Produzione Energia elettrica
...	...

Identificazione dei pericoli mediante HAZID

L'identificazione dei pericoli viene realizzata analizzando le funzioni elementari (quelle di più basso livello) emerse dall'analisi funzionale. Per ciascuna di queste funzioni si determineranno le possibili deviazioni, le cause che le generano (guasti, errori umani, eventi esterni), gli effetti ai fini della sicurezza e della produttività.

Operativamente, l'analisi viene condotta riempiendo le tabelle HAZID di cui si riporta la struttura in Tabella 2.

Tabella 2: Tabella HAZID

Funzione principale	Funzione elementare	Fase Operativa	Pericolo/Dev. di Funzione	Cause	Conseguenze	F	D	R	Salvaguardie esistenti	Raccomandazioni

Gli indici di Frequenza (F), Danno (D) e Rischio (R) saranno stimati sulla base di una valutazione qualitativa che deriva dall'esperienza dell'analista e degli operatori di impianto, con riferimento alla classificazione qui oltre riportata.

Tabella 3: Classificazione per Frequenza

FREQUENZA	
F	**Periodo di ritorno / Frequenza Annuale**
1	Estremamente improbabile, non atteso nella vita del sistema
2	Remoto: non dovrebbe accadere nella vita del sistema
3	Poco probabile: atteso al più una volta nella vita del sistema
4	Probabile: atteso poche volte nella vita del sistema
5	Inatteso: atteso più volte nella vita del sistema

Tabella 4: Classificazione per Danno

DANNO		
D	**Entità**	**Descrizione del danno**
1	Trascurabile	Nessun danno alle persone, funzioni di sicurezza completamente disponibili
2	Minore	Danni lievi alle persone e/o perdita parziale delle funzioni di sicurezza
3	Severo	Danni gravi alle persone e/o perdita completa delle funzioni di sicurezza
4	Critico	Decessi tra il personale di impianto e/o perdita completa delle funzioni di sicurezza
5	Catastrofico	Elevato numero di decessi, anche tra la popolazione esterna e distruzione dell'impianto.

Nell'associare le stime di Frequenza e Danno ai singoli eventi si procede con le seguenti ipotesi:

- <u>per le funzioni operative:</u>
  la **frequenza** si stima con riferimento alla causa di maggior frequenza in grado di generare la deviazione della funzione stessa;
  il **danno** viene stimato nell'ipotesi che le salvaguardie presenti intervengano correttamente.
- <u>per le funzioni di protezione/sicurezza:</u>
  la **frequenza** si stima considerando l'accadimento contemporaneo dei due eventi qui oltre indicati:
  1) la frequenza relativa alla causa di maggior frequenza che fa perdere la funzione di protezione/sicurezza e contemporaneamente,
  2) l'intervento di un'anomalia nel processo che richieda l'intervento della funzione di protezione/sicurezza stessa.

  il **danno** viene stimato tenendo conto che la funzione di protezione/sicurezza non è disponibile.

refined. The fourth edition is directed towards simplifying the index calculation.

The fourth edition contains, in addition, an evaluation of the Maximum Probable Property Damage (MPPD), which is determined from the Fire and Explosion Index (F & EI). It also introduces a Toxicity Index (TI), which is determined separately.

The procedure for calculating the F & EI and the MPPD is shown in *Figure 8.5*.

The *Guide* is intended to apply only to process conditions and not to auxiliary units such as fired heaters, power generating plants, plant water systems, control rooms and office buildings, but it can be applied to bench-scale laboratories and pilot plants.

The F & EI is determined separately for the several units of the process. The Guide states

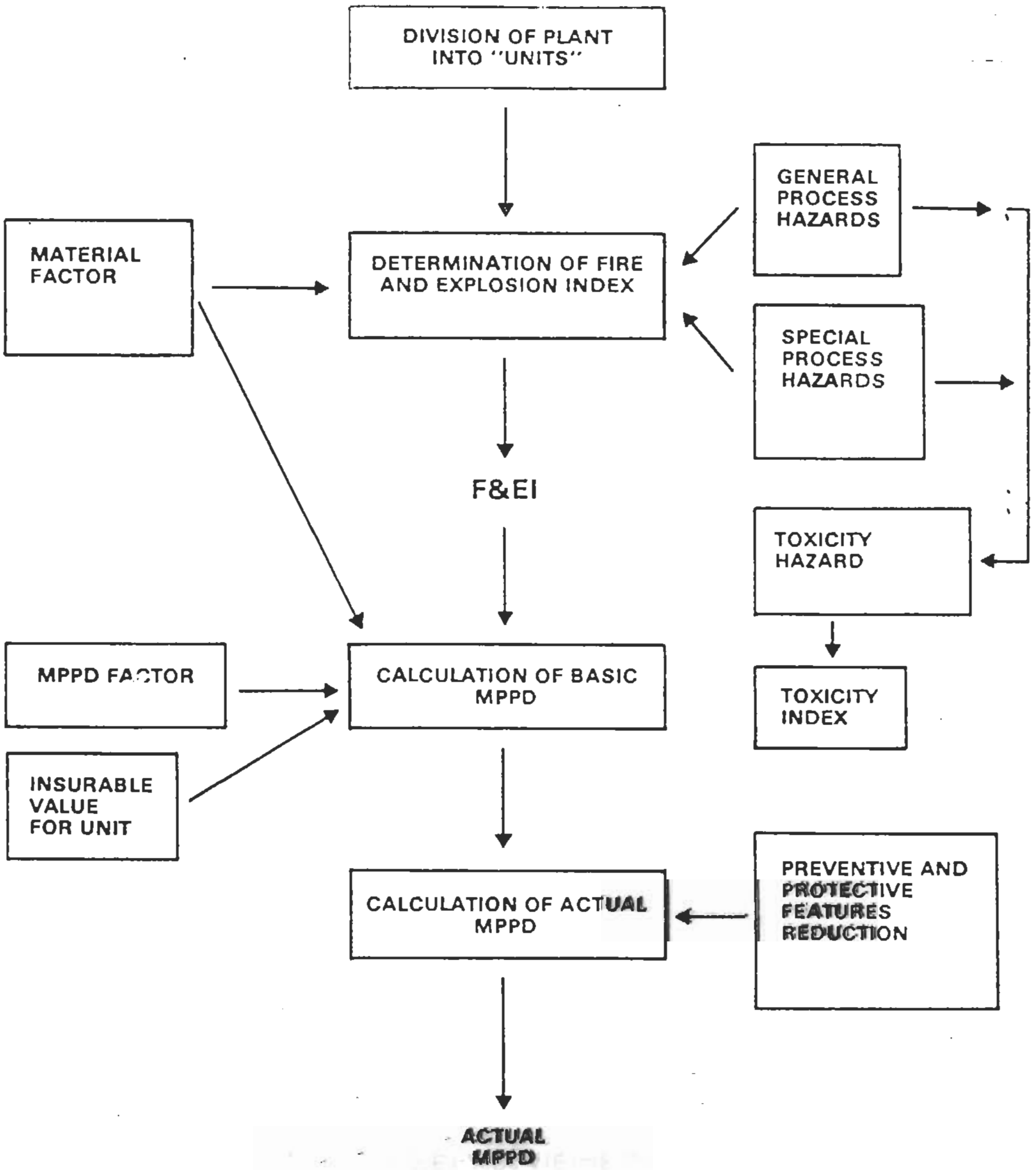


Figure 8.5 Procedure for calculating Fire and Explosion Index and Maximum Probable Property Damage (Dow Chemical Company, 1976)

'A "unit" is defined as a part of a plant that can be readily and locally characterised as a separate entity. Generally a "unit" consists of a segment of the overall process. In some instances, it may consist of a portion of a plant that is separated from the remainder by distance or by fire and/or barrier walls. In others, it may be an area in which a particular hazard exists.'

In evaluating tank farms the storage of individual items should be treated separately. In evaluating plants handling combustible dusts the division of the plant into units demands particular care.

The F & EI is a number which indicates the fire and/or explosion hazard of the particular unit. The factors which are used in calculating this index are

(1) Material Factor;
(2) General Process Hazards;
(3) Special Process Hazards.

The Material Factor (MF) is a measure of the energy potential of the most hazardous material or mixture of materials present in the unit in sufficient quantity actually to present the hazard. The MF is a number in the range from 1 to 40 and is determined using only two properties, the flammability and the reactivity.

For substances for which there is an NFPA fire rating N_f and reactivity rating N_r the MF is obtained from these as follows:

	Material Factor				
N_r	0	1	2	3	4
N_f					
0	0	14	24	29	40
1	4	14	24	29	40
2	10	14	24	29	40
3	16	16	24	29	40
4	21	21	24	29	40

Thus for ethylene oxide with $N_f = 4$, $N_r = 3$, MF = 29.

The fire and reactivity ratings and MFs of selected chemicals are given in *Table 8.8*.

For substances for which there is no NFPA classification the following method is applied. For flammability rating use is made of the flash point or of the factor H_{cv}. This latter factor is calculated by multiplying the heat of combustion (kcal/mol) by the vapour pressure at 80°F (atm), taking a vapour pressure of 1.0 for materials boiling below 80°F. For reactivity rating

Table 8.8 Dow Fire and Explosion Index: Material Factors for selected chemicals (Dow Chemical Company, 1976)

	Heat of combustion[a] ΔH_c (BTU/lb)	*NFPA classification* health N_h	fire N_f	reactivity N_r	*Material Factor* MF
Acetone	12 300	1	3	0	16
Acetylene	20 700	1	4	3	29
Ammonia	8 000	3	1	0	4
Benzene	17 300	2	3	0	16
Butane	19 700	1	4	0	21
Carbon disulphide	6 100	2	3	0	16
Carbon monoxide	4 300	2	4	0	21
Cyclohexane	18 700	1	3	0	16
Ethane	20 400	1	4	0	21
Ethylene	20 800	1	4	2	24
Ethylene dichloride	4 600	2	3	0	16
Ethylene oxide	11 700	2	4	3	29
Hydrogen	51 600	0	4	0	21
Methane	21 500	1	4	0	21
Propane	19 900	1	4	0	21
Propylene	19 700	1	4	1	21
Styrene	17 400	2	3	2	24
Toluene	17 400	2	3	0	16
Vinyl chloride	8 000	2	4	1	21

The following are oxidizing materials which have been assigned Material Factor values based on N_r or, where no N_r is available, an arbitrary value has been assigned:

	N_h	N_f	N_r	MF
Ammonium nitrate	2	0	3	29
Chlorine	3			16
Oxygen				14

[a] This is the net heat of combustion, which is the value obtained when the water formed is considered to be in the vapour state.

use is made of the decomposition temperature T_d, which is computed from chemical structure thermal data. The relations applied are

Flash point (°F)	H_{cv}	N_f	T_d (K)	N_r
None	$< 10^{-5}$	0	< 830	0
> 200	10^{-5}–0.6	1 and	830–935	1
100–200	0.6–10	2	935–1010	2
0–100	10–150	3	1010–1080	3
< 0	> 150	4	> 1080	4

The *Guide* gives the following example of this method. For propylene oxide

Molecular weight	58
Flash point	< −20°F
Vapour pressure (27°C)	566 mmHg
Heat of combustion	13 200 BTU/lb
Decomposition temperature	675°C

Then

Flash point < −20°F $\quad N_f = 4$

$H_{cv} = 316 \qquad N_f = 4$ check

$T_d = 948$ K $\qquad N_r = 2$

Hence

Material Factor = 24

In about a third of cases this method will differ from the NFPA rating by one unit, but this is not to be considered significant.

The MF for dusts is determined by a separate method. The approach is based on the explosion severity of the dust as determined by the Bureau of Mines method. This explosion severity is the product of the maximum pressure and maximum rate of pressure rise in the test relative to those of Pittsburgh coal dust. For the latter dust

Maximum pressure = 90 psi

Maximum rate of pressure rise = 2300 psi/s

This dust is assigned the following MF

Material Factor = 10

The MF for another dust is obtained by scaling up from that for Pittsburgh coal dust.

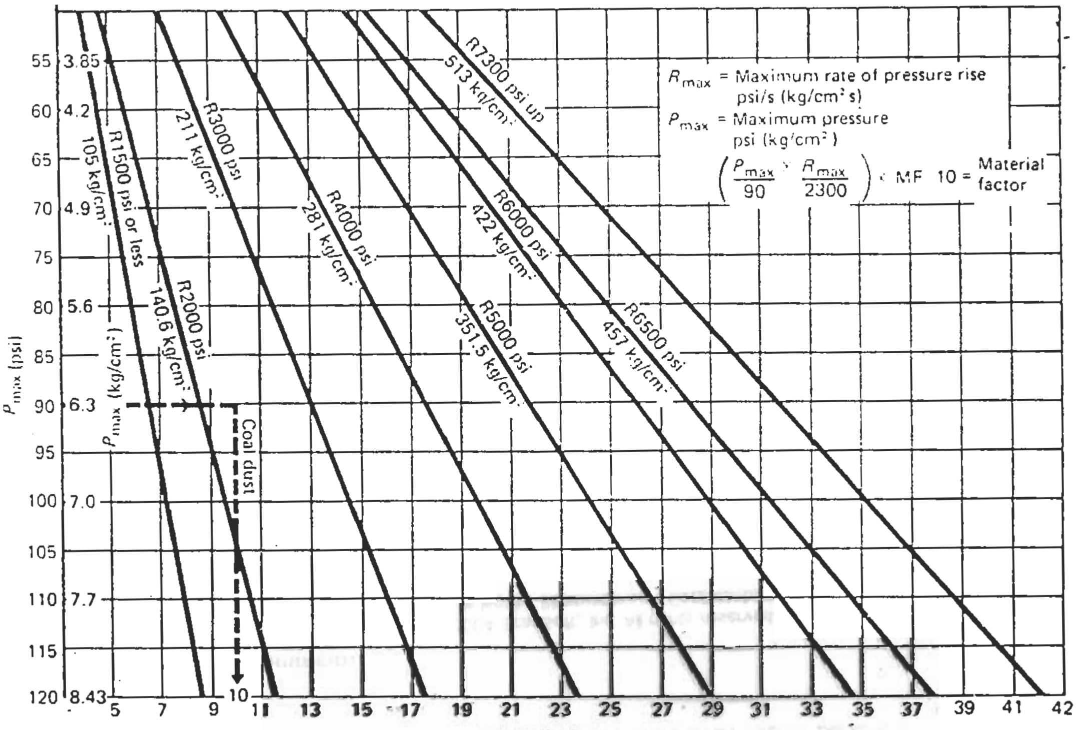


Figure 8.6 Dow Fire and Explosion Index: Material Factor for combustible dusts (**Dow Chemical Company,** 1976)

The *Guide* gives the following example. For alpha cellulose

Maximum pressure = 117 psi
Maximum rate of pressure rise = 8000 psi/s

Hence

$$\text{Material Factor} = \frac{117}{90} \times \frac{8000}{2300} \times 10 = 45.2$$

Alternatively, it is considered adequate to use the MF obtained from *Figure 8.6*.

This MF should be used only for dusts in process. For dusts in storage the heat of combustion method should be used.

The General Process Hazards (GPH) and Special Process Hazards (SPH) are taken into account as penalties which are applied to the Material Factor

$$\text{F \& EI} = \text{MF} \times \left(\frac{100 + \text{GPH}}{100}\right) \times \left(\frac{100 + \text{SPH}}{100}\right) \tag{8.8.1}$$

The penalties applicable to GPHs are shown in *Table 8.9* and the penalties applicable to SPHs are shown in *Table 8.10*.

The Toxicity Index is included for the purpose of evaluating the process exposure level for toxicity hazard. It is defined as

$$\text{TI} = \frac{T_h}{100}\left(\frac{P + S}{100}\right) \tag{8.8.2}$$

where T_h is the factor for the most hazardous material in the process that is present in an appreciable quantity with the lowest Threshold Limit Value (TLV); P the total GPH penalties used; and S the total SPH penalties used.

The T_h factor is obtained from the NFPA health rating N_h as follows:

N_h	T_h
0	0
1	50
2	125
3	250
4	325

Values of N_h for selected chemicals are given in *Table 8.8*. In some cases the TLV of a material is not

Table 8.9 Dow Fire and Explosion Index: penalties for General Process Hazards (Dow Chemical Company, 1976)

A Exothermic reactions:

1 Hydrogenation, hydrolysis, aromatization, isomerization, sulphonation and neutralization = 30% penalty

2 Alkylation, amination by ammonolysis, condensation, oxidation[(a)] and polymerization = 50% penalty

3 Halogenation = 75% penalty

4 Nitration = 125% penalty

B Endothermic reactions:

Calcination, electrolysis, pyrolysis and cracking = 20% penalty

C Material handling and transfer:

1 Loading and unloading of Class I flammable liquids or LPG (flash point less than 100°F) = 50% penalty

2 Use of centrifuges, batch mixing in open containers, multiplicity of reactions in same equipment = 50% penalty

3 Processing combustible dusts: grinding, blending, bagging, filters or drying = 50% penalty

4 Indoor warehousing and storage:
Class II combustible liquids = 25% penalty
Combustible solids = 75% penalty
Class I flammable liquids = 100% penalty

D Enclosed process units:

Processing flammable liquids or gases or location of dust collectors in buildings = 30% penalty

(a) In oxidation reactions involving vigorous oxidizing agents such as chlorates, perchlorates, permanganates, hypochlorous acid and salts, sodium chlorite, chlorine dioxide, nitric acid, inorganic peroxides or nitrogen tetroxide = 100% penalty.

Table 8.10 Dow Fire and Explosion Index: penalties for Special Process Hazards (Dow Chemical Company, 1976)

A Process temperature:

1 Apply penalty when process or handling conditions are above flash point of material = 25 % penalty

2 Apply penalty when above conditions are in excess of boiling point = 60 % penalty

3 Materials such as hexane, fuel oil #1 and carbon disulphide have low autoignition temperatures and can be ignited on hot steam lines = 75 % penalty

B Low pressure:

No penalty is required for processes that operate at atmospheric or sub-atmospheric pressure so that air leaking into the system will not create a hazard. Example: Vacuum distillation of glycols, chlorine compression.

1 When air leaking into the system could create a hazard, apply a 50 % penalty. Example: Handling pyrophoric materials, diolefins with hazard of peroxide formation and catalysed polymerization; 1,3-butadiene with air forms explosive peroxides

2 Hydrogen-collection systems require a 50 % penalty. No penalty if not collected

3 Any vacuum distillation at less than 500 mmHg should be penalized 75 % if air or contaminants leaking into the system could create a hazard

C Operation in or near flammable range:

1 Storage of Class I flammable liquids requires a penalty of 50 % for outdoor tanks (flash point below 100°F (37.8°C))

2 For processes that operate close to the flammable limits or where it is necessary to use instrumentation and/or nitrogen or air purge to stay outside the explosive limits use a 75 % penalty. Examples: Oxidation of toluene to benzoic acid, rubber dissolving, direct oxidation in ethylene oxide process

3 For processes that generally operate in the flammable range, use a 100 % penalty. Examples: Ethylene oxide distillation or storage

D Dust explosion hazard:

Transferring combustible dusts by air to silos, hoppers or dust collectors is a potential exposure for an explosion. Good bonding and grounding of the transfer system are a must to minimize the exposure. However, this does not assure that an ignition source will not be available

The penalty factor is based on the energy potential of the dust—maximum rate of pressure rise (psi/s). As the energy potential goes up, the required penalty factor increases

The maximum rate of pressure rise in psi/s and maximum pressure are used to evaluate a hazardous condition. The following table is a guide for determining the potential exposure based on the maximum rate of pressure rise:

PENALTY CHART

Rating	*Maximum pressure rise* (psi/s)	*Penalty* (%)	*Particle size* (μm)	*Tyler mesh size thru*
Very weak	500 or less	5	175 +	60–80
Weak	500–1300	10	150–175	80–100
Moderate	1300–2000	20	100–150	100–150
Strong	2000–2600	40	75–100	150–200
Severe	2600 up	80	Less than 75	200 +

The particle sizes shown along with their respective mesh sizes are from Hartmann bomb tests of various dusts. *It is not to be assumed that all dusts of these particle sizes will develop the maximum pressure rise indicated.* Generally dust particles > 150 μm will not develop pressure in excess of 1300 psi/s, while particle sizes < 150 μm are much more likely to develop pressure up to 3500 psi/s

Two factors are important in assigning a hazard range for dusts: (1) the particle size, and (2) energy of dusts to be evaluated (maximum rate of pressure rise)

The 1976 revised NFPA 68, Vol. 14, *Explosion Venting Guide* has established three classes of dusts according to maximum rate of pressure rise as follows: ST-1 up to 7300 psi/s (513 kg/cm^2 s); ST-2 7300–22 000 psi/s (513–1547.8 kg/cm^2 s); ST-3 above 22 000 psi/s (1547.8 kg/cm^2 s). A required vent area guide for each dust class is shown in the Standard. It should be recognized that 90 % of all dusts do not exceed the 7300 psi/s rate of pressure rise y, 1976)

lty

d ca

air leaking into

pyrophoric
e with air forms

eaking into the

ow 100°F

tation and/or
n of toluene to

ylene oxide

or an explosion.
er, this does not

si/s). As the

ous condition.
of pressure rise:

ler mesh
e thru

0–80
0–100
0–150
0–200
0 +

various dusts. *It*
cated. Generally
0 µm are much

gy of dusts to be

s according to
psi/s
ach dust
00 psi/s rate of

Table 8.10—*continued*

E Operating pressure:

Operating pressures above atmospheric pressure require a penalty, which will increase as the operating pressure increases. For a pressure range up to 3000 psig (210 kg/cm^2) a factor is to be used as indicated in *Figure 8.7(a)*

For processes above 3000 psig, the design is outside the range of standard codes, and lens ring joints, cone seals or equivalent closures must be used in flange design. Pressures from 3000 psig to 10 000 psig are penalized 100%; above 10 000 psig use a penalty of 150%. *(Penalties are not applicable to extrusion or moulding operations)*

The penalty curve in *Figure 8.7(a)* is for flammable and combustible liquids and must be corrected for other materials as follows:

1 Highly viscous materials such as tars, bitumen, heavy lubricating or hydraulic oils and asphalts—multiply penalty by 0.70

2 Compressed gases—multiply penalty by 1.2

3 Liquefied flammable gases—multiply penalty by 1.3

F Low temperature:

1 For processes that utilize carbon steel construction and operate between 50 and −20°F add 30%

2 For processes that operate below −20°F add 50%

The purpose is to make allowance for presumed brittleness of ordinary carbon steel. If it is known that the temperature of the steel is above the transition temperature, the penalty is not required

G Quantity of flammable material (*Figures 8.7b* and *8.7c*):

1 In Process (*Figure 8.7b*)

The purpose of this penalty is to recognize the additional exposure to a process unit as quantities of flammables increase

To obtain penalty, multiply pounds of material × BTU per pound to arrive at total BTUs

Enter *Figure 8.7(b)* at corresponding BTUs, go up to curve and across to % penalty

Use quantity of material in largest process vessel or train of process vessels connected together. Shutoff valves which can be actuated from a remote location can be considered to reduce the exposure by half the total volume. Combustible liquids do not receive a penalty unless process temperature is above flash point of material

2 In Storage (*Figure 8.7c*)

When flammable and combustible liquids are in storage, there is a lower level of exposure. This is directly related to the flash point and boiling point of the specific material. Identification of flammable and combustible liquids are as follows:

Class I (flammable) = flash point below 100°C (37.8°C) and vapour pressure not exceeding 40 psia at 100°F

Class II (combustible) = flash point at or above 100°F and below 140°F (60°C)

Class IIIA (combustible) = flash point at or above 140°C and below 200°F (93.4°C)

Class IIIB (combustible) = flash point at or above 200°F

There is no penalty required for Class IIIA and IIIB materials in storage

The penalty arrived at in this section relates to the total BTUs available in any one tank and is in addition to other penalties that have been applied

There are three curves in *Figure 8.7(c)*: C for Class II combustible liquids, B for Class I flammable liquids and A for materials with a vapour pressure in excess of 40 psia at 100°F (37.8°C), which includes liquefied gases

The penalty is based on the total BTUs in any single storage vessel. To obtain penalty, multiply pounds of material × BTU/lb to get total BTUs. Enter *Figure 8.7(c)* at corresponding BTUs, go up to curve which represents material and read across for % penalty

Examples: 100M gal styrene = 100M × 7.5 × 17.4M = 13 × 10^9 = 86% penalty
100M gal diethyl benzene = 100M × 7.5 × 18M = 13.5 × 10^9 = 57% penalty

(continued on page 158)

Table 8.10—*continued*

3 Combustible solids

Figure 8.7(d) provides an approach to obtaining a penalty factor for handling, processing and storage of combustible solids. There is a variable range of densities per cubic foot and BTUs per pound of solids, for example:

	lb/ft³	BTU/lb
Magnesium	109	10 600
Paper	58	7 500
Wood	38–48	7 500
Polyethylene	32	20 100
Methocel®, cellulose ethers	25	6 500

The curves were developed to account for total pounds in storage or process and the BTUs available

To determine the penalty, it is necessary to calculate the number of pounds of material involved. The total pounds are then correlated to the proper BTU curve

A = 12M BTU/lb and over

B = under 12M BTU/lb

Example: 150M ft³ of urethane is 270M lb. Enter chart at 270M and go up to curve A (since BTU per lb of urethane is more than 12M, penalty for this quantity is 40%)

H Corrosion and erosion hazards:

These factors should be assessed both from internal and external corrosion. Some areas to consider are: influence of minor impurities in the process fluid on corrosion; external corrosion from breakdown in paint; resistant linings (plastics, brick, etc.) exposure to breakdown at seams, joints or pinholes. Apply the following penalties:

1 Corrosion rate less than 0.5 mm/year with risk of pitting or local erosion = 10%

2 Corrosion rate over 0.5 mm and less than 1 mm/year = 20%

3 Corrosion rate over 1 mm/year = 50%

J Leakage—joints and packing:

Gaskets, sealing of joints or shafts and packing can be a source of leaks particularly where thermal and pressure cycling occurs. A penalty factor should be selected according to the design and materials chosen for these items as follows:

1 No penalty required for welded joints and bellows assemblies or double mechanical seals for pumps

2 Pump and gland seals likely to give some leakages of a minor nature = 10%

3 Processes known to give regular leakage problems on pumps and flange joints = 20%

4 Process fluids penetrating in nature, abrasive slurries which cause continuous problems of sealing = 40%

---

consistent with the N_h rating and where this is so the following guide is used to calculate the T_h factor:

	add to T_h factor
TLV $\leqslant$ 5 ppm	125
5 ppm < TLV $\leqslant$ 50 ppm	75
50 ppm < TLV $\leqslant$ 100 ppm	50

The *Guide* gives a number of examples of the determination of the F & EI and the Toxicity Index. *Figure 8.8* shows one of these examples for ethane and propane in the furnace/quench unit of a light hydrocarbon processing plant.

Units are classified according to the value of the F & EI. The following classification is used:

F & EI	*Degree of hazard*
1–50	Light
51–81	Moderate
82–107	Intermediate
108–133	Heavy
134 up	Severe

As already stated, the object of the F & EI is to provide guidance on the degree of fire protection required. The fire protection features recommended in

of
, for

total pounds

lb of

re: influence of
stant linings
es:

d pressure
nese items as

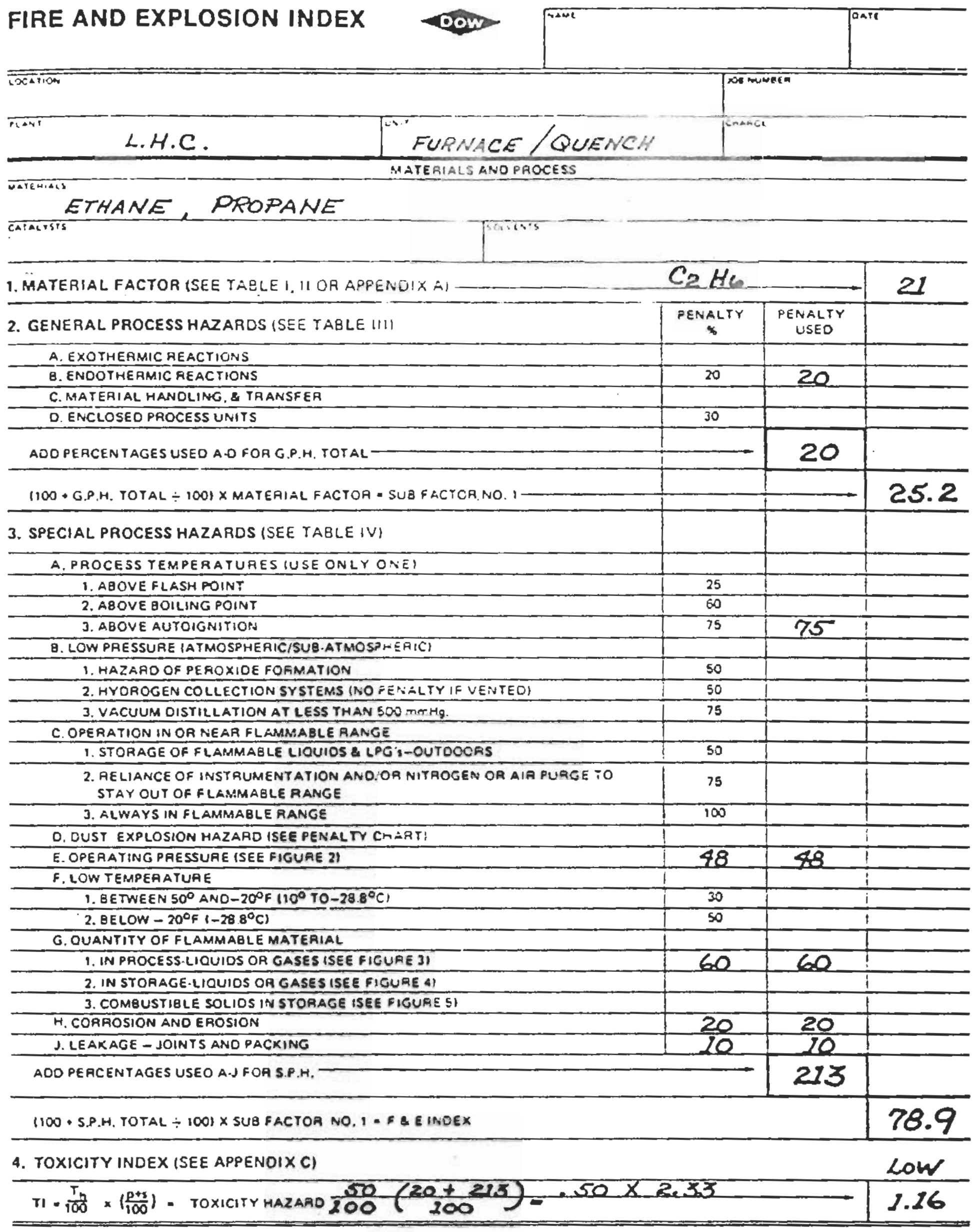
ps

= 40%

e value of the
used:

d

e F & EI is to
fire protection
commended in



FIRE AND EXPLOSION INDEX

NAME

DATE

LOCATION

JOB NUMBER

PLANT L.H.C.

UNIT FURNACE / QUENCH

CHARGE

MATERIALS AND PROCESS

MATERIALS ETHANE , PROPANE

CATALYSTS

SOLVENTS

1. MATERIAL FACTOR (SEE TABLE I, II OR APPENDIX A) C_2H_6 →			21
2. GENERAL PROCESS HAZARDS (SEE TABLE III)	PENALTY %	PENALTY USED	
A. EXOTHERMIC REACTIONS			
B. ENDOTHERMIC REACTIONS	20	20	
C. MATERIAL HANDLING, & TRANSFER			
D. ENCLOSED PROCESS UNITS	30		
ADD PERCENTAGES USED A-D FOR G.P.H. TOTAL →		20	
(100 + G.P.H. TOTAL ÷ 100) X MATERIAL FACTOR = SUB FACTOR NO. 1 →			25.2
3. SPECIAL PROCESS HAZARDS (SEE TABLE IV)			
A. PROCESS TEMPERATURES (USE ONLY ONE)			
1. ABOVE FLASH POINT	25		
2. ABOVE BOILING POINT	60		
3. ABOVE AUTOIGNITION	75	75	
B. LOW PRESSURE (ATMOSPHERIC/SUB-ATMOSPHERIC)			
1. HAZARD OF PEROXIDE FORMATION	50		
2. HYDROGEN COLLECTION SYSTEMS (NO PENALTY IF VENTED)	50		
3. VACUUM DISTILLATION AT LESS THAN 500 mmHg.	75		
C. OPERATION IN OR NEAR FLAMMABLE RANGE			
1. STORAGE OF FLAMMABLE LIQUIDS & LPG's—OUTDOORS	50		
2. RELIANCE OF INSTRUMENTATION AND/OR NITROGEN OR AIR PURGE TO STAY OUT OF FLAMMABLE RANGE	75		
3. ALWAYS IN FLAMMABLE RANGE	100		
D. DUST EXPLOSION HAZARD (SEE PENALTY CHART)			
E. OPERATING PRESSURE (SEE FIGURE 2)	48	48	
F. LOW TEMPERATURE			
1. BETWEEN 50° AND −20°F (10° TO −28.8°C)	30		
2. BELOW − 20°F (−28.8°C)	50		
G. QUANTITY OF FLAMMABLE MATERIAL			
1. IN PROCESS-LIQUIDS OR GASES (SEE FIGURE 3)	60	60	
2. IN STORAGE-LIQUIDS OR GASES (SEE FIGURE 4)			
3. COMBUSTIBLE SOLIDS IN STORAGE (SEE FIGURE 5)			
H. CORROSION AND EROSION	20	20	
J. LEAKAGE — JOINTS AND PACKING	10	10	
ADD PERCENTAGES USED A-J FOR S.P.H. →		213	
(100 + S.P.H. TOTAL ÷ 100) X SUB FACTOR NO. 1 = F & E INDEX			78.9
4. TOXICITY INDEX (SEE APPENDIX C)			LOW
$TI = \frac{T_h}{100} \times \left(\frac{p+s}{100}\right) =$ TOXICITY HAZARD $\frac{50}{100}\left(\frac{20+213}{100}\right) = .50 \times 2.33$ →			1.16

Figure 8.8 Dow Fire and Explosion Index: assessment form showing illustrative calculation (Dow Chemical Company, 1976)