APPENDIX 15

Application of MIMAH and MIRAS:
A fictitious example

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1. Introduction

This appendix presents a fictitious example of application of MIMAH and MIRAS. These methodologies are presented in the main report.

In this fictitious example, only a pressure storage of ethylene oxide and the associated critical event CE7 "Breach on shell in liquid phase" will be fully detailed.

All the given data are reasonably realistic.

2. MIMAH step 1: Collect needed information

Collect general data about the plant in order to have an overview of the plant and of the processes:
- Plant layout
- Brief description of processes
- Brief description of equipment and pipes
All these data are supposed to be available.

3. MIMAH step 2: Identify the potentially hazardous equipment in the plant

On the basis of information collected in step 1, a list of the hazardous substances present in the plant, having one or several risk phrases mentioned in the typology of hazardous substances, and a list of equipment containing these substances are drawn up. It is also necessary to determine which is the type of equipment among the 16 types defined in the typology of equipment and which is the physical state of the substance in the equipment.

The result of this step 2 is the Table 1 with the following (fictitious) data (only the substance "ethylene oxide" is fully considered in the example):

<table>
<thead>
<tr>
<th>Name of the substance</th>
<th>Risk phrases</th>
<th>Name of the equipment</th>
<th>Type of equipment</th>
<th>State of the substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substance 1</td>
<td>R11</td>
<td>D-283</td>
<td>EQ6: Atmospheric storage</td>
<td>Liquid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stream 2</td>
<td>EQ10: Pipe</td>
<td>Liquid</td>
</tr>
<tr>
<td>Substance 2</td>
<td>R23</td>
<td>T-305</td>
<td>EQ7: Cryogenic storage</td>
<td>Liquid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stream 5</td>
<td>EQ10: Pipe</td>
<td>Gas</td>
</tr>
<tr>
<td>Substance 3</td>
<td>R26</td>
<td>R-102</td>
<td>EQ12: Equipment involving chemical reaction</td>
<td>Gas</td>
</tr>
</tbody>
</table>
4. MIMAH step 3: Select relevant hazardous equipment

In this step, the relevant hazardous equipment are selected in applying the "method for the selection of equipment to be studied", described in the appendix 2.

To use this method, the following data are needed for each equipment identified as potentially hazardous in the step2:

- Name of the equipment
- Type of equipment
- Substance handled
- Physical state
- Boiling temperature (in °C)
- Service temperature (in °C)
- Risk phrases
- Hazardous classification
- Mass contained in the equipment (in kg) or, for flow through equipment (as pipes), the mass released in 10 minutes

It is then possible to build a table with these data and the calculations required by the method (see the example presented in Table 2).
Table 2: Application of the method for the selection of relevant hazardous equipment

The result of this method is the selection of relevant hazardous equipment for which the mass of substance is higher or equal to the mass threshold. The threshold is defined according to the hazardous properties of the substance, its physical state and it can be adjusted according to its possibility of vaporisation and eventually the location of the equipment with respect to another hazardous equipment in case of possible domino effects.
Let us note that, in this fictitious example, it was supposed that the reference mass has to be adjusted in case of domino effects only for the first equipment. Let us also note that the "contained" quantity for the pipes corresponds to the mass released in ten minutes.

5. **MIMAH step 4: For each selected equipment, associate critical events**

For each equipment selected in the step3, some critical events can be associated.

To simplify the example of application, only the **pressure storage of ethylene oxide**, selected as relevant hazardous equipment in the step2, will be studied according to MIMAH.

In order to determine the critical events associated to the selected equipment and to build the generic bowties in the following steps, the data used are the following ones:

- The equipment chosen is a storage vessel containing ethylene oxide.
- The equipment type is "pressure storage" (EQ4).
- The substance physical state is "Two-phase" (STAT3).
- The risk phrases associated with ethylene oxide are:
  - R12: Extremely flammable
  - R23: Toxic by inhalation, in contact with skin and if swallowed

As explained in the appendix 3, the compatibility between the equipment type and the substance physical state must be checked. In our case, it can be seen in the matrix STAT-EQ that STAT3 (two-phase) and EQ4 (pressure storage) are compatible.

As explained in the appendix 3, critical events likely to occur on pressure storage are given in the matrix EQ-CE. Those likely to occur with a substance in two-phase state are given in the matrix STAT-CE. The combination of these information gives as result that **6 critical events** must be retained and associated with the pressure storage of ethylene oxide (two-phase state substance)

- CE5: start of fire (LPI)
- CE6: breach on shell in vapour phase
- CE7: breach on the shell in liquid phase
- CE8: leak from liquid pipe
- CE9: leak from gas pipe
- CE10: catastrophic rupture
The selection of these critical events is also shown in Table 3.

**Table 3: critical events retained**

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Two-phase</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ4</td>
<td>STA3</td>
<td></td>
</tr>
</tbody>
</table>

6. **MIMAH step 5: For each critical event, build a fault tree**

For each critical event associated with a selected hazardous equipment, a fault tree can be built.

With the help of table 6 given in the main report, it is possible to choose among the 14 generic fault trees, given in the appendix 4, which fault trees must be considered according to the critical event studied. If several fault trees are mentioned for a single critical event, each fault tree must be taken into account.

To simplify further the example of application, only the critical event "**CE7: Breach on shell in liquid phase**" will be considered. For this critical event, three generic fault trees must be considered:

- FT Large breach on shell
- FT Medium breach on shell
- FT Small breach on shell

The three generic fault trees, detailed in the appendix 4, should be considered as checklists of possible causes of the critical event CE7. They should be modified (add or remove causes) to become adapted to the actual characteristics of the equipment and after discussion with the industrialists.

For the example of application, the three adapted fault trees were built. They are presented in Figure 1, Figure 2 and Figure 3. In these fault trees, there are only "OR" gates. They are not drawn.

These fault trees, while fictitious and simplified, are realistic ones.
Overfilling vessel causes overpressure
- Internal overpressure (liquid)
- Filled beyond normal level
- Excessive liquid transfer (due to human error)
- Natural causes (snow, ice, wind...)
- Loose placed on equipment
- Support fails
- Overloading
- Support fails
- High amplitude vibrations
- Shear stress
- Dilatation
- Domino effect (fire)
- Special work / Hot work
- Natural causes (snow, ice, wind...)
- Loads placed on equipment
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact
- Missiles (domino effect)
- Inappropriate material
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Design error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Design error
- Human error
- Wrong material used
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
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- Inappropriate assembling
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- Brittle rupture
- Impact by bullet
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- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
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- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
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- Specifications not met during building
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- Brittle rupture
- Impact by bullet
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- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Design error
- Human error
- Specifications not met during building
- Wrong specifications
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembling procedures
- Design error
- Human error
- Inappropriate material
- Insufficient structure initial mechanical properties
- Brittle rupture
- Impact by bullet
- Inappropriate dimensions
- Inappropriate assembling
- Inappropriate assembling procedure
- Wrong assembling procedure
- Non respect of assembly
- Figure 1: Adapted fault tree for "Large Breach on shell"
Figure 2: Adapted fault tree for "Medium breach on shell"
7. MIMAH step 6: For each critical event, build an event tree

For each critical event associated with a selected hazardous equipment, an event tree is built with an automatic method based on matrices (see appendix 5). The data used in this method are the critical event considered, the physical state and the hazardous properties of the substance.

7.1 Construction of the event tree without taking into account the risk phrases:

For the critical event "CE7: Breach on shell in liquid phase" chosen as example and, for which three fault trees have been generated (see the precedent step, the step 6), only one event tree has to be built.

The construction of this event tree is summarised below (see also appendix 5).

First of all, the matrix CE-STAT-SCE must be used to choose the secondary critical events to be retained. It can be seen that two SCE must be selected: SCE3 "pool formation" and SCE7 "Two-phase jet". Secondly, the matrix SCE-TCE gives information about the TCE (tertiary critical events) retained. There are three TCE retained for SCE3 "Pool formation": TCE4 pool ignited, TCE5 gas dispersion and TCE11 pool not ignited / pool dispersion. There are two TCE retained for SCE7 "Two-phase jet": TCE5 "Gas dispersion" and TCE9 "Two-phase jet ignited". Finally, the matrix TCE-DP gives the dangerous phenomena for each TCE:
for TCE4: DP1 poolfire, DP6 toxic cloud and DP11 environmental damage
for TCE5: DP4 VCE, DP5 flashfire, DP6 toxic cloud and DP11 environmental damage
for TCE11: DP11 environmental damage
for TCE9: DP3 jetfire, DP6 toxic cloud and DP11 environmental damage

The event tree presented in Figure 4 is then obtained ("AND" and "OR" gates are implicitly present in event trees but are not drawn at this stage).

Figure 4: event tree for the CE7 "breach on shell in liquid phase" without taking into account the risk phrases
7.2 Construction of the event tree taking into account the risk phrases:

Depending on the risk phrases associated with the hazardous substances, some dangerous phenomena may be deleted from the event trees. Additional conditions have to be used for that purpose (see appendix 5).

As mentioned before, the risk phrases associated with ethylene oxide are:

- R12: Extremely Flammable
- R23: Toxic by inhalation, in contact with skin and if swallowed

The links between risk phrases and dangerous phenomena lead, in this case, to the additional following rules:

**R 12 - Extremely flammable.**

- DP: poolfire, tankfire, jetfire, VCE, flashfire, fireball
- DP1 and DP2 and DP3 and DP4 and DP5 and DP10

**R 23 - Toxic by inhalation.**

- DP: toxic cloud

This DP will be selected only in the following case:

- it should be noted that, in the event trees, the DP "toxic cloud" can occur after a release of a toxic substance, or as a consequence of a fire if the substance is likely to emit toxic vapours when it is in a fire (R101 – R100). Here, for the risk phrase R23, the substance is a toxic one and not a secondary product resulting from a fire, and thus the DP "toxic cloud" must only be selected if a release and dispersion of a toxic substance is considered. It means that the TCE must be either TCE5 (gas dispersion) or TCE14 (dust dispersion).

\[
DP6 \text{ if } TCE5 \text{ or } TCE14
\]

With these rules, it is possible to examine the event trees built without taking into account the risk phrases (see Figure 4), and to delete some branches to give the new event trees with the influence of the risk phrases (shown in Figure 5). In the example, for the critical event "CE7: Breach on shell in liquid phase" (Figure 4), the dangerous phenomenon "Environmental damage" is no more retained.
8. MIMAH step 7: For each selected equipment, build the complete bow-tie

The MIMAH methodology ends with the construction of complete bow-ties for each selected equipment.

For the **pressure storage of ethylene oxide** and the critical event **CE7 "Breach on shell in liquid phase"**, each bow-tie is obtained by the association of the critical event, its corresponding fault tree on the left (see chapter 6) and its corresponding event tree on the right (see chapter 7). For this example, the number of bow-ties is equal to three, i.e. the number of fault trees developed for the studied critical event (see chapter 7).

The three complete bowtie are given in Figure 6, Figure 7 and Figure 8.

The Figure 6 corresponds to the bowtie for a large breach on shell in liquid phase.

The Figure 7 corresponds to the bowtie for a medium breach on shell in liquid phase.

The Figure 8 corresponds to the bowtie for a small breach on shell in liquid phase.
Figure 6: Complete bowtie for "Large breach on shell in liquid phase" taking into account the risk phrases
Figure 7: Complete bowtie for "Medium breach on shell in liquid phase" taking into account the risk phrases
Degradation of mechanical properties
Small breach on shell in liquid phase

Pool formation
Gas dispersion

Pool ignited
Flashfire
Toxic cloud
VCE

Two-phase jet
Gas dispersion

Two-phase jet ignited
Flashfire
Toxic cloud
Jetfire

Figure 8: Complete bowtie for "Small breach on shell in liquid phase" taking into account the risk phrases

These bow-ties, result of the whole MIMAH method, present the major accident scenarios, assuming that no safety systems (including safety management systems) are installed or that they are ineffective. They are the basis for the application of the MIRAS methodology.
9. MIRAS Step 1: Collect needed data

Additional data will be required all along the MIRAS steps. The list of information needed is given in Table 4.

Needed data are linked with the step during which they will be used. The reader can choose to collect all the data at the same time, or to collect data progressively when they are needed. We will suppose that all data needed are available.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description of data needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: Collect needed data</td>
<td>See below</td>
</tr>
<tr>
<td>Step 2: Make a choice between step 3 or step 4</td>
<td>No additional data</td>
</tr>
</tbody>
</table>
| Step 3: Calculate the frequency of the critical event by means of the analysis of the fault tree | A meeting with industrialists concerned could be fruitful to achieve this step.  
• Fault trees built during the MIMAH part  
• Initiating events frequencies / probabilities  
• Safety barriers on the fault tree side; to be identified on the basis of the check lists of appendix 8, with the help of Process Instrumentation Diagrams, with the results of risk assessment previously performed (like HAZOP)  
• Information for the evaluation of performance of safety barriers: architecture of the barriers, probability of failure on demand, response time, etc |
| Step 4: Estimate the frequency of the critical event by means of generic critical events frequencies | No additional data                                                                       |
| Step 5: Calculate the frequencies of Dangerous Phenomena | A meeting with industrialists concerned could be fruitful to achieve this step.  
• Event trees built during the MIMAH part  
• Ignition probabilities  
• Safety barriers on the event tree side; to be identified on the basis of the check lists of appendix 8, with the help of Process Instrumentation Diagrams, with the results of risk assessment previously performed (like HAZOP)  
• Information for the evaluation of performance of safety barriers: architecture of the barriers, probability of failure on demand, response time, etc |
| Step 6: Estimate the class of consequences of Dangerous Phenomena | No additional data                                                                       |
We will suppose, in this example, that all needed data can be obtained.

10. **MIRAS Step 2: Make a choice between step 3 or step 4**

Step 3 and step 4 have the same goal: estimate the frequency of the critical event for the considered bow-tie.

In the step 3, a complete analysis of the fault tree, starting from the frequencies (probabilities) of the initiating events and taking into account the influence of safety barriers in order to calculate the frequency of the critical event is made.

Step 4 is an alternative to step 3. If the frequency of the critical event cannot be calculated on the basis of the analysis of the fault tree (step 3), an other possibility is to evaluate it by means of generic critical event frequencies.

In this example, we will only develop the step 3.

11. **MIRAS Step 3: Calculate the frequency of the critical event by means of the analysis of the fault tree**

In this example of application, we will only show how to estimate the frequency of the critical event for the fault tree "large breach on shell in liquid phase", taking into account the initiating events characteristics, the performances and the effects of safety barriers.

11.1 **MIRAS Step 3.A.: Estimate initiating events frequencies (or probabilities)**

The objective of this step is to provide frequency (probability) figures to be placed at the beginning of the fault tree, for the bow-ties studied.

When possible, it is recommended to use plant specific data if they are available. Or, at least, to try to estimate the frequencies of initiating events with the plant staff, with the help of qualitative frequencies given in Table 5.
Table 5: Qualitative definitions of initiating events frequencies

<table>
<thead>
<tr>
<th>FREQUENCY OF OCCURRENCE PER YEAR</th>
<th>CLASS</th>
<th>Qualitative definition</th>
<th>Quantitative definition</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low frequency</td>
<td></td>
<td>Unlikely to occur.</td>
<td>F ≤ 10^{-4} /year</td>
<td>F_4</td>
</tr>
<tr>
<td>Low frequency</td>
<td></td>
<td>The critical event (for the given cause) might happen. It has already happened in similar installations (once by 1000 years)</td>
<td>10^{-4} /year &lt; F ≤ 10^{-3} /year</td>
<td>F_3</td>
</tr>
<tr>
<td>Low frequency</td>
<td></td>
<td>The critical event (for the given cause) might happen. It has already happened in similar installations or on the site (once by 100 years)</td>
<td>10^{-3} /year &lt; F ≤ 10^{-2} /year</td>
<td>F_2</td>
</tr>
<tr>
<td>Possible – High frequency</td>
<td></td>
<td>May happen. Has already happened in the site (once during 10 years)</td>
<td>10^{-2} /year &lt; F ≤ 10^{-1} /year</td>
<td>F_1</td>
</tr>
<tr>
<td>Likely – Very high frequency</td>
<td></td>
<td>Has already happened several times in the site</td>
<td>F ≥ 10^{-1}/year</td>
<td>F_0</td>
</tr>
</tbody>
</table>

If it is not possible to estimate these frequencies, appendix 7 gives an overview of data available for the frequencies (or probabilities) of initiating events.

These frequencies will be expressed in frequency per year. Even if other units could be used, the unit "year^{-1}" will be the more convenient for the following steps.

For the sake of the example, the estimated frequencies of initiating events are written down in the fault tree: "large breach on shell in liquid phase" (see Figure 9).

This fault tree only includes "OR" gates (which are not drawn). It could be seen that, as the case may be, initiating events are undesirable events, direct causes or necessary and sufficient conditions. The estimated frequencies used are invented but remain realistic.
Application of MIMAH and of MIRAS: Example

Overfilling
- vessel causes overpressure
  - internal overpressure (liquid)
    - filled beyond normal level
    - excessive liquid transfer (due to human error)
  - rupture tied to excessive mechanical stress due to external causes
    - overloading
      - support fails
      - high amplitude vibrations
      - shear stress
      - dilatation
        - domino effect (fire)
    - special work / hot work
      - large breach on shell in liquid phase
    - external fire
      - insufficient structure initial mechanical properties
        - brittle rupture
      - impact
        - missiles (domino effect)
        - inappropriate material
          - inappropriate dimensions
          - inappropriate assembling procedure
          - non respect of assembling procedures
  - natural causes (snow, ice, wind, …)
    - loads placed on equipment
    - external fire
    - human error
      - wrong material used
        - specifications not including building
        - wrong specifications
        - wrong assembling procedure
        - non respect of assembling procedures
    - design error
      - insufficient structure initial mechanical properties
        - inappropriate material
    - special work / hot work
  - design error
  - human error

Figure 9: frequencies of initiating events on the fault tree

11.2 MIRAS Step 3.B.: Identify safety functions and safety barriers on the fault tree

Starting from the fault tree built with MIMAH, the objective is to obtain a fault tree on which safety barriers are placed at the right place.

To achieve this goal, it is proposed to review systematically the fault tree.

Each event of a tree, branch per branch, must be examined and the following question should be asked: "Is there a safety barrier which avoids, prevents or controls this event?". If yes, this safety barrier must be placed on the branch. The barrier will be placed upstream of an event if it avoids or prevents this event. If it controls this event, it has to be placed downstream.

This identification can (should) be made with the industrialists (operators, safety officers, …), with the help of "process and instrumentation diagrams" and "flow diagrams" or with any other existing documentation.

A checklist (see appendix 8) of possible safety functions and safety barriers can also be used to define what should be implemented on a new plant or to improve an unsatisfactory safety level in an existing plant.
For the sake of the example, various safety functions and barriers are placed on the fault tree "large breach on shell in liquid phase" (see Figure 10).

**Figure 10: safety functions and barriers on the fault tree**

11.3 MIRAS Step 3.C.: Assessment of the performances of safety barriers

The performances of safety barriers is defined according to three parameters:

- Its **level of confidence** (LC) linked to its probability of failure on demand (PFD).
- Its adequate capacity to take the required action (specific size or volume, physical strength, etc.) or **effectiveness** (E).
- Its **response time** (RT).

The way to assess these parameters is explained in details in appendix 9.

In a first step, the level of confidence assessed with the help of instruction given in appendix 9 is the "design" level of confidence. But the performance of the safety barrier could decrease when time is going. This could occur for the multiple reasons; for example a bad inspection.
program, a loss of knowledge of the operators, the clogging up of some devices… All these reasons can be related to the quality of the safety management system.

In a second step, it is thus needed to assess the quality of the safety management system and its influence on the performances of the safety barriers. Details about the modifications of the performances of the safety barriers according to the quality of the safety management system are available in the ARAMIS report related to the safety management system.

In the example of application, only the "design" levels of confidence of the safety barriers were estimated. These levels are written down in the fault tree "Large breach on shell in liquid phase" (see Figure 11).

Figure 11: "design" levels of confidence of safety functions and barriers
Let us make some comments about the barriers used in the example:

- "Design protected" avoid barriers are, in fact, prevention barriers with a very high level of confidence (of course obvious evidence is required). Causes protected by such barriers can be ignored in the calculation of the critical event frequency.

- A domino effect due to a neighbouring fire can be prevented by fire walls erected around equipment. It is supposed, here, that the level of confidence of this barrier is LC2.

- The overfilling of the storage is controlled by an interlock with a high level emergency stop. It is supposed, here, that the level of confidence of this barriers is LC1.

- Operator errors can be prevented through training and operating procedures. The estimated level of confidence of these barriers, at the design level, is supposed to be LC2. The actual level of confidence of these barriers can, of course, be influenced by the quality of the management system.

11.4 MIRAS Step 3.D.: Calculate the frequency of the critical event

After the evaluation of the initiating events characteristics, the identification of the safety barriers and the evaluation of their performances, it is possible, at this stage, to analyse the fault trees in order to calculate the frequency of the associated critical event. The analysis is made by a gate-to-gate method and takes into account the safety barriers on the fault trees.

The ways to take into account the effects of safety barriers are the following ones:

- The "avoid" barriers imply that the event located just downstream is supposed impossible. The corresponding branch will thus not influence the critical event frequency anymore.

- For the "control" and "prevent" barriers, the rule is the following:

If the level of confidence of a barrier on a branch is equal to \( n \), then the frequency of the downstream event on the branch is reduced by a factor \( 10^n \).

The frequencies of the various events in the fault tree and, finally, of the critical event, taking the safety barriers into account, can thus be calculated. The results for the example are presented in Figure 12 (only "OR" gates which are not drawn). In the example, the estimated critical event frequency is \( 4.3 \times 10^{-5} \)/year. This value, which obtained for a fictitious example, seems reasonable.
**Figure 12: Fault tree with the frequency of CE "large breach on shell in liquid phase"**

**12. MIRAS Step 4: Estimate the frequency of the critical event by means of generic critical events frequencies**

If the frequency of the critical event cannot be calculated on the basis of the analysis of the fault tree (step 3), an other possibility is to evaluate it by means of generic critical event frequencies.

This step is not considered in the example.

**13. MIRAS Step 5: Calculate the frequencies of Dangerous Phenomena**

The objective, at this stage, is to proceed step by step in the event tree to obtain, as output, the frequency of each dangerous phenomenon. First of all, the "AND and OR" gates are represented in the event tree. In a second step, the transmission probabilities in the tree have to be assessed. Finally, during the third step, safety barriers related to the event tree side have to be taken into account, both in terms of consequences and frequency of dangerous phenomena.
a) Presentation of "AND and OR" gates in the event tree

In the generic event trees built with the MIMAH methodology (see chapter 7), there is no AND and OR gates explicitly drawn. In fact, these gates are implicitly included in the event trees. These gates must now be drawn (see appendix 11).

**AND gates** are located between an event and its simultaneous consequences (for example a breach on a two-phase storage, under the liquid level, has two consequences occurring simultaneously – a two-phase jet and a pool formation). These outcomes are linked by a AND gate.

**OR gates** appear downstream an event if one of the consequent events may occur and the others not. For example, if we consider the pool formation, a direct ignition can occur and we have then the "pool ignited" phenomenon, and in the other case we have the dispersion of the gas. Events linked by a OR gate are mutually exclusive.

Figure 13 presents the event tree obtained by MIMAH (CE7 "Breach on shell in liquid phase", Figure 5) in which "AND" and "OR" gates have been represented as well as the various transmission (conditional) probabilities they introduce.
Figure 13: Event tree for CE7 with the "AND/OR" gates
b) Evaluation of transmission (conditional) probabilities

When OR gates appear in the event tree, figures for the transmission probabilities linked with these gates must be assessed.

The transmission probabilities to be assessed in the example are the following ones:

- Probability of rain-out (Prain-out)
- Probability of immediate ignition (Pii (R) if rain-out and Pii (TP) if not rain-out)
- Probability of delayed ignition (Pdi)
- Probability of VCE (Pvce)

These transmission probabilities depend on a lot of parameters (see deliverable D.1.C., paragraph 3.11.3), these parameters and these probabilities should be discussed with the industrialists on site.

Some values of these probabilities are proposed in the appendix 12.

For the example, the chosen values (based on the values proposed in the appendix 12) for these transmission probabilities are the following ones:

- Prain-out = 0.5
- Pii (R) = 0.5 (some prevention barriers: e.g. presence of a retention pool and the material is explosion proof)
- Pii (TP) = 0.7 (some prevention barriers: the material is explosion proof)
- Pdi = 0.7 (ignition source type: unloading by lorry)
- Pvce = 2/3 (due to strong obstruction)

c) Influence of safety barriers on the event tree

The objective is now to identify safety barriers on the event tree, and then to quantify their influence.

For the identification of the safety barriers, the method proposed is identical to the one used for the fault tree: it is proposed to review systematically the event tree. Each event of the tree, branch per branch, must be examined and the following question should be asked: "Is there a safety barrier which prevents, controls or limits this event?". If yes, the safety barrier must be placed on the branch. The barrier will generally be placed upstream of an event if it prevents this event. If it controls or limits this event, it has to be placed downstream.

This identification can be made with the industrialists (safety officers, operators, ...), with the help of "process and instrumentation diagrams" and "flow diagrams" or with any other existing documentation.
A checklist (see appendix 8) of possible safety functions and safety barriers can also be used to define what should be implemented on a new plant or to improve an unsatisfactory safety level in an existing plant.

The procedure of evaluation of performances of safety barriers identified is also the same as for the barriers in the fault tree. To be considered as relevant, a barrier must meet the minimum requirements expressed in appendix 9. Then, the level of confidence, the effectiveness and the response time have to be evaluated.

Depending on the type of barrier (prevention, control, limitation), the method to take this barrier into account in the event tree will be different.

The ways to take into account the effects of safety barriers are the following ones:

- In the event tree, the "prevention" barriers are mainly related to the probability of ignition. They do not have to be placed directly in the trees, but serve qualitatively to evaluate the probability of ignition, as showed in the precedent paragraph.

- In the event tree, the "control" barriers introduce a kind of OR gate. One branch concerns the successful action of the barrier, and leads to a safe situation where the accident is under control. The other branch concerns the failure of the safety barrier, allowing the further development of the scenario. The frequency of the event on this branch is equal to the frequency of the event upstream of the barrier, multiplied by $10^{-LC}$ (where LC is the level of confidence of the barrier).

- In the event tree, when the limitation/mitigation barriers are considered, two branches must be built, one if the barrier succeeds and another one, if the barrier fails. Both branches have to be kept in the event tree, because they will lead to different dangerous phenomena, one with less severe consequence but a higher frequency, and the other one with more severe consequence but a lower frequency. The frequencies calculation is linked with the level of confidence of the safety barrier.

For the example of application, we retain only two safety barriers in the event tree:

- A retention bund which limits the extent of the pool (passive barrier, no LC considered but an efficiency of 100% retained)

- The foam injection on the pool after some minutes (the response time depends on the system of leak detection which limits the gas dispersion with a level of confidence, LC2.

Lest us note that the retention bund will only limit the source term leading to "pool fire", "VCE", "flashfire" and "toxic cloud" (the bund limits the evaporation area). That is why, in the event tree, these dangerous phenomena are noted "with limited source term" (this will influence eventually the classes of consequences).

Let us also note that, if it works, the foam injection will limit the potential effects of the pool evaporation (evaporation limited in the time). That is why, in the event tree, some dangerous phenomena are noted "with limited effects".

Finally, if there are no barriers, the dangerous phenomena will be noted "fully developed".
The frequencies of dangerous phenomena taking into account the safety barriers and the transmission probabilities are calculated and indicated on the event tree studied in this example, in Figure 14.

Figure 14: Event tree with the frequencies of dangerous phenomena for the large breach on shell in liquid phase
The output of this step is a list of dangerous phenomena (DP) (see Table 6) associated to the critical event "Large breach on shell in liquid phase". The frequency of each dangerous phenomenon is calculated, and limitations are taken into account (DP with a limited or not limited source term, limitations or not of the effects).

**Table 6: List of dangerous phenomena in the event tree**

<table>
<thead>
<tr>
<th>Dangerous phenomenon</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poolfire with limited source term</td>
<td>1.07.10^{-5}/year</td>
</tr>
<tr>
<td>VCE with limited source term and effects</td>
<td>4.9.10^{-6}/year</td>
</tr>
<tr>
<td>Flashfire with limited source term and effects</td>
<td>2.5.10^{-6}/year</td>
</tr>
<tr>
<td>Toxic cloud with limited source term and effects</td>
<td>3.18.10^{-6}/year</td>
</tr>
<tr>
<td>VCE with limited source term</td>
<td>4.9.10^{-8}/year</td>
</tr>
<tr>
<td>Flashfire with limited source term</td>
<td>2.5.10^{-8}/year</td>
</tr>
<tr>
<td>Toxic cloud with limited source term</td>
<td>3.21.10^{-8}/year</td>
</tr>
<tr>
<td>Fully developed jetfire</td>
<td>1.5.10^{-5}/year</td>
</tr>
<tr>
<td>Fully developed VCE</td>
<td>3.10^{-6}/year</td>
</tr>
<tr>
<td>Fully developed flashfire</td>
<td>1.5.10^{-6}/year</td>
</tr>
<tr>
<td>Fully developed toxic cloud</td>
<td>1.9.10^{-6}/year</td>
</tr>
</tbody>
</table>

These results, while purely fictitious, seems realistic.

**14. MIRAS Step 6: Estimate the class of consequences of Dangerous Phenomena**

The selection of Reference Accident Scenarios is based on the evaluation of the frequency of Dangerous Phenomena, and of their potential consequences. At this stage, it is thus necessary to evaluate roughly the consequences of each Dangerous Phenomenon.

This evaluation of the potential consequences is only qualitative. The qualitative assessment of the consequences of Dangerous Phenomena is based on four classes of consequences defined in Table 7. These classes are defined according to potential consequences in term of domino effects, effects on human targets and effects on the environment. Among the three categories of consequences (human, environmental and domino effects), one takes as final consequences class, the most serious consequences class. This choice is conservative.
Table 7: Class of consequences

<table>
<thead>
<tr>
<th>Domino effect</th>
<th>Effect on human target</th>
<th>Effect on environment</th>
<th>CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>See note under Table 7</td>
<td>No injury or slight injury with no stoppage of work</td>
<td>No action necessary, just watching</td>
<td>C₁</td>
</tr>
<tr>
<td>See note under Table 7</td>
<td>Injury leading to an hospitalisation &gt; 24 hours</td>
<td>Serious effects on environment, requiring local means of intervention</td>
<td>C₂</td>
</tr>
<tr>
<td>See note under Table 7</td>
<td>Irreversible injuries or death inside the site, Reversible injuries outside the site</td>
<td>Effects on environment outside the site, requiring national means</td>
<td>C₃</td>
</tr>
<tr>
<td>See note under Table 7</td>
<td>Irreversible injuries or death outside the site</td>
<td>Irreversible effects on environment outside the site, requiring national means</td>
<td>C₄</td>
</tr>
</tbody>
</table>

Note for domino effects: Let us consider a Dangerous Phenomenon, noted DP1, likely to induce a domino effect and the Dangerous Phenomenon, noted DP2, caused by this domino effect. For example a Vapour Cloud Explosion (DP1) could cause the rupture of a pipe due to the overpressure generated, the leak of flammable liquid and then a poolfire fed by the liquid flowing from the ruptured pipe (DP2). The consequences classes for DP1 and DP2 will be evaluated only on the basis of their potential human and environmental effects. If it appears that the consequence class for DP2 is higher than the consequence class for DP1, then the consequence class for DP1 shall be raised to the consequence class of DP2.

Thus, in the example of application, for each Dangerous Phenomenon identified, a class of consequence was chosen according to the definitions given in Table 7 (or from the rough classes of consequences given in Table 13 of the main report).

The output of this step, as shown in Table 8, is a list of dangerous phenomena (DP) associated to the critical event "large breach on shell in liquid phase", with their frequency and their class of consequences:

Table 8: Frequency and consequences class of dangerous phenomena

<table>
<thead>
<tr>
<th>Dangerous phenomenon</th>
<th>Frequency</th>
<th>Class of consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poolfire with limited source term</td>
<td>1.07.10⁻⁵/year</td>
<td>C2</td>
</tr>
<tr>
<td>VCE with limited source term and effects</td>
<td>4.9.10⁻⁶/year</td>
<td>C3</td>
</tr>
<tr>
<td>Flashfire with limited source term and effects</td>
<td>2.5.10⁻⁶/year</td>
<td>C2</td>
</tr>
</tbody>
</table>
### Application of MIMAH and of MIRAS: Example

<table>
<thead>
<tr>
<th>Dangerous phenomenon</th>
<th>Frequency</th>
<th>Class of consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic cloud with limited source term and effects</td>
<td>$3.18 \times 10^{-6}$/year</td>
<td>C2</td>
</tr>
<tr>
<td>VCE with limited source term</td>
<td>$4.9 \times 10^{-8}$/year</td>
<td>C4</td>
</tr>
<tr>
<td>Flashfire with limited source term</td>
<td>$2.5 \times 10^{-8}$/year</td>
<td>C3</td>
</tr>
<tr>
<td>Toxic cloud with limited source term</td>
<td>$3.21 \times 10^{-8}$/year</td>
<td>C3</td>
</tr>
<tr>
<td>Fully developed jetfire</td>
<td>$1.5 \times 10^{-5}$/year</td>
<td>C2</td>
</tr>
<tr>
<td>Fully developed VCE</td>
<td>$3.10^{-6}$/year</td>
<td>C4</td>
</tr>
<tr>
<td>Fully developed flashfire</td>
<td>$1.5 \times 10^{-6}$/year</td>
<td>C3</td>
</tr>
<tr>
<td>Fully developed toxic cloud</td>
<td>$1.9 \times 10^{-6}$/year</td>
<td>C3</td>
</tr>
</tbody>
</table>

### 15. MIRAS Step 7: Use the risk matrix to select Reference Accident Scenarios

The objective of this step is to select the Reference Accident Scenarios which will have to be modelled in the calculation of the severity.

The tool used here is a Risk Matrix (Figure 15). The X-axis corresponds to the four consequence classes, and the Y-axis corresponds to the frequency of the Dangerous Phenomena. Three zones are defined in this matrix:

- The lower green zone ("Negligible effects" zone) corresponds to dangerous phenomena with a low enough frequency and/or consequences which will probably have no actual effects on the severity.

- The intermediate yellow zone ("Medium effects" zone) corresponds to dangerous phenomena which will probably have actual effects on the severity and will then be selected to be modelled for the severity calculations. These dangerous phenomena correspond to Reference Accident Scenarios.

- The upper red zone ("High effects" zone) corresponds to very dangerous phenomena which will surely have actual effects on the severity. Corresponding accident scenarios should be revisited in order to put additional safety systems in place. However, if nothing is changed, these dangerous phenomena shall be selected, in their present state, to be modelled for the severity calculations. Of course, these dangerous phenomena correspond to Reference Accident Scenarios.
From the results presented in the event tree (Figure 14) and in Table 8, each Dangerous Phenomena identified in our example can placed in the risk matrix, according to its frequency and its class of consequence (see Figure 16).

Thus, it appears that six Reference Accident Scenarios (corresponding to the reference dangerous phenomena located in the "yellow" or "red" zones) will have to be modelled for the severity calculations:
✓ Fully developed jetfire
✓ Fully developed VCE
✓ Fully developed flashfire
✓ Fully developed toxic cloud
✓ Poolfire with limited source term
✓ VCE with limited source term and effects

16. MIRAS Step 8: Prepare information for the calculation of the Severity

The last bowtie(s) obtained by the MIRAS methodology (including the influence of safety systems) (for our example, see Figure 12 for the left part of bowtie and Figure 14 for the right part of bowtie), the risk matrix with all dangerous phenomena (for our example, see Figure 16) and the reference accident scenarios are the basis for the severity mapping.

In addition, for each reference accident scenario, some complementary information are required for severity mapping. These information are summarised hereunder:

✓ The equipment type
✓ The design/rupture pressure and temperature of the equipment
✓ The height of liquid
✓ The properties of the hazardous substance (substance state, hazardous properties, risk phrases)
✓ The quantity of substance available:
  • Mass in the equipment
  • Flow entering in the equipment
✓ The operating conditions inside the equipment (temperature, pressure)
✓ The bow-tie with the fault tree, the branches leading to reference accident scenarios (DP in yellow or red zone) in the event tree and with the efficient safety barriers.
✓ The critical event
  • For a breach: localisation, diameter, liquid height above the hole and release time
  • For the calculation of the rain-out, the presence of obstacles in the direction of the two-phase jet (if any)
✓ The dangerous phenomenon with its frequency (frequency per year)
✓ The ignition sources on the site (to verify the presence of ignition sources in the flammability zone of the cloud)
The wind rose

The average meteorological conditions on the site (stability class, wind velocity, temperature, pressure, humidity, cloud coverage,...)

Presence and characteristics of safety barriers which may affect the severity modelling (presence of a bund, …)

Description of the site surroundings, including localisation of the schools, hospitals,..

…

17. Conclusion

In this appendix, an application of the MIMAH and MIRAS tools has been presented on the basis of a fictitious and simplified example.

The objective was to make concrete these methodologies described in the main report and in the other appendices.

While the example is a fictitious one, we tried to use data and to obtain results as realistic as possible. The case studies realised during the ARAMIS project turned out to be very useful in that frame.

However, we would like to underline once more that the example is purely fictitious and that the results obtained shall never be used out of this context.