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 1: List of potentially hazardous equipment identified

Name of the substance	*Risk phrases*	*Name of the equipment*	*Type of equipment*	*State of the substance*
Substance 1	R11	D-283	EQ6: Atmospheric storage	Liquid
		Stream 2	EQ10: Pipe	Liquid
Substance 2	R23	T-305	EQ7: Cryogenic storage	Liquid
		Stream 5	EQ10: Pipe	Gas
Substance 3	R26	R-102	EQ12: Equipment involving chemical reaction	Gas

Name of the substance	*Risk phrases*	*Name of the equipment*	*Type of equipment*	*State of the substance*
Ethylene oxide	R12, R23	Truck for unloading	EQ8: Pressure transport equipment	Two-phase
		Stream 4 (Unloading pipe)	EQ10: Pipe	Liquid
		T-310 (ethylene oxide storage)	EQ4: Pressure storage	Two-phase
Substance 5	R8	R-254	Eq13: Equipment devoted to the physical or chemical separation of substances	Solid
		T-256	EQ1: Mass solid storage	Solid

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).

N° Equipment	Equipment	Type of equipment	Substance	Physical state	Boiling T (p atm) in °C or decomposition temp. for solid	Service T in °C	Risk phrases	Hazard classification	Contained quantity (kg)	Reference Mass Ma (kg)	S1 Coeff. (for the liquids)	S2 Coeff. (for liquids)	S Coeff. (for liquids)	Mass Mb (kg)	Selection if M>=Mb	Distance from the nearest selected equipment (m)	Name of the nearest selected equipment	S3	Mc (kg)	Selection if D<50 m and M>Mc
1	D-283	EQ6: Atmospheric storage	Substance1	Liquid	126	25	R11	F+	5000	10000	0.10	0	0.10	100000	no	2	cryogenic storage	0.1	10000	no
2	Stream 2	EQ10: Pipe	Substance1	Liquid	126	25	R11	F+	200	10000	0.10	0	0.10	100000	no					
3	T-305	EQ7: Cryogenic storage	Substance2	Liquid	-34	-34	R23	T	35000	10000	1.00	0.68	1.68	5952	yes					
4	Stream 5	EQ10: Pipe	Substance2	Gas	-34	85	R23	T	460	1000			1.00	1000	no					
5	R-102	EQ12: Equipment involving chemical reaction	Substance3	Gas	7.5	80	R26	T+	25	100			1.00	100	no					
6	Truck of unloading	EQ8: Pressure transport equipment	Ethylene oxide	Two-phase	11	5	R12, R23	F, T	25000	10000	0.87	0	0.87	11482	yes					
7	Stream 4 (Unloading pipe)	EQ10: Pipe	Ethylene oxide	Liquid	11	15	R12, R23	F, T	4200	10000	1.10	0	1.10	9120	no					
8	T-310 (ammoniac storage)	EQ4: Pressure storage	Ethylene oxide	Two-phase	11	5	R12, R23	F, T	54660	10000	0.87	0	0.87	11482	yes					
9	R-254	Eq13: Equipment devoted to the physical or chemical separation of substances	Substance5	Solid	210	20	R8	O	350	10000			1.00	10000	no					
10	T-256	EQ1: Mass solid storage	Substance5	Solid	210	20	R8	O	20000	10000			1.00	10000	yes					

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

		CE1 Decomposition	CE2 Explosion	CE3 Materials set in motion (entrainment by air)	CE4 Materials set in motion (entrainment by a liquid)	CE5 Start of a fire (LPI)	CE6 Breach on the 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	CE11 Vessel collapse	CE12 Collapse of the roof
Pressure	EQ4					X	X	X	X	X	X		
Two-phase	STAT3					X	X	X	X	X	X		
Results						**X**	**X**	**X**	**X**	**X**	**X**		

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.

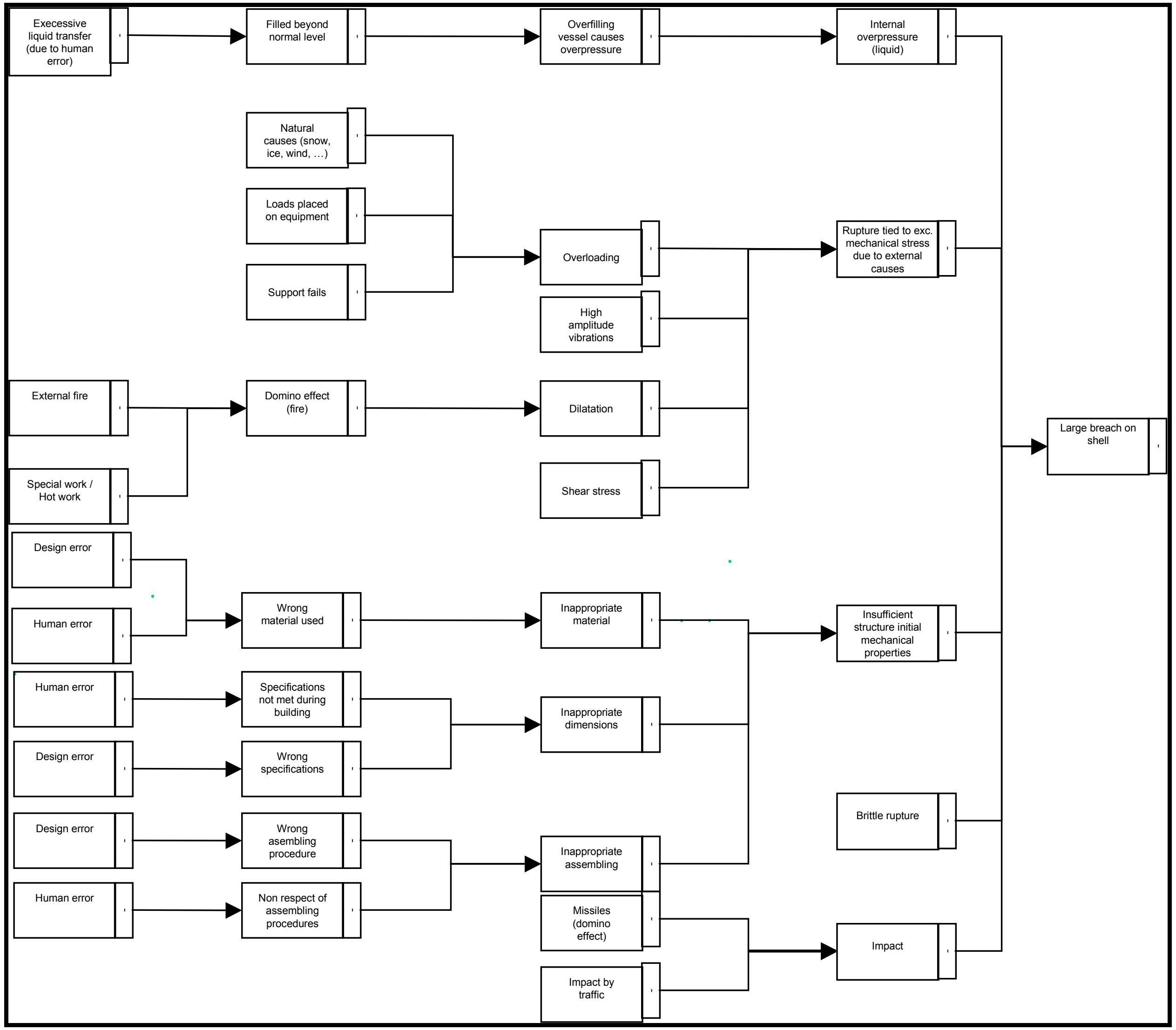

Figure 1: Adapted fault tree for "Large Breach on shell"

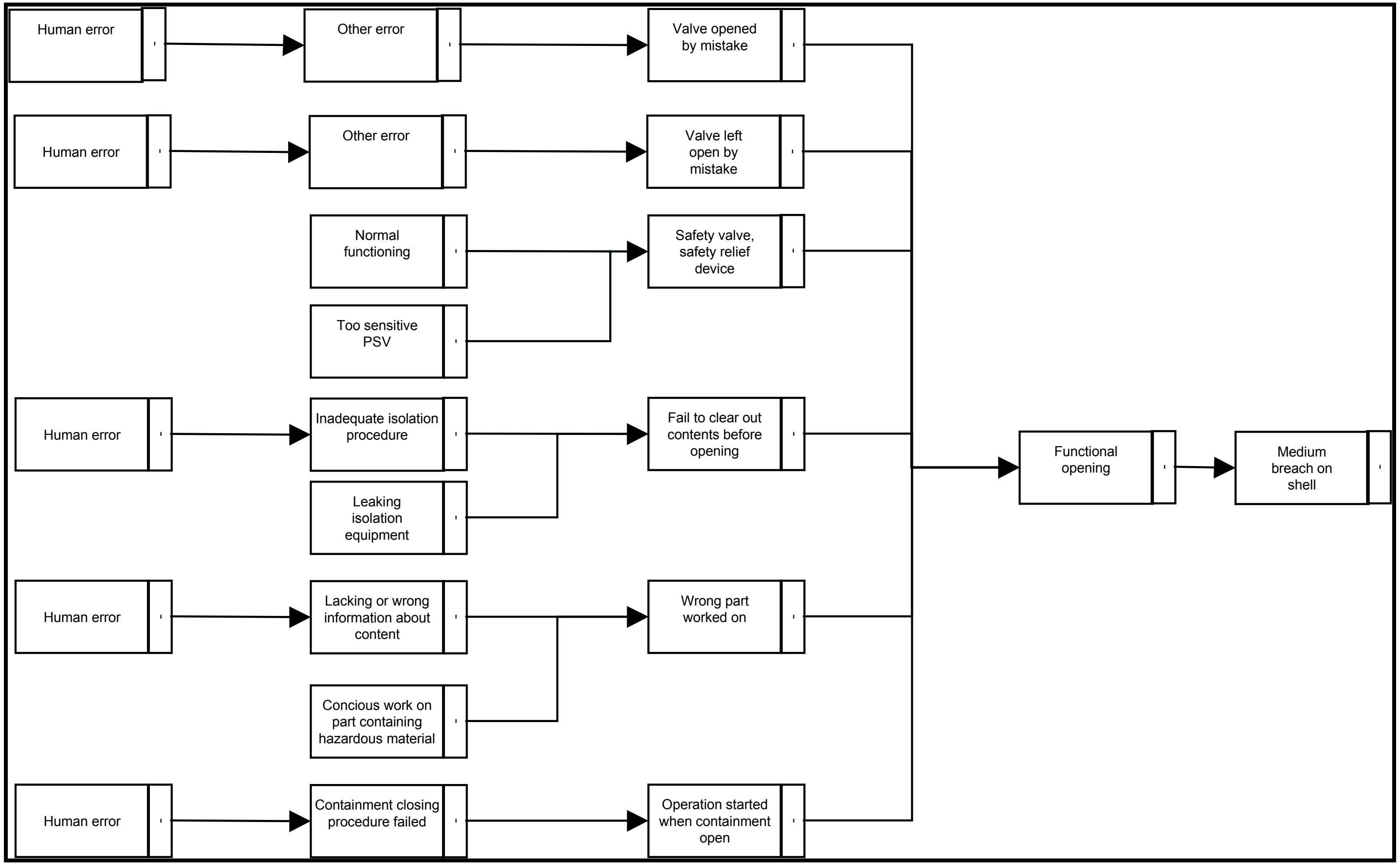

Figure 2: Adapted fault tree for "Medium breach on shell"

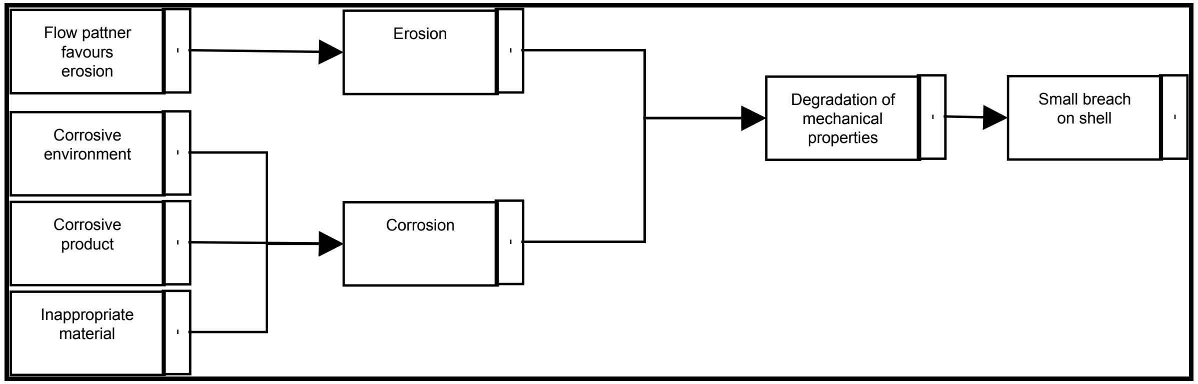

Figure 3: Adapted fault tree for "Small breach on shell"

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).

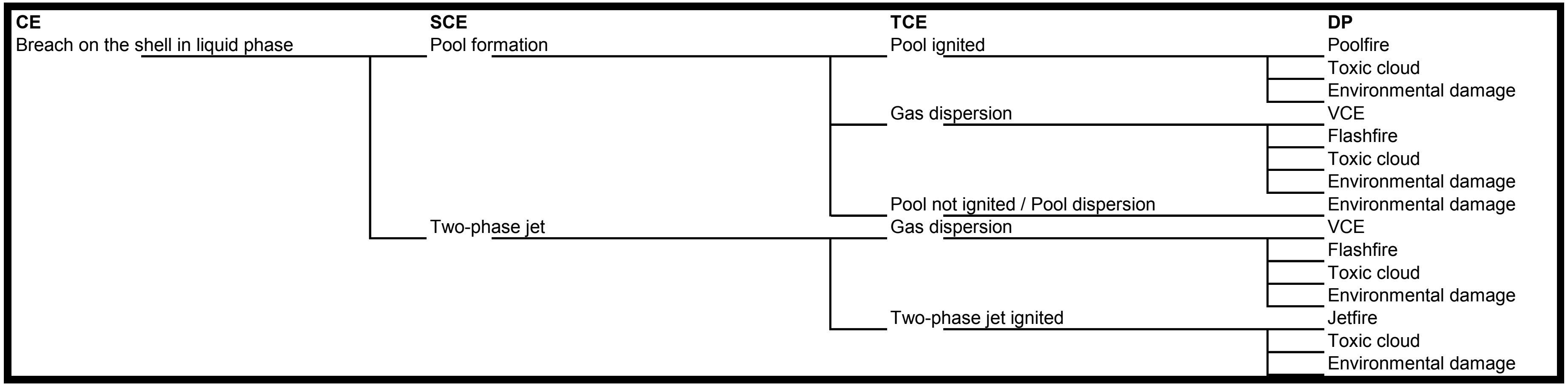

Figure 4: event tree for the CE7 "breach on shell in liquid phase" without taking into account the risk phrases

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 if TCE5 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.

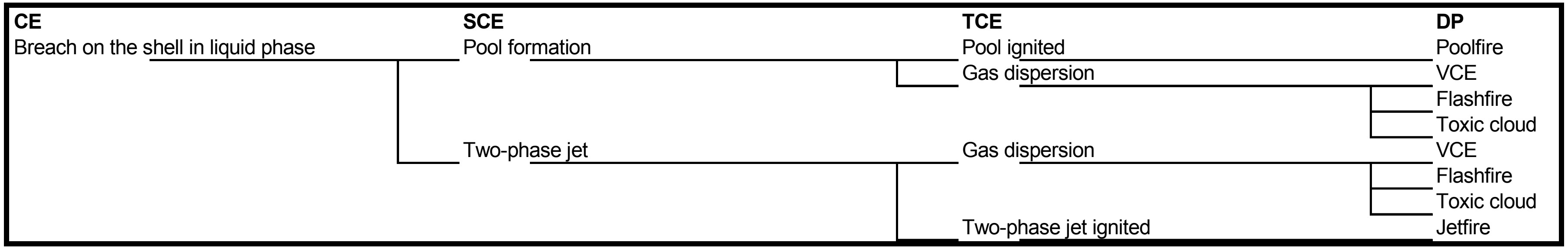

Figure 5: event tree for the CE7 "breach on shell in liquid phase" taking into account the risk phrases

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.

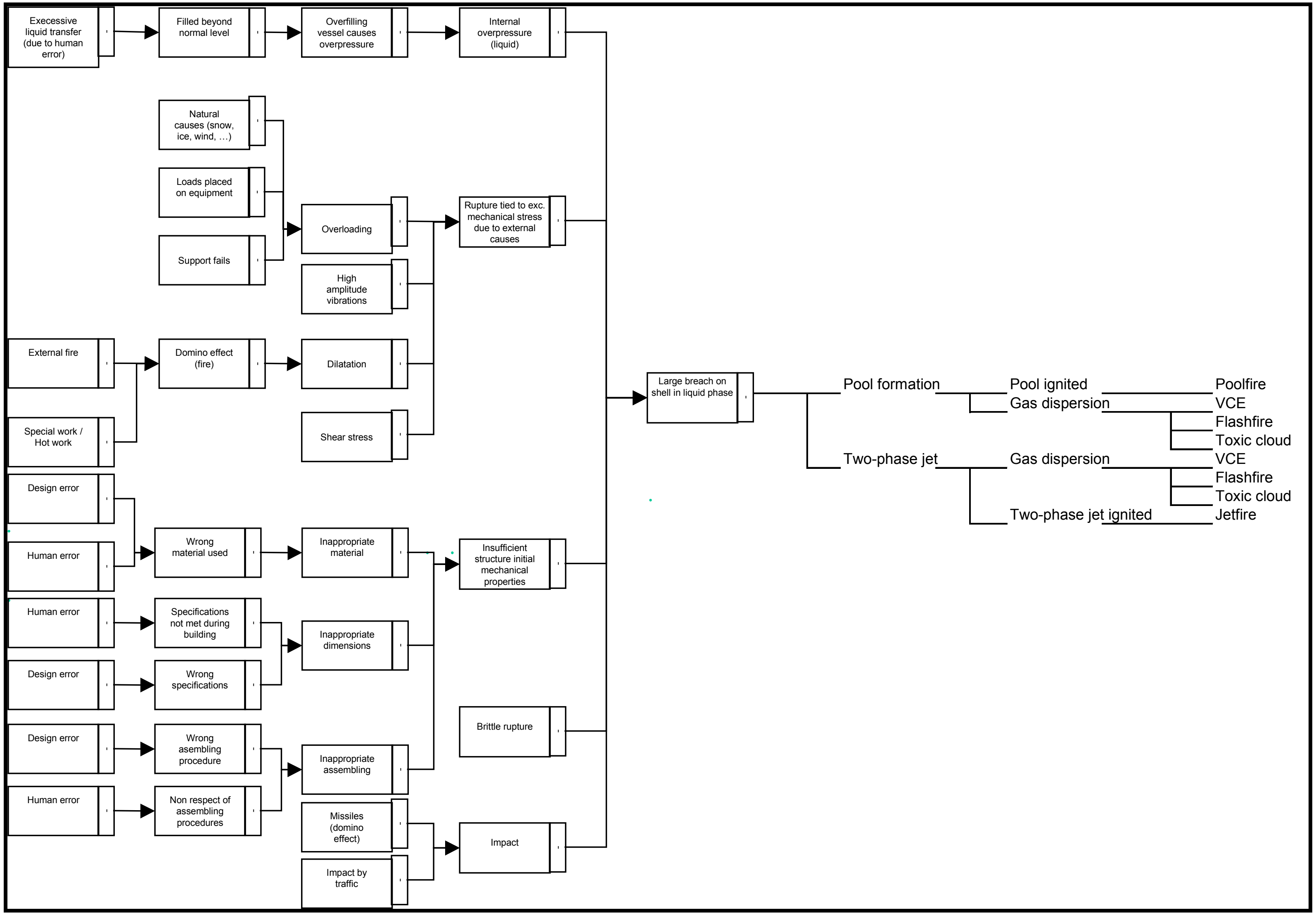

Figure 6: Complete bowtie for "Large breach on shell in liquid phase" taking into account the risk phrases

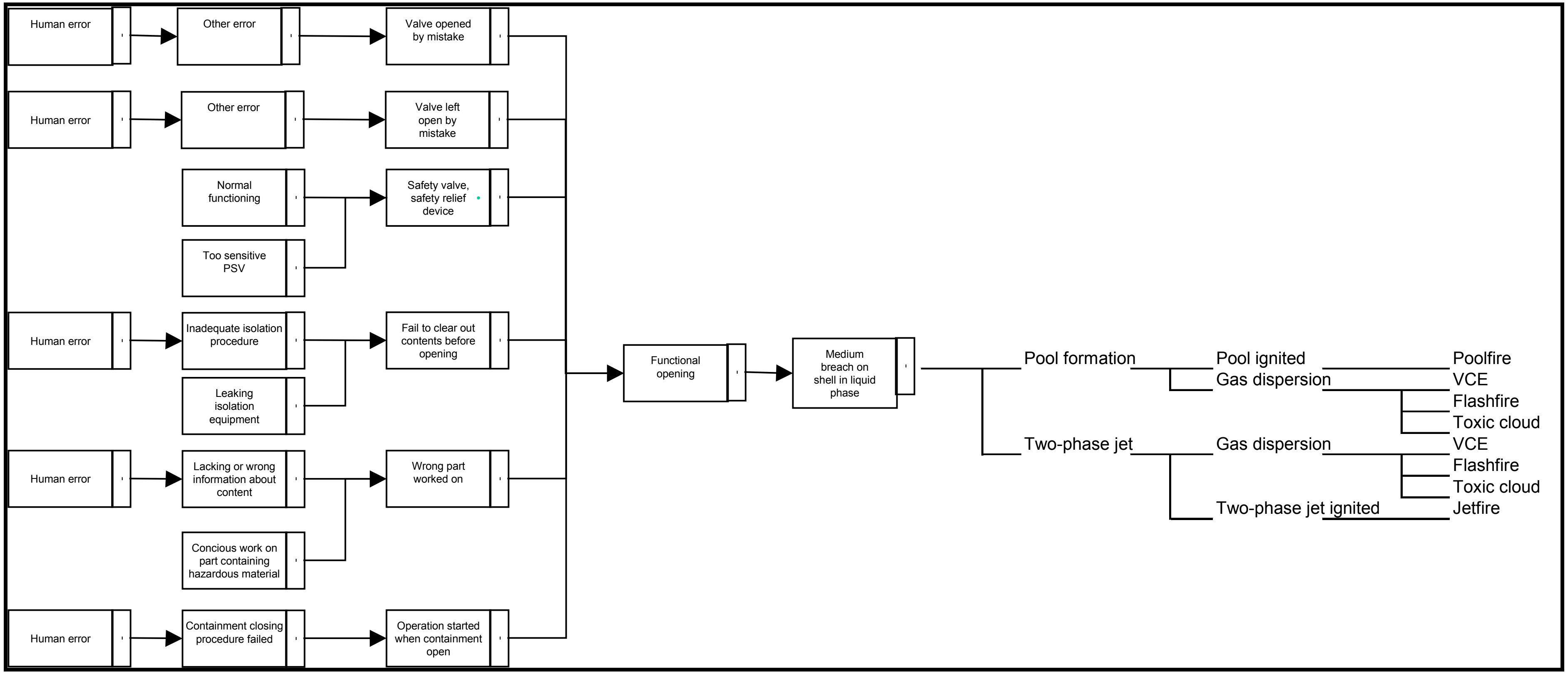

Figure 7: Complete bowtie for "Medium breach on shell in liquid phase" taking into account the risk phrases

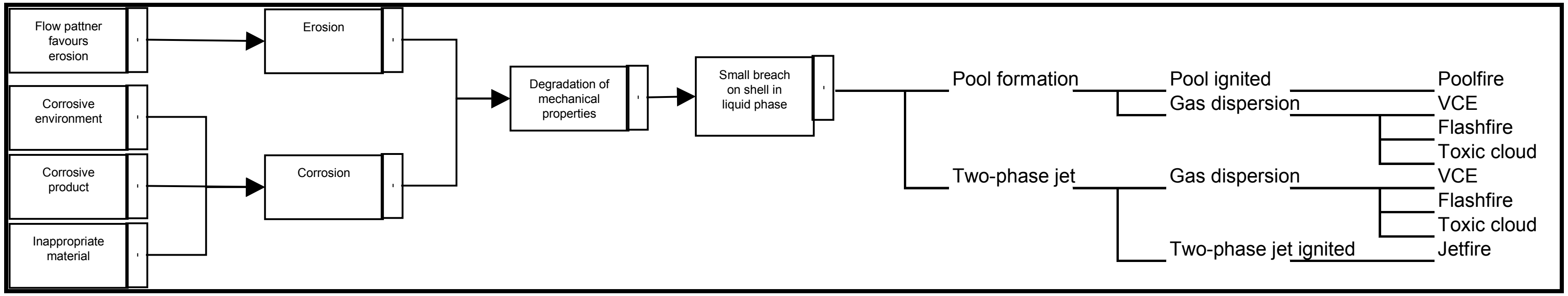

Figure 8: Complete bowtie for "Small breach on shell in liquid phase" taking into account the risk phrases

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 4: Data needed for the MIRAS part

Step	Description of data needed
Step 1: Collect needed data	See below
Step 2: Make a choice between step 3 or step 4	No additional data
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

Step	Description of data needed
Step 7: Use the risk matrix to choose Reference Accident Scenarios	No additional data
Step 8: Prepare information for the calculation of the Severity	• Characteristics of equipment for which one (or several) Reference Accident Scenarios has been retained (for example dimensions of the vessel, size of the bund, …) • Wind rose and meteorological conditions • Description of the site surroundings (populated area including schools, hospitals, …)

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

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

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.

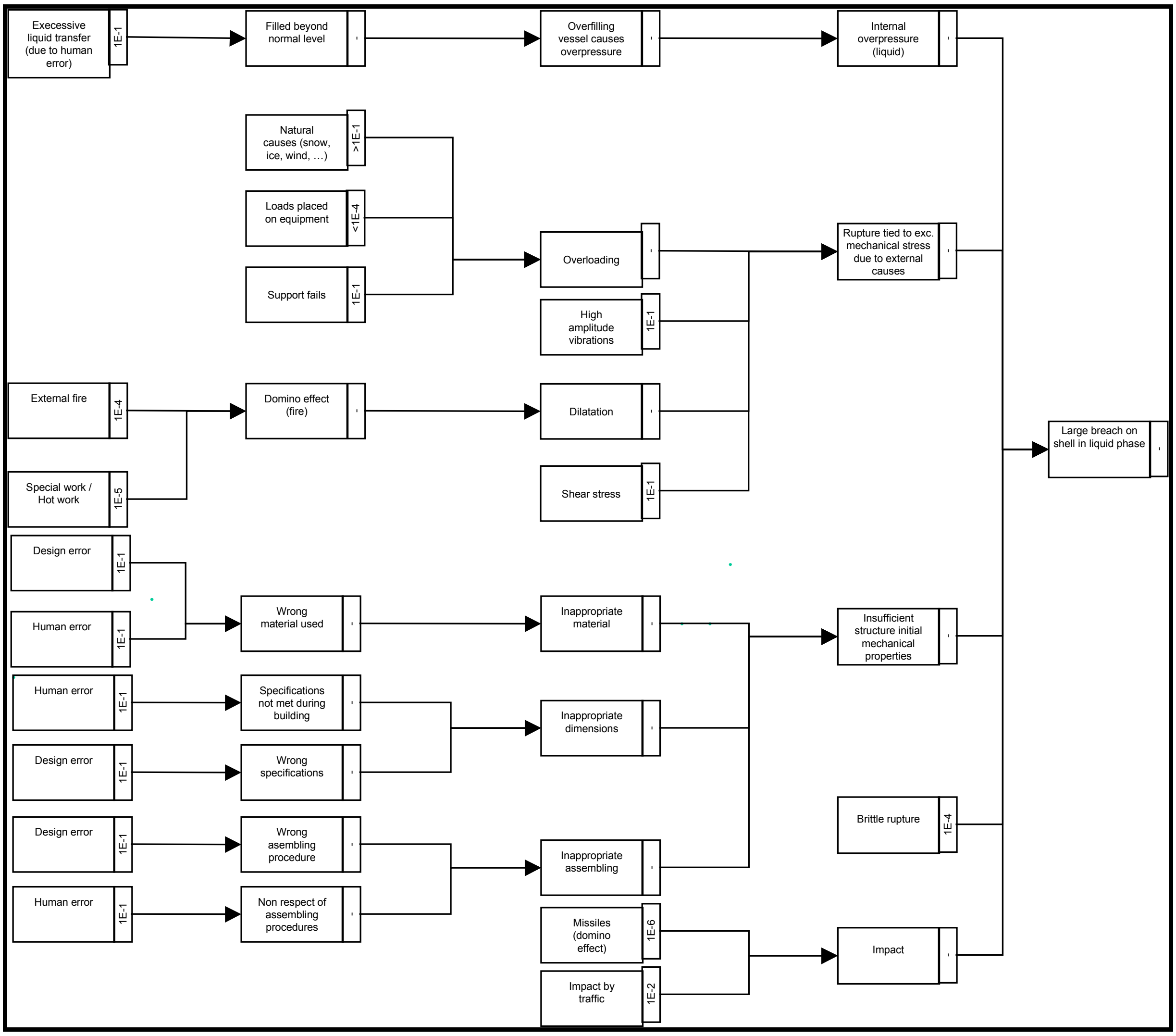

Figure 9: frequencies of initiating events on the fault tree

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).

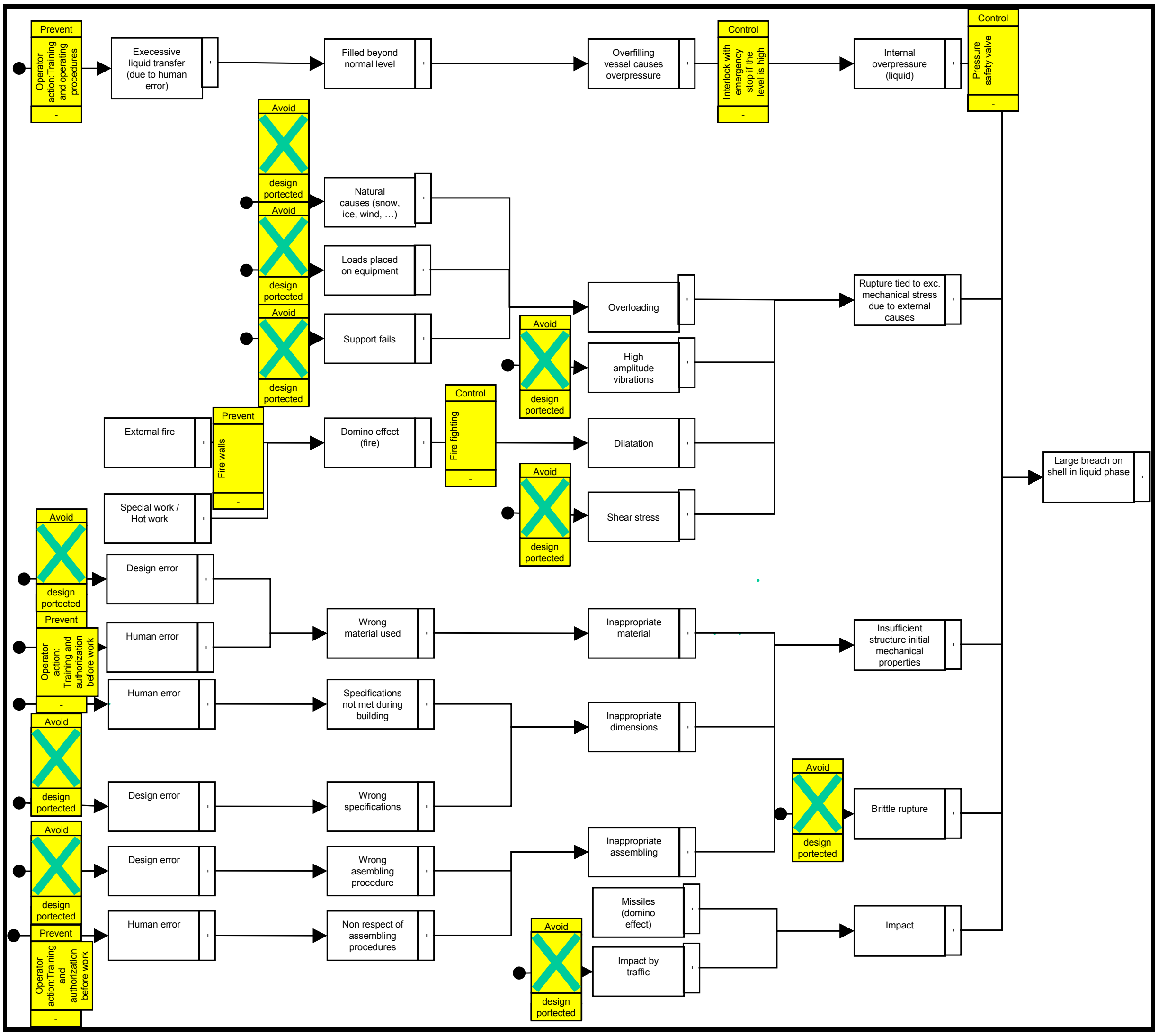

Figure 10: safety functions and barriers on the fault tree

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).

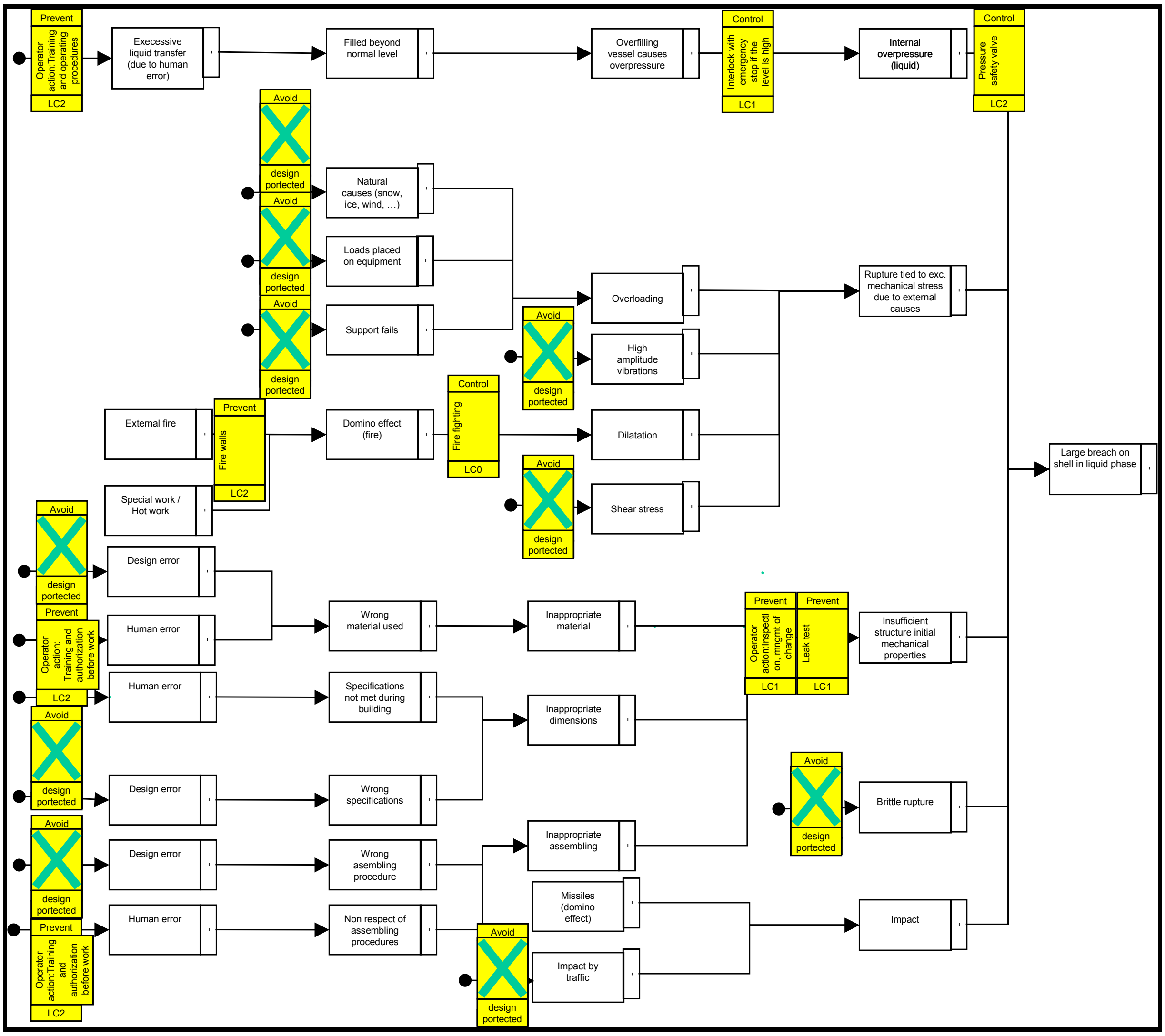

Figure 11: "design" levels of confidence of safety functions and barriers

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 $4.3.10^{-5}$/year. This value, which obtained for a fictitious example, seems reasonable.

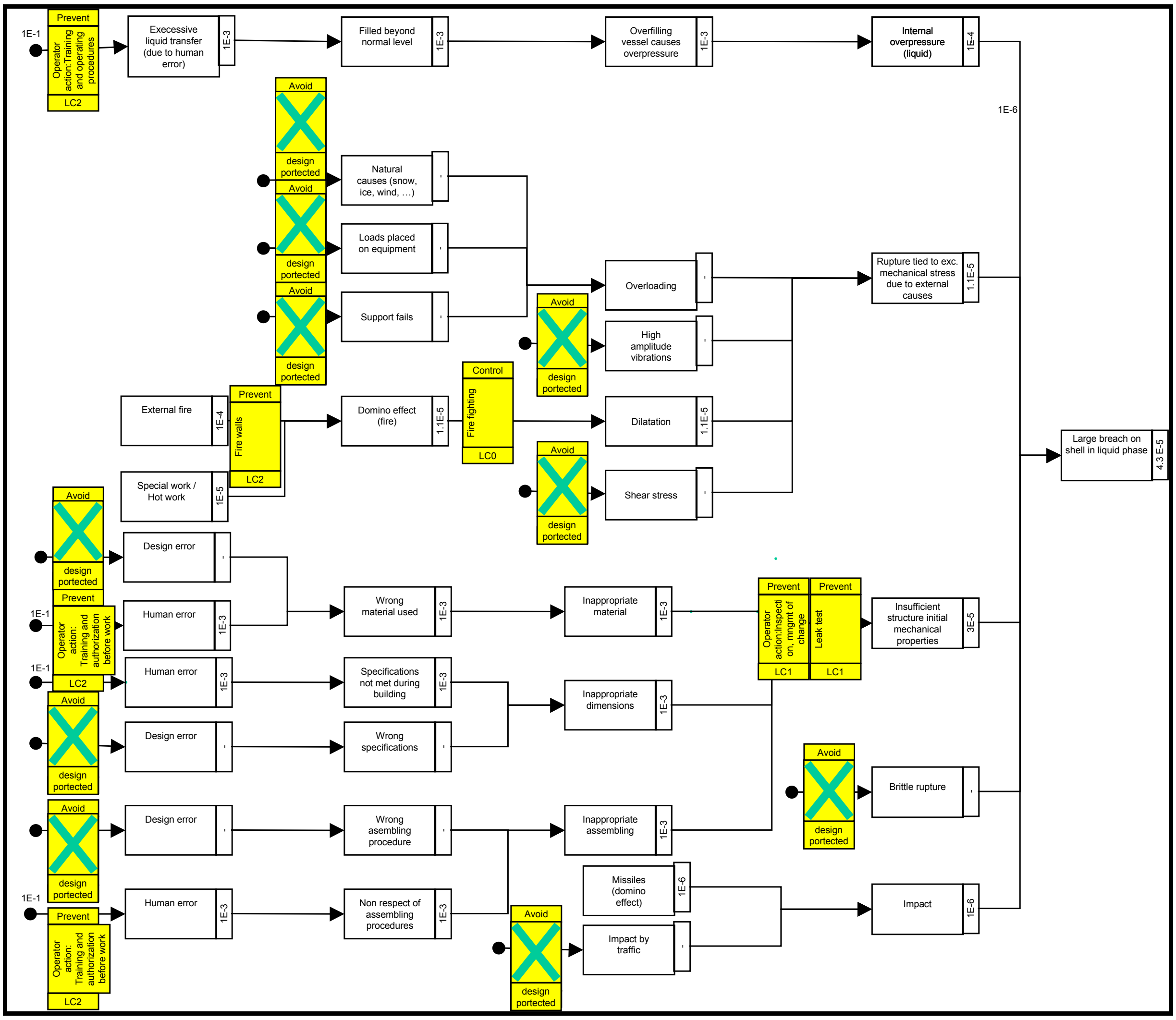

Figure 12: Fault tree with the frequency of CE "large breach on shell in liquid phase"

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 habe 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.

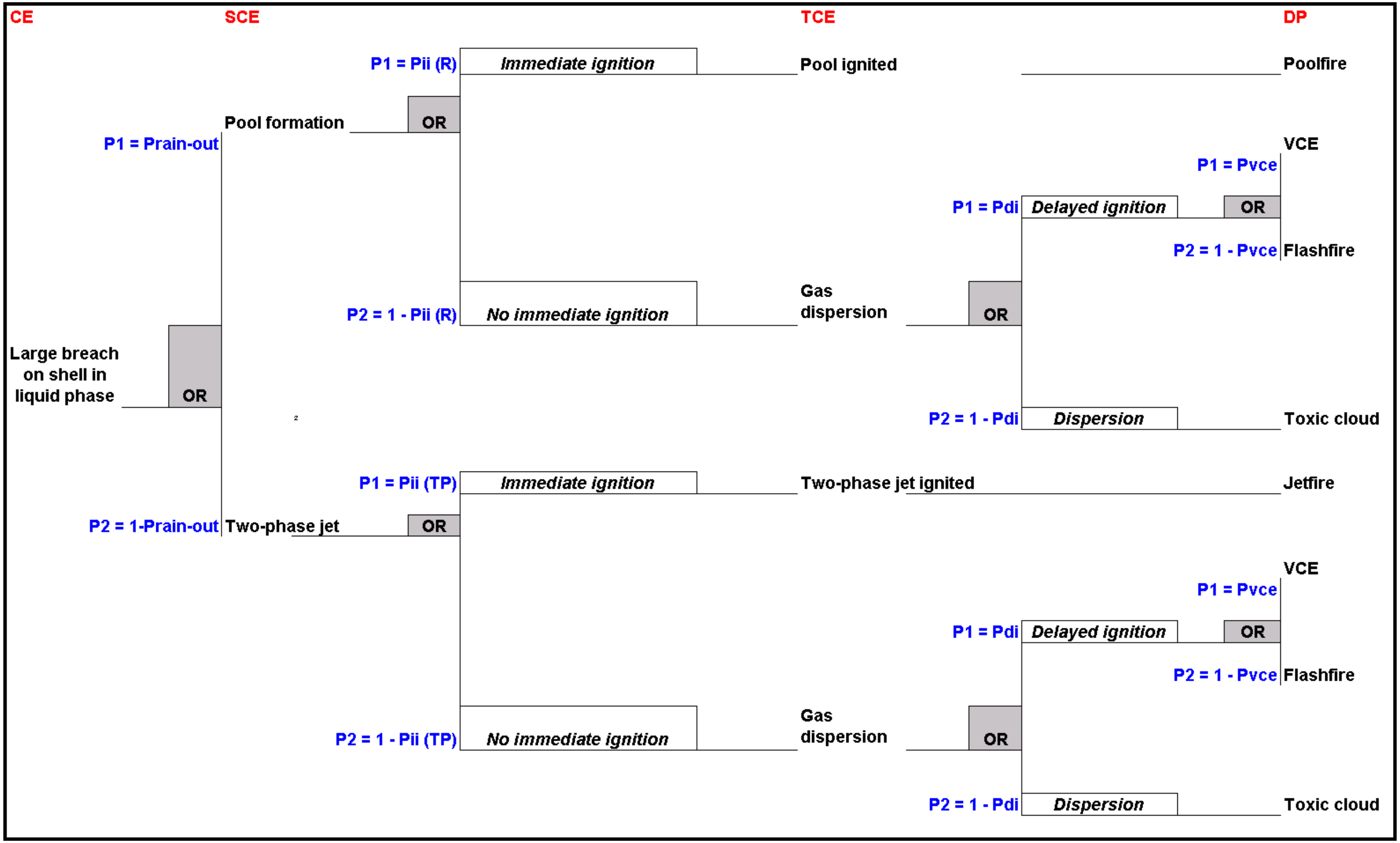

Figure 13: Event tree for CE7 with the "AND/OR" gates

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 an other 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.

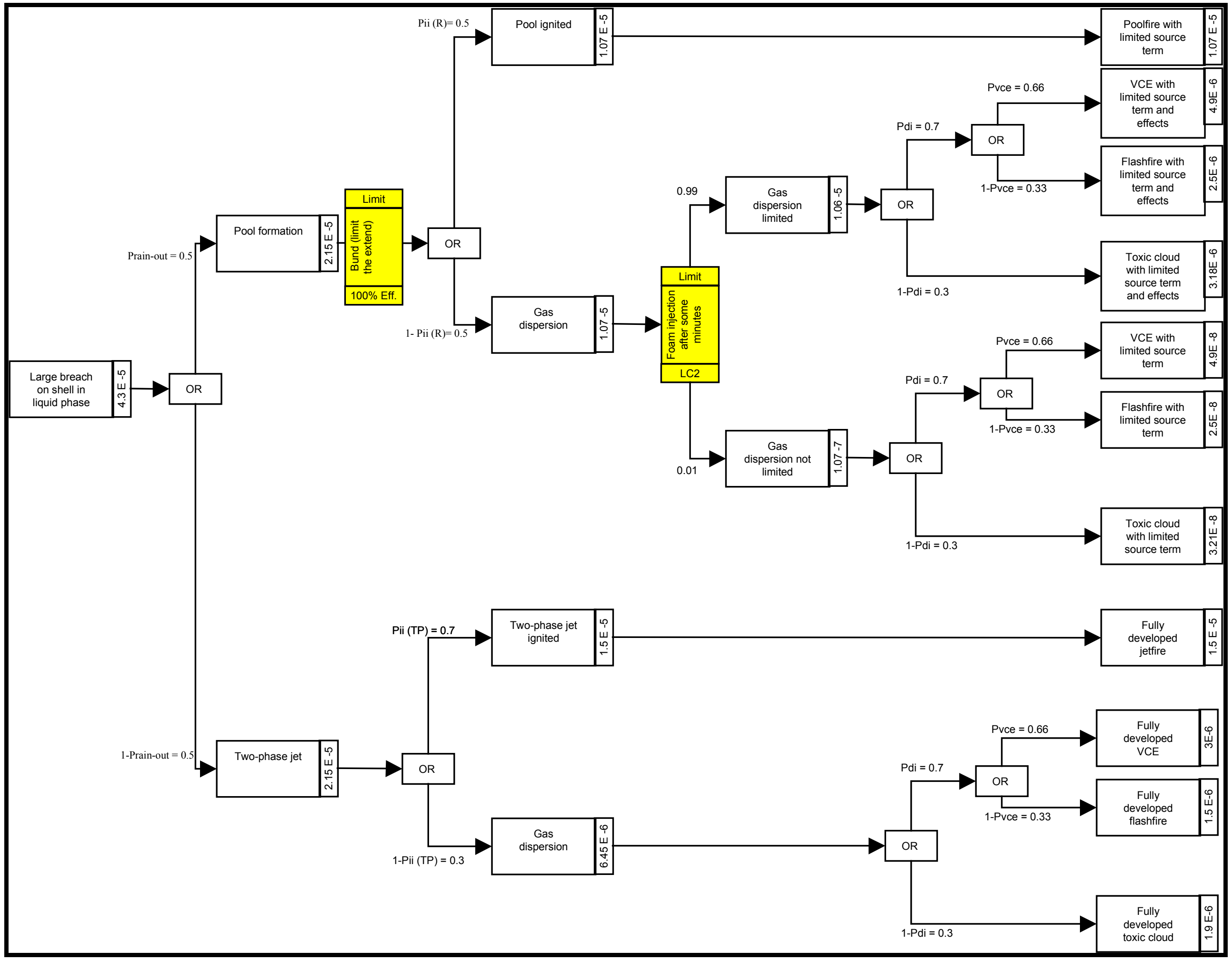

Figure 14: Event tree with the frequencies of dangerous phenomena for the large breach on shell in liquid phase

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

Dangerous phenomenon	*Frequency*
Poolfire with limited source term	$1.07.10^{-5}$/year
VCE with limited source term and effects	$4.9.10^{-6}$/year
Flashfire with limited source term and effects	$2.5.10^{-6}$/year
Toxic cloud with limited source term and effects	$3.18.10^{-6}$/year
VCE with limited source term	$4.9.10^{-8}$/year
Flashfire with limited source term	$2.5.10^{-8}$/year
Toxic cloud with limited source term	$3.21.10^{-8}$/year
Fully developed jetfire	$1.5.10^{-5}$/year
Fully developed VCE	3.10^{-6}/year
Fully developed flashfire	$1.5.10^{-6}$/year
Fully developed toxic cloud	$1.9.10^{-6}$/year

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

CONSEQUENCES			CLASS
Domino effect	**Effect on human target**	**Effect on environment**	**Ranking**
See note under **Table 7**	No injury or slight injury with no stoppage of work	No action necessary, just watching	C_1
See note under **Table 7**	Injury leading to an hospitalisation > 24 hours	Serious effects on environment, requiring local means of intervention	C_2
See note under **Table 7**	Irreversible injuries or death inside the site, Reversible injuries outside the site	Effects on environment outside the site, requiring national means	C_3
See note under **Table 7**	Irreversible injuries or death outside the site	Irreversible effects on environment outside the site, requiring national means	C_4

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 feeded 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

Dangerous phenomenon	*Frequency*	*Class of consequences*
Poolfire with limited source term	$1.07.10^{-5}$/year	C2
VCE with limited source term and effects	$4.9.10^{-6}$/year	C3
Flashfire with limited source term and effects	$2.5.10^{-6}$/year	C2

Dangerous phenomenon	*Frequency*	*Class of consequences*
Toxic cloud with limited source term and effects	$3.18.10^{-6}$/year	C2
VCE with limited source term	$4.9.10^{-8}$/year	C4
Flashfire with limited source term	$2.5.10^{-8}$/year	C3
Toxic cloud with limited source term	$3.21.10^{-8}$/year	C3
Fully developed jetfire	$1.5.10^{-5}$/year	C2
Fully developed VCE	3.10^{-6}/year	C4
Fully developed flashfire	$1.5.10^{-6}$/year	C3
Fully developed toxic cloud	$1.9.10^{-6}$/year	C3

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.

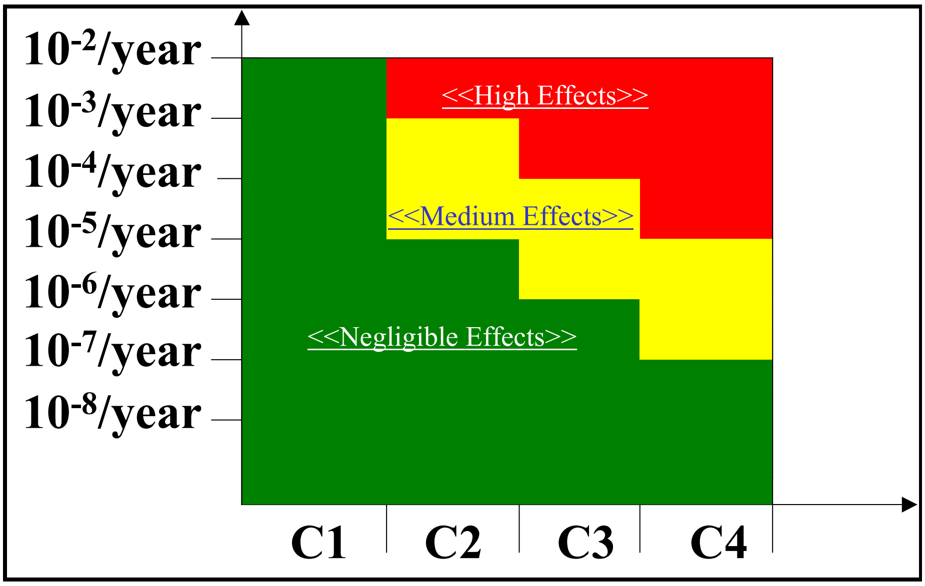

Figure 15: Risk matrix

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).

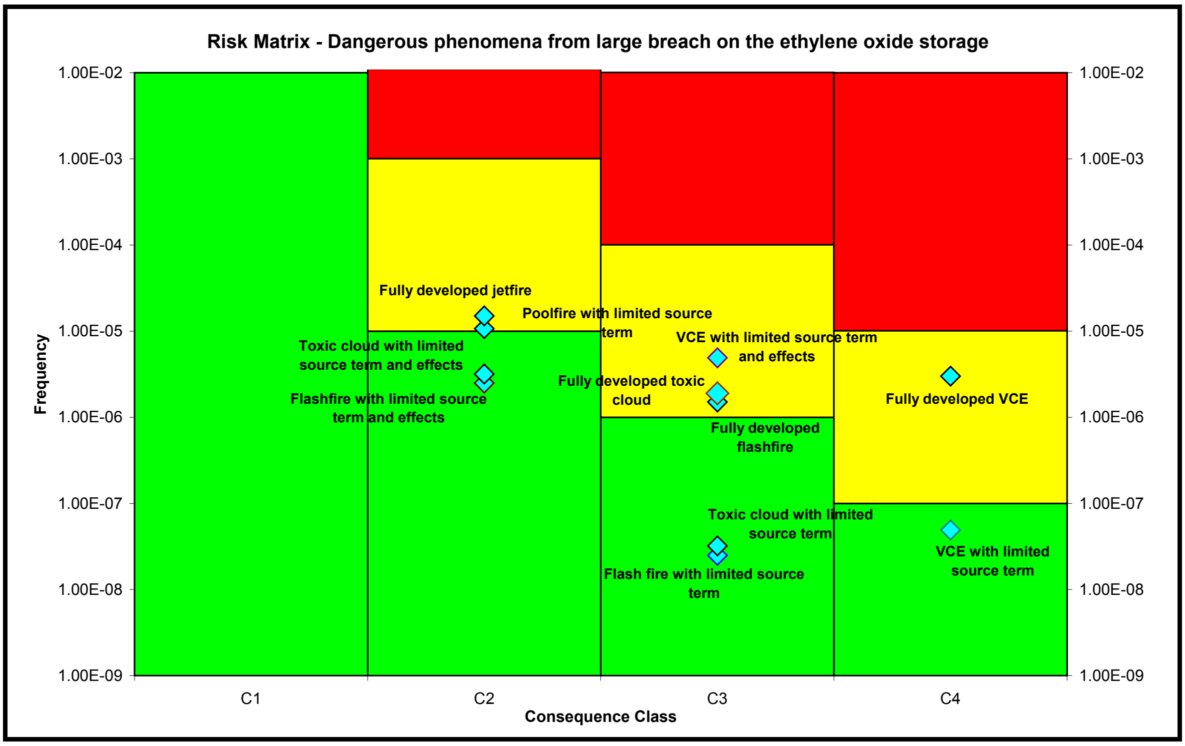

Figure 16: Risk matrix with dangerous phenomena from large breach on shell in liquid phase

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.