**Risk of Major Accidents in Plants producing Energy from Wastes**

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**1. Introduction**

Biomasses and wastes are a renewable source of energy whose main characteristics are to be: 1) intrinsically linked to the territory as they are available everywhere and widely distributed; 2) one of the tools indicated for the reduction of greenhouse gas emissions into the atmosphere: the CO2 balance relating to the conversion of biomasses and wastes into energy is considered neutral. Due to their diversity, numerous conversion technologies are available, producing many final forms of energy: electricity (thermal energy), liquid fuels, biogas, synthesis gas, etc.

However, the technologies currently available for the conversion of biomasses and wastes into useful forms of energy entail critical issues from the point of view of either the operability of the plants or the health of the workers. Therefore, even for these types of systems, it is not possible to neglect the conduction of an accurate risk assessment. However, universally accepted hazard identification techniques such as HazOp are too expensive both in terms of money, personnel employed, and time dedicated to the analysis. Furthermore, they are not strictly targeted to the type of plant being analyzed. Therefore, in this work, a simple but effective hazard identification technique called Advanced Recursive Operability Analysis (AROA) was selected. Such a technique, coupled with others for either the qualification of the failure modes of plant components or the quantification of the probability of occurrence of accidents, allowed to carry out a complete risk analysis with limited time efforts.

The AROA technique was applied to an incineration plant using a fluidized bed waste gasifier. The results showed how it is possible to quickly identify the main criticalities of this type of systems also making the identification of the ATEX zones around the equipment practically straightforward.

**2. Methods**

Quantitative Risk Analysis (QRA) is a complex task performed to either qualify or quantify the risks associated with the operation of potentially dangerous installations. The first step of whatever QRA procedure is the identification of all hazards present into the plant: this is called, Hazards Identification (HI) phase. Hazards identification represents a fundamental activity: not identified hazards will remain hidden until the occurrence of the related accidents[1]. Among all the different HI methodologies, HazOp is the most known and widely applied. Unfortunately, all information collected in a HazOp table are not structured for the following step of the QRA, that is the probabilistic quantification of the hazardous states of the plant. Such step, which is usually done using a Fault Tree Analysis (FTA), can be made less expensive using an Advanced Recursive Operability Analysis (AROA)[2] instead of a classic HazOp.

A typical AROA Table is structured as presented in Table 1 (the progressive numeration of the records, that is of each row, was omitted).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Node-Deviation-Variable** | **Causes** | **Consequences due to protections failure** | **Plant state following the correct intervention of safety functions** | **Protections** | **Top Event** |
| **Manual** | **Automatic safety systems** |
| **Alarms** | **Operator Actions** |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |  |

**Table 1.** Structure of a AROA Table.

In the present work, an AROA was applied to a standard incinerator using a fluidized bed gasifier which processes organic wastes.

**3. Results and discussion**

Figure 1 reports the simplified P&ID of the gasification plant layout.



**Figure 1.** Simplified P&ID of the fluidized bed gasifier.

Referring to the P&ID reported in Figure 1, the system can be divided into 6 nodes:

* Node 1: identifies the fluidized bed reactor (R-01) where either the combustion (Z1) or the pyrolysis of the wastes (Z2) occurs. Air and a high-pressure assistant gas enter from the bottom of R-01. Process variables considered and their deviations (between square brackets) are reported in the following:
1. (TZ1) Temperature in Zone 1 (Combustion Zone) [h, l]
2. (TZ2) Temperature in Zone 2 (Pyrolysis Zone) [h, l]
3. (P) Pressure [h, hh]
4. (CH2) Hydrogen concentration [h]
* Node 2: identifies the loading auger section. Process variables considered and their deviations (between square brackets) are reported in the following:
1. (F) Flow rate of wastes [No, h]
2. (N) Torque at the loading auger [h]
* Node 3: identifies the vapor line used to adjust the syngas composition. Process variables considered and their deviations (between square brackets) are reported in the following:
1. (F) Water vapor flowrate [l]
* Node 4: identifies the air supply necessary for correctly operating the combustion zone of the gasifier. Process variables considered and their deviations (between square brackets) are reported in the following:
1. (F) Air flowrate [l, h]
* Node 5: identifies the High-Pressure (HP) combustible gas necessary to correctly operate the combustion zone of the gasifier. Process variables considered and their deviations (between square brackets) are reported in the following:
1. (F) HP gas flowrate [l, h]
* Node 6: identifies the cyclone used for the abatement of the dusts generated from the waste processing and flow. Such a node was analyzed only from the embrittlement point of view (see Table 2).

The deviations indicated by the letters in the square brackets stand for high (h), low (l) or absence (No). The repetition of the letter expresses an intensification of the deviation (except for the absence). For example (hhP) symbolizes a very high pressure.

Table 2 summarizes the analysis carried out in the present work.

**Table 2.** AROA for the gasification plant portion analyzed within this work.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **NDV** | **Causes** | **Consequences due to protections failure****(3)** | **Plant state following the correct intervention of safety functions****(4)** | **Protection** | **TE** |
| **Manual** | **Automatic safety systems** |
| **Alarms** | **Operator Actions on components** |
| 4hF | 1) FIC-02 Fail HighOR2) V-02 Fail Open | 1hTZ1 | 1hTZ1 | - | - | - | - |
| 5hF | 1) TIC-02 Fail LowOR2) V-03 Fail Open  | 1hTZ1 | 1hTZ1 | - | - | - | - |
| 1hTZ1 | 1) 5hFOR2) 4hF | 1hTZ2 | 1hTZ2 | - | - | - | - |
| 1hTZ2 | 1hTZ1 | 1hP1hCH2 | 1hP1hCH2 | - | - | - | - |
| 1hP | 1hTZ2 | 1hhP | Gases to Flare | PAH-01 | - | PSV-01 | - |
| 1hhP | 1hP | Reactor Collapse+VCE | 2hNPSV-01 collapse (H2 and CO release – Jet Fire from PSV-01) | - | - | Reactor Resistance Pressure  | TE1 (3)TE2 (4) |
| 1hCH2 | 1hTZ2OR3lF | Embrittlement of CY-01 | Embrittlement of CY-01 | - | - | - |  |
| Embrittlement of CY-01 | 1hCH2 | H2 and CO release – Possible Jet Fire from hydrogen cracks | Operability not compromised - Maintenance required | - | - | Resistance to corrosion of CY-01 | TE3(3) |
| **NDV** | **Causes** | **Consequences due to protections failure****(3)** | **Plant state following the correct intervention of safety functions****(4)** | **Protection** | **TE** |
| **Manual** | **Automatic safety systems** |  |
| **Alarms** | **Operator Actions on components** |  |  |
| 3lF | 1) FIC-01 Fail HighOR2) V-01 Fail Closed | 1hCH2 | 1hCH2 | - | - | - | - |
| 2NoF | 2hN (I-01)ORM-01 brokenORMRC-01 broken (no rotation) | 1lTZ1 | 1lTZ1 | - | - | - | - |
| 2hN | 1hhPORClogging (water in the feed) | Tearing of the RC-01/S-01 connection with further dispersion of combustible material (Dust Explosion) | 2NoF | NAH-01 | - | I-01(M-01 off) | TE4 (3) |
| 2hF | 1) MRC-01 fail to operateOR2) TIC-01 Fail High | 1lTZ2 | 1lTZ2 | - | - | - | - |
| 1lTZ1 | 1) 2NoFOR2) 4lFOR3) 5lF | 1lTZ2 | 1lTZ2 | - | - | - | - |
| 1lTZ2 | 1) 2hFOR2) 1lTZ1 | 1lCH2(Syngas out of specifics) | 1lCH2(Syngas out of specifics) | - | - | - | TE5 (3 and 4) |
| 4lF | 1) FIC-02 Fail LowOR2) V-02 Fail Closed | 1lTZ11lTZ2 | 1lTZ11lTZ2 | - | - | - | - |
| 5lF | 1) TIC-02 Fail HighOR2) V-03 Fail Closed  | 1lTZ11lTZ2 | 1lTZ11lTZ2 | - | - | - | - |

Analyzing Table 2, five main potential Top Events (TEs) can be easily identified:

1. TE1: Reactor collapse followed by a Vapor Cloud Explosion (VCE)
2. TE2: PSV-01 collapse with subsequent H2 and CO release - Jet fire from PSV-01
3. TE3: H2 and CO release with possible jet fire from hydrogen cracks (CY-01)
4. TE4: Tearing of the RC-01/S-01 connection with further dispersion of combustible material (Dust Explosion)
5. TE5: Production of a syngas out of specifics

Top Events from 1 to 4 represent criticalities linked to safety problems while TE5 is well representative of an operability concern linked to the composition of the syngas produced. It is very important to underline that 5 Top Events were identified using only 16 records of an AROA Table. This means that a strong reduction of the time necessary for the overall analysis of the plant portion was achieved.

Starting from the AROA Table, it was also possible to automatically generate the related Fault Trees for a subsequent risk quantification step. Figure 2 reports a portion of the overall Fault Tree corresponding to the AROA Table.



**Figure 2.** Portion of the overall Fault Tree.

In order to simplify the logic representation of each record (REC) in terms of either consequences due to either the failure or the correct operation of the protection means, the exits from each inhibit gate (I) assume the following meaning: the direct exit (upward) refers to the consequences reported in column (3) of the AROA Table (Table 2), while the lateral exit refers to the consequences listed in column (4): practically, either the NOT gate or the relative protection are tacit.

Observing Figure 2, it is possible to notice that gates I1, I2 and I5 are not “saturated” from a safety point of view; this means that no protective means have been forecast at that level for the analyzed plant. This represents a huge loss of safety that must be properly counteracted. As the sake of example, I5 could be saturated by introducing a hydrogen analyzer with the related alarms in case of either too high or too low hydrogen concentrations. Successively, proper actions could be also scheduled.

Another relevant point arising from Figure 2 is that all Top Events are linked together in a compact structure: that is, all TEs can be found in a unique fault tree. Only TE5 is missing in Figure 2 for a pure “criticality of representation” reason: TE5 comes from the 2NoF line of failures (as it comes out from Table 2), which was terminated to provide a better visibility of all the other TEs (instead concentrated in a more compact logic structure).

**4. Conclusions**

This work highlighted how fundamental the contribution of a complete and adequate risk analysis is in the field of industrial prevention of potentially dangerous scenarios in gasification plants.

From the recursive operability analysis carried out on a simplified portion of a real fluid bed waste gasifier it was possible to trace a 5 Top Events using only 16 records of a suitably customized ROA Table. This is a very important advantage of the ROA with respect to all the standard Hazard Identification techniques.

Moreover, the possibility of a direct logic conversion of each record of the AROA table in a portion of a more complex fault tree permits to easily identify potential criticalities of the plant in terms of: 1) lack of protective means (both devices or procedures); 2) design problems linked to the processes to be carried out.

Particularly, the lack of suitable procedures and protection devices specifically designed to saturate, from the safety point of view, each level of the plant can be easily identified by simple observation of the final fault tree. This greatly simplify and target the subsequent plant modification to comply with the maximum reasonably achievable level of safety.

**References**

1. P.M. Contini, S. Contini, S. Copelli, R. Rota, M. Demichela, Safety and Reliability of Complex Engineered Systems - Proceedings of the 25th European Safety and Reliability Conference, ESREL 2015 (2015) 347-355
2. M. Barozzi, S. Contini, M. Raboni, V. Torretta, V. Casson Moreno, S. Copelli, Journal of Loss Prevention in the Process Industries 71 (2021) art. no. 104468