Integrated Process Risk Management (IPRM) for Refineries and Petrochemical Complexes

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Abstract – Integrated Process Risk Management (IPRM) is a methodology for predicting the risk of production losses during normal plant operation by calculating the frequencies and durations of plant upsets due to component failures and/or operator errors. This paper presents two case-studies that demonstrate how the IPRM can be used to model cooling water process changes in a 50,000 BPD refinery, and to assess their impacts on the plant production. The IPRM relates production losses to the performance of the major components and the process design. In addition, it is shown how the IPRM provides a basis for the allocation of plant resources in support of plant operation and maintenance activities.

I. INTRODUCTION

The concept of Integrated Process Risk Management is relatively new but is fast gaining acceptance as a key decision-making tool in some industries such as nuclear power generation [1, 2 and 3]. Obviously the reason for embracing the IPRM methodology in the chemical industry is the need to be competitive by maximizing productivity. The IPRM can be used to optimize the maintenance plans, prioritize the process modifications, and rank the production-related significance of equipment and processes in a complex plant. It can also be used to optimize spare-parts inventory and other procurement tasks.

The main inputs and key elements of the IPRM methodology are plant historical failure data, operation and engineering experience, and plant documentation such as: operating manuals, process flow diagrams (PFD) and piping and instrumentation diagrams (P&ID). These elements are integrated to arrive at a suitable performance indicator such as the overall production loss estimate or the net present value of the plant. In 2004, NSS[1] developed a prototype risk-informed asset management model for a company in Ontario, Canada [4]. The model was intended to show how IPRM methodology can be used to optimize plant design, operation and maintenance decision-making. The IPRM methodology can also be utilized by insurance companies, financial organizations, safety regulators and environmental organizations to quantify risks and predict production losses (including accident costs) in any chemical plant across the country, and rank them accordingly.

The objective of this paper is to look at two case-studies to explain the methodology, and illustrate the applications.

II. THEORY AND METHODOLOGY

The IPRM model includes a logical representation of the plant component failures and human interactions leading to production losses. The logic is based on the plant process design, component operation and the associated failure frequencies, probabilities and restoration times. The model captures any redundancies in design. The logic can be expressed in a number of ways such as reliability block diagrams, event trees and fault trees. The logic can be solved to express the plant production losses in terms of the constituent component failures. All event sequences can be easily integrated into a production loss equation via a “high level logic” fault tree. This fault tree can then be interrogated to estimate the frequency of the production loss contributions from the failure combinations of the individual components. These frequencies are combined with the corresponding duration and the production loss levels (e.g., 10%, 20% … or 100%) to estimate the expected production loss either on a yearly basis or integrated over a given period (e.g., the remaining life of plant). The details of the IPRM methodology can be found in reference [4]; however, a simplified process is described in the following paragraphs.

The model development process consists of the following major elements:

[1] NSS is an engineering consulting company providing specialized product and services to the nuclear, chemical, oil and gas industries (www.nssl.ca).

- Identifying the most important processes and support systems (i.e., utilities) that are considered major potential contributors to production loss. The list of the most important processes needs to be derived by a systematic review of plant performance data as well as input from the plant engineers and managers. The level of detail should be kept at the major component level, such as pumps, heat exchangers, etc.

- Creating event sequence tables for each component, in each system based on historical data, operating experience, review of the plant operating manuals, PFDs and P&IDs. The results should be summarized in a failure mode and effects analysis (FMEA) table.

- Developing the fault tree diagram of the plant based on the FMEA table. A computer software application was used in this work to develop the fault tree logic.

- Assigning the failure frequencies, durations and production loss consequences to each event. These are primarily collected from past experiences and maintenance work reports.

- Developing a production loss spreadsheet that uses the fault tree frequencies as input and calculates the production losses in term of dollars. This spreadsheet is used to demonstrate the capability to do "what if" assessments in the IPRM model with a user friendly interface. Microsoft Excel was used to develop this interface.

The FMEA tables form the basis of the IPRM model. The fault tree model consists of a top event representing the complete loss of production at the plant. There might be several "top events" representing partial loss of production due to unavailability of different units and processes. Each individual top event represents the production loss associated with the corresponding unit. For each process unit, production losses can be further categorized according to the possible production loss percentages for that unit as identified in the corresponding FMEA table. The fault tree logic is arranged for each process such that the termination point is the combination of component failures that contribute to the generation losses. Therefore, each process should be divided into separate sub-trees based on the production loss percentages. For the purpose of this paper, we decided to focus on a cooling water supply system, which is common to many chemical and petrochemical plants, and only two production loss levels of 100% and 40% were examined.

There are two main data elements required for the IPRM model, component failure rates (including human error probabilities) and the corresponding restoration times. In addition, test intervals of some dormant components and maintenance outage data (i.e., duration and frequency) are also used to estimate the probability of failure of the dormant components and the probability of a component being under planned maintenance. The sources of the failure rates used in this work included plant experience, process engineer judgment, and a generic database used by other plants. In instances where the plant data was readily available, it was used. The restoration times assigned to the component failure events were noted in the FMEA tables based on a review of historical events and the operators' input.

The IPRM fault tree logic is solved using Boolean algebra to get a list of component failures that will lead to production losses. The results are stored in an output file called "cutsets solution". Each cutset shows a combination of failures for a possible production loss scenario and the frequency of that particular event happening. Table 1 shows the top 20 cutsets which are the most likely failure scenarios in cooling water supply system. Each row in Table 1 shows a sequence of component failures or a cutset that can lead to a production loss. The first column contains the frequency of the failure sequence of a cutset in given row. The second, third and fourth columns contain the actual failure events (e.g., storm, high lake temperature) or component failures (e.g., pump trip, human error, pipe break). The fifth column contains the longest event duration. The sixth column indicates the level of production loss (i.e., consequence). For example, 0.4 means that the failure sequence in question leads to 40% reduction in the unit output. The seventh column shows the plant capacity and finally the last column shows the production loss due to the event (i.e., quantified risk). For example, the second last row of Table 1 indicates a scenario when the lake temperature is high, and one of the pump screens is on maintenance, and all of a sudden one of the running pumps trips due to loss of electrical supply from the motor control center. This simultaneous failure will lead to 40% power loss and the frequency of such event is expected to be 6.61E-05 occurrences per year.

In this project, the cutset solution was imported into Microsoft Excel spreadsheet and a user interface was developed in Microsoft Visual Basic. The output from the spreadsheet was used to rank the processes. A typical process significance ranking diagram is shown in Figure 1. This graph shows what portion of the overall production loss would be due to losses in what units. The units with larger area would obviously have higher significance.

The IPRM is also useful to help prioritize the maintenance and improvement activities within each process unit. The risk-informed prioritization helps to reduce plant downtime and losses due to accidents. This is explained in the following case studies.

III. CASE-STUDIES

The cooling water supply system, along with instrument air, super-heated steam and electricity, is one of the utilities required for operation of any chemical plant. In this case-study we are interested in quantifying and assessing the risk associated with the loss of cooling water and the consequent production losses in a 50,000 barrel per day (BPD) refinery. The plant was assumed to have processes such as: fractionation (atmospheric and vacuum), fluidized catalytic cracking, alkylation, reforming, lube tower, extraction, dewaxing and so on.

Loss of cooling water to the main condenser of the fractionation columns would directly affect the reflux ratio, and heat and mass balance of the distillation tower. Consequently, the flow rate and the composition of the side streams would be affected. This would have a direct impact on all process units. Whereas, the loss of cooling water to the heat exchangers in one of the production units, such as extraction process, would only have impact on that particular unit and the consequences (i.e., production losses) would be much less significant.

The cooling water model included three supply pumps. The plant operating manual requires running either 2 or 3 of the pumps during normal operations. Three pumps are needed for summer time, once the cooling water supply temperature increases. Based on the historical weather data the probability of observing hot and humid summer days where the plant is located is about 0.2 (i.e., less than 2 months a year). In the meantime, the operating manual requirement is to:

i. Shutdown the fractionation unit on loss of two cooling water supply pumps in summer conditions.
ii. Shutdown one of the production units, and redirect the cooling water to the fractionation, if one of the cooling water supply pumps is unavailable in summer conditions.

The consequences of the above mentioned scenarios for loss of two out of three, and loss of one out of three pumps were translated into 100% production loss and 40% production loss, respectively.

Case-Study A: Installing one additional cooling water supply pump

Due to plant ageing, the reliability of the cooling water pumps was degraded. Therefore, in order to improve the reliability of the plant, it was suggested to install one additional pump to guarantee a continuous supply of cooling water all year round; particularly in summer. The cost of modification was in the order of $50,000. The plant management needed to decide on the priority of this modification proposal.

In order to make a decision, the first step was to develop a baseline IPRM fault tree model (with all equipment in-service). The model was solved at zero truncation level to capture all the possible production loss contributors. Then the results of the baseline model were used to compare the alternatives in the plant design and/or operation. In this case-study the alternative design was to use four pumps in the model.

After solving the baseline IPRM fault tree model with three pumps in service for 20% of the time, 350,000 liters/year production loss was estimated due to impairments in the cooling water supply system (cooling water supply unit unavailable). The alternative IPRM fault tree model with four pumps in service (and 20% probability of hot summer days) showed 348,000 liters/year production loss. In other words the improvement that the extra pump would make was insignificant. The return of investment (ROI) for this modification would have been approximately 250 years. Therefore, the proposal was rejected.

However, it is important to note that the same scenario in a different plant could have a quite different outcome. For example, if plant was located in a place where the probability of hot summer days could be as much as P=0.6, the result would change. Also, the main reason for observing a small difference between the two scenarios was the low failure frequency of each pump. In a plant with higher historical failure rates the results could be different.

The effectiveness of the preventive maintenance program on the pumps can also be easily quantified and ranked by using the IPRM fault tree model. For maintenance optimization, it is only required to change the failure rate of the desired components in the baseline model, and calculate how much the overall production loss changes. In this case-study the actual failure rate of the pumps was 0.01 occurrences/year (i.e., once in 100 years of operation) with 24 hrs time to recover. If the failure rate was increased to 0.1 occurrences/year (i.e., once in 10 years of operation), it was noticed that the overall production loss would not increase significantly. Therefore, it was concluded that the preventive maintenance frequency on these pumps can be decreased without a significant increase in risk of production loss due to cooling water pump trip.

Case-Study B: Installing one additional cooling water supply control valve

An alternative design change proposal was installation of a second back-up pneumatic control valve that supplies cooling water to the main header in the fractionation unit. Currently, there is only one valve installed at the boundary of the fractionation unit. This valve adjusts the flow of the cooling water so that the loads in the fractionation unit are supplied first, then the remaining water supplies other loads in the other process units. As can be seen in the top 20 cutsets for the baseline IPRM model, Table [1], a single forced outage event (CW-PV501-FO due to gasket leak, rubber component failure, or CW-PV501-HE due to a human error in the operation of the valve), would directly lead to a 100% loss of production. The frequency of such events is estimated to be around 0.01 occurrences/year.

Similar to what was done in case-study "A", a new fault-tree model was developed with two valves in parallel, and the total production loss estimates compared. The results showed that the baseline 350,000 liters/year production loss drops dramatically to 23,000 liters/year loss once the back-up valve is installed. The modification cost was estimated to be around $20,000, and that translated into a less than a year ROI.

IV. CONCLUSIONS

The purpose of this paper was to demonstrate the usefulness of a risk-based decision support system that can be used as a tool to integrate risks and quantify the consequences in term of production losses. The two case studies in this paper show how the IPRM tool can be used to perform "what-if" assessments in support of plant day-to-day operation. It was demonstrated that the IPRM methodology provides the capability to relate the plant production losses to the performance of the major components and hence provides a basis for the allocation of the plant resources in support of plant operation and maintenance activities.

The IPRM methodology is a fairly new concept, and just recently was adopted by nuclear power plants in US and Canada [3, 4]. One of the main advantages of the IPRM methodology is the fact that production losses can be integrated with accident related costs (i.e., economic effects) and environmental damages in one model and then the results can be translated into equivalent dollars for decision-making purposes.

In addition, with process significance ranking capabilities, the IPRM showed that it can help operation and maintenance staff in scheduling the component maintenance activities. It can be used to rank equipment importance in a process unit, and also to rank importance of different process units in a complex plant. This would have direct application in inventory optimization.

V. REFERENCES

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Figure 1: Process Significance Ranking Diagram

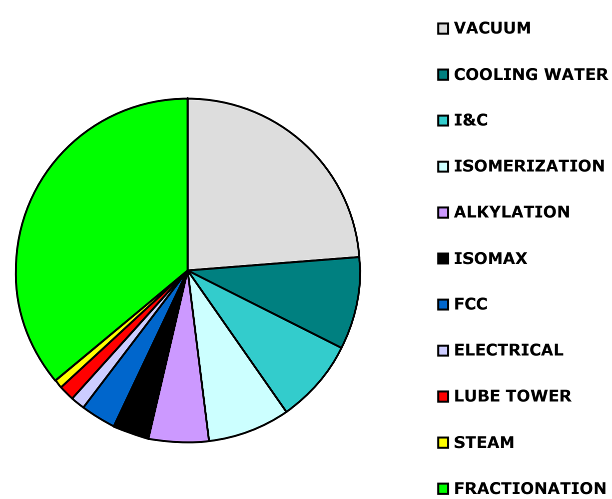

Figure 2: Fault tree diagram for a portion of cooling water supply circuit

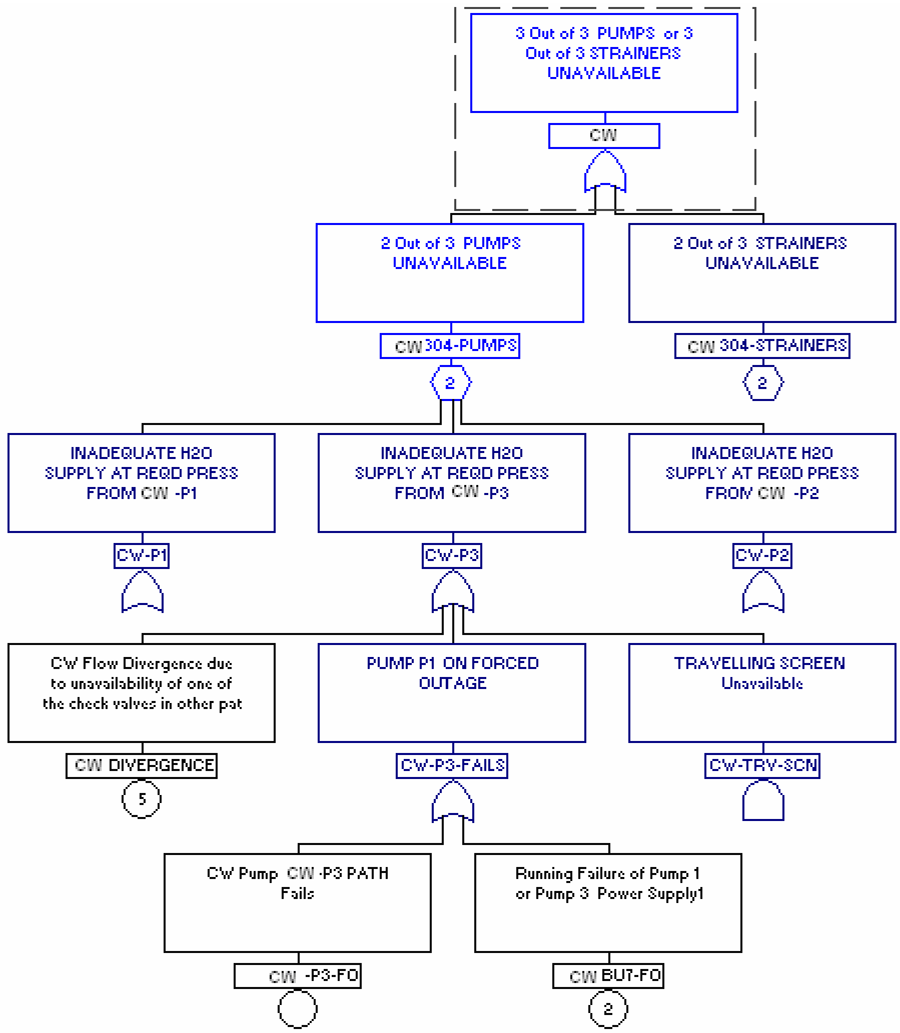

Table 1: Top portion of the cutset solution for cooling water supply system

Frequency (occr/yr)	Event1	Event2	Event3	Durations (hrs)	Production Loss Ratio	Unit Capacity (liter/hrs)	Production Loss (liter/yr)
1.00E-02	CW-PV501-FO			50	1	333,333	2.E+05
1.00E-02	CW-PV501-HE			50	1	333,333	2.E+05
1.00E-03	L-FF			12	1	333,333	4.E+03
2.80E-04	DIVERGENCE	LAKE-TMP-H		12	1	333,333	1.E+03
2.80E-04	DIVERGENCE	LAKE-TMP-L		12	1	333,333	1.E+03
2.40E-04	BU7-FO	LAKE-TMP-VH		12	1	333,333	1.E+03
1.86E-04	DIVERGENCE	LAKE-TMP-VH		12	1	333,333	7.E+02
1.86E-04	DIVERGENCE	LAKE-TMP-VL		12	1	333,333	7.E+02
3.60E-04	BU7-FO	LAKE-TMP-H		12	0.4	333,333	6.E+02
3.60E-04	BU7-FO	LAKE-TMP-L		12	0.4	333,333	6.E+02
2.80E-04	DIVERGENCE	LAKE-TMP-H		12	0.4	333,333	4.E+02
2.80E-04	DIVERGENCE	LAKE-TMP-L		12	0.4	333,333	4.E+02
2.50E-04	CW-GA1-SO	SUMMER		12	0.4	333,333	4.E+02
2.40E-04	BU7-FO	LAKE-TMP-VH		12	0.4	333,333	4.E+02
1.86E-04	DIVERGENCE	LAKE-TMP-VH		12	0.4	333,333	3.E+02
7.36E-05	MCC451-UV	CW-SC2-FO	LAKE-TMP-H	12	1	333,333	3.E+02
7.36E-05	MCC451-UV	CW-SC2-FO	LAKE-TMP-L	12	1	333,333	3.E+02
6.84E-05	MCC451-UV	CW-SC2-MO	LAKE-TMP-H	12	1	333,333	3.E+02
6.84E-05	MCC451-UV	CW-SC2-MO	LAKE-TMP-L	12	1	333,333	3.E+02
6.60E-05	CW-SC1-FO	CW-SC2-FO	LAKE-TMP-H	12	1	333,333	3.E+02