Achieving Six Sigma Through Fault Tree Analysis

Angela E. Summers, Ph.D., P.E., Risk Assessment Manager
PCE, Triconex Corporation
Max Newby • Lead Production Engineer • Al Sather • Process Safety Leader • GE Plastics

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Introduction

GE Plastics has a firm commitment to achieve world class quality through the Six Sigma program. This program requires that the manufacturing facilities achieve a level of quality control so that there are only 3.4 quality failures out of one million opportunities. In order to accomplish this target, the individual manufacturing facilities must achieve the absolute lowest level of failure throughout the production process. This paper focuses on the efforts of one manufacturing facility to achieve Six Sigma. This facility will be referred to as the “Manufacturing Plant.”

Discussion

For the Six Sigma program, the Manufacturing Plant personnel initiated a program designed to achieve the required quality criteria. In addition to Six Sigma goals, there were OSHA process safety management (PSM) issues that needed to be addressed. The facility was in compliance with PSM, but there were projects under consideration for improvements to the process, including upgrades to the basic process control system (BPCS) and the emergency shutdown system (ESD).

The Manufacturing Plant, like most processes throughout Industry, had many opportunities for improvement. The central point of the Six Sigma program was to find those opportunities that would yield the largest return in quality and savings. It was apparent that a comprehensive investigation of the process had to be performed to identify the key areas for improvement. The program had to place emphasis on balancing production, quality, and safety.

Production issues are always important, since it is quite easy to set a goal of 100% on-spec material and to create this wondrous product in a laboratory setting using laboratory glassware and a Ph.D. chemist. However, in the real world, we are not interested in manufacturing grams of perfect product. We are instead interested in manufacturing hundreds of thousands or millions of pounds of product, while consistently achieving the quality specifications for the product.

Safety is also directly tied to quality. If viewed at a process level, a process safety event is caused by loss of process control. Since process control yields quality product, a safety event is really nothing more than a quality event that had gone completely awry. Safety budgets focus on minimizing these large quality excursions. All quality problems cannot be handled under the safety budget. It was essential that the Manufacturing Plant personnel determine where to focus efforts for the safety and quality control expenditures. The Manufacturing Plant personnel determined that they needed three elements for an effective program: team chemistry, team challenge and the right tools.

Team Chemistry

For the Manufacturing Plant study, a team was assembled with representatives from technology, operations, engineering, and safety. Team members were chosen based on their knowledge of the process under study. In addition to the core members of the team, additional personnel were identified to serve as contacts for supplementary information that might be required during the execution of the study, such as drafting, maintenance, and operations.

Team Challenge

When conducting an audit of this type, it is easy for the investigation to turn into a finger-pointing game of "That's not the way you are supposed to do that!" and "This is caused by your department!" The team was challenged to think about the business not about their particular function. The team was focused on identifying the opportunities for quality improvement.

Tools

Fault tree analysis (FTA) was chosen for the modeling of the processes used to control the production quality. These processes included make-up of the reactants and the feed pumping/metering to the reaction tanks.

Fault tree analysis (FTA) was developed in the 1960s by Bell Laboratories during the Polaris Missile Project. It was utilized to evaluate the probability of an inadvertent launching of a Minuteman missile. FTA has been used extensively by the military, the space program, and the nuclear industry. It is a highly adaptable logic diagram based technique that can be readily applied to the chemical processing.
FTA was chosen, because it is a very structured, systematic, and rigorous technique that lends itself well to quantification. It was felt that the only way to prioritize the multitude of potential causes for loss of product quality was to determine numerically how much each cause contributed to the loss. In this way, solid interactions between the actions taken to improve product quality and the actual events generated could be established.

Further, the fault trees are constructed using failure logic. This approach looks at how the failure of a particular basic element or set of elements can trigger a top event. For this study, the basic elements consisted of the instrumentation and equipment associated with the production, the manual operator actions, and the quality control actions. The top event was defined as something that leads directly to loss of product quality. The entire process is analyzed in a top down procedure, with each new intermediate event being broken down into its potential causes. Thus, the fault tree analysis procedure leads to a greater understanding of the true "failure logic" within the process.

Methodology

Once the team chemistry, team challenge and tools were identified the program was initiated. The documentation required for this study included:

- P&IDs
- Operating procedures
- Reports on the kinetics and thermodynamics of the reaction
- Maintenance information
- Failure rate data for the instrumentation and equipment

The Manufacturing Plant production involves a number of different reactants and additives. Each reactant or additive is made up prior to use and batched into the reactant tanks according to recipe cards. The recipes correspond to different products that are manufactured in the process unit throughout the year. Since there are so many products, the Manufacturing Plant team decided to focus on the quality control of the reactant mixture and subsequent reaction, rather than focusing on the manufacturing of an individual product that had to meet a particular specification.

The Manufacturing Plant team created a table listing all of the reactants and additives. For each reactant/additive, the following was identified:

- purpose of each reactant,
- product quality issues with each reactant, and
- what steps are taken in the process to control the reactant.

For Redox 1 addition to the reactant tanks, the table entry looked as shown in Table 1.

The fault trees were developed based on the information provided in the table and the process P&IDs. The batch manufacturing process utilized a combination of manual operator control and automatic control. This meant that it was necessary for the Manufacturing Plant Improvement Team to interview operations concerning all of the steps that they utilized to control the process and product quality. For the study to be successful, it was paramount that the effect of any applicable quality control step was considered. In this way, a quantitative representation of all of the potential failures could be determined and the true impact on the overall success or failure in product quality could be ascertained.

For the Redox 1 example, the initial fault tree was developed as shown in Figure 1. The top event is incorrect make-up of the Redox 1 solution. The immediate causes of incorrect Redox 1 make-up are as follows:

- incorrect number of bags of Redox 1 added
- incorrect amount of acid added
- incorrect metering of water into the tank
- loss of mixing in the tank, and

- loss of temperature control of the solution.

Once the fault tree structure was finalized, failure rate data was utilized with a FTA tool to quantify the fault tree. Failure rate data can be obtained from plant experience or from industry published data. For this study, the failure rate data was obtained from industry data sources and these numbers were verified with actual operating experience. The data was obtained for all field components, including instrumentation, equipment, relays, logic controllers, etc.

Examples of industry data sources are as follows:
1. (SRD) *"Safety & Reliability Directorate."*

2. *"Offshore Reliability Data Handbook,"* 2nd Edition, Det Norske Veritas Industri Norge as DNV Technica, Norway, 1992.

3. *"Process Equipment Reliability Data,"* Center for Chemical Processing Safety, NY, NY, 1989.

4. *"Non-Electronic Parts Reliability Data,"* Reliability Analysis Center, Rome, NY, 1991.
5. *"Failure Mode/Mechanism Distributions,"* Reliability Analysis Center, Rome, NY, 1991.

Since operator interactions and quality control steps are dependent on plant operation, these data were calculated from plant operating experience. For the Redox 1 example, the number of times that an operator was expected to make a mistake in the addition of the bags of Redox 1 or acid was estimated based on the experience of the Operations Foreman and Manufacturing Plant Superintendent.

Fault tree analysis involves the use of Boolean algebra for the mathematical quantification. Therefore, a computer model was used for quantification of the fault trees. The computer model selected was capable of performing the minimum cut set determination and of performing the Boolean algebra. If short-cut calculation techniques had been used, the results could have been incorrect.

When the fault tree cut sets were quantified, the results were presented to all team members for review (See Table 2). The results were examined to determine whether they matched actual plant experience. The overall probability for the Redox 1 make-up to be done incorrectly was 3.093E-03 per year. Examination of the percent contribution of the cut-sets to the overall failure rate showed that loss of agitation contributed over 75% to the failure rate. However, the manufacturing plant operational data did not indicate that loss of agitation had been a major contributor to previous off-spec Redox 1 batches.

Since the failure rate and the percent contributions were higher than was expected, the fault tree was examined to determine what might be going on in the manufacturing process to improve on this failure rate. It was determined that there were some operator verifications that had not been included. The bags of Redox 1 and the acid were added manually by the operator. The top of the make-up tanks was opened so that these chemicals could be added to the tank. When adding the chemicals, it would be readily apparent to the operator that the agitator was not moving. This meant that there was actually an operator verification of mixing. Since the water level in the tank was within the operator's viewing range and the heat from the water warmed the tank, the operator also served as verification of the water addition and temperature control. When these variables were included, the fault tree was re-drawn (Figure 2).

The Manufacturing Plant team estimated the probability that the operator would not conduct each of the operator checks. The fault tree cut-sets were then quantified. The probability of the Redox 1 make-up being incorrect decreased to 1.09E-4 per year. The percent contribution of the elements changes dramatically (Table 3). The main contributor to the failure rate was the addition of the acid and the bags of Redox 1. This matched actual plant experience.

It was determined that further improvement in the quality control in the Redox 1 make-up step could be achieved by improving the procedure for the manual addition of the Redox 1 and acid. By improving the procedure, the probability of the incorrect number of bags of Redox 1 being added or the incorrect amount of acid being injected would be reduced. Since these two items account for essentially 100% of the current failure potential, reducing the probability of the incorrect addition would have an immediate impact on the quality of the Redox 1 make-up.

The above procedure was repeated for reactant make-up step and each reactant addition step. When the assessment was complete, the Manufacturing Plant team had developed an action item list that was not based on “a magic wish-list,” but was based instead on the quantification of the potential failure events. The action item list included the following:

- Improve start-up procedures
- Improve clarity of recipe procedures
- Examine the human element involved in the flow control steps for some of the reactants
- Improve control of reactant flows more closely to insure that the reactant mix is correct
- Improve testing and maintenance frequency on several process critical components
- Provide better control of the main reaction initiator package to insure that the reaction occurs when they want it to and how they want it to

Conclusions

The Manufacturing Plant study was successful because of the comprehensive approach to the study. The assessment used an interdisciplinary team of professionals from operations, engineering, and safety. The team was challenged to think not about their own particular function but about improving the quality of the product. The impact of recommended improvements was defined quantitatively using fault tree analysis, providing sufficient justification to upper management for project approval.

The benefit of this analysis went beyond the simple quantification of the probability of making an off-spec product. The analysis was utilized to identify the weak points in the quality control system. The analysis established priorities for the Manufacturing Plant for future projects aimed at improving the Manufacturing Plant.

Additional benefit was derived from the process of taking apart the process control system bit by bit during the modeling. This enabled the project team to identify areas in which significant improvement could be made in the control system with minimal change in the normal operation of the unit.

Table 1. Example entry from the GE Plastics Manufacturing Plant Improvement Study

Flow	Purpose	Issues	Comments
Redox 1	Redox 1 is the activator for the INITIATOR	Low flow can result in retarded reaction rate, poor conversion. High flow can cause early depletion of INITIATOR, resulting in the same effects as low flow INITIATOR. Redox 1 make-ups at improper temperatures can cause problems. At the time of make-up, visual color check is done.	Redox 1 solution is made up every 16 hours or so. As stated in the issues category, the Redox 1 solution does have a finite batch shelf life.

Figure 1. Fault Tree Developed for the Redox 1 Make-up

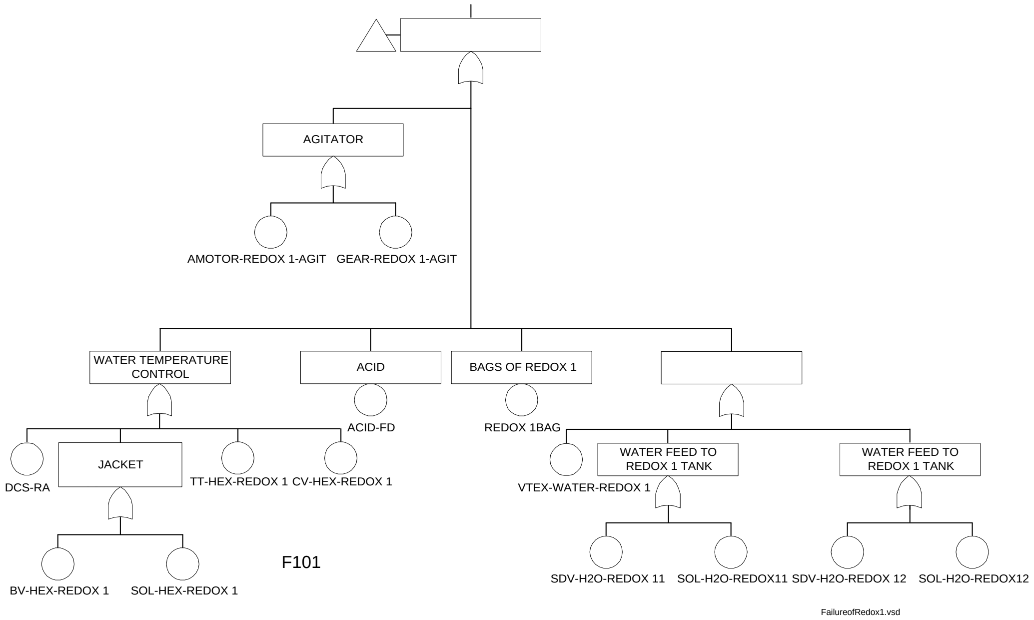

Table 2. Results of the Fault Tree Analysis of the Redox 1 Make-up

Basic Event in Fault Tree	Percent Contribution of the Basic Event to the Probability to Fail %
GEAR-REDOX 1-AGIT	75.0
DCS-RA	8.0
AMOTOR-REDOX 1-AGIT	2.4
BV-HEX-REDOX 1	1.9
SDV-H2O-REDOX 12	1.9
SDV-H2O-REDOX 11	1.9
CV-HEX-REDOX 1	1.7
VTEX-WATER-REDOX 1	1.7
REDOX 1BAG	1.7
ACID-FD	1.7
TT-HEX-REDOX 1	1.3
SOL-H2O-REDOX 12	0.3
SOL-HEX-REDOX 1	0.3
SOL-H2O-REDOX 11	0.3

Figure 2. Revised Fault Tree for the Redox 1 Make-up

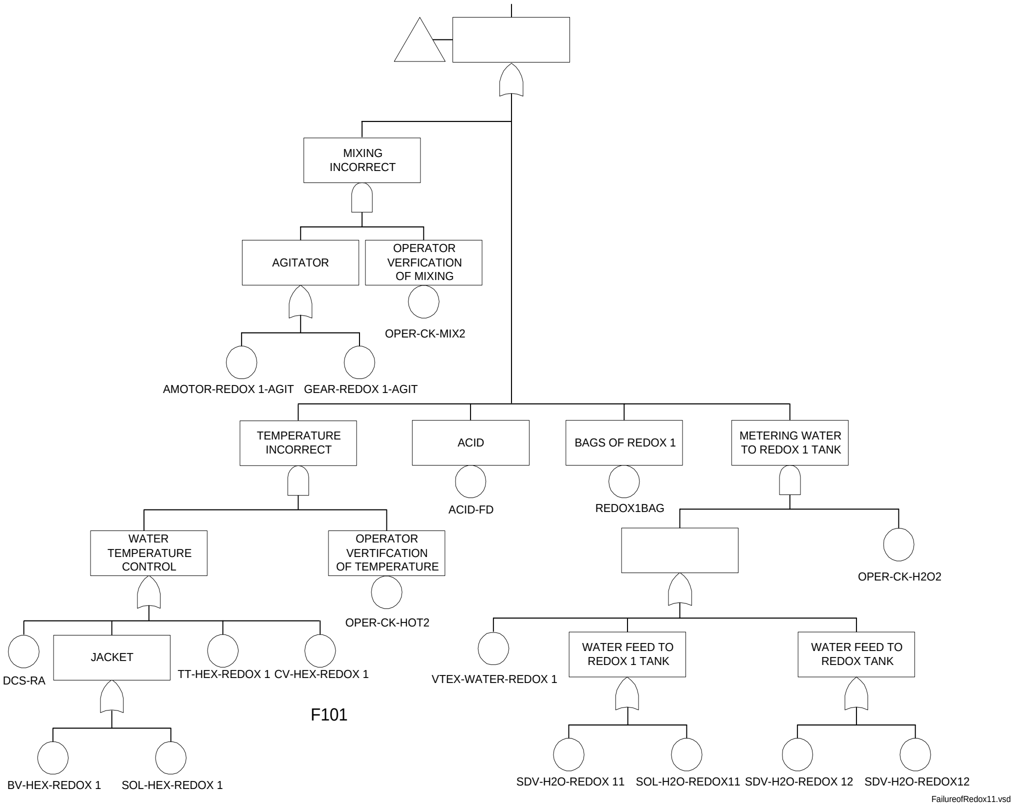

Table 3. Revised Results from the Fault Tree Analysis of the Redox 1 Make-up

Basic Event in Fault Tree	Percent Contribution of the Basic Event to the Probability to Fail %
ACID-FD	50
REDOX 1BAG	50
GEAR-REDOX 1-AGIT, OPER-CK-MIX2	0
OPER-CK-HOT2, DCS-RA	0
AMOTOR-REDOX 1-AGIT, OPER-CK-MIX2	0
OPER-CK-H2O2, SDV-H2O-REDOX 11	0
OPER-CK-H2O2, SDV-H2O-REDOX 12	0
OPER-CK-HOT2, BV-HEX-REDOX 1	0
OPER-CK-HOT2, CV-HEX-REDOX 1	0
OPER-CK-H2O2, VTEX-WATER-REDOX 1	0
OPER-CK-HOT2, TT-HEX-REDOX 1	0
OPER-CK-HOT2, SOL-HEX-REDOX 1	0
OPER-CK-H2O2, SOL-H2O-REDOX 12	0
OPER-CK-H2O2, SOL-H2O-REDOX 11	0