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Risk Based Inspection Prioritization Applied to an Ammonia Plant

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A la suite des succès dans l'application d'une approche basée sur le risque à l'exploitation de l'équipement dans l'industrie du raffinage et de la pétrochimie, une inspection basée sur le risque (RBI) a été effectuée dans une unité d'ammoniac. Les unités d'ammoniac expérimentent des mécanismes de dommage tels que l'attaque par l'hydrogène à haute température dans la section reforming et les sections de "shift conversion", le cracking avec effort de corrosion à l'amine, et réduction du CO_2 dans la section absorption/régénération de CO_2 et la corrosion externe sous insolation. Ces mécanismes de dommage ainsi que d'autres comme la fracture due à la fragilité ont été utilisés pour déterminer la probabilité d'une défectuosité dans une pièce de l'équipement. Cette information, combinée à une analyse de conséquence à servi à quantifier le risque pour chaque pièce de l'équipement. La priorité au risque à permis à l'usine de déterminer le niveau optimum d'inspection ou l'efficacité de l'inspection nécessaire pour maintenir le risque couru par l'équipement à son niveau actuel à mesure que l'équipement vieillit ou de réduire le risque subi par l'équipement si le présent niveau de risque est inacceptable. L'analyse pour l'usine de Ince a été un succès en ce sens qu'elle a confirmé les parties principales de l'usine posant problème et confirmé que les inspections effectuées dans le passé étaient efficaces. Certaines parties de l'équipement ont été identifiées comme à haut risque à l'examen et nécessitant une inspection supplémentaire le prochain examen. D'autres parties ont été identifiées comme à risque limité et, en conséquence, le plan d'inspection sur ces parties sera réduit ou les intervalles d'inspections seront allongés. L'usine sera capable d'augmenter la sécurité de l'unité en minimisant le risque par un emploi judicieux des fonds d'inspection. Les économies de coûts d'inspection et de maintenance associés ont été estimées à $ 237.500 pour un retour sur investissement (RDI) de 5:1. Les économies annualisées ont été estimées à $ 47.500 égale à une réduction de 5% du budget de maintenance et d'inspection.

Abstract

Following successes in applying a risk based approach to equipment management in the refining and petrochemical industry, a risk based inspection (RBI) assessment was performed in an ammonia plant. Ammonia plants experience damage mechanisms such as high temperature hydrogen attack in the reforming section and shift conversion sections, amine stress corrosion cracking and CO_2 thinning in the CO_2 absorption/regeneration section and external corrosion under insulation. These damage mechanisms along with others such as brittle fracture were used to determine the likelihood of failure for equipment items. This information combined with a consequence analysis was used to quantify risk for each piece of equipment. Risk prioritization enabled the plant to determine the optimum level of inspection or inspection effectiveness required to maintain the risk of equipment at its present level as the equipment ages or to reduce the risk of equipment if the present level of risk is unacceptable. The ince ammonia plant assessment was successful in that it confirmed the plant's major areas of concern and confirmed that the inspections performed in the past were effective. Some equipment items were identified as high risk by the assessment and will require additional inspection during the next

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turnaround. Other items were identified as low risk and as a result, the inspection scope on these items will be reduced or their inspection intervals will be extended. The plant will be able to increase the safety of the unit by minimizing the risk through effective use of its inspection funds. The inspection and associated maintenance cost savings were estimated at $237,500 for a Return on the Investment (ROI) of 5:1. The annualized savings were estimated at $47,500, which equated to a 5% reduction of their maintenance and inspection budget.

1. INTRODUCTION

This paper describes a project that was conducted in an ammonia plant. The goal of the project was to increase the safety of the plant by minimizing the risk. Risk Based Inspection (RBI) was used to achieve this objective by optimizing the inspection plans. By evaluating the likelihood of a failure and the potential consequences (i.e. the risks) in the fixed equipment and associated piping, inspection plans were developed to minimize operating risks. RBI offers a tool to evaluate the present risk of a plant based on past inspection history, process operating conditions and fluids, and damage mechanisms active in the plant. The present risk can then be forecast into the future and inspection, new metallurgy, new design or other mitigation efforts can be directed to the equipment items, which present the greatest risk.

The RBI methodology has been in development since the early 90's as a response to a desire by companies in the refining and petrochemical industry to develop risk based prioritization and management systems. The API RBI methodology, used in this study, was developed as an industry-sponsored project under the direction of the American Petroleum Institute (API). This methodology has gained acceptance in the refining industry during the past 3 years and more recently in other sectors of the petrochemical and chemical industries.

METHODOLOGY

In general, the RBI methodology can be qualitative or quantitative. The qualitative methodology is generally used to quickly prioritize various operating units or sections of plants based on risk and to identify the high risk systems. A more detailed analysis using a quantitative methodology can be applied to the higher risk units or sections of plants. In this way time and effort are directed to gathering data for higher risk items. The quantitative method prioritizes equipment, typically including piping, by calculating likelihood and consequence values for every piece of equipment in the system.

Quantitative Analysis

The Ammonia plant chose to apply the quantitative method. The systems included in the prioritization were the desulfurization reactors, primary and secondary reformers, CO shift converters, CO2 absorption, methanator, and NH3 synthesis. Fixed equipment and piping were included in the analysis. The project began with the collection of process, equipment and other information from the plant management database, PFDs, P&IDs, material balances, and inspection records. Each equipment item within the plant was evaluated with regard to likelihood of failure, consequence of failure and remaining life. The consequence and likelihood for each scenario were combined to obtain the risk. Both current and future risk were estimated and used to develop the risk prioritization.

Likelihood of Failure Analysis

The likelihood of failure is dependent on the environment/material interaction, actual design data, operational history, experience with this or similar services, etc. Figure 1 illustrates the different elements of this analysis. During this phase of the analysis potential damage mechanisms are identified and past inspection histories are gathered to identify active damage mechanisms and measured damage rates. The analysis is done using the systematic approach and methodology developed, as outlined in the API Base Resource Document on Risk Based Inspection (API 581) [1]. The information is analyzed using different "Technical Modules" which are a systematic method used to assess the effect of specific failure mechanisms on the likelihood of failure. The following damage mechanisms are available in the methodology.

- External corrosion i.e. general or localised atmospheric corrosion, corrosion under insulation (CUI) etc and external cracking for austenitic stainless steels.
- Internal corrosion i.e. general and localised corrosion in various environments (hydrocarbons containing water, sea water, water-injection systems, amine treating, CO2, hydrochloric-, sulfuric-, and hydrofluoric acids)
- Stress corrosion cracking in various environments (caustic, amine, chlorides, H2S, etc.)
- High temperature phenomena (oxidation, hydrogen attack, thermal fatigue)
- Fatigue caused by vibration and flow effects (slugging/choking)
- Brittle fracture (low temperature/low toughness fracture, temper embrittlement, 885 degree embrittlement, and sigma phase embrittlement)

The damage mechanisms of particular concern in the ammonia plant study included external corrosion, corrosion under insulation, high temperature oxidation, high temperature hydrogen attack, carbonic acid thinning and amine cracking. Each of these damage mechanisms is handled by a Technical Module presently in the software.

The calculation method for likelihood of failure associated with the failure mechanisms is based on Structural Reliability Analysis (SRA) [2], where the stochastic uncertainty in the basic variables, in particular the uncertainty in the determination of the damage rate and the inspection effectiveness, are taken into account. An important feature of this theory is its ability to include both the prior damage estimates and the outcome from the inspections in the derivation of the updated posterior likelihood of failure (Bayes' Theorem).

The level of information gained from an inspection depends heavily on the quality and extent (coverage) of the inspection carried out. The inspection quality is modeled either by discrete probabilities for the inspection effectiveness for the inspection method applied.

Consequence Analysis

A simplified consequence modelling methodology is applied, similar to that used in a traditional Quantitative Risk Assessment. The methodology is based on an event tree approach and uses pre-simulated effect-scenarios to simplify the calculational time required for analysis. The following factors are considered in the consequence calculation: fluid type and phase, toxicity, inventory available for release and type of leak (leak/rupture). The consequence effects are reported as four main consequence categories, as follows:

- Flammable events (fire/explosion resulting in personnel injury and equipment damage)
- Toxic releases (personnel injury)
- Environmental risks (cost of environmental clean-up)
- Business interruption (lost/deferred production) and asset repair after failure

The consequence of flammable and toxic events are typically used to calculate risk based on personnel safety and equipment damage. Another method of measuring consequence is financial. Cost data related to lost production, outage, asset repair, adjacent repair and environmental clean-up are used to calculate financial risks.

2. RISK RANKING

Risk is a function of likelihood and consequence of failure. In a RBI analysis, each of consequence and likelihood of failure are categorized in 5 groups giving a total of 25 risk combinations. A risk matrix is an effective way of representing the risk combinations. Each piece of equipment can be placed on the matrix. It allows comparison of plant risk at a given point in time and helps prioritise the risk reduction efforts for different levels of risk (Figure 2).
The consequence of failure was reported in two main categories; one related to personnel safety and one related to economic losses. A target level of acceptable risk, or risk criteria, was determined. The acceptable level of risk was used to determine an acceptance line in the risk matrix. For components above the acceptance line, steps were taken to reduce the risk. For components below the acceptance line, other options exist such as using the financial risk to optimize the risk reduction effort. This risk matrix was used to direct inspection/maintenance planning as described in the next section. Performing inspection reduces likelihood of failure. Reduction of the consequence was limited to reduction by improved detection and mitigation systems.

3. RISK BASED INSPECTION PLANNING

RBI planning involves focusing the inspection efforts in order to reduce risk of failure. Therefore, an essential part of RBI planning is to establish the most cost-effective approach of satisfying the failure acceptance or acceptable likelihood of failure criteria. The key to RBI planning is to use the method of probabilistic inspection updating, as a central part of the RBI concept. The methodology to establish the inspection interval is based on selected combinations of inspection methods i.e. inspection effectiveness, number of inspections and inspection intervals that can ensure that the risk (area or financial risk) is reduced by a certain factor depending on the location in the Quantitative Risk Matrix, as shown in Figure 3. Part of the likelihood of failure analysis involves assigning levels of effectiveness for past inspections. The effectiveness of the inspection methods to detect the damage mechanisms is evaluated and characterised based on five inspection effectiveness categories: Highly effective, Usually effective, Fairly effective, Poorly effective and Ineffective. Assignment of categories is based on professional judgement and expert opinion. These categories are applied during the RBI planning. The starting point to evaluate different inspection programs is to calculate the likelihood of failure for the different damage states, accounting for the previous inspection results and the maintenance history of the equipment.

One of the most important criteria is the capability of the inspection methods to detect the characteristics of the relevant damage mechanisms. The damage mechanisms considered cover:

- Thinning (external corrosion, corrosion under insulation (CUI) and internal corrosion)
- Surface-connected cracking
- Subsurface cracking
- Microfissuring/microvoid formation
- Metallurgical changes
- Dimensional changes
- Blistering
- Material property changes

Study Results

The RBI assessment performed included 144 fixed pressure vessels (vessels, columns, exchangers and air coolers) and 180 piping items. The following degradation models were identified as being active mechanisms in the plant: Internal Thinning, Atmospheric Corrosion, Corrosion under Insulation, High Temperature Hydrogen Attack and Creep.

Likelihood of failure, consequence of failure (loss of containment/leaks) and risk were calculated in terms of injury to employees and equipment damage. Current (1999) risk values were calculated and the current risk matrix is shown in Figure 4. The ammonia plant risk levels are typical in that 10 to 20% of equipment in the ammonia and refining industry fall into the High Risk category. The equipment items that calculated to be in the High Risk category included 15 piping items, 2 vessels, 1 exchanger and 1 heater. Table 1. summarizes the damage mechanisms and susceptibility for the top ten risk items.

Table 1. Top Ten High Risk Items

Equipment Type	Description	Risk Value	Primary Damage Mechanism	Likelihood Factor	Consequence Factor	Likelihood Category	Consequence Category
EXCHANGER	Reformer Gas Boiler-Shell	3330	HTHA	1800	11860	5	E
HEATER	Primary Reformer Tubes	1104	Creep	5000	33457	5	E
VESSEL	Ammonia Converter	950	HTHA	800	7610	4	E
VESSEL	Purge Gas Ammonia Stripper	204	Internal Thinning	265	4933	4	E
2" PIPE	NH3 Stripper	4	Internal Localized Thinning and CUI	485	2381	4	E
4" PIPE	Syn Gas Chiller	4	Internal Thinning and CUI	96	26097	3	E

2" PIPE	NH3 Synthesis Secondary Separator	4	Atmospheric Corrosion	525	1788	4	E
2" PIPE	Ammonia Refrigeration	4	CUI	260	2840	4	E
16" PIPE	CO2 Absorption	2	Internal Localized Thinning	801	5881	4	E
16" PIPE	CO2 Absorption	1	Internal Localized Thinning and Atmospheric Corrosion	706	5853.	4	E

The corresponding risk for a five year look-ahead was calculated assuming that no inspections would be done during this time period. The projected future risks with no inspection are presented in Figure 5. Of the 336 pieces of equipment, 10% (32 pieces) of the equipment items were projected to rise from an acceptable level of risk into the unacceptable level by year 2005. An inspection plan was developed that directed the inspection efforts toward items above the unacceptable risk level. The prioritization enabled the plant to determine the optimum level of inspection or inspection effectiveness required to maintain the risk of equipment at its present level as the equipment ages or to reduce the risk of equipment when the present level of risk is unacceptable. Table 2. shows some typical inspection planning recommendations that resulted from the RBI analysis.

Table 2. Inspection Planning Recommendations.

Equipment ID	Description	Risk Rank	Likelihood Driver	Damage Factor without Inspection by 2005	Damage Factor with Inspection by 2005	Recommended Internal Thinning Inspection Level	Comments
Exchanger	Reformer Gas	High	HTHA, Highly suscep-tible	2000	800	2B	Maximum interval of 2.5 years to maintain factor of 400 minimum value only (for CS only). The recommended inspection technique involves a combination of Backscatter, Velocity Ratio, and Spectrum Analysis followed up with field metallography. See Inspection Effectiveness Tables for HTHA.

12" -Pipe	NH3 Synthesis Preheat	High	Atmospheric Corrosion	520	20	1A	Inspection for External Thinning only. This may include UT thickness measurements and visual inspection. See inspection effectiveness tables for external corrosion of non-insulated equipment.
8"-Pipe	Desulfuri-zation	Medium High	Atmosphe-ric Corrosion	125	35	1B	Inspection for External Thinning only. This may include UT thickness measurements and visual inspection. See inspection effectiveness tables for external corrosion of non-insulated equipment.
10" -Pipe	Desulfuri-zation	Medium High	Internal Localised Thinning	290	20	1A	Inspect for actual thickness with spot UT and update the age and rate of corrosion. Possible UT scanning for localised corrosion.

Implementation of the inspection planning recommendations developed by DNV together with plant personnel will result in a projected risk profile for the year 2005 as shown in Figure 6. This ammonia plant showed a large number of low likelihood/high consequence items. Since inspection planning only addresses likelihood of failure, reducing the risk associated with these items would require additional consequence mitigation or detection efforts. The RBI analysis also confirmed that past inspection efforts at the ammonia plant have been effective in minimizing the risk to personnel and equipment. The benefits of implementing the inspection plan can also be seen in Table 3. which summarizes the current and future risk projections before and after inspection. The inspection and associated maintenance cost savings were estimated at $237,500 for a Return on the Investment (ROI) of 5:1. The annualized savings were estimated at $47,500, which equated to a 5% reduction of their maintenance and inspection budget.

Table 3. Current and future risk projections before and after inspection

Risk Rankings	Current (1999)		Year 5 (2005) Before inspection		Year 5 (2005) After inspection	
	Items	% of Total	Items	% of Total	Items	% of Total
High	19	5.65	24	7.14	20	5.95
Medium High	185	55.06	187	55.65	181	53.87
Medium	78	23.21	75	22.32	82	24.40
Low	54	16.07	50	14.88	53	15.77
Total	336		336		336	

4. CONCLUSIONS

Risk Based Inspection is a subset of a Risk Based Management system. It gives management the tools it needs to make cost/benefit decisions regarding inspection and inspection related maintenance activities.

Risk is a good criterion for prioritizing inspection efforts because:
- Highest priority items are easily identified as the highest risk items
- Risk can be measured in personnel safety and economic terms
- Inspection and maintenance activities can be justified on a cost/benefit basis

API RBI is an effective tool for prioritizing inspection for the ammonia industry. For likelihood of failure analysis, damage mechanisms such as localized thinning due to CO_2, HTHA, amine stress corrosion cracking, and corrosion under insulation which are active in ammonia plants are found in the RBI technical modules. For consequence analysis, the toxic effects of ammonia and fluids typically handled by ammonia plants are also found of the RBI consequence model.

5. REFERENCES
[1]   API Committee on Refinery Equipment: *"Base Resource Document on Risk based Inspection"*. Prepared by DNV Industry Inc. Houston Texas January 1998.
[2]   Madsen, H.O., Lind, N.C. and Krenk, S., *"Methods of Structural Safety"*, Prentice-Hall,

Engelwood Cliffs, N.J. 1986
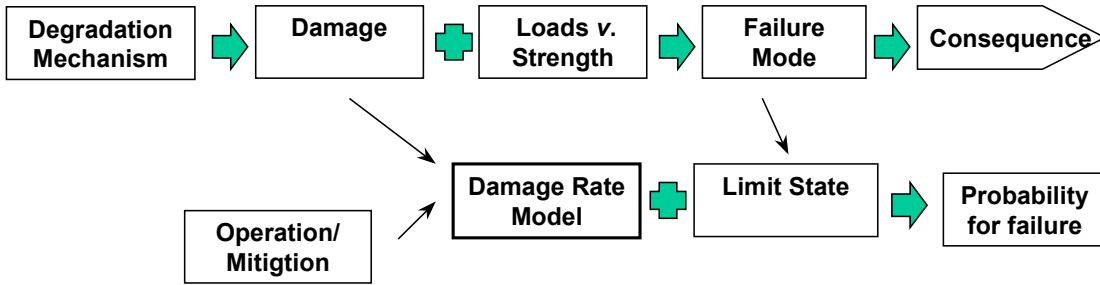
Figure 1.   Elements in the Probability of Failure modelling
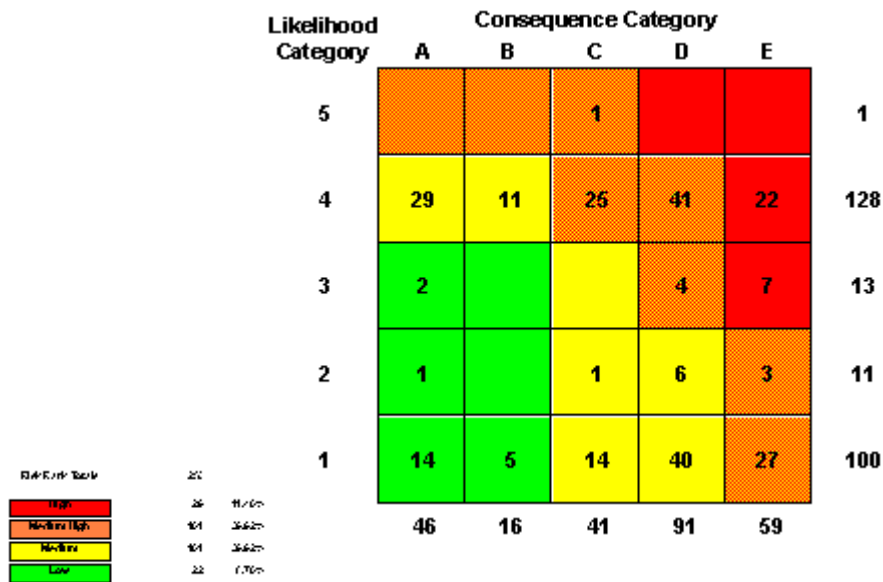
Figure 2.   Risk ranking matrix with typical equipment distribution for the quantitative method

Risk reduction factor

	A	B	C	D	E
5	3	3	5	10	25
4	2	2	5	5	25
1	1	1	2	5	10
2	1	1	1	1	2
1	1	1	1	1	2

Likelihood category

Consequence category

Figure 3. **Risk reduction factors for establishing inspection effectiveness, number and frequency of inspection for the quantitative method**

AMMONIA PLANT - CURRENT RBI STATUS

Risk Rank Count

Consequence Category							
		A	B	C	D	E	
Likelihood Category	5	6		1		2	9
	4	18	5	2	4	11	40
	3	3	4	4	1	6	18
	2	6	5		5	24	40
	1	21	15	9	37	147	229
	Totals	54	29	16	47	190	
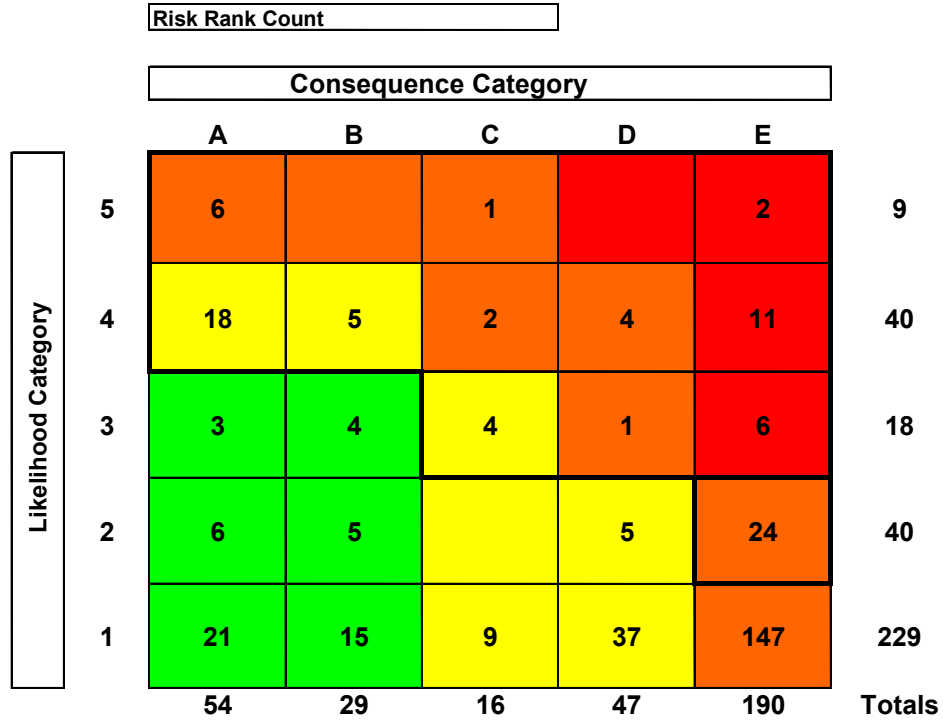
Risk Rank Totals		% Risk
High	19	5.65
Medium High	185	55.06
Medium	78	23.21
Low	54	16.07

Ranges

Consequences		Likelihood	
<=100	A	<= 2	1
<= 1000	B	<= 20	2
<= 3000	C	<= 100	3
<=10000	D	<= 1000	4
> 10000	E	>1000	5

Figure 4. Ammonia Plant – Current (Yr 1999) RBI Status
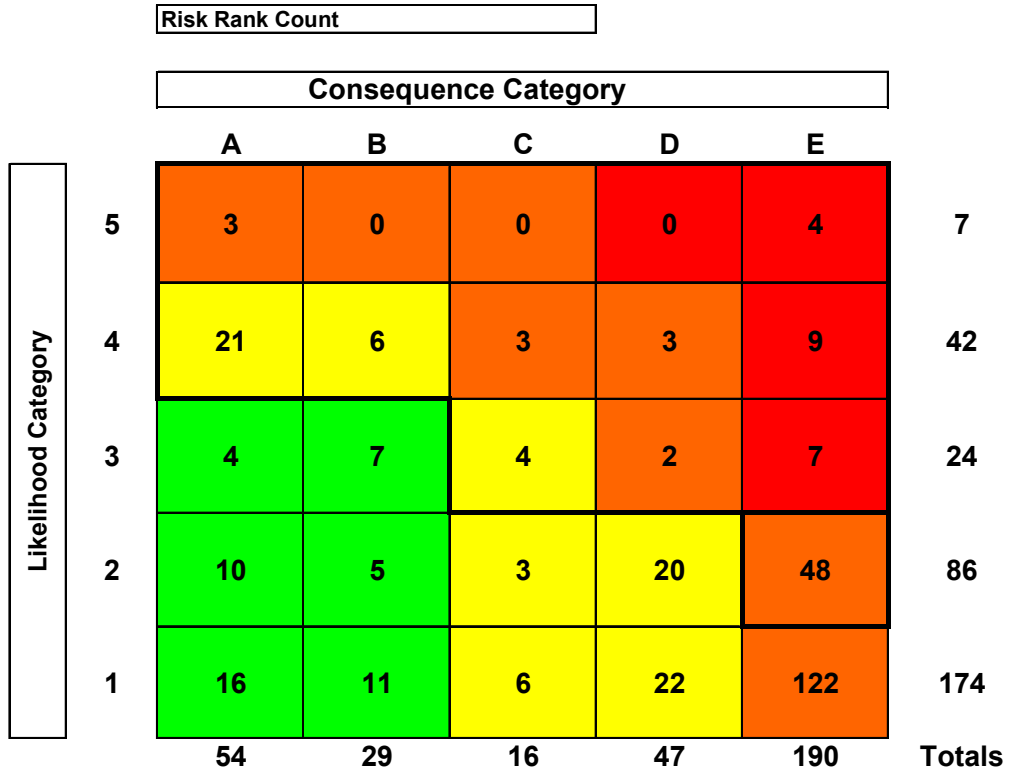
AMMONIA PLANT - 2005 NO INSPECTION

Risk Rank Count

Consequence Category

	A	B	C	D	E	
5	9		1	1	4	15
4	16	8	3	5	14	46
3	3	5	3	2	5	18
2	10	5	3	17	45	80
1	16	11	6	22	122	177
	54	**29**	**16**	**47**	**190**	**Totals**

Likelihood Category

Risk Rank Totals		% Risk
High	24	7.14
Medium High	187	55.65
Medium	75	22.32
Low	50	14.88

Ranges			
Consequences		**Likelihood**	
<=100	A	<= 2	1
<= 1000	B	<= 20	2
<= 3000	C	<= 100	3
<=10000	D	<= 1000	4
> 10000	E	>1000	5

Figure 5. Ammonia Plant – Yr 2005 RBI Projection Without Inspection

AMMONIA PLANT - 2005 WITH INSPECTION

Risk Rank Count

		Consequence Category					
		A	B	C	D	E	
Likelihood Category	5	3	0	0	0	4	7
	4	21	6	3	3	9	42
	3	4	7	4	2	7	24
	2	10	5	3	20	48	86
	1	16	11	6	22	122	174
		54	29	16	47	190	Totals

Risk Rank Totals		% Risk
High	20	5.95
Medium High	181	53.87
Medium	82	24.40
Low	53	15.77

Ranges			
Consequences		**Likelihood**	
<=100	A	<= 2	1
<= 1000	B	<= 20	2
<= 3000	C	<= 100	3
<=10000	D	<= 1000	4
> 10000	E	>1000	5

Figure 6. Ammonia Plant – Yr 2005 RBI ProjectionWith Inspection