AN INTEGRATED APPROACH TO ESTABLISHING THE HAZARDS, RISKS AND CONTROLS AT A MAJOR COPPER SMELTING SITE IN SOUTHERN AFRICA

Roderick Prior, Principal Consultant, SHExellence cc, South Africa

A major copper smelting site in Southern Africa was concerned about the process safety risks (in particular explosions and toxic releases) on the site. Site management requested an analysis of these risks and the adequacy of the related controls / safeguards. The author was contracted to do the work. Incidents had occurred in earlier years. The Site had undergone process safety training including senior management training.

The main plants on the site are:

- Hot Metals Section including smelting and conversion
- Sulphuric Acid production
- Two Oxygen Plants
- Slag Plant
- Effluent treatment

The plants varied in age from 50 years to 5 years.

The Site processes complex copper concentrate to a 98.5% blister copper. It employs around 1000 people. Numerous hazardous chemicals are stored and used.

The initial phase of work involved doing HAZOPs across all site activities. Where information was lacking, a HAZID approach was used. HAZOPs were of both the continuous and batch variety. Risk Assessments were done for each scenario. This allowed the major risks to be highlighted.

A number of health risks were identified on the Site. These included sulphur containing gases from the acid plant.

In a second phase the 12 highest risks were selected from the initial phase work which had revealed 52 major risk scenarios.

These were subjected to an intensive analysis as follows

- Fault Ttree analysis for full understanding of the cause structure
- Bow Tie analysis to identify existing barriers and barriers that were needed for each selected scenario.

The potential for major explosions in the Oxygen Plants and Smelter was recognised as a major threat.

In addition to the several hundred actions identified during the HAZOP phase, 47 actions were identified during the Fault Tree / Bow Tie phase. The actions identified in the second phase were largely different to those of the first phase. This shows the importance of using all the PSM techniques together to extract maximum value. Some actions like testing trips and eliminating bypassing of trips were seen as critical in improving safety.

In addition, the adequacy of the occupied buildings was evaluated using the CIA (UK) approach. The risk data from the analyses were used as a significant input to the evaluation. It was found that almost all buildings (some quite old) were unacceptably close to major hazards. Recommendations were made to management to improve the situation.

The different analytic Process Safety techniques fitted well together. The paper illustrates how this was done, problems that were encountered and some of the findings that were made. The author believes that the positive and negative experience gained in this recent project will be of value to others working in the risk management area. The work was carried out in 2018/2019.

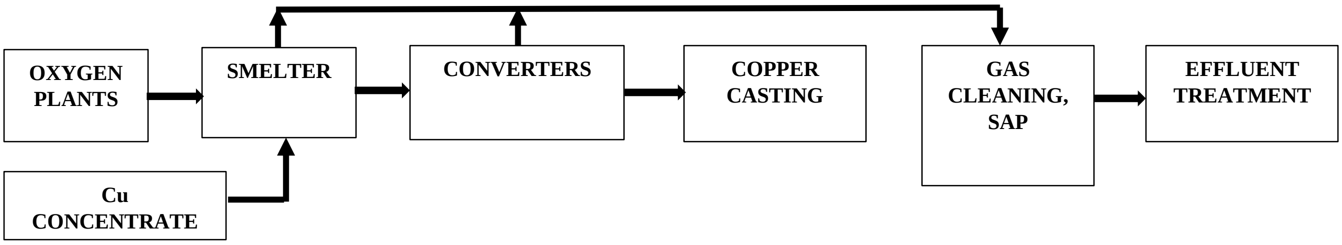
KEYWORDS: Hazard Identification, Risk Assessment, Occupied Buildings

1. INTRODUCTION

A major copper smelting operation in Southern Africa, employing around 1000 people, processes copper concentrate through a number of process steps to 98.5% pure blister copper. The main process units are listed below and shown in Figure 1:

- Hot Metals Section including smelting and conversion
- Sulphuric Acid production
- Two Oxygen Plants
- Slag Plant
- Effluent treatment

Figure 1 Process Flow diagram showing major process steps



The plants range in age from old (50 years) to new (5 years). There have been incidents in the past, mainly toxic gas escapes, and explosions in the smelter / convertors. A large fire occurred fairly recently involving the storage of large quantities of PAX (sodium n-propyl xanthate).

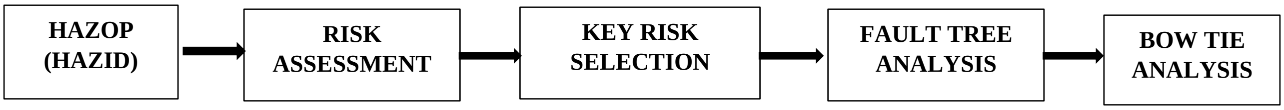
Management was concerned that the major hazards on the site may not have all been identified and that safeguards might be inadequate. The author was contracted to address these concerns. The work took place over four visits of about 3 weeks duration each time.

HAZOPs had been carried out on most of the plants, but some studies were very old.

2 THE METHODOLGY

The sequence of analytic steps used in the Study is shown in Figure 2 below:

Figure2 Analytic Studies used in the Hazard and Risk Analysis on the Copper Processing Plant



2.1 HAZARD IDENTIFICATION

It was decided at the beginning of the project that full HAZOPs would be done on each unit. Although previous HAZOPs existed in one form or another, they were of varying age and quality. The best approach was to start from scratch and generate a consistent set of HAZOP studies which would be a sound basis for later risk assessment and analysis. Full recording was employed. The HAZOP deviations used were the author's generic set.

For most of the plants, the continuous form of the HAZOP was fully applicable. Although the Piping and Instrumentation Diagrams were at least five years old, they were sufficiently accurate to do the studies. However, in some areas, namely the Smelter and Gas Cleaning, new P&IDs had been recently produced but were not well done and it was decided to take a HAZID approach. This higher-level hazard identification was conducted largely informally to supplement the detailed HAZOP questioning and worked well.

Where major items of equipment were concerned, start up, shutdown and important stages like slag / metal pouring steps were considered using the batch form of HAZOP. This was also done informally but it was found easy to integrate these steps within the framework of the continuous HAZOP process.

2.2 INITIAL HAZOP FINDINGS AND ACTIONS

The HAZOP Studies generated a very high level of recommendations, namely 675, with the majority (255) arising in the Gas Cleaning, Sulphuric Acid Plant and Effluent Treatment Plants. These are shown in Table 1 below.

Table 1 HAZOP Recommendations by Plant

PLANT	NO OF RECOMMENDATIONS
OXYGEN PLANT	140
SMELTER	134
CONVERTER PLANT	47
GAS CLEANING, SULPHURIC ACID, EFFLUENT TREATMENT	255
SLAG PLANT	99
TOTAL	675

There are many manual operations and many recommendations were aimed at automating manual tasks. This has both safety and operational advantages. Many recommendations were about verifying and improving the Preventative Maintenance activities and gaining more knowledge of aspects of plant operation. The high number of recommendations probably reflects the age of much of the equipment, many manual tasks and inadequate previous hazard studies. The fields of hardware (plant), systems and people were all covered in suggested actions.

Some previous HAZOP Study Reports were available, but these were not directly used. The author has found that trying to compare studies is difficult, time consuming and can obscure the fresh approach that is being undertaken.

Major common issues and resulting risks across the plants included:

- Many more Safety Instrumented Systems (trips) to avoid reliance on human interventions.
- Presence of redundant plant leading to increased chances of human error
- Explosion risks in and around the furnace / converters due to inadvertent water contact with molten metal
- The unknown reliability (SIL value) of trips, no testing of trips and a practice of bypassing trips.
- Possible gas explosion at burners
- Release of sulphur dioxide and sulphur trioxide on site and to surrounds
- Presence of hydrogen gas in several places
- Oxygen Plant explosions in the cold box
- Shortage of critical spares

2.3 RISK ASSESSMENT

The Company Risk Matrix was used to evaluate all the risks. This is shown in Appendix 2. It was relatively straight forward to carry out the risk rating. This was done partially by the HAZOP team and by the Study Leader. It was found to be disruptive to the HAZOP process to risk rate during the actual deviation analysis. Where the risks were rated solely by the Team Leader, these were referred back to the team on the next day and agreed or amended.

High risks were seen as those causing fatalities, significant business loss, serious environmental damage and where there was a reasonable probability of the event happening (actual plant history and other plant incidents)

The risk assessment resulted in the following results as shown below in Table 2:

Table 2 Risk Assessment results

Risk Level	Number of Risks
HIGH RISK	52
MEDIUM RISK	231
LOW RISK	655
TOTAL	938

2.4 SELECTION OF KEY RISKS

The client had specified that the highest 12 risks on the Site should be studied further to ensure the causes of the events were fully understood and that the adequacy (or otherwise) of the barriers / safeguards was well established. Out of the 52 high risks identified in the HAZOP Studies, 12 were selected as presenting the highest risks in terms of multiple fatalities, fatal effects of toxic substances and loss of production / assets / profits. The only environmental aspect was considered in the release of SO_2 / SO_3.It was possible to combine a few of the risks. It was noted that the balance of the high risks should be addressed as soon as time and resources permitted.

The 12 risks selected for analysis are shown in the Table 3 below:

Table 3 Identified Key Risks

PLANT	CAUSE	WORST CASE CONSEQUENCE
OXYGEN PLANT	Air blockage for various reasons	Compressor damage, filter implosion
OXYGEN	Dry vaporisation of GOX	Large explosion
OXYGEN	Excess hydrocarbons in column	Large explosion
SMELTER	High bath level, other overflows/leaks	Fire / explosion
SMELTER	No cooling water, trapped water	Water / metal explosion
CONVERTER	Ladle spills – various reasons	Explosion with water, burns
CONVERTER	Charge matte on oxide, charge skulls	Violent reaction, foam, metal spillage

CONVERTER	No cooling water, high pressure	Steam produced, leaks & explosion
GAS CLEANING / ACID / ETP	H2 production in various parts of plant	Explosion, fatalities, plant damage
GAS CLEANING / ACID / ETP	SO2 Converter bed holed, leaks in HE	Major SO2 & SO3 emissions
SLAG	Poor storage / handling of PAX	Fire, explosion, toxic release

2.4 METHODOLOGY FOR ANALYSIS OF KEY RISKS

Although the HAZOPS had revealed many of the scenario causes, it was felt that some causes may have been omitted, were unclear or not sufficiently fundamental. It was proposed and accepted that a Fault Tree Analysis should be employed to systematically expose the root causes for each scenario.

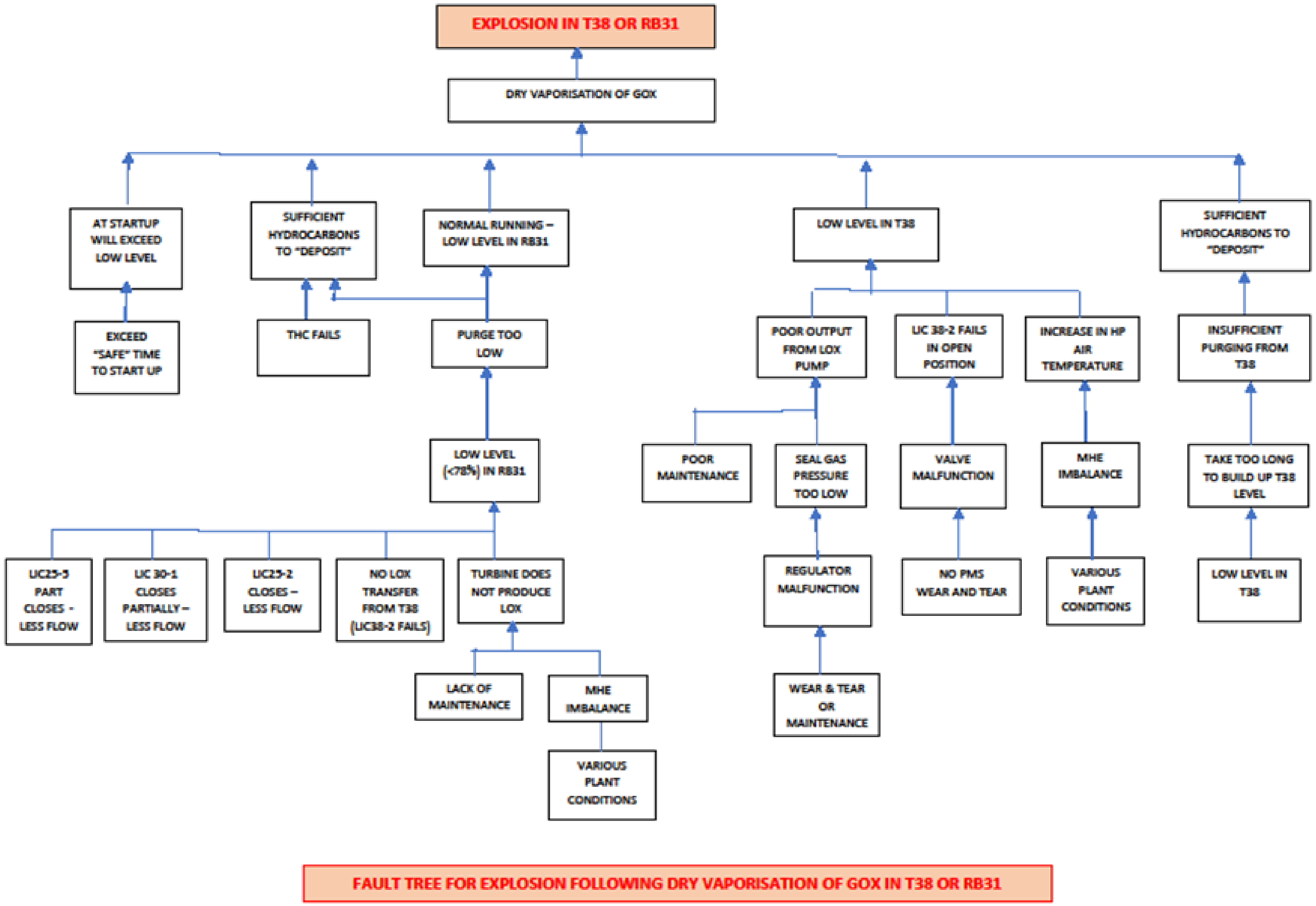
The Bow Tie analytic method was chosen to analyse the adequacy of barriers. Following the Fault Tree Analysis for a particular risk, a Bow Tie Analysis was performed by the team. Again, this was done using “sticky notes” and drawing sheets. No propriety software was used. The CCPS book “Bow Ties in Risk Management (2018)” was used as a guide (Ref 1). It was felt that the Bow Tie approach was particularly suitable for this step as it is highly visual, facilitates teamwork and can be rapidly modified as needed.

2.5 FAULT TREE ANALYSIS (FTA)

For each risk the “top event” was chosen. This was normally a major loss of containment. The direct causes of the event were determined by discussion. In turn, each cause in every layer was analysed in the “cause – effect” mode to determine the underlying layer of causes. In general, the analysis went down 5 layers to where “root causes” could be unearthed. Some of the fault trees were quite complex and, in the report, had to be split into two or three Fault Trees which then need to be combined for complete understanding of the incident cause structure. Every attempt was made to make the analysis as comprehensive as possible. Root causes were sought in the areas of equipment, systems and people.

An example of one of the simpler Fault Trees is shown below in Figure 3.

Figure 3 Fault Tree for Explosion in the Oxygen Plant following dry vaporisation of gaseous oxygen in the vaporiser / reboiler



2.6 ANALYSIS OF THE KEY RISKS USING BOWTIE (BTA)

The "top event" was taken as the major loss of containment in the scenario. With the input from the relevant HAZOP and the Fault Tree Analysis, threats (causes) were selected and consequences defined. Consequences included the worst-case scenarios without consideration of the very low frequencies with which they may occur. The HAZOP also provided much of the input to define "Preventative Barriers" and "Mitigating Barriers". However, the team and particularly the operating personnel supplied a lot of the barrier input.

The Bow Ties were split into two halves to fit on report pages. The Left-Hand Side (LHS) of the threats (causes) and the Right-Hand Sides (LHS) of the consequences need to be joined to present the full Bow Tie picture.

"Degradation Factors" (those conditions which can affect the performance of a preventative or mitigating barrier) were identified for many but not all the barriers. These are shown in pink blocks in the BTA. Several generic degradation factors were found. There was only a passing examination of "Degradation Controls" as this would have made the Bow Tie Analysis extremely complicated and extended the study considerably.

When the Bow Tie was completed, the group considered the adequacy of the barriers. This was done in a subjective manner including comparison to best practice in similar companies and others in related fields. The proposed new barriers are largely different to the recommendations for improvement made in the HAZOP studies.

The Bow Tie Diagrams were constructed manually without using software. This was very time consuming and is not recommended.

To be absolutely clear as to whether new barriers are needed a quantitative set of LOPA – SIL Determinations would have to be carried out.

An example of the detailed Bow Ties created is shown below. The cause side (Left Hand Side) and consequence side (Right Hand Side) need to be "joined up" to show the full Bow Tie. Figures 2 and 3 illustrate the two parts of the Bow Tie.

Figure 2 Bow Tie (Left Hand Side) for the explosive contact between molten metal from the Smelter and Water

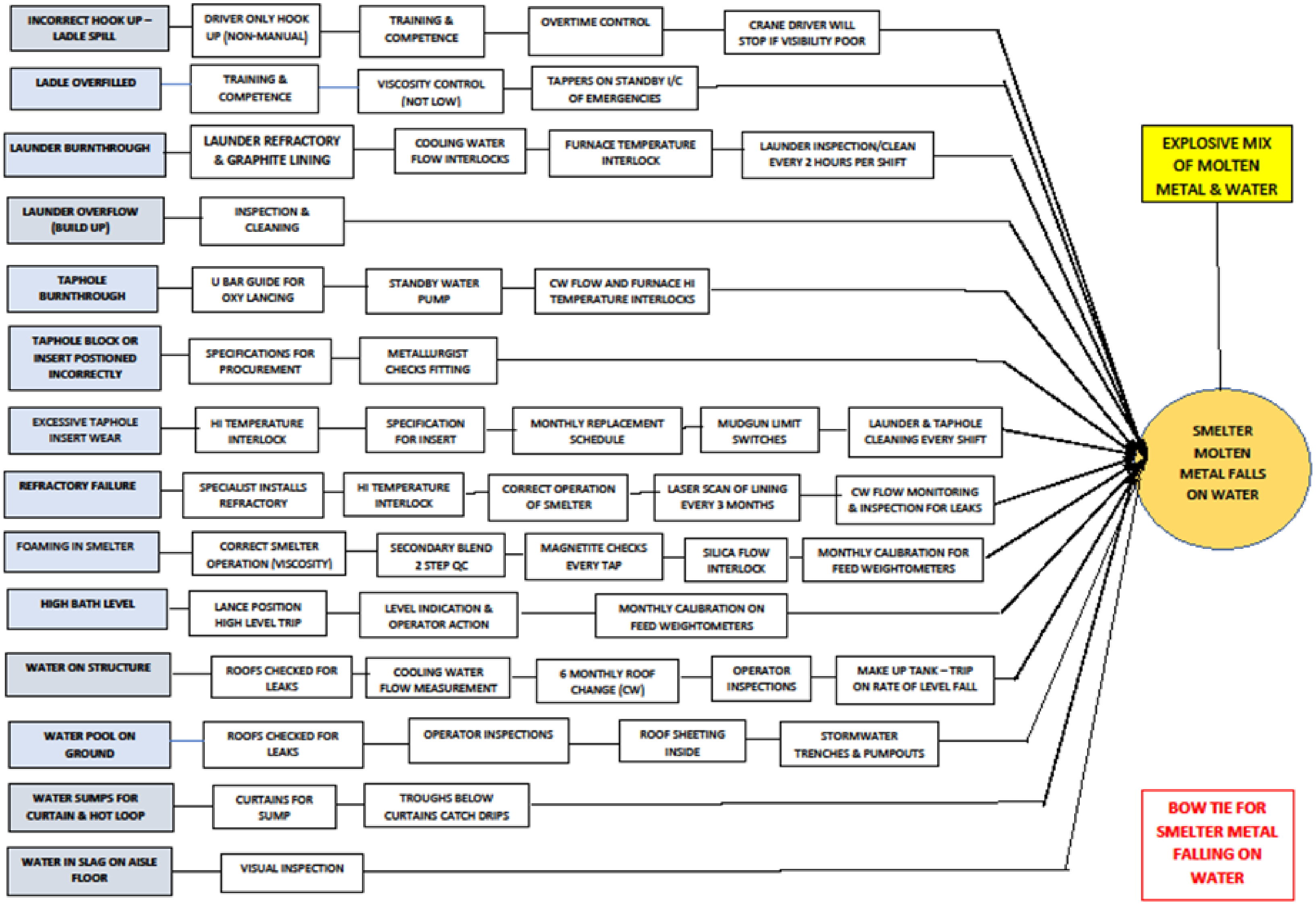
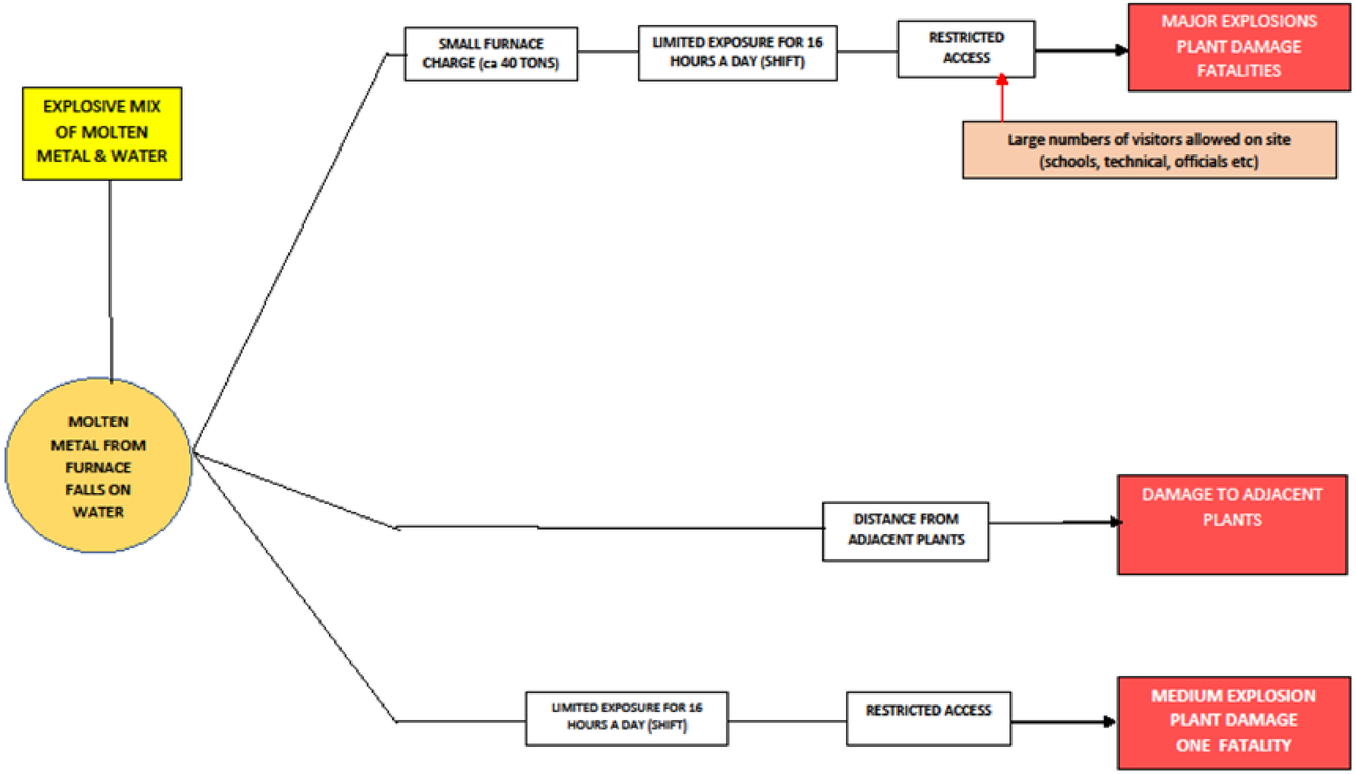


Figure 3 Bow Tie (Right Hand Side) for the explosive contact between molten metal from the Smelter and Water



3. RESULTS AND FINDINGS

47 Additional recommendations were made during the FTA / BTA stages. These differed from the earlier HAZOP findings in that they tended to be broader, "bigger picture" actions usually in the form of further barriers. These recommendations also covered the three areas of plant, systems and people. The combination of HAZOP and FTA / BTA produced a more comprehensive set of actions which appears superior to either exercise carried out alone.

Degradation Factors for many barriers were considered. Where a trip / interlock was the prime preventative barrier, the issues of lack of testing and unknown design reliability were seen as serious degradation issues.

Lack of information on aspects like the maximum level of hydrocarbons allowable in the Oxygen Plant cold box meant that a very practical approach was needed with input from plant designers and reports on incidents in the industry. The size of a possible incident here was very difficult to establish.

For some scenarios many possible causes were found. These resulted in very large Fault Trees. One example was the molten metal / water explosion risk which, effectively, had to be split into three Fault Trees which need to be combined for a full understanding of the scenario.

The analyses highlighted the need for consistent high-quality Preventative Maintenance, operator training, paying attention and better visibility in areas where metal fumes are produced.

A thorough understanding of the metallurgy of smelting and converting specific copper concentrates was also recognised as a core competence to prevent incidents.

For the scenario of SO2 / SO3 leaks which could affect people living outside the site, many preventative barriers (7) were noted. The lessons from the Texas City disaster (2005) where 12 barriers appear to have failed were noted by the team to bring realism to how good barriers might be or not be.

The scenario of a sodium n-propyl xanthate (PAX) fire / explosion incident at the Slag Plant revealed that the preventative barriers were weak and needed reinforcement. The Site had experienced a major fire with this material a few years ago.

4. OCCUPIED BUILDINGS

The Site was concerned that occupants of buildings close to process and storage hazards are being exposed to unacceptable risks. These risks could be associated with explosions, fires and toxic gases. The buildings include control rooms, offices, workshops, meeting rooms and warehouses.

The Chemical Industries Association book (2011) on occupied buildings (Ref.2) was used as a guide for this work.

A related exercise was carried out on the safety of the occupied buildings on the site. Information from the studies (largely input from the HAZOPS) was used to roughly dimension the impact zones from the possible incidents.

Specific explosion sources and mechanisms were determined. Fire sources and releases of sulphur dioxide and sulphur trioxide were also considered. The position and number of occupants of buildings close to these hazards was determined. Worst case scenarios were considered for the hazardous events. It was impossible to calculate the sizes of explosions but, by comparison to past incidents elsewhere, it was possible to estimate what the worst-case impacts might be.

It was concluded that Oxygen Plant explosions, followed by molten metal / water explosions, would create the most serious consequences. The likelihood of major Oxygen Plant incidents was low but many hot metal / water incidents are experienced worldwide. Following this work, a major Air Separation explosion took place in July 2019 in China where 15 people died.

The buildings at the Site have not been constructed to withstand any size of explosion or the impact of major fires and toxic gases. The buildings have also been placed for convenience and available space but with no regard for protection against major incidents. The main construction method was a single or double layer of bricks and large glass windows. A large number of people in buildings are within 100 meters of the Oxygen Plant cold boxes. The Emergency Services are 50 meters away. In the event of a major oxygen event, they would be needed but could well be incapacitated. Some control rooms are within 10 meters of the major hazard. The main offices are within the danger zone of the Oxygen Plant.

The Site has taken the initiative to move the Smelter control room operator from being on the plant with no real protection to a building about 50 meters away.

It was recommended that people should be moved away and that buildings be strengthened to reduce the risk. Some low-cost options are possible. In particular, glass windows should be replaced by polycarbonate windows, external or internal posts to strengthen the brickwork, stee, panels added to the building sides or spray-on coatings to add to the building strength. The Report contains much technical information to assist in the judgement calls which will be needed in the future

5. OVERALL CONCLUSIONS

To establish the top risks on a large site required the application of several process safety techniques / methodologies. These were:

HAZOP – both continuous and batch

HAZID

Risk Assessment – semi quantitative

Fault Tree Analysis

Bow Tie Analysis

Assessment of Occupied Buildings

The techniques followed on in a logical sequence. The techniques were not always used in fully formal mode. Experience of the Study Leader and the teams played a big role in making the process work. It was interesting the HAZOP flushed out many actions, but the later processes added to the action list. This was not expected. Many serious issues were detected and the full set of 52 high risk scenarios need resolution before the Site under scrutiny can claim to have significantly reduced its risk profile.

It was concluded that all occupied buildings on the site are inadequate to prevent injury to people who use the buildings. Explosions, in particular, are likely to severely damage many of the buildings. Some measures were suggested to strengthen the buildings but this will only have a minor impact.

APPENDICES

APPENDIX 1: REFERENCES

Ref 1. CCPS / Energy Institute, Wiley, 2018 “BOW TIES in RISK MANAGEMENT – A Concept Book for Process Safety

Ref 2. Chemical Industries Association, 3rd edition, 2011 Guidance for the location and design of occupied buildings on chemical manufacturing sites

APPENDIX 2: RISK MATRIX

RISK MATRIX

LIKELIHOOD RATING							
	E	**Almost Certain** - Expected to occur within days to weeks, e.g. ~99% probability	L_{18}	M_{11}	H_6	H_3	H_1
	D	**Likely** - Likely to occur in weeks to months, e.g. >50% probability	L_{20}	M_{14}	M_{10}	H_4	H_2
	C	**Possible** - Has happened before and may occur in months to years, e.g. between 20% and 50% probability	L_{22}	L_{19}	M_{12}	H_7	H_5
	B	**Unlikely** - May occur but not anticipated, e.g. between 1% and 20% probability or could occur in years to decades	L_{24}	L_{21}	M_{15}	M_{13}	H_8
	A	**Rare** - Will only occur under exceptional circumstances, e.g. <1% probability or '100-year event'	L_{25}	L_{23}	M_{17}	M_{16}	H_9
			1 - Very Low	2 - Low	3 - Medium	4 - High	5 - Very High

IMPACT RATING

	1 - Very Low	2 - Low	3 - Medium	4 - High	5 - Very High
Operations	<1 week production loss; Minor legal and/or regulatory issues to be addressed in the ordinary course of business; Event requires considerable management time over several days.	1-2 weeks production loss; Legal and/or regulatory issues to be addressed outside the ordinary course of business but without significant impact; Significant event requiring 1-4 weeks of time for corporate and/or site directors.	14-30 day production loss; Significant legal/regulatory issues with potential litigation/regulatory investigation; Major event requiring 1-2 months of time for corporate and/or site directors.	30-60 day production loss; Significant litigation, criminal and/or regulatory proceedings; Site-level crisis requiring several months of time for site senior leadership team and/or corporate management support.	>60 day production loss; Litigation, criminal and/or regulatory proceedings with highest level financial impact, including class action proceedings and/or incarceration of executives; DPM-level crisis requiring several months of time for company executives.
Financial	<$3M annual cash flow or the equivalent thereof (from a NAV perspective) if not an annual recurring event	$3M-5M annual cash flow or the equivalent thereof (from a NAV perspective), if not an annual recurring event	$5M-15M annual cash flow or the equivalent thereof (from a NAV perspective), if not an annual recurring event Net earnings significantly less than planned	$15M-30M annual cash flow or the equivalent thereof (from a NAV perspective), if not an annual recurring event	$30M annual cash flow or the equivalent thereof (from a NAV perspective), if not an annual recurring event Default of a material agreement having major consequences (e.g. breach of debt covenants)
Health and Safety	Injury or illness requiring medical treatment with expected full recovery.	Injury or illness requiring lost time or restriction of duties, medical treatment and on-going management up to 1 week.	Injury or illness requiring lost time or restriction of duties, medical treatment and on-going management up to 3 months; Occupational illness with moderate irreversible effects.	Major injury or illness resulting in a fatality or life-threatening condition, weeks of hospitalization and/or long-term or permanent disability; Multiple injuries requiring medical treatment and lost time or restricted work.	Multiple exposures to extreme health hazard resulting in long-term hospitalization, life-threatening or permanently debilitating illness or multiple fatalities.
Environment	Incident causing temporary, promptly reversible environmental impact requiring no remediation. Below regulatory reportable thresholds	Incident causing short-term, reversible environmental impact requiring minor remediation. Greater than permit conditions or regulatory reporting threshold.	Incident causing short-medium term, widespread reversible environmental impact requiring moderate remediation (~1 month recovery).	Incident causing medium-long term, widespread serious environmental impact requiring significant remediation (~1-3 years).	Incident causing disastrous, potentially irreversible environmental impact with long-term effect requiring major remediation effort (>3 years).
Stakeholder Relations / Reputation	Local complaint(s) to site via informal means.	Local media coverage. Persistent, formal complaint(s) to site and/or local regulator. Reputation is moderately affected with a small number of site-focused people.	Multiple formal grievances for one issue. Local media coverage / NGO criticism / extensive social media activity over several days. Reputation is adversely affected with local government and a large number of people in the region.	Multiple formal grievances for one issue not resolved at local/regional level in 90 days. State or national government or regulator involvement. Significant adverse national media/ public/NGO/social media attention. May lose license to operate or fail to gain needed approvals.	Serious negative national, international and social media coverage. Formal grievance(s) alleging major misconduct. Significant impact on share price for several months. State or national government support withdrawn.