Risk control at lower cost

by Rob Bos*[1], Suzanne Mooij[1], Leen Pronk[2], and Wessel Bergsma[2]

1 PIMS International, Haren, Netherlands
2 Gasunie, Groningen, Netherlands

GASUNIE OPERATES the first cross-border network in Europe, a network that ranks amongst the largest high pressure gas pipeline grids in Europe consisting of over 15,000km of pipeline in the Netherlands and northern Germany, dozens of installations, and 1,300 gas receiving stations. Due to the reliability and strategic location of the grid in relation to expanding international gas flows, the Gasunie network forms the core of what is called the northwest European 'gas roundabout'. In 2010, the annual gas throughput totalled approximately 125 billion cubic metres. Safety, reliability, and sustainability have always been the key elements in Gasunie's operational practice and, as a consequence, much effort has been made to keep the condition of the infrastructure, which originates from 1960, up to current standards.

GTS, a wholly-owned subsidiary of Gasunie, is the designated national transmission system operator in the Netherlands. One of GTS's key missions is the non-discriminatory provision of safe and reliable gas transmission services. Such services should enhance security of supply and the proper functioning of the gas market. As a consequence, GTS has a strong drive for continuous improvement on the pipeline-integrity-management system (PIMS) that is already in place.

Gasunie and GTS are utilizing high-integrity standards for their assets. This is not only reflected in the design standards that have been applied, but is also expressed in daily operations and maintenance practice of the company combined with a strong drive for continuous improvement.

Managing the integrity of pipelines is such a comprehensive matter that it requires the involvement of several disciplines. Therefore, an integral approach is very important. This paper provides an overview of the relevant aspects for the integrity management of pipelines and shows how these aspects are related.

PIMS practice in GTS

GTS has extended the operational PIMS practice in 2011 with a new approach in which transparency and a continuous improvement are key issues. As a result, the process of continuously improving PIMS, which used to be focussed on the regular operational, maintenance, and safety elements, has recently been enhanced with a focus on the following aspects of PIMS:

- Bow-tie risk analyses. Risks are evaluated for the four sub-areas: transport, technical integrity, environment, and organization.
- Performance indicators. Performance indicators are derived from the Bow-tie risk-analysis approach in order to monitor integrity performance.
- PIMS-plan. Periodically, (annually, in principle) a PIMS plan is formulated which contains the most important achievements of the past year and which lists the proposed improvements.

*Corresponding author's contact details:
tel: +31 6 2420 2452
email: rob.bos@europims.nl

A major part of the improvement of the PIMS in GTS involves the introduction of the Bow-tie risk-analysis method. This method measures the actual integrity management of the pipelines or facilities concerned, and determines opportunities for improvement in a systematic manner. The approach to risk management carefully considers both results in terms of integrity and cost. In this paper, the Bow-tie risk-analysis method is described in more detail.

Legal developments

With this new method of integrity and risk management, GTS complies with the new legislation in the Netherlands on pipeline-integrity management. This new law, called the BEVB (on external safety of pipelines) has strengthened GTS in its objectives to become the best-in-class. This has resulted in the enhanced risk-management methodology which is the main subject of this paper, not limited to external safety, but extended to a number of areas of risk as will be described below. In fact, in this study, external safety has proven to be no issue at all. The paper describes the review of current condition of the 17,000 sub-surface valves that are part of the pipeline system and the way the Bow-tie technique has

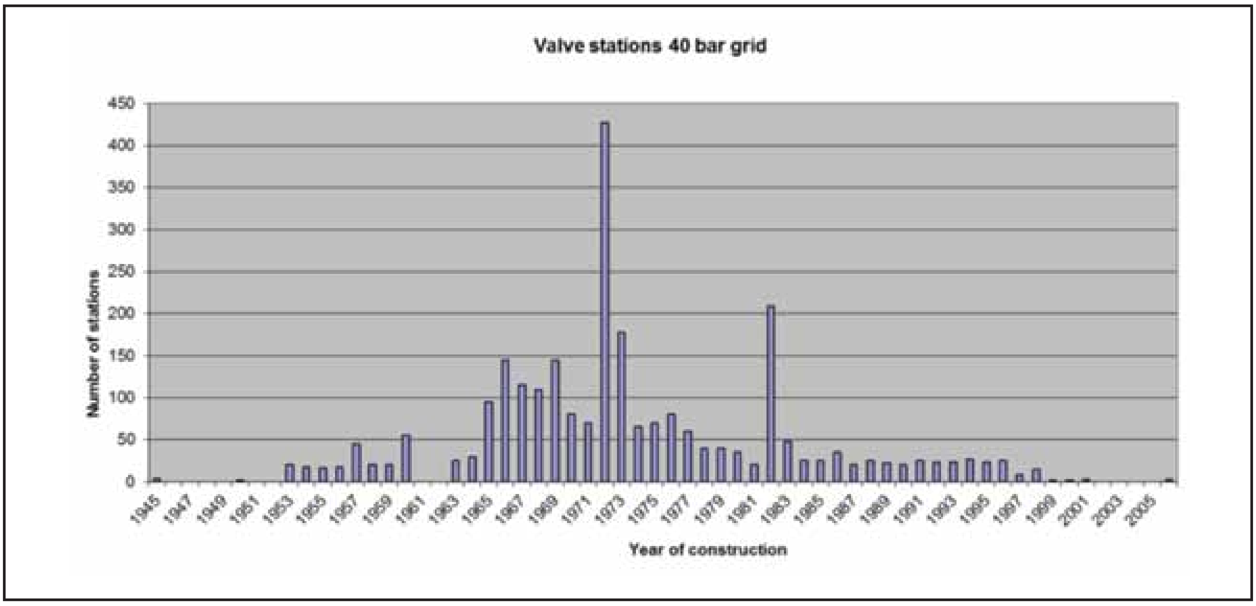

Fig.1. Construction dates of GTS' sub-surface valves.

supported GTS in the decision-making process regarding investment decisions which are based on both technical and economical parameters.

Scope

The main sections of the GTS grid operate at 40 bar and contain around 17,000 sub-surface valves from a wide range of manufacturers which include, in alphabetic order:

- Argus
- Audco / Rockwell / Nordstrom
- Cameron / TK / Cort
- Christensens
- Elita / Porringern
- Grove
- M&J / LPG / NDSM
- Mokveld
- Newman Milliken / Hattersley
- Pibiviesse
- RMA
- Saut du Tarn
- Thevignot
- WKM

The number of operational valves from these manufacturers varies between just a few to several thousand. In order not to affect the manufacturers' reputation, results of the analyses of these reports have been made anonymous, as shown in Table 1 in which the valves are categorized by type.

Manufacturer	Valve type	Number in operation
A	Axial on-off	457
B	Ball	108
C	Ball	1558
D	Ball	402
E	Ball	7
F	Ball	397
G	Ball	13
H	Gate	3572
I	Gate	865
J	Knife gate	790
K	Plug	4900
L	Plug	957
M	Plug	1355
N	Plug	227

Table 1.Valve types according to manufacturer.

A review of the construction dates of these sub-surface valves is given in the Fig.1. As can be seen a considerable number of these valves is have been in operation for around 40 years. Recent reports on corrosion and other time-related ageing effects have strengthened GTS in its opinion that a review is required. This has been begun, and the maintenance / replacement programme for these sub-surface valves in the 40-bar grid is being intensified.

Aims

GTS has taken the decision to execute this sub-surface valve assessment using a risk-based approach, and the recently developed risk-assessment methodology (based on the advanced Bow-tie technology) was selected. The major objectives of the project are:

- to investigate the risk level of the sub-surface valves (the risk-matrix parameters) on:
  - safety
  - security of supply
  - costs
  - environment
  - reputation

- to investigate the average lifetime of the sub-surface valves in the 40-bar grid

- to find the main cause of deterioration of the valves, for example:
  - ageing (corrosion, wear, third-party interference, etc.)
  - geographic conditions (soil/ground water composition, medium composition, etc.)
  - manufacturer (type, material, fittings, etc.)
  - function (isolation, by-pass)

- to reconsider current maintenance practice and replacement policy if it is concluded that certain valves:
  - do not meet the above-mentioned criteria, i.e. have reached end-of-life status
  - require investigation of the possibilities for repair, modification, and / or replacement if they have met their end-of-life status
  - are far from their end-of-life status
  - to define maintenance / operational measures to be taken during the transition period for those valves which need replacement, if applicable.

Methods

General

The methodology applied, that has been recently developed by GTS and PIMS International BV in close co-operation with Gaz de France Suez and Total EP, is based on the conventional Bow-tie methodology but offers a considerable amount of additional management information because it has been extended with:

- four sub-sectors of risk assessment covering the risk-management aspects of:
  - environment
  - organization
  - transport
  - technical integrity

- a sub-division of the main barriers to the threats and consequences in the seven life-cycle barriers, both for preventive and suppressive mitigation measures:
  - design
  - construction
  - commissioning
  - operations
  - maintenance
  - third-party interference prevention
  - mothballing / removal

- The sub-division in these life-cycle barriers enables the comparison of the efficiency of mitigation measures taken for different life cycles (for example, design measures vs maintenance measures) to find the most efficient package of mitigation measures for the whole lifetime of the assets. In general, most asset managers have to deal with existing infrastructure, in which case the inventory of mitigation measures for the life cycles of design, construction, and commissioning do not appear relevant; however, the inventory of escalating factors and accompanied mitigation measures for these life cycles clearly show:
  - which missing measures from design, construction, and commissioning need to be compensated for;
  - which adaptations in design, construction, and commissioning should be applied in new constructions to improve the lifetime efficiency.

- incorporation of effectiveness and costs of any of the mitigating measures;
- incorporation of the Deming cycle: transparent plan-do-check-act (PDCA) by the inventory and implementation of new mitigation measures, based on efficiency considerations (improvements);
- incorporation of life-cycle cost optimization (LCC) by the inventory and ranking of all (existing and new) mitigation measures, based on efficiency considerations for all life cycles;
- inventory of the actual risk level by means of a risk matrix and the implementation of risk-mitigation measures when the matrix criteria are not met.

This results in the basic configuration of the Bow-tie shown in Fig.2.

Bow-tie risk-analysis method

The Bow-tie method developed by GTS and PI is based on the inventory of costs and effectiveness of all mitigation measures (existing and improvements) applied by the pipeline operator to minimize the failure frequency and the consequences of unwanted events.

(Note that the availability of high-quality data in the pipeline asset register is of great help for the (semi-)quantification of threats, consequences, and measures for different levels of the pipeline system; however, if such data are not available, expert opinion can do the job as well. In that case, the assessment should be considered to be a semi-quantitative risk analysis.)

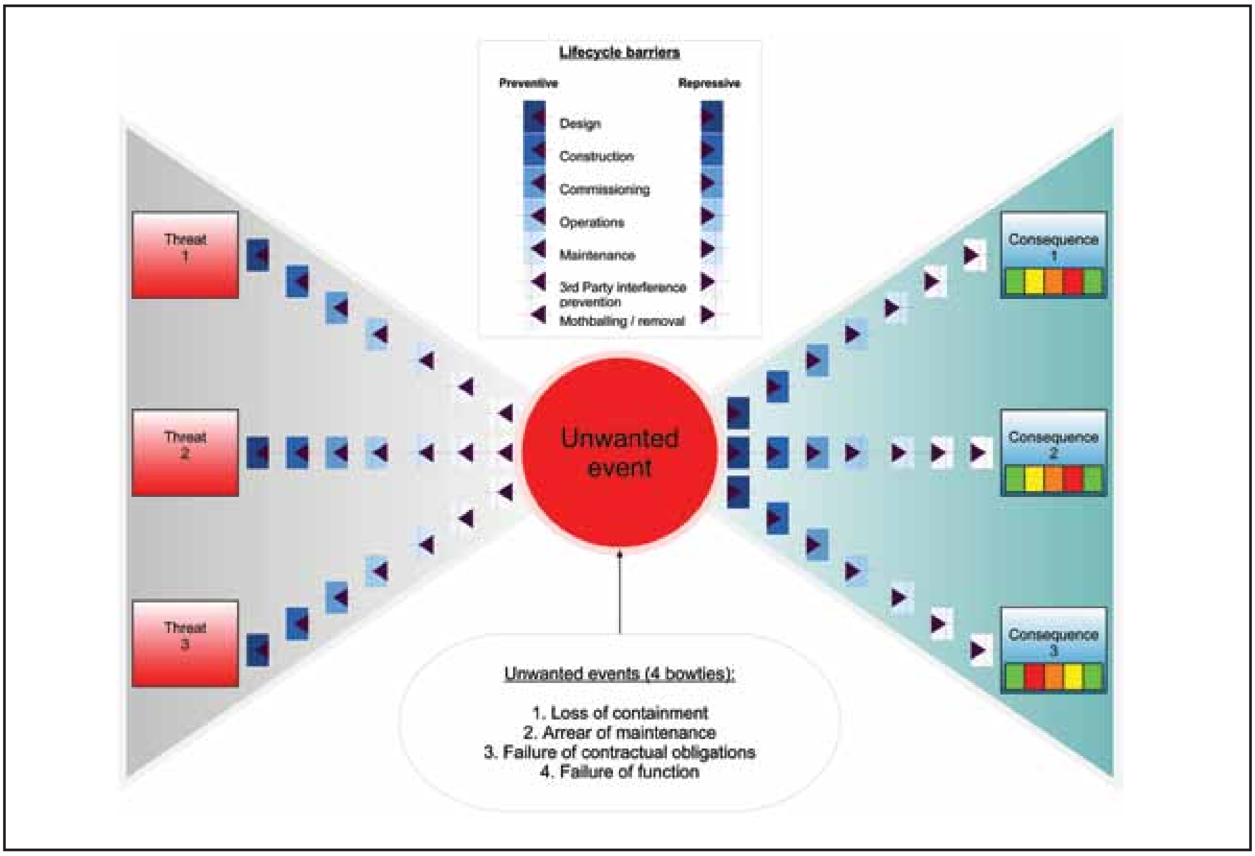

Fig.2. The GTS Bow-tie diagram.

This Bow-tie risk analyses method involves the following steps:

1. Assignment of workshop members. This team should at least have the following expertise: valves (in this particular case), third-party interference, cathodic protection, coating, corrosion phenomena, inspection techniques, maintenance engineering, operations, engineering, and financials, and should be managed by a facilitator who is experienced in the field of integrity management.

2. Inventory of unwanted events for each of the following subsectors: GTS focuses on the following unwanted events (which is a legal requirement):

Subsector	***Unwanted event***
Environment	Loss of containment
Organization	Backlog in carrying out maintenance
Transport[1]	Failure of contractual obligations
Technical integrity	Failure of function

3. Inventory of the consequences for each of the unwanted events including a check on the current risk level of each of these consequences using the GTS risk matrix on the following aspects: financial damage; environment; reputation; security of supply; and safety. Aspects are score based on the expert opinion / knowledge of the expert team.

(Note: The ranking of the current risk level is based on the assessment of the worst-case scenario: what happened or might happen in the near future and at what interval when no additional mitigations are applied.

The appointment of two independent teams, in particular for high-consequence decisions, is highly advised to guarantee maximum objectivity of their conclusions and recommendations; this has not been applied in this study. If applied, two teams have to be established, one each to undertake:

- *the inventory at the current risk level*
- *the inventory after implementation of the new mitigation measures.)*

4. Development of one fully developed Bow-tie for each of the subsectors; for each Bow-tie:

   a. The identification and quantification (effectiveness and costs) of threats that could result in an unwanted event (preventive measures, Fig.2, left part).

[1] The standard unwanted event is “Consequential loss of erroneous medium composition”. Because Gasunie deals only with inert gases, it has been decided also to introduce the unwanted event “Failure of contractual obligations”.

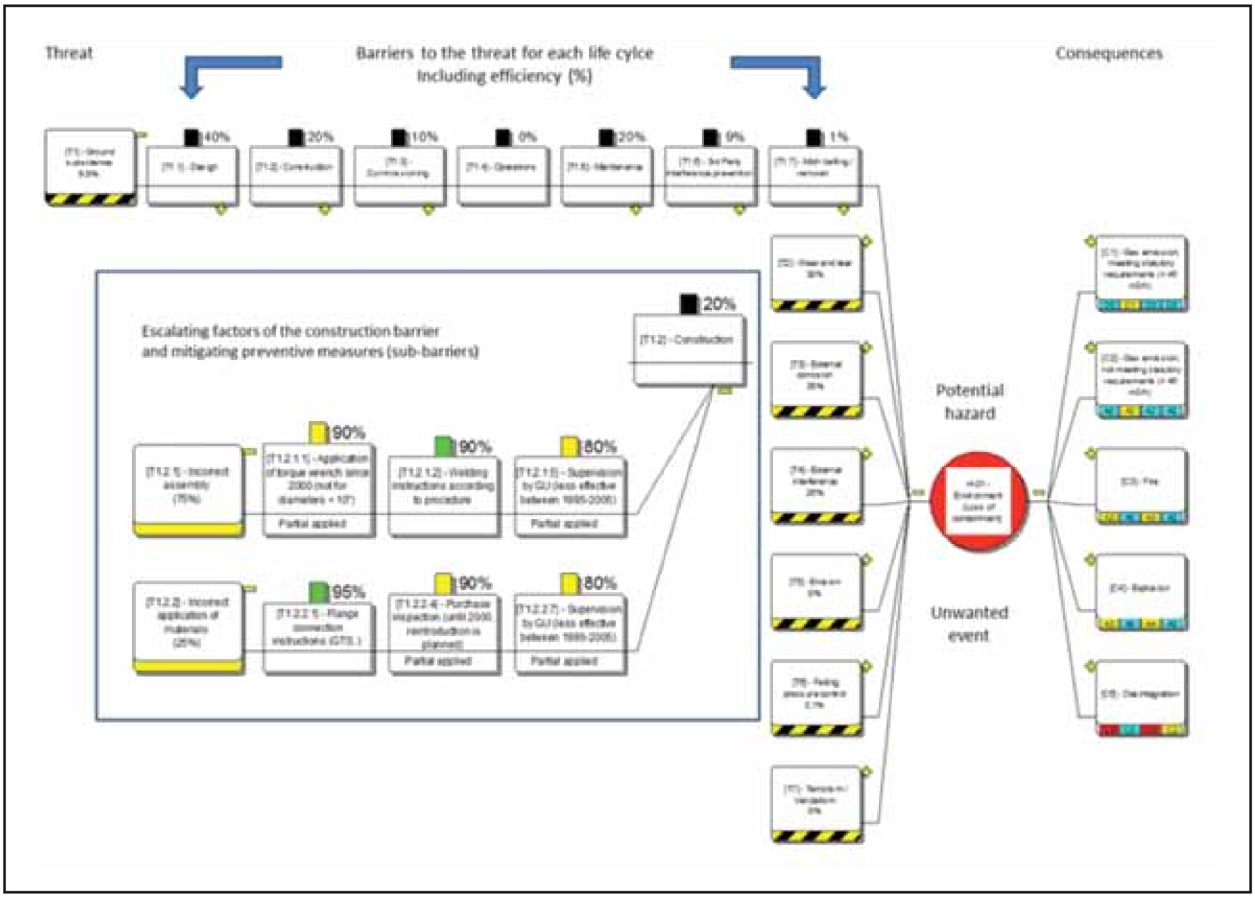

Fig.3. Detail of the Bow-tie diagram for sub-surface valves.

b. The definition of the seven preventive life-cycle barriers that are installed to prevent and / or minimize occurrence of the unwanted event.

c. The identification of the escalating factors for each of the preventive life-cycle barriers that could reduce the effectiveness of each of the barriers.

d. The identification of existing and potential measures for each of the escalating factors that could prevent and / or limit the effect of the factor in initiating the unwanted event, defined per life cycle. Examples of these measures are:

   i. Design: code applied, steel grade, coating type, wall thickness, cathodic protection-design.

   ii. Construction: supplier qualification, supervision to meet design and construction specs.

   iii. Commissioning: quality check of: pressure control system, welds, fittings and cathodic protection, test criteria / conditions / medium, hand-over of asset register operating instructions and maintenance requirements.

   iv. Operations: education on operations manual and ESD-system, incident reports.

   v. Maintenance: maintenance concept, support on maintenance planning and other organizational issues, material supply / alternatives, education and training, requirement for maintenance / failure reports.

   vi. Mothballing / cleaning / removal: removal of superfluous objects, registration of condition of removed objects.

e. The definition of the seven suppressive life-cycle barriers that are installed to prevent and / or minimize the consequences of the unwanted event, to be defined for each of the consequences (Fig.2, right).

f. The identification of escalating factors for each of the suppressive life-cycle barriers that could reduce the effectiveness of the mitigation measures, to be defined for each of the consequences.

g. The identification of existing and potential measures for each of the escalating factors that could prevent and/or limit the consequence of the unwanted event (such as loss of containment) defined per life cycle. Examples of these measures are:

   i. Design: gas detection and/or ignition source availability.

   ii. Construction: prevention of spark-inducing materials in ground bed.

   iii. Commissioning: quality check of ignition-initiating sources.

   iv. Operations: emergency plan.

   v. Maintenance: application of non-igniting tools, gas-detection tool.

   vi. Mothballing/removal: procedures to prevent nearby damage whilst removing superfluous objects.

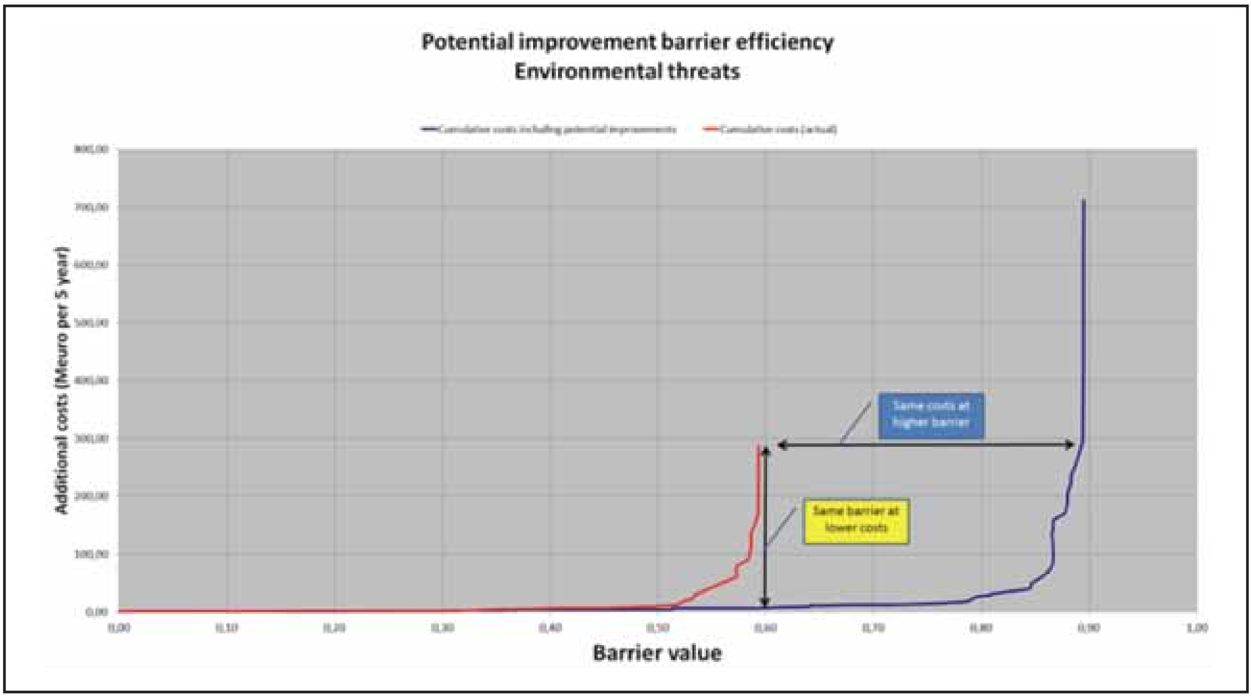

Fig.4. Opportunities for LCC-optimization.

5. Calculation and ranking of effectiveness and efficiency of all of the existing and new proposed (i.e. improvements) mitigation measures.
6. Calculation of the most efficient set of mitigation measures based on a mix of existing and new mitigation measures.
7. Calculation of life-cycle efficiency and life-cycle optimization.
8. Calculation of the risk-reducing effect of the new barriers in the risk matrix, both on failure frequency and consequence.
9. Calculation of performance indicators (actual and potential).

Workshops

The Bow-tie risk assessments are performed in a number of workshops, in general taking three days to investigate each object-type. These workshops are attended by around eight experts in the relevant fields, and involve the following steps:

- Development of a full developed Bow-tie for each of the subsectors (four in total).
- Data processing and analyses.
- Expert judgement of the results of the analyses.
- Trend analyses based on maintenance reports (the SAP module Plant Maintenance (PM) is applied in GTS for maintenance reporting) and incident reports.
- Definition of conclusions and recommendations including a review of existing maintenance and replacement policies.
- Report to management.

Bow-tie detailed view

Figure 3 shows a detail of the Bow-tie diagram for sub-surface valves (safety aspects), and represents the preventive part of the Bow-tie (the left part) including some of the mitigation measures taken to prevent the unwanted event occurring (the blue box). In this example, the mitigation measures with a green tab are already implemented, the mitigating measures with the yellow tab are not implemented yet but have been proposed by the expert team during the workshop as a new mitigation measure (i.e., an improvement).

LCC calculations

The Bow-tie includes both the effectiveness of the mitigation measures and the corresponding costs, enabling the user to evaluate the economics of current and new measures to either gain the same effectiveness of integrity management at lower costs or to achieve a higher level of threat control at the same costs, as is demonstrated in Fig.3. The red line represents current practice: which barrier value (x-axis) can be achieved at what cost (y-axis). The blue line represents the potential of new proposed mitigation measures. Both lines are constructed on the basis of the costs and the effectiveness of the mitigation measures; however, these are not shown on the x-axis due to the fact that there are too many (around 130).

Figure 3 very clearly shows the opportunities for LCC-optimization, which are:

- same barrier of mitigation measures at lower costs = cost saving
- same costs of mitigation measures at higher barrier = increase of effectiveness

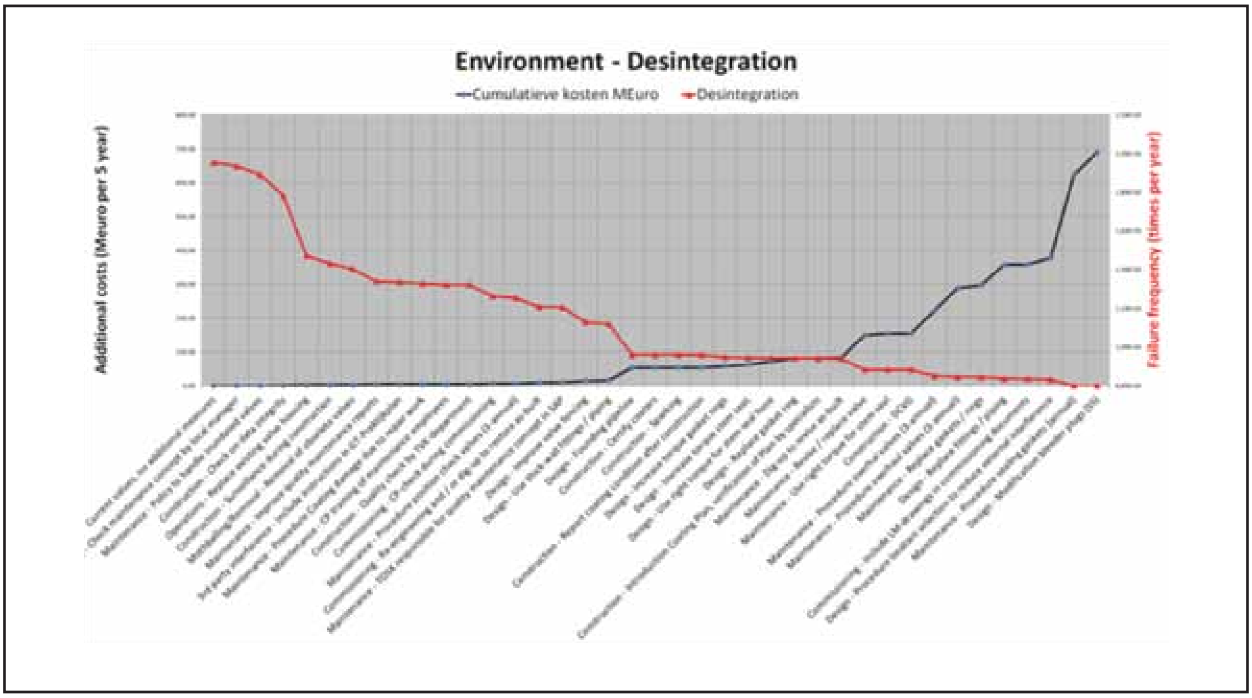

Fig.5.The cumulative effect of the new mitigating measures (improvements) on the reduction of the failure frequency.

(Note: The above-mentioned analysis include the effect of mitigation measures for the full lifetime of the assets. For existing infrastructure, revision of the design, construction, and commission mitigation measures cannot be applied. For this reason, the analysis offers the functionality to skip these life cycles in the inventory of improvements, and compensation of the missing barriers has to be found in the other life-cycle barriers.)

Priority-setting of mitigation measures

Priority-setting of mitigation measures is performed by analysing the results of the Bow-tie risk analysis. Figure 5 shows the relationship between improvement measures (a mix of all life-cycle-related measures), failure frequency, and cost. Since measures are ranked according to efficiency (= max. barrier value/€), the choice for a new failure frequency directly shows the most efficient set of measures.

(Note: It is assumed that all mitigating measures are independent. Figure 5 shows the cumulative effect of only the new mitigation measures (improvements) on the reduction of the failure frequency (red line). The black line represents the cumulative costs (at five-year intervals). As a consequence, the effect of – for example – measure 5 is based on the impact of measures 1 to 5. It is clearly demonstrated that spending only 20% of the cost will result in an approximate 80% reduction of the failure frequency.)

In order to fully support decision-making with regard to the proposed measures, the threats and consequences that were identified during the Bow-tie sessions are incorporated in the standard SAP PM maintenance reports. This means that as well as the (usual) identification data of the object, the frequency, cause, and consequence of the unwanted event as they were analysed during the Bow-tie risk analysis are reported to support management decisions on maintenance optimization.

This means that when a loss of containment is experienced, the cause should be reported in SAP PM. This can be done by selection from a table with a choice of threats reported in the Bow-tie analyses. For example: (1) external interference (excavation), (2) external interference (ram piling), (3) system gains higher pressure than design pressure, etc. The consequences need to be selected as well, for which a choice should be made from the short list of (consequences) shown on the right side of the Bow-tie. For example: (1) gas emission, (2) environmental damage, (3) fire, (4) explosion, etc.

In a similar way, the causes and consequences of other undesirable events for the other subsectors are reported in SAP.

Management information

Success factors (SF)

Success factors are used to represent the result of the company's integrity-management practice. They are visualized and quantified by the number of incidences of the unwanted events as applied in the development of the Bow-tie analyses.

Performance indicators (PI)

Performance indicators represent the way the SFs are managed by the company; for example, the number of the loss-of-containment incidences can be influenced by the

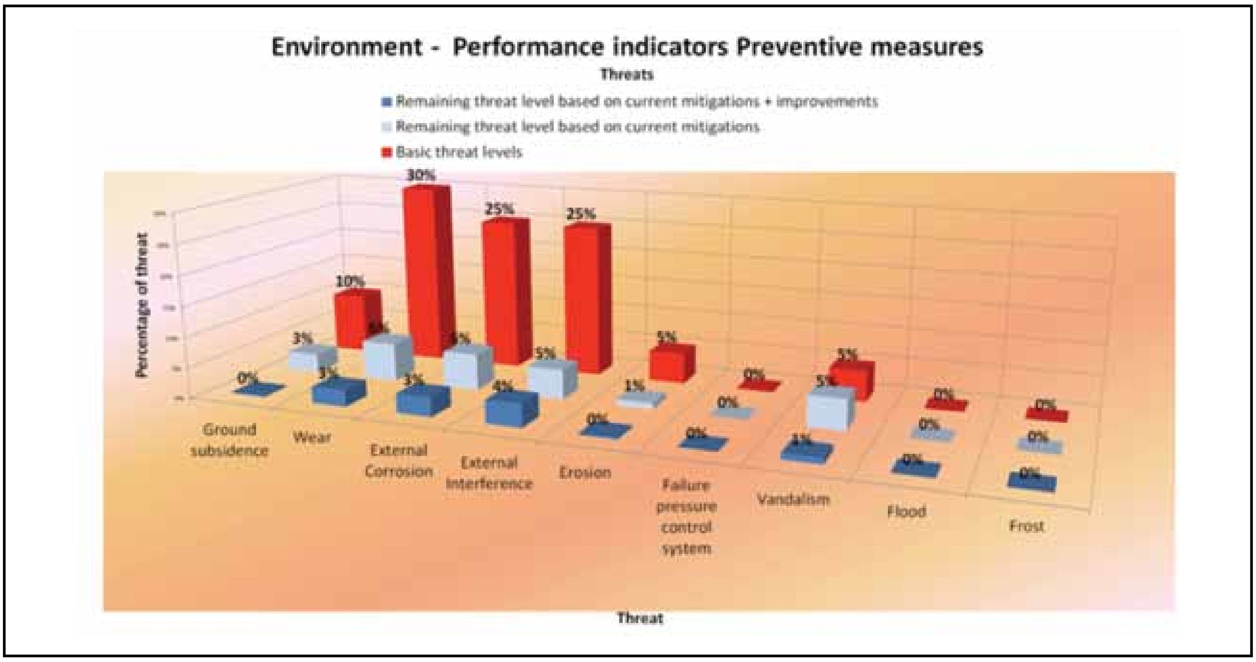

Fig.6. GTS' conventional performance indicators (PIs).

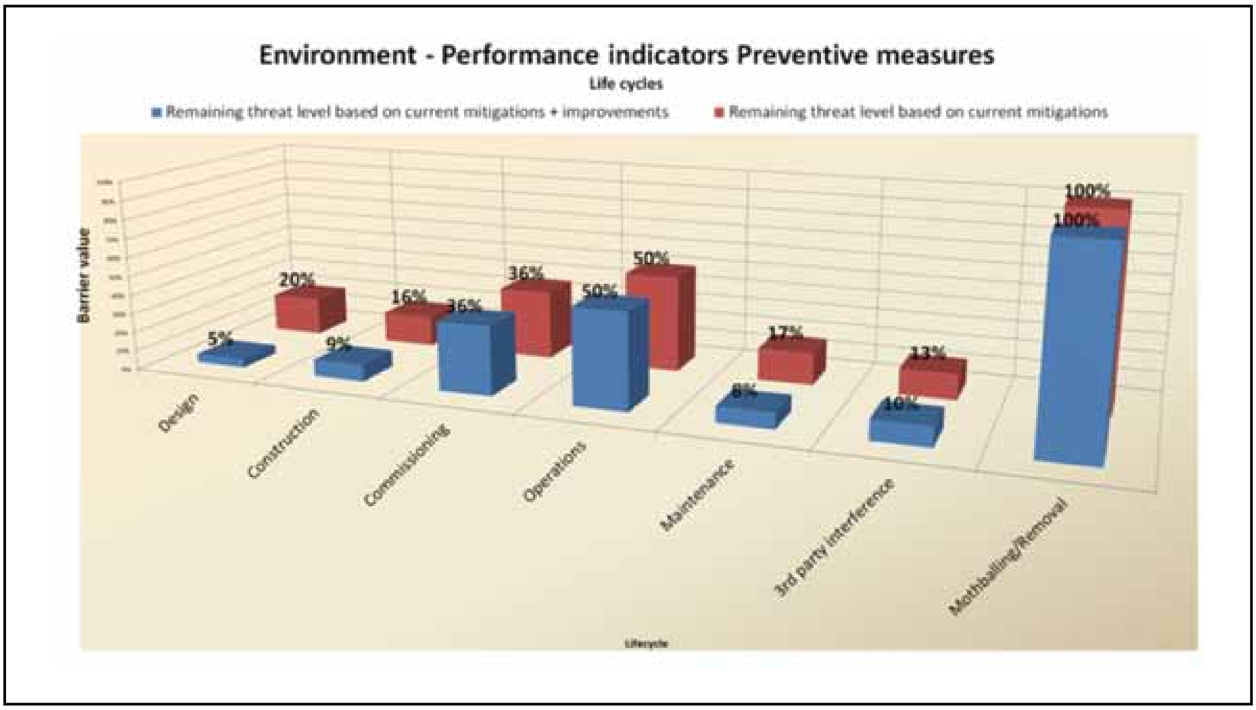

Fig.7. The score on GTS' enhanced preventive life cycle PIs.

implementation and/or avoidance of certain mitigation measures. The selection of the mitigation measures that have to be implemented (or not) to manage the SF properly is based on the policy of the company on that particular SF: identifying what is the accepted number of unwanted events. The effectiveness of the implemented measures represents the integrity-management quality of the company, and is determined with the Bow-tie methodology. Examples of PIs are given in the following paragraphs.

PIs are derived from the Bow-ties and are quantified by the calculation of the combined effect of all mitigation measures for the neutralization of all threats and all consequences. The following PIs are derived from the Bow-tie method:

- $PI_{\text{Threat control}}$
- $PI_{\text{Preventive life-cycle threat control}}$
- $PI_{\text{Consequence control}}$
- $PI_{\text{Suppressive life-cycle threat control}}$

(Note: In-depth calculation of the PI-level of an object requires connection between the Bow-tie diagram and the asset register of that object, in order to distinguish between different objects with the same function. Difference in object parameters can result in different effectiveness of the mitigation measures that are in place. As an example: changes in depth of cover of a pipeline, a mitigation measure against third-party interference, will result in changes in effectiveness of this mitigation measure along the pipeline route.)

The value of each PI is calculated using PIMS International software, similar to the method that is used to calculate the combined effectiveness of mitigation measures as described earlier. To illustrate this, an example of the results of the preventive PI calculation has been given to illustrate the usefulness of these PIs in the characterization of the management control. Options for improvement can be found easily, and the prospects for each of the life cycles is presented in Figs 6 and 7. The major difference between the PI characteristics of threat control and life-cycle control have been emphasized to provide a clear understanding of the strength of this new method of risk assessment.

1. The conventional way of PI definition is to focus on the management of threats. This ends, in general, with the definition of the PIThreat control which is the reduction in threat level for each individual threat that has been achieved by the preventive measures that are in place and the maximum reduction level that can be achieved by the implementation of the new mitigation preventive measures (the preventive improvements). The analyses of all Bow-tie parameters results in Fig.6, which represents the values of GTS' conventional performance indicators.

   Figure 6 shows that the actual management of threats has resulted in a substantial reduction of the basic threat levels (in an estimate made by the expert team). Next to that, it demonstrates that additional (new) mitigation measures can be implemented to achieve even better control. Whether these new measures are going to be implemented or not depends on the company's policy regarding its experienced frequency of the unwanted event (in this case, loss of containment). The figure shows that further reduction is optional if this frequency (the SF) is considered to be too high. The selection of new mitigation measures can be made on the basis of the available Bow-tie diagram and the efficiency plots (see paragraph above on priority setting).

2. The enhanced method introduced by PIMS International and GTS should be considered as a very practical extension to the conventional method. It enables the asset manager to be realistic, and to skip the opportunities of threat reductions that are out of scope (for example, a design review is not an option for reducing the risk level of the existing infrastructure). The method supplies a direct focus on the effectiveness of the life-cycle-related mitigation measures and, as a consequence, enables the operator to focus on the actual (economic) performance of the company's life-cycle management practice. The performance of the (whole of the) company is measured by the PIPreventive life-cycle threat control .This indicator represents the reduction in threat level for each individual life-cycle phase that has been achieved by the preventive measures that are in place and the maximum reduction level that can be achieved by the implementation of the new mitigating preventive measures (the preventive improvements). The analyses of all Bow-tie parameters results in Fig.7, which represents the score on GTS' enhanced preventive life-cycle performance indicators.

   Figure 7 indicates that a reduction of the frequency of an unwanted event can be achieved by the implementation of new mitigation measures for the following life cycles:

Life cycle	*Threat-reduction potential*
Design	from 20% to 5%
Construction	from 16% to 9%
Maintenance	from 17% to 8%
Third-party interference	from 13% to 10%

   As has been mentioned above, design and construction barriers are not an option for an existing infrastructure. This means that the majority of threat reduction has to be achieved by the implementation of new maintenance measures (reduction from 17% to 8%) and reduction of the third-party interference (from 13% to 10%). The selection of the most efficient new mitigation measures should be made on the basis of the available Bow-tie diagram and the efficiency plots.

Shift in the risk matrix resulting from new mitigation measures

The effect of the proposed mitigation measures can be visualized in the matrix shown in Fig.8 which includes the risk level of the current situation as it has been ranked by the experts in the workshop: the small black squares. Next to that, the effect of the new mitigation measures that have been proposed by the experts is (after processing by the software) are presented as the blue squares. As can be seen, the blue square has a shift to the left (reduction of failure frequency affected by the new preventive mitigation measures) and a shift to the top (reduction of consequence resulting from the new suppressive mitigation measures). This is achieved by the introduction of an x-axis scale which is a log scale related to the frequency of the unwanted event, and a y-axis log scale of the consequence which, in this case, is related to the cost.

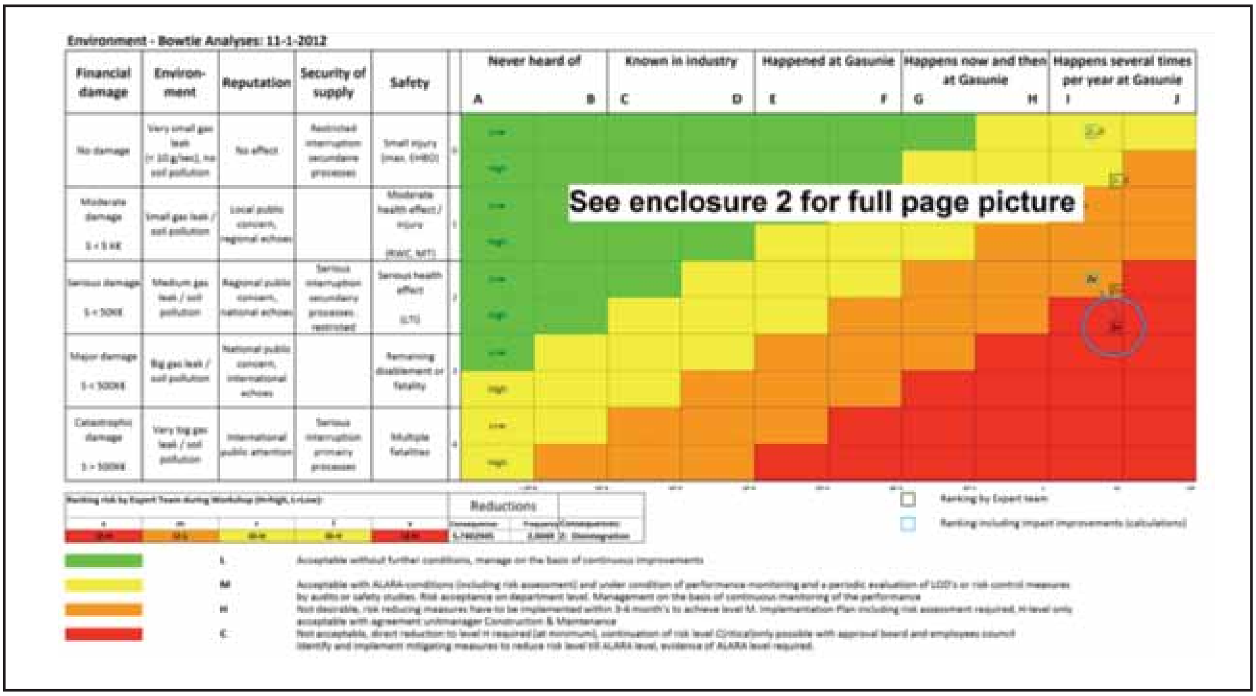

Fig.8. The effect of the proposed mitigation measures.

As an example, consider she score of the safety-effect[2] of the disintegration consequence (Z_v) that has been ranked by the expert team on 2Ihigh = red (see light blue circle). The ranking is positioned in the right-bottom corner of the corresponding area instead of the conventional method of ranking (indicating the complete area), i.e. the right bottom corner represents the score 2Ihigh.

The shift to the left which results from the mitigating effect of the new preventive measures and the shift to the top which results from the mitigating effect of the new suppressive measures brings the score out of the red zone into the orange zone.

As been demonstrated in this example, leaving the orange zone is not an available option and, as a result, a decision has to be made whether the orange++ zone is acceptable for the company or not. If not, more fundamental actions have to be taken to meet the company policy on asset integrity, such as renovation, replacement, etc. If the orange zone is acceptable, additional analyses have to be made to find the minimum number of mitigations required to leave the red zone. Although the cost of the mitigation measures have to be included, the method delivers the most efficient set of mitigation measures (preventive and suppressive) that is required to manage the risk level in an appropriate and sophisticated way.

In the end, this enhanced Bow-tie method supplies the asset manager with all the information required to support risk-management practice in a structured way, and enables the (legal) integrity requirements to be met in the most transparent and efficient manner.

Results

Ranking of the risk matrix

In the following discussion, all the results have been made anonymous. 14 different valves were ranked in an exercise carried out by an expert team, and this resulted into the matrix shown in Fig.9 (a random example relating to one of the 14 valve manufacturers). As can be seen, two 'criticals' (red scores) have been reported as a consequence of 'disintegration' resulting from the 'loss of containment' (in this case a relative small leak) unwanted event:

- safety risk
- financial damage

(Note: The current level of the safety aspect of disintegration (score Vv) gives a yellow score (see the left blue circle), and no injuries are reported up to that point. However, the expert team holds the opinion that further deterioration of the valves may result in serious injuries to the field engineers in the near future if no additional mitigation is taken, and has decided to caution GTS' management that direct action is required in order to prevent this happening. As a result, the team assigned the red score to the safety aspect of disintegration (see the right blue circle).

Closer investigation of the cause of this red score has resulted in the conclusion that this is the effect of corrosion of the drain and seal accessories of the valves. In particular, operation of the corroded gas taps might result in the near future in disintegration of the tap with fitting material rapidly dispersed. Whenever this happens, serious injury

2. Note that each risk area does have its own risk definition, and that risk areas cannot be compared to each other. Obviously, these risk areas also differ in priority.

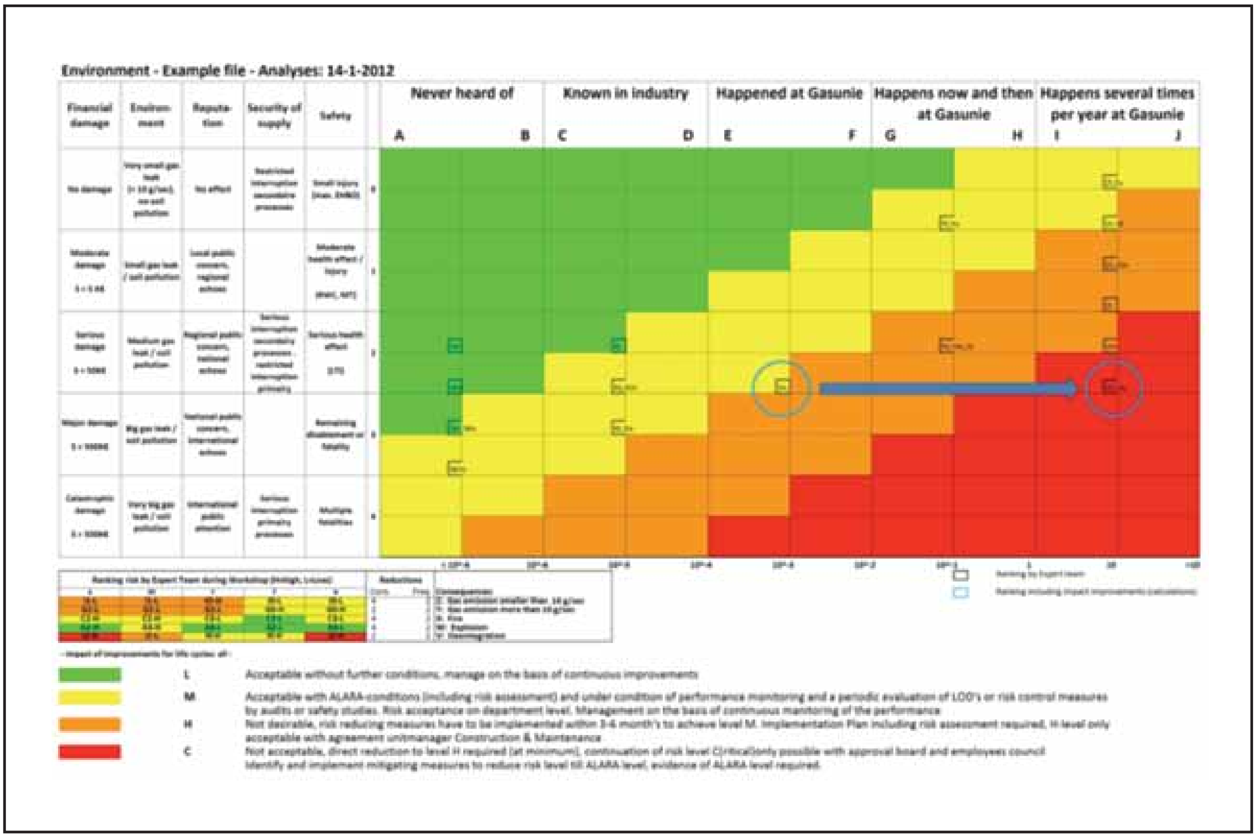

Fig.9. Risk-matrix ranking for one of the 14 valve manufacturers.

of the field engineer who is operating the tap can be anticipated; according to GTS' policy, the red level score requires immediate action. On the basis of this, GTS has decided to take immediate action:

- A technical bulletin was published with the instruction to stop the operation of drain and seal taps, and if this is not possible, to protect the field engineers when operating the taps.
- A feasibility study to be executed on the potential of risk reduction by additional mitigation measures.

Feasibility study

The Bow-tie method was selected to investigate the shift of the risk scores in the matrix by additional preventive and suppressive mitigation measures (improvements) as proposed by the expert team, and Fig.10 shows the result of this exercise. In Fig.10, the risk level of the current situation – as ranked by the experts in the workshop – is shown as the black squares. Next to that, the effect of the new mitigation measures on the shift of the ranking has been calculated on the basis of the additional (new) measures that have been proposed by the experts, and processed by the software. The calculated scores are presented in the graph as the blue squares. The figure shows that a reduction of both safety risk and financial damage risk is achieved by the additional mitigation measures, although unfortunately not enough: both scores are still in the red area. This resulted in the conclusion that further action was required to meet GTS' risk standards, and the following study was started:

1. The investigation of the main cause of the deterioration of the valves: the following potential causes were investigated (similar to a Pareto analysis):
   - ageing (including corrosion, wear, third-party interference)
   - geographic conditions (including soil/ground water composition, medium composition)
   - manufacturer (including type, material, fittings)
   - function (isolation, by-pass).
   - The manufacturer-type showed up as the major driver in the mechanism of deterioration.

2. The inventory of valve types that meet GTS risk standards and those that do not.

3. If required, replacement of the valves would be a time-consuming operation, and it was therefore decided that prioritization of the replacement programme was required. The prioritization has been executed on the basis of the score of the different makes on all aspects of the risk matrix.

4. Investigation of the score of new valves on the basis of the Bow-tie parameters to rank them on the potential risk, both now and in the future.

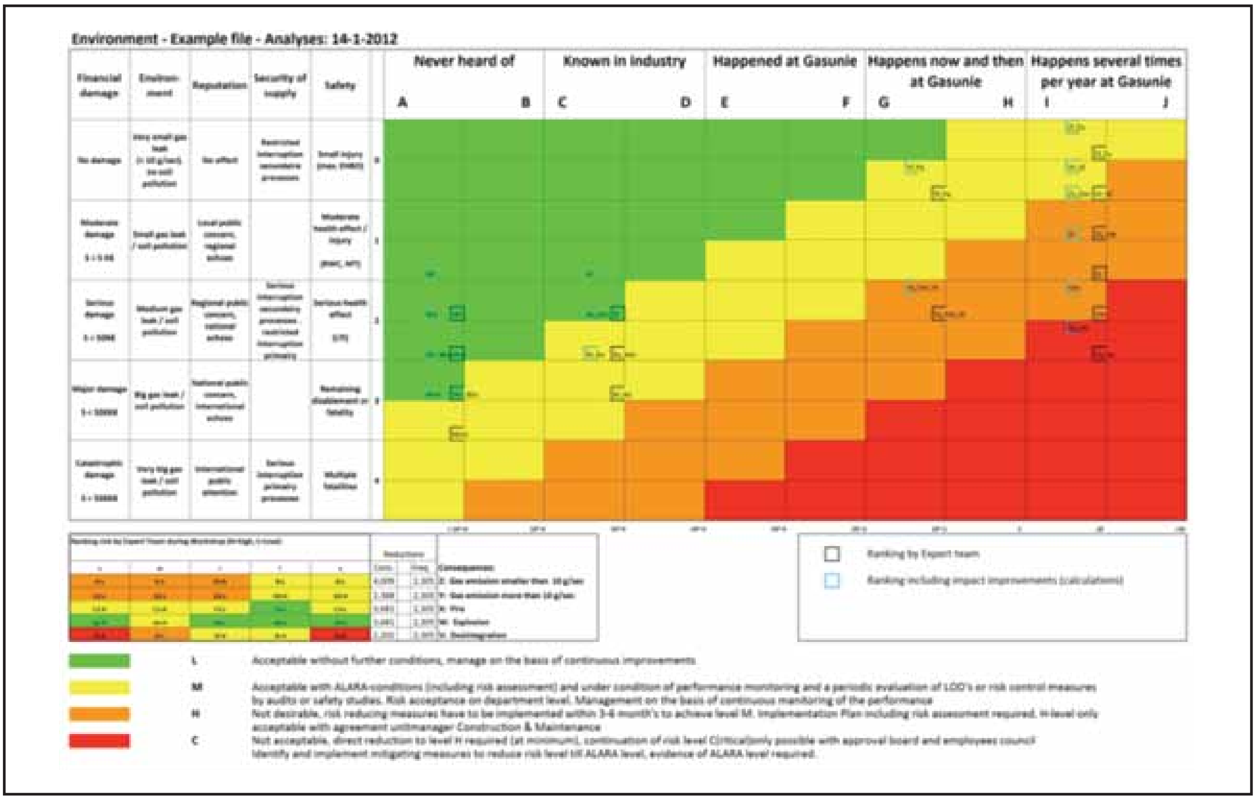

Fig.10 Feasibility study result.

Manufacturer	Type	Average year of construction	Number	Estimated future safety risk score
B	Ball	1991	108	
K	Plug	1973	4900	
C	Ball	1979	1558	
L	plug	1992	957	
J	Knife-gate	1978	790	
D	Ball	1985	402	
H	Gate	1977	3572	
A	Axial on-off	1974	457	
M	Plug	1972	1355	
E	Ball	1996	7	
F	Ball	2007	397	
G	Ball	1976	13	
N	plug	1974	227	
I	Gate	1972	865	

Table 2. Review of the future safety risk score for all valve types.

Inventory of valve types that meet GTS risk standards

A review of the score of all the valve concerned is presented in Table 2, which clearly shows that most valves will not meet the safety criteria in the near future. The main threats to valve integrity are shown in Fig.11, in which the light blue bars represent the actual threat level, based on the application of the mitigating measures that are in place, the Performance Indicators. Wear, external corrosion, external interference, and vandalism are the most important threats at this moment (each of which is 5%-6%, which means that all of them are controlled for about 80%). All of these threats have the option to reduce the threat level by the implementation of the additional mitigation measures that have been proposed by the expert team during the workshop and which are shown by the dark blue bars. The risk matrix that has been discussed above, however, shows that these additional mitigation measures will not have the effect of moving the valve integrity out of the red zone.

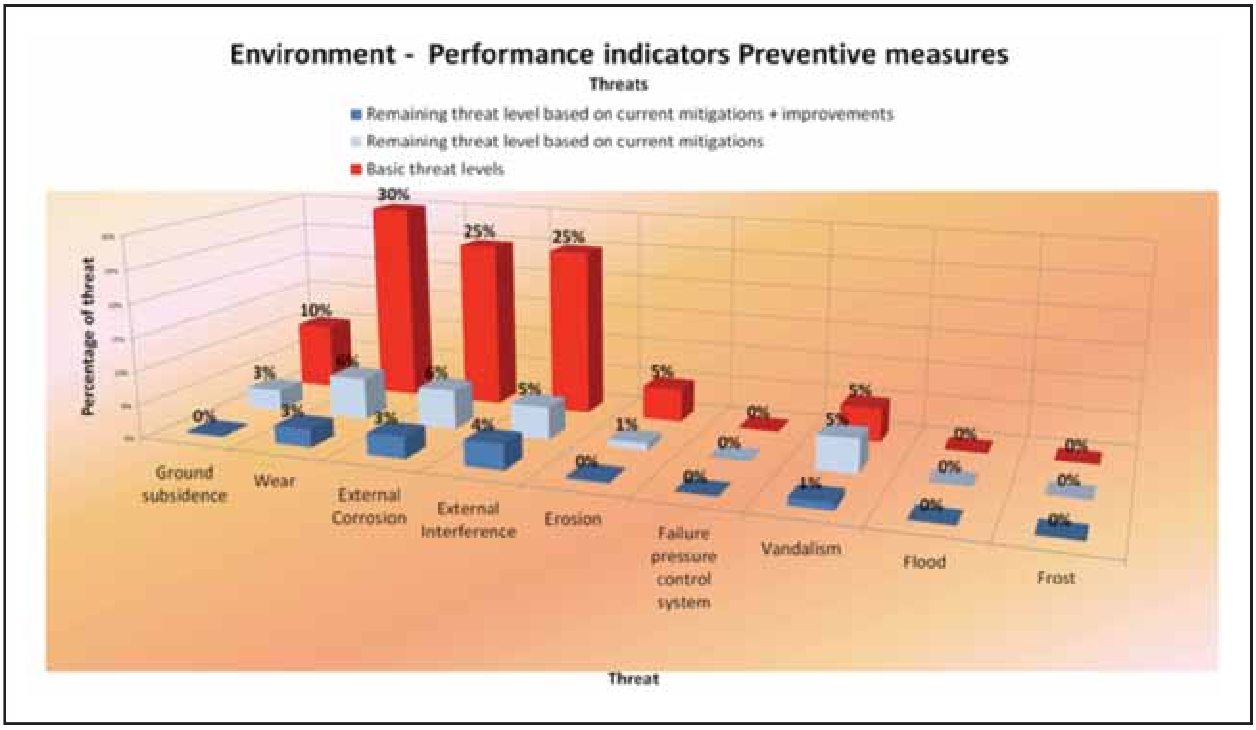

Fig.11. The main threat to valve integrity.

Prioritization replacement programme and experimental study

It was clear to GTS that the valves that had a red score on the safety aspect need to be replaced. Because the lead time of such a project is rather long, it was considered desirable to find a method of sub-ranking of the valves that need replacement, in other words to differentiate between the 'bad' and the 'ugly'. For this reason, a pilot study was been carried out to investigate the possibility of further ranking by scoring the matrix parameters.

The following relative-ranking factors were introduced to enable ranking of valves from the various different manufacturers:

Colour scores:	*Ranking*	*Aspects of matrix*	*Ranking*
Red	3	Safety	10
Orange	2	Costs	2
Yellow	1	Environment	5
Green	0	Reputation	3
		Security of supply	8

The yellow score is acceptable under the GTS' condition of As Low As Reasonably Acceptable (ALARA). For this reason the standard is calculated on the basis of the yellow score in combination with the above-mentioned aspect ranking, a technique of virtual ranking. The number of 'criticals' (consequences that have red scores) in the overall assessment is six, i.e. the level of risk of the following six consequences was concluded not to be acceptable:

- disintegration (failure of drain and seal connections)
- control on loss of containment during calamities
- isolation fails during maintenance work
- grid separation fails
- failure of function causes unwanted downstream effects
- doesn't meet requirements on License to Operate.

The scores of these aspects of the matrix on these six consequences were then been used to differentiate between all the valves. This brings the virtual standard (i.e. the maximum allowable risk level) to: 6 x (10 + 2 + 5 + 3 + 8) = 168. All valves having a score above 168 do not meet this virtual risk standard. The results of the analysis is presented in Fig.12, where clearly the ball and gate valves do not meet this 'virtual' standard with one exception: ball valve F.

Pilot study: ranking new valves on the basis of design parameters and theoretical mitigations

Because the use of ball valves as the main isolation valves is considered by GTS to be essential for the execution of pig runs, the company has decided to extend the Bow-tie analysis to more recently designed ball valves to find out if more recent design types have a better risk score than the valves of older designs which are in operation.

This pilot study was carried out by the same group of experts. Analyses were carried out to find correlations between the Bow-tie parameters and the final score in the risk matrix. In the end, the summarized value of all the preventive mitigation measures proved to be the major factor in predicting the risk score of the new valves with unknown risk-profiles.

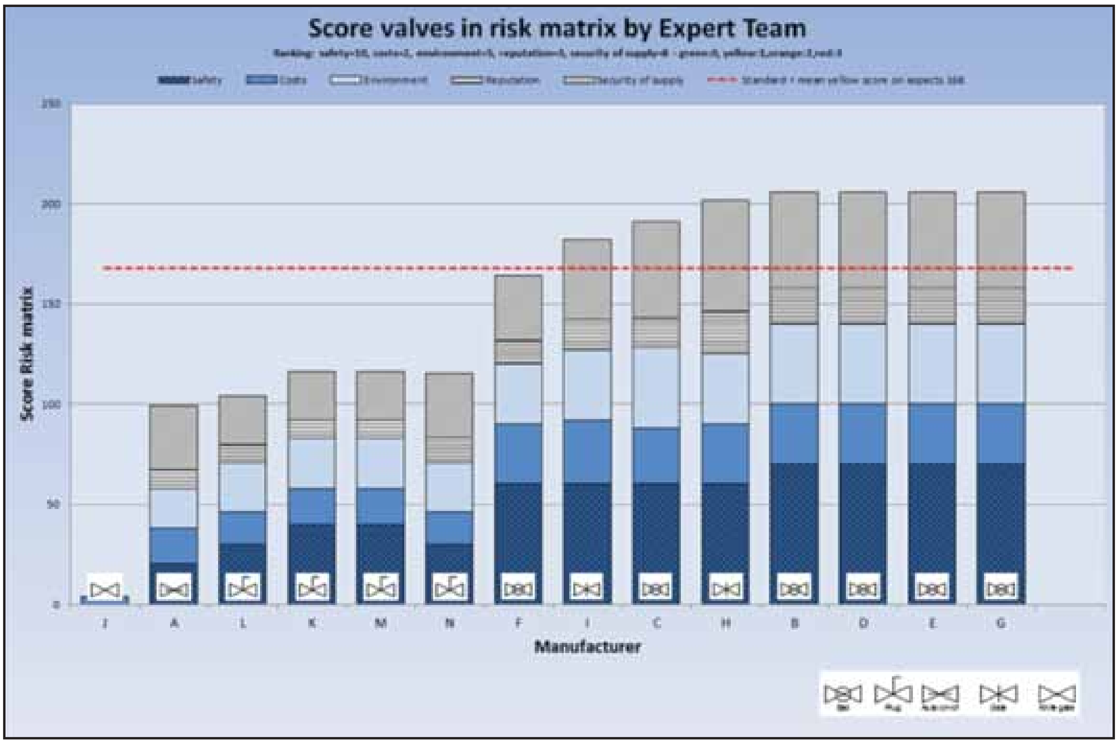

Fig.12. Example of the 'virtual standard'.

This is shown in Fig.13 where the relationship between the summarized preventive barrier values of the Bow-tie (blue line) and the virtual risk level (red line) can be seen. In summary:

- high barrier value → low risk level in matrix (and vice versa)

The green line in Fig.13 shows the relationship between risk level and the virtual standard (i.e. the maximum allowable risk level):

- R_p = summarized barrier value > 1.68 gives an acceptable virtual risk level

This results in the definition of R_p as the predicted risk level based on the summarized barrier value of all mitigation measures from the Bow-tie analyses.

This factor R_p has been used to compare the risk score of unknown, new, valves as a selection criterion. An example of the result of this way of risk ranking is given in the following: the new design of valve C has been investigated by the expert team and all mitigation measures were reassessed on the basis of the valve parameters that were supplied by the manufacturer. Next, the summarized preventive barrier value was calculated with the result: R_p (new design) = 1.78. Conversion of this calculated R_p value into the virtual risk value can be done via the green dotted line in the graph of Fig.14, which shows the increased value of the R_p for the new valve C compared to that of the old design that originates from around 40 year ago. This higher value is the result of the modifications that the supplier has made to the original design and, as a consequence, the modifications result in an expected virtual risk level in the matrix of 108, which means that the new valve will meet the virtual risk criteria now and for up to 40 years of operation. The development of the Bow-ties for other comparable valves (and their manufacturers) is continuing and the values of R_p will be used as selection criteria for the valve (both manufacturer and configuration) that will be selected for the replacement programme.

It should be noted that this methodology applied can be used – and is going to be used – for all GTS' infrastructure assets.

Summary and conclusions

A new method of integrity and risk control has been developed with the following benefits:

- full transparency in threat mitigations and consequence control
- complete integration of all relevant risk areas
- perfect match between risk control and cost containment.

A new and enhanced method of risk assessment has been developed by GTS and PIMS International that enables the pipeline operator to:

- Meet governmental requirements on risk management by controlling not only the safety risks but also the risk of environmental damage, loss of reputation, security of supply, and costs, in a highly transparent way.
- Determine the performance of integrity management with performance indicators that can easily be derived from the Bow-tie diagram.

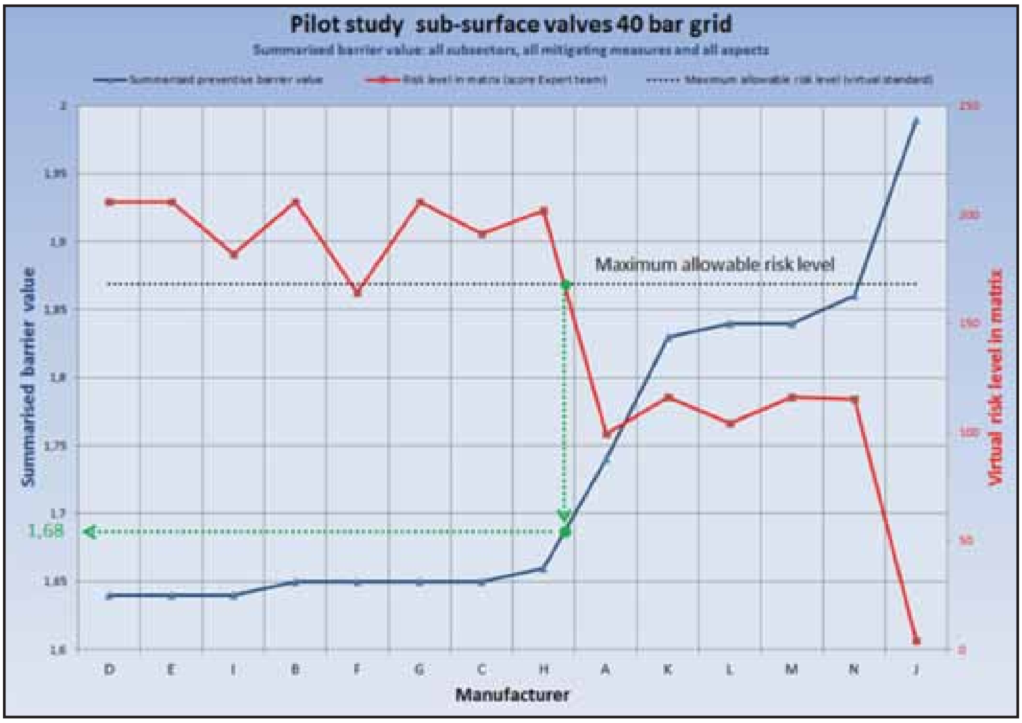

Fig.13. Relationship between the preventive barrier values of the Bow-tie (blue line) and the virtual risk level (red line).

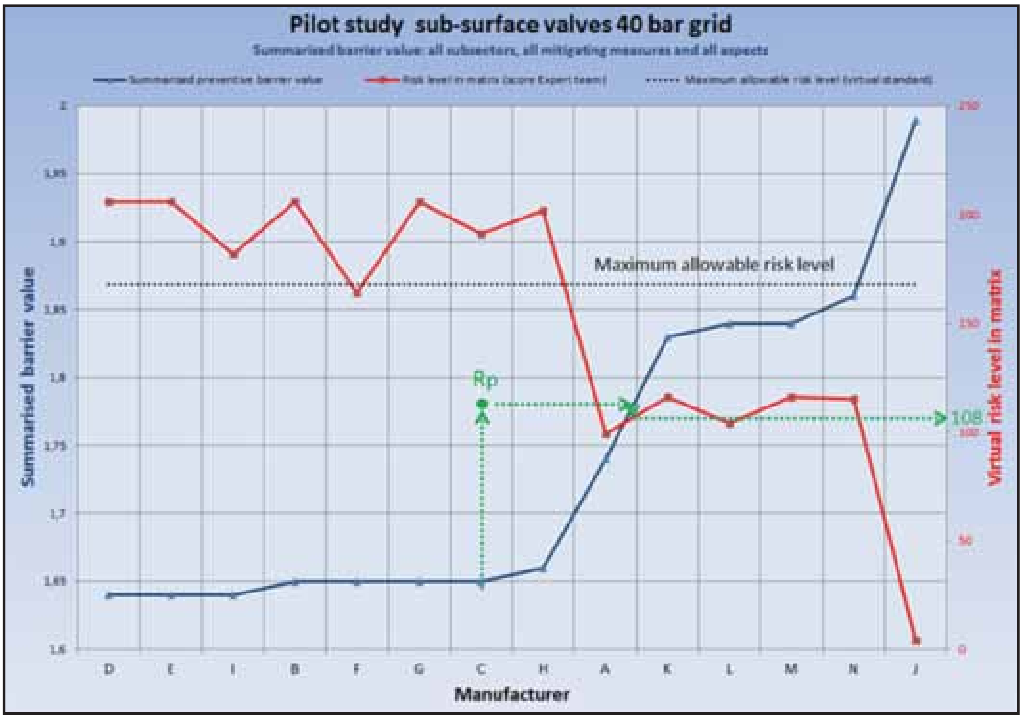

Fig.14.The increased in value of Rp for the new design of valve C compared to that of the old design.

- Save money in daily practice by the application of life-cycle cost optimization which is supported by a software tool that is based on the extended Bow-tie methodology, and which enables balancing of all existing and new mitigation measures for all life cycles based on efficiency, allowing the most economical way to be found of operating the infrastructure.
- Find improvements on risk management (new mitigation measures) in a highly structured way, and extend the effectiveness of expert-team risk-assessment sessions to a higher level of quality.
- Make decisions on risk-based equipment selection on the drawing board by analysing the parameters of a Bow-tie diagram that has been developed using the equipment characteristics.

Assessment of the integrity of the sub-surface valves in GTS' 40-bar grid has been carried out by using the new risk-assessment method with the following conclusions:

- The sub-surface gate and ball valves are meeting their end-of-life after 40 years of operation.
- Plug, knife-gate, and axial on-off valves last longer than gate and ball valves; however, they cannot be used on pipelines which are required to be piggable.
- The parameters of ball valves of recent designs perform better under the combined risk of safety, environmental damage, loss of reputation, security of supply, and cost when compared to the 40-year old designs.

Appendix 1: Algorithms used for efficiency calculation

1. The sum of the effectiveness of the main barriers should always be 100%, and is factor representing the relative contribution of each of the life cycles (design, construction, etc.) for the prevention of the unwanted event occurring (in this case: loss of containment).
2. The value of the effectiveness of the main barriers will be reduced by the effect of escalating factors. An explanation of this reducing effect is given below.
3. The 'incorrect assembly' escalating factor represents 75% of the reducing effect of both escalations to the current barrier value of construction. This means that without any mitigation measure for this factor, only 25% of the barrier value of construction would remain, i.e. 25% x 20% = 5%;
4. At this moment only one mitigation measure against the 'incorrect assembly' escalating factor has been implemented. This measure is called 'welding instructions according to procedure' and has a barrier value of 90% (green barrier). This means that 90% of the escalating factor is compensated for and, as a result, 10% of the reducing effect of the escalation factor still has an effect which results in a reduction of the main barrier 'construction' down to:

   20 x (1 – (0.1 x 0.75)) = 18.5%.

5. The total value of all mitigation measures (incl. the yellow ones – the improvements) for the 'incorrect assembly' escalating factor is:

   1 - (1 - 0.9) x (1 - 0.9) x (1 - 0.8) = 0. 998 i.e. a 99.8% barrier.

   This means that the implementation of all barriers including the yellow ones results in a reduced value of the main 'construction' barrier down to:

   20 x (1 – (0.002 x 0.75)) = 19.970%, i.e. a reduction of 0.030%.

6. The total value of all mitigation measures (including the yellow ones, the improvements) for the 'incorrect application of materials' escalating factor is:

   1 - (1 – 0.95) x (1 – 0.9) x (1 – 0.8) = 0.999 i.e. a 99.9% barrier.

   This means that the implementation of the yellow barriers results in a reduced value of the main 'construction' barrier down to:

   20 x (1 – 0.001 x 0.25) = 19.995% i.e. a reduction of 0.005%.

7. The total effect of both escalating factors for the remaining value of the main 'construction' barrier when all mitigating measures are implemented is a reduction down to:

   20% x (1- (0.030 + 0.005)) = 19.965%.

8. This reduction of the main barrier will result in an increase of the effect of the threat of ground subsidence to the frequency of the 'loss of containment' unwanted event of:

   0.035 x 9.9% = 0.35% (approx.).

9. The effect of all the mitigating measures in the Bow-tie diagram is calculated in a similar way. Whether implementation of a certain mitigation measure is efficient depends on its cost. Once the cost of all the mitigation measures have been incorporated, the efficiency of any individual measure can be calculated, and it can then be ranked on the basis of its individual efficiency, no matter where it is positioned in the diagram (or life cycle). This final table with all the mitigation measures ranked on their efficiencies enables the operator to take the next steps required to implement life-cycle cost optimization.

(*Note: The Bow-tie has been developed on the right-hand side of the unwanted event as well, which enables not only economic optimization of suppressive measures to be evaluated, but also enables GTS to find the most efficient control of risk by balancing between preventive and suppressive measures.)*

Appendix 2: Gasunie's risk matrix.

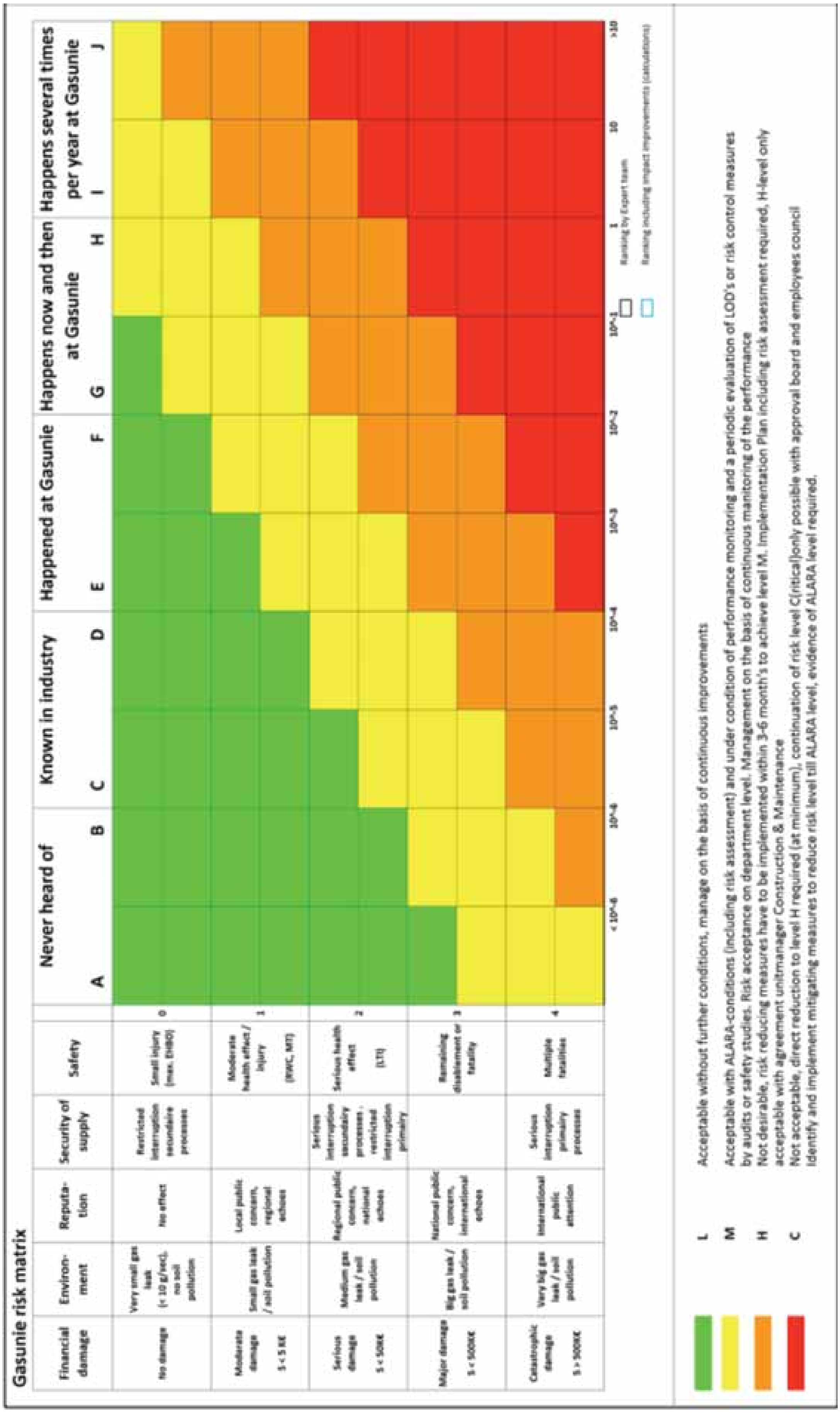

Fig. I5. Gasunie's risk matrix.