CHEMICAL ENGINEERING TRANSACTIONS

VOL. 31, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti

ISBN 978-88-95608-22-8; **ISSN** 1974-9791

DOI: 10.3303/CET1331002

Quantifying Safety with a QRA: To Agree on the Results, the Method Should Be Explicit

Hans Boot

TNO, Dep. Urban Environment and Safety,PO Box 80015 , 3508 TA, UTRECHT, The Netherlands
hans.boot@tno.nl

Nowadays, more and more countries are starting to use QRA based methods to quantify the risk in terms of “individual” or “societal” risk. Although it seems as if there is a consensus about what a PR contour or FN curve actually is, it turns out that the implicit calculation method required to generate such a result is far from standardized. In practice, it is often not even transparent or traceable how these risk criteria were (or should have been) constructed. Recent benchmark studies in Belgium pointed out that even a straightforward comparison of a tank storage park could end up with differences up to 400 %. These differences are of course unwanted, and for obvious reasons transparency and traceability of the underlying calculation method should be improved.
TNO has been working on a complete revision of its QRA tool, and much effort has been put in the usage of a standardized method to obtain transparent, traceable results in terms of the resulting quantified risk values itself. Unfortunately, while comparing the results with other tools, it appeared that substantial differences could be associated with several steps of the calculation, due to differences in the consequence models used, the damage (lethality) relations applied, the typical governing parameters used in the models, and last but not least, the risk calculation method itself. This paper describes the nature and origin of the potential calculation differences, and will provide solutions to improve transparency and traceability, aimed at obtaining comparable results by different QRA applications.

1. The use of QRA methods in the Netherlands

Being a densely populated and highly industrialised country, there has been a lot of attention for safety assessments in the Netherlands. In this context, the Netherlands were one of the first countries to introduce obligatory QRA’s (Quantitative Risk Assessments) for SEVESO sites and transport activities.
Nowadays, many QRA studies have been performed –extensively using criteria like “Individual Risk Contours” and “Societal Risk Curve” - to evaluate possible safety bottlenecks. For both stationary installations and transportation QRA’s, standardized methods and tools have been established to be able to verify the safety situation with current legislative standards.
Originally, the efforts to obtain transparent and traceable results were aimed at providing guidelines on “How to” perform a consequence analysis and “How to” perform a QRA. This is how the famous “Yellow book” (how to calculate physical effects, CPR14E, 2006), “Green book” (how to translate overpressure, heat radiation and toxic dose into lethality, CPR16E, 2005) and “Purple book” (how to perform a QRA, CPR18E, 2005) were established. However, because it appeared that even with these guidelines, substantial differences in calculated risk values could be obtained, the Dutch Government used a rather radical solution to get rid of these differences; they simply prescribed the software to use for the QRA (Uijt de Haag, 2007).
From the point of view of “consistency in legislation” one can understand this choice; the use of standardised packages should ensure reproducible answers, even when being used by different people. However, from the scientific point of view, this didn’t exactly improve the insight on the understanding how these differences could occur. Furthermore, we should be aware that the calculation of a risk contour or societal risk curve doesn’t provide an “absolute truth”. The answers of a QRA are highly affected by many implicit assumptions and choices, failure frequencies used, or parameters entered. The required inputs may also involve a lot of subjectivity and dramatically influence the outcome.

Please cite this article as: Boot H., 2013, Quantifying safety with a qra: to agree on the results, the method should be explicit, Chemical Engineering Transactions, 31, 7-12 DOI: 10.3303/CET1331002

This is why the current approach of the Flemish administration (LNE, 2012), where different models, methods and influencing parameters are investigated, will probably lead to a more clear regulation, because they try to prescribe the method rather than the implementation, making the calculation method itself explicitly transparent and traceable.

2. Review of the QRA calculation method

Ever since the ’80-s, where TNO was responsible for the “Yellow book” (CPR14E) and the “Green book” (CPR16E) TNO has also provided a software implementation of the methods described in these books. Apart from EFFECTS, a consequence modelling tool, a dedicated QRA tool called “RISKCURVES” has been available. A few years ago, the EFFECTS consequence modelling tool was completely rebuild, now including recent insights in consequence modelling (Boot, 2012). Recently, as a follow up of the consequence modelling developments, TNO’s QRA suite was also completely renewed. Although the biggest challenge was to include the new “Loss of Containment” model chains from the new EFFECTS version, a lot of effort was put in comparing results with previous versions and other software packages. As a developer TNO was highly aware of the sensitivities of customers for “a change in results”. Since TNO is providing RISKCURVES in many countries across the world, results were compared with the previous version (using different consequence models), but also with other QRA applications (RBM-II, SAFETI-NL). Obviously, differences were expected, but after thorough analysis it was found out that there were multiple reasons why an “individual risk contour” or “societal risk curve” could come out very differently.

3. Potential reasons for differences in results from a QRA

As already stated, the calculation procedure of a QRA -involving a consequence calculation, a frequency estimation, event probabilities and entering many inputs- can never end up with a “absolute truth” in terms of societal risk or individual risk. However, even when using the same inputs, it appeared that implicit, sometimes even undocumented assumptions would influence the outcome of a QRA calculation. In the following paragraphs we will list the potential reasons for differences that were discovered.

3.1 Differences in the consequence models applied

To determine a risk of a “loss of containment” event, the first step is to calculate the distances up to which lethal effects, resulting from the release hazardous materials, can be found. This “consequence calculation” can involve an outflow calculation, an evaporation or dispersion model, but also fire and explosion (overpressure) models are involved within the consequence calculation.
It is well known that the implementation of the “dense gas” dispersion may have big influences on the reported concentration distances, but it appeared that the method by which a time dependent release/evaporation rate was transferred to a (semi continuous) dispersion model can be undocumented (using time segments, average rate, or “Purple book” representative rate). Not only the internal dispersion model might differ, but also vapour cloud explosion phenomena can be described using the TNT-equivalency or the more sophisticated “Multi Energy” method, potentially leading to totally different overpressure contours. Even for fire and heat radiation phenomena, different approaches (e.g. “Yellow book” models versus “Dynamic BLEVE” (Martinsen, 1999), or “two zone pool fire model” (Rew and Hubert, 1997)are possible.

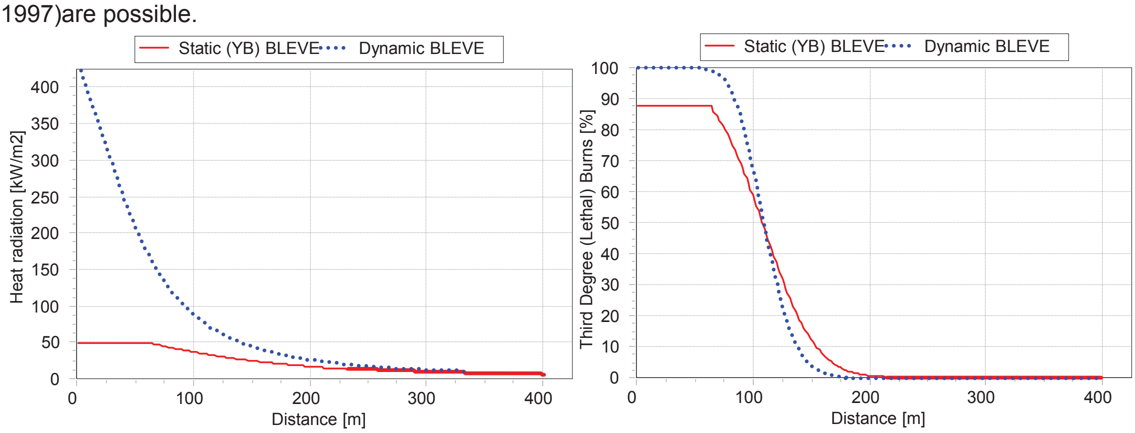

Figure 1: Differences in heat radiation (left) and lethal burns (right) for Yellow book BLEVE (red line) and Dynamic BLEVE (Blue line)

As long as the calculation method, the answers for intermediate calculations, and the resulting effect distances are explicitly reported (for different stability class situations), the reasons for differences in risk values will at least be traceable.
A good approach to be able to fulfil different demands in different situations is to offer different models (e.g. TNT model and Multi Energy model) inside the QRA application. In order to be able to use "consequence distances" calculated by other models, a program like RISKCURVES can also work with a "Damage definition" allowing to enter a toxic lethality footprint, BLEVE circle, overpressure contours etc., as calculated by external programs, This damage definition can thus be used to eliminate the impact of a different consequence model.

3.2 Differences in damage relations

Another crucial step in calculating distances of specific phenomena (heat radiation levels, peak overpressures, pressure impulses or toxic doses) is the translation into damage criteria. For a QRA, this "damage" is usually expressed as "%lethality" (probability of death) for both inside and outside situations. A general relation in damage models is the so-called probit function (CPR16E, 2005):

$Pr = A + B \,.\, Ln(D)$, where the dose D can be:

toxic dose, $D = C^n.t$, with C in [mg/m^3 or ppm]
heat load, $D = Q^n.t$, with Q in [W/m^2]
pressure impulse, $D = P^n.t$, with P in [bar or Pa]

The probit value Pr is a measure of probability of the damage (e.g. %death), and A, B and n are substance or effect specific constants. Although the Green book already gives good guidelines for those damage relations, not all countries use the same approaches. Even within Europe itself, there is no harmony in the toxic probit constants or threshold concentrations for toxic chemicals. This means that, in order to be able to perform toxic dose calculations in different countries, the typical probit values (specific A, B and n values assigned to chemicals) need to be adjustable. When comparing results, it is obvious that the toxic probit constants need to be reported explicitly.
Apart from the obvious toxic damage relations, the probit method can also be used on overpressure damage, or heat radiation damage. Although there is more consensus on heat radiation, countries like Brazil appear to use a different n-exponent in the heat radiation probit.
For overpressure damage, different approaches are used; the damage can be based on threshold overpressure levels (e.g > 0.3 bar peak overpressure is regarded as "total destruction, 100% lethality, values between 0.1 and 0.3 bar correspond to a 2.5 % lethality inside due to glass fragments), but it is also possible to use "probit based" relations for lethality due to overpressure. Again, to make calculations comparable, the damage translation constants needs to be editable, and should be explicitly reported. One often neglected issue is the distinction between "inside" and "outside" lethality due to a physical effect. Since the calculation of "societal risk" involves the potential protection of population that is inside houses, both lethality categories should be incorporated in the calculation. For toxic damage, a simplification by stating "lethality inside is 10 % of lethality outside" is often applied. Although this approximation seems justifiable at first sight, it appears that for higher toxic doses - note that a 5 times exceeding of 100 % lethality dose outside would still provide only 10 % lethality inside-, this assumption can be very optimistic.

Furthermore, the passing time of the cloud and n-probit will have big influence on inside lethality. A better approach for inside toxic lethality would be to include an inside dose calculation based on an average ventilation rate. This can also be used to account for countries with a warm climate, where housings are designed for optimal ventilation (no glass windows). Although simplifications for inside toxic lethality tend to make the calculation procedure more "transparent", they can lead to a big underestimation of the actual lethality, and thus lead to big differences in QRA results.
For individual risk calculation, which by definition is based upon an "unprotected, 100 % outside, (free field?)" calculation, it is not always obvious if overpressure damage due to fragments (buildings, glass) are included or excluded in the QRA. Again, this damage relation should be explicitly reported to make the calculation comparable.

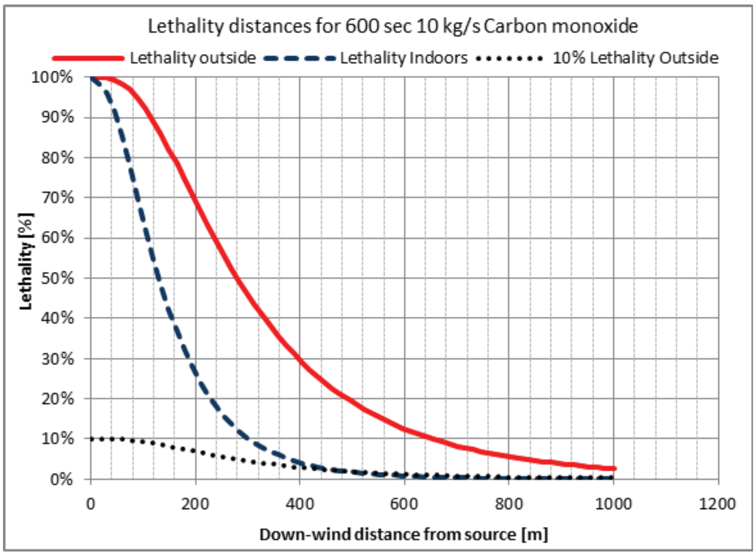

Figure 2: Lethality outside, lethality indoors based on ventilation rate of 1 refreshment / h (dashed) and lethality indoors based on 10 % outside simplification (dotted) versus distance for a semi continuous Carbon Monoxide release (used CO probit n = 1)

3.3 Differences in values of dominating parameters

In order to perform a full consequence calculation for a specific "loss of containment" scenario, a large number of input parameters have to be provided. For a leak scenario, involving an outflow calculation, a contraction coefficient is of major importance. For a pool evaporation, the solar heat radiation and pool thickness (related to subsoil roughness) may dramatically affect the evaporation rate. For a pool fire model, the burning speed (related to chemical) and soot fraction of the flame will strongly influence the outcome. Even a well-recognised model as "neutral gas dispersion" is highly affected by its dispersion σ_Y and σ_Z values, and unfortunately, these values tend to be obscured to its users and are often not explicitly reported.

The best way to obtain reproducible results for these kind of influences would be to prescribe values for "standard" situations. This is what has been done in the Dutch "Purple book" and later in the Dutch "SAFETI-NL program" where many parameters have been fixed to specific values. Unfortunately, this also eliminates the possibility to take into account specific local situations or exceptional situations. For instance, pool size limitation (usage of bunds, dykes, drains) can be an important effect reducing measure (pool fire, pool evaporation), so one should have the possibility to evaluate this effect and modify these kind of parameters. Furthermore, the meaning of parameters is not always obvious; a maximum toxic exposure duration may be explained as "time until sheltering", as a "passing time of the cloud" or even as a "release duration".

Of course, awareness of these influencing parameters is of great importance when performing a QRA, but unfortunately, one can only see the influence when starting to manipulate the values.

One good way out of this dilemma is to prescribe default values for these parameters, but allow deviating with arguments ("because of local situation") and explicitly report the values used inside the final QRA.

3.4 Differences in the risk calculation method itself

When starting comparing QRA results from different packages, the expectation was that the consequence model results were the main reason for differences in the calculated risks. Of course, apart from the consequence part, the failure frequency of the LOC event, applied for the scenarios, and weather statistics are other main components in the risk calculation, but these values are (almost) always explicitly reported and can be modified to make the QRA based on the same situation.

Because the RISKCURVES QRA application allows the use of a "damage definition" (a lethality footprint used as an interface to take results from another external consequence model), it is possible to use completely identical input for the QRA calculation. It appeared that even while using identical frequencies and consequence results, non-negligible differences in results were obtained. This implied that the QRA calculation method itself might be implemented differently.

Since all applications evaluated claimed to use the "Purple book" method for calculating Individual risk (IR) and societal risk (F-N curve), a further analysis of degrees of freedom within this method was required.

The purple book provides two procedures to obtain IR (individual risk) and the FN curve (societal risk). Basically, these schemes describe that risk should be calculated by cumulating all possible weather classes (each having a probability of occurring), for all corresponding wind directions (with a provided statistical probability of wind occurring from that direction), for all LOC events.
With respect to the individual risk, even when comparing toxic scenarios, (thus eliminating influence of “ignition points”) differences in the order of magnitude of 50 % were found, especially at short distances. When digging into the potential reasons for these differences,it appeared that some QRA routines used a rather simplified method to translate a toxic footprint into blocks having an equal “effective cloud width” (ECW).

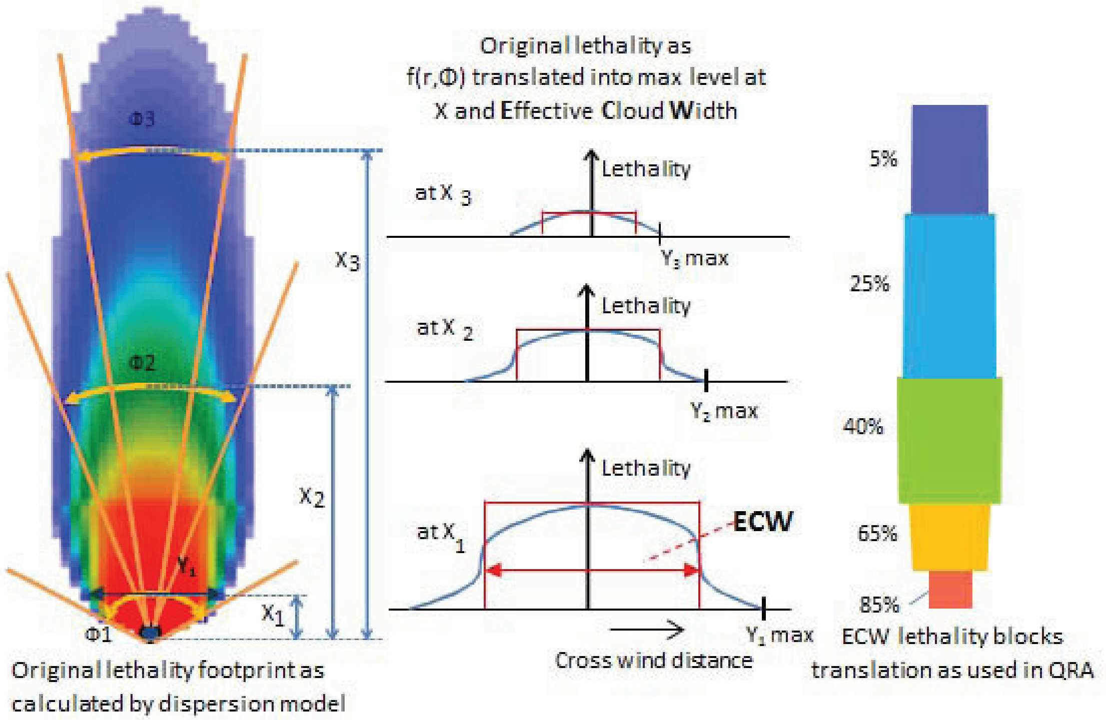

Figure 3: Example of an original toxic lethality footprint (left side), translated into discrete blocks (right side) using an “effective cloud width” (ECW) and uniform lethality over the cloud width

Although the Purple book describes the potential use of this “effective cloud width” for toxic scenarios, the translation into a limited number of blocks with equal “representative lethality” may lead to serious underestimation of risks. Especially at shorter distances, the “real” cloud angle and lethality may be considerably higher than an averaged block value for ECW and lethality.
For a “societal risk” one can even challenge the legitimacy of using an “effective cloud width”; since the original toxic footprint is translated into a smaller footprint having a higher lethality (uniform over the width). When projecting a smaller but more lethal cloud on a distributed population, the number of people affected (as used in the FN graph) may deviate largely from those by the original toxic footprint, simply because the area affected may differ a lot. The net effect can both be over- or underestimating, depending on the presence of population concentrations. Apart from that, it appeared that some methods use a population definition as polygons, containing population, where the number of victims is calculated as the overlap of an “Effective Cloud Width” blocks with those population polygons.
Again, these simplifications can be over- and underestimating, depending on the size of the cloud in relation to population area polygons.
The bottom-line of the observations with respect to the QRA method itself is that the current guidelines still offer too many degrees of freedom. Furthermore, it is often unclear how the QRA calculation itself has been implemented and what internal resolution (grid size for risk cells) or interpolation method is used.

4. Evaluation and conclusions

Although the methodology of Quantitative Risk Assessment is being used more and more, and criteria like "individual risk" and "societal risk" are sometimes even incorporated in safety legislation, the implicit calculation method to derive these criteria appears far from standardised. Although the available QRA tools appear to be providing the same type of results in terms of risk contours and FN curves, it is not always traceable how these risk criteria have been constructed. From a "Safety" point of view this is a highly unwanted situation because such a "quantification" of risk is not reproducible and therefore useless as a criterion. Acceptance of the results of a QRA as a measure for safety requires an explicit reporting on:

1- The consequence models that have been used, including theoretical background information and info on connection of models. This allows judgement whether these models are "fit for purpose". Reporting of intermediate results will help understanding the flow of the calculation.

2- The damage relations (probits, threshold values) used for both inside and outside lethality. Since there is no international (not even a European) consensus on lethality probits, these values have to be editable, and explicitly reported.

3- The dominating parameters (Sigma's for dispersion, contraction coefficients, soot fractions, fraction confined explosive mass) used inside the models. Prescribing certain defaults will help create uniformity, but a flexibility is required to be able to describe dedicated situations (evaluating specific risk reducing measures).

4- The internal risk calculation method used: which discretisation steps, grid size and interpolation assumptions have been used. Although the QRA calculation method looks well established at first sight, different mathematical methods for processing frequencies with lethality's can provide non-negligible deviations in cumulated risks.

Only transparently and traceable reported QRA results can be verified, and for that reason the internal calculation method has to be explicit. This implies that "black box" models or methods need to be revealed, and suppliers of QRA tools will need to provide more background information. And that of course, includes TNO itself.

References

Boot H., 2012, Developments in Consequence Modelling of Accidental Releases of Hazardous Materials, Conf. "Safety Engineering" , Ostrava, Czech Republic, 17 Oct. 2012, DOI 10.2478/v0281-012-0006-9.

CPR14E, Committee for the Prevention of Disasters (CPR) publication CPR 14E, The Yellow book, Methods for the calculation of physical effects due to releases of hazardous materials, third edition second revised print 2005, republished as PGS2 in 2006.

CPR16E, Committee for the Prevention of Disasters (CPR) publication CPR16E, The Green book, Methods for the determination of possible damage to people and objects resulting from release of hazardous materials, 1992, republished as PGS1 in 2005.

CPR18E, Committee for the Prevention of Disasters (CPR) publication CPR 18, The Purple book, Guidelines for Quantitative Risk Assessment, 1999, republished as PGS 3, 2005.

LNE, 2012, Vlaamse Overheid, Departement Leefmilieu, Natuur en Energie, "Onderzoek naar modellen voor gebruik in de kwantitatieve risicoanalyse" (Study on models for application in quantitative risk analysis) , Bestek nr. LNE AMNE/dVR/KI/201100027.

Martinsen W. E. and Marx J. D., 1999, An Improved Model for the Prediction of Radiant Heat Flux from Fireballs," International Conference and Workshop on Modelling the Consequences of Accidental Releases of Hazardous Materials, ISBN 0-8169-0781-1, Center for Chemical Process Safety of the American Institute of Chemical Engineers, pp. 605-621, 1999.

RBM v2.0, 2011, Risico Berekening Methode Vs.2, QRA software for transport installations, provided by AVIV, Enschede through Rijkswaterstaat, The Netherlands. (Dutch Ministry of Infrastructure and the environment). <www .rijkswaterstaat.nl/kenniscentrum/veiligheid/rbmii/documenten>, accessed 20.08.2012

Rew, P.J, Hubert, W.G.,1996, Development of a pool fire thermal radiation model, HSE contract research report no. 96.

RISKCURVES 9.05, 2012, QRA software by TNO, Utrecht, The Netherlands <www.tno.nl/riskcurves>.

SAFETI-NL 6.54, 2009, QRA software as prescribed in Dutch REVI guidelines, provided by DNV-software Londen through RIVM, The Netherlands. (Dutch Ministry of Infrastructure and the environment), <www.rivm.nl/Onderwerpen/Onderwerpen/S/SAFETI_NL>, accessed 20.08.2013

Uijt de Haag P. 2007. QRAs for Dutch installations, 12th symp loss prevention and safety promotion in the process industries, Edinburgh, U.K.: pp. 22e24 May,