How QMU Can Support Risk Assessment at the ORP: A simple illustration

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Overview

In this document, we revisit different analyses of the Hanford Waste Treatment Plant (WTP) storage tanks. The performance metric of interest is the time to lower flammability limit (TTLFL); a measure of how much time is available before a dangerous hydrogen gas buildup would develop, in the event of ventilation failure in a given tank. We draw data from two sources: Table 4-3 from Hu (2007), and Table 6 from Frankel et al. (2017).

We provide two presentations of the data; one in terms of the raw TTLFL, and one framed by Quantified Margins and Uncertainties (QMU). A direct comparison reveals that QMU better contextualizes the data by highlighting margin *and uncertainty*. Framing the problem in terms of margin gives the reported values a signed meaning – cases with negative margin are flagged immediately as issues. Reporting uncertainty gives the results interpretable magnitudes – cases where uncertainty prevents certification of positive margin are problematic, and warrant further investigation. This enables a quick read of the data – cases that are not acceptably safe can be identified, enabling mitigation.

Previous Analysis (Hu)

We first consider a previous published analysis of the Hanford WTP tanks' time to lower flammability limit (TTLFL).[1] The TTLFL is a measure of safety. The waste storage tanks at Hanford contain radioactive materials which produce ionizing radiation, which in turn spur the production of hydrogen gas. This hydrogen can build in concentration within a tank to a flammable concentration – the TTLFL is a measure of the time necessary for this process to occur. Aside from the primary hydrogen explosion hazard, there is additional concern about the release of hazardous material. The release of radioactive material into the surrounding biosphere is of grave concern, due to the potential for harm to the environment and public.

To prevent an explosion, the Hanford tanks have active ventilation systems. However, in the event of ventilation failure, either due to mechanical fatigue or an inciting accident (e.g. an earthquake), only passive ventilation is available to slow the hydrogen accumulation rate. Part of the objective in studying the TTLFL is to plan for such off-nominal conditions – in the event that active ventilation is lost, how much time is available to detect and correct a hydrogen buildup? The criterion for 'how long is safe enough' is an important operational question, one that must be raised and answered in order to ensure safety at the WTP.

Hu (2007) [1] estimated the TTLFL for both ventilated and non-ventilated conditions. These estimates were based on dynamical models of hydrogen concentration, and upon estimated concentrations of materials within each waste tank – the so-called Best Basis Inventory (BBI). Note that while the full BBI data are given as nominal values [1, Appendix A], the 2007 report does not provide uncertainties in these estimates. Therefore, the resulting TTLFL estimates are provided as best-estimates, without any quantification of their attendant uncertainties.

Figure 1 presents the data from Hu (2007) [1] – note that this presentation allows for relative comparison between the tanks, as well as absolute values of TTLFL. This visualization presents the raw data for assessing safety, but lacks some desirable features. Without expert knowledge of 'what is safe', the raw TTLFL values lack *context*, and require a reader to consult additional materials in order to assess safety. As we mentioned,

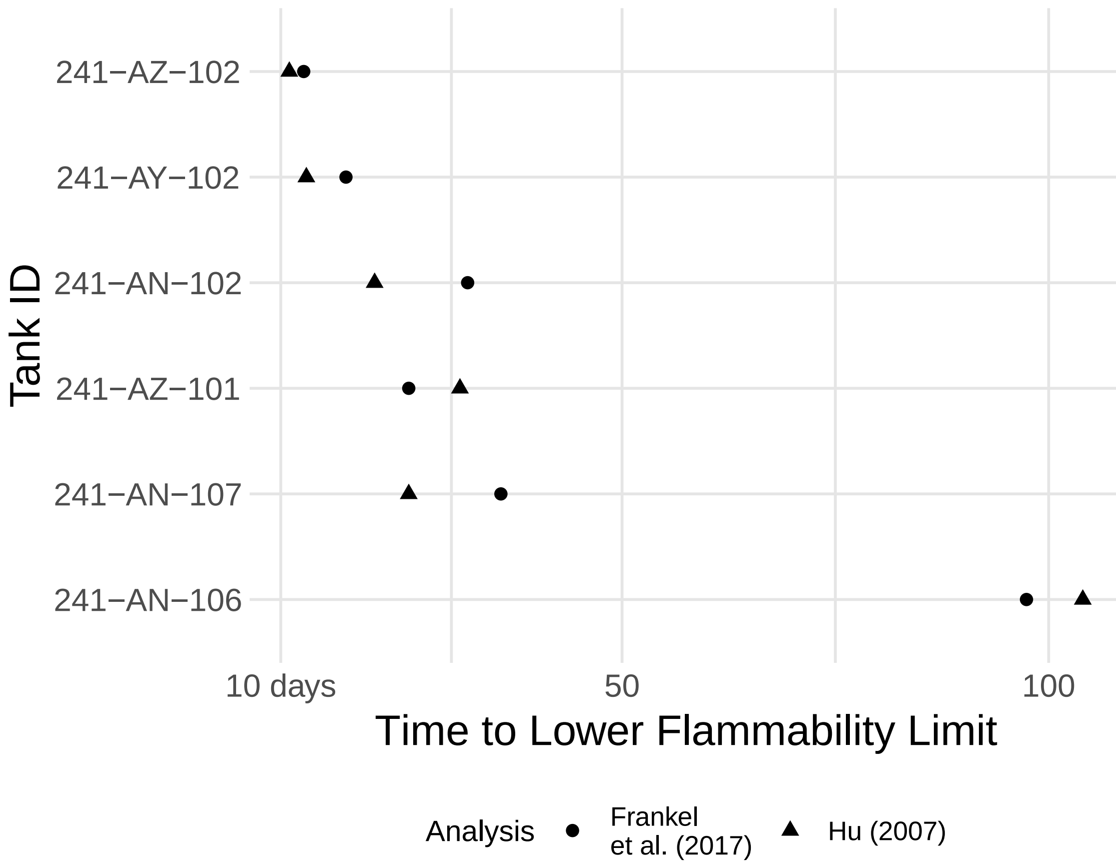

Figure 1: TTLFL data from Hu (2007) and Frankel et al. (2017).

the BBI is an estimate subject to uncertainties, such as sampling and measurement errors. These uncertainties may affect decision making; suppose the nominal estimate for a given tank is above an acceptable TTLFL threshold, but that its attendant uncertainty is large enough that a credible state may be below safe conditions. In such a case, a decision maker could achieve greater confidence in the safety of that tank either by increasing the TTLFL (say, through modifying the ventilation system), or by reducing the uncertainty in the BBI (by gathering more information).

Below, we will introduce a framework which enables the analysis sketched in the previous paragraph – Quantified Margins and Uncertainties.

Quantified Margins and Uncertainties

Quantified Margins and Uncertainties is a framework intended to raise the proper questions (how safe is safe enough?), focus activities in the correct arena (estimation of both nominal conditions *and* uncertainties), and ultimately clarify communication and facilitate decision-making. Here we introduce QMU, then apply it to the Hanford WTP.

The QMU Framework

QMU is an analysis framework, one which emphasizes key elements of the design and certification of engineering systems.[3] It has a number of steps, each of which helps to ensure that critical aspects of complex systems are addressed:

1. Identify and estimate a set of key performance metrics (PM) for the system
2. Determine for the PM a set of extreme values (EV) which are compatible with successful system performance
3. Estimate the uncertainties in both the PM and EV
4. Report results in terms of margins and uncertainties

Point 1 focuses on *system* performance P, ensuring a system-level view. There is a risk in complex systems of missing interactions between components; a focus on system performance requires the analyst to consider these interactions.

Point 2 requires the analyst to establish extreme values V for each PM P – these extreme values (EV) define bounds for the PM compatible with successful downstream performance of the system. The determination of these EV inherently requires some amount of engineering judgement. Such judgement will always be predicated on assumptions and subject to uncertainty and debate; however, *explicitly including* this step in the QMU framework ensures these issues are considered and documented. A decision maker reviewing results under the QMU framework knows that certain assumptions had to be accepted in order to define the thresholds, and might question these assumptions as part of the decision process.

Point 3 is the conventional practice of *uncertainty quantification* (UQ); the task of identifying and propagating sources of uncertainty through complex systems to the downstream PM. The myriad techniques for doing UQ are beyond the scope of this report. QMU is formally distinct from uncertainty quantification; it does not dictate how to estimate performance metrics or uncertainties. Instead, predicted quantities and their uncertainties are inputs to the QMU framework.[3]

Point 4 'closes the loop', and requires that results be presented in a fashion that facilitates decision making.

A margin $M = P - V$ is the difference between a PM and its associated extreme value. This construction lends obvious meaning to the sign of the margin, with positive values corresponding to conditions compatible with success. A negative margin in QMU does *not* mean failure or degraded performance is guaranteed, but instead that *one cannot certify successful operation*.

Each uncertainty U is associated with a performance metric, and quantifies contributions both from the estimated performance, *and* the gate. The uncertainties lend meaning to the *magnitude* of margin terms. This can be made quantitative through the *confidence ratio* $Q = M/U$. The confidence ratio (CR) is similar in spirit to the signal-to-noise (SNR) ratio; while increasing SNR indicates greater efficency, increasing CR indicates greater confidence in a system. In contrast, the CR can become negative (indicating a severe lack of confidence), and should not necessarily approach infinity, which would indicate an overbuilt system.

The question of 'how safe is safe enough?' is intimately linked to that of 'how large a Q is safe enough?' This is a challenging question, one which includes many concerns beyond the purely technical. Note that even once a precise statement of acceptable failure probability has been made, depending on the precise formulation of QMU employed – either fully probabilistic or based on intervals – the precise value of Q, and thus acceptable values, will change.

In practice, one reports not just confidence ratios, but also the margin and uncertainty terms. This provides some flexibility in how results can be presented, which we will demonstrate below.

QMU was developed by the national labs to support the certification of nuclear weapons; it was designed with high-consequence decisions in mind and is, *by design*, a conservative analysis and decision-support framework. The nature of the Hanford WTP is similarly high-consequence – the release of radioactive material into the environment is an *unacceptable* failure. In this sense, QMU is well-suited for to support the Hanford WTP.

Application of QMU to the Hanford WTP

To apply QMU to the Hanford WTP problem, we must work through all 4 steps of the framework.

1. Identify and estimate a set of key performance metrics (PM) for the system

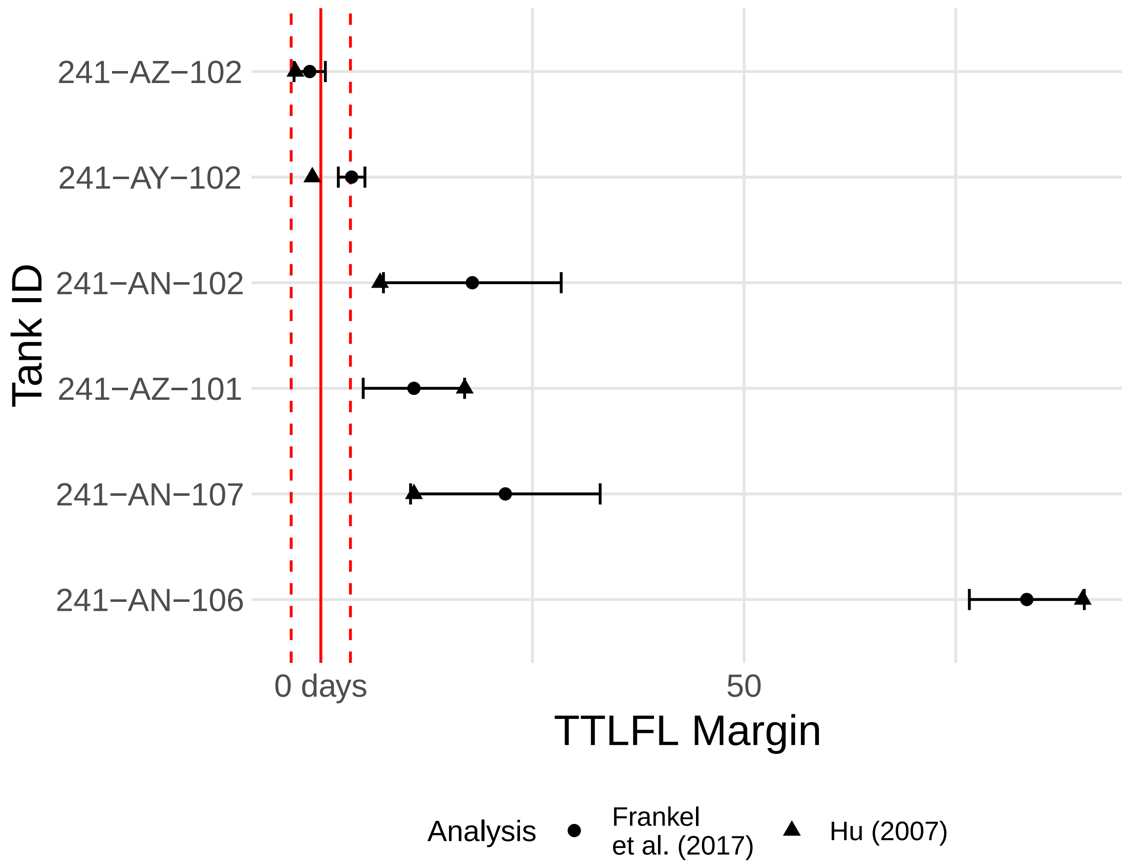

Figure 2: Visual QMU report for tank TTLFL values.

Following Hu (2007) [1], we select the time to lower flammability limit (TTLFL) as the primary system performance metric. We present nominal estimates from both Hu (2007) [1] and Frankel et al. (2017) [2].

2. Determine for the PM a set of extreme values (EV) which are compatible with successful system performance

We select 14 days as the critical value. This is in keeping with Frankel et al. (2017) [2], but is fundamentally an *engineering judgement*, and therefore subject to debate and revision. To model this, we assign an uncertainty of ± 3.5 days to the critical value.

3. Estimate the uncertainties in both the PM and EV

Frankel et al. (2017) [2] carried out a UQ analysis much like Hu (2007) [1]; we refer any interested readers to that report for further details. Suffice to say we consider interval QMU results from their work.

4. Report results in terms of margins and uncertainties

Figure 2 visually depicts some advantages of QMU. Nominal conditions to the right of $M = 0$ are asserted to be compatible with success; this assertion is based on the selection of the gate threshold T. Presenting the results in terms of margin naturally calls attention to this fact; even a casual observer must wonder what `0 days` refers to in Figure 2. Drawing this attention is part of the advantage of the QMU framework, as it forces one to ask the right questions. Upon viewing Figure 1, one is certainly informed by the best estimates, but may simply accept these uncritically. Upon viewing Figure 2, one cannot help but ask what the significance of the red band at zero is – the point of zero margin (and its uncertainty), defined by the chosen extreme values. This invites the viewer to question the results, and ultimately consider whether the chosen threshold is appropriate. Note that framing in terms of margin does not add any new information, but simply presents the available data in a form that facilitates communication and decision making.

The QMU framework *does* require information above nominal estimates in the form of uncertainties; in Figure 2 these are presented as intervals. The intervals which exclude zero correspond to tanks we can certify meet our defined performance gates; only Tank 241-AZ-102 (among those considered) does not meet this requirement. Note that the conclusions one can draw from the QMU results are richer still; Tank 241-AN-106 may be under-utilized, based on its extreme margin value, as compared with its attendant uncertainty.

Bibliography

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[3] Sharp and Wood-Schultz, “QMU and Nuclear Weapons Certification: What’s under the hood?” (2003)

[4] Committee on the Evaluation of Quantification of Margins and Uncertainties Methodology for Assessing and Certifying the Reliability of the Nuclear Stockpile; Division on Engineering and Physical Sciences; National Research Council, “Evaluation of Quantification of Margins and Uncertainties Methodology for Assessing and Certifying the Reliability of the Nuclear Stockpile” (2009)