'For a successful arrival of the hydrogen economy improve now the confidence level of risk assessments!'

Hans Pasman

Emeritus Delft University of Technology, NL

Research Professor MKOPSC, Texas A&M

hjpasman@gmail.com

- Intro and H_2 -perspective
- Quantitative Risk Assessment in general
- Wish-list for hydrogen risk analysis
- Conclusions of what can be done

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The Hydrogen Economy; hydrogen hazards

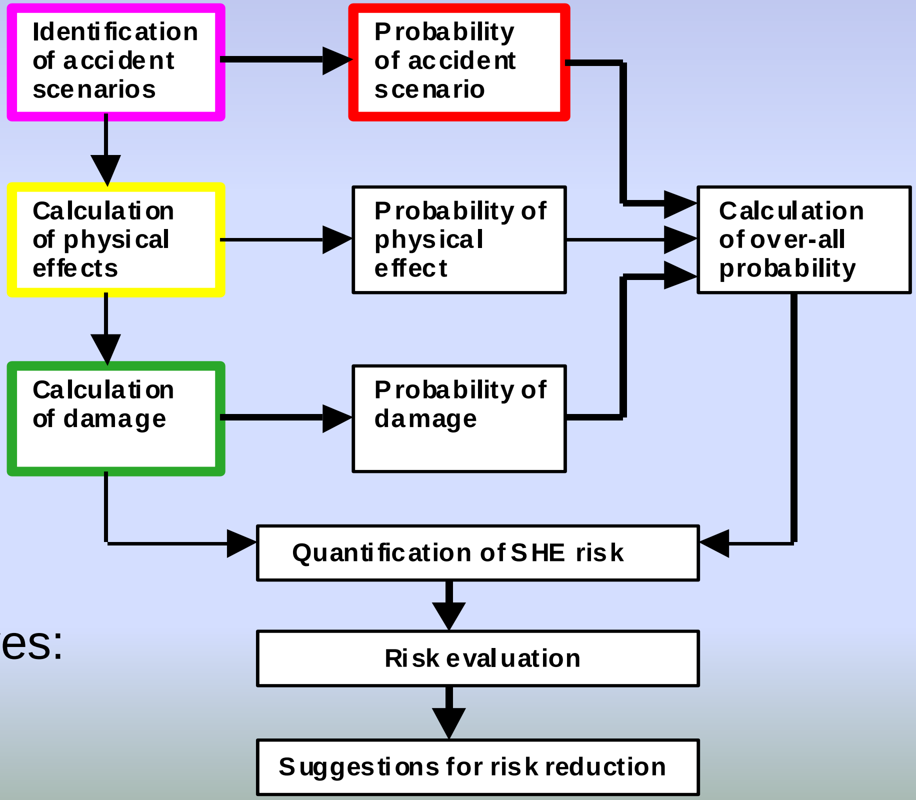
- The world now feels the need to reduce CO_2 –emissions and to become less dependent on oil, but there will be a long transition period
- Hydrogen is not toxic, although there is an asphyxiation hazard
- Its eagerness to combine with oxygen can cause problems (LEL - UEL)
- It is the large scale of utilization that will bring incidents
- Psychological impact of fatalities in transition period causes set-back
- Competent authorities will require QRA for LUP and license
- Recent risk studies with hydrocarbon fuels was right initiative as presented in recent DNV and IEA (Tchouvelev) reports
- However, more is necessary as previous experience with HCs showed

QRA in general

Quantitative Risk Assessment why :

1. To make an operation safer: preventive and protective measures, S & Cs
2. For Land Use Planning, LUP: QRA for or by competent authority (*fatalities*)
3. For licensing of plant: more detailed assessment
4. For emergency planning: response operations (*injuries*), self-rescue

and how:



Simplified derivatives:
e.g. LOPA

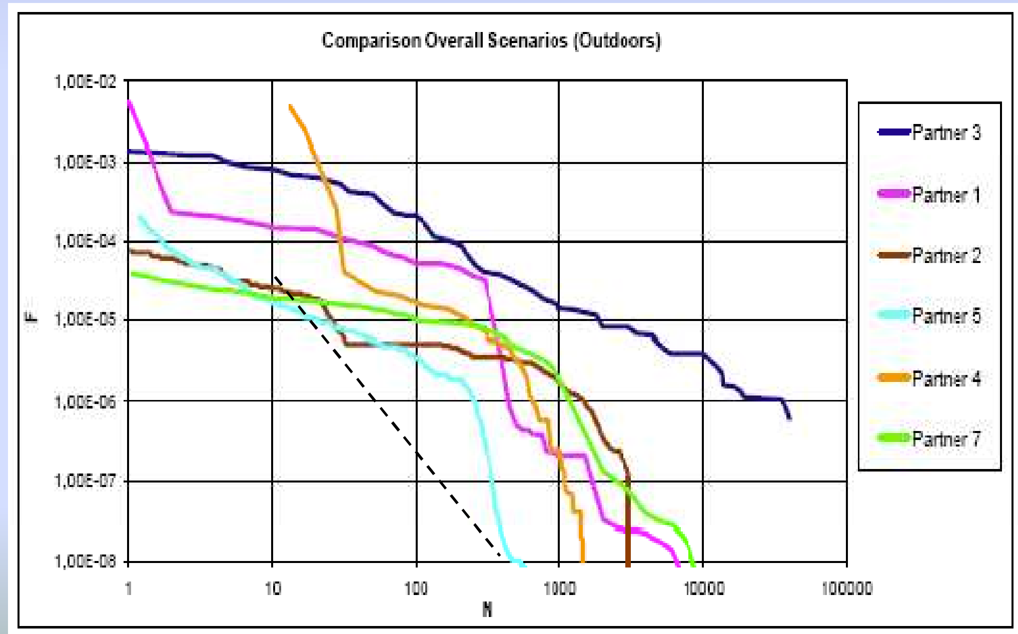
QRA: Strengths and Weaknesses

- Strengths:
  - Insight where are risk sources and what is effect in- and outside premises installation
  - Large consequence balanced by low probability, Risk = Consequence x Probability:
    - Optimum use of space
    - Equity of risk distribution
- Weaknesses: uncertainties and spread of results:

  e.g. EU Project ASSURANCE, by Lauridsen et al., 2002

- 7 Experienced teams, RA on Ammonia storage plant in Denmark (following a previous exercise in 1992), free in choosing scenarios, using own models and data

Individual risk contours 10^{-5}/yr
Smallest and largest outcome



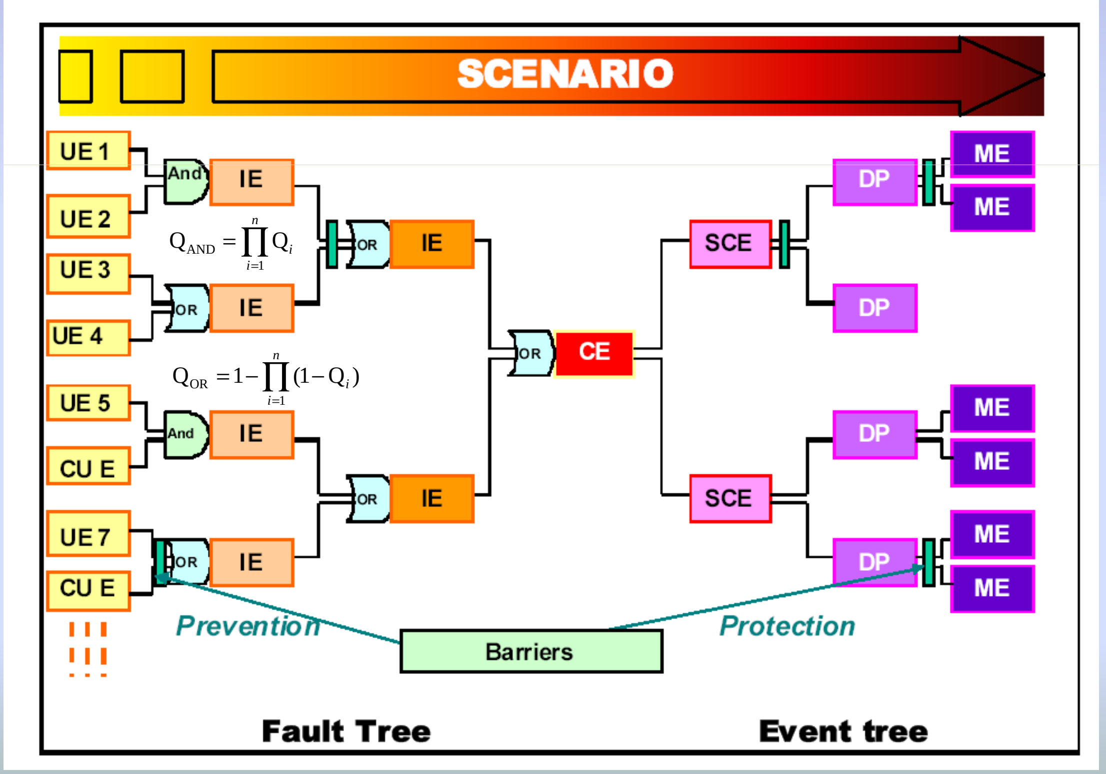
Societal risk *F-N* curves (Exceedance frequency *F* of *N* fatalities versus *N* fatalities). Dashed curve NL criterion

EU Project ASSURANCE, Lauridsen et al., 2002: Sources of uncertainty

Uncertainty Factor	Importance
Differences in the qualitative analysis	**
Factors relating to frequency assessment:	
Frequency assessments of pipeline failures	***
Frequency assessments of loading arm failures	****
Frequency assessments of pressurized tank failures	****
Frequency assessments of cryogenic tank failures	***
Factors relating to consequence assessment:	
Definition of the scenario	*****
Modelling of release rate from long pipeline	***
Modelling of release rate from short pipeline	*
Release time (i.e. operator or shut-down system reaction time)	***
Choice of light, neutral or heavy gas model for dispersion	****
Differences in dispersion calculation codes	***
"Analyst conservatism" or judgment	***

Improvement actions EU:

- *ARAMIS scenario generation: Bowtie (Check list, What-if, HAZOP, FMEA)*
- *SMEDIS (Scientific Model Evaluation of Dense Gas Dispersion Models) protocols*
- *EWGLUP: European WG for Land Use Planning*



BOWTIE

UE = Unwanted Event e.g. human act

CU E = Current Event condition, direct cause

IE = Initiating Event e.g. pump fails

CE = Critical Event, 12 types: leak, start of fire

SCE = Secondary CE, escalation

DP = Dangerous Phenomena, 13 types VCE, pool fire, jet fire etc.

ME = Major Event, 4 types: overpressure, heat radiation, toxic load, pollution

Barriers: Preventive, Protective, Mitigative

QRAs are done in case of conflicting interests

In such situation opposing statements of scientists frustrate.
Therefore advice to H_2 -community to agree early on models and data, without cutting off future improvements:

Wish-list hydrogen QRA models and data

A. SCENARIOS:

1. A list of standard representative scenarios of e.g. distribution center, tank station and car collision in tunnel incidents
2. Get inspiration by browsing the hydrogen data base with additional HAZOPs, FMEAs
3. Make bow-ties and select. Selected ones in ARAMIS language are called Reference Accident Scenarios
4. The ICHS conference papers give already quite a few inputs on e.g. tank stations and garages

B. Frequency of leak and failure mode:

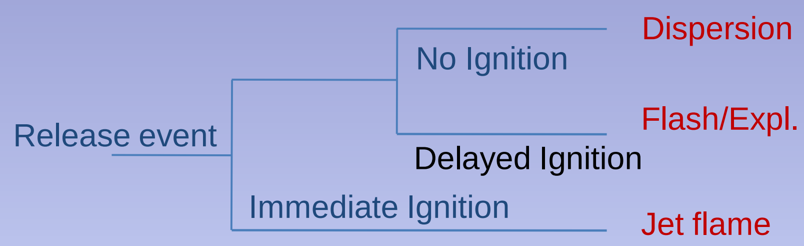
- Known fact hydrogen leaks easier than hydrocarbons (HC)
- Relying on HC leak frequencies is therefore not recommended
- HC stationary installation failure modes and their rates are unreliable – history often unknown – HSE UK data possibly best
- Offshore data HC leaks are better organized – also HSE UK, OREDA data base, Spouge model, PSP 24, 4 (2005) 249-257:

$$F(d) = f(D)\, d^m + F_{rup}$$

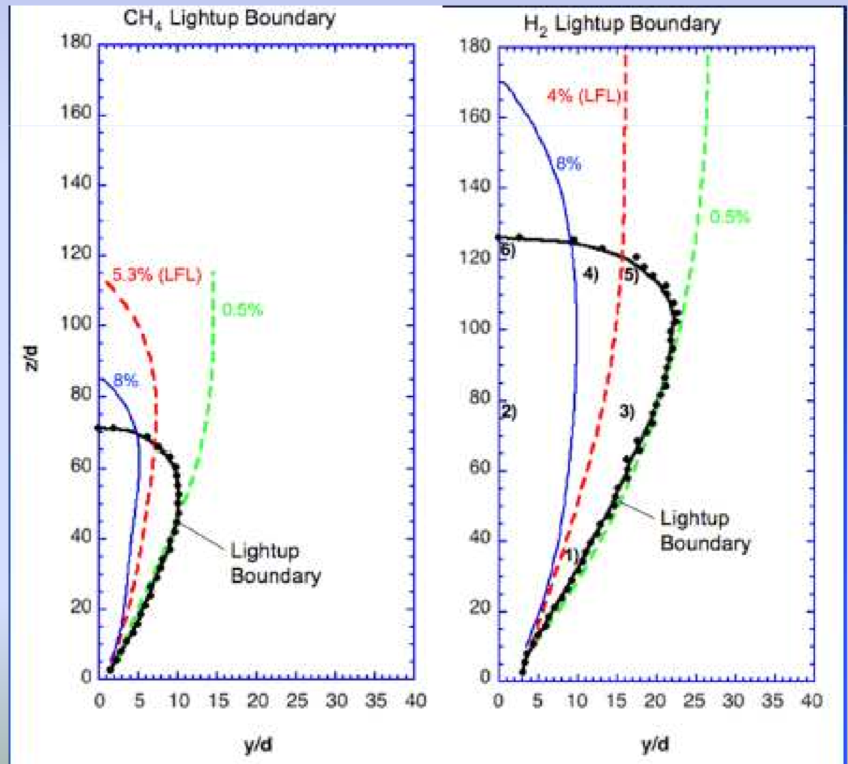
- Translation to H_2 -environment required
- After writing this paper, Sandia report with attractive Bayesian approach by LaChance et al., SAND2009-0874, March 2009.

C. Probability of ignition: another hot debated point!

- Given leak, what is probability value in event tree of none, delayed of immediate ignition



- Sources of information:
  - Historical data: confusing and HC (IEA Task 19 – Tchouvelev)
  - Number and type of ignition sources in the environment
  - Other environmental conditions wind, confinement etc. influencing flame growth
  - Probability of self-ignition at leak increases with release flow rate (HySafe Del. No. 71)



- Further study strongly recommended, e.g. see Schefer et al., Sandia, this conference

D. Flash fire or explosion, questions?

- Difference in behavior *gaseous* leak versus *cryogenic* release. Do we know it sufficiently?
- As regards explosion: do we know effect of confinement and congestion in practical situations on flame velocity so that we can predict overpressures with adequate accuracy?
- What about scale effects? Tests with relatively small amounts versus accidental releases of large amounts?
- Fire effects with distance? Radiation heat flux? Fatality and injury probits? (For *jet* fires LaChance et al., SAND2009-0874, March 2009 offers a host of data and an extensive risk analysis.)
- Explosion effects: increase with scale? Overpressure, impulse probits. (Generally speaking given overpressure-time of an explosion, reasonable estimates can be made for effects on people and structures)

E. Computational Fluid Dynamics models

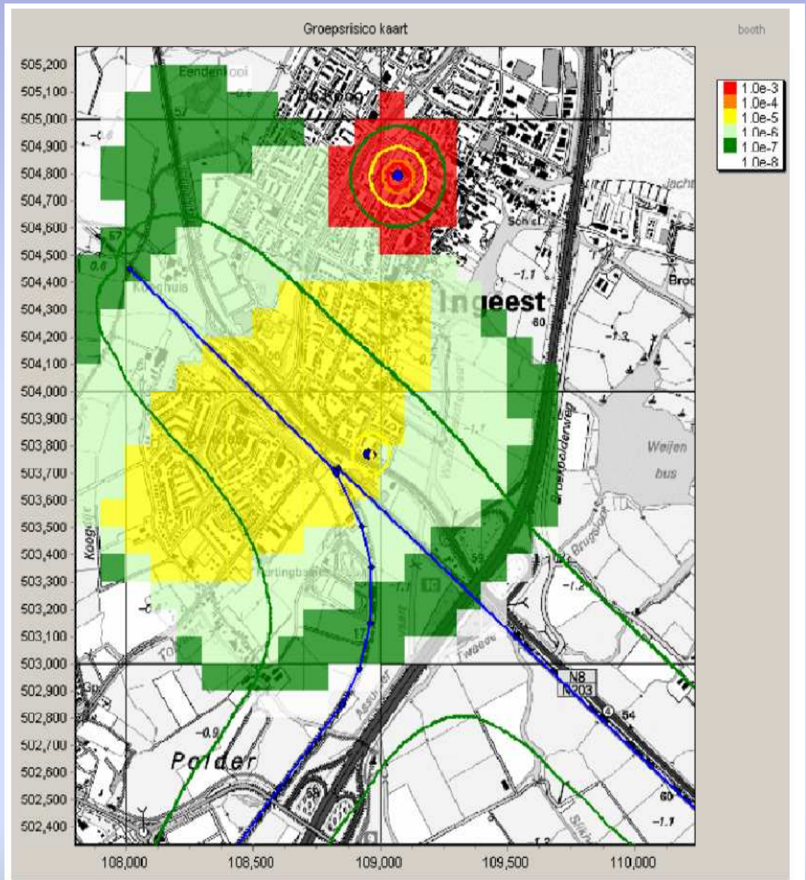
- Tests are usually done in simple geometry. CFD enables prediction for geometric complex situations, both for dispersion and explosion
- Standard Benchmark Exercise Problems, SBEPs, are a great idea to test codes and compare CFD results, but this is not enough.
- Project SMEDIS learned codes have to be transparent, verifiable and robust, hence not black-box, traceable and reproducible.
- SMEDIS protocol assesses physics model, verifies translation in algorithms and validates against field data. Hanna et al. developed statistical performance data for dispersion.
- Projects MERGE, EMERGE and JIP compared code results for explosive clouds, all HC, but no SMEDIS type action.
- H_2 -community would make a strong impression if it could come up with codes certified for risk analysis.

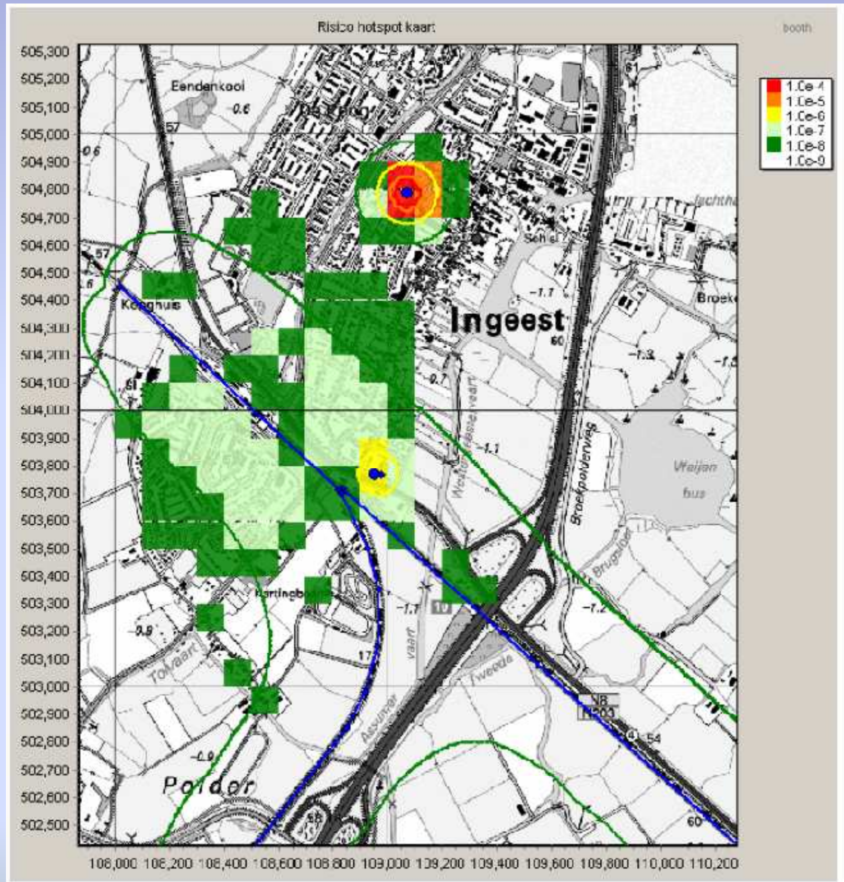
F. Risk presentation and acceptance

Individual risk: distance to fatality probability $10^{-5} – 10^{-6}$ /yr, contours

Group risk: More than 10 fatalities once in 10^5 years /installation? *F-N* curve

Group risk presentation TNO/RIVM in GIS with population density:





Risk matrix; business/cost-benefit measures: F-$, VaR, EAL, risk spectrum

G. The finishing touch

- Uncertainties: Incomplete possibilities, lack of knowledge.
- Appreciation of risk: Judge (10-based) logarithms of the risk values (Weber-Fechner law), e.g. LOPA credits
- Decision making:
  - Weighing *benefits against risks*(France: PPRT-CLIC; U.S. RMP)
  - Theory: Multi-attribute (dis-)*utility* function decision maker – calibration
  - Emergency responders *judgment*: Control of incident, number and nature of injured; possibilities of self-rescue (time duration of incident); access routes

Conclusions

- For a successful transition *prepare* for risk assessment.
- If left to the 'market' risk results will show large *spread*.
  - To counter cf. ARAMIS *Reference accident scenarios* have to be formulated.
  - Component *leak* frequencies, *ignition* probabilities have to be established.
  - CFD codes can become certified. SBEPs is good start.
- *Decision* criteria are more than just individual and group risk. Economy comes in. Uncertainties have to be coped with.
- It may pay to install an international H_2 QRA working group to *recommend* certain models and data