HYDROGEN IMPLEMENTING AGREEMENT

Uniform Risk Acceptance and Harm Criteria - IEA HIA Task 19 Perspective

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AN IMPLEMENTING AGREEMENT OF THE INTERNATIONAL ENERGY AGENCY

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Outline

1. Overview of IEA HIA Task 19 Activities
2. Risk acceptance criteria review
3. Survey of Harm Criteria and Approaches
4. Summary

Task 19 Organization

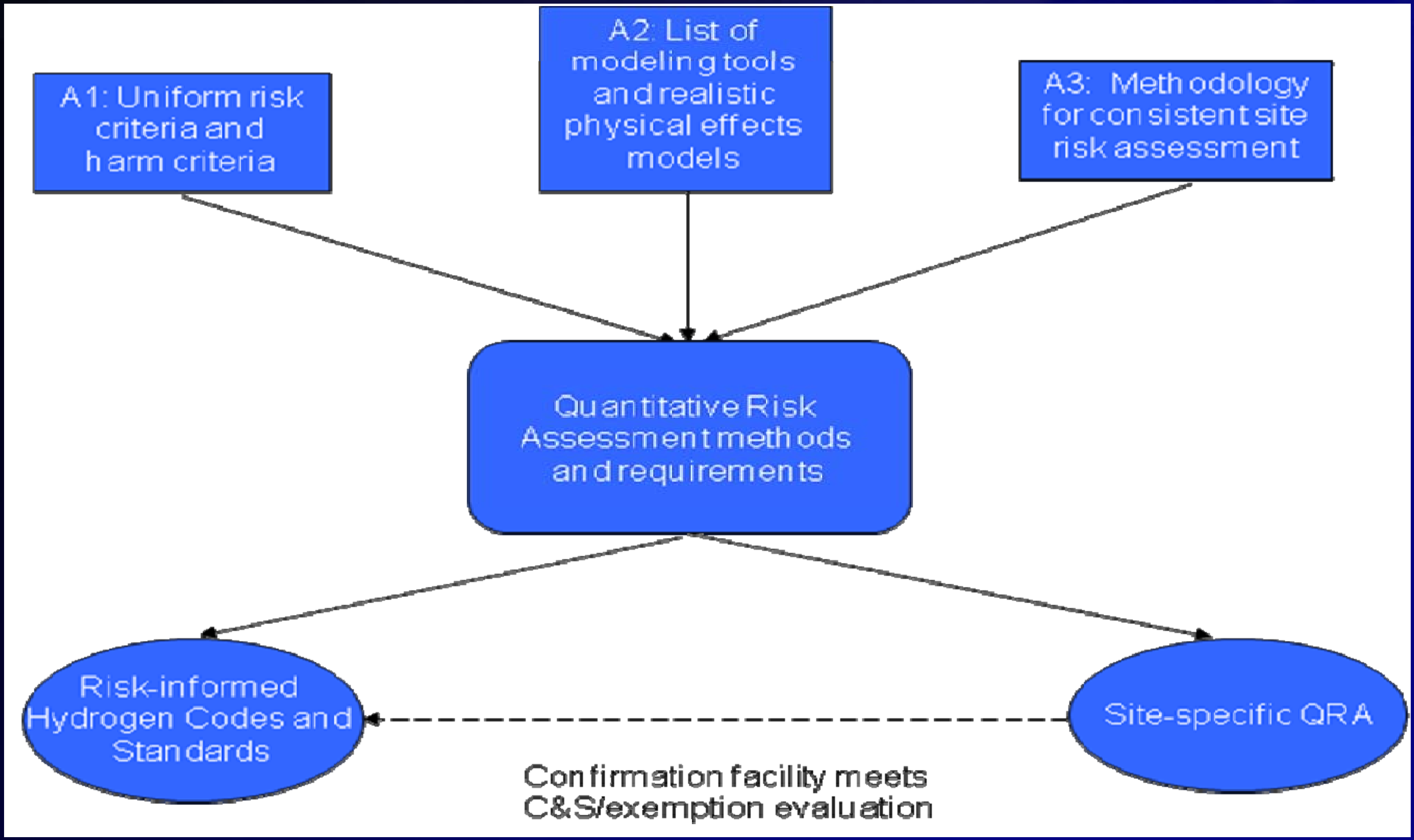
The objectives of the International Energy Agency Hydrogen Implementing Agreement Task 19 efforts on Hydrogen Safety are to develop predictive methods, data and other information that will facilitate the accelerated adoption of hydrogen systems.

A. Risk Management: Risk and safety definitions and concepts, link with risk-informed C&S, engineering physical effects models, methodology for consistent site QRA

B. Experimental &Testing Program: Evaluate the nature and consequences of safety-related events under a range of real-life scenarios, environments and mitigation measures

C. Information Dissemination: Develop targeted information packages for stakeholder groups

Subtask A – Work Plan & Activities Interface



Goal of Activity A1

- Discuss risk and safety concepts
- Develop uniform risk acceptance criteria
  - Types of risk measures
  - Risk targets
  - Survey currently used risk criteria
  - Provide guidance on selection of uniform risk acceptance criteria
- Develop uniform harm criteria for use in hydrogen QRA
  - Define criteria for all types of hydrogen accidents
  - Survey of currently used measures
  - Provide guidance on selection of uniform harm criteria
- Develop link to risk-informed codes and standards

Risk Acceptance Criteria

- Uniformly accepted risk criteria are required for use in QRA applications (e.g., to develop risk-informed codes and standards)
- Options for selecting risk criteria:
  - Based on *statistics* from existing stations (gasoline and CNG)
    - limited data available
    - data includes accidents other than accidental releases
    - NFPA data for gasoline stations in U.S. suggests frequency of deaths and injuries per station are ~$2x10^{-5}$/yr and ~$3x10^{-4}$/yr, respectively
  - Based on *estimated risk* for existing stations
    - limited analyses are available
    - differences in facilities affects comparison of risk
  - Comparing with *general risk in society* – hydrogen should not increase the general risk level in society
    - Risk of death ~ $2\text{-}4x10^{-4}$/yr; risk of injury ~ 0.09/yr in U.S.
    - Fraction of total risk from just fires ($1.3x10^{-5}$/yr in the U.S.) and explosions ($6x10^{-7}$/yr in the U.S.)

Risk Measures

- Human injury or fatality
  - Individual risk – probability that an average unprotected person, permanently located at a certain location, is killed or injured due to an accident
  - Societal risk – probability that multiple people within an area are killed or injured due to an accident (typically represented on an FN curve)
- Others
  - Economic loss – typically expressed in terms of loss value (lost income and replacement cost)
  - Environmental damage – can be expressed in terms of time required to recover damage to ecosystem

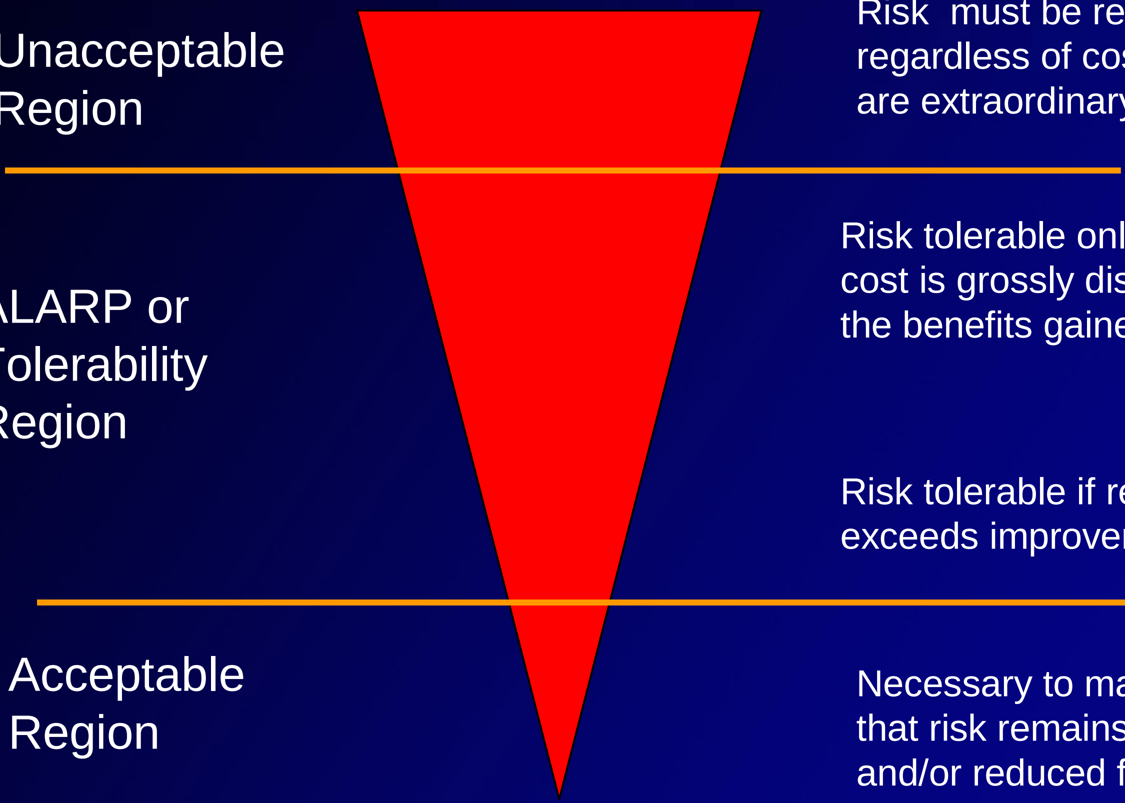
Risk Exposed Persons

- Public (3rd Party) – people located outside the facility boundary
  - People living and working near the facility
  - People visiting or traveling near the facility
- Customers (2^{nd} Party) – people using the facility
  - Limited exposure period
- Facility operators (1st Party) – personnel involved in operation, inspection, and maintenance of the facility
  - Generally assumed these people accept higher risk levels than for customers and outside public

As Low As Reasonably Practicable (ALARP)

- There are no zero risk situations
- Managing risk to a reasonable level is achievable
- Acceptable risk represents the level below which an investment should be made to further reduce risk
  - Cost-benefit analysis
- Acceptable risk represents the *minimum risk* level that must be *obtained, regardless of cost*
- The ALARP principle is that the *residual* risk should be As Low As Reasonably Practicable – risk reducing measures are feasible and their costs are not larger than the benefits

ALARP Concept – Individual Risk



Unacceptable Region

Risk must be reduced regardless of cost unless there are extraordinary circumstances

ALARP or Tolerability Region

Risk tolerable only if reduction cost is grossly disproportionate to the benefits gained

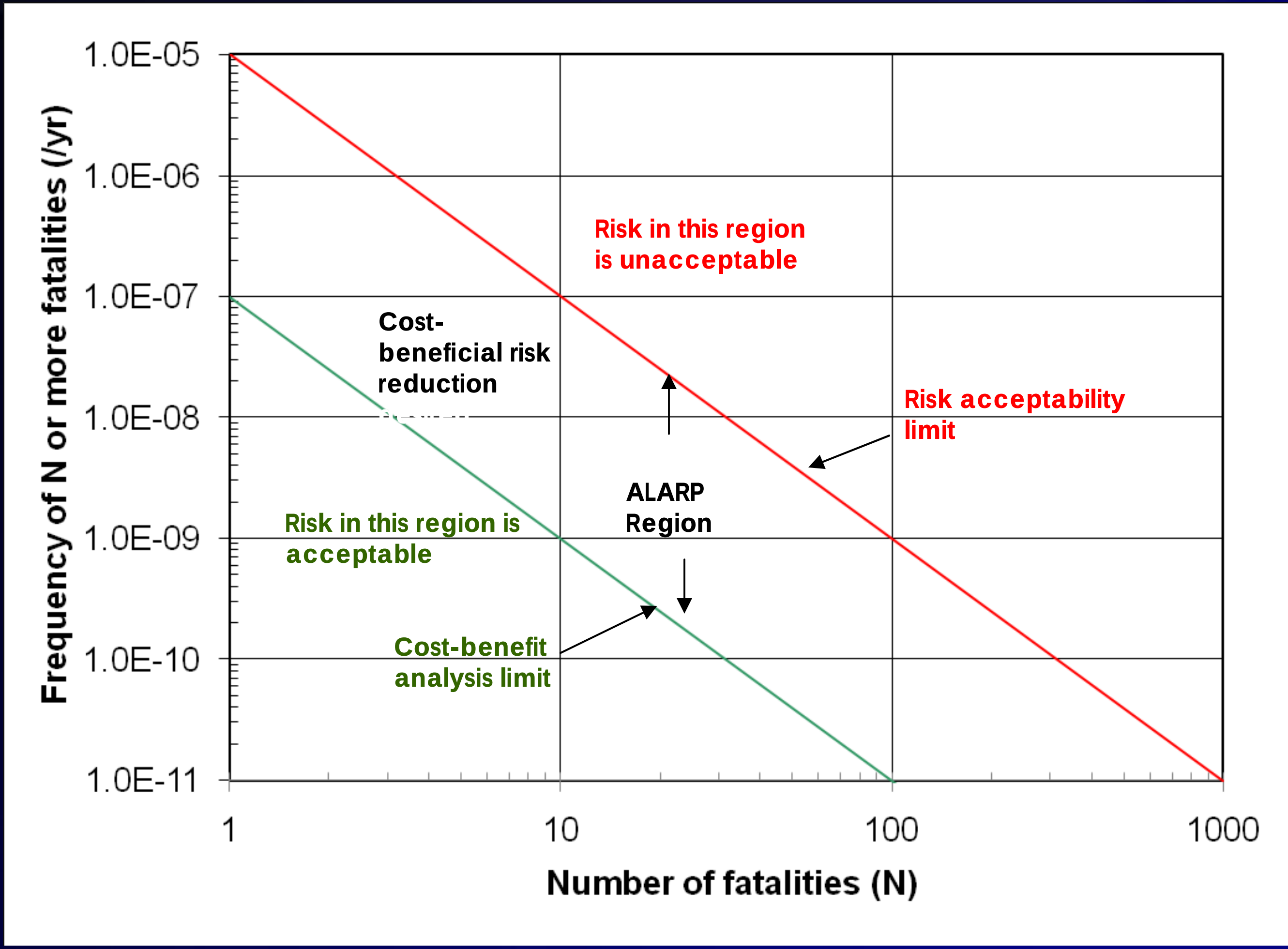
Risk tolerable if reduction cost exceeds improvement achieved

Acceptable Region

Necessary to maintain assurance that risk remains at this level and/or reduced further if reasonably practical

Negligible Risk

ALARP Concept – FN Curve



Survey of Risk Criteria

Individual Risk (3rd Party)

- Public risk measures expressed in terms of fatalities
- Some organizations and countries suggest using the fraction of the total risk from all other unintentional injuries
  - USNRC safety goal for nuclear power plants is 0.1% of accidental death rate ($5x10^{-7}$/yr).
  - EIHP specified the value to be 1% of the average fatality death rate of $1x10^{-4}$/yr or 1x10-6/yr;
  - EIGA has suggested an individual risk value of $3.5x10^{-5}$/yr (~1/6 the average fatality risk)
- Some countries use harm criteria only (e.g., France) and some do not have numerical criteria (e.g., Germany, U.S., Canada)

Customers (2nd Party)

- European Integrated Hydrogen Project – $1x10^{-4}$/yr

Worker risk (1st Party)

- European Integrated Hydrogen Project – $1x10^{-4}$/yr
- United Kingdom – $1x10^{-3}$/yr

Survey of Individual Risk Criteria for Public

Individual Risk Criteria	United Kingdom	The Netherlands	Hungary	Czech Republic	Australia
10^{-4}	Intolerable limit for members of the public				
10^{-5}	Risk has to be lowered to ALARP	Limit for existing installations, ALARA principal applies	Upper limit	Limit for existing installations, risk reduction applied.	Limit for new installations
10^{-6}	Broadly acceptable risk level	Limit for new installations and general limit after 2010, ALARA principal applies	Lower limit	Limit for new installations	
10^{-7}	Negligible level of risk				Negligible level of risk
10^{-8}		Negligible level of risk			

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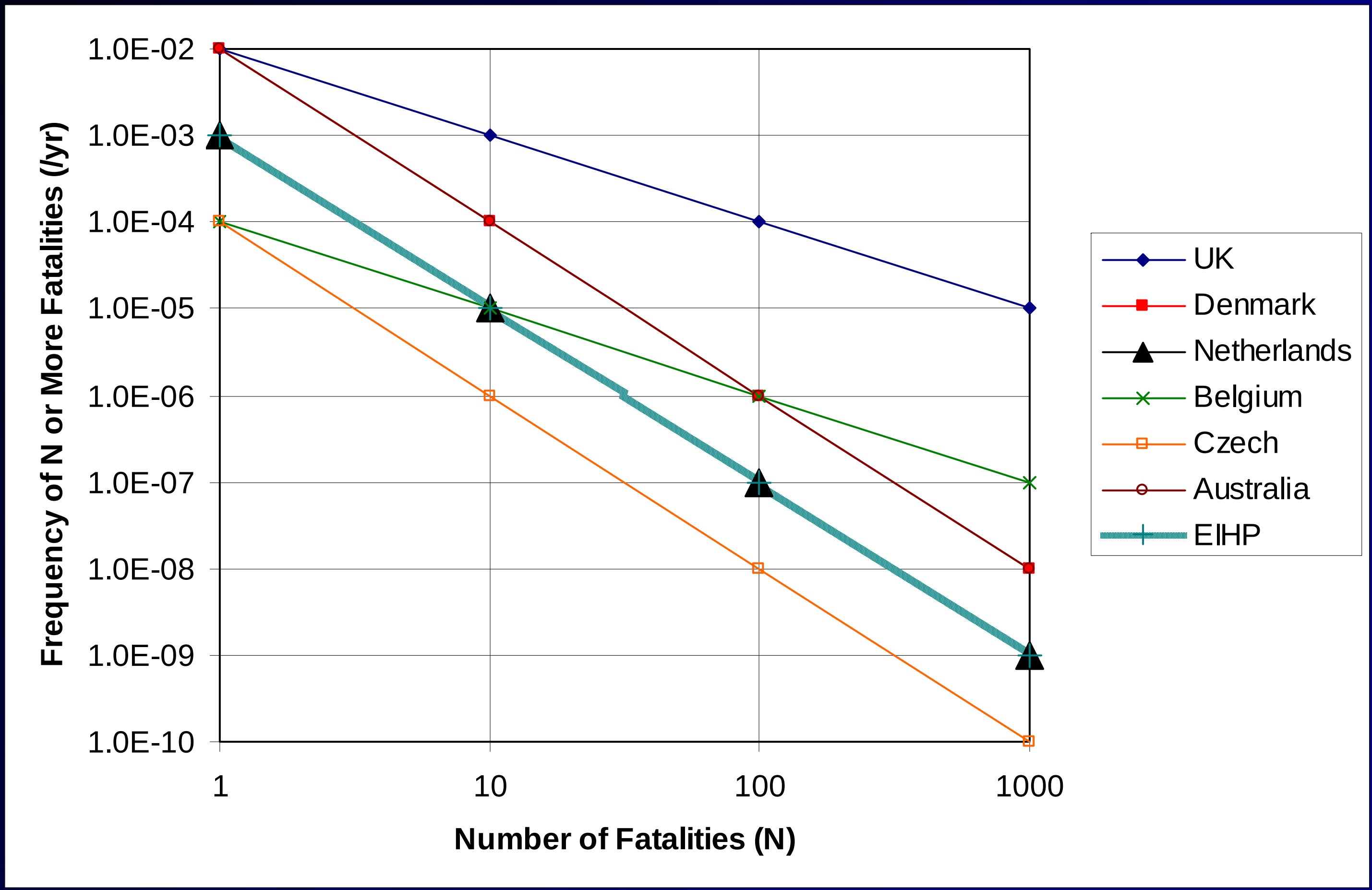
Survey of Societal Risk Criteria for Public



Risk Criteria in Conoco Philips Offshore

Personnel Risk – FAR (the statistical *expected number of fatalities per 100 million exposed hours*)

$FAR_{All\ onboard} < 10$

$FAR_{exposed\ group} < 25$

Impairment of Main Safety Functions

The probability of impairment of any main safety function shall be less than

1×10^{-4} per year per type of accidental event

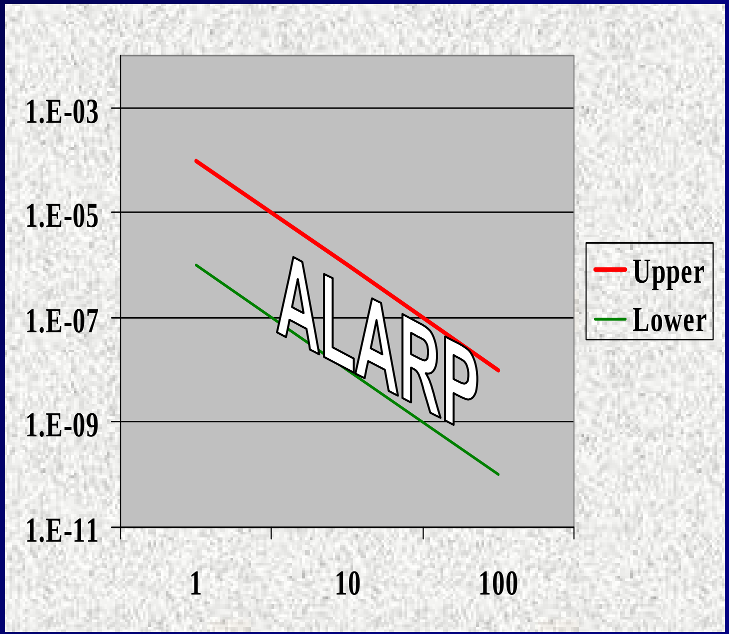
Norwegian Petroleum Directorate guidelines suggest alternatively to use a total frequency of 5×10^{-4}/yr for all accidents for all safety functions

Risk Criteria Onshore Norway

- Personnel Risk Onshore installations
  - Snøhvit LNG plant: $FAR_{All\ Personnel} < 5$
- Third party risk:

Individual: Most exposed individual: Fatality risk < 10^{-5} per year (Statoil)

Societal : F-N curve



Suggested Guidance on Public (3rd Party) Risk Criteria

Individual Risk – ALARP with following criteria:

- ✓24/7 exposure – site independent – generic and more conservative guideline
- ✓Most exposed individual – site specific guideline

▪**Acceptable risk level < $1x10^{-5}$/yr**

- ✓Basis – Comparative risk to gasoline stations, 10% of risk to society from all other accidents, representative value used by most countries

▪**Cost-benefit analysis limit – $1x10^{-7}$/yr**

- ✓Basis – Representative of most countries

Societal Risk – Adopt EIHP ALARP FN curve

- ✓Basis – risk aversion factor of 2 and with a pivot point for 10 fatalities of 1 $x10^{-5}$/yr for acceptable risk curve and $1x10^{-7}$/yr for cost-benefit analysis limit curve

Suggested Guidance on 2nd & 1st Party Risk Criteria

Customer (2nd Party) and Worker Risk (1st Party):

- Conventional Approach: use traditional frequency of fatality per year (like in individual risk). Suggested acceptable risk for both 2nd and 1st party < 1×10^{-4}/yr
  - ✓Basis – Order of magnitude higher than the individual acceptable risk value
  - ✓Both customers and workers accept higher risk vs general public not using the refuelling facility
- Alternative approach – use FAR similar to oil & gas / process industry approach (per 100 million hrs).
  - ✓Option 1: FAR can be calculated from gasoline station statistics (*e.g. NFPA data*) and adopted for hydrogen stations
  - ✓Option 2: use existing statisitics for gasoline cars: e.g. *FAR for drivers is 25 and for passengers is 29 per 100 million hrs (UK)*
    - ➢Both drivers and passengers should accept *at least the same level of risk* for vehicle refuelling as they accept while using their vehicles

Harm Criteria

A harm criterion is used to translate the consequences of an accident, evaluated from deterministic models, to a probability of harm to people, structures, or components.

- Harm criteria are required for full range of accidents modeled in QRA
  - Jet fires, flash fires, pool fires, vapor cloud explosions (VCEs), and Boiling Liquid Expanding Vapor Explosion (BLEVE)
- Accident consequences
  - Thermal effects (direct flame contact, high air temperatures, and radiation heat flux)
  - Overpressure effects (direct and indirect)
  - Others (asphyxiation, cryogenic)
- Primary interest is human harm criteria but also need to consider equipment and structures
  - For people, harm criteria can be expressed in terms of injury or fatalities

Direct Flame Contact

- Third degree burns over large part of the body results in a high probability of death
- Thus, can conservatively assume that direct flame contact results in death
- Alternatively, burn mortality data can be used to generate probability of fatality

Burn Mortality Data for 40 - 44 Year Old Age Group

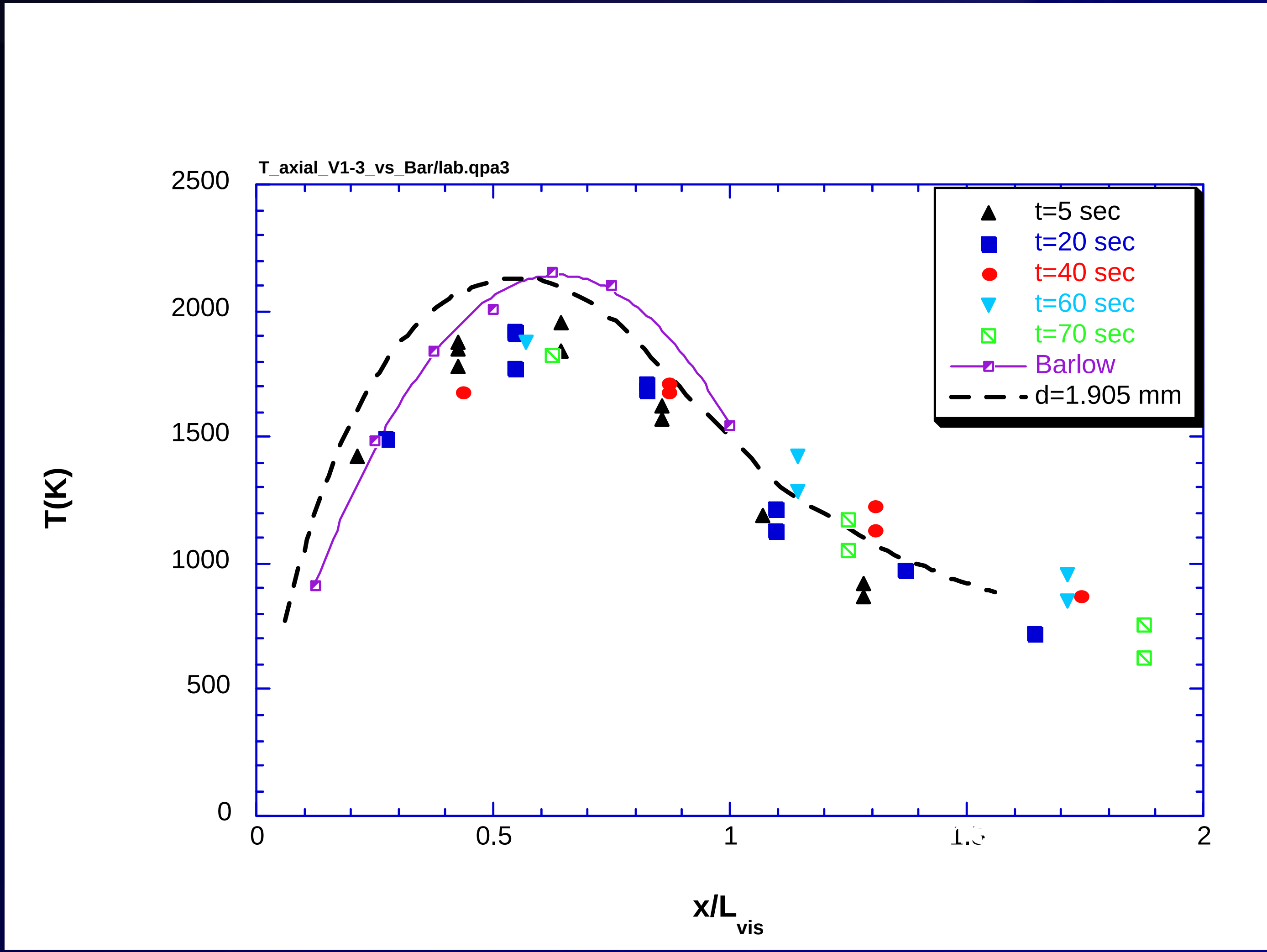
Body Area Burned (%)	Probability of Fatality
78-100	1.0
68-77	0.9
63-67	0.8
53-62	0.7
48-52	0.6
43-47	0.4
33-42	0.3
28-32	0.2
18-27	0.1
0-17	0.0

Elevated Air Temperature Effects

Temperature (°C)	Effects
100	Burns throughout respiratory tract, humid air or steam
127	Difficult breathing (dry air), skin pain
149	Mouth breathing very difficult, temperature limit for escape
160	Rapid, unbearable pain with dry skin
182	Irreversible injury in 30 seconds
204	Respiratory system tolerance time less than 4 minutes with wet skin
309	Third degree burns for a 20 second exposure, causes burns to larynx after a few minutes, escape improbable

Recommended air temperature criteria: 300°C

H_2 Flame Temperature Profile



Types of Radiation Harm Criteria

- Single criteria
  - Specified heat flux level and exposure time
  - Specified thermal dose
  - Use of a single criteria is generally used in deterministic evaluations and is not easily utilized in the probabilistic evaluations in QRAs
- Continuous criteria
  - Probit functions
  - Probit functions are particularly useful in QRA since they can provide harm probabilities for the range of accidents included in the risk assessment

Heat Flux Levels

- Example human harm criteria (assumes exposed skin):
  - 1.6 kW/m^2 – no harm for long exposures
  - 4 to 5 kW/m^2 - pain for 20 second exposure
  - 9.5 kW/m^2 -Second degree burns within 20 seconds
  - 12.5 to 15 kW/m^2 - 1% lethality in 1 minute
  - 25 kW/m^2 - 100% lethality in 1 minute, injury within 10 seconds
  - 35 to 37.5 kW/m^2 - 1% lethality in 10 seconds

Heat Flux Levels (cont.)

- Example equipment/structure harm criteria
  - 4 kW/m^2 – glass breakage (>30 minute exposure time)
  - 12.5 to 15 kW/m^2 – piloted ignition of wood (>30 minute exposure time)
  - 18 to 20 kW/m^2 – cable insulation degrades (>30 minute exposure time) 25 to 32 kW/m^2 – unpiloted ignition of wood steel structure deformation (>30 minute exposure time)
  - 35 to 37.5 kW/m^2 – process equipment and structural damage (>30 minute exposure time)
  - 100 kW/m^2 – steel structure collapse (>30 minute exposure time)

Thermal Dose

Combines heat flux intensity (I) and exposure time (t) into a single parameter

$$\text{Thermal Dose} = I^{4/3}t$$

- Accounts for time-dependent behavior of fire (heat flux)
- Also allows for modeling escape
- Heat flux/time curve can be integrated to get total dose for each scenario
- Selected thermal dose value - “Dangerous Dose” or LD_{50} can be used as a criteria
- Several Probit functions are available to evaluate probability of fatality or injury as function of thermal dose

Radiation Burn Data

Burn Severity	Thermal Dose $(kW/m^2)^{4/3}s$*	
	Ultraviolet	Infrared
First Degree	260-440	80-130
Second Degree	670-1100	240-730
Third Degree	1220-3100	870-2640

*Many factors account for range of values including the type of heat source and type of animal skin used (some values are from nuclear blast data)

For hydrocarbon fires: The impact of an infrared dose is 2.23 stronger than ultraviolet dose

Thermal Dose Value

- "Dangerous Dose" – Usually defined as dose resulting in death to 1% of exposed population
- LD_{50} – 50% of exposed population would die
- Use of a point value is not suitable for QRAs since the consequences from analyzed accidents can result in a full spectrum of thermal doses and associated harm potential.

Source	Dosage $(kW/m^2)^{4/3}s$ for infrared radiation: Dangerous Dose	Dosage $(kW/m^2)^{4/3}s$ for infrared radiation: LD_{50}
Eisenberg	960	2380
Tsao & Perry	420	1050
TNO	520	3600[1]
Lees	1655	3600[1]
HSE	1000	2000

[1] Based on ignition of clothing at 3600 $(kW/m^2)^{4/3}s$

Fatality Probit Functions

Probit	Probit Equation	Comment
Eisenberg	Y = -38.48 + 2.56 ln V	Based on nuclear data from Hiroshima and Nagasaki (ultraviolet)
Tsao & Perry	Y = -36.38 + 2.56 ln V	Eisenberg model modified to account for infrared (2.23 factor)
TNO	Y= -37.23 + 2.56 ln V	Tsao and Perry model modified to account for clothing (14% factor)
Lees	Y = -29.02 + 1.99 ln V'	Accounts for clothing, based on porcine skin experiments using ultraviolet source

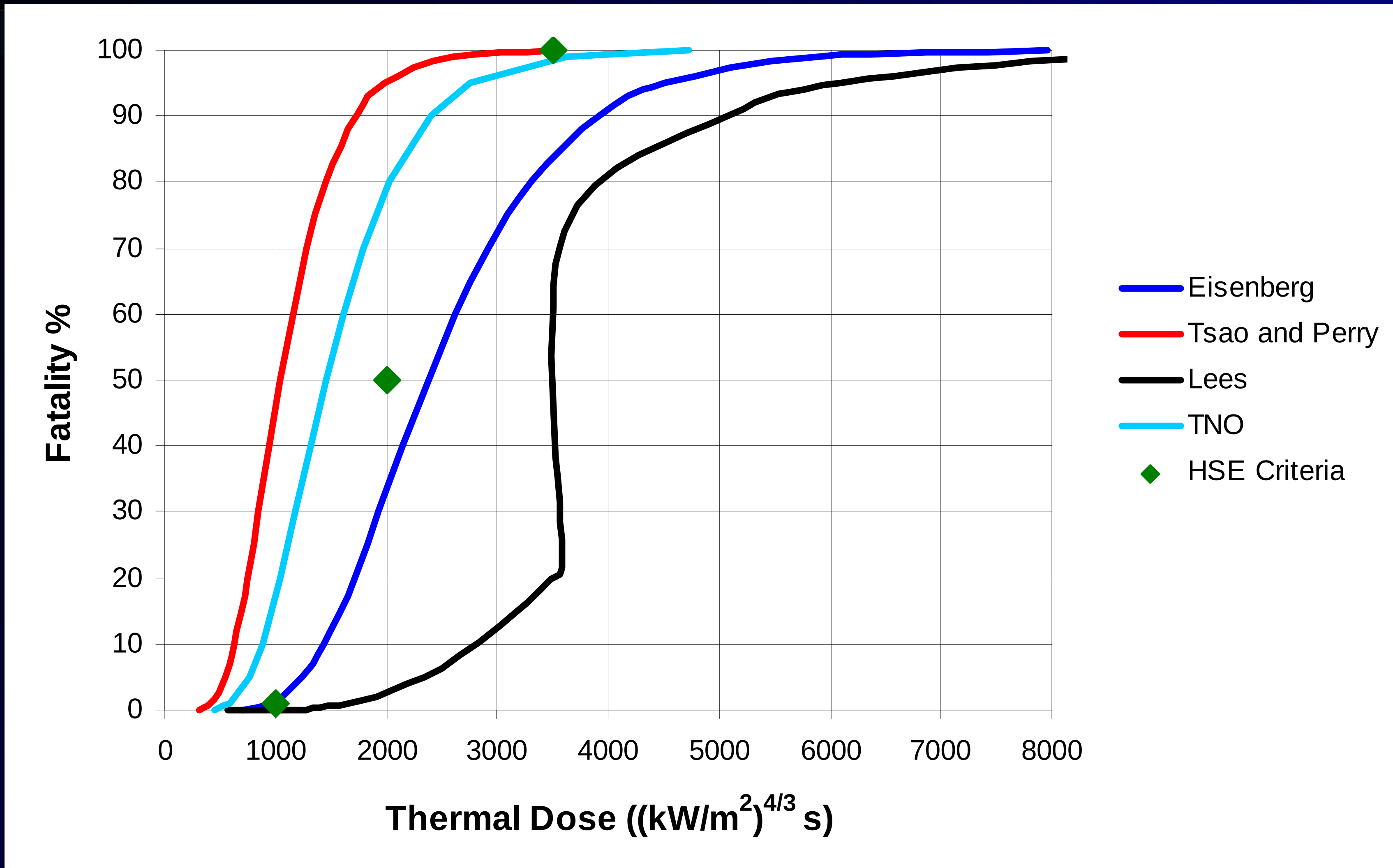
P(fatality) = 50*(1+(Y-5)/ABS(Y-5)+ERF(ABS(Y-5)/SQRT(2)))

Y= probit function

V = $I^{4/3}t$ = thermal dose in $(W/m^2)^{4/3}s$

V' = $F*I^{4/3}t$ = thermal dose in $(W/m^2)^{4/3}s$ where F=0.5 for normally clothed population and 1.0 when clothing ignition occurs

Fatality Probit Comparison



Probit Function Selection

- Selected probit function needs to include both infrared and ultraviolet spectrum
  - Infrared contribution for hydrogen much less than for hydrocarbons
  - Lees and Eisenberg probits only include ultraviolet
  - Eisenberg probit function is being used in hydrocarbon applications even though it does not include the infrared spectrum
- Eisenberg, Tsao and Perry, and TNO probit functions all based on uncertain data from Hiroshima
- TNO and Lees probits include effects of clothing; others inherently include effects of clothing ignition
- Preliminary recommendation is to use both Eisenberg and Tsao and Perry probit functions to bound the probability evaluations for hydrogen accidents

Overpressure Effects

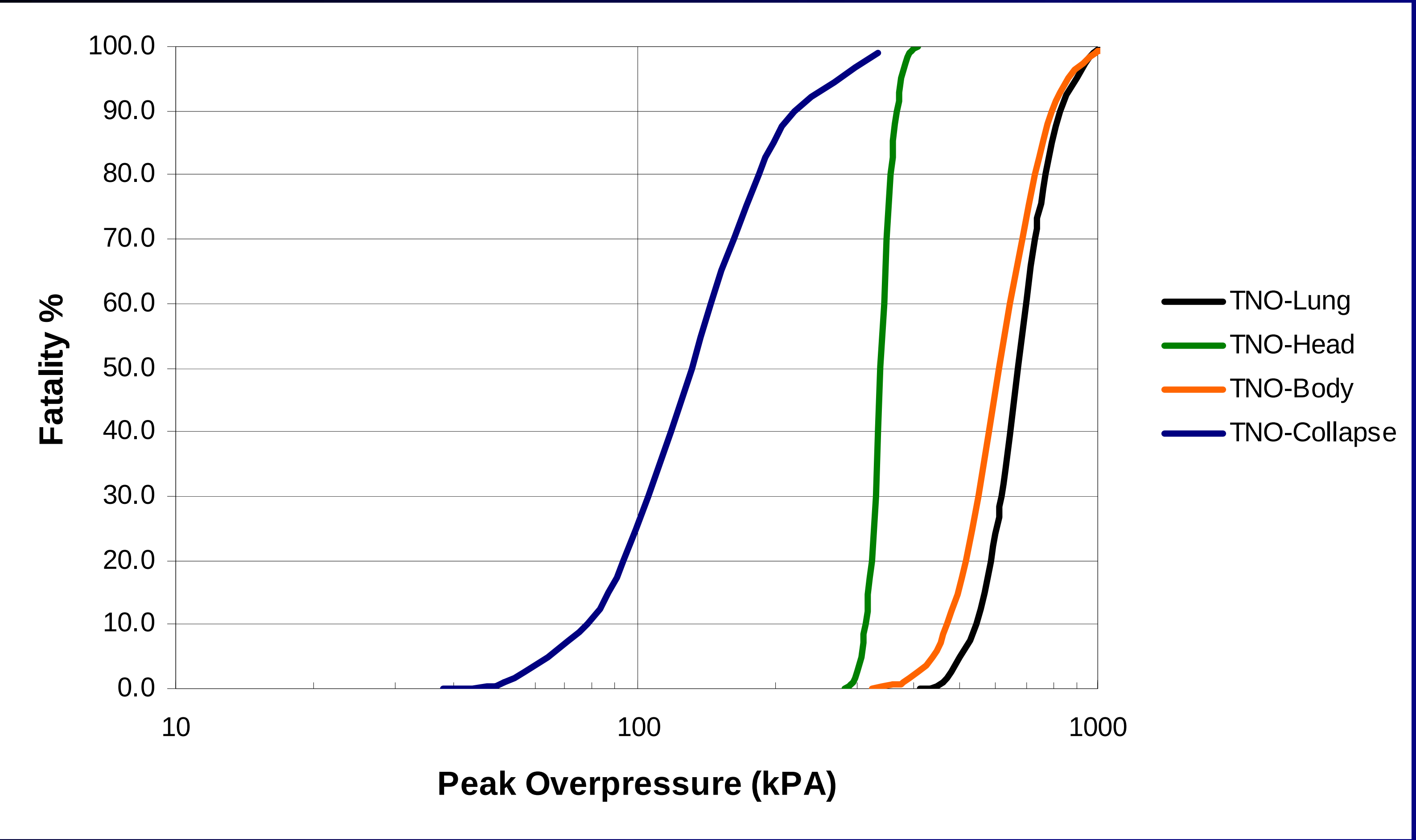
- There are both direct and indirect overpressure effects on people
- Main direct effect is sudden increase in pressure that occurs as blast wave passes that effects pressure sensitive organs (ears and lungs)
- Indirect effects include fragments from explosion source and structures, violent body translation, and building collapse

Overpressure Harm Criteria

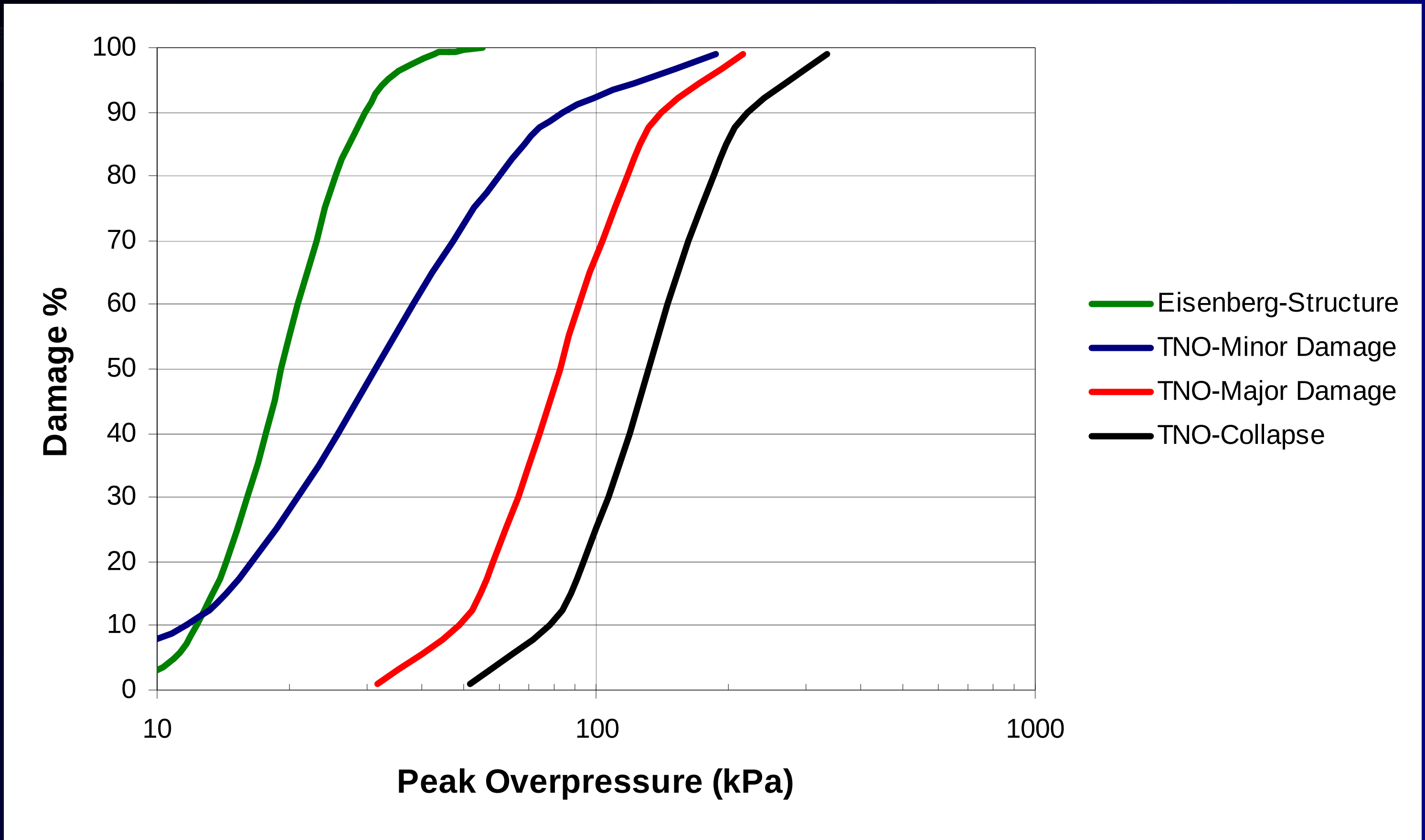
Peak Overpressure	Effects on Structures and People
1 – 6.9 kPa	Glass damage, injury from flying glass
10 – 20 kPa	People knocked down or thrown against objects
17 – 40 kPa	Heavy damage to equipment and structures 50% probability of serious wounds from flying objects 1% death from lung hemorrhage
48 – 69 kPa	100% fatality from flying objects
70 kPa	Complete structural collapse
55 – 110 kPa	People can be thrown a distance
83 – 103 kPa	Threshold of lung hemorrhage
138 – 172 kPa	50% fatality from lung hemorrhage
207 – 241 kPa	90% fatality from lung hemorrhage

Indirect Vs Direct Effects

TNO probits provide consistent framework for evaluating overpressure effects



Structural Probits



Minor damage – breakage of glass, displacement of door frames, roof damage
Major damage – major cracks in walls, collapse of some walls
Collapse – total collapse of structure

Suggested Guidance on Harm Criteria

- Direct flame contact
  - Assume a fatality if located within plume (2 X flame length)
- Radiation heat flux
  - Use of thermal dose criteria may be preferable to radiation heat flux criteria (useful for deterministic evaluations but not for QRA)
  - Probit functions are a better option since they give probability as function of dose (no hydrogen-specific probit function available)
  - Use of both the Tsao and Perry and Eisenberg probit functions are recommended in order to evaluate the uncertainty in the harm predictions for hydrogen fires
- Overpressure effects
  - Indirect effects (structural collapse, missiles, body translation) are more important than direct health effects (lung damage)
  - Probit functions are a better option than the use of selected overpressure criteria
  - TNO probits are recommended since they provide consistent framework for evaluating overpressure effects

Summary

- Suggested uniform risk acceptance and harm criteria have been developed and are being considered for endorsement by IEA Task 19 members.
- Report should be available in ~6 months.
- Suggested guidelines need to be tested.
- Other issues that need be addressed:
  - Other hazards (asphyxiation, cryogenic)
  - Uncertainties in risk evaluation
  - Guidance on cost-benefit analysis
- IEA HIA Task 19 experts are committed to this work and would welcome additional participation.

Thank You!

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