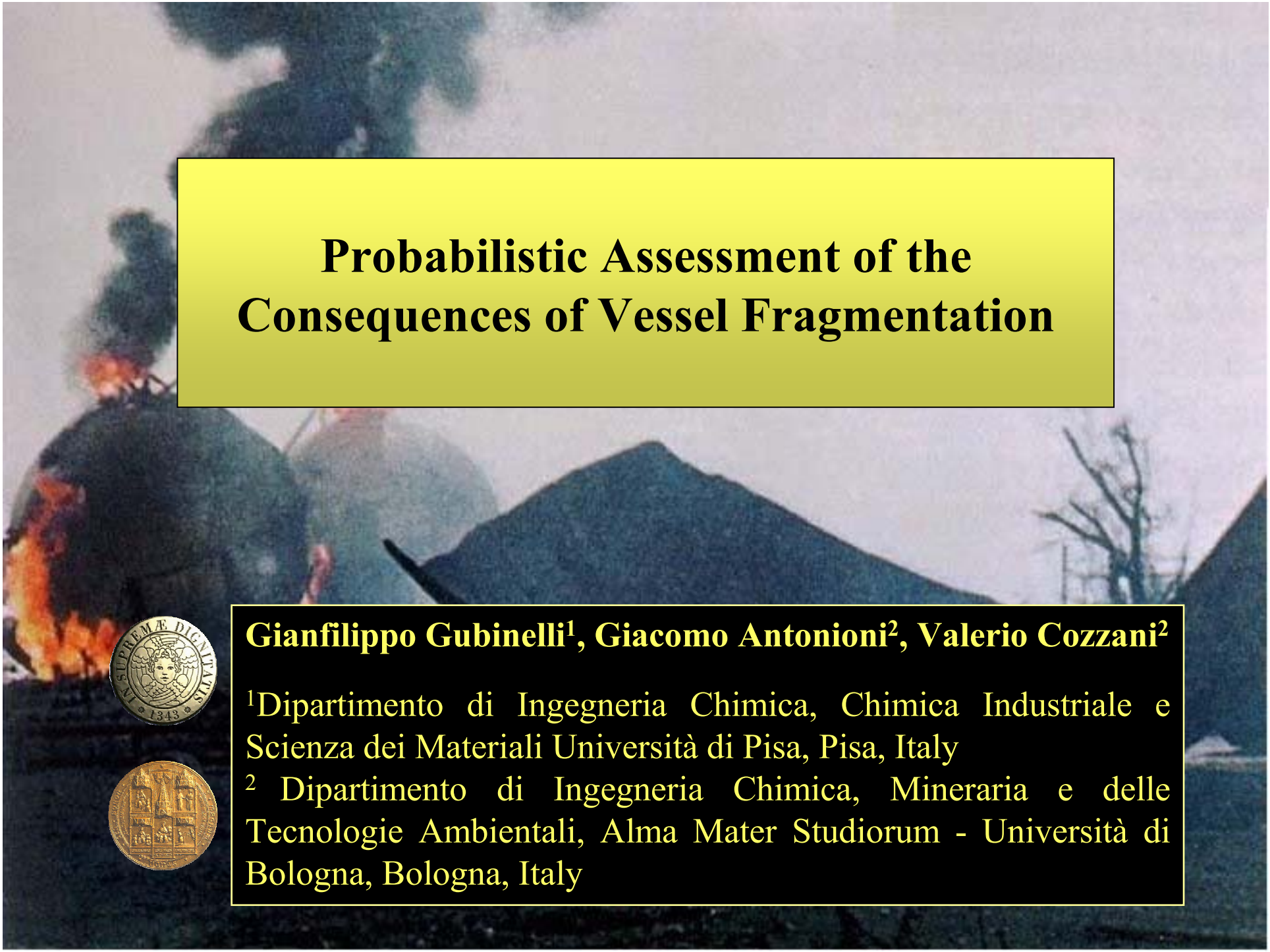

Probabilistic Assessment of the Consequences of Vessel Fragmentation

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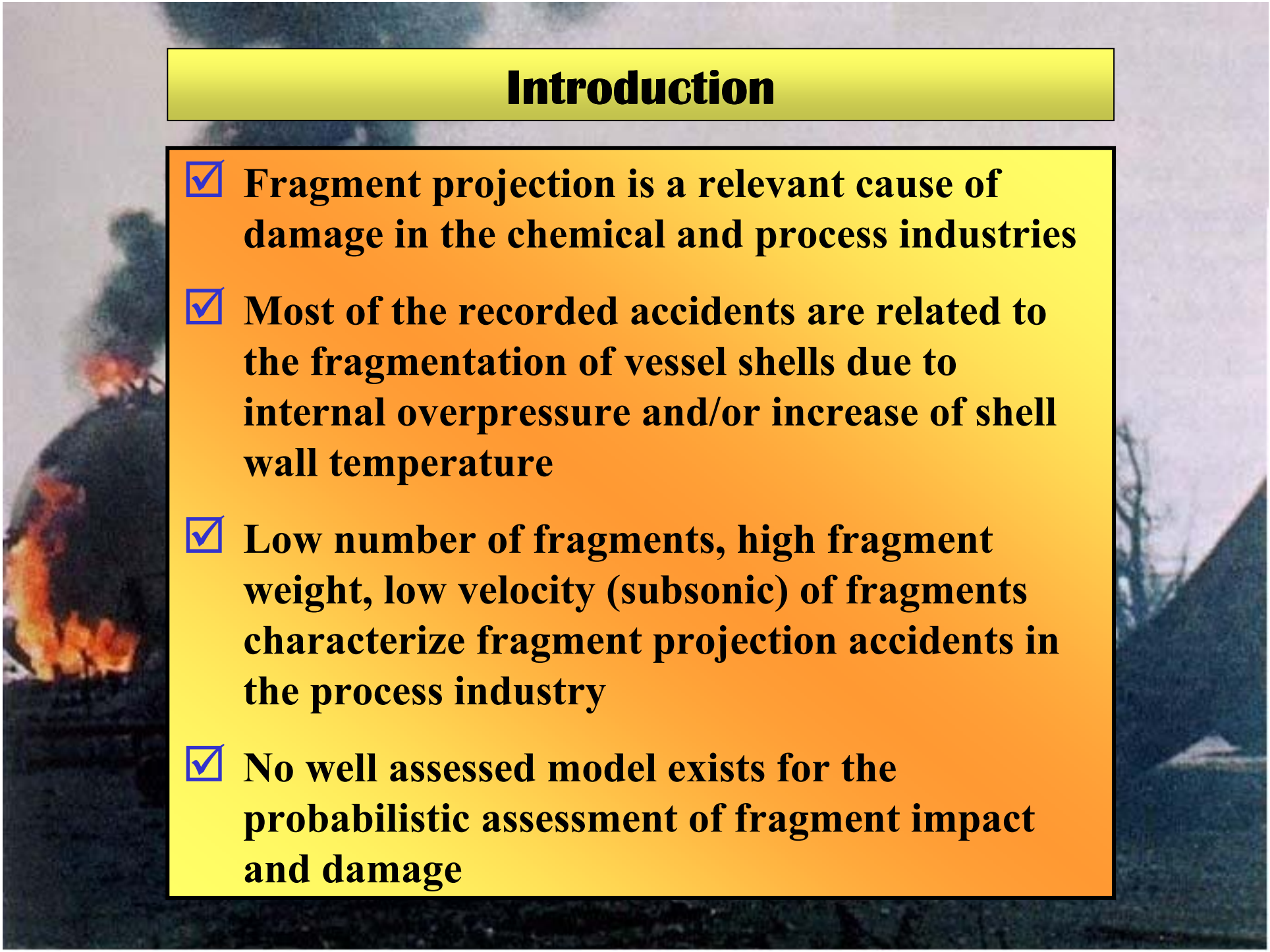
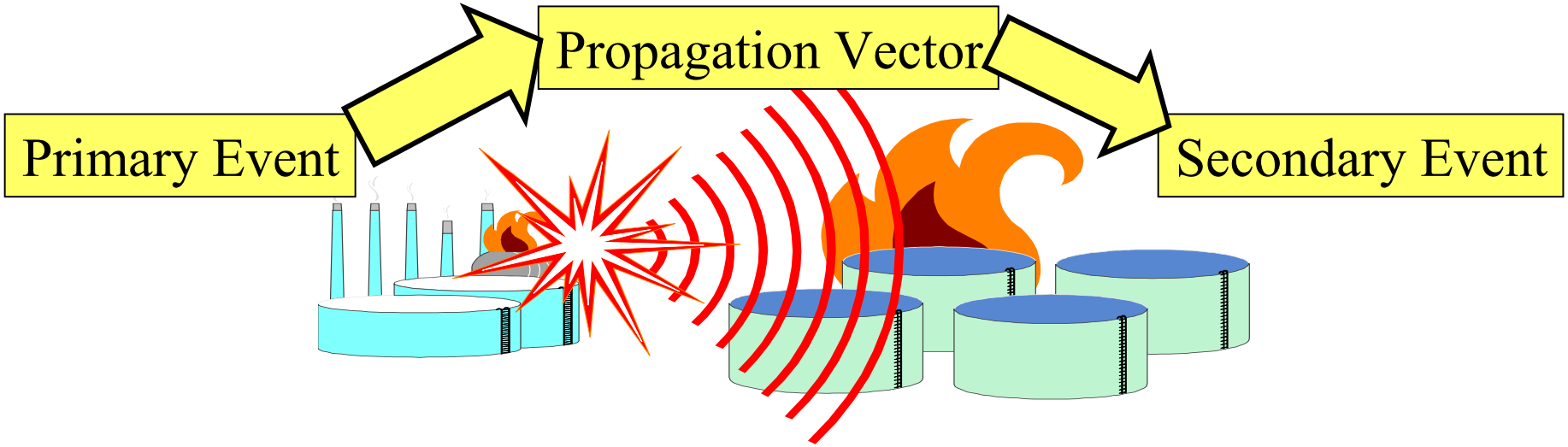


Introduction

- ☑ Fragment projection is a relevant cause of damage in the chemical and process industries
- ☑ Most of the recorded accidents are related to the fragmentation of vessel shells due to internal overpressure and/or increase of shell wall temperature
- ☑ Low number of fragments, high fragment weight, low velocity (subsonic) of fragments characterize fragment projection accidents in the process industry
- ☑ No well assessed model exists for the probabilistic assessment of fragment impact and damage

INTRODUCTION: Domino Effect caused by Fragments



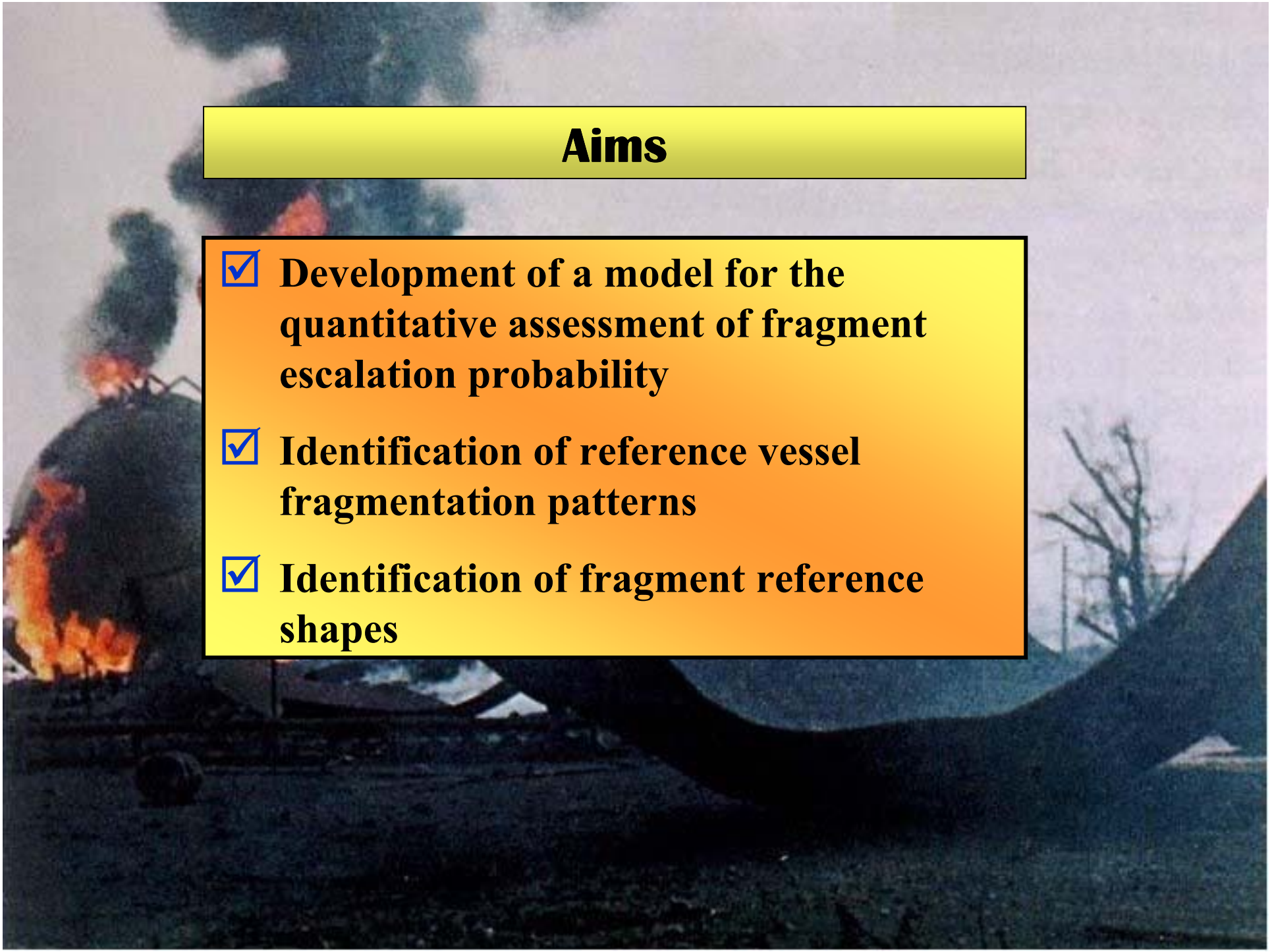
$$f_{dom} = f_1 \square P_{1\ 2}$$

Primary Event Frequency

Probability of Escalation

Probability of Escalation depends on:

- **Type of Primary Scenario**
- **Type of Primary Vessel**
- **Type of Target**
- **Type of Secondary Vessel**



Aims

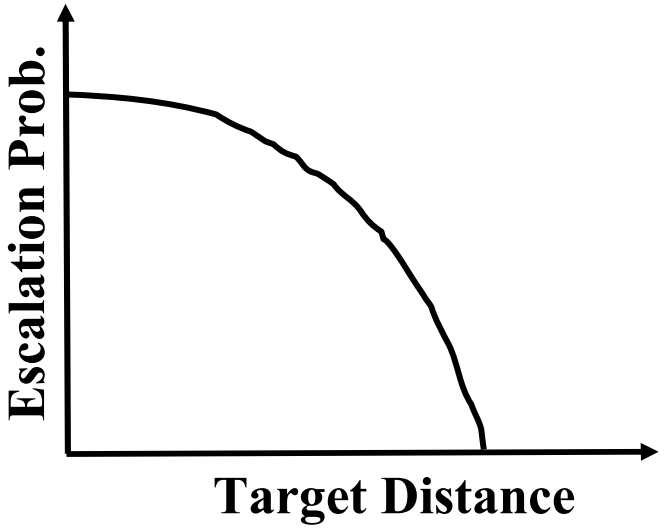
- ☑ Development of a model for the quantitative assessment of fragment escalation probability
- ☑ Identification of reference vessel fragmentation patterns
- ☑ Identification of fragment reference shapes

Model Structure

Vessel Data (shape, dimension)

Event Data (type, vessel condition at failure)

Target Data (type, dimension, position)



Probabilistic Model for Fragment Generation (number, shape, initial velocity)

Model for the evaluation of the probability of impact of a fragment with defined mass, shape and initial velocity on a target

Probabilistic model for target damage given the impact

Model

Probability of Escalation due to Fragments

Propagation Vector: FRAGMENTS assumptions:

the probability that two fragments impact on the same target is sufficiently low

a "limited" number of fragments is generated in the primary event

$$f_{dom} = \sum_{F} f_{dom,F}$$

The frequency of escalation due to the fragmentation of a primary equipment can be evaluated as the sum of the escalation frequencies due to each fragment generated

$$P_{1\ 2} = \sum_{F} P_{1\ 2,F}$$

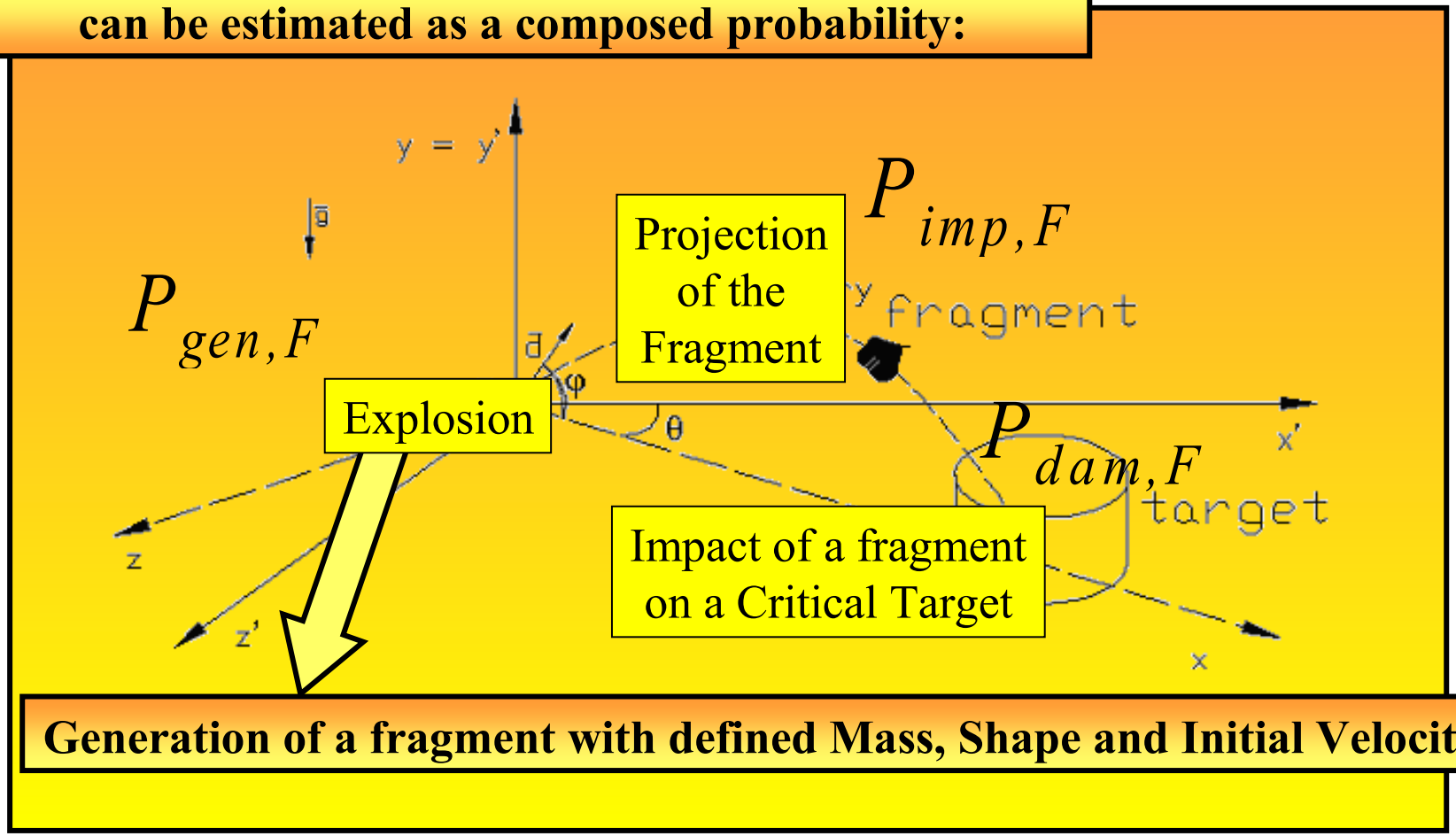
The probability of escalation can be evaluated if it is possible to estimate the probability of escalation due to each fragment

$$f_{dom,F} = f_{I} \cdot P_{1\ 2,F}$$

The approach can be based on the calculation of the escalation probability of escalation due to each fragment

Escalation probability of a single fragment

The probability of escalation due to a single fragment can be estimated as a composed probability:



Generation of a fragment with defined Mass, Shape and Initial Velocity

Escalation probability of a single fragment

Three conditioned probability values are necessary to evaluate the propagation probability due to a single fragment:

$P_{gen,F}$: the probability of the fragment F (with defined mass, shape and initial velocity) to be generated in the primary event. ***Influence of primary scenario and primary vessel.***

$P_{imp,F}$: the probability of impact between the fragment and a target. ***A ballistic and geometrical problem.***

$P_{dam,F}$: the probability of target damage given the impact with the fragment. ***Influence of secondary vessel, fragment shape and velocity.***

Probability Composition

$$P_{1\quad 2,F} = P_{gen,F} \square P_{imp,F} \square P_{dam,F}$$

Fragmentation Pattern Probability (P_{gen})

Database on Fragmentation Accidents

Source	N.
Journals	37
MARS DB	2
NTSB	8
Westin	35
Holden	33
Private Data	5
SHELL	1

121 Past Accidents Analyzed
Data on 143 Vessel
Fragmentation events

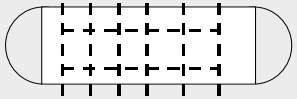
Detailed information on…

Primary Accident: Site, Date, Cause, Vessel type
Vessel sizes, Primary event causing fragmentation, etc..

Detailed information on fracture mode,
fragment shape, etc.

Detailed information on impact and damage

Likely fragmentation patterns

	Id	BLEVE (F)	PE, BLEVE (NF)	CEx	RR	Total
	CV1	0	0	0	29	2
	CV2	59	67	90	43	62
	CV3	12	8	0	0	
	CV4	0	13	0		
	CV7	29	8	0	14	22
	CV11	0	4	0	0	1
	CV21	0	0	10	14	2

Primary Event

f(FP) = 62%

$N_F = 2$

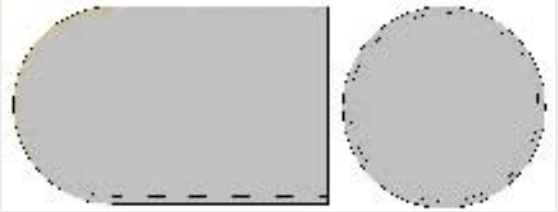
Available data on past accidents and fracture theory allowed the identification of a limited number of fragmentation patterns

Estimation of fragment drag coefficient

Fragmentation pattern and frequencies f(FP)

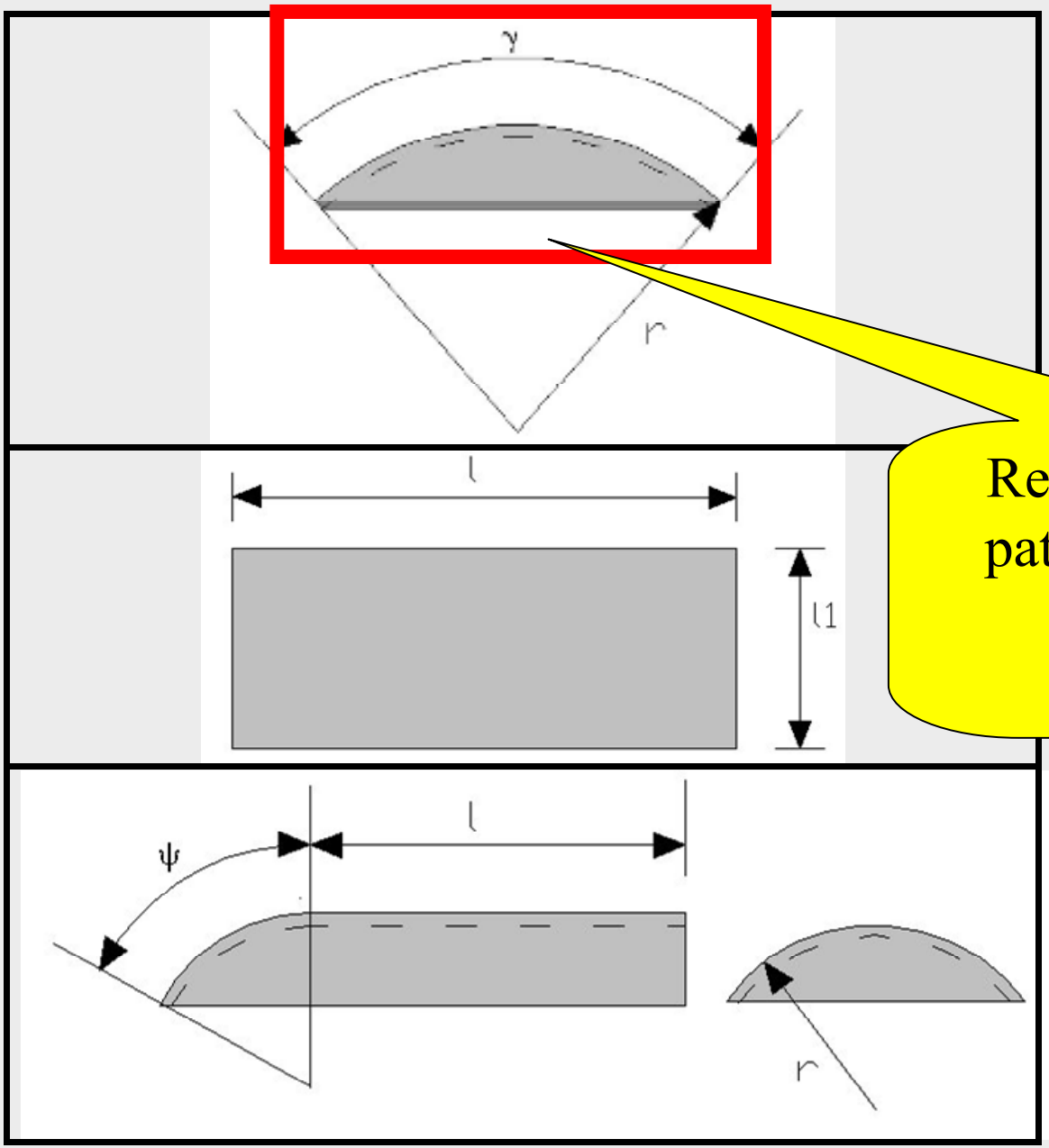
Actual fragment shapes

Reference Fragment Shapes



Simplified functions for drag factor calculation based on reference shapes

Examples of Reference Shapes

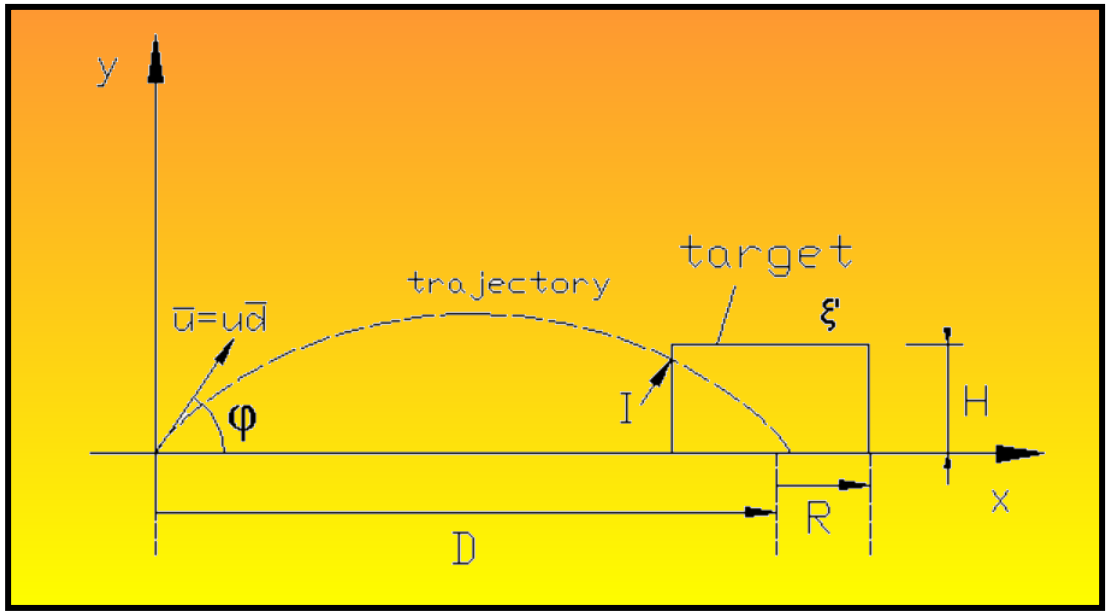


Reference Fragmentation patterns result in a limited number of reference fragment shapes

Evaluation of impact probability

The trajectory and the velocity of the mass centre of the fragment is used to describe the trajectory and velocity of the entire fragment

With a reasonable approximation the fragment trajectory could be represented on a plane perpendicular to the ground



$$x_0 = 0;$$

$$y_0 = 0;$$

$$\dot{x}_0 = u\cos\ \square$$

$$\dot{y}_0 = u\sin\ \square$$

$$\frac{d^2x}{dt^2} + k\left(\frac{dx}{dt}\right)^2 = 0$$

$$\frac{d^2y}{dt^2} - 1^n k\left(\frac{dy}{dt}\right)^2 + g = 0$$

Evaluation of impact probability (II)

$x_0 = 0;$

$y_0 = 0;$

$\dot{x}_0 = u \cos \square$

$\dot{y}_0 = u \sin \square$

$$\frac{d^2 x}{dt^2} + k \left(\frac{dx}{dt} \right)^2 = 0$$

$$\frac{d^2 y}{dt^2} - 1^n k \left(\frac{dy}{dt} \right)^2 + g = 0$$

Input Parameters

u: initial velocity of the fragment

φ: initial angle of the fragment

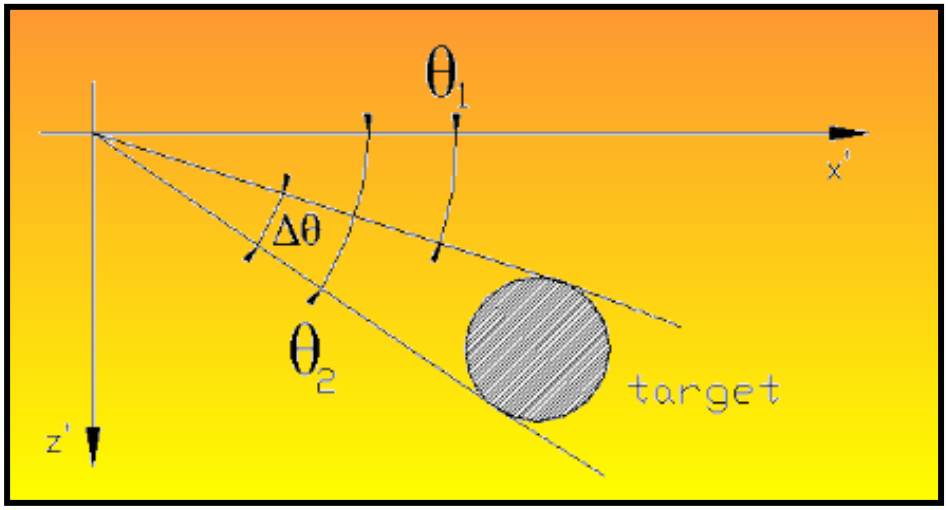
k: Fragments Drag Factor

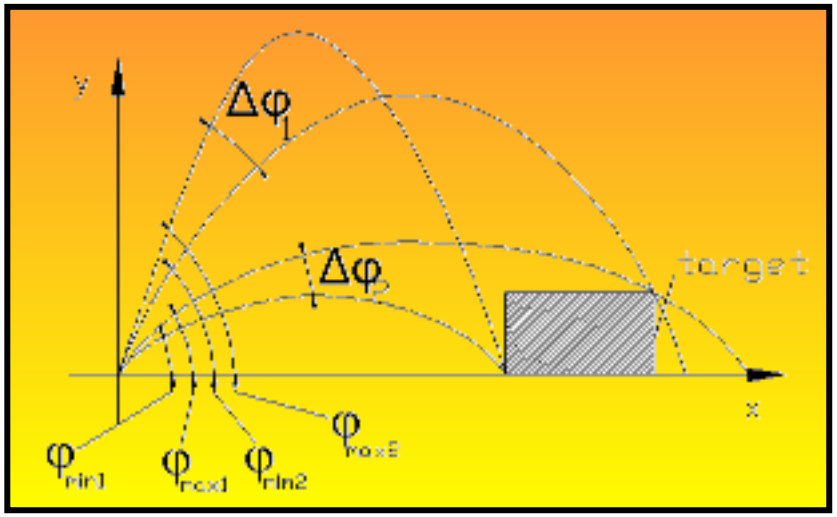
Assumption: Chunky Fragments

$$k = a \left(\frac{C_D A_D}{M} \right) - b$$

Definition of k using the approach and the data by Baker et al. (these were validated using experimental results)

The available model: evaluation of impact probability





$$P_{F,d}(\theta,\varphi) = p(\theta,\varphi)\,d\theta\,d\varphi$$

Probability of a Fragment F to be projected in a given direction d. A user-defined p.d.f. is required

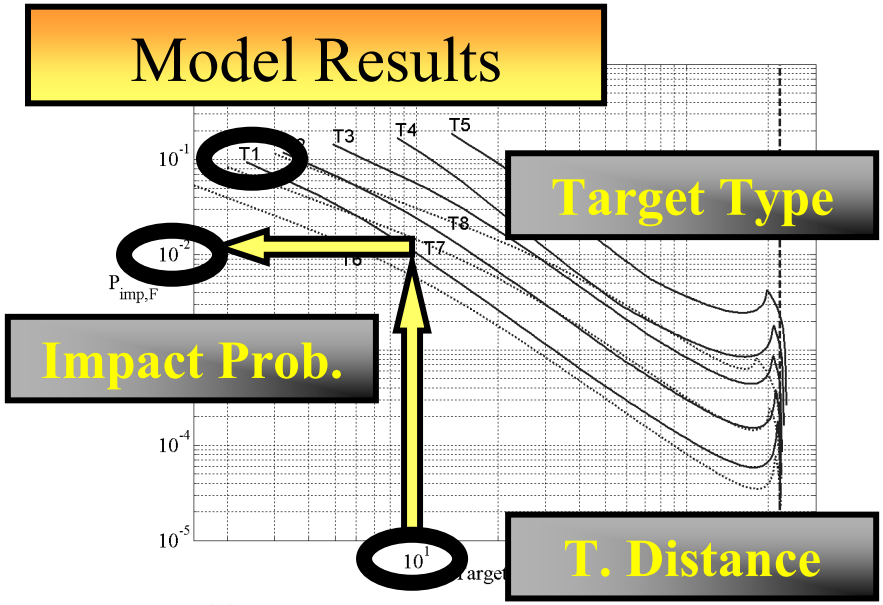
$$P_{imp,F} = \int_{\Delta\theta}\int_{\Delta\varphi} p_{dir}(\theta,\varphi)\,d\theta\,d\varphi$$

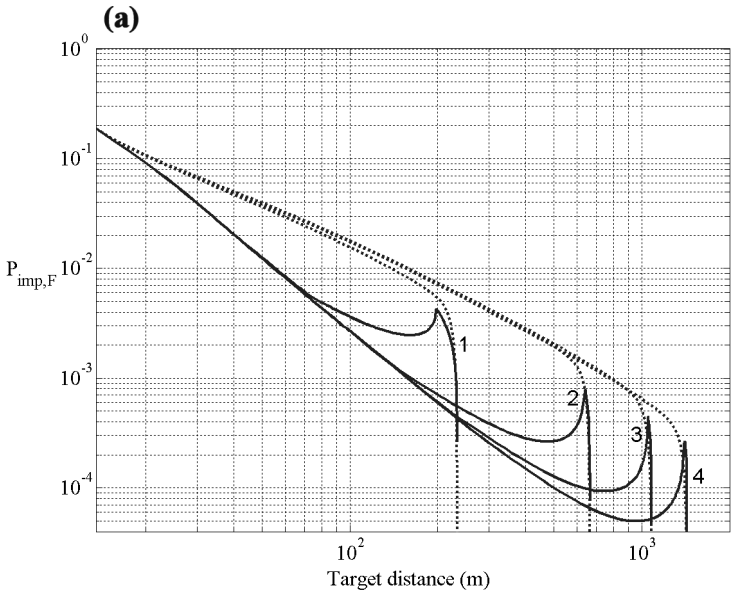
Probability of impact

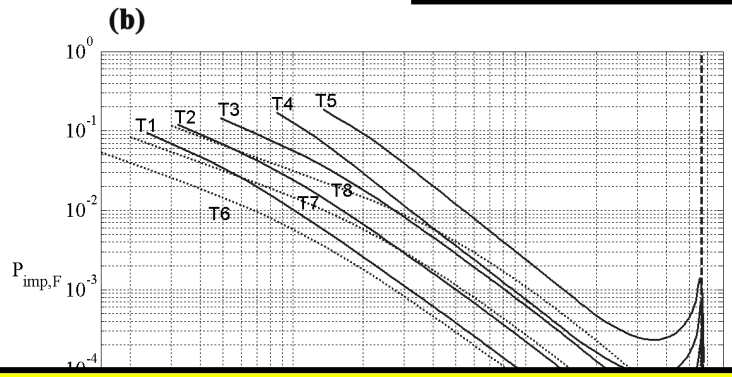
The modification of the pdf allows introducing preferential directions

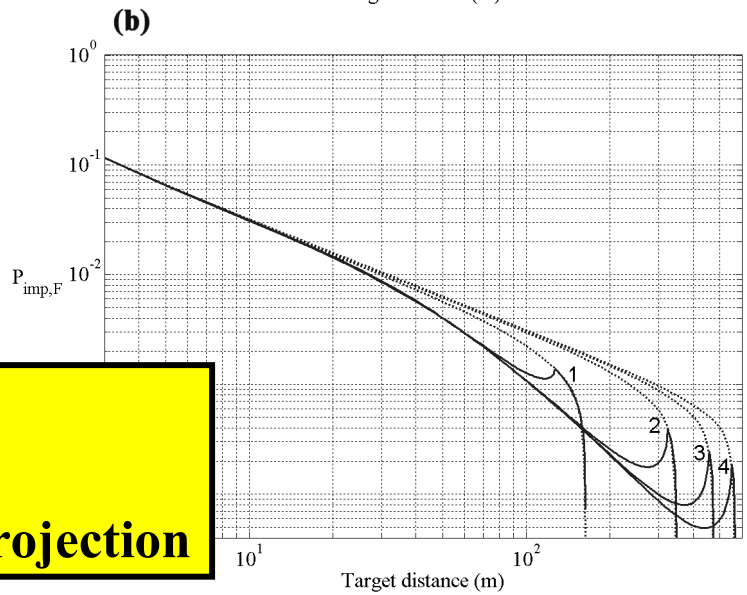
PROBABILITY OF IMPACT: Examples of Results

Model Results

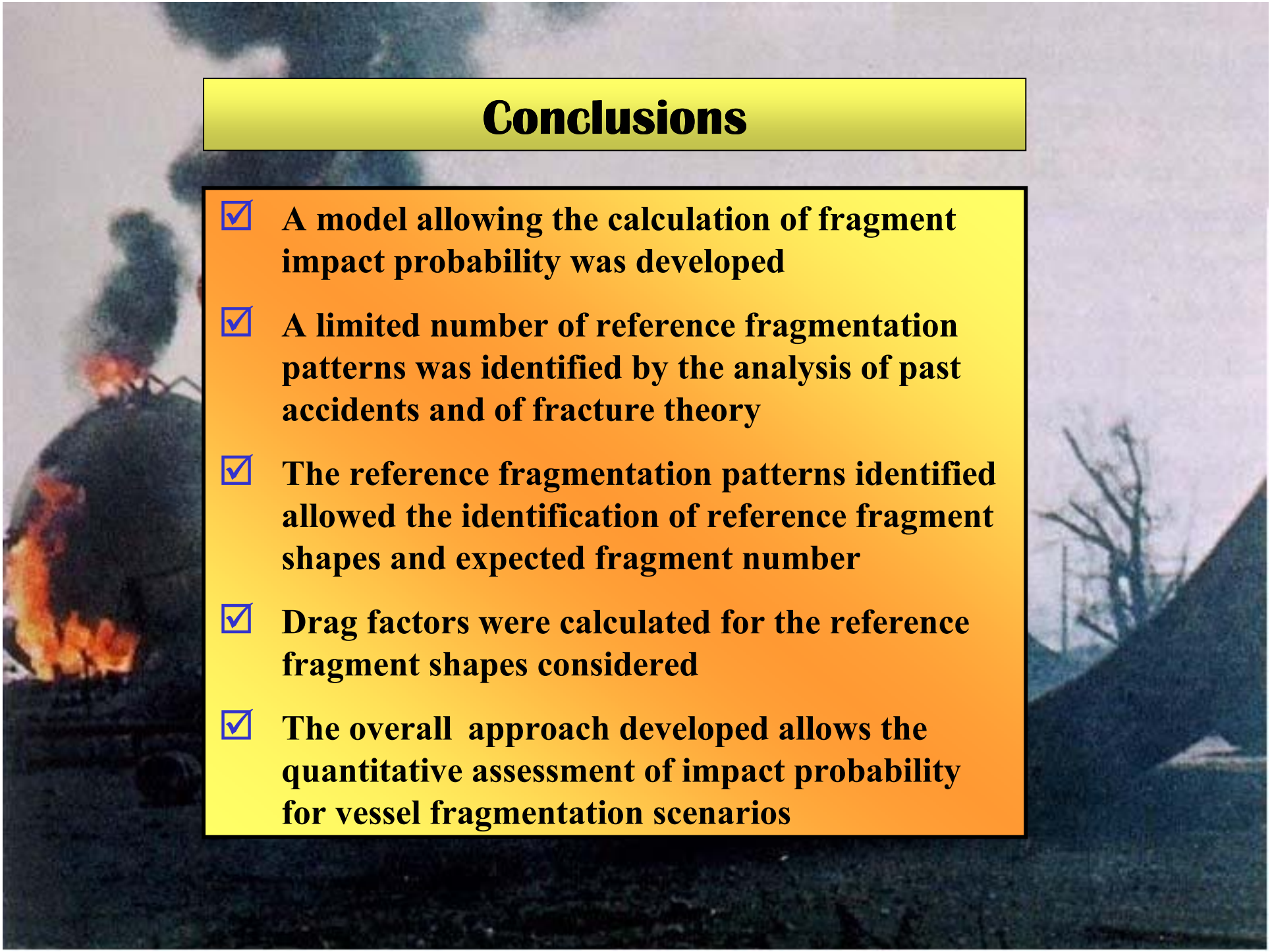








For a Fragment with
- **given initial velocity**
- **uniform p.d.f. for Initial angle of projection**



Conclusions

- ☑ A model allowing the calculation of fragment impact probability was developed
- ☑ A limited number of reference fragmentation patterns was identified by the analysis of past accidents and of fracture theory
- ☑ The reference fragmentation patterns identified allowed the identification of reference fragment shapes and expected fragment number
- ☑ Drag factors were calculated for the reference fragment shapes considered
- ☑ The overall approach developed allows the quantitative assessment of impact probability for vessel fragmentation scenarios