

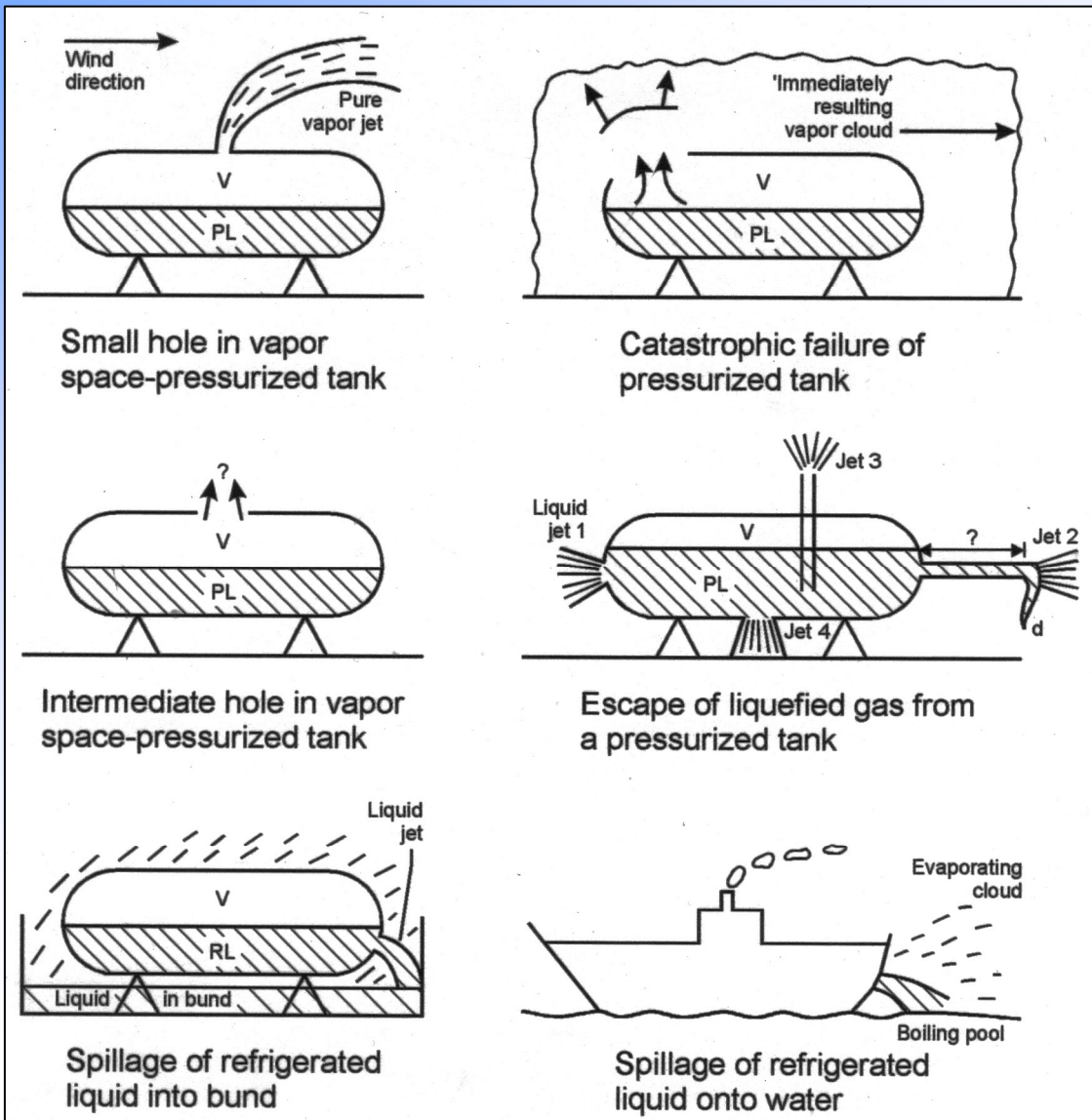
# **SAFETY CONSIDERATIONS ON LIQUID HYDROGEN (PART 2)**

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**Research Center Jülich, Germany**

**2<sup>nd</sup> European Summer School on Hydrogen Safety  
Belfast, July 30 – August 8, 2007**

# Types of Cryogen Release

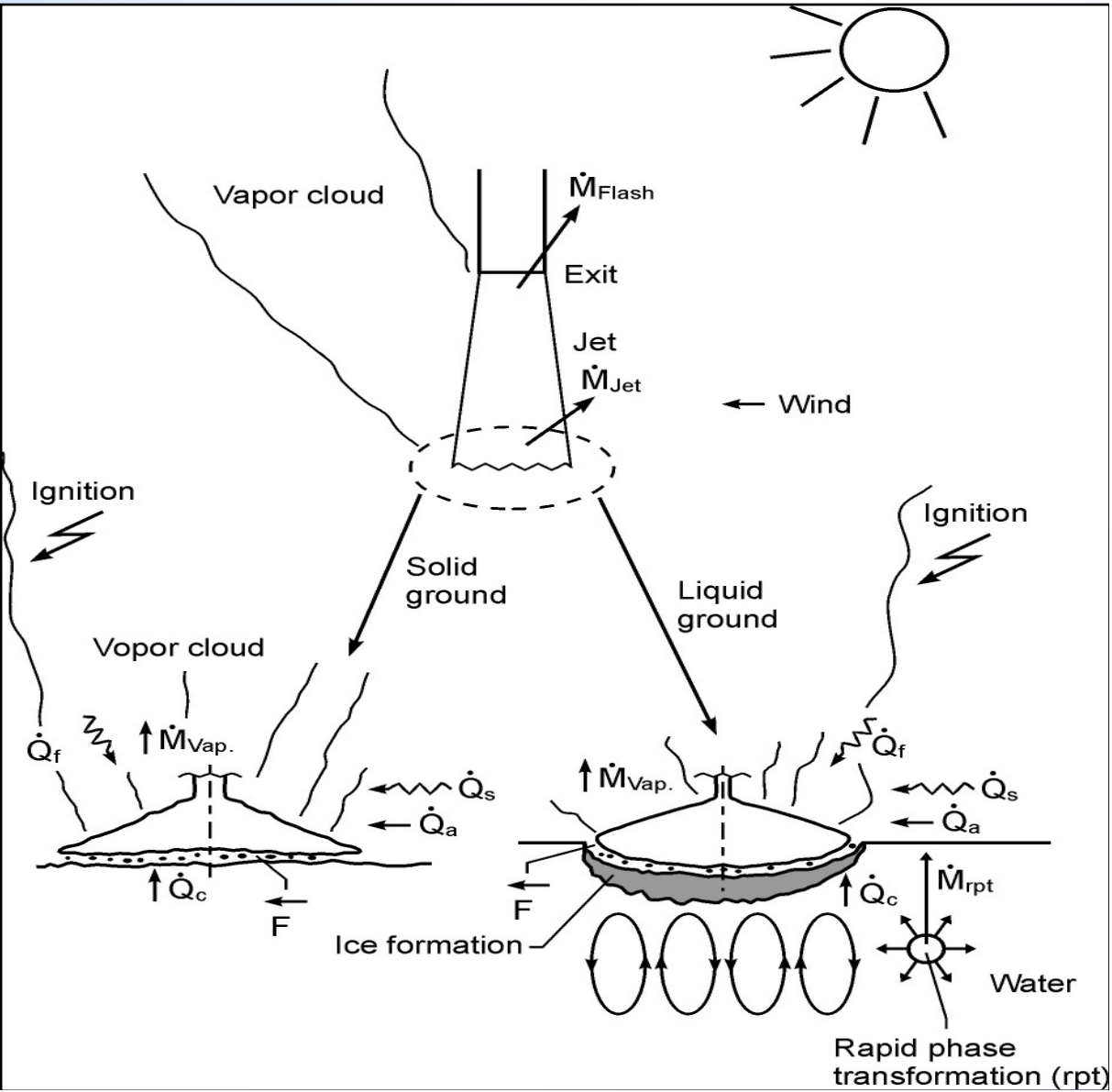


- Catastrophic failure from high internal pressure
- Release of a jet stream of liquid or gas or two-phase mixture from pressurized system
- Release of liquid forming pool on the ground

# Cryogenic Pool Phenomena



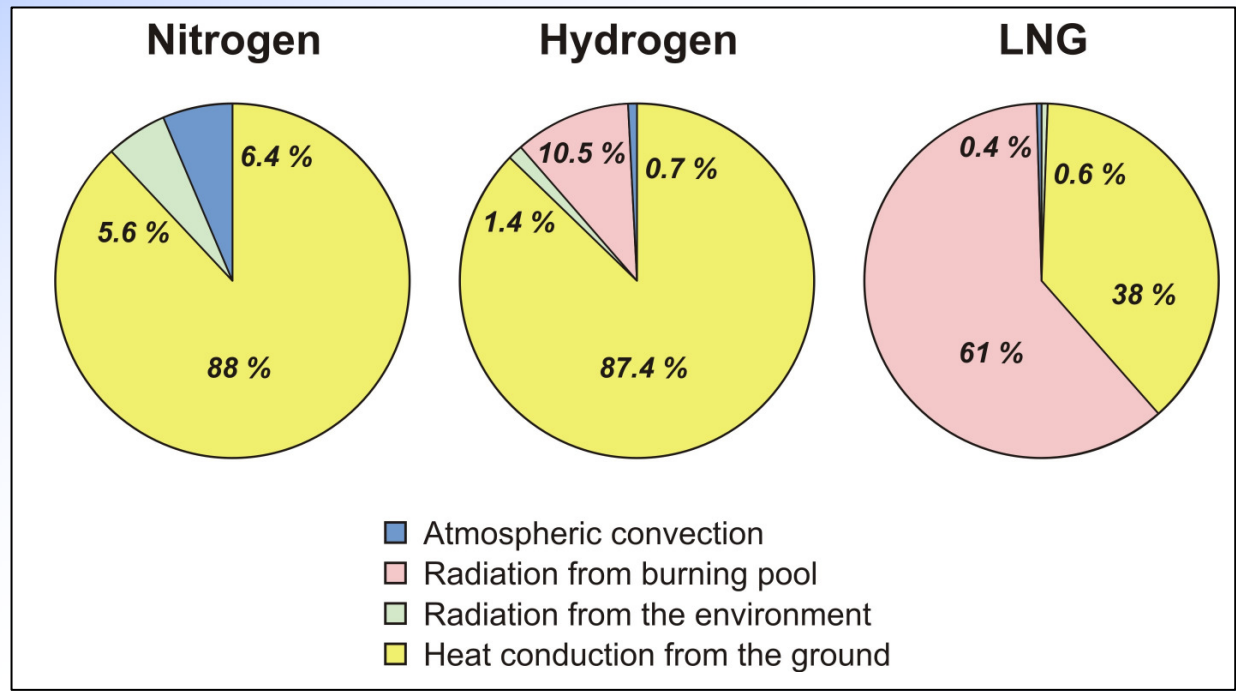
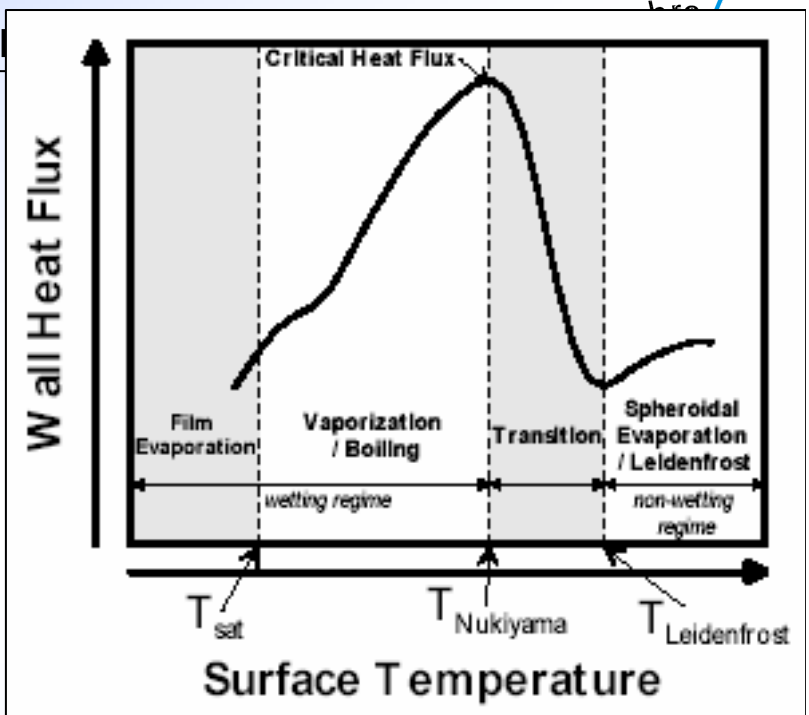
150 l of LN<sub>2</sub> spilled on water



For

# Vaporization of a Cryogen

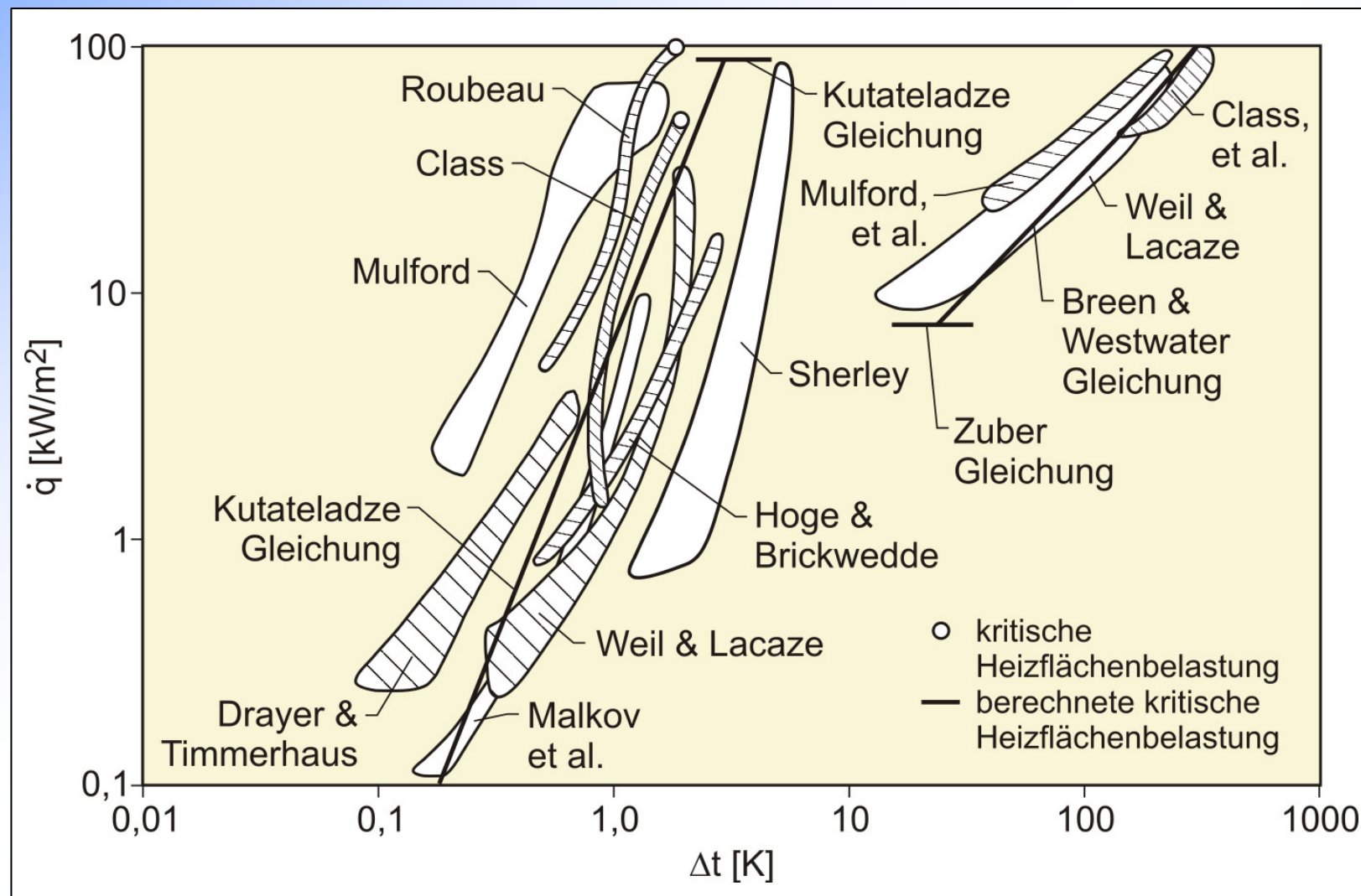
Film boiling  
Transition phase  
Nucleate boiling



Heat flux density vs. temperature

Heat sources

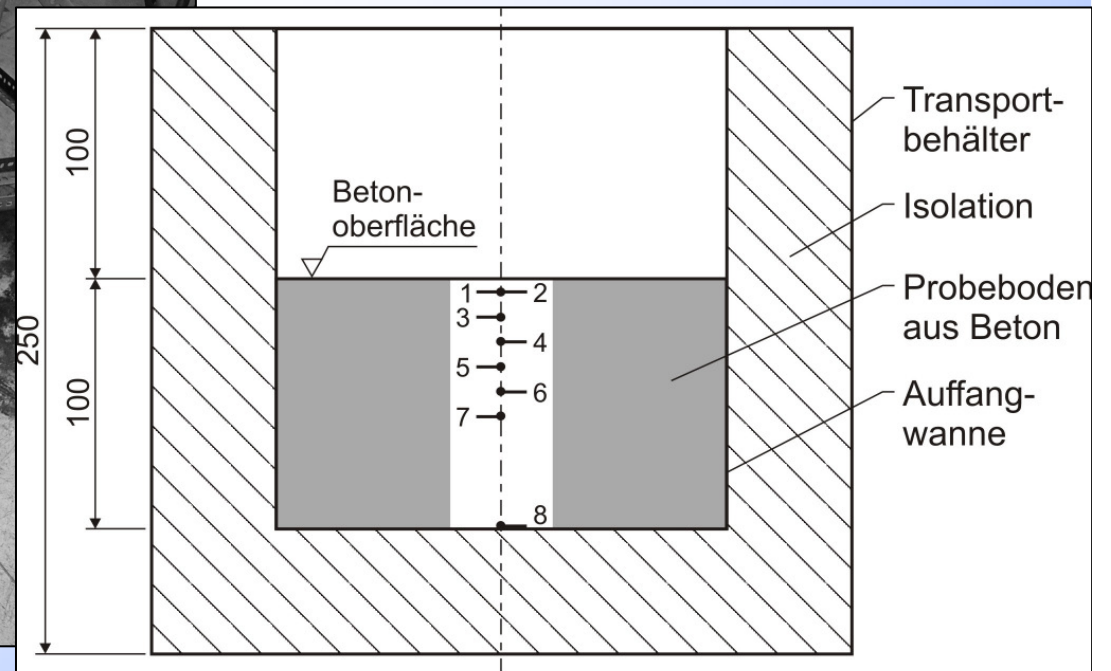
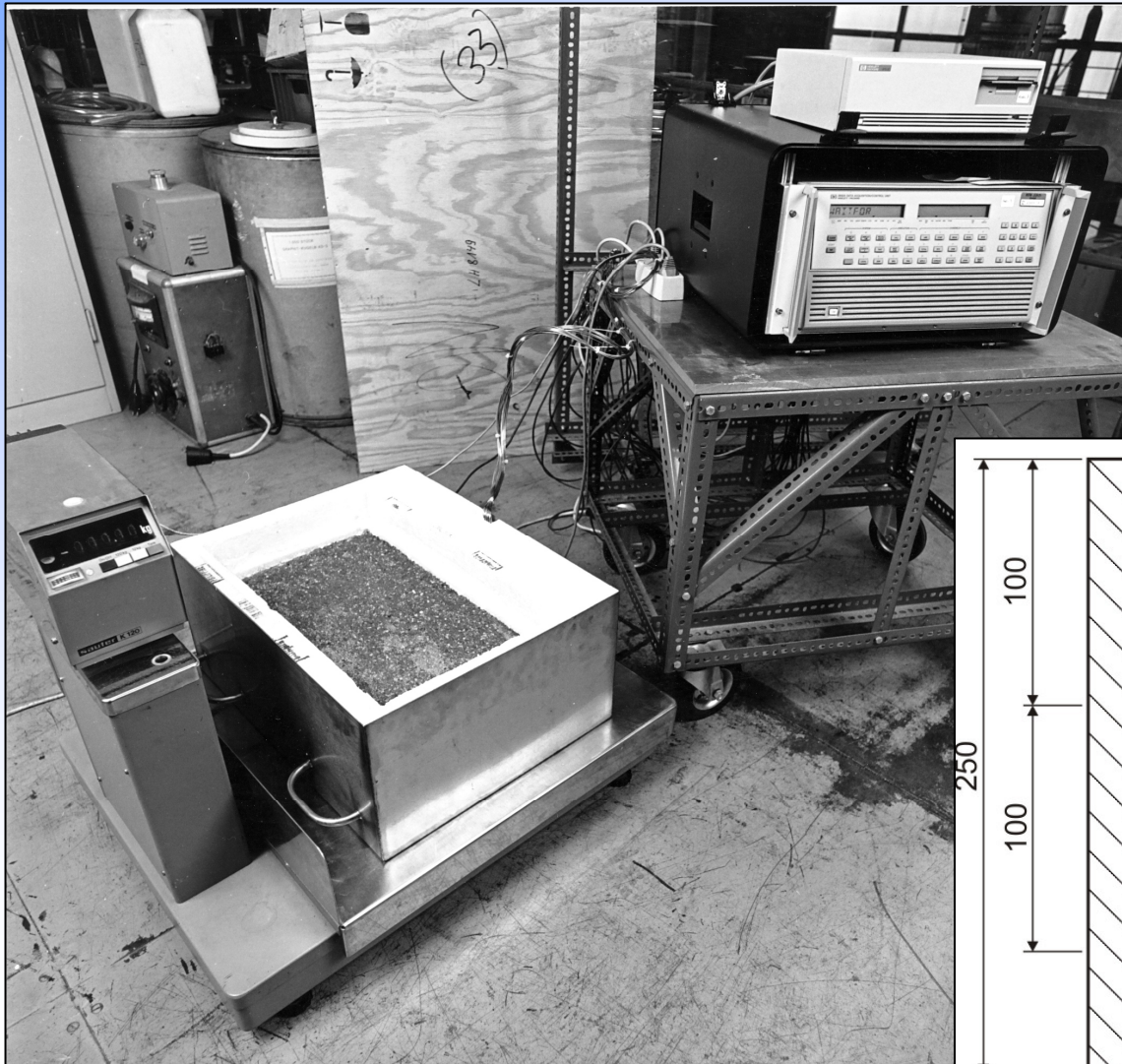
# Nukiyama Curve of Heat Flux Density



# Vaporization Tests with LN<sub>2</sub>

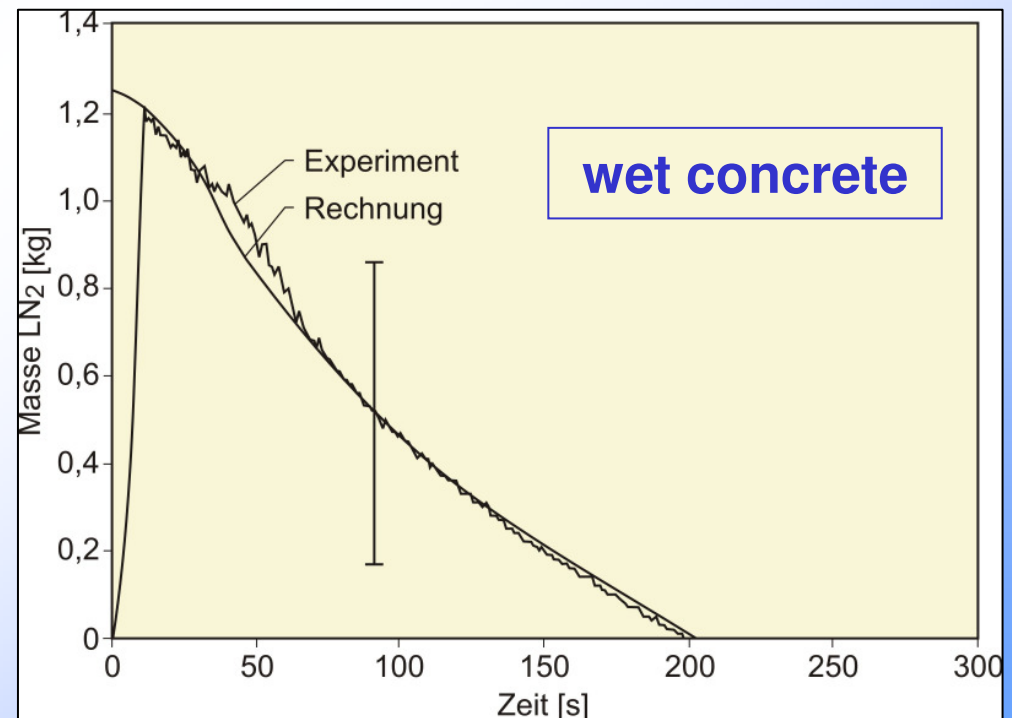
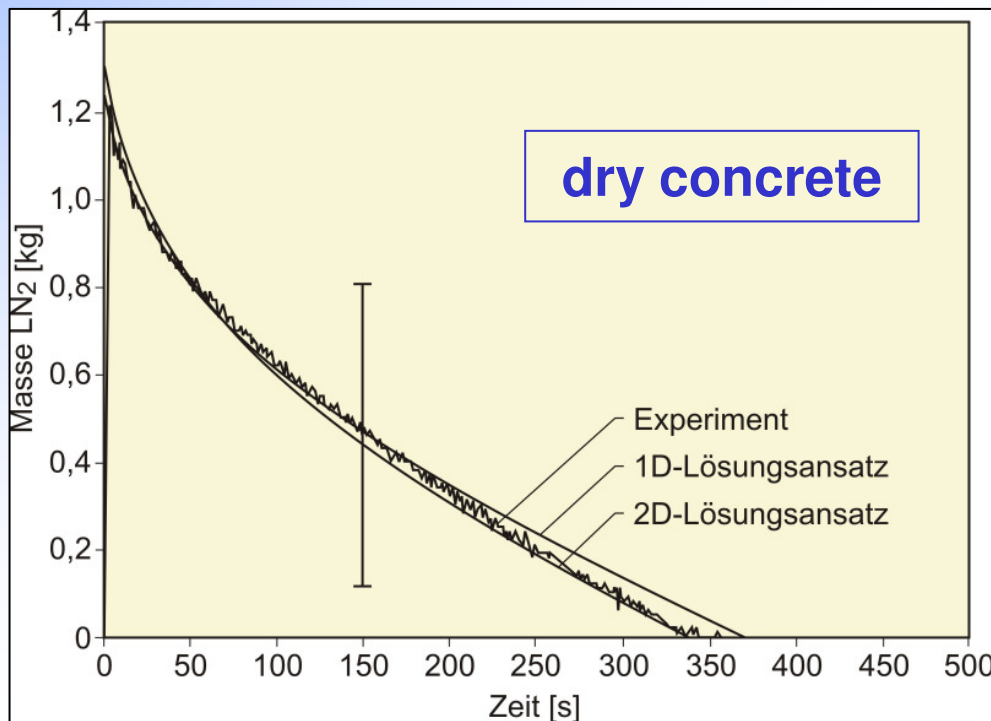
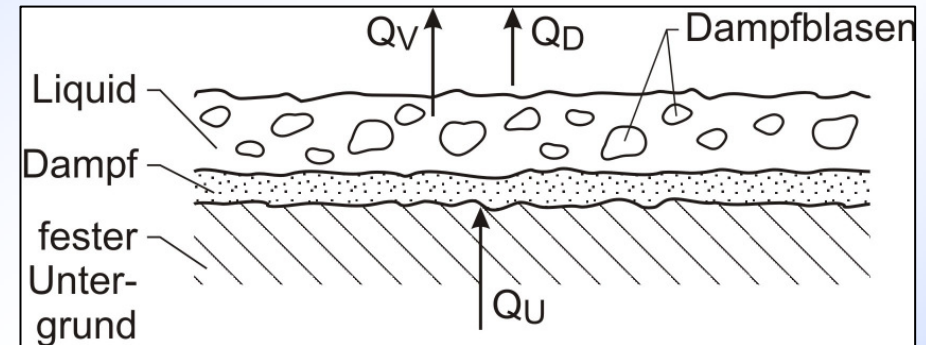
Isolated bodies of

- bitumen  
(road surface)
- concrete wet / dry



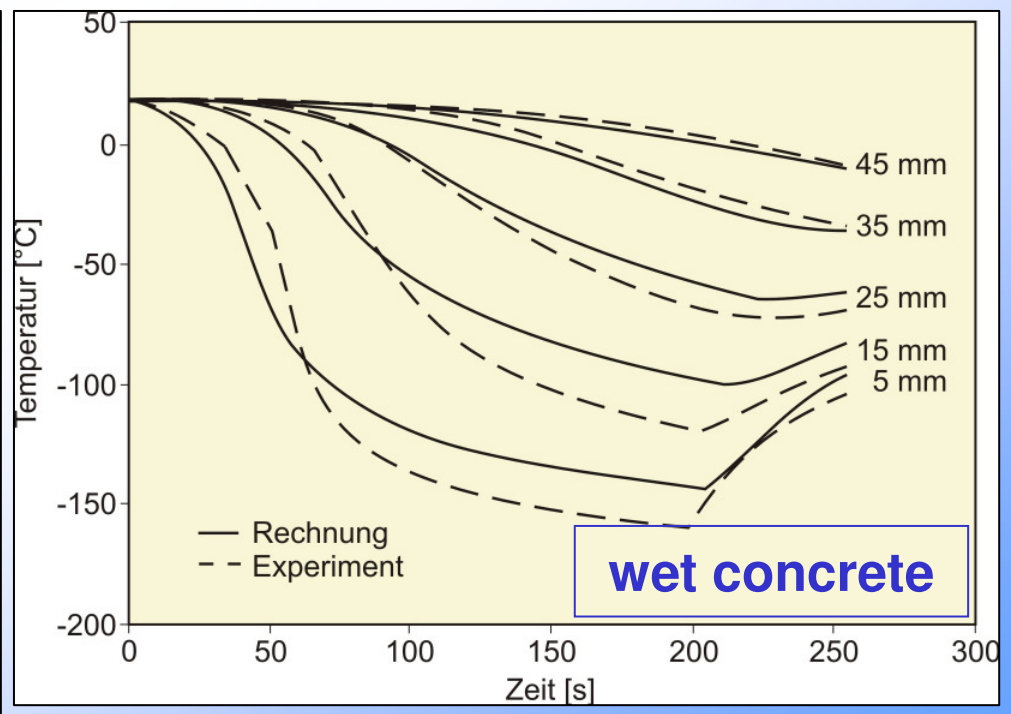
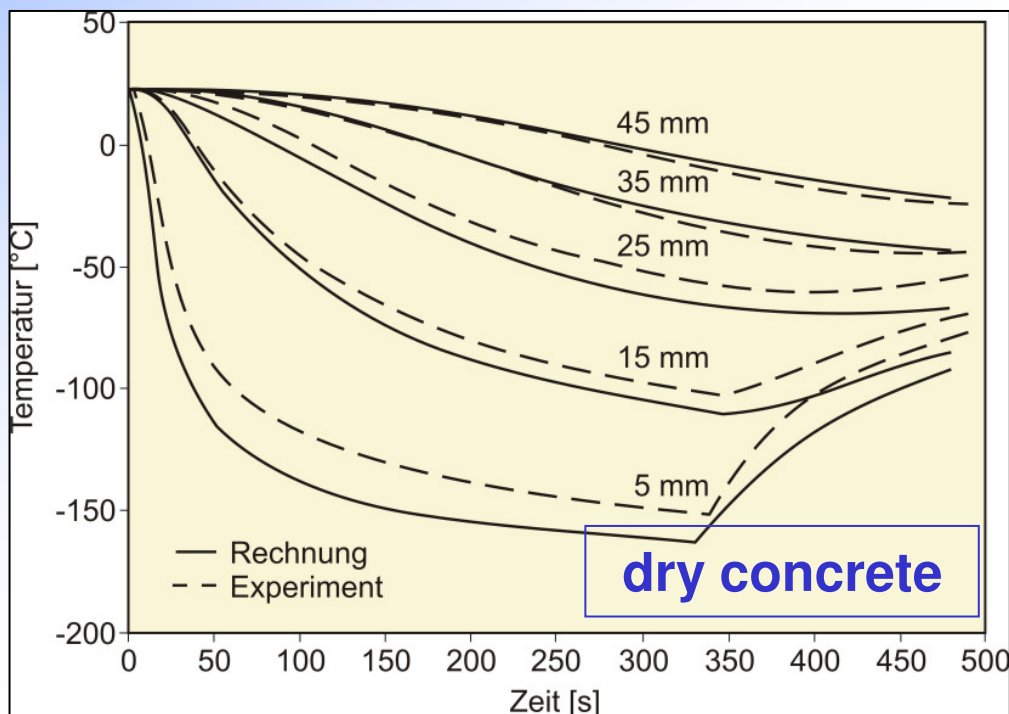
# Vaporization of 1.5 l of LN<sub>2</sub>

Mass loss



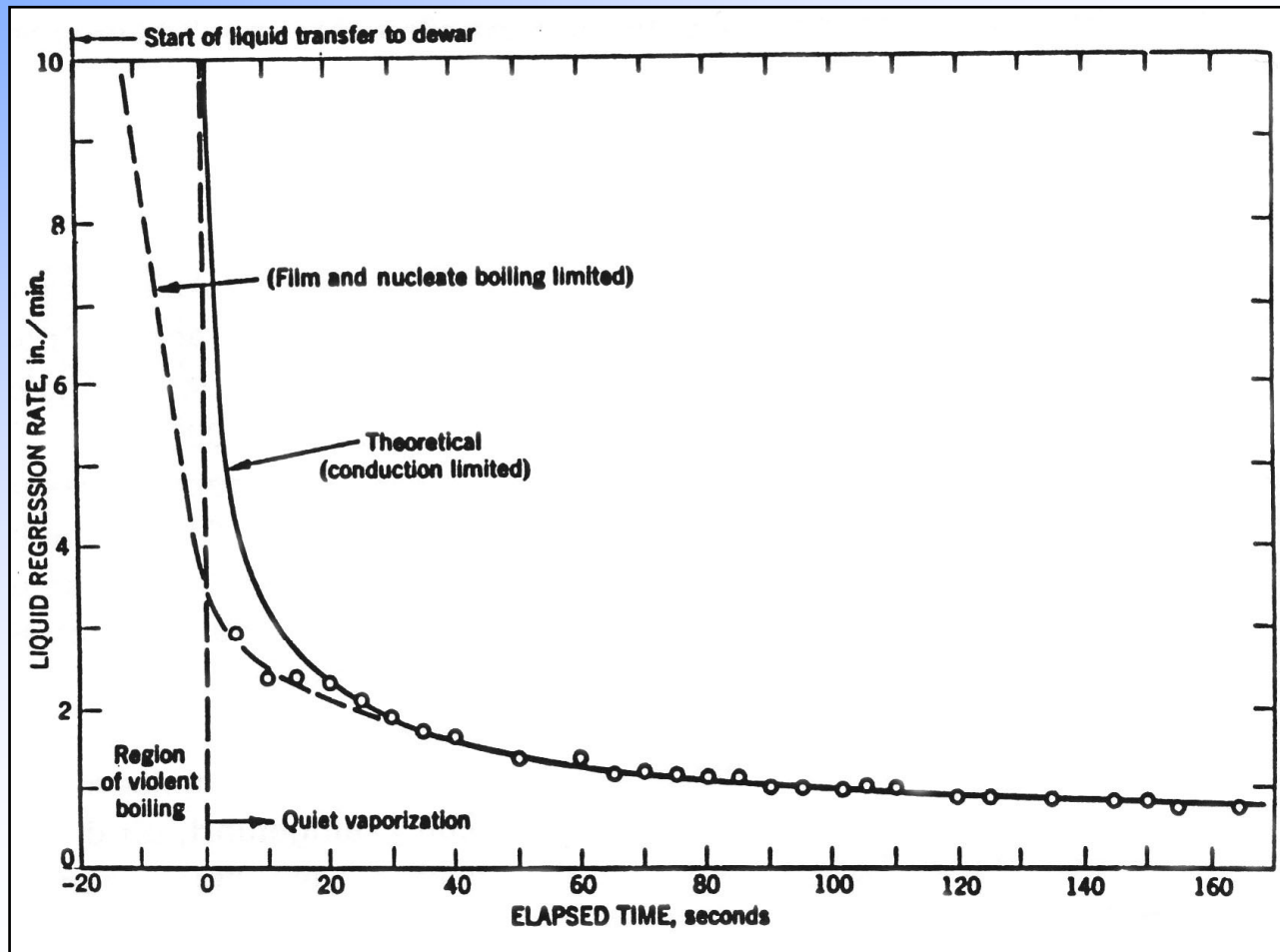
# Vaporization of 1.5 l of LN<sub>2</sub>

## Temperatures in depth





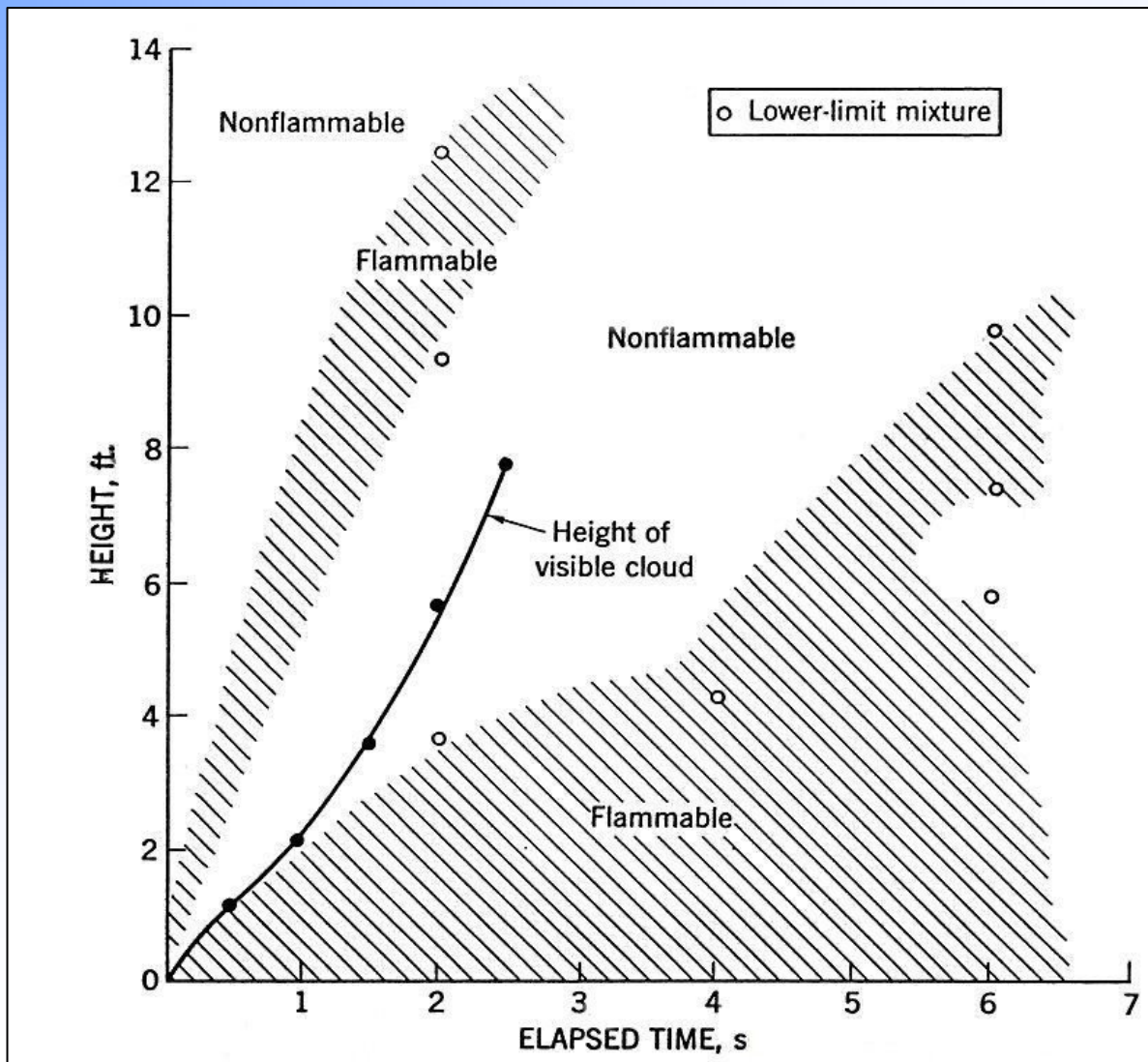
# LH<sub>2</sub> Pool Regression



**Body:**  
paraffin wax  
in 65 mm dewar

Zabetakis 1960

# Vaporization Behavior of LH<sub>2</sub>



**Release of 3 l of LH<sub>2</sub>  
No wind**

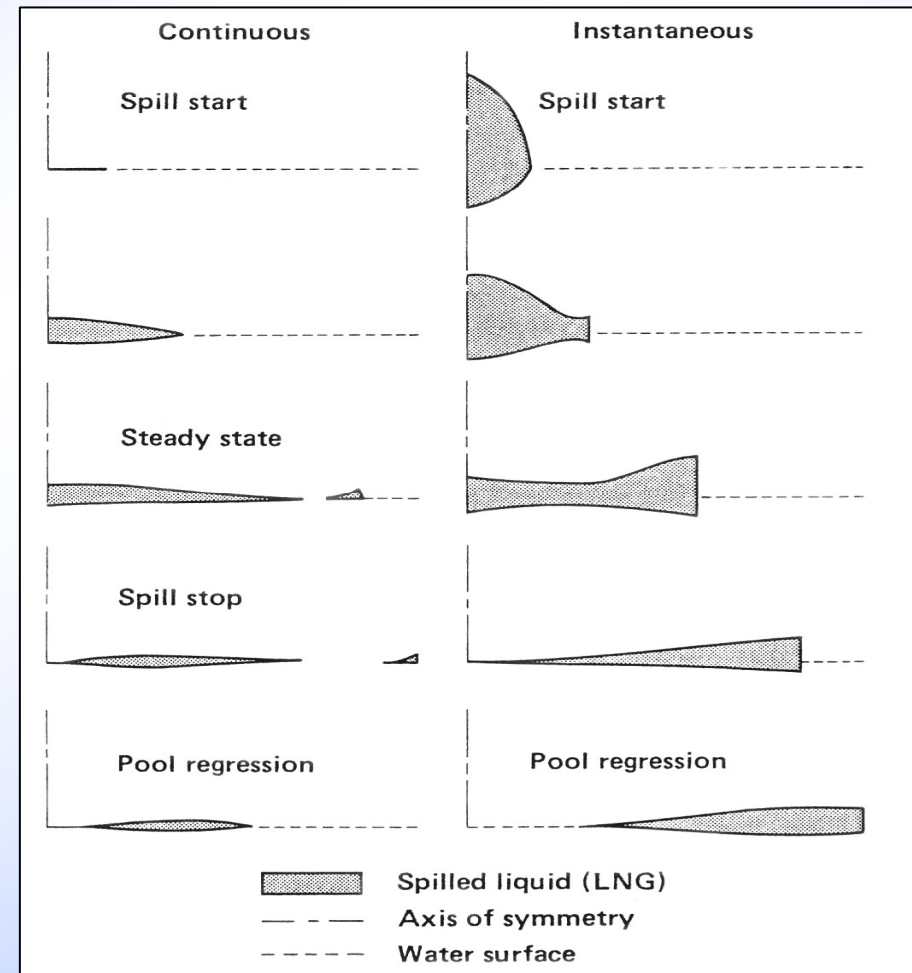
**Zabetakis 1960**

# Cryogen Pool Spreading

Strongly depending on

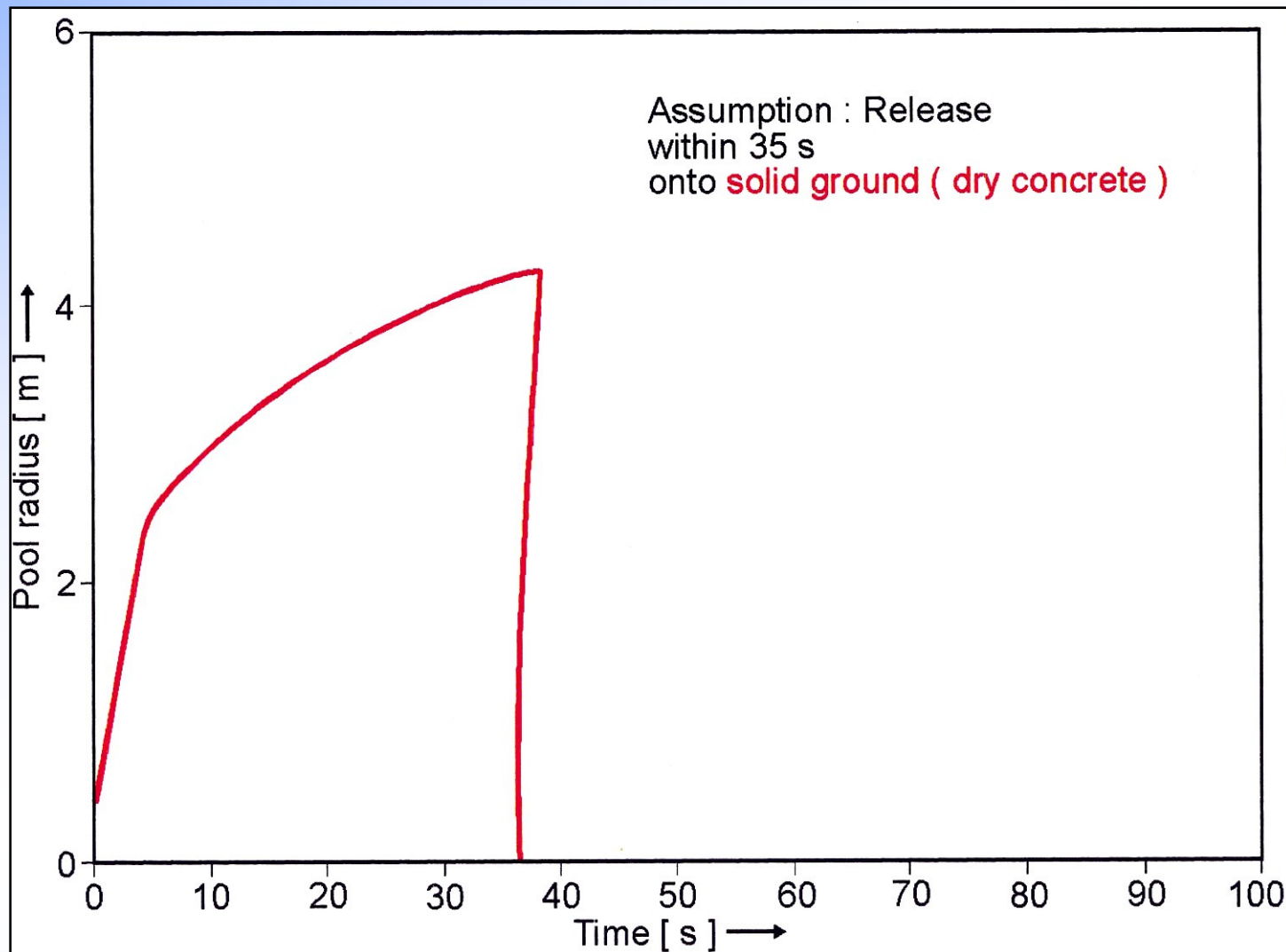
- release mode  
(instantaneous / continuous)
- type of ground  
(solid / liquid)

Release on water

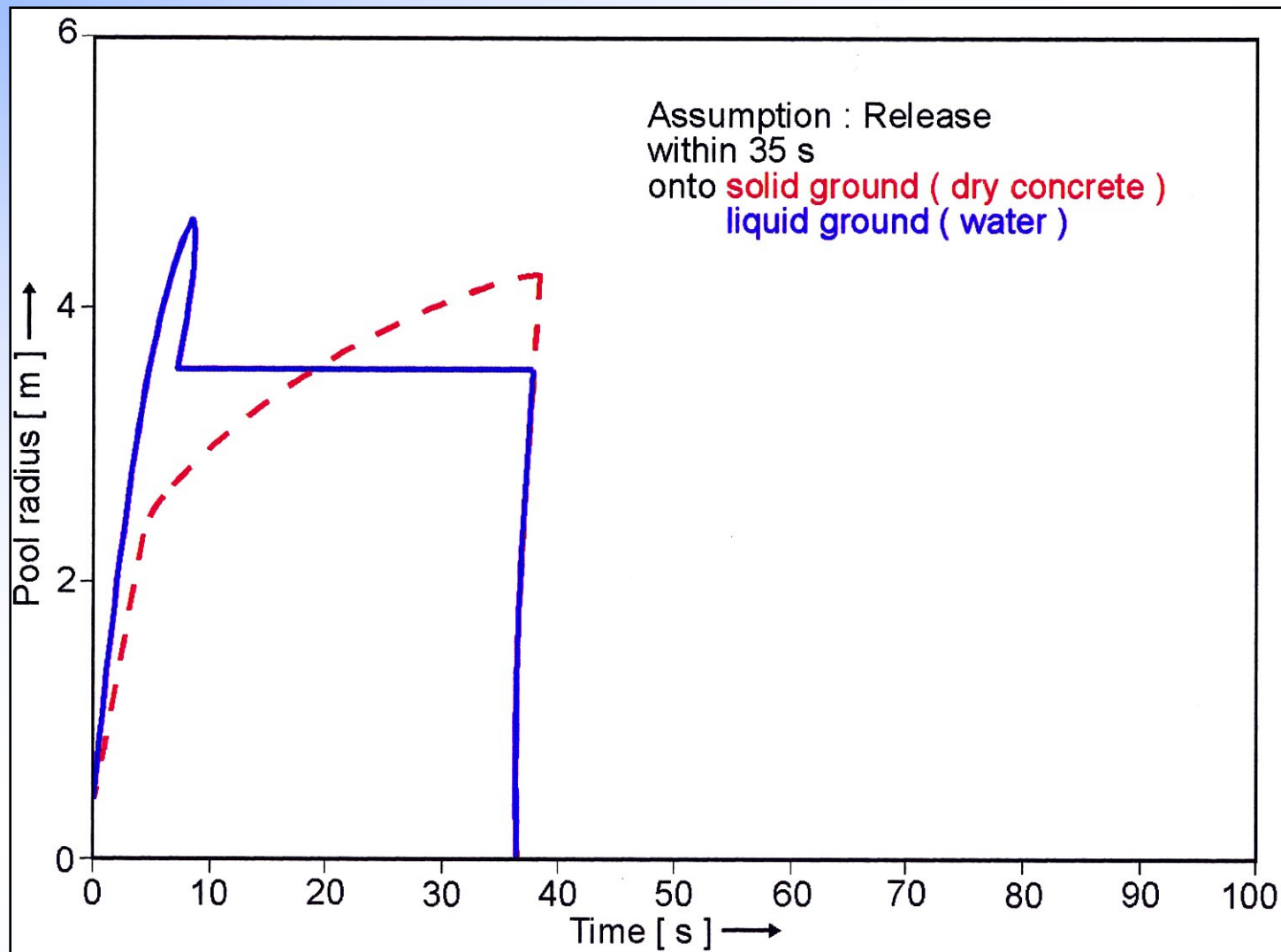


Brandeis 1983

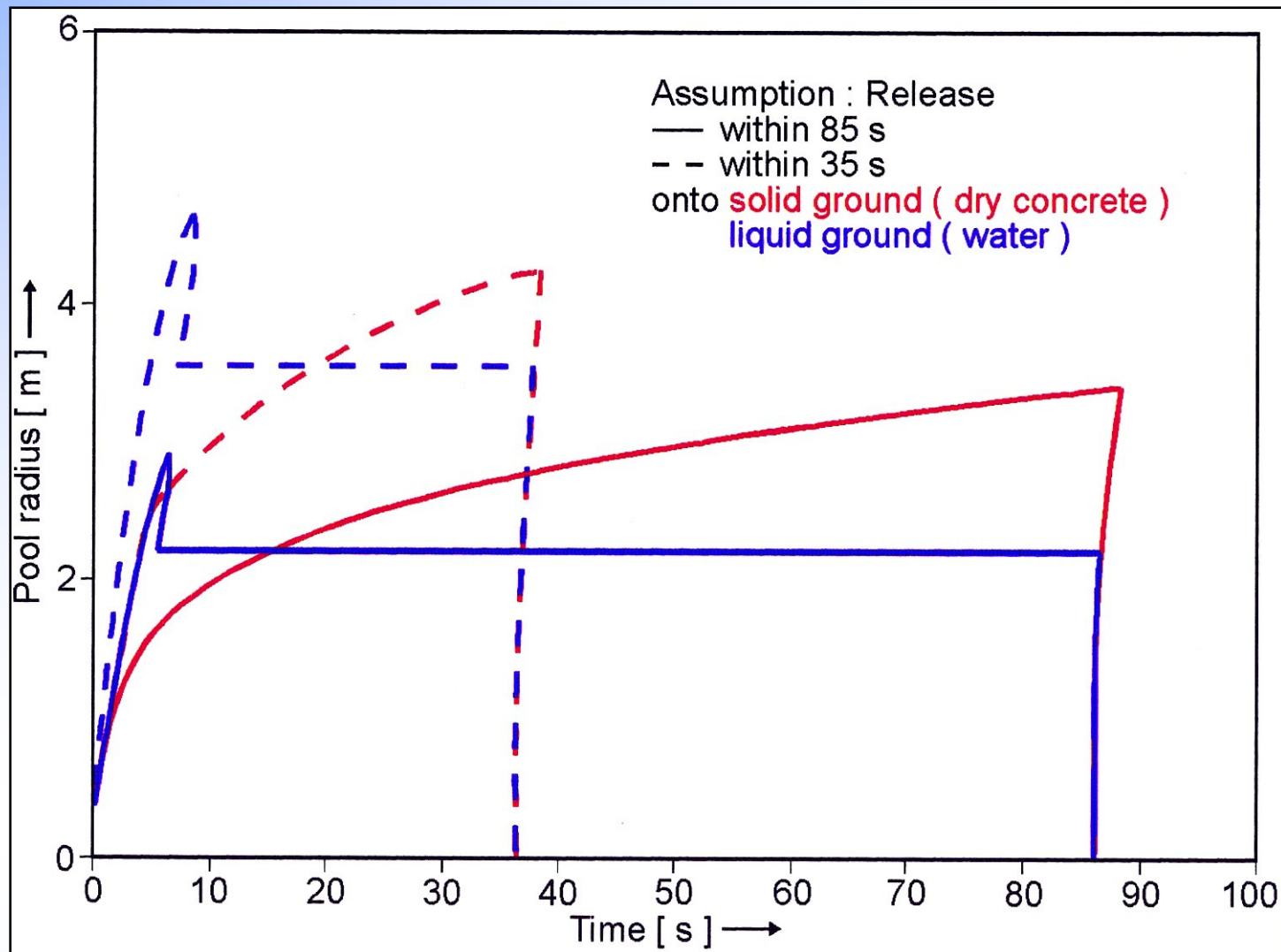
# Cryogenic Pool Behavior (1)



## Cryogenic Pool Behavior (2)

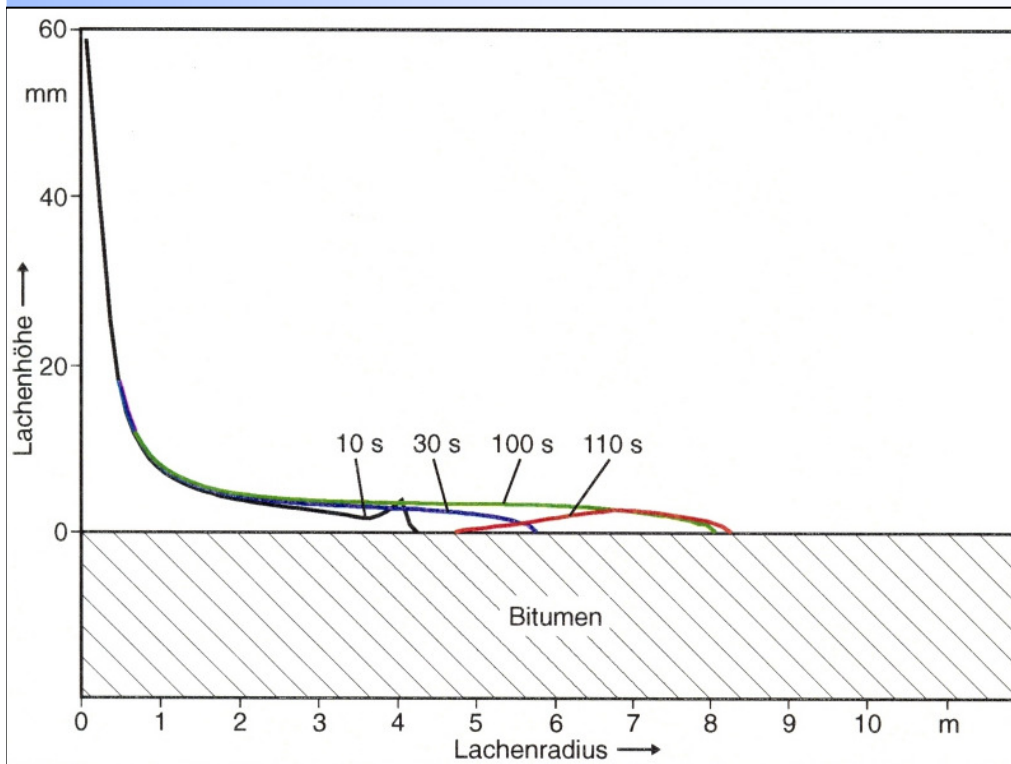


# Cryogenic Pool Behavior (3)

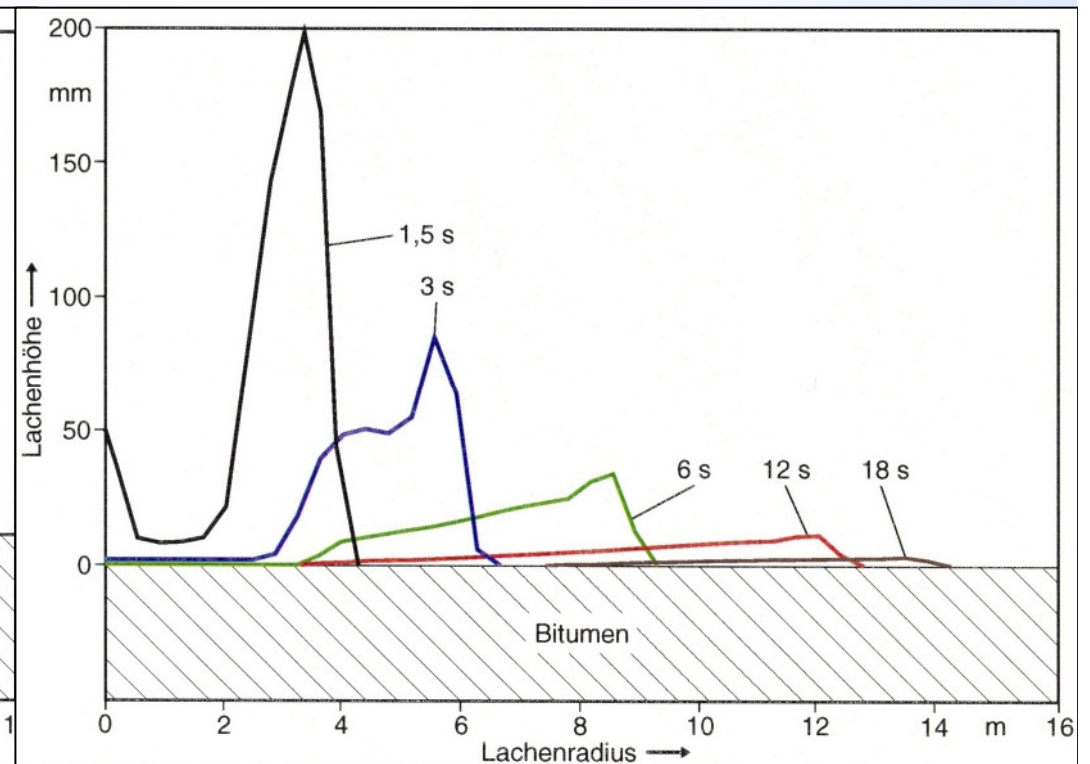


# Cryogenic Pool Behavior (4)

## Pool Profile

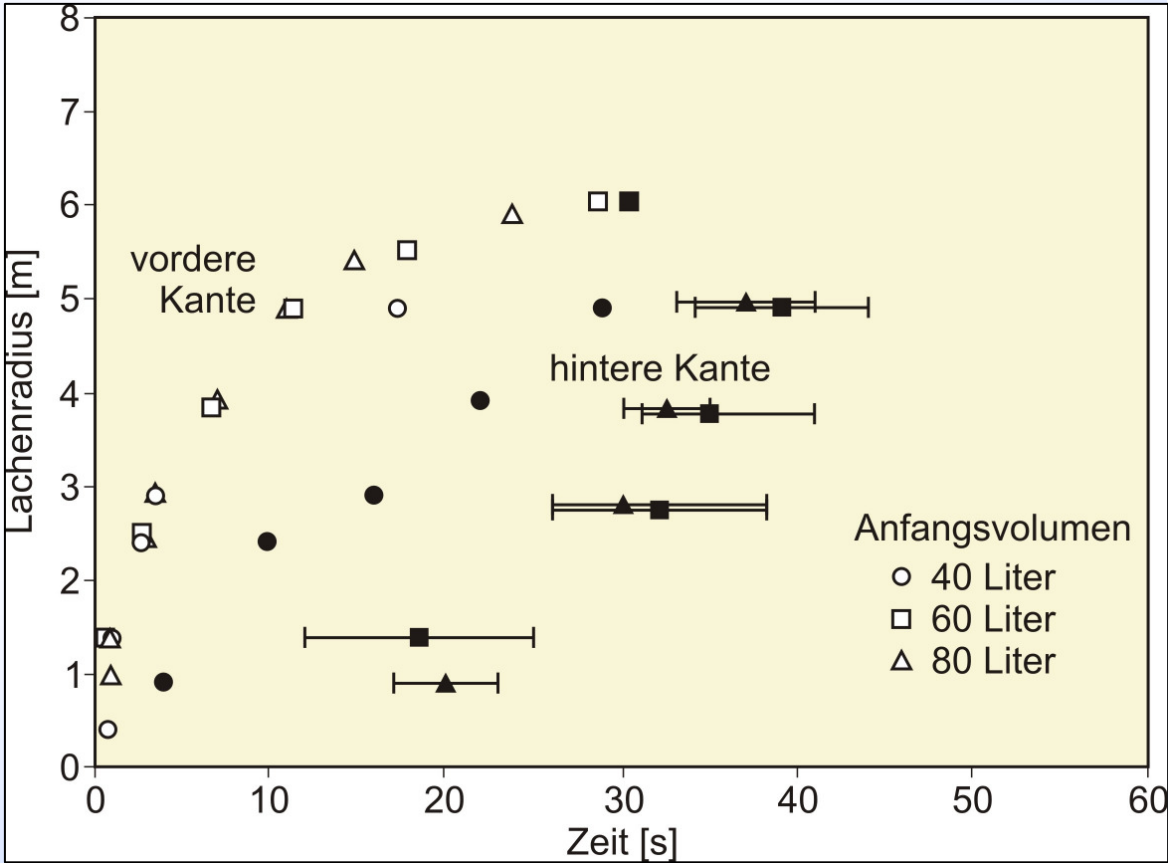


continuous release



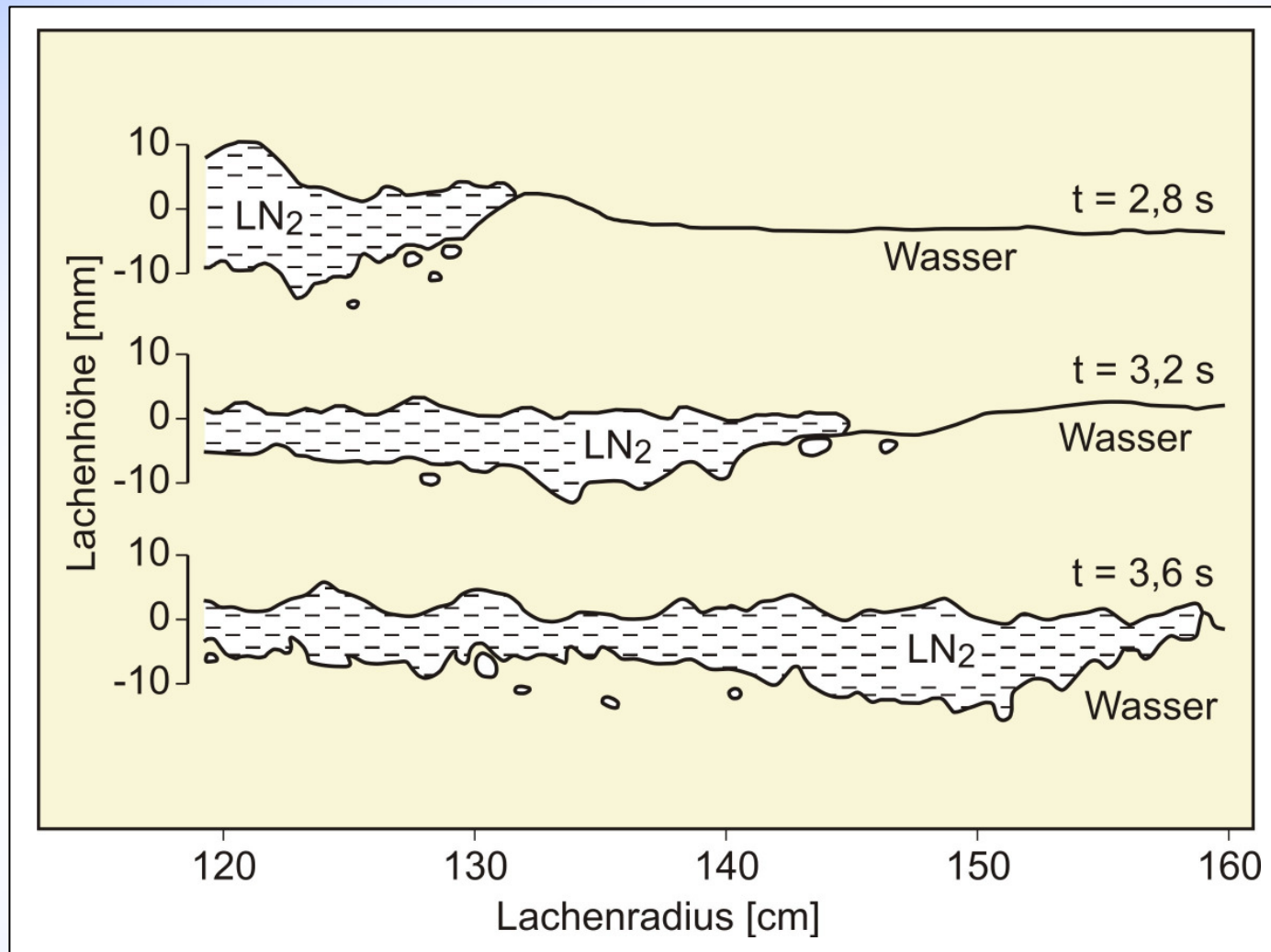
instantaneous release

# LN<sub>2</sub> Spill Tests on Water (KIWI) at FZJ

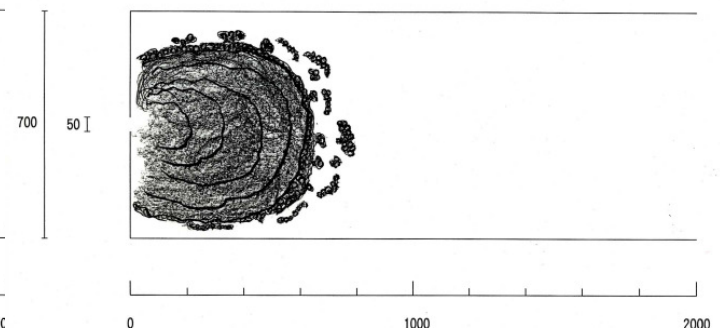
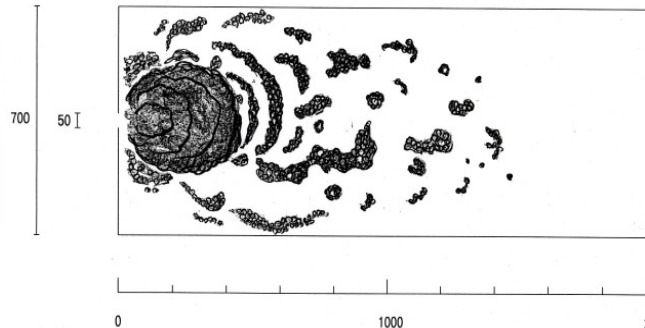
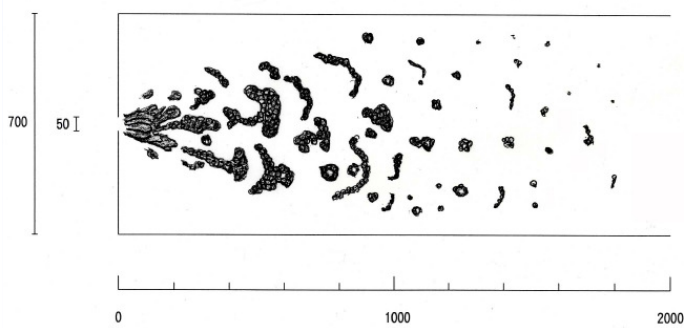
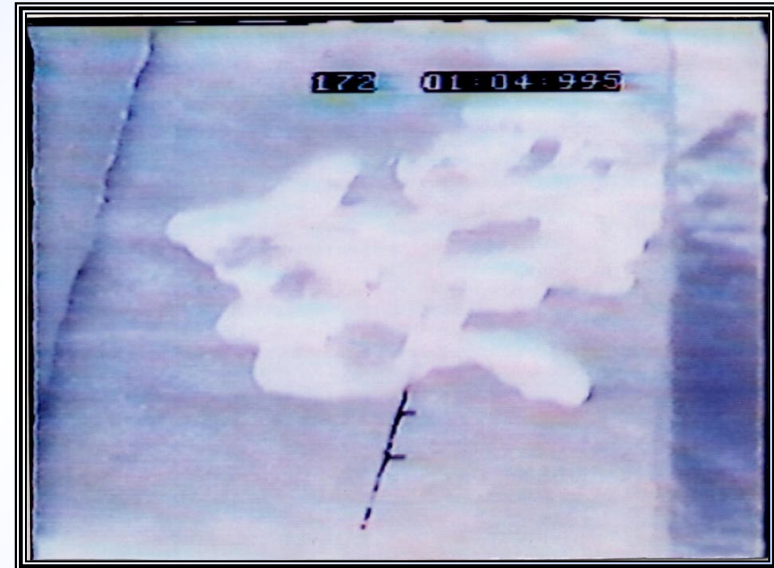
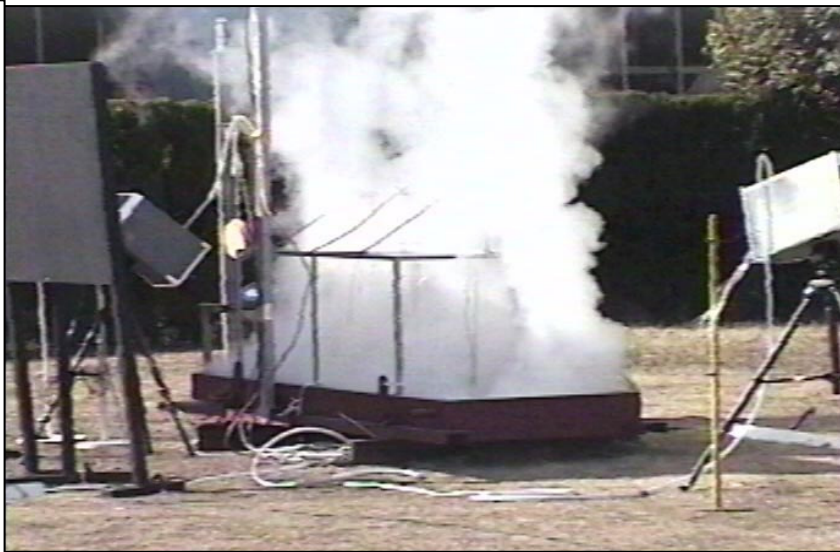




# LN<sub>2</sub> Pool Shape and Ice Formation

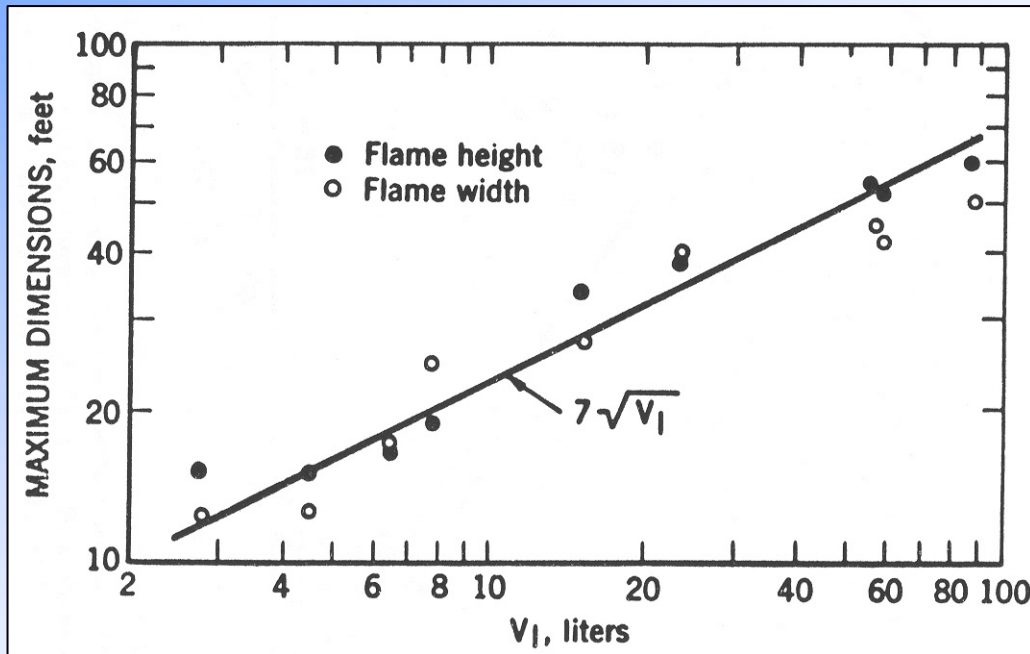


# WE-NET LH<sub>2</sub> Spill Tests (1993 + 2000)



Chitose 2002

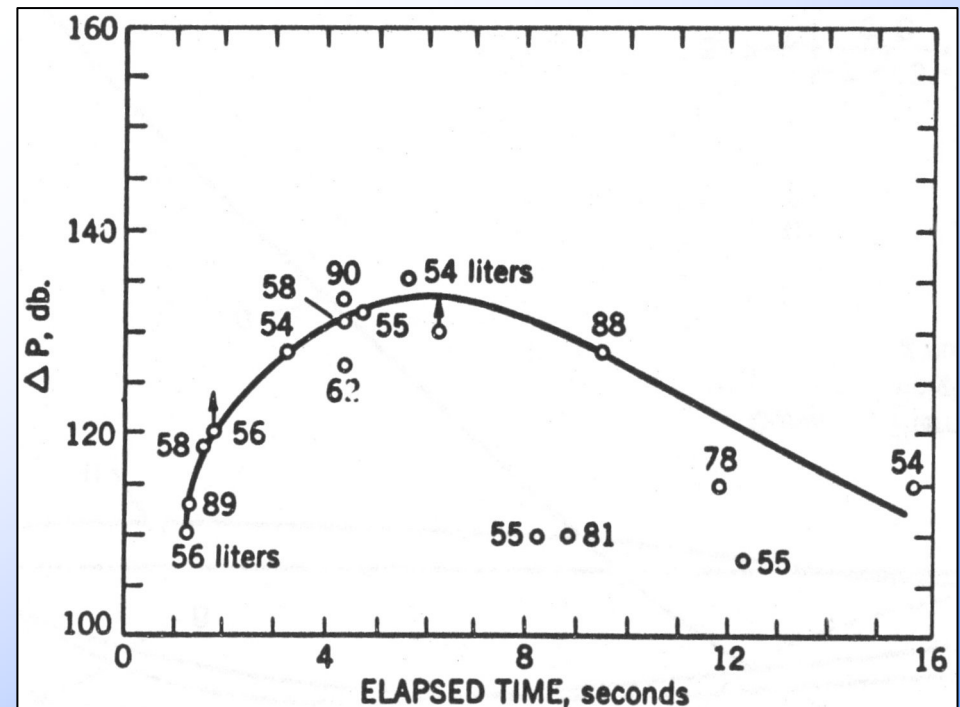
# Cryogenic Pool Burning



Flame geometry

Zabetakis 1960

Overpressure

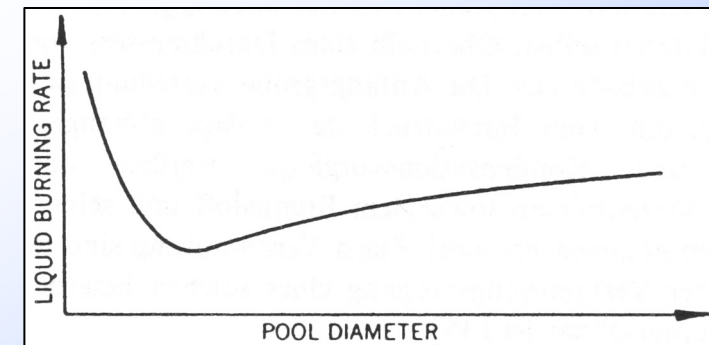
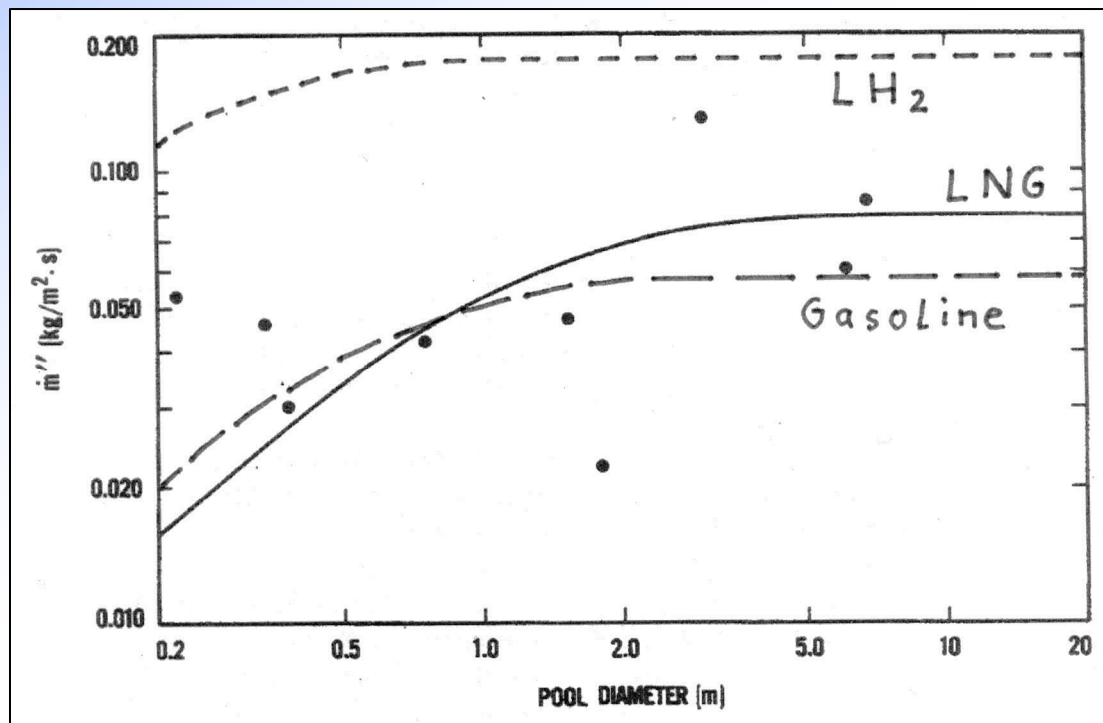


# Cryogenic Pool Burning

Regression depending on pool diameter:

$D < 0.2$  m: heat transport by conduction dominant

$D > 0.2$  m: heat transport by radiation dominant



Brabauskas 1983

## Computer Model LAUV

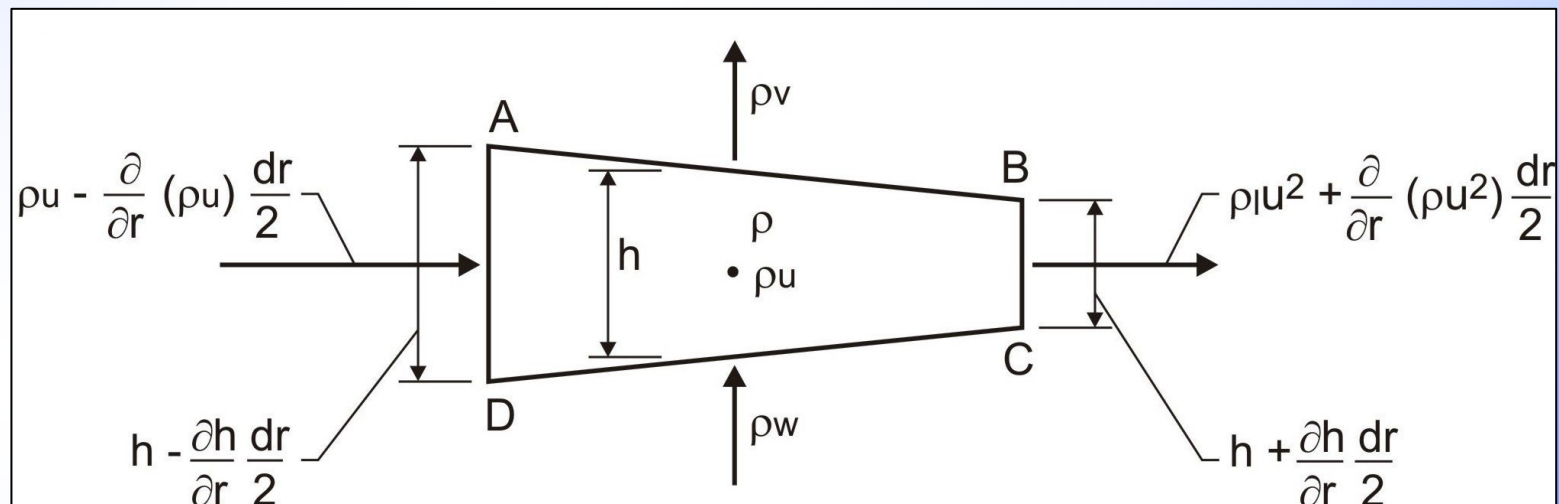
- Simulation of radial spreading of a cryogenic liquid on the basis of the **shallow-layer** differential equations;
- Instantaneous and continuous release on solid, humid, or liquid ground;
- Heat conduction equation applied, if ground is solid;
- Ice formation, if ground is water;
- Atmospheric convection and insolation neglected;
- **Validation** against LN<sub>2</sub> and LH<sub>2</sub> spill tests and LNG spill test data from literature.

# Shallow-Layer Equations

## 1. Conservation of mass

$$\frac{\partial(rh)}{\partial t} + \frac{\partial(urh)}{\partial r} + r(v - w) = 0$$

$v$  – vaporization rate,  $w$  – source rate, m/s

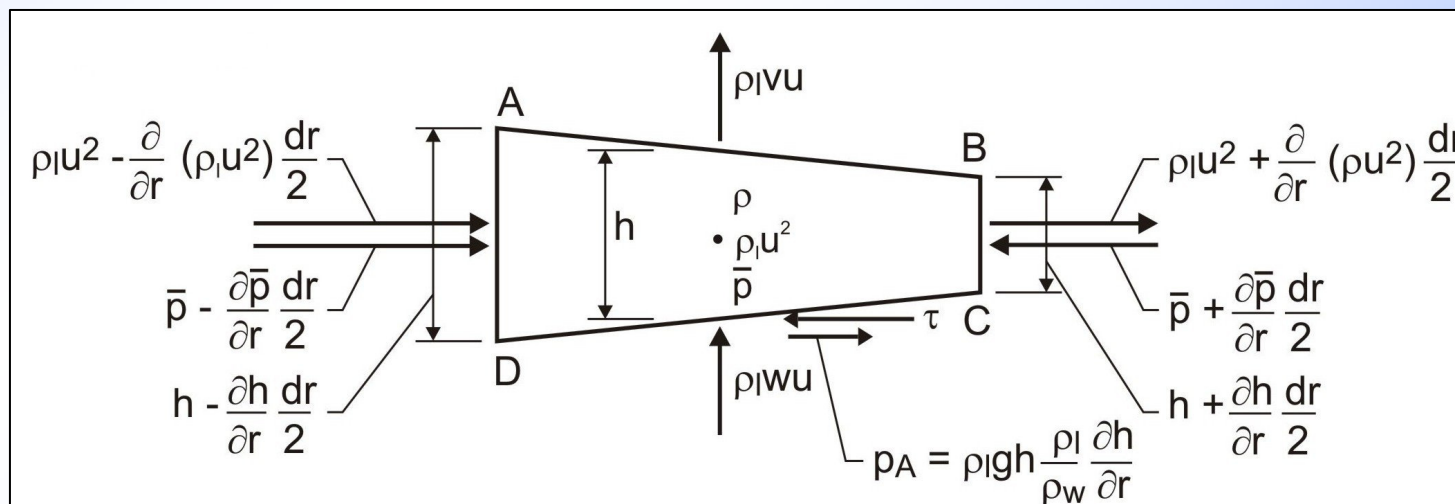


# Shallow-Layer Equations

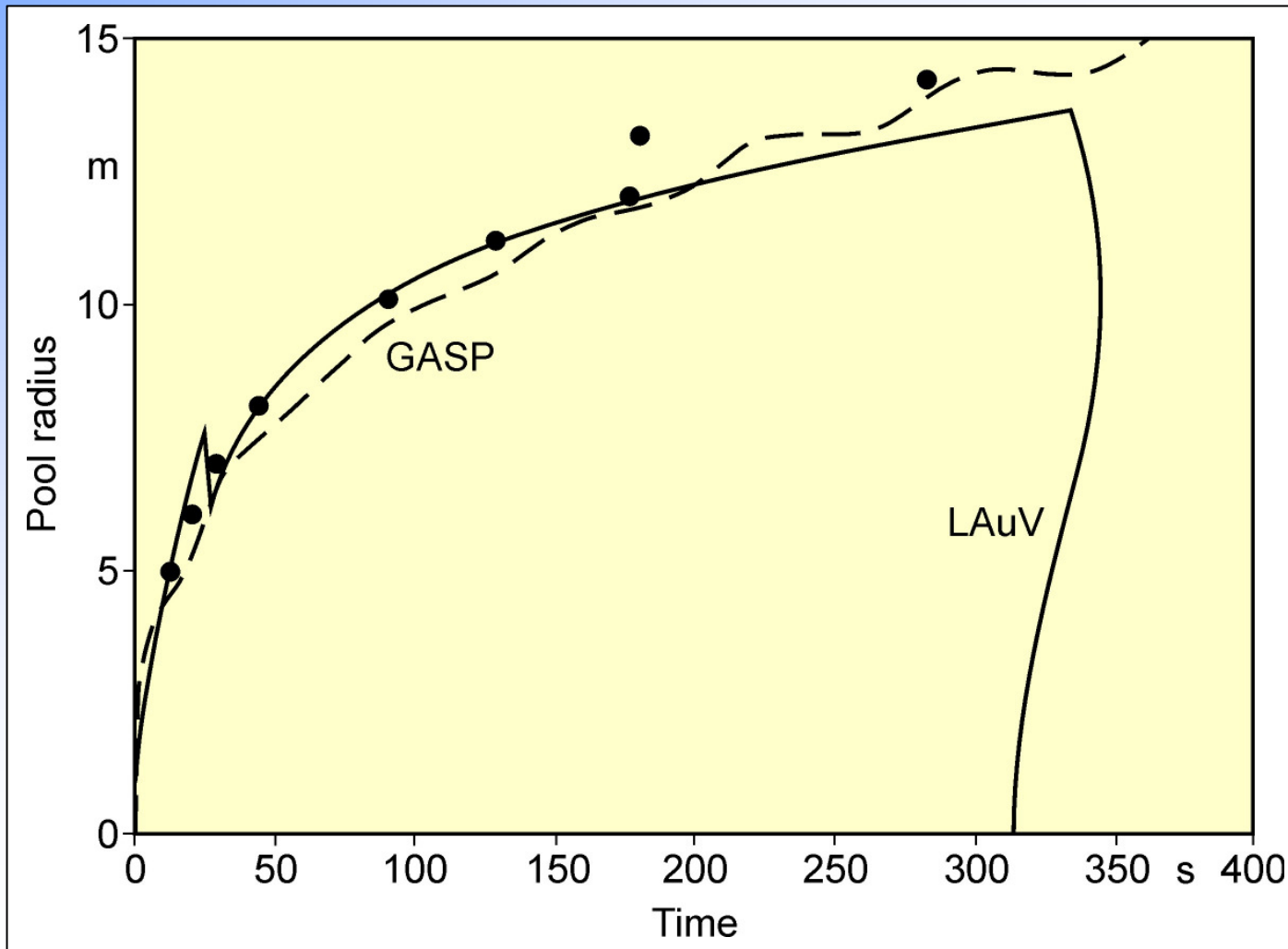
## 2. Conservation of momentum

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial r} \left( \frac{u^2}{2} + \delta g h \right) + \frac{F}{h} = 0$$

$\delta$  – reduction factor,  $F$  – friction force



# LAUV Postcalculation of LNG Spill

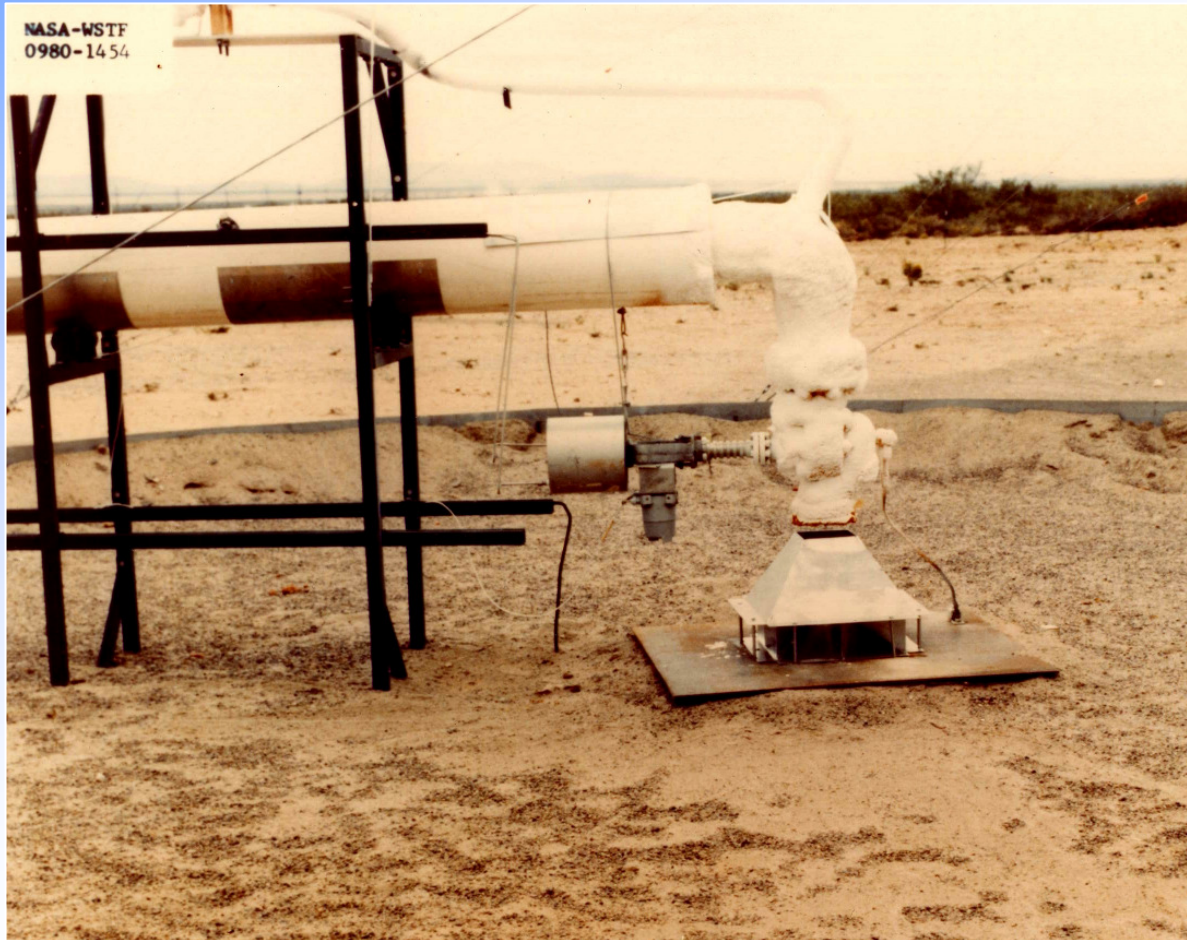


**2.5 m<sup>3</sup> of LNG  
in 300 s  
at varying rate**

**dry concrete**



## NASA LH<sub>2</sub> Spill Tests (1980)

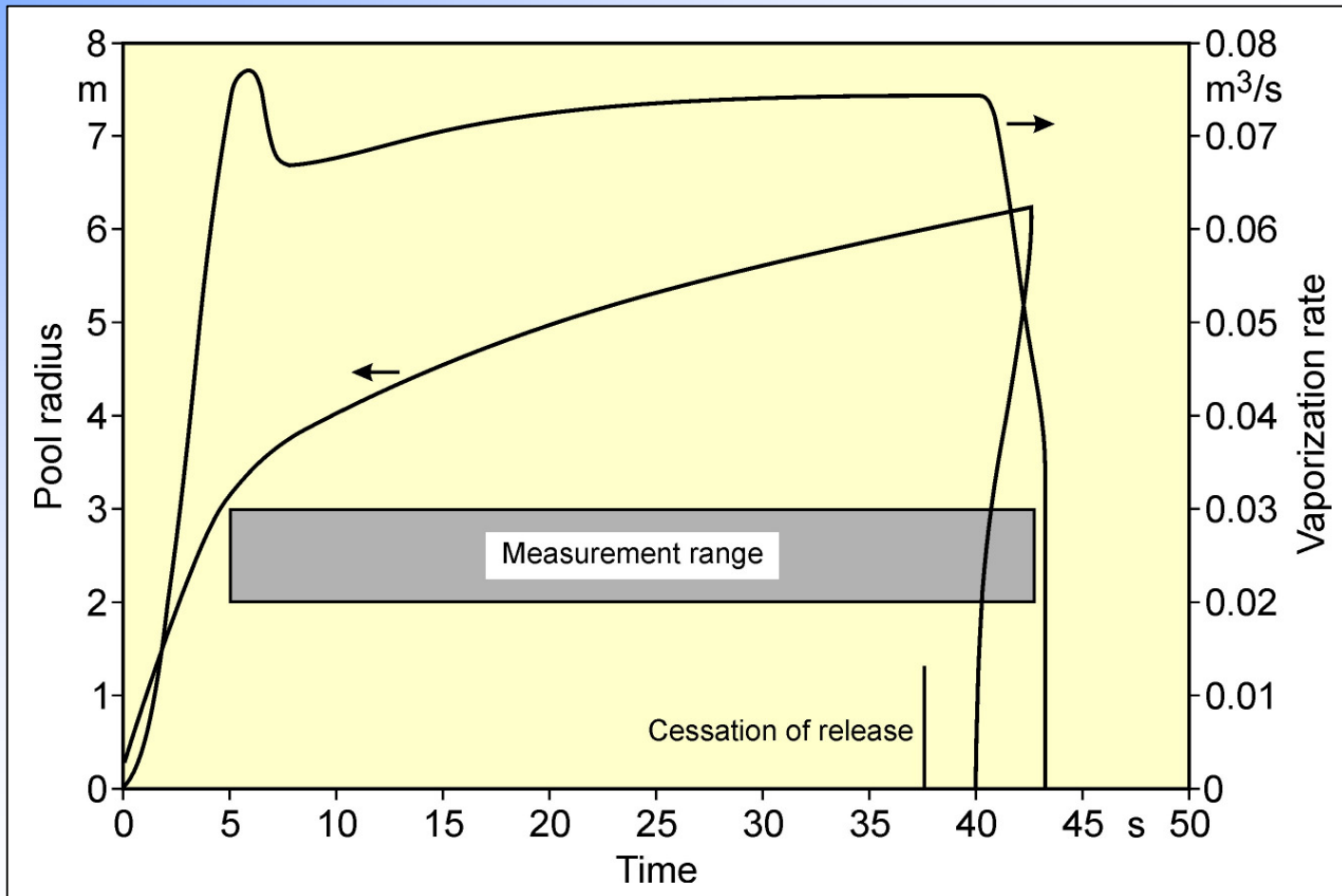


9.2 m dia spill pond

NASA  
Aeronautics and  
Administration  
LANGLEY  
RESEARCH CENTER

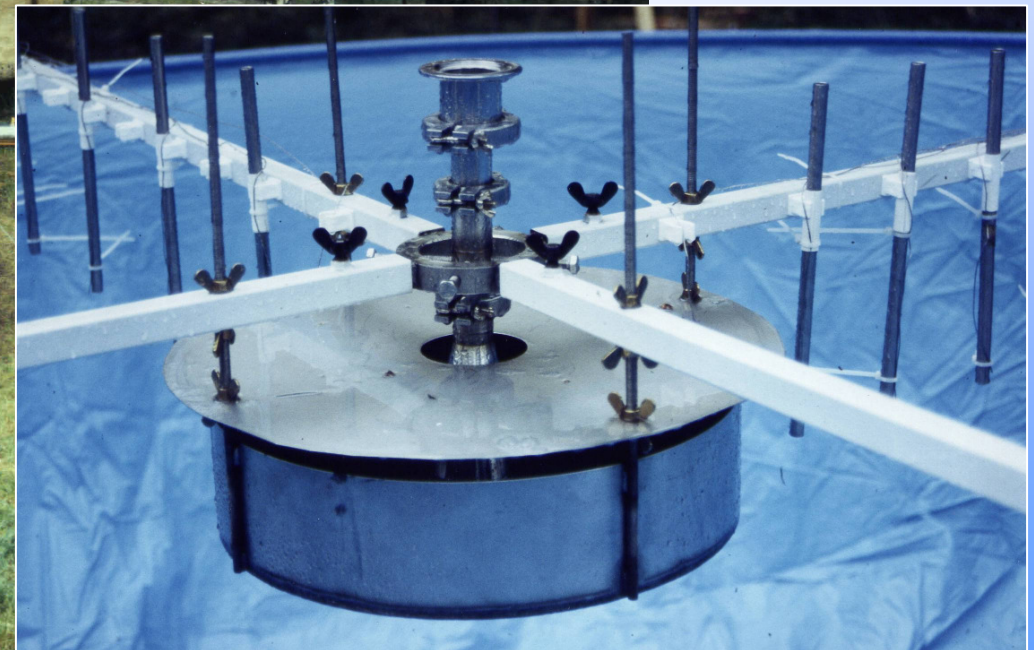
Courtesy Jose Chirivella, Ergo-Tech Systems Inc.

# LAUV Postcalculation of NASA Test #6

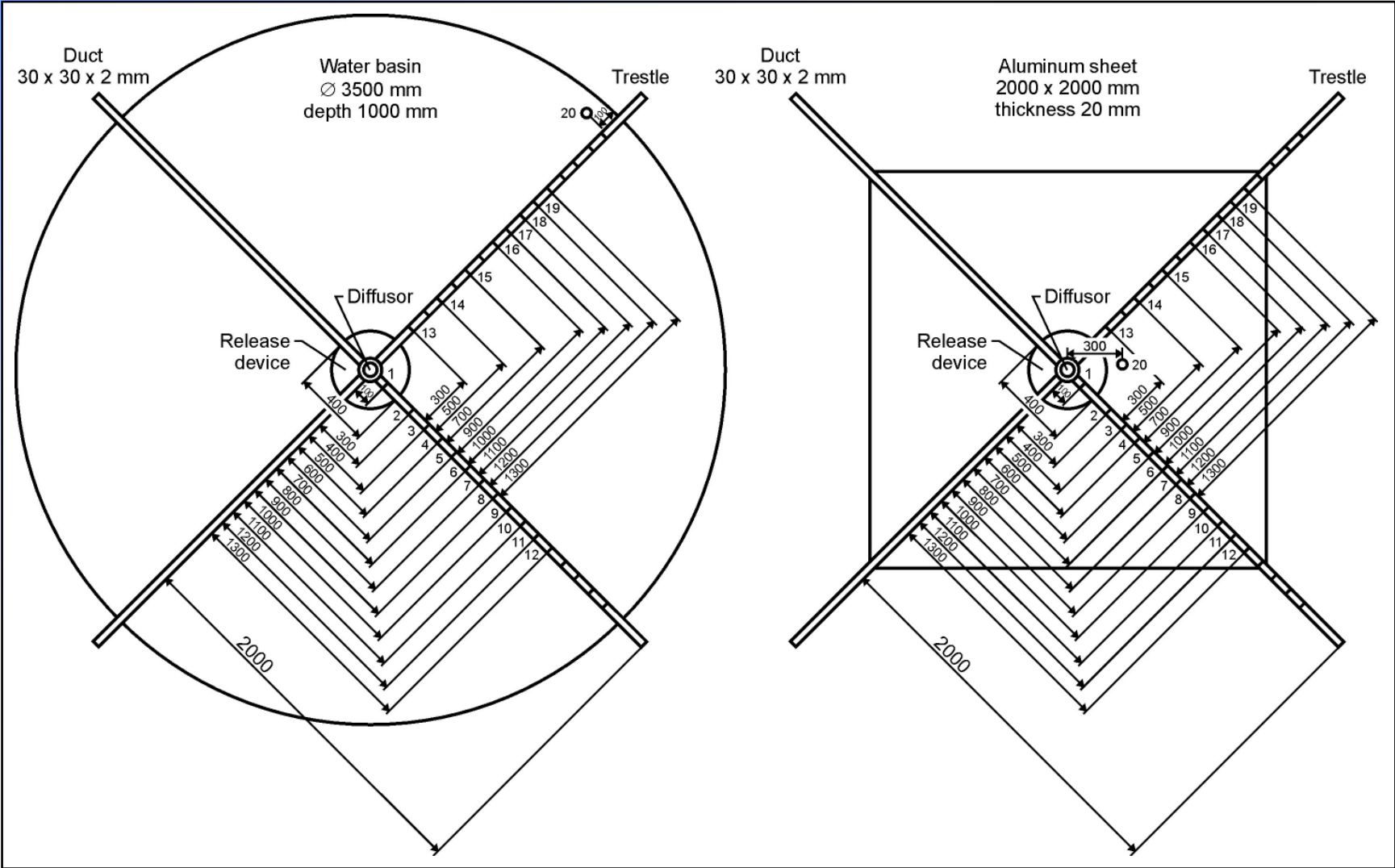


**5.1 m<sup>3</sup> of LH<sub>2</sub>  
in 38 s  
compact sand**

# BAM LH<sub>2</sub> Spill Tests in Cottbus (1994)



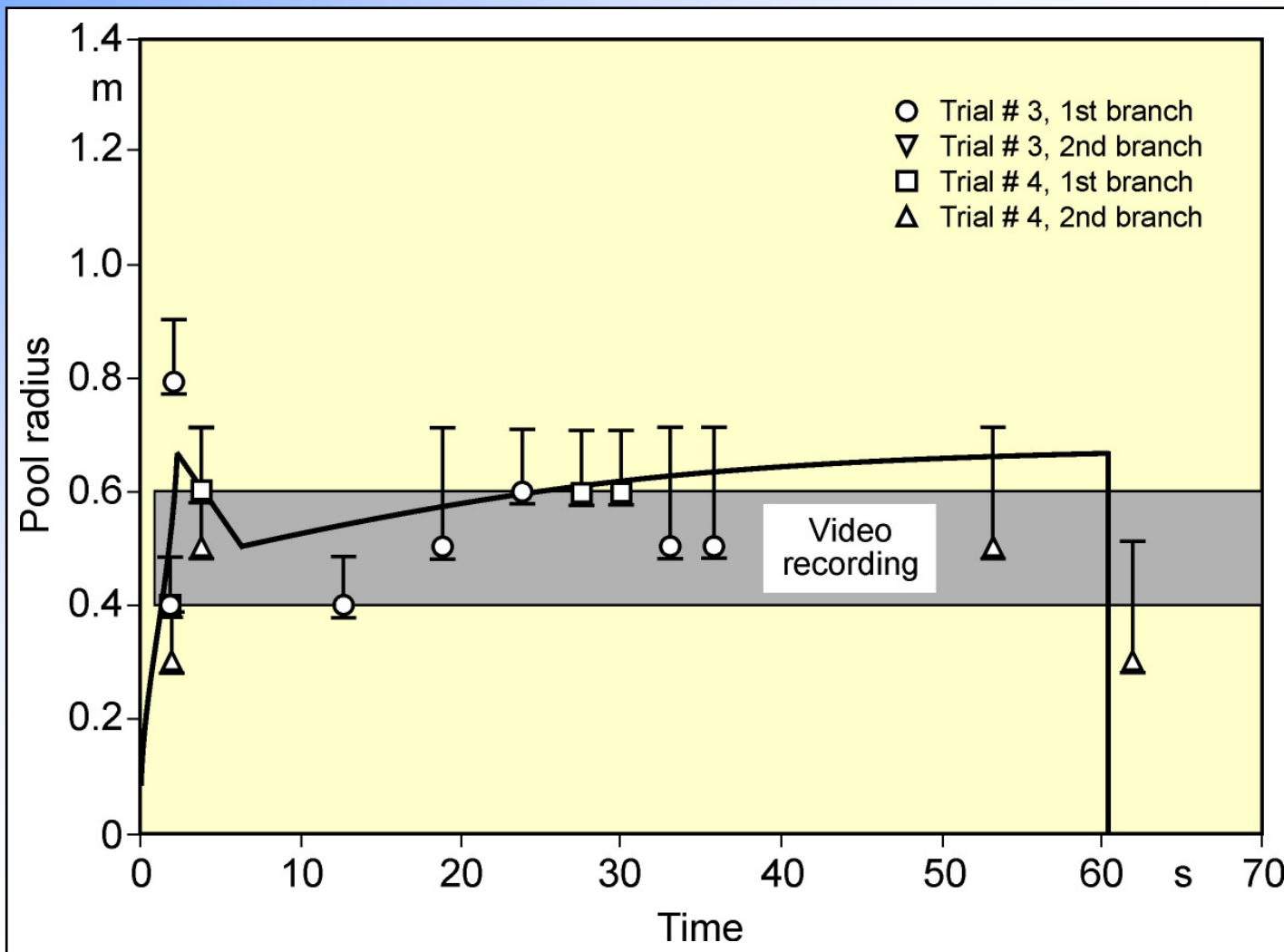
# LH<sub>2</sub> Spill Test Arrangement



# LH<sub>2</sub> Spill Test on Water

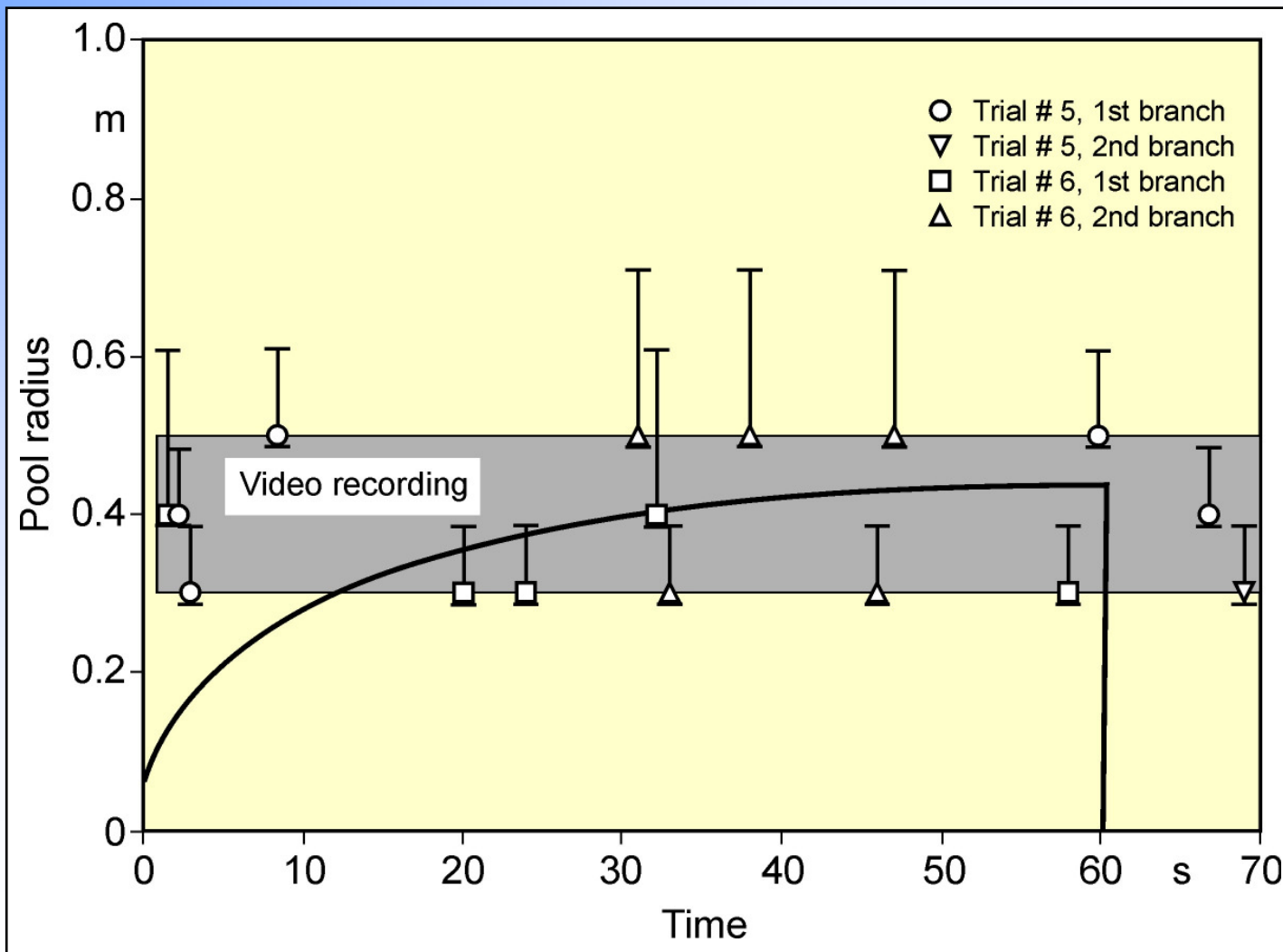


# LAUV Postcalculation – LH<sub>2</sub> Spill on Water



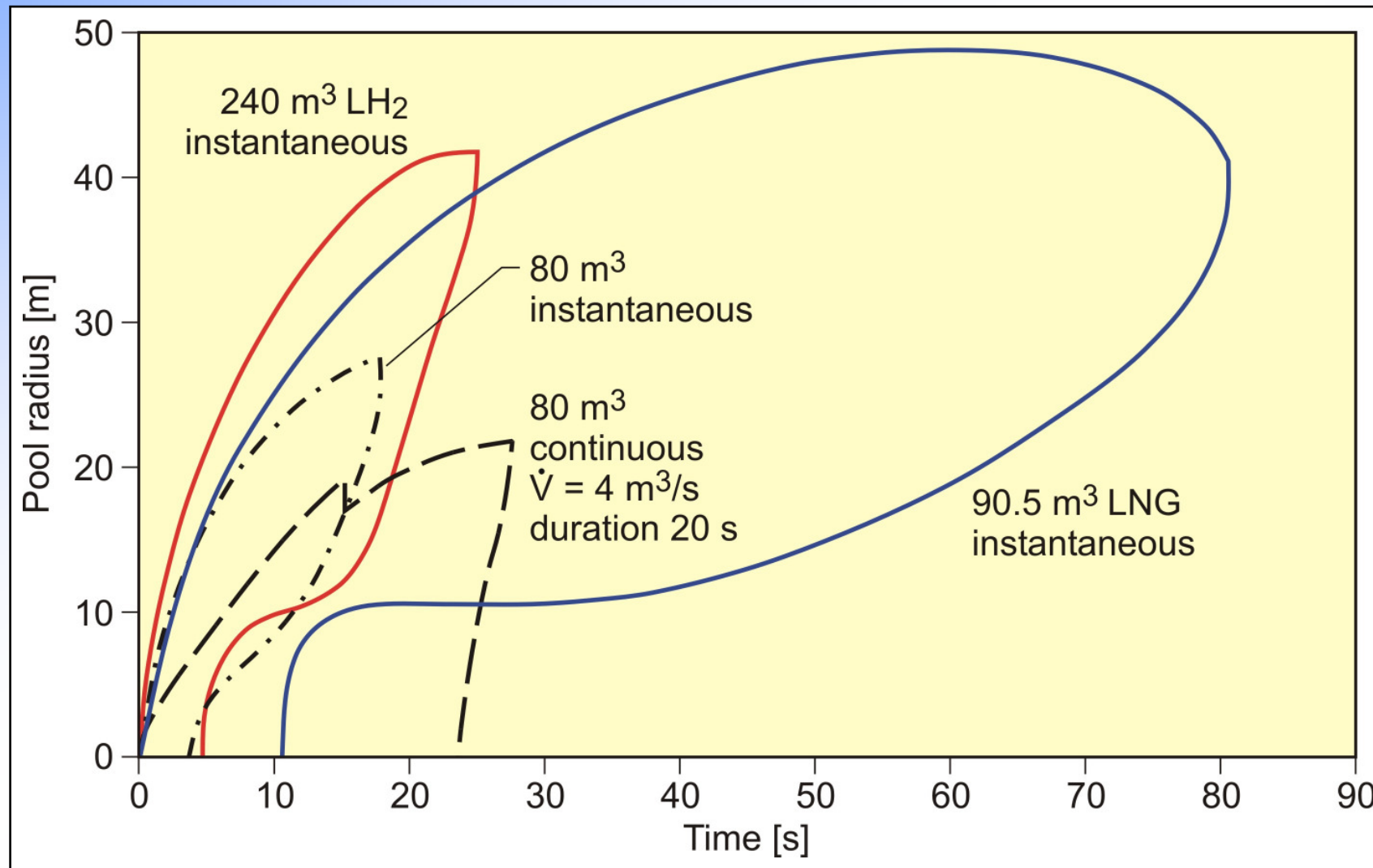
**5 l of LH<sub>2</sub>  
in 62 s**

# LAUV Postcalculation – LH<sub>2</sub> Spill on Al Plate



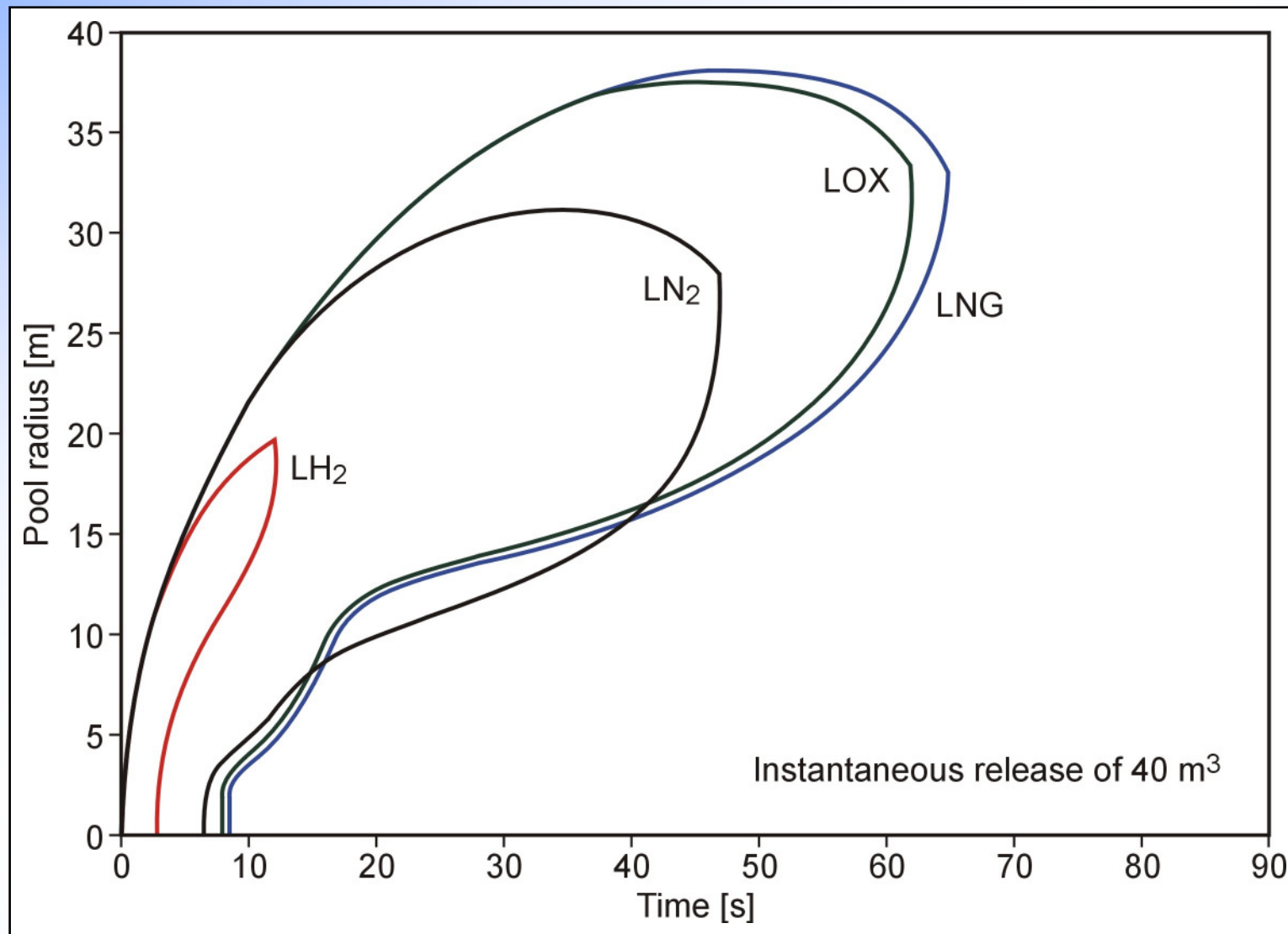
**6 l of LH<sub>2</sub>  
in 62 s**

# Prediction LH<sub>2</sub> Release from CRYOPLANE Tank

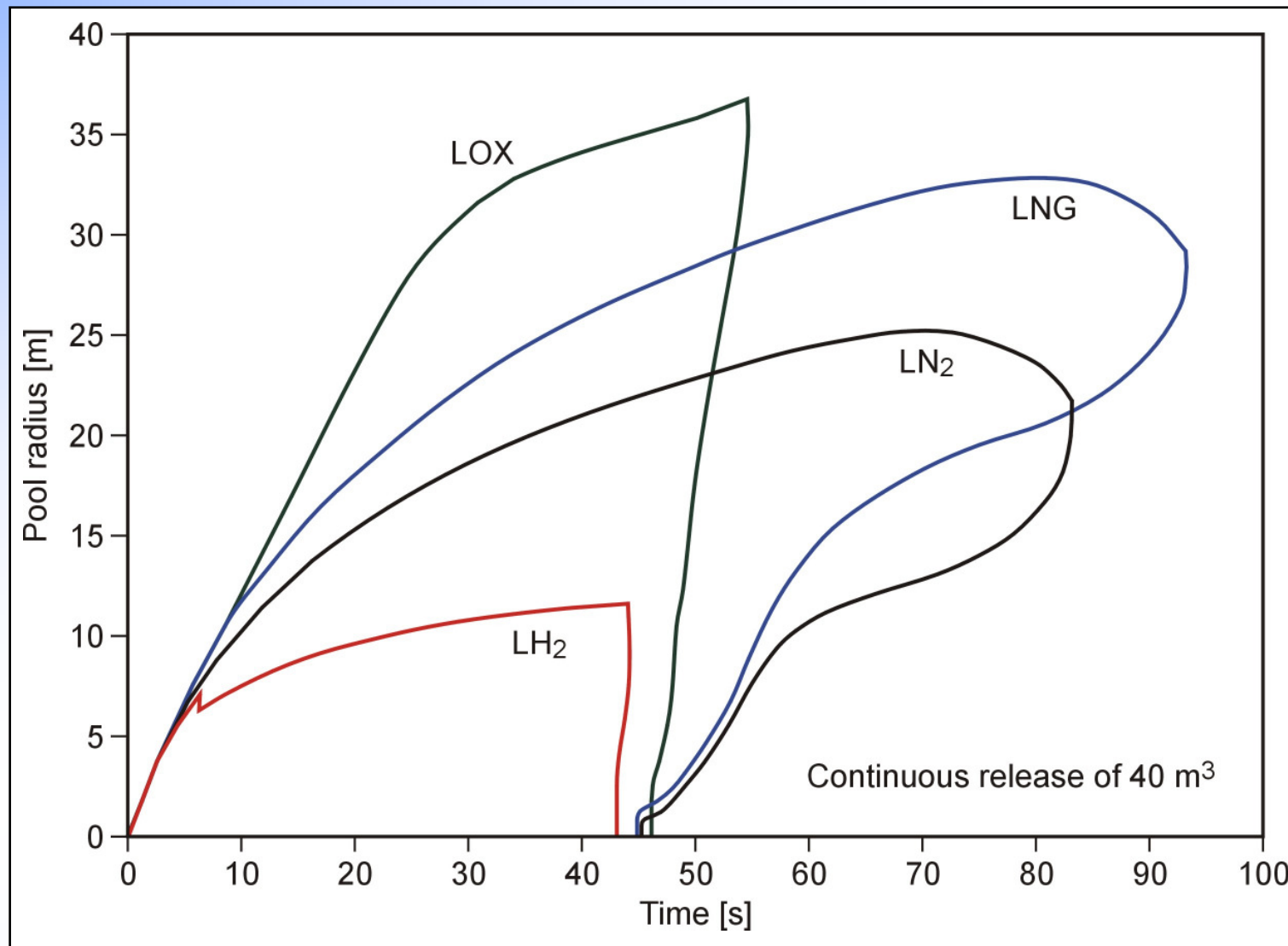




# Comparison of Different Cryogenics (1)



## Comparison of Different Cryogenics (2)



## Conclusions

- **Phenomena** of cryogen pool spreading and vaporization are principally understood.
- **Modeling** efforts have led to simplified, but appropriate simulation of phenomena.
- **Experimental data** basis for LH<sub>2</sub> is still very poor and needs further extension.

**Thank you  
for your kind attention !**

**email: [k.verfondern@fz-juelich.de](mailto:k.verfondern@fz-juelich.de)**