COMBEX-2013

# Explosion hazards of rocket launch failure

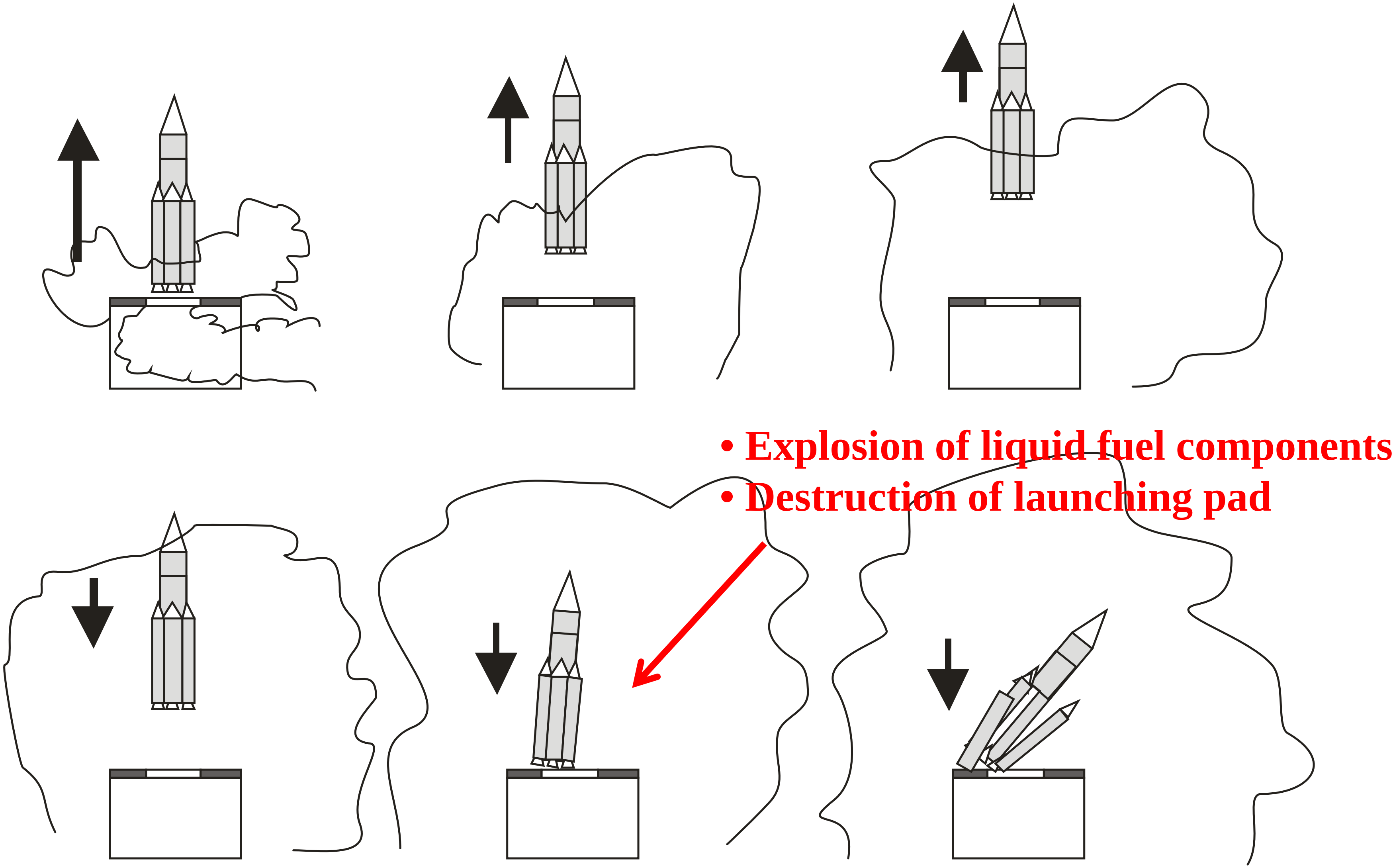
**Borisov A.A., Frolov S.M., Shamshin I.O.**

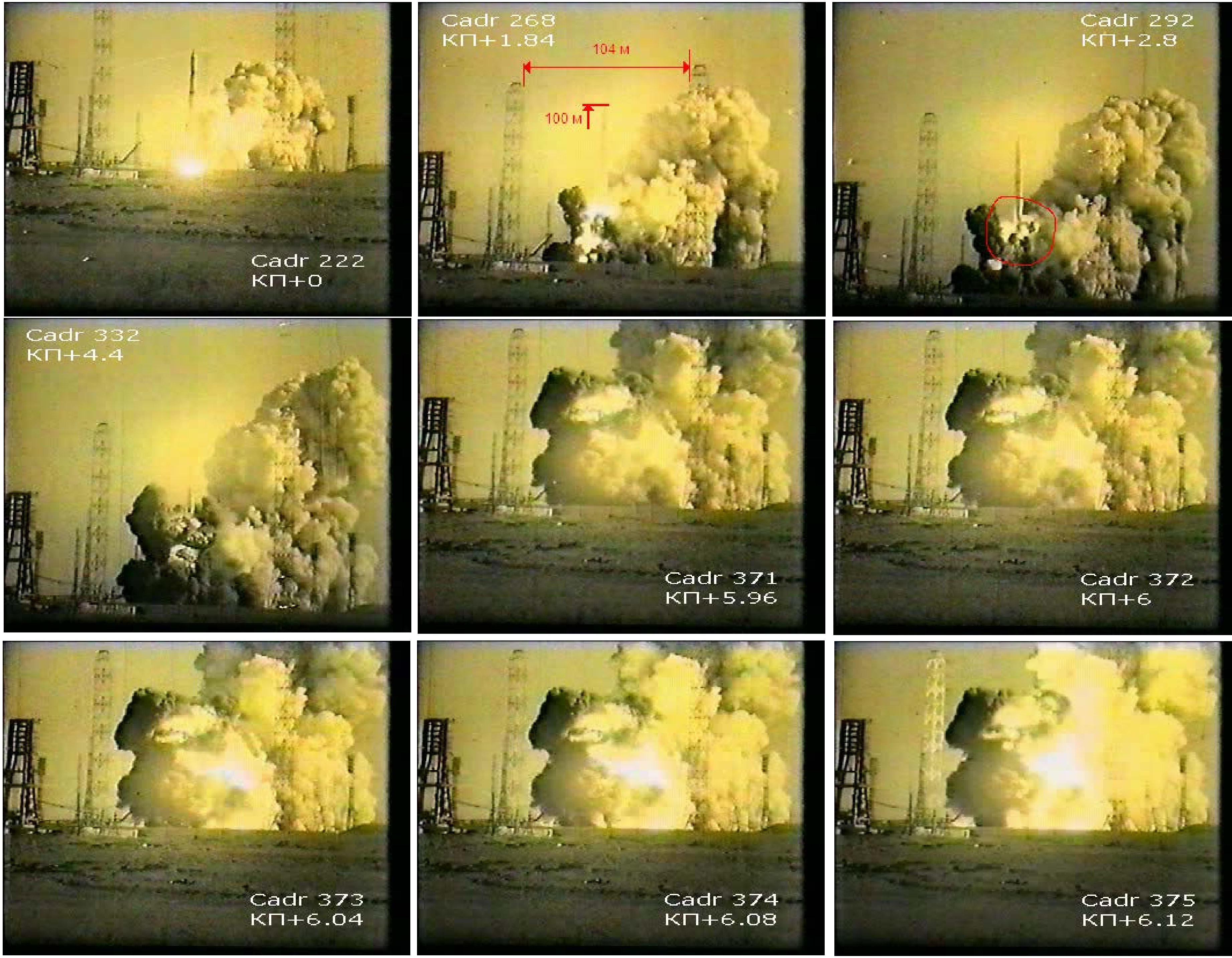
**Semenov Institute of Chemical Physics**

**Moscow, Russia**

# Contents

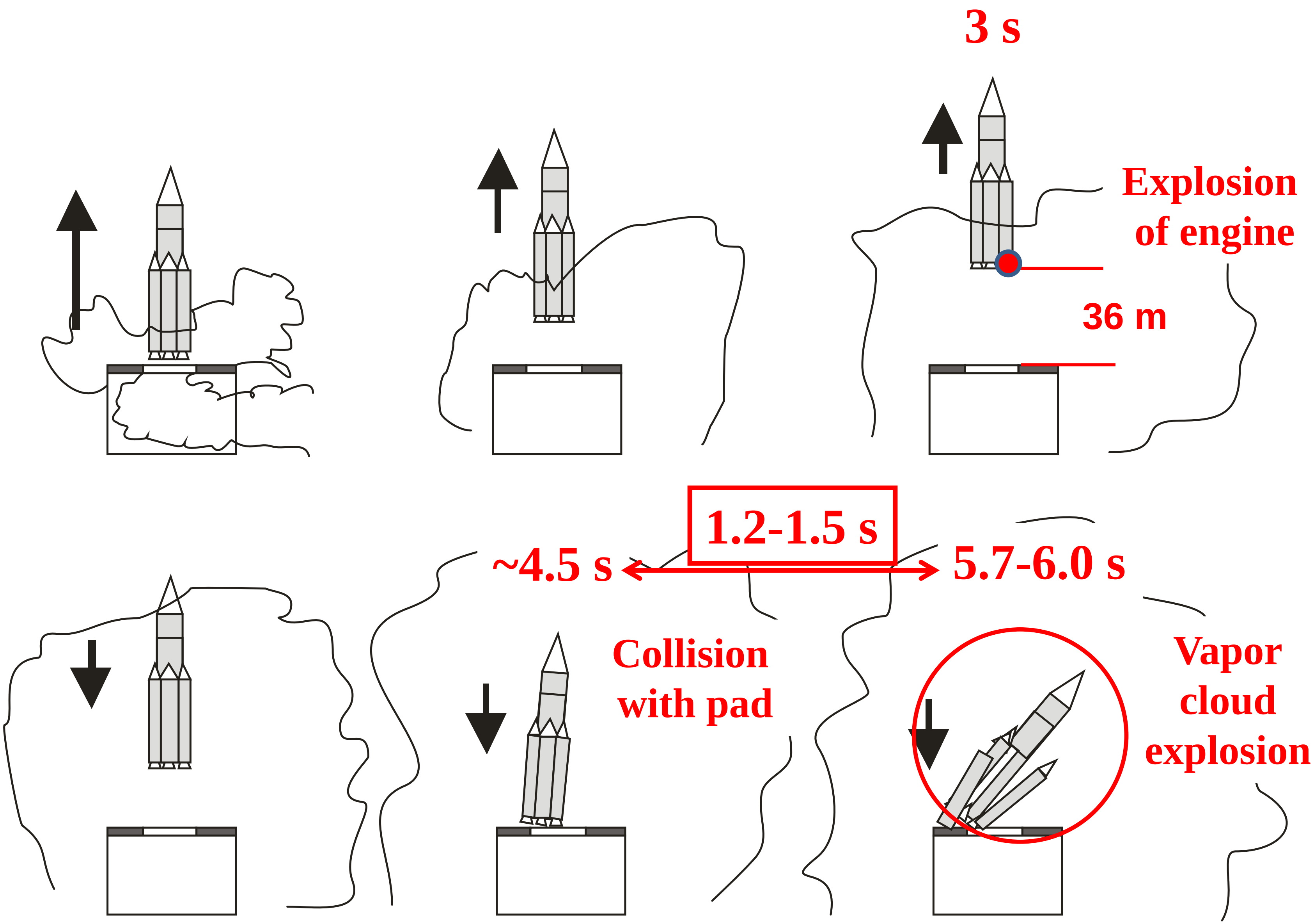
# Most hazardous scenario of rocket launch accident



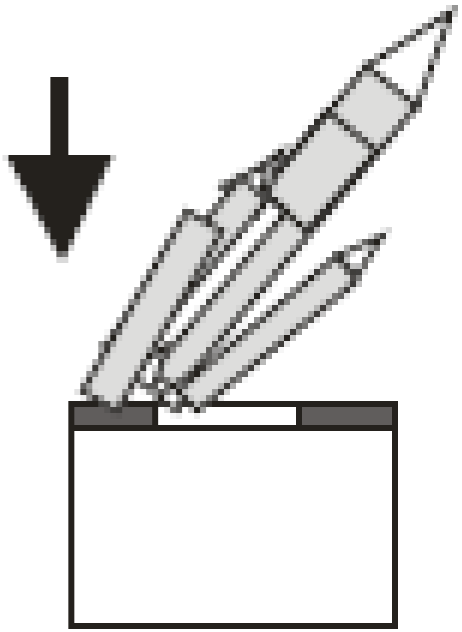


Cadr 222
КП+0
Cadr 268
КП+1.84
104 м
100 м
Cadr 292
КП+2.8
Cadr 332
КП+4.4
Cadr 371
КП+5.96
Cadr 372
КП+6
Cadr 373
КП+6.04
Cadr 374
КП+6.08
Cadr 375
КП+6.12

# Characteristic length and time scales

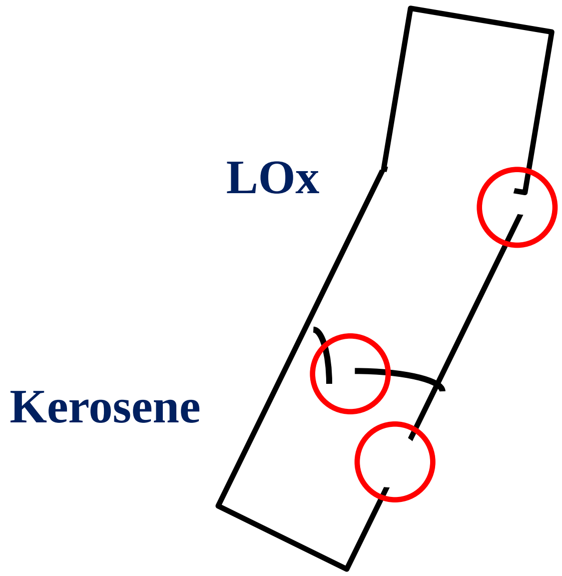


# Phenomenology-I



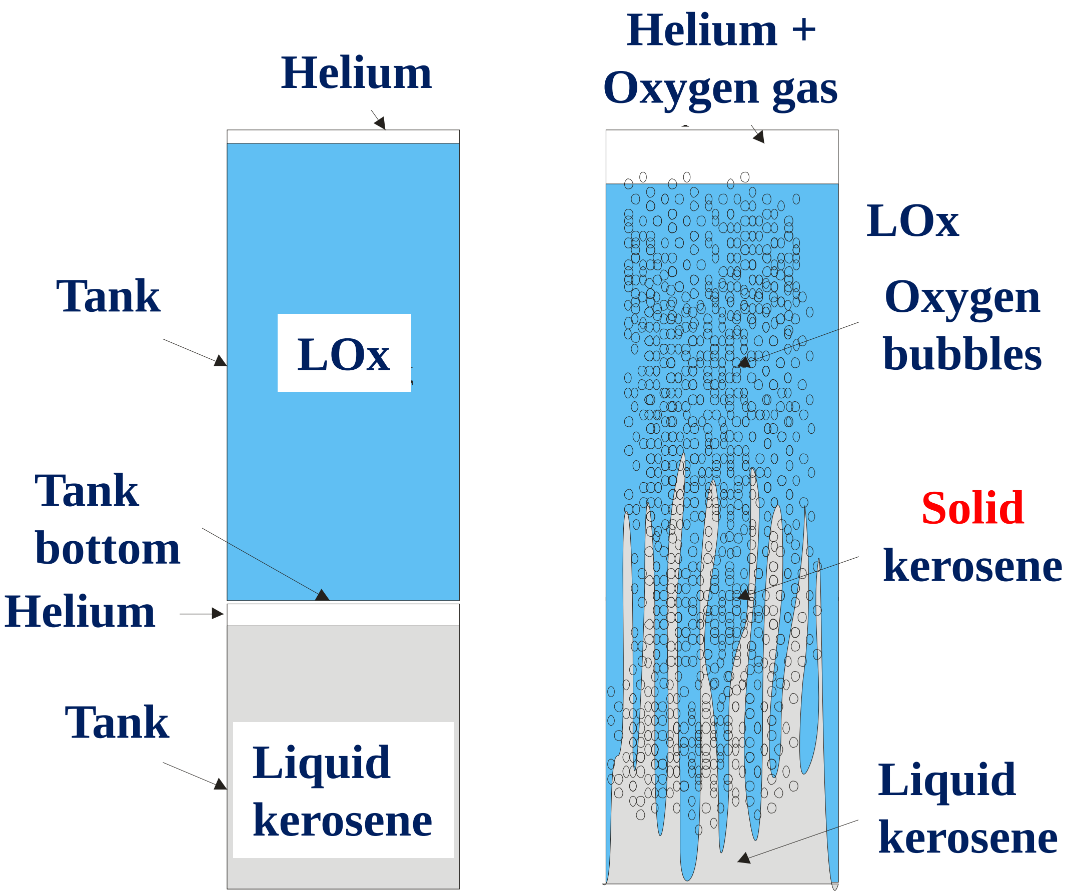
- **Collision with launching pad results in mechanical destructions of fuel and oxidizer tanks**

# Phenomenology-II




- **Both** **internal (between tanks) and external openings and cracks form**

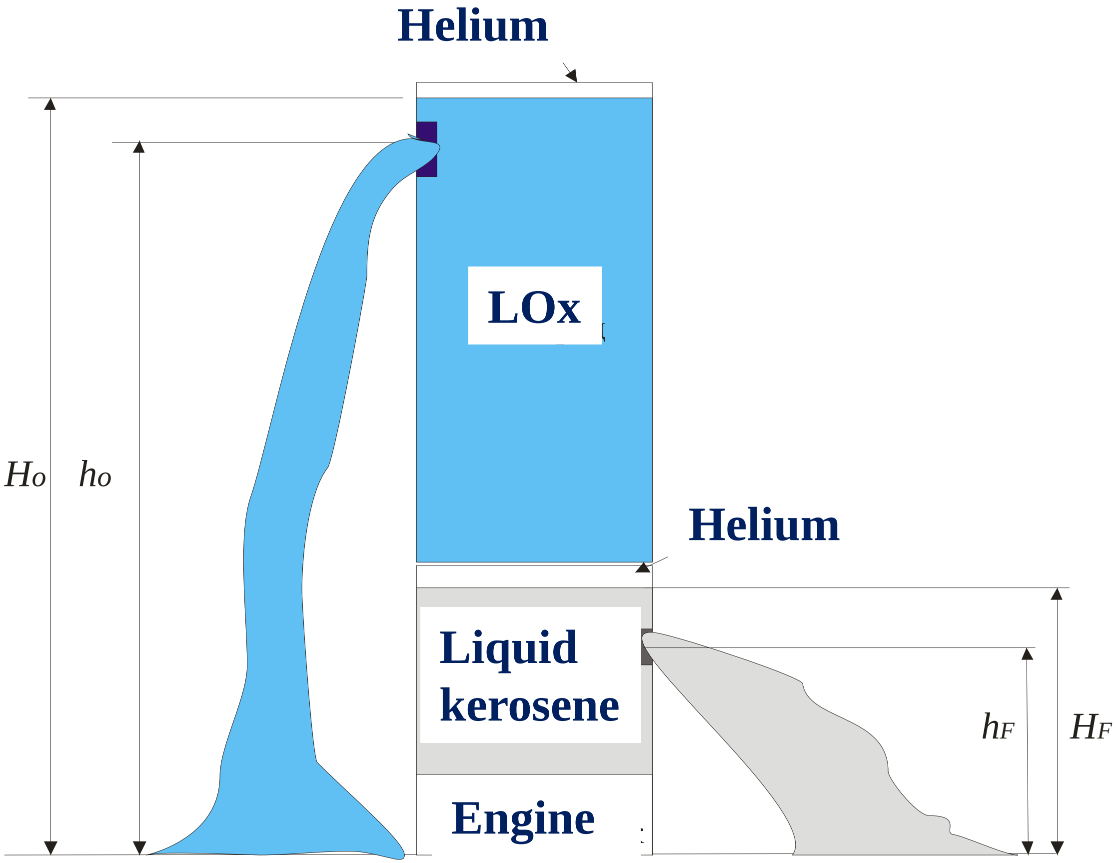
# Phenomenology-III

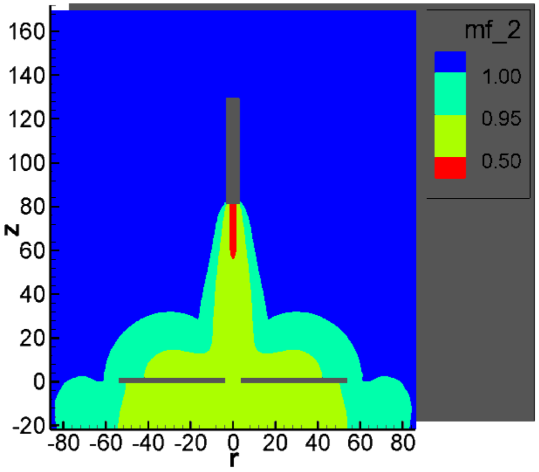



Oxyliquid

- Internal openings and cracks result in penetration of LOx into liquid kerosene with OXYLIQUID formation LOx boiling, fast vaporization and pressure buildup in fuel tanks

# Phenomenology-IV

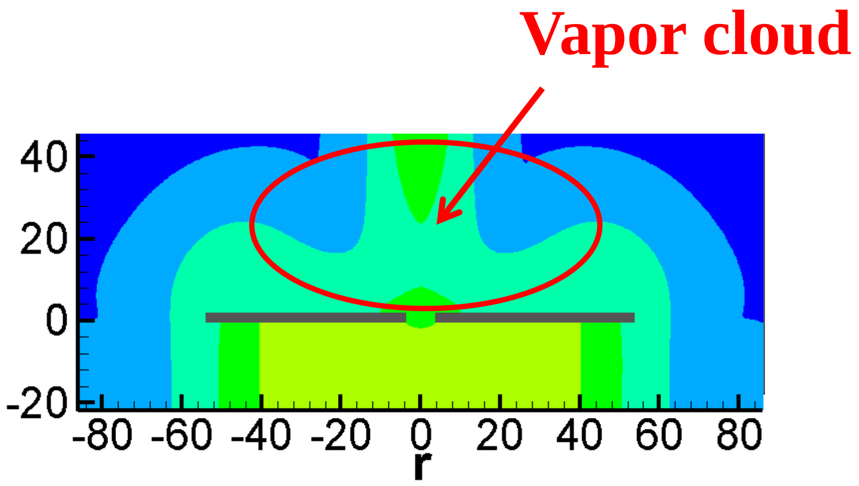



Thermik

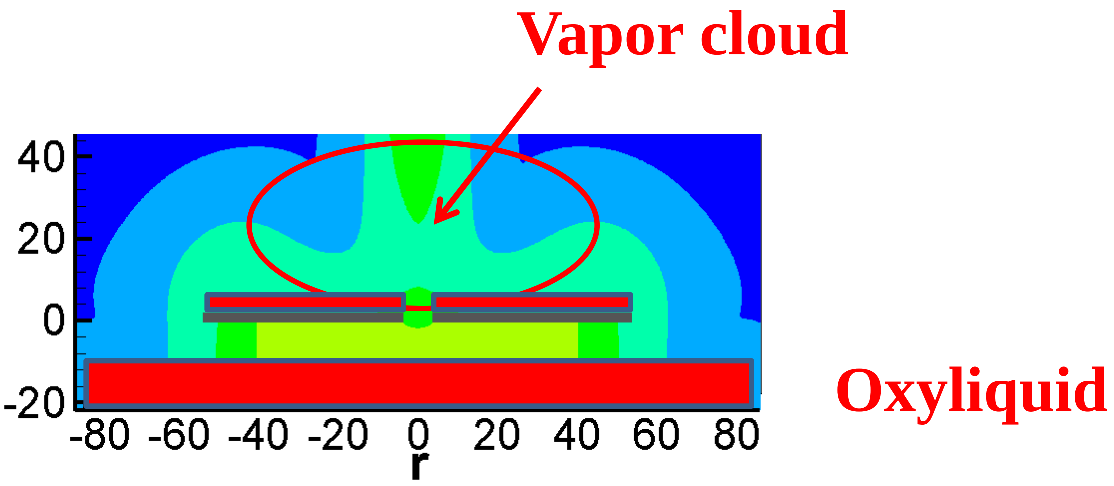
- **External openings result in spraying of fuel components in the ambience – large-scale turbulent thermik of engine combustion products**

# Phenomenology-V




- **Contact of LOx and kerosene with hot combustion products results in their vaporization and formation of vapor cloud**

# Phenomenology-VI




• Spillage of fuel components results in the formation of pool, further gasification of LOx, cooling of surfaces and thermik gases, formation of oxyliquid on the launching pad and in gas channel

# Two-stage scenario of explosion

**Stage 1: Detonation of a certain volume of oxyliquid**

**Stage 2: Detonation of vapor cloud**

**Spillage of fuel components does not contribute much to homogeneous and/or heterogeneous mixture formation and its effect on explosion energy can be neglected**

# Main hazards

- Blast wave(s)
- Fragments
- Fire
- Pollution

# Blast wave

## Two main issues:

Key issue

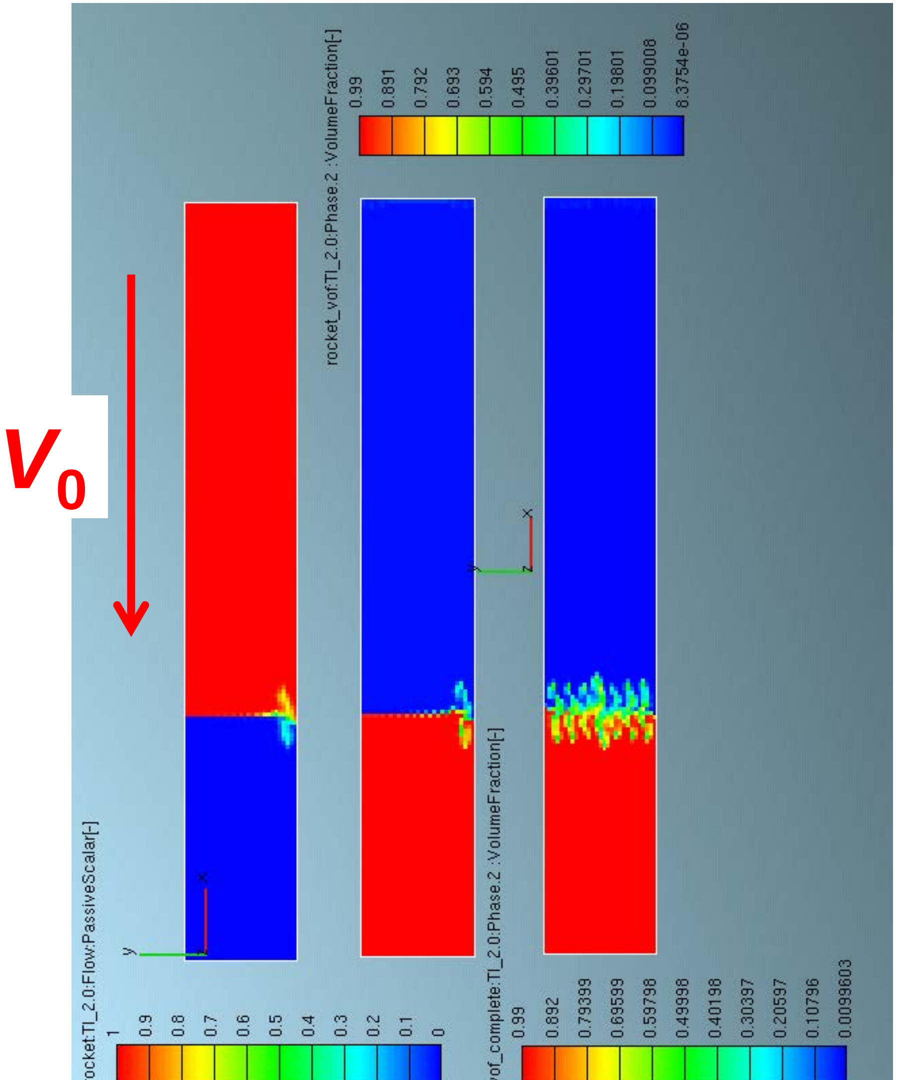
(1) Estimate the amount of fuel components involved in the explosion

(2) Determine the parameters of the blast wave propagating in the surroundings

# Amount of fuel components involved in the explosion

- Mass and composition of oxyliquid formed during delay time between collision and explosion
- Dimensions and structure of the turbulent thermik of hot combustion products formed over the launching pad
- Dimensions and composition of vapor cloud formed during delay time

# Mass and composition of oxyliquid



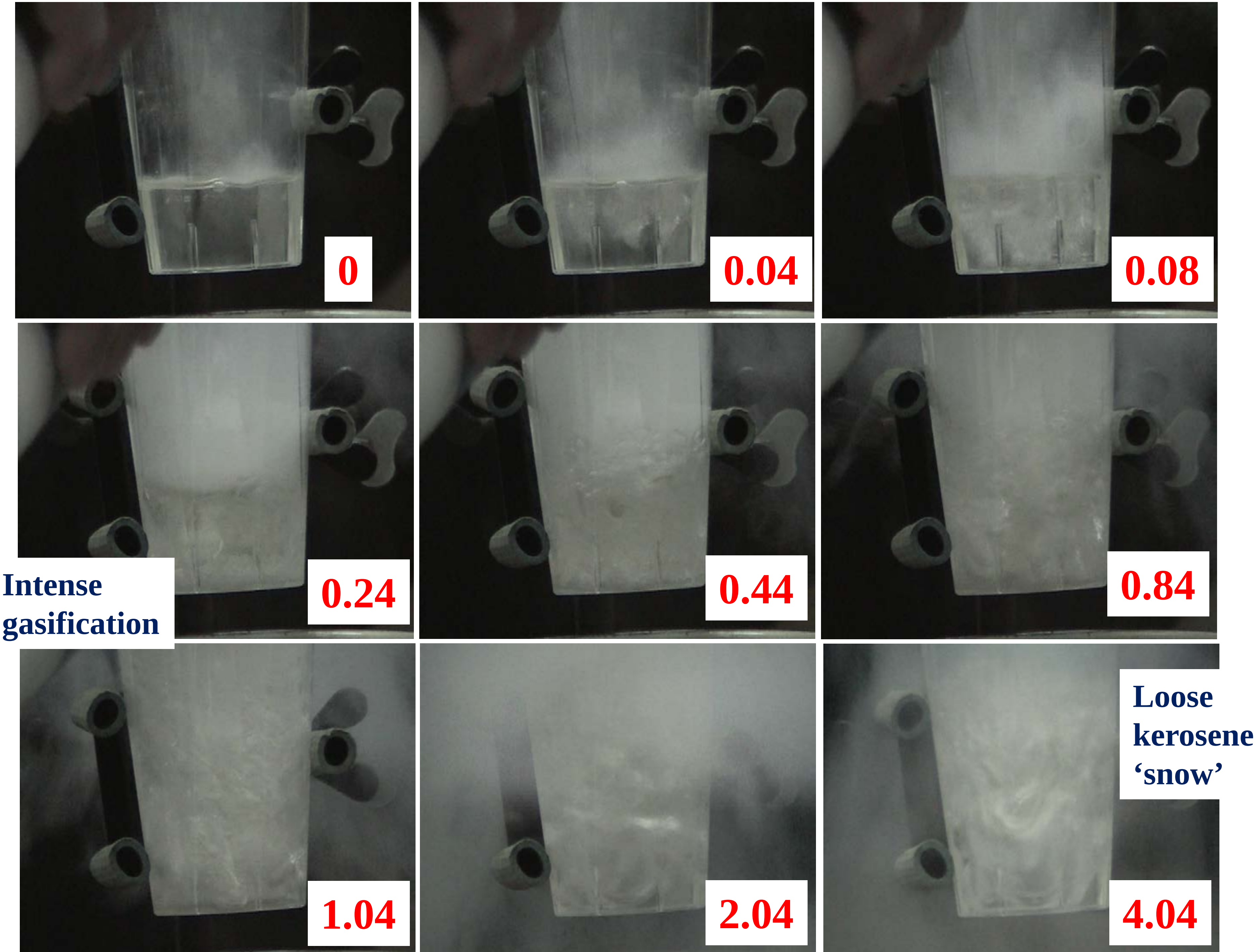

**Delay time**
**between collision and explosion**

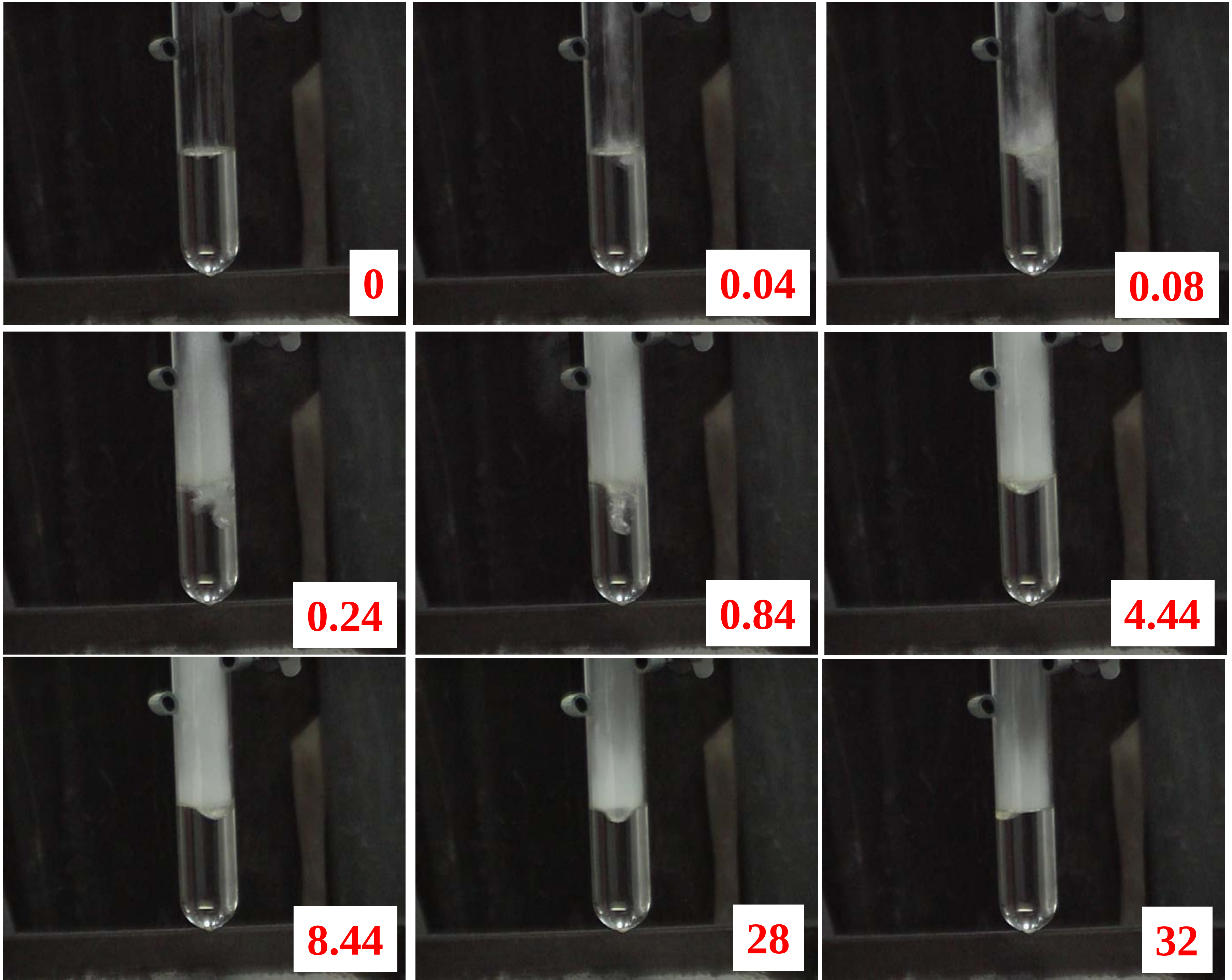
$$\tau = \frac{L}{\sqrt{2 \cdot 0{,}2 g_0 h}} = (0.2 - 3.5)\ \mathrm{s}$$

**Time of tank collapse**
**(~1.5 s in real accident)**

**Mass of oxyliquid formed**
**is 1–2% (at most)**
**of total fuel mass**

**Detonation of oxyliquid**
**initiates vapor cloud explosion**


0
0.04
0.08
Intense gasification
0.24
0.44
0.84
1.04
2.04
Loose kerosene 'snow'
4.04


0
0.04
0.08
0.24
0.84
4.44
8.44
28
32

# Oxyliquid structure

- **Porosity** of kerosene ‘snow’ is about 0.2 – 0.3
- Volume fraction of LOx in oxyliquid is only **0.2 – 0.3** rather than 0.72 (stoichiometric LOx – kerosene mixture), i.e. **oxyliquid is essentially fuel rich**
- **Pores are filled with both LOx and GOx, i.e. oxyliquid density is low**
- **Detonation parameters of oxyliquid should be close to detonation of gaseous mixtures**

# Detonation parameters of loose and dense oxyliquids (stoich.)

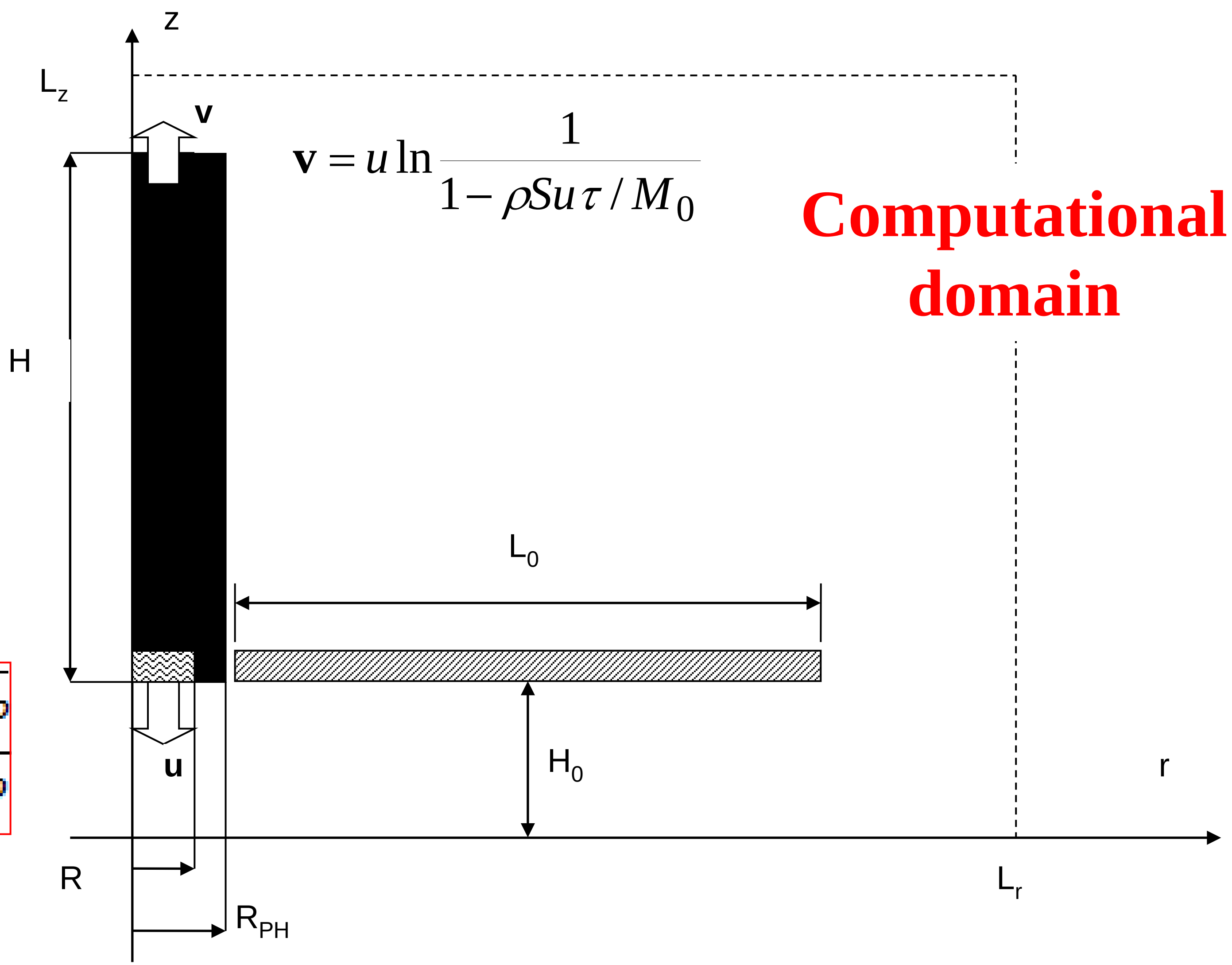
| No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Initial density, kg/m$^3$** | **33,3** | **66,6** | **133,1** | **266,3** | **532,5** | **1066** |
| **Detonation velocity, m/s** | **2602** | **2703** | **2879** | **3221** | **3944** | **5599** |
| Temperature, K | 4754 | 4946 | 5151 | 5377 | 5647 | 5945 |
| **Pressure, kbar** | **1,017** | **2,139** | **4,624** | **10,62** | 27,82 | 94,21 |
| Density, kg/m$^3$ | 60,632 | 118,76 | 229,09 | 432,65 | 801,73 | 1484,2 |

- **High local detonation pressures may result in considerable local destructions**

# Detonation parameters of dense oxyliquids (var. comp.)

| No | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| **Equivalence ratio** | **0,5** | **1** | **1,5** | **2** |
| $M_{ox}/M_{fu}$ | 6,844 | 3,422 | 2,281 | 1,711 |
| Initial density, kg/m$^3$ | 1097,6 | **1065,6** | 1041,3 | 1022,4 |
| **Detonation velocity, m/s** | **4966** | **5599** | **6438** | **6170** |
| Temperature, K | 4717 | 5945 | 4990 | 4483 |
| Pressure, kbar | 73,41 | 94,21 | 122,0 | 123,4 |
| Density, kg/m$^3$ | 1506,1 | 1484,2 | 1451,7 | 1497,0 |

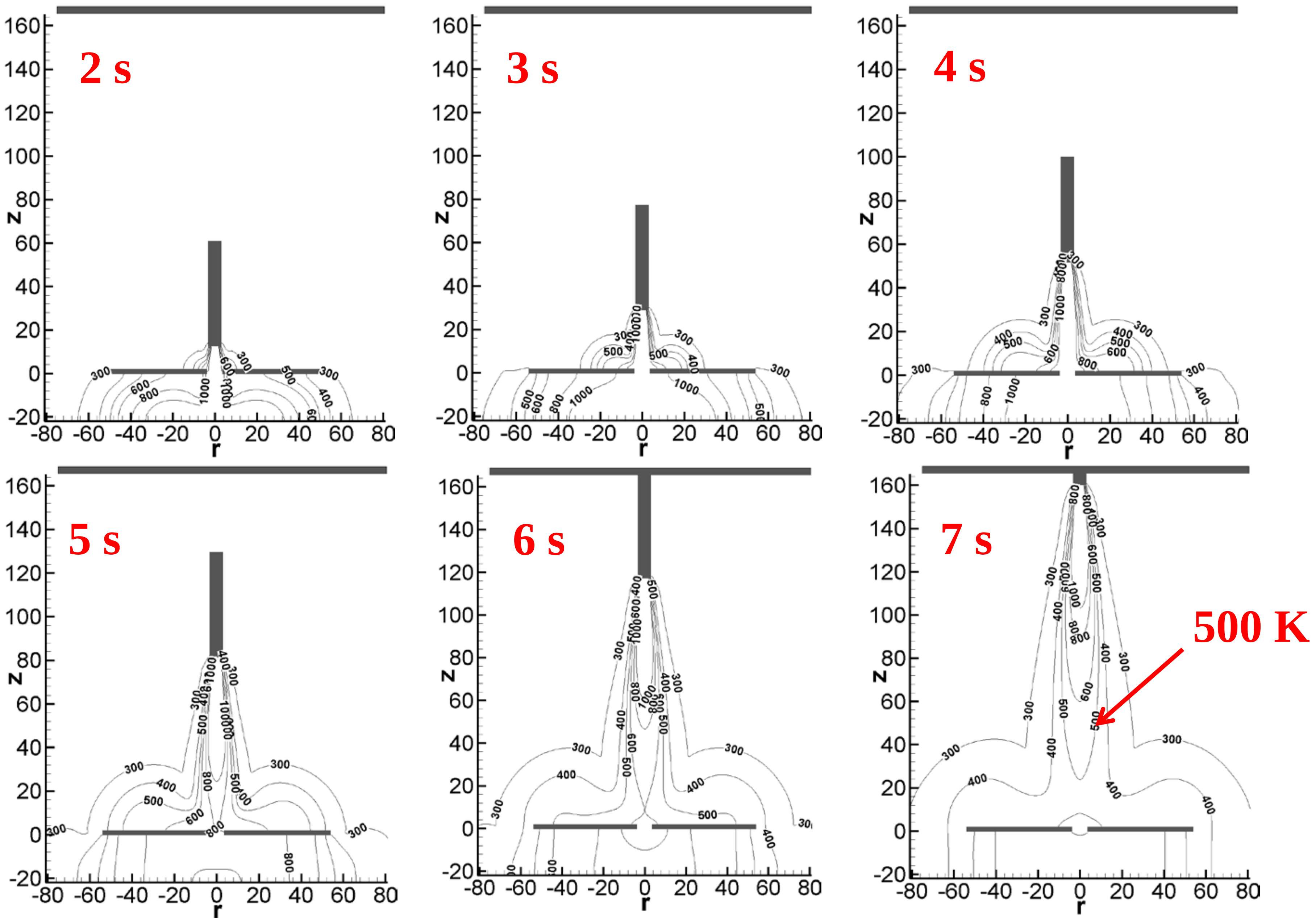
# Turbulent thermik



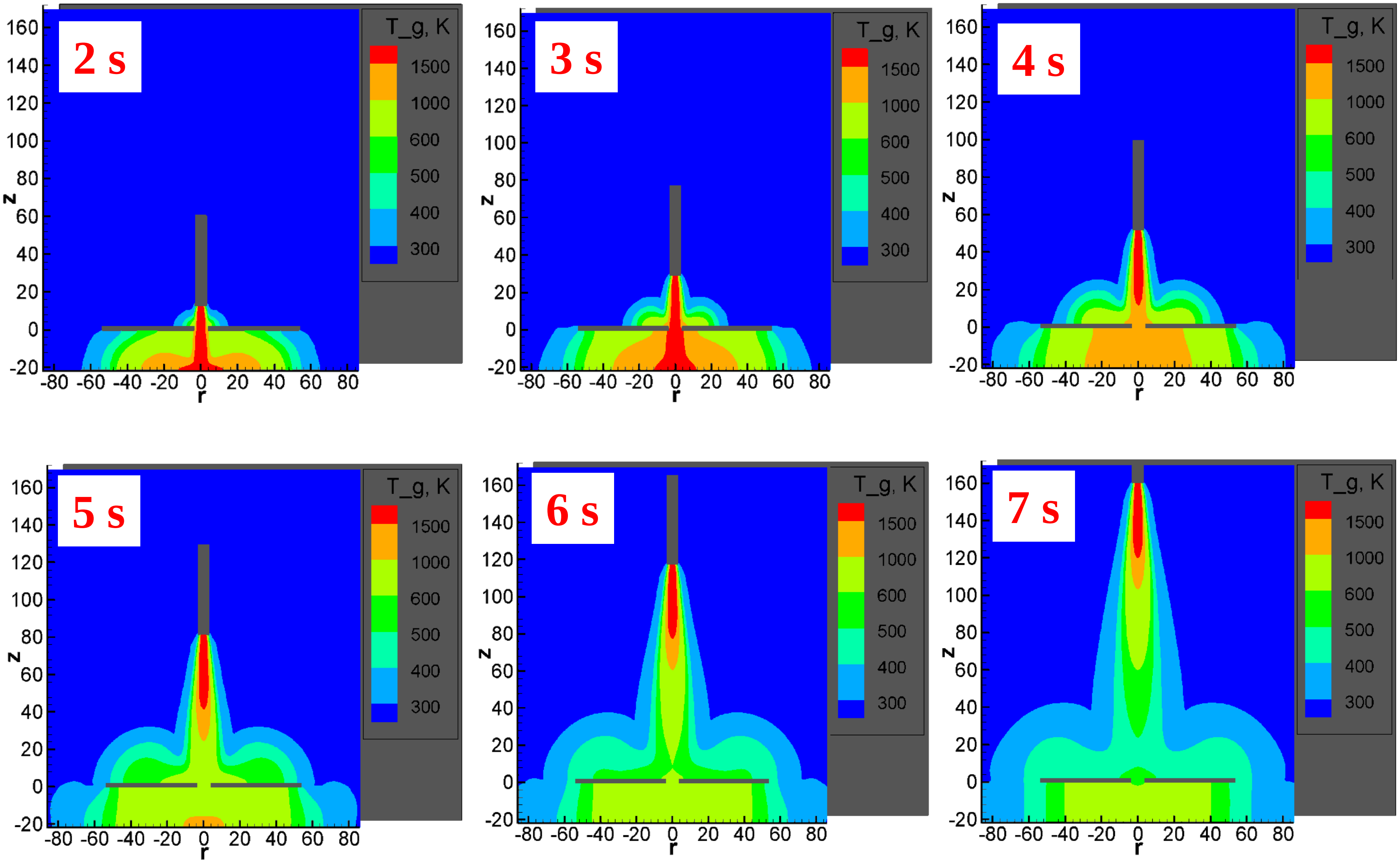

$$\mathbf{v} = u \ln \frac{1}{1 - \rho S u \tau / M_0}$$

$$u = \sqrt{\frac{gP}{A\rho}}$$

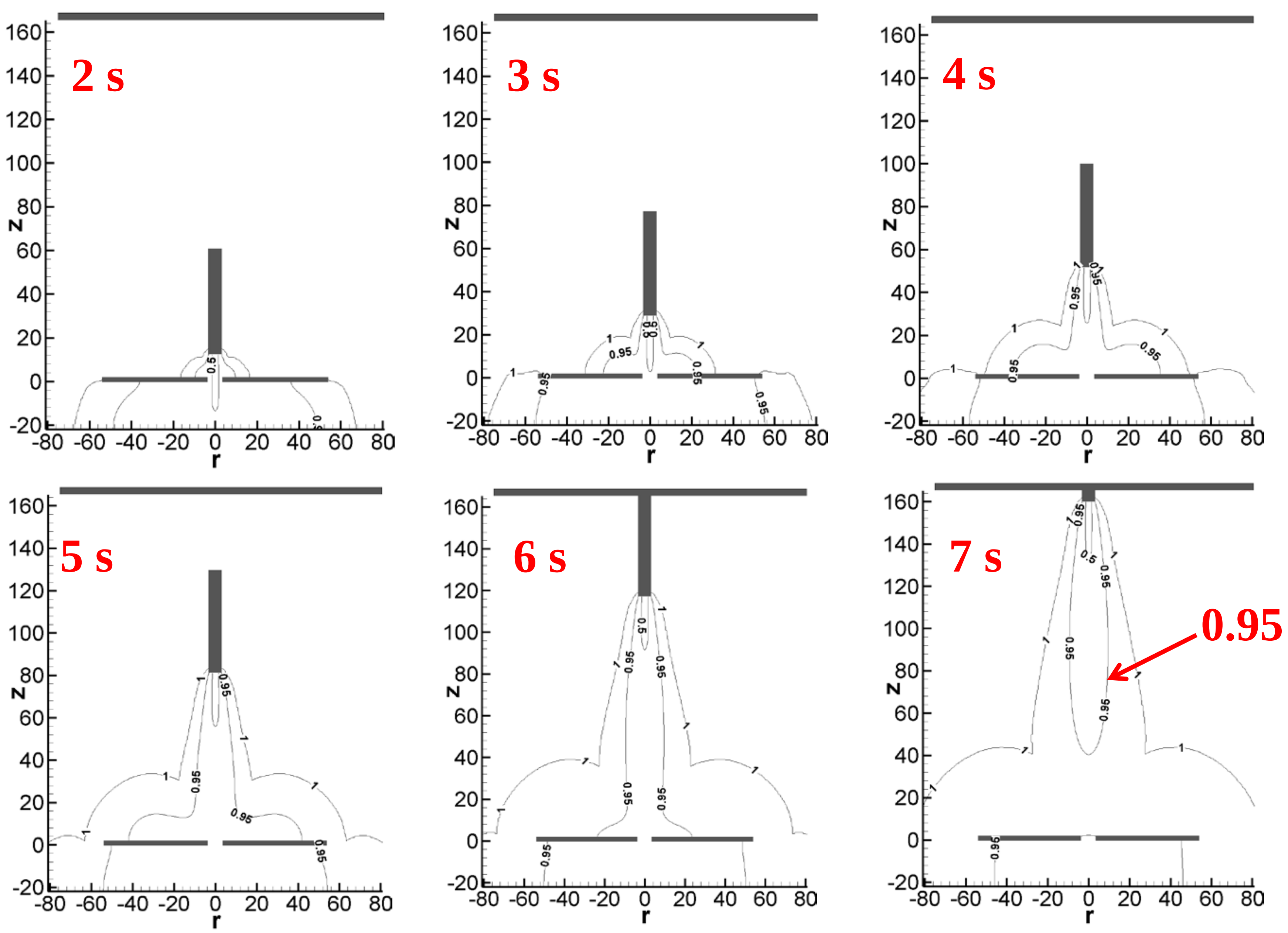
# Predicted temperature isolines



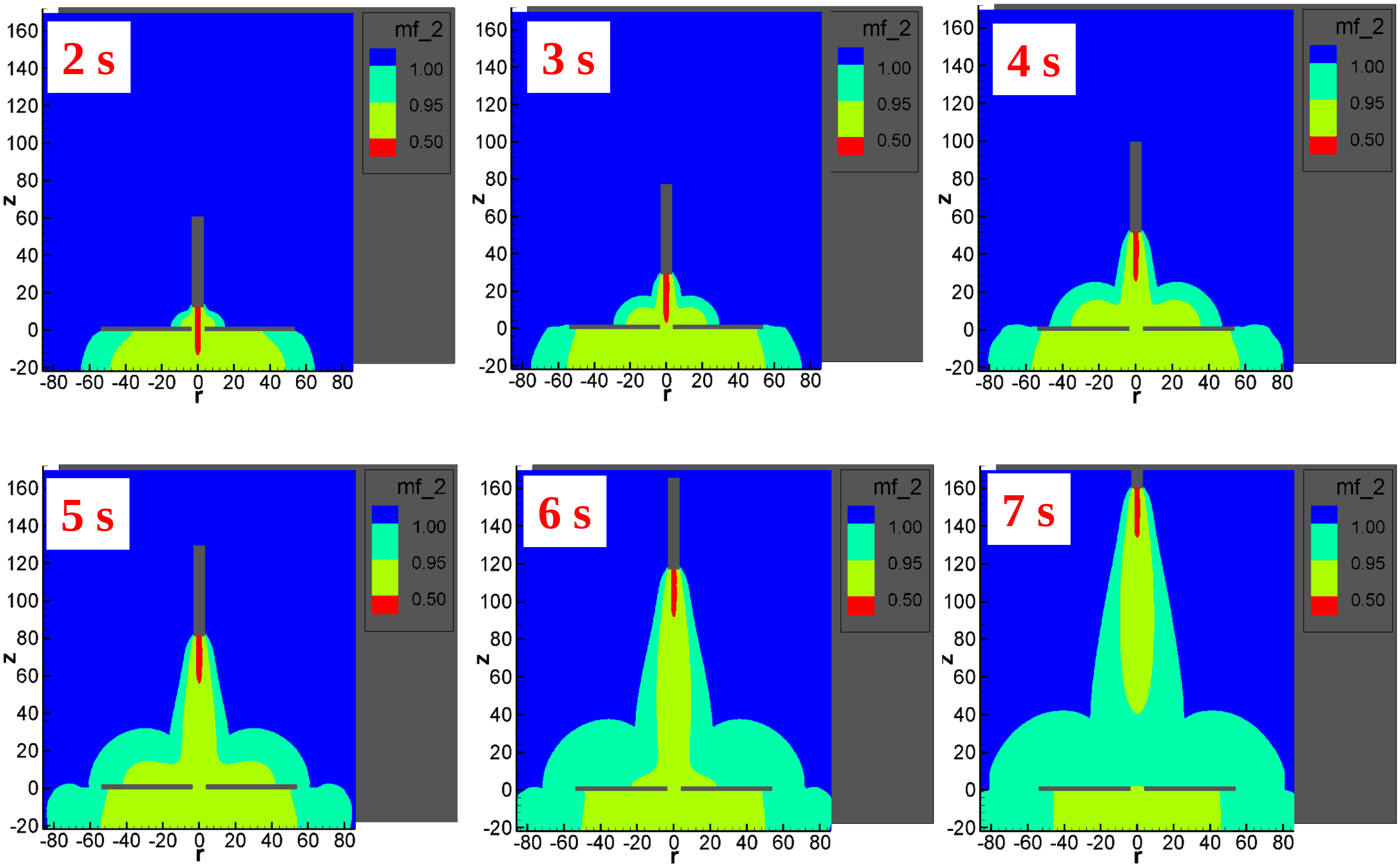
# Predicted temperature profiles



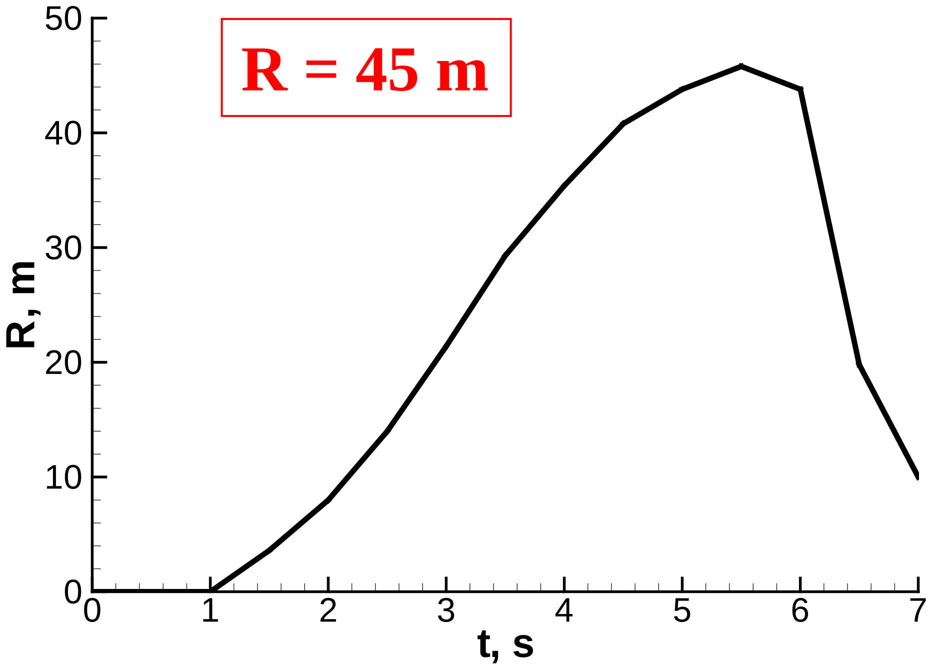
# Predicted isolines of air mass fraction



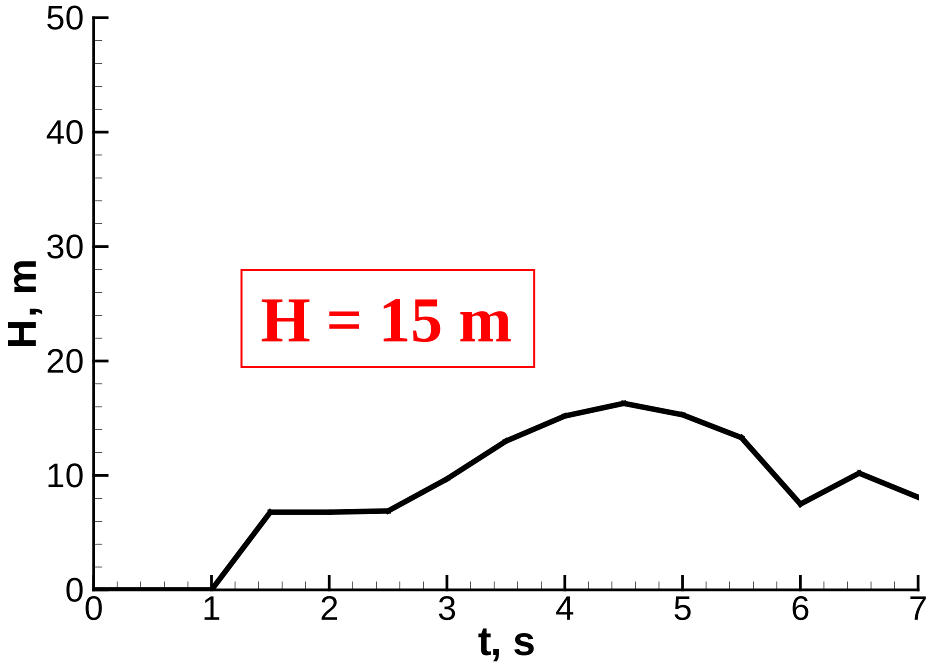
# Predicted profiles of air mass fraction



# Dimensions of turbulent thermik:
# T = 500 K



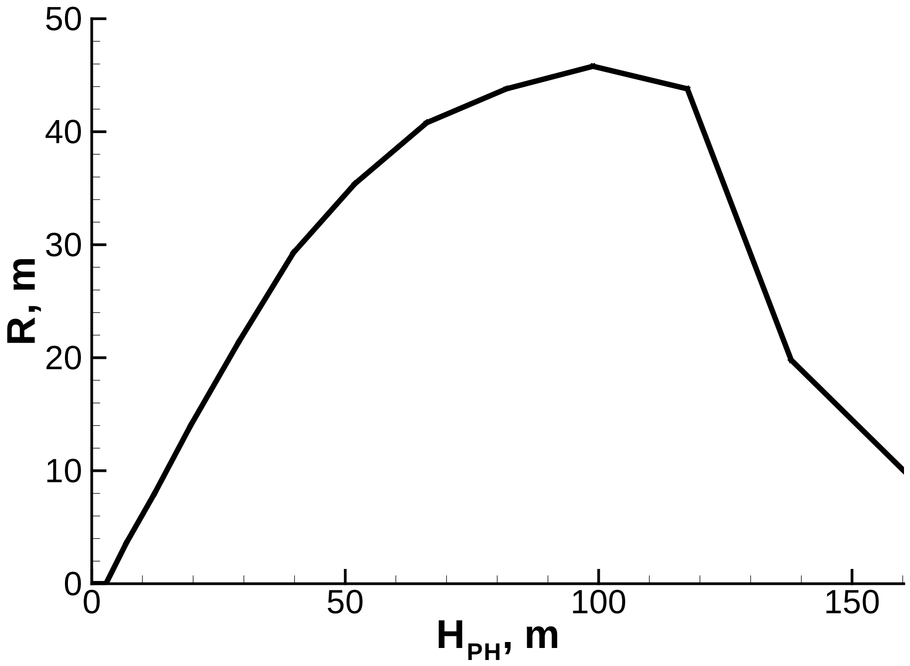

Radius vs Time

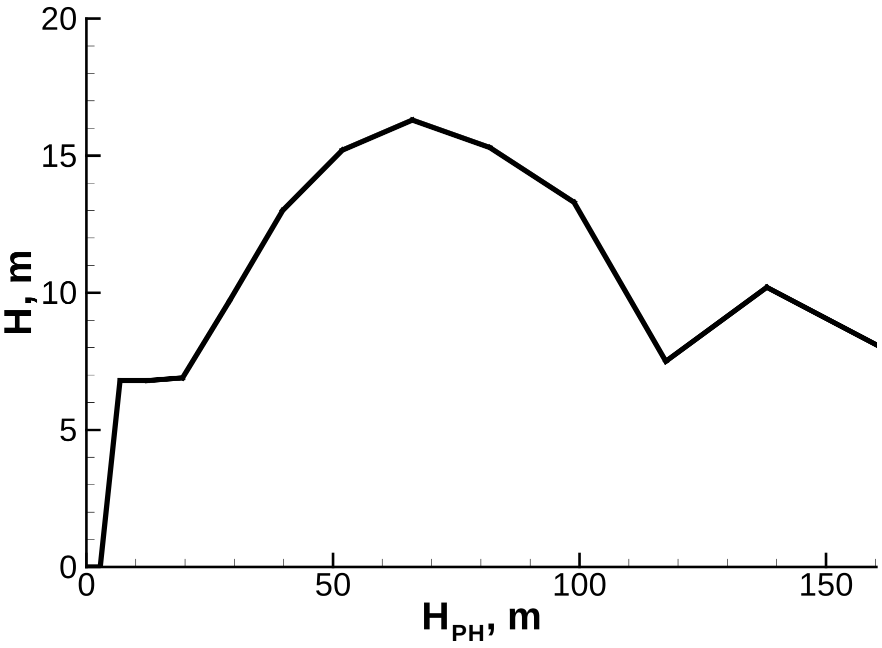



Height vs Time

# Dimensions of turbulent thermik:

# T = 500 K



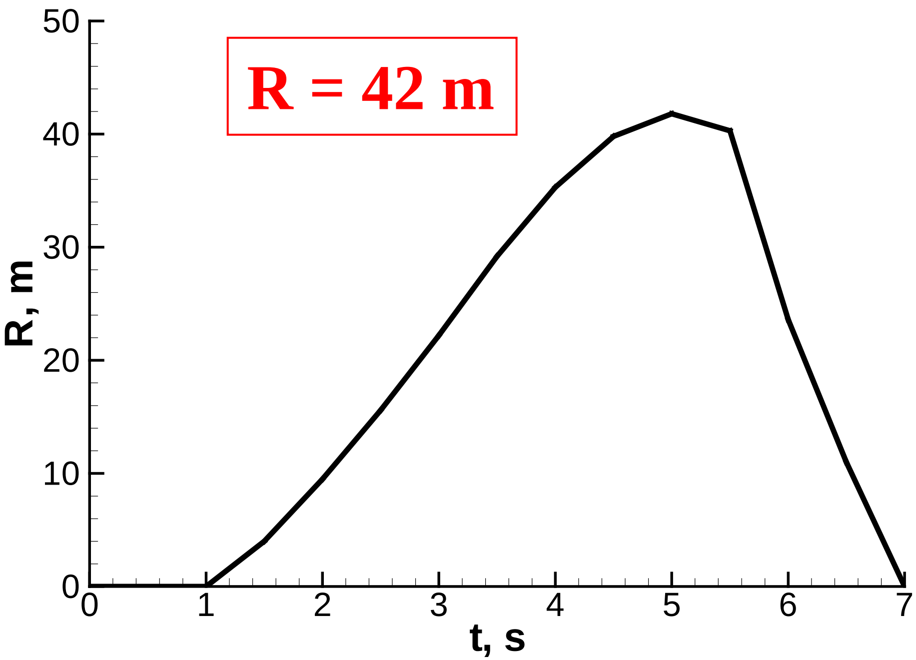




**Radius vs Altitude**

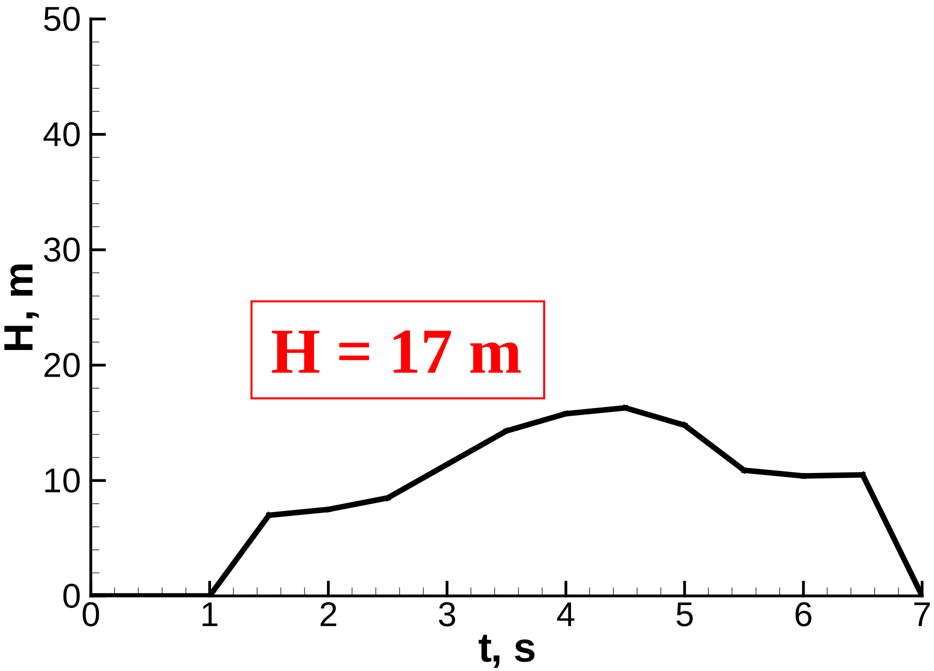
**Height vs Altitude**

# Dimensions of turbulent thermik:

# $Y_{air} = 0.95$




Radius vs Time




Height vs Time

- **Large cylindrical thermik 80 to 100 m in diameter and 15 to 20 m high creates conditions for vapor cloud formation**

# Kerosene vapor concentration in thermik-I

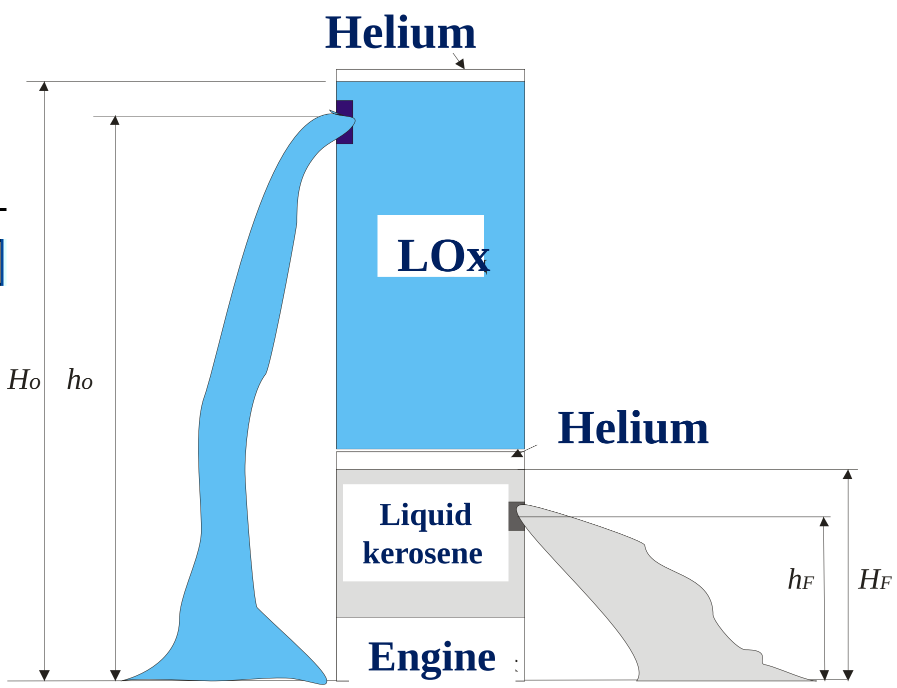
- **Maximum concentration of kerosene vapor (no LOx leakage, most conservative scenario)**

**Flow velocity through opening** $v = \sqrt{\frac{2}{\rho}[p + \rho g(H_F - h_F)]}$

**Residence time** $t = \sqrt{\frac{2h_F}{g}}$

**Spray penetration**

$$L = vt = v\sqrt{\frac{2h_F}{g}} = \sqrt{\frac{4h_F}{\rho g}[p + \rho g(H_F - h_F)]}$$




**25-35 m**

- **Kerosene spray is inside thermik**

# Kerosene vapor concentration in thermik-II

## Mass flow rate of kerosene through openings

$$G = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \rho v_i S_i = \rho v \sum_{i=1}^{n} S_i = \rho v S$$

## Evolution of kerosene level in tanks

$$z = z_0 - u\tau \qquad u \approx \frac{S}{A} v$$

$$t_e = z_0 / u.$$ **(time to tank empty)**

## Mass of kerosene spray injection

**at** $\tau < t_e \qquad M = A\rho(z_0 - z) = S\rho v\tau$

**at** $\tau \geq t_e \qquad M = A\rho z_0$

## Size and number of kerosene drops: $d_0 =$ **0.5 – 2 mm**

$$N = \dot{N}t = \frac{vSt}{\left(\frac{\pi}{6} d_0^3\right)}$$

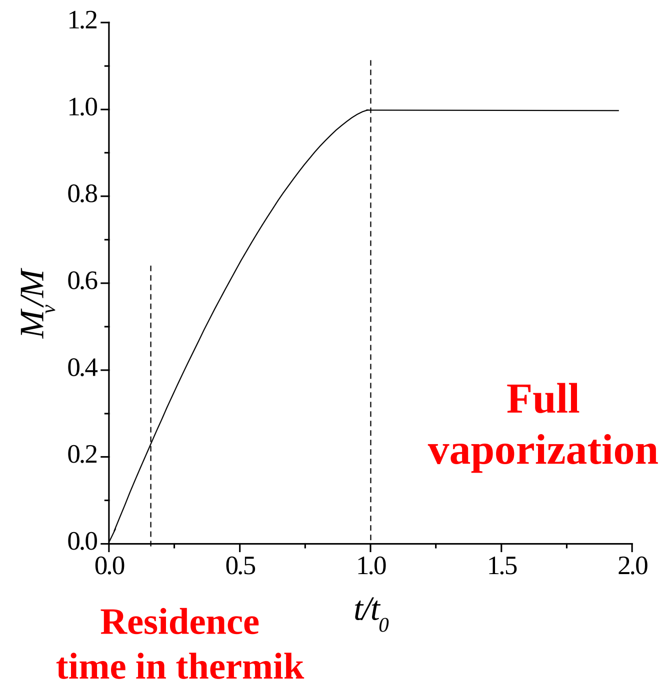
# Kerosene vapor concentration in thermik-III

## Vaporization of a single kerosene drop: $d^2 = d_0^2 - Kt$

$$t_0 = \frac{d_0^2}{K} \qquad \dot{m} = \frac{dm}{dt} = \frac{d}{dt}\left(\frac{\pi}{6}\rho d^3\right) = \frac{\pi}{2}\rho d^2 \frac{d(d)}{dt} = \frac{\pi}{4}\rho d \frac{d(d^2)}{dt} = -\frac{\pi}{4}\rho K d$$

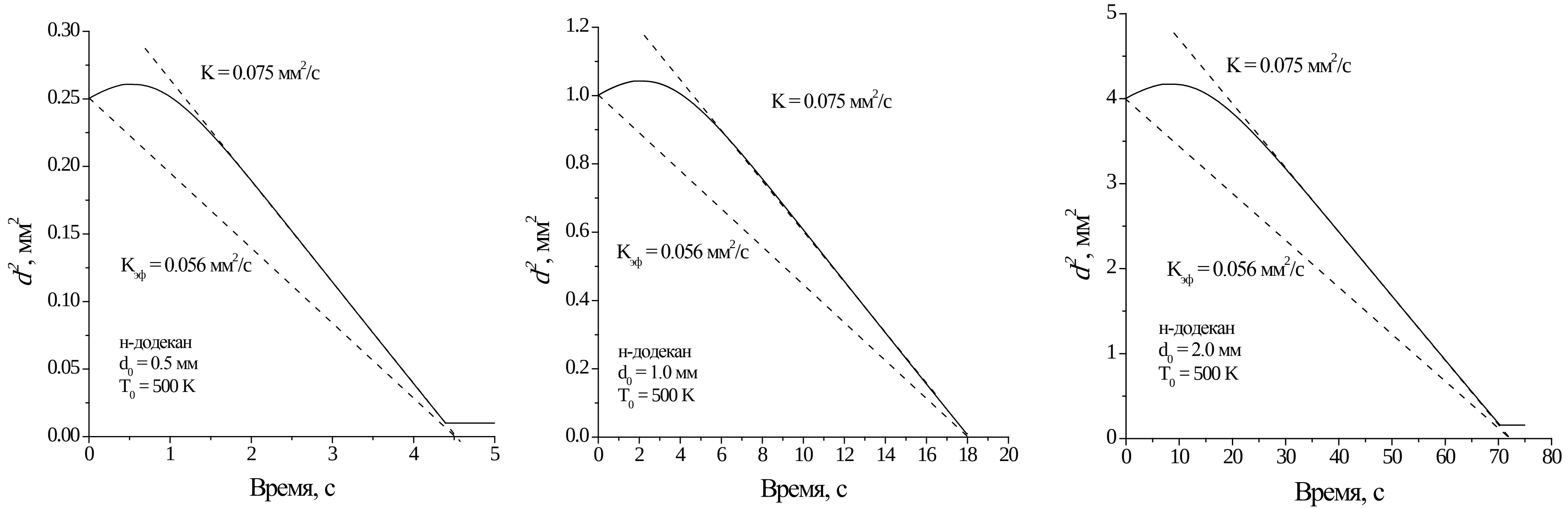
## Vaporization of kerosene drops in spray:

$$\frac{M_v}{M} = 1 - \frac{\frac{1}{5}\left(3\frac{t}{t_0}+2\right)\left(1-\frac{t}{t_0}\right)^{3/2} - \frac{2}{5}\left(1-\frac{t}{t_0}\right)^{5/2}}{\frac{t}{t_0}}$$



# Kerosene vapor concentration in thermik-IV

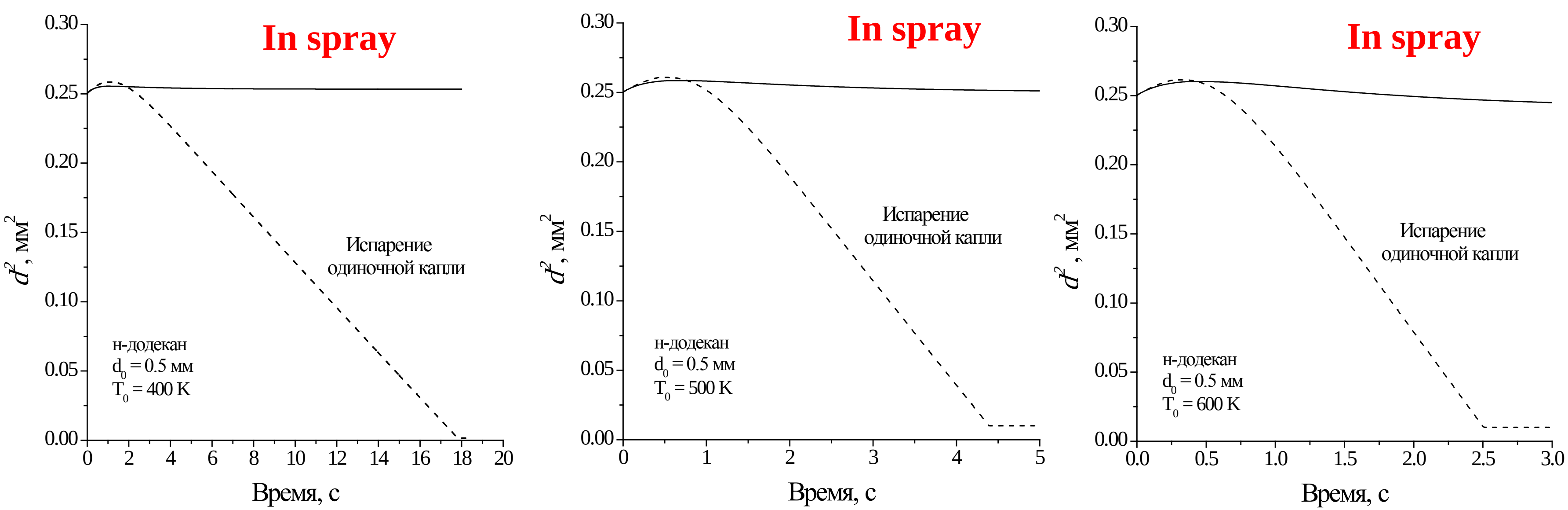
## Kerosene evaporation constant




- Depending on temperature in thermik, 3 to 60% of 0.5-mm drops, 0.1 to 3% of 1-mm drops and ~0% of 2-mm drops are evaporated during time delay between collision and explosion

# Kerosene vapor concentration in thermik: less conservative scenario

## Drops in spray evaporate slower: R/d = 10




- **Depending on temperature in thermik, 2.5 to 7% of 0.5-mm drops and ~0% of 1 and 2-mm drops are evaporated during time delay between collision and explosion**
- **No cooling effect of LOx is taken into account**

# Amount of fuel components involved in the explosion: Results

- The amount of prevaporized kerosene is only ~5% of kerosene injected by sprays even at full kerosene leakage (the stoichiometric amount of oxygen is a factor of 2.75 higher)

- The most conservative estimate for prevaporized fuel involved in explosion is 7%, the least conservative estimate is 2.5%

- These estimates correlate with available experimental data of PJRO project (USA) (5-16% of total mass of fuel components)

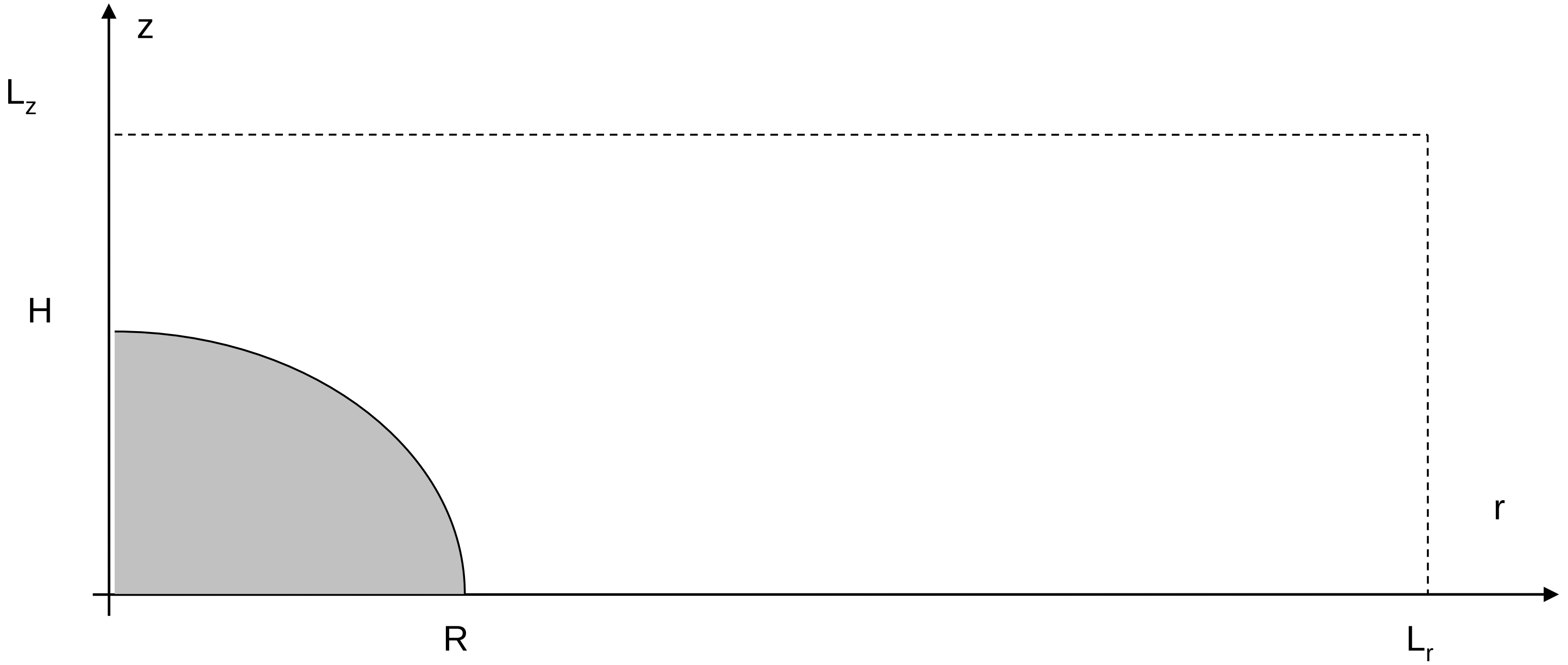
# Blast wave

## Two main issues:

(1) Estimate **the amount of fuel components involved in the explosion**

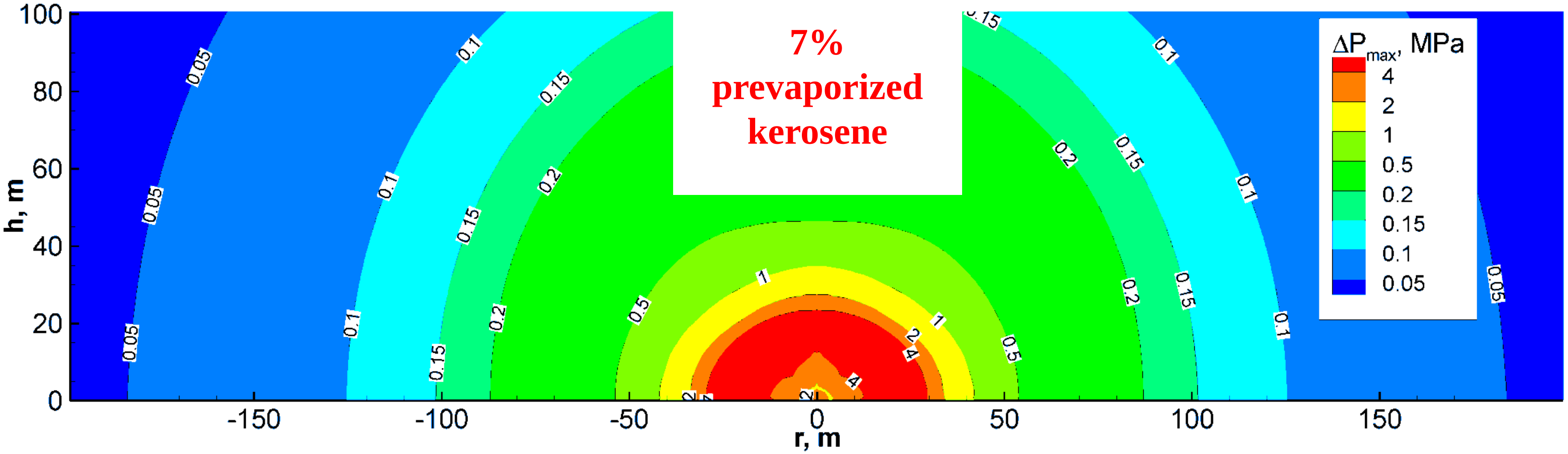
(2) Determine **the parameters of the blast wave propagating in the surroundings**

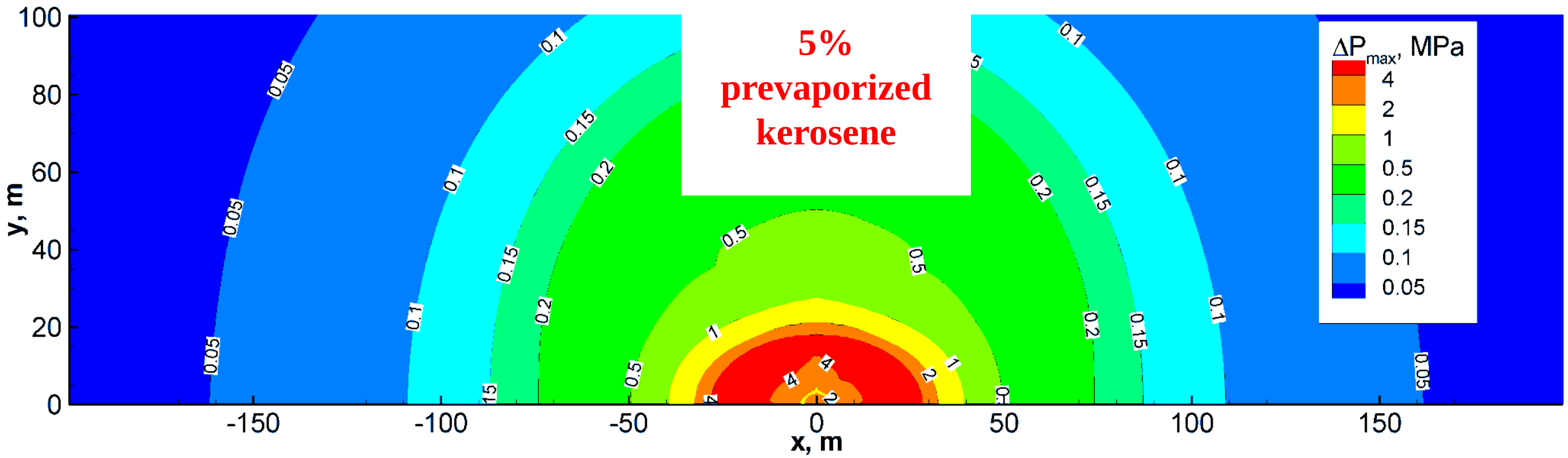
# Computational domain



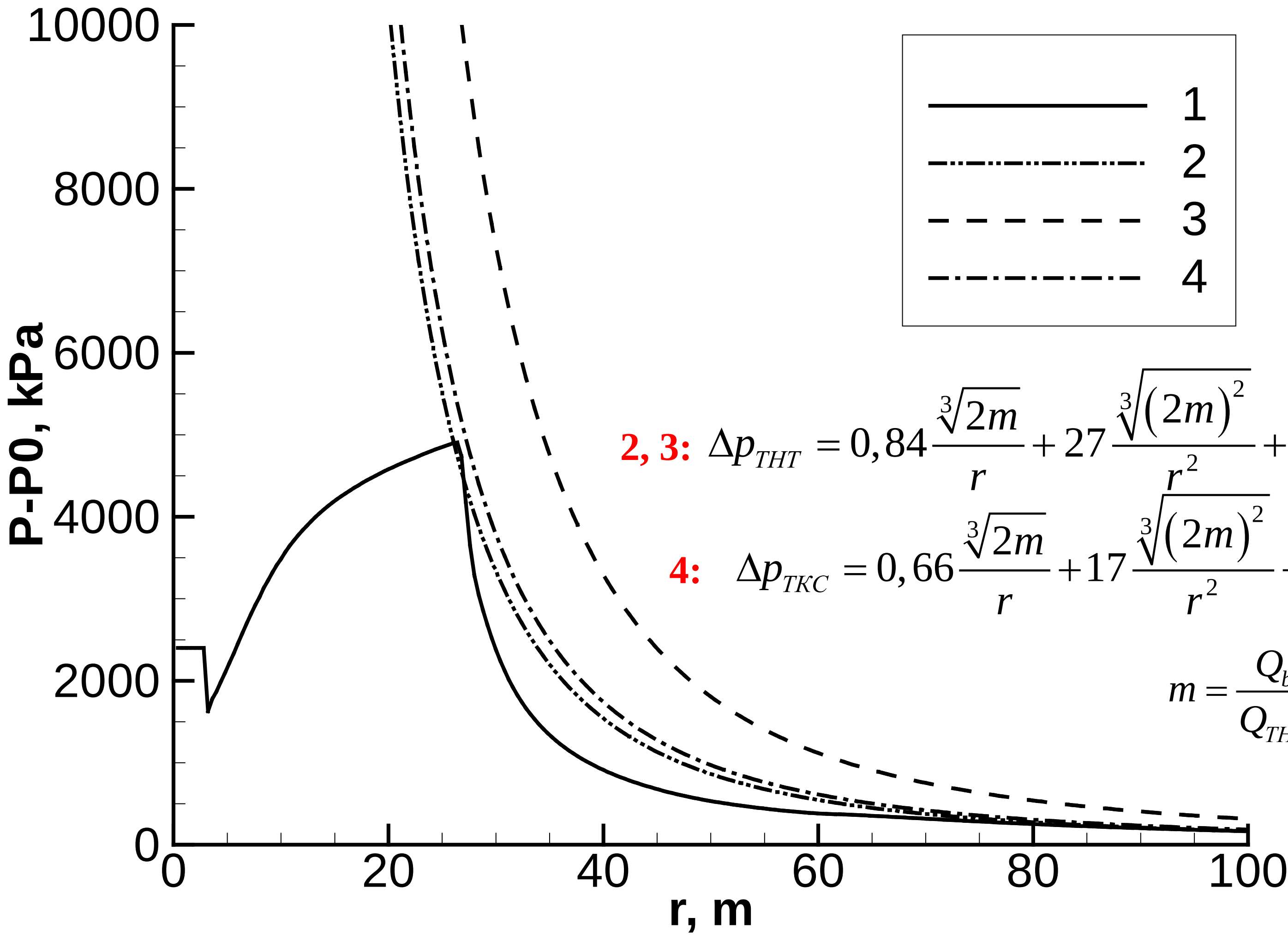

**7, 5, or 2.5% prevaporized kerosene**

# Maximum overpressure



# Overpressure in the blast wave



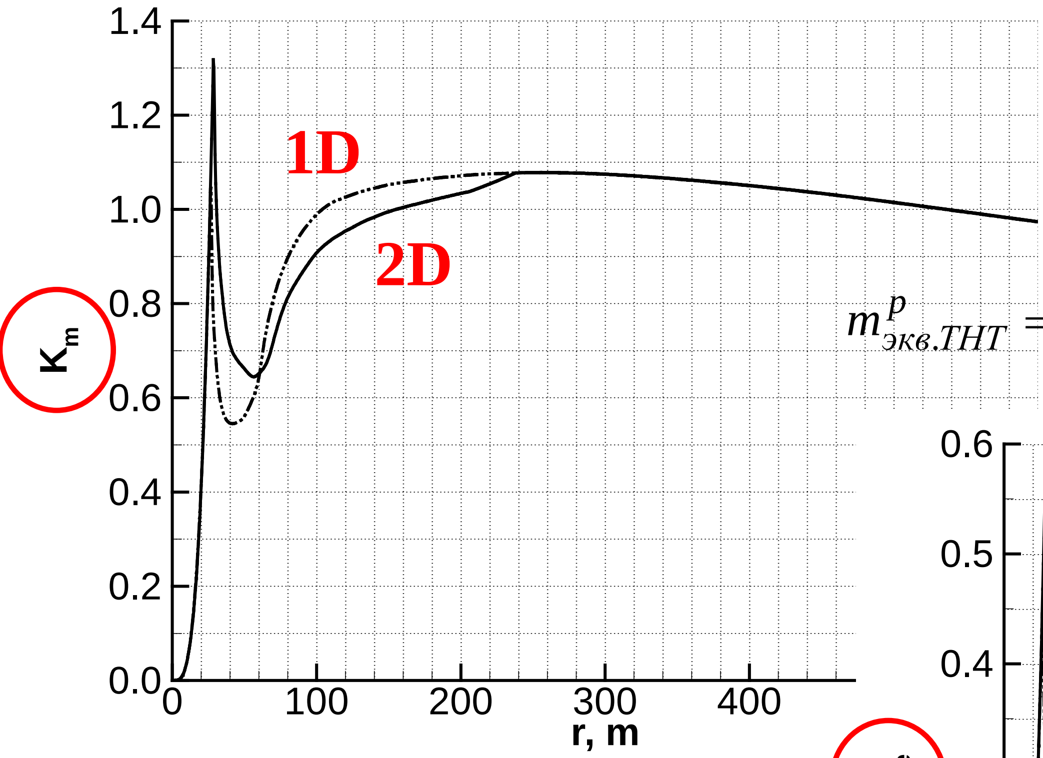

**7% prevaporized kerosene**

**2, 3:** $$\Delta p_{THT} = 0,84\frac{\sqrt[3]{2m}}{r} + 27\frac{\sqrt[3]{(2m)^2}}{r^2} + 700\frac{\sqrt[3]{(2m)^3}}{r^3}, \text{ MПa}$$

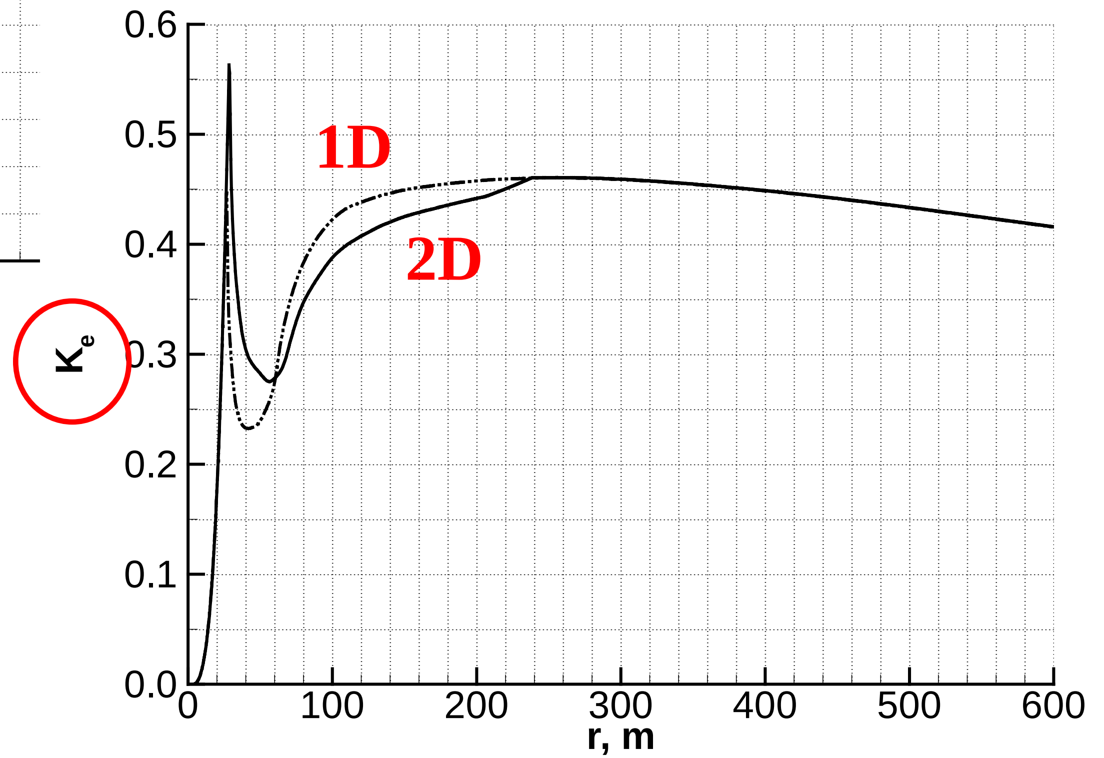
**4:** $$\Delta p_{TKC} = 0,66\frac{\sqrt[3]{2m}}{r} + 17\frac{\sqrt[3]{(2m)^2}}{r^2} + 343\frac{\sqrt[3]{(2m)^3}}{r^3}, \text{ MПa}$$

$$m = \frac{Q_b}{Q_{THT}}\rho_0 V_0$$

# TNT equivalency (pressure)

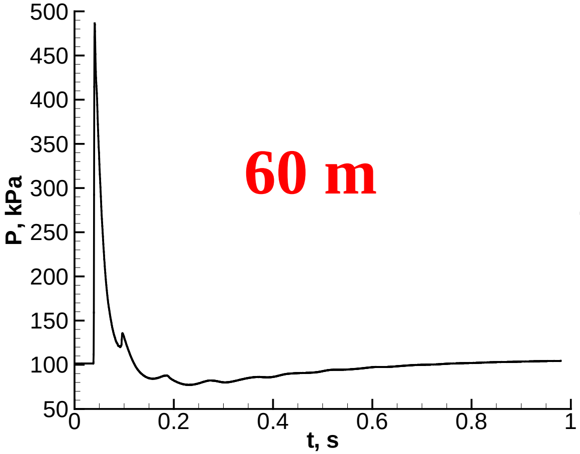


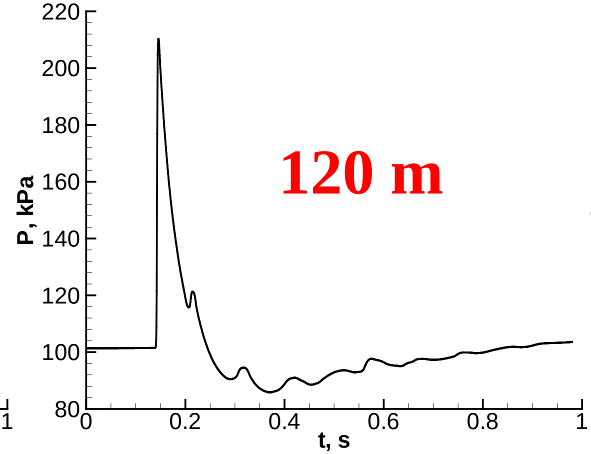

$$m^{p}_{экв.THT} = K_e \frac{Q_b}{Q_{THT}} M = K_e \frac{Q_b}{Q_{THT}} (1+\phi)\chi M^{0}_{f}$$

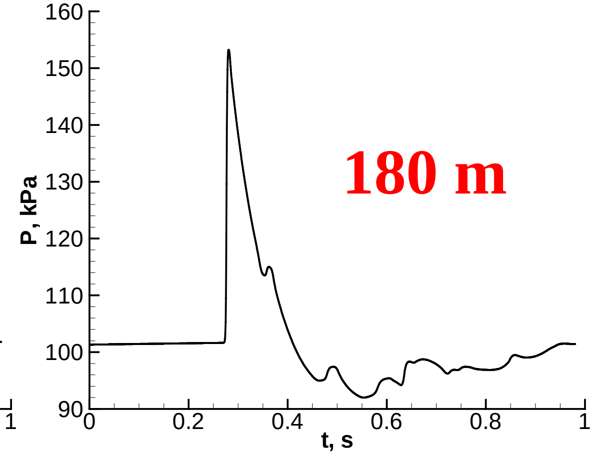


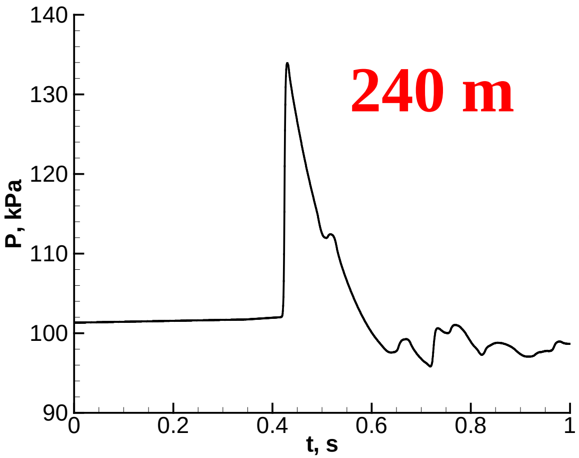

7%
prevaporized
kerosene

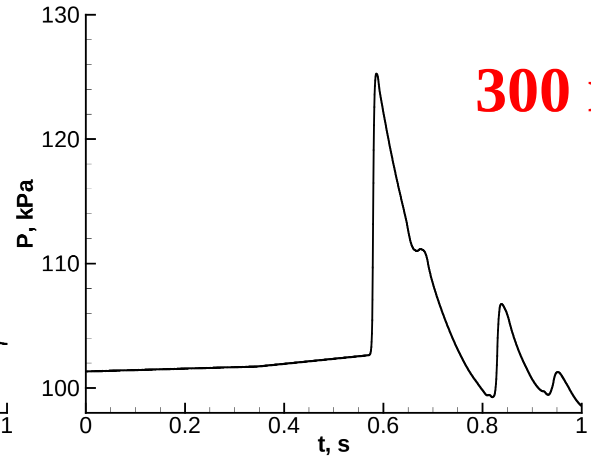
# Shape of blast wave




$$I = \int_0^{\tau_+} \left( p - p_0 \right) dt$$

- **TNT equivalency in terms of impulse is somewhat larger than in terms of pressure (by 20-30%)**

# Main conclusions

- Rocket launch explosion accidents involve no more than 2.5–7% prevaporized hydrocarbon fuel
- Vapor cloud detonation is most probably initiated by explosion of loose oxyliquid formed due to penetration of LOx into kerosene (detonation velocity is 2500–3500 m/s)
- TNT equivalency of vapor cloud explosion in terms of both blast impulse and pressure should be considered