CAVITATION OF LIQUIDS IN SHOCK WAVES AS A SUBJECT OF INVESTIGATION BY PROTON RADIOGRAPHY

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- **Subject:**

  Influence of kinetic of homogeneous nucleation and bubble growth on the value of negative pressure and spall pulse form.

- **Liquids:**
  - **Water, Methanol, Glycerol, Hexane, Hexadecane,**
  - **Pentadecane, and transformer oil.**

The maximum values of tensile strength of water P_s measured by static methods

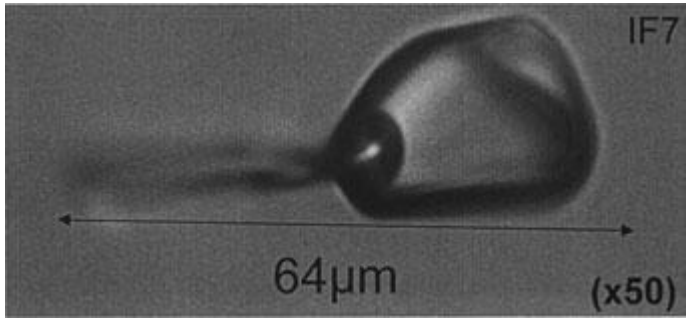
Method	Ref.	T, ^{0}C	P_s, MPa
Berthelot tubes	[1]	40	16
Berthelot tubes	[2]	53	18.5
Centrifugation	[3]	10	27.7
Acoustic cavitation	[4]	30	21
Inclusion analysis	[5]	40-47	140

REFERENCES

1. Henderson S.J. and Speedy R.J. J.Phys.Chem. 1980. V.13, P.778.
2. Hiro K., Ohde Y., and Tanzawa Y. J.Phys. D: Appl. Phys. 2003. V.36, P.592.
3. Briggs L.J. J. Appl. Phys. 1950. V.21, P.721.
4. Greenspan M. and Tschiegg C.E. J.Res.Nat.Bur.Stand. C. 1967. V.71, P.299.
5. Zheng Q., Durben D.J., Wolf G.H., and Angell C.A. Science. 1991. V.254, P.829.

Metastability of inclusion fluids

M.El Mekki, C.Ramboz, L.Mercury, K.Shmulovich, F.Caupin. "Metastability of inclusion fluids: inclusion volume and shape control; preliminary kinetic data". Int.Conf. "Metastable systems under pressure", 4-9 October 2008, Odessa, Russia.

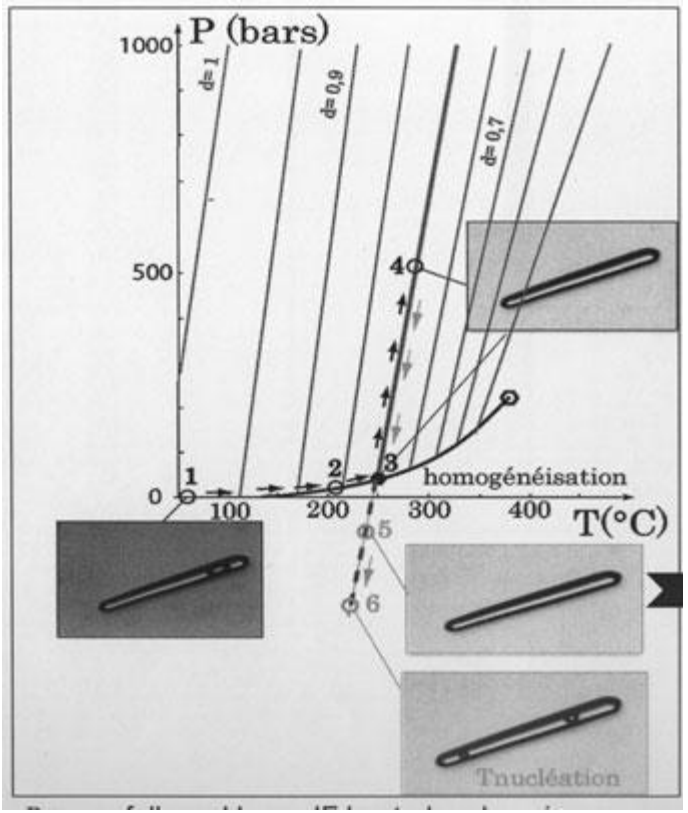


- **A pure water inclusion (in quartz) – 140 MPa and 42^{0}C**

(Zheng Q., Durben D.J., Wolf G.H., and Angell C.A. *Science*. 1991)

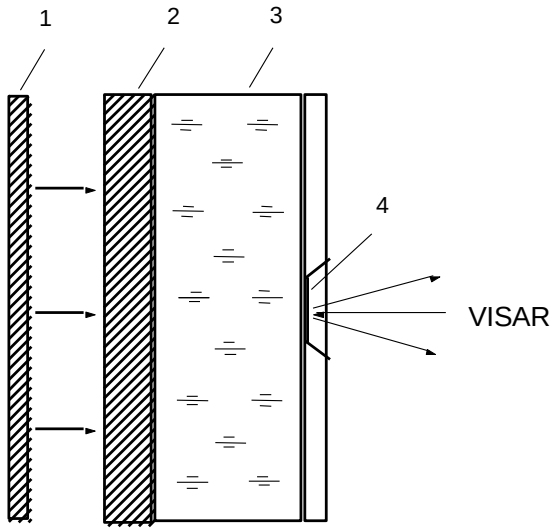
- **A 5m $CaCl_2$ inclusion (in quartz) – 146 MPa and 100^{0}C**

(Shmulovich K.I., Mercury L., Thiery R., Ramboz C., Mekki M.E. *Geochimica et Cosmochimica Acta*. 2008)



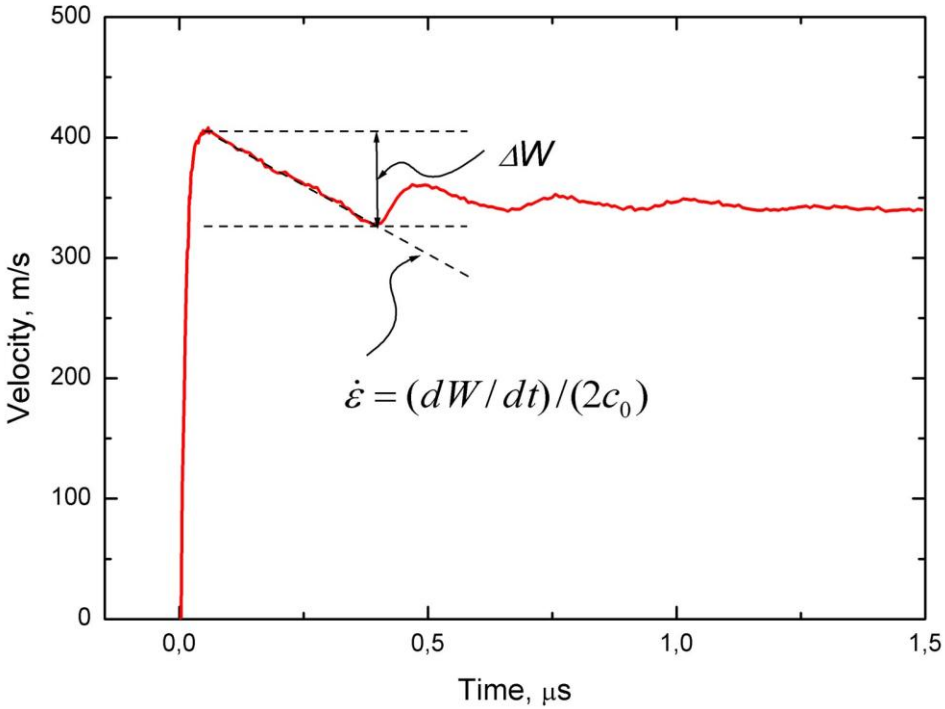
THE SCHEME OF EXPERIMENTS

Experimental setup



1 - impactor (h=0.2-2 mm, W=660 m/s);
2 - PMMA screen (2 mm);
3 - investigated liquid;
4 - 7 μm Al foil.

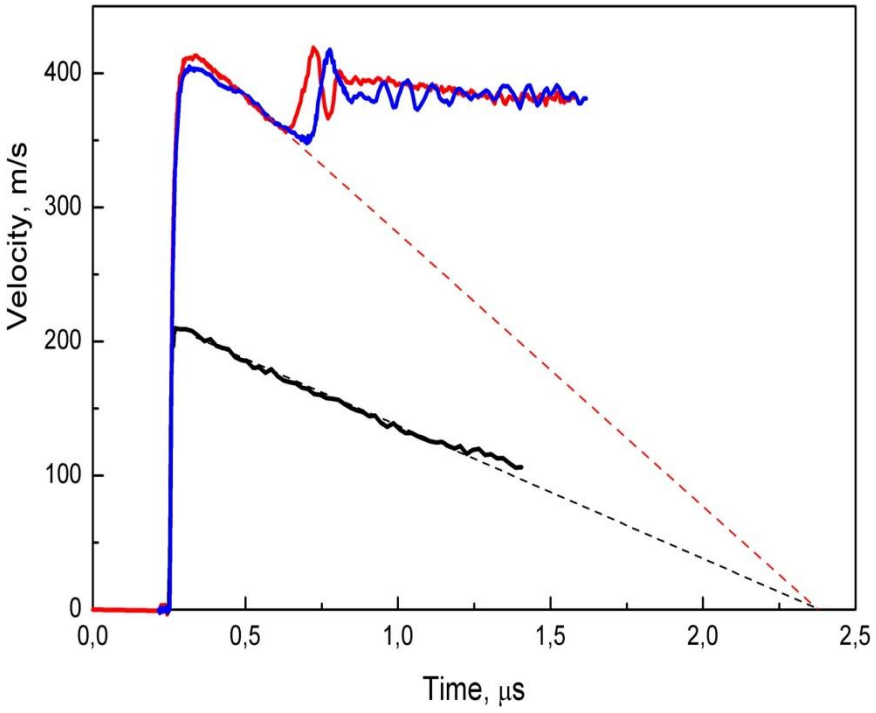
Experimental results



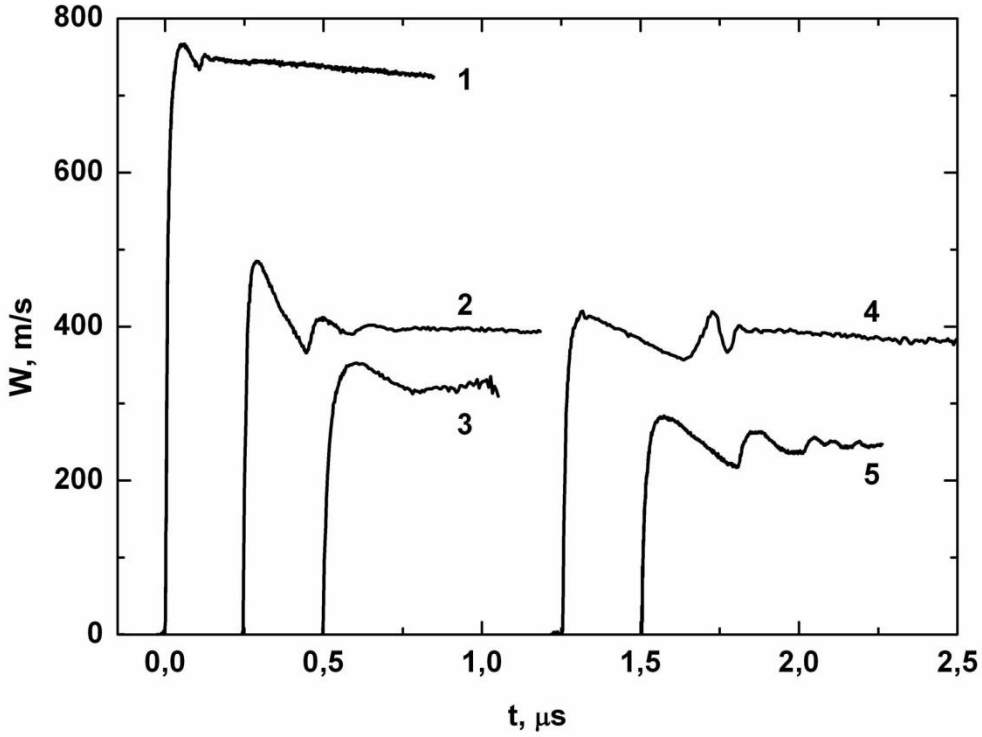
The tensile stress value P_s just before spalling is determined by the linear approximation:

$$P_s = 0.5\rho_0 c_0 \Delta W$$

Profiles of free surface velocity

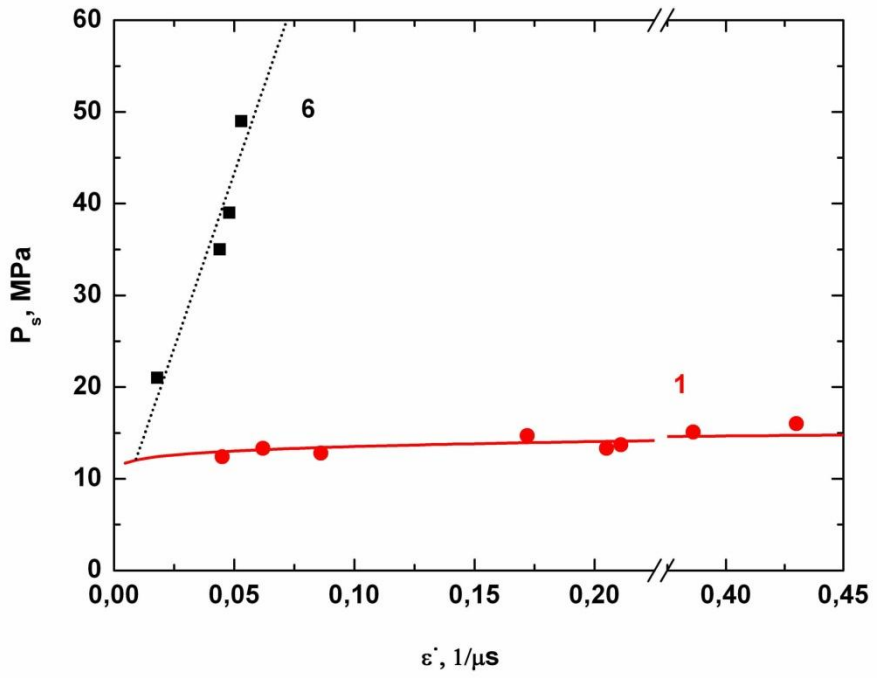


Free surface velocity (red and blue) and particle velocity (black) in the shots with water. Red and black curves are distillate water.

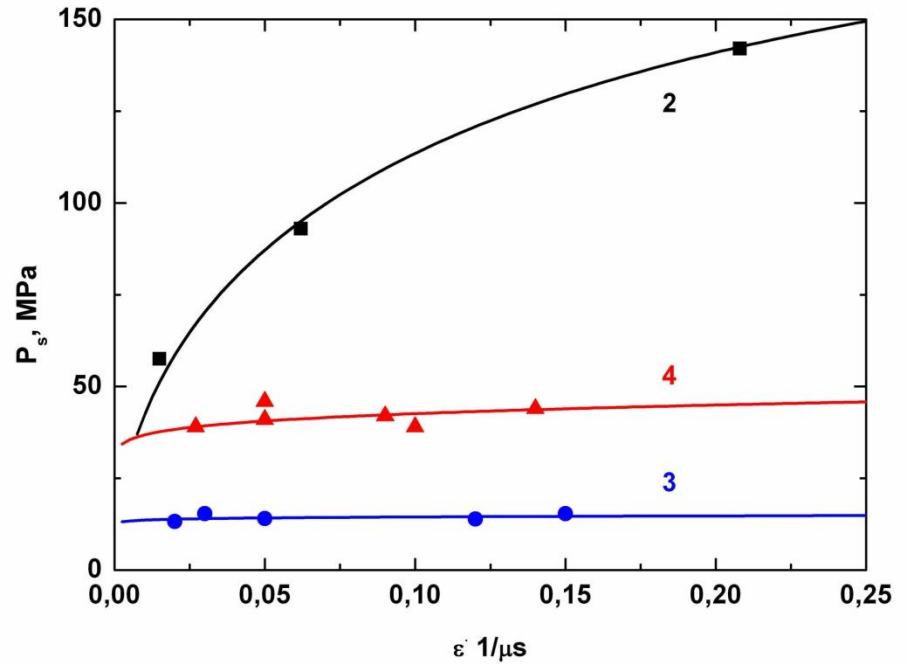


Free surface velocity: 1–ethanol, 2-glycerol, 3–hexane, 4–water at T=20 0 C, 5-hexadecane.

Spall strength as a function of strain rate



Spall strength as a function strain rate. 1-etanol, 6-water at T=0.7 0C.



Spall strength as a function strain rate. 2-glicerol, 3-hexane, 4-water at T=20 ^{0}C .

Theory of homogeneous bubble nucleation

The number of critical voids formed per unit volume per unit time J is given by *

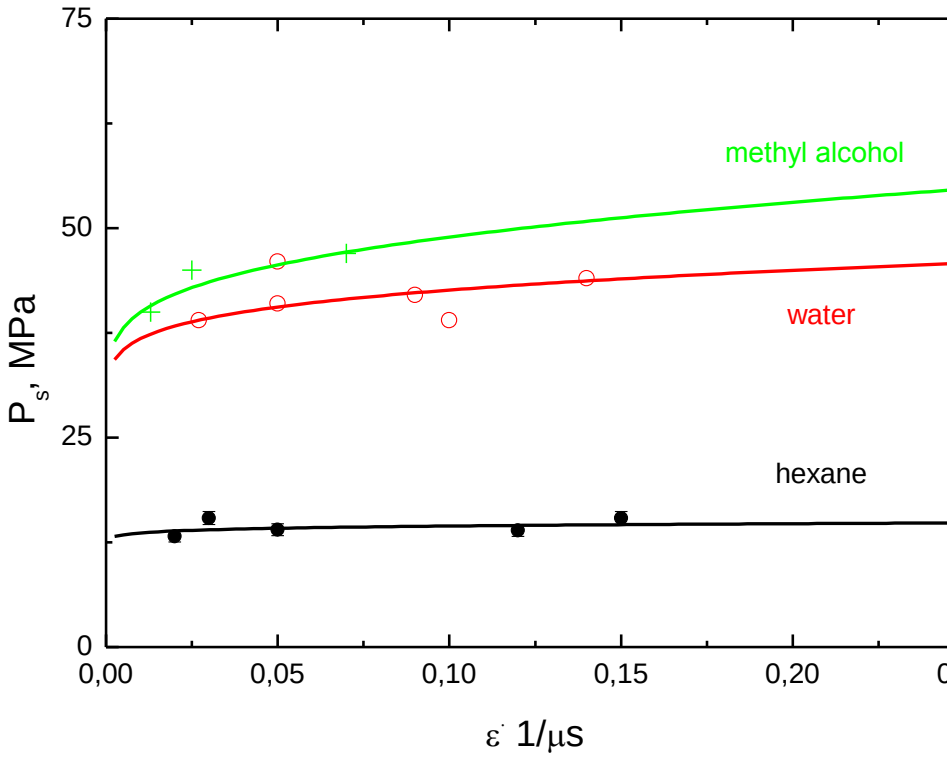
$$J = N_0 \frac{\sigma}{\eta}\sqrt{\frac{\sigma}{kT}}\exp\left(-\frac{16\pi\sigma^3}{3P_s^2 kT}\right), \qquad (1)$$

where N_0 is the number density of molecules, σ is the surface energy of the liquid, η is the viscosity, T is the temperature (^{0}K), k is Bolzmann constant.

It follows from Eq. (1), the dependence of spall strength on a strain rate can be rewritten

$$P_s \approx A \Big/ \sqrt{\ln\left(B/\dot{\varepsilon}\right)}$$

* Zeldovich Ya.B. Zhurnal Eksp. Tekh. Fiz. 1942. Vol.12, No. 11/12, P. 525.



Tensile stress as a function of strain rate.
Water: A=110 Mpa, B=10^{16} 1/s.
Hexane: A= 62 Mpa, B=10^{13} 1/s.
Methyl alcohol: A=200 MPa, B=10^{13} 1/s.

Theory of homogeneous bubble nucleation

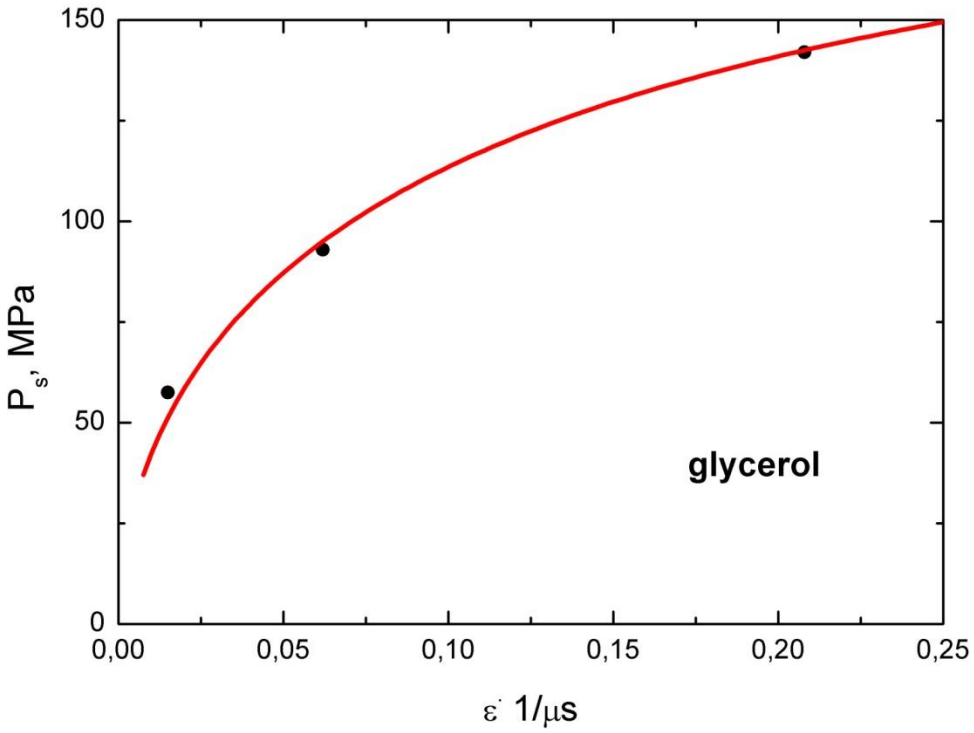
To estimate the strain rate influence on the viscosity nearly the freezing point (291 K), a simple relaxation model was used:

$$\dot{\eta} \sim -\eta / \tau, \qquad (1)$$

where τ is the characteristic time of glycerol.

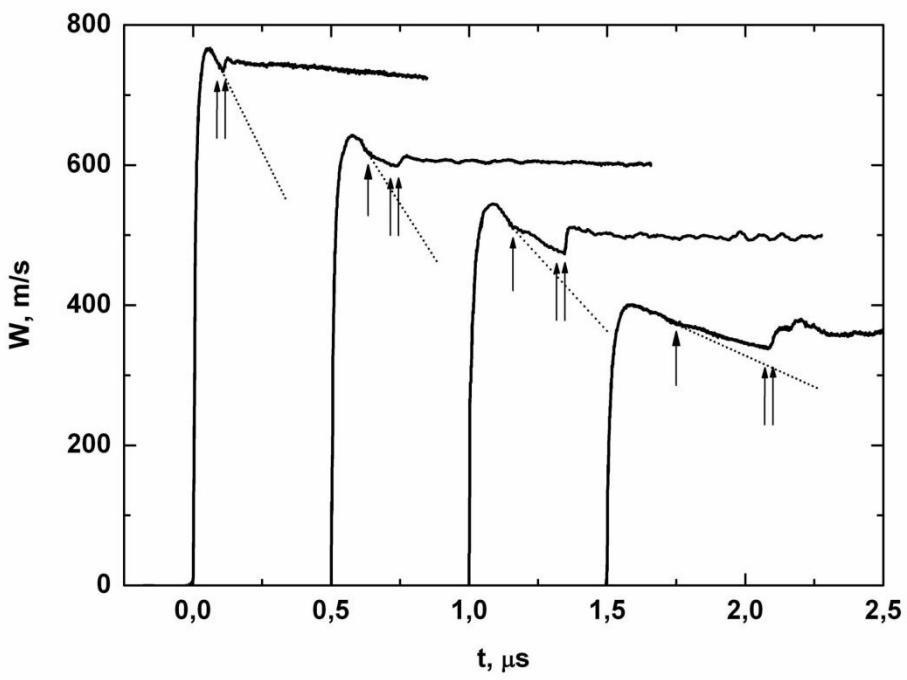
According to a solution for the nucleation rate J and for the equation (1), the dependence of spall strength on a strain rate can be rewritten

$$P_s \approx A / \sqrt{\ln(B \cdot \exp(1/\tau\dot{\varepsilon})/\dot{\varepsilon})}$$



Tensile stress as a function of strain rate.
A=970 Mpa, B=10^{15} 1/s, τ=0.2 μs.

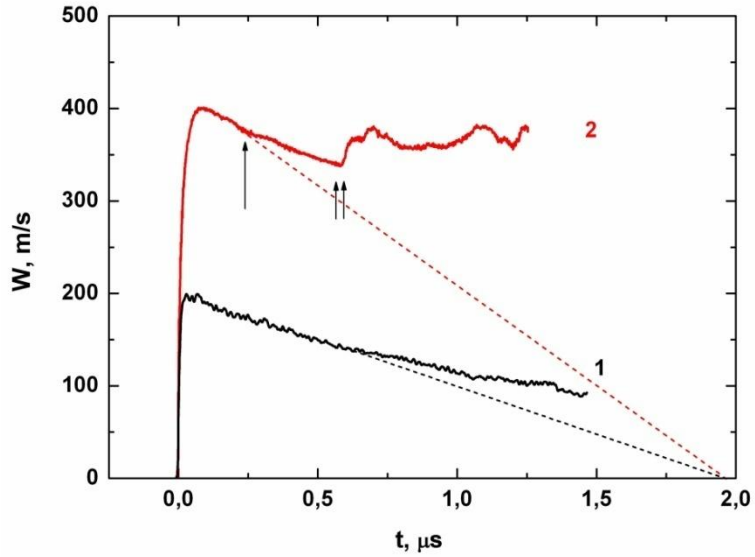
Two-stage failure under cavitation

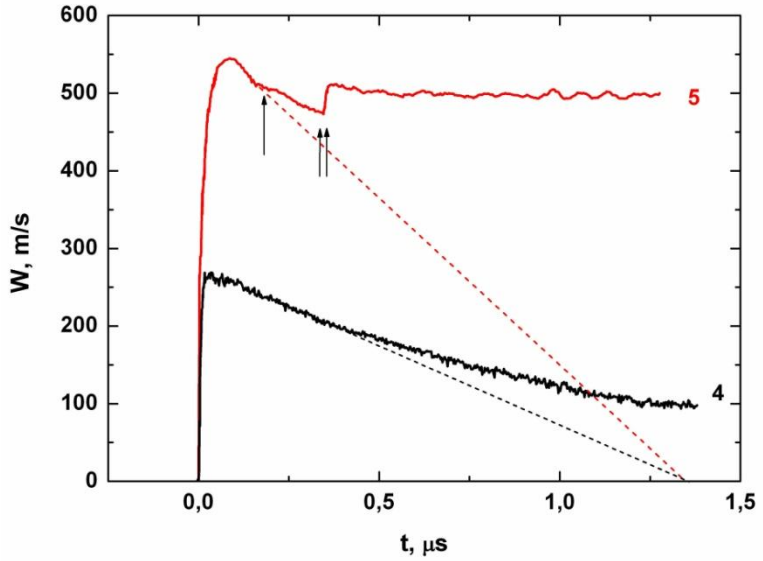


Free surface velocity for ethanol.

$$\langle P_s \rangle = 14 \text{ MPa}$$

Free surface velocity (2, 5) and particle velocity (1, 4) for ethanol.

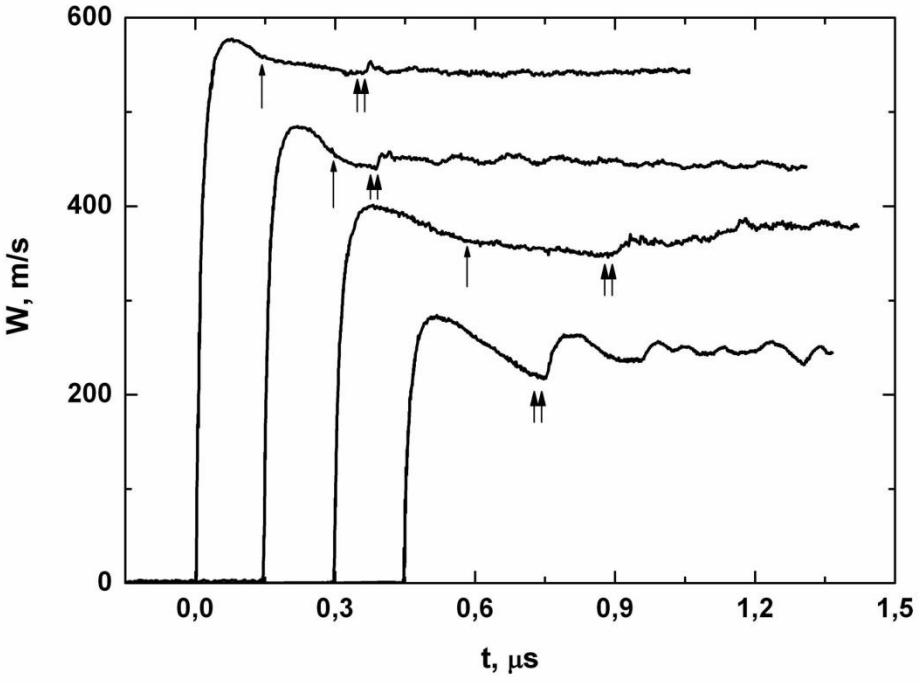




Two-stage failure under cavitation

Hexadecane $C_{16}H_{34}$

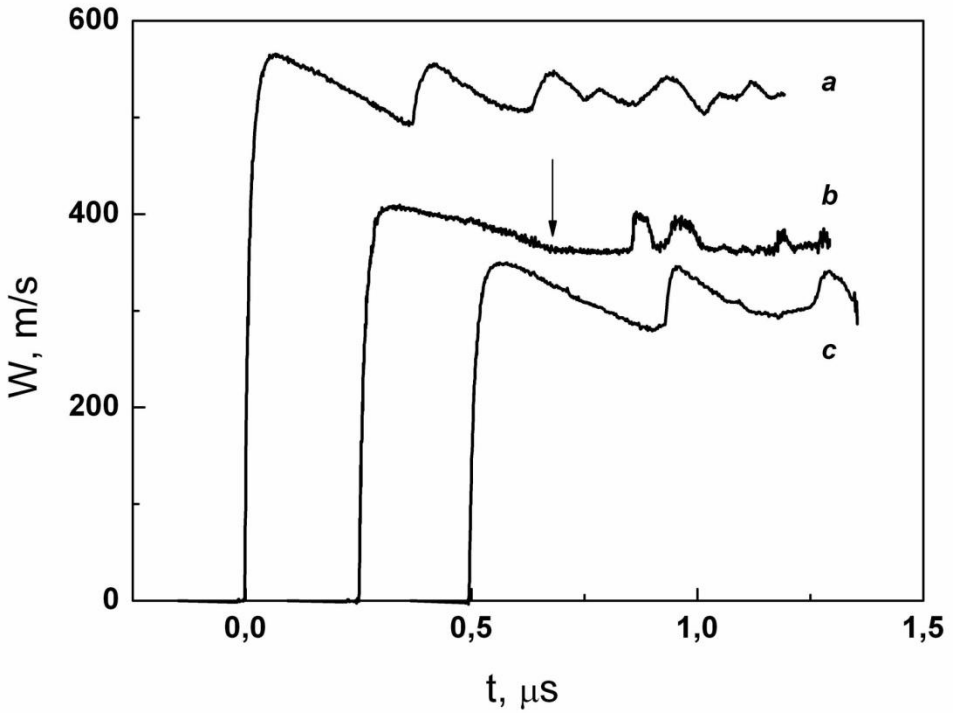
ρ_0=0.73 g/cm^3, c_0=1,33 km/s



Free surface velocity for hexadecane.

Transformer oil $C_{20}H_{41,6}O_{0,3}$

ρ_0=0.895 g/cm^3, c_0=1,445 km/s



Free surface velocity for transformer oil .

The possibility of PROTON RADIOGRAPHY application in experiments with liquid cavitation

- ✓ **Typical sizes: bubble ~ 1 μm, cavitation zone ~ 100 μm, sample – 5 mm.**
- ✓ **Required spatial resolution: <10 μm.**
- ✓ **Field of view: 5-10 mm**
- ✓ **Typical velocities: D ~ 1.5 mm/μs, U ~ 0.6 mm/μs, strain rate – 10^5 s^{-1}.**
- ✓ **Required time resolution: < 20 ns**
- ✓ **Initial density: ~ 1 g/cc.**
- ✓ **Density difference in shock wave: ~ 0.1 g/cc,**
- ✓ **Density difference at the spall: from initial to zero.**

CONCLUSIONS

- **Theory of homogeneous bubble nucleation explains the dependence of measured tensile strength from the strain rate and shock wave amplitude.**
- **Two-stage failure under cavitation was observed for ethanol, hexadecane, and transformer oil. In this case the negative pressures depend on the bubble-growth kinetics.**

But:

✓*No experimental information about process of cavitation development in liquids for testing and improving of dynamic fracture models.*

- **Spall fracture in liquids takes place as a results of homogeneous nucleation.**

But:

✓*The model liquid fracture on the basic theory of homogeneous nucleation still hasn't been proved by direct experimental observations.*

- **So the data on mechanisms and kinetics of this process that could be obtained by proton radiography technique are much needed.**