Multiphysics in Food processing using underwater shock wave

Director/Professor

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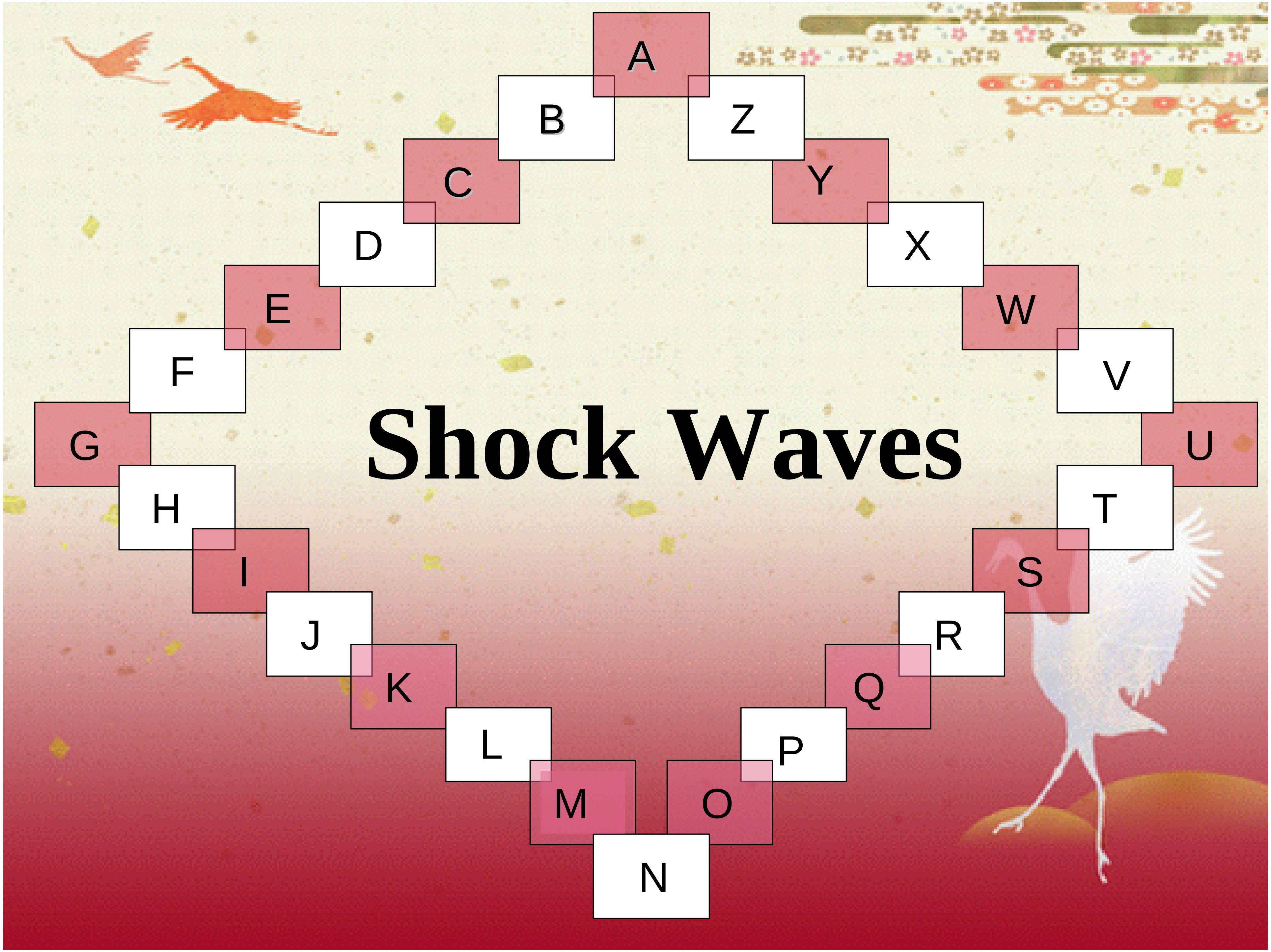
JAPAN


Shock Waves
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z

A:Animal,Agriculture

- Daily
- Meat
- Cheese
- Yogurt
- Ham

TOP

B:Biology

- Gene
- Bio technology

TOP

C:Cryogenic

- Cryogenic

TOP

D:Development

- Devlopment
- Tunnel
- Subway
- New　technolgy

TOP

E:Envelopment, explosive

- Explosives
- Envelopments
- Global heating

TOP

F:Food,fluid

- Food processing
- Soften
- Extraction
- Coffee Powder

TOP

G:Gas

- Gas　Dynamics
- Turbine Flows
- Shock　Tube

TOP

H:Hyper velocity

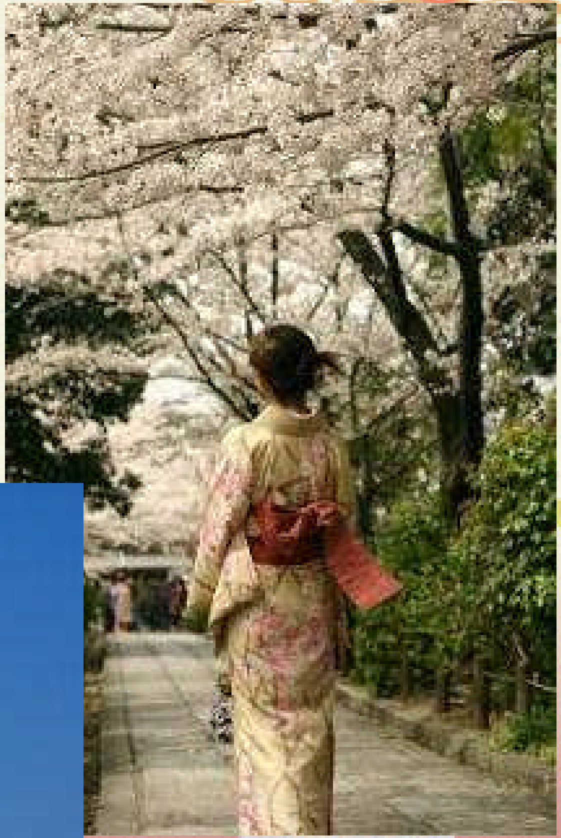
- Metal Jet
- Water Jet

TOP

I:Inspection

TOP

J:Japan



TOP

K:Kumamoto

TOP

L:Life science

- Gene
- Medicine

TOP

M:Metal processing

- Explosive welding
- Explosive forming
- Powder compaction
- Coating

TOP

N:Nature

- Thunder
- Earth Quick
- Meteorite
- K-T boundary

TOP

O:Ozone depletion

- Ozone Sterilization
  Ozone layer

TOP

P:Pharmacy

- Extraction
- New　Phermacy

TOP

Q:Quasi state

- Quasi Steady Phenomena

TOP

R:Risk,recycle

- Risk management
- Risk Inspection
- Recycle for Glass
- Recycle

TOP

S:Soil,sterilization

- Improvement of Soil
- Sterilization

TOP

T:Textile

- Jute
- Cotton
- Permeability
- Stain

TOP

U:UV,underwater

- Underwater Shock wave
- Devices
- Principle
- Application

TOP

V:Visualization

- High speed Camera
- High speed Video
- Streak Camera

TOP

W:Wood

- Permeability
- Flame retardant
- Insulation

TOP

X:X-ray

- X-ray

TOP

Y:Y&Y

- Yacht
- Yield point

TOP

Z:Zoology

- Shock and Zoo
-

TOP

Why underwater shock waves are used ?

- The sound velocity of water is about 1500m/s in room temperature, the strength of underwater shock wave is easy up to about 100Mpa.
- The strength of underwater shock waves are very easy controlled using reflection ,diffraction or refraction or concentration.
- The duration time of underwater shock wave is also controlled by the configuration design of water container.
- In the case of underwater shock wave, the un-heated processing is possible.
- The underwater shock wave is generated not only by explosion of explosives but also by the high currents.

Control of the Strength of Shock wave

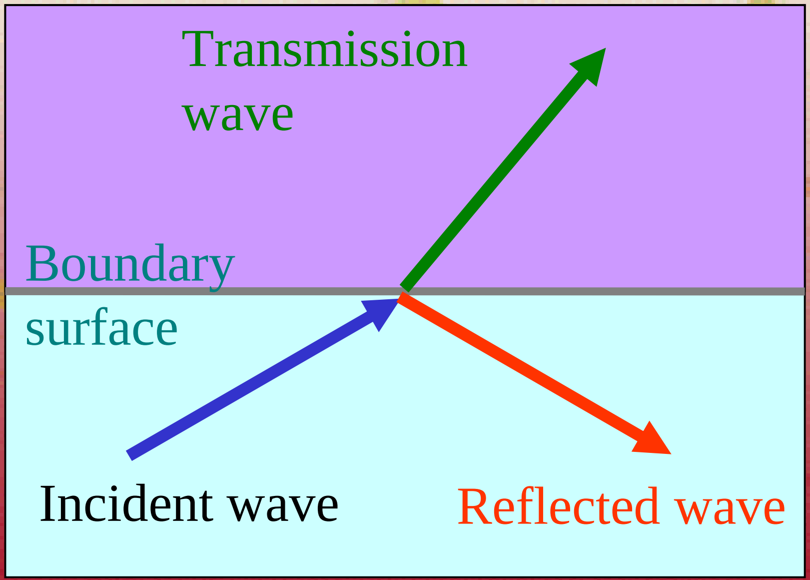
- By combination the shock reflection or diffraction,
  the strength of underwater shock wave can be well controlled.

- Also the underwater shock wave well concentrated in a point using a suitable pressure vessels which has an ellipsoid configuration.

- In followings ,I will show the example processing such as ;
  powder compaction, Metal forming, Wood treatment and
  food processing

Shock wave treatment for food

- Generation methods
  - Under water explosion
  - High voltage electric discharge in water
- Properties
  - High pressure, very short duration of action



Condenser bank for Food processing

Condenser bank

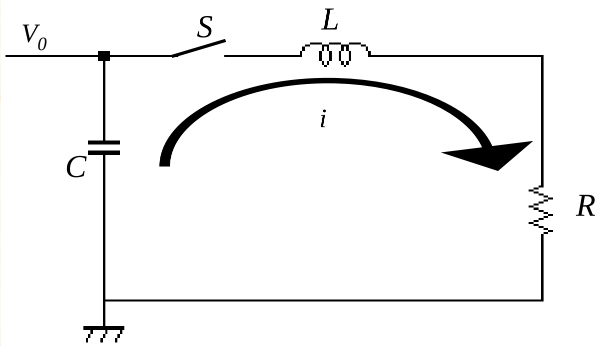
NICHICON Co.

Maximum voltage: 40 kV

Electrical capacitance: 12.5μF (constant)

Maximum energy: 10 kJ

Discharge waveform: Damped Oscillation



Basic circuit of a condenser

Damped Oscillation

$R^2 < 4L/C$

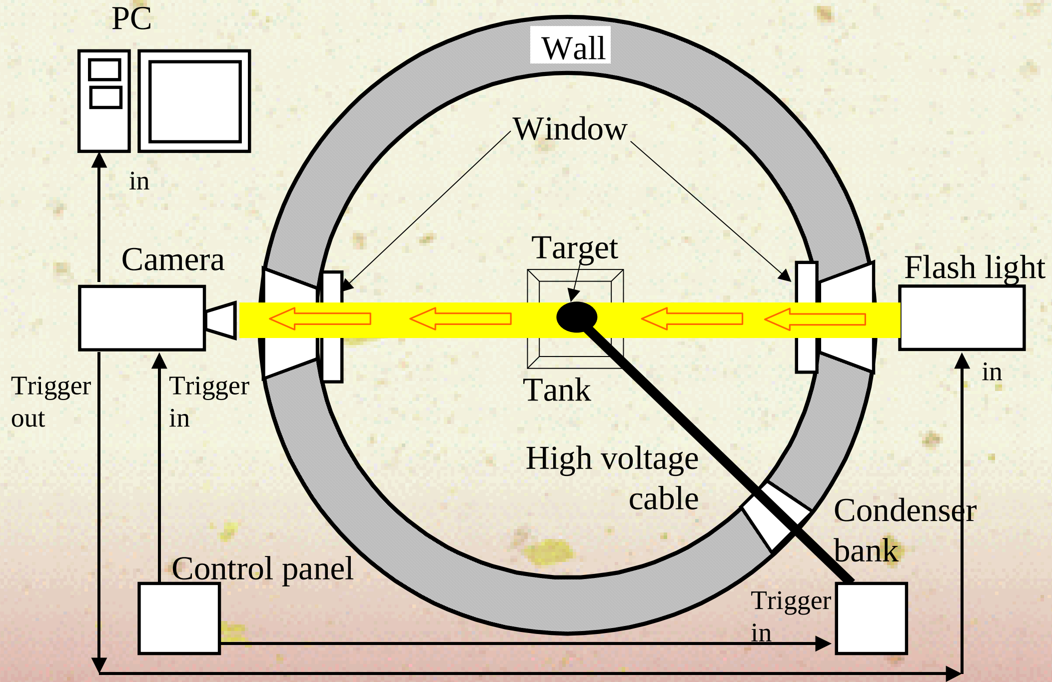
$$i = \frac{V_0}{\omega_0 L} \exp\left(-\frac{R}{2L}t\right) \sin \omega_0 t$$

Metal wire

Metal wire	Composition (%)	Density (kg.m^{-3})	Electrical Resistivity (10^{-8} Ω.m)	Melting point (K)	Thermal conductivity (W.m^{-1}.K^{-1})	Coefficient of linear expansion (10^{-6} K^{-1})
Copper	Cu (99.9)	8960	1.67	1356	401	16.5
Aluminum	Al (99.9)	2690	2.65	933	237	23.0
Alumel	Mn(1.8), Si(1.7), Al(1.2), Ni(95)	8150	33	1400	30	12
Titanium	Ti (99.5)	4540	42	1933	21.9	8.5
SUS304	Cr(18), Ni(8), Fe(74)	7093	71	1693	36	14.7
Nichrome	Ni(80), Cr(20)	8052	109	1673	17	11.7

Diameter: 0.1mm, 0.3mm, 0.5mm

Visual observation



IMACON468

HADLAND PHOTONICS

interframe times 10ns to 1ms in 10ns steps independently variable, number of channels framing:4 streak:1

Arc Flash

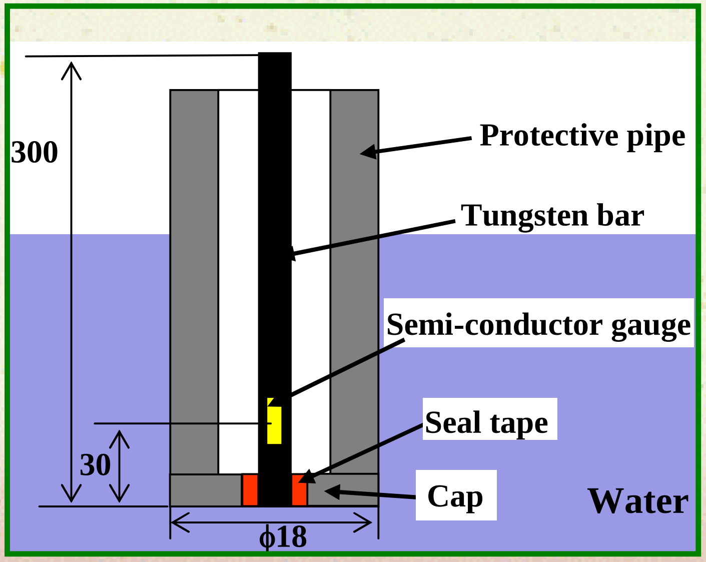
NISSIN ELECTRIC Co., LTD.

Power supply: AC100V

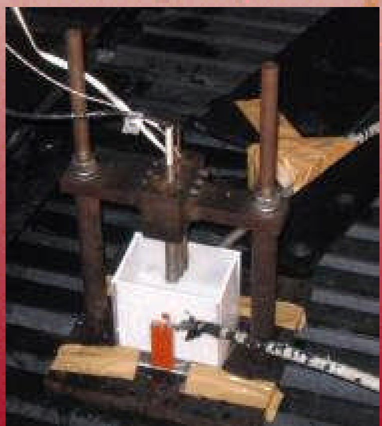
Out-put supply; 50-200J/F

Half-amplitude level of luminescene: 150-350μs

Pressure converter



Schematic diagram of pressure transducer



Stress in tungsten bar ; P_B

$$P_B = \frac{2E}{G \cdot V_C} \cdot K_1 \cdot V_{out}$$

Pressure of underwater shock wave; P_w

$$P_w = \frac{1 + \dfrac{\rho_w \cdot C_w}{\rho_B \cdot C_B}}{2} \cdot P_B \cdot K_2$$

Tungsten bar

ρ_B=19088kg/m^3, C_B=4650m/s, E=412.7GPa

Water

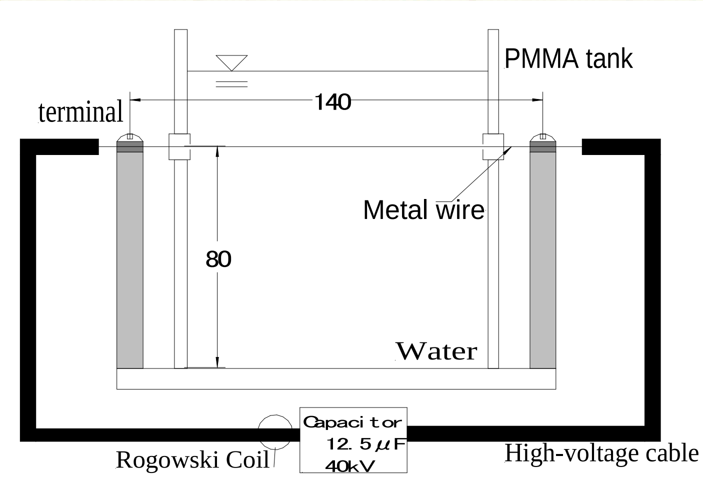
ρ_w=1000kg/m^3, C_w=1490m/s

Parameters

K_1=1.173, K_2=1.4, , G=144(gauge factor)

V_C;circuit voltage, V_{out};output voltage

Impressed current measurement to metal wire



Experimental setup in this study

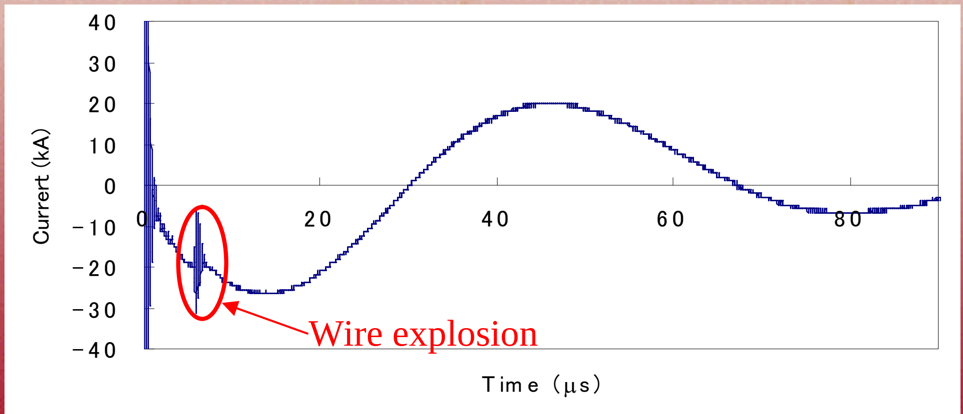
Electric resistance of metal wire

$$R = \rho \frac{L}{A}$$

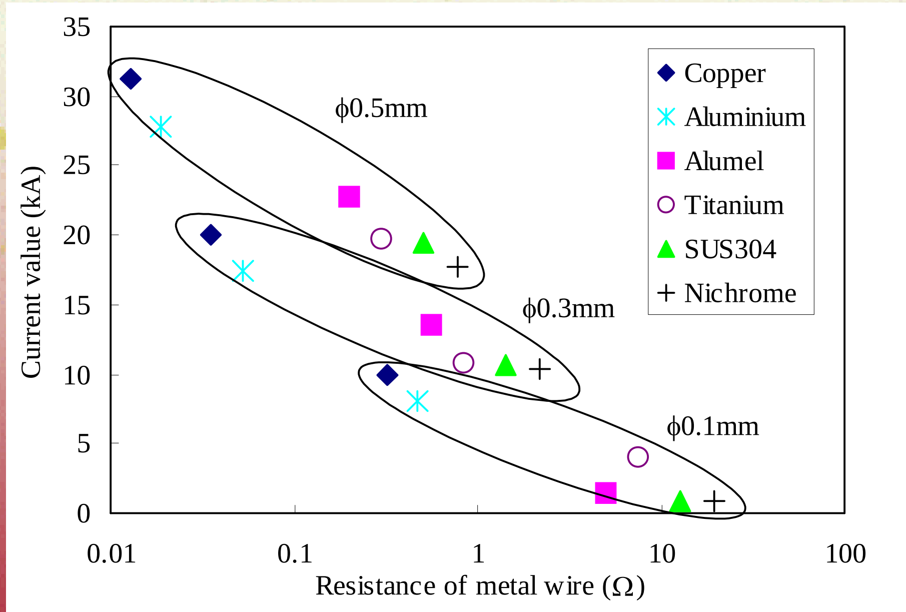
r: Electrical resistance of metal wire

L: length (140mm)

A: cross-section area of metal wire

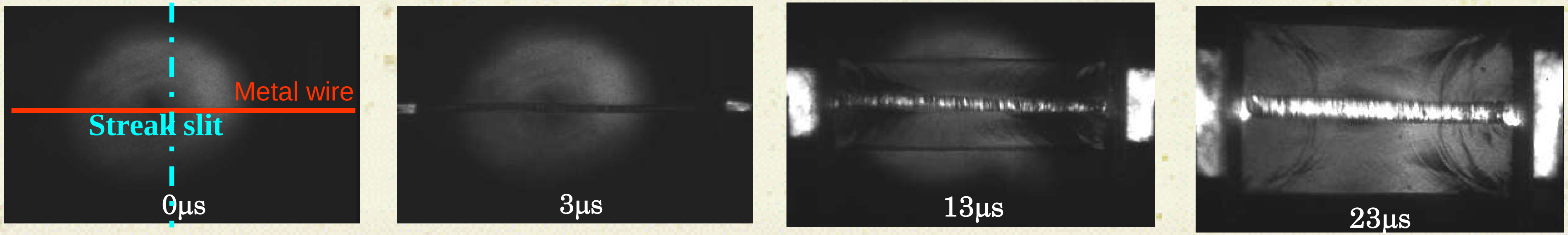


Typical waveform of current (Cu, ϕ0.3mm)

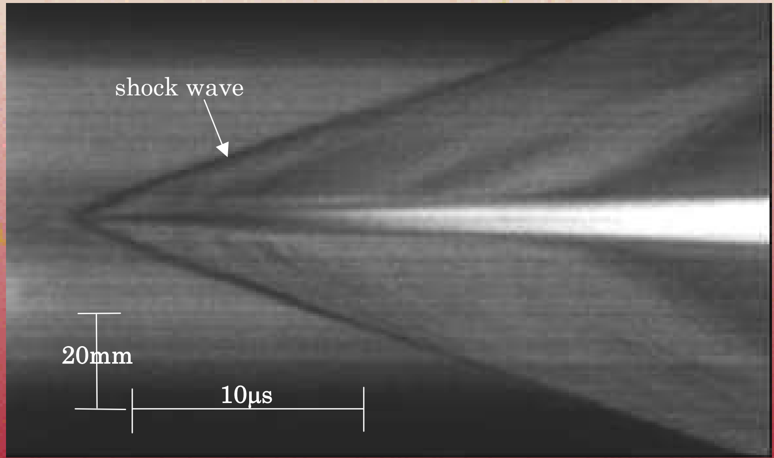


Relation between resistance of metal wire and current value

Visual observation of underwater shock wave produced by wire explosion

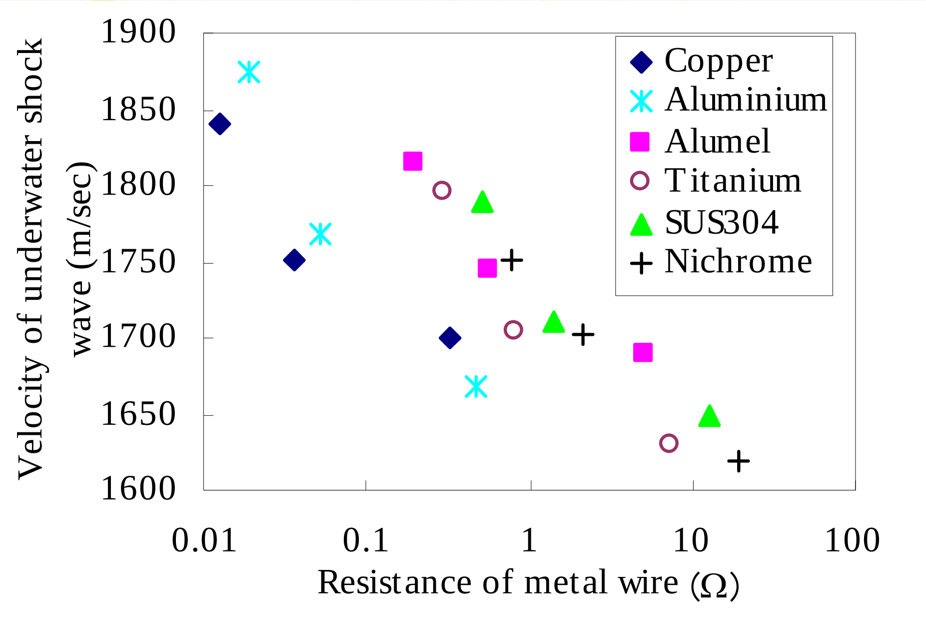


Framing photographs of underwater shock wave produced by wire explosion

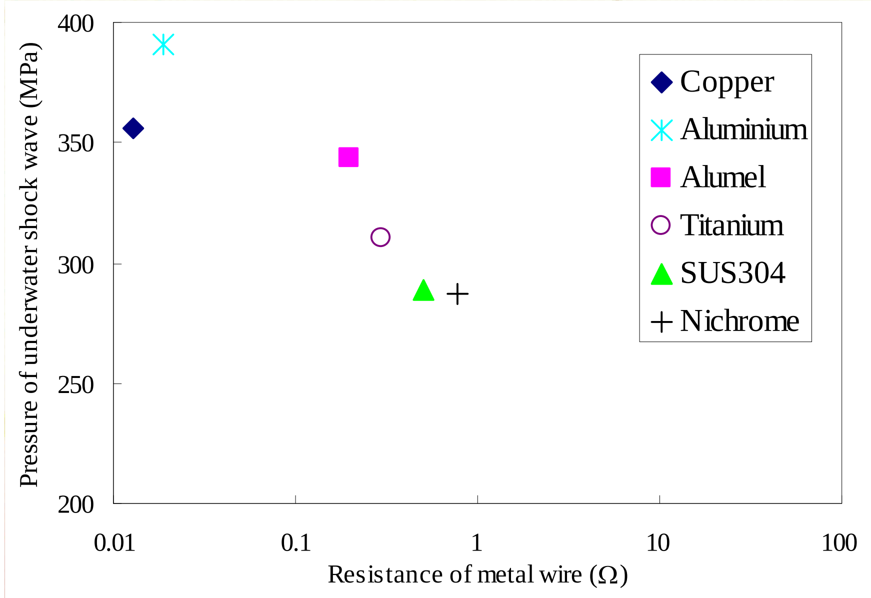


Streak photograph of underwater shock wave produced by wire explosion

Rapidity of underwater shock wave produced by wire explosion



Relation between resistance of metal wire and velocity of underwater shock wave



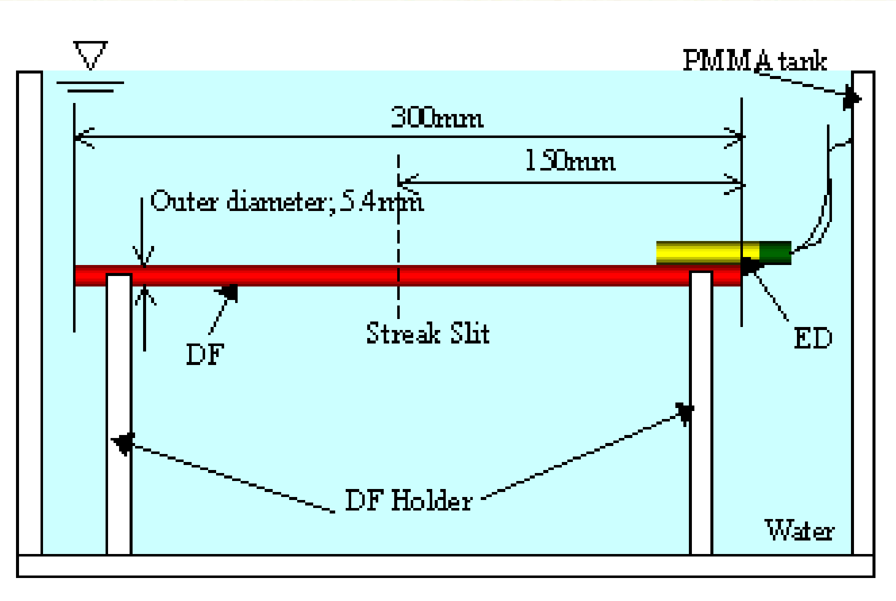
Relation between resistance of metal wires of ϕ0.5mm and pressure of underwater shock wave

There is a different tendency in the wire of aluminium.

Thermite reaction

By the reaction between O (included in H2O) and Al, a large amount of heat is generated.

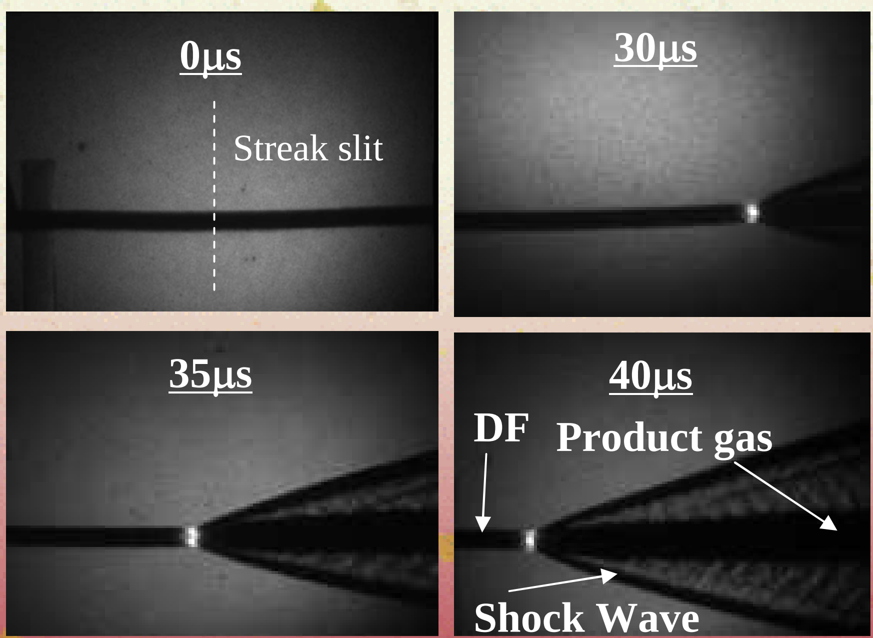
Visual observation of underwater shock wave produced by DF



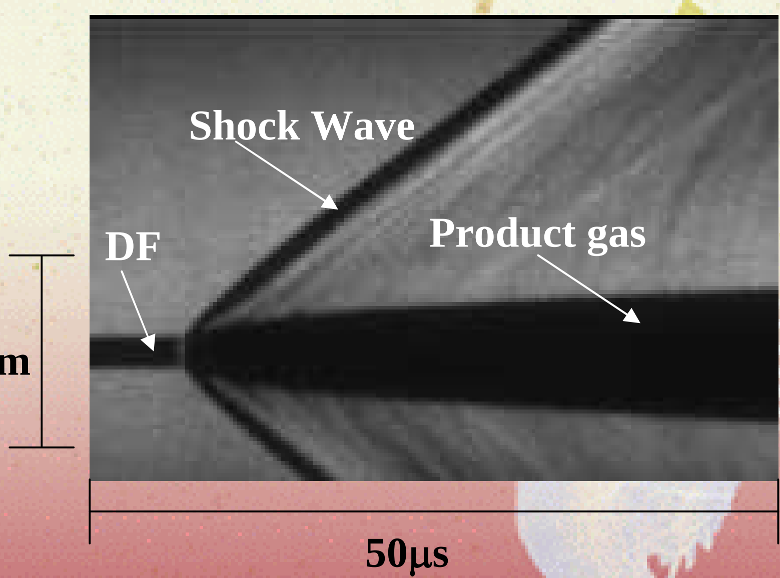
DF: Detonating fuse
produced by Nippon Kayaku Co. LTD.
Detonation Velocity: 6308m/s
Diameter: 5.4mm

ED: No.6 Electric Detonator
produced by ASAHIKASEI Chemicals Co.

Visual observation of underwater shock wave produced by DF

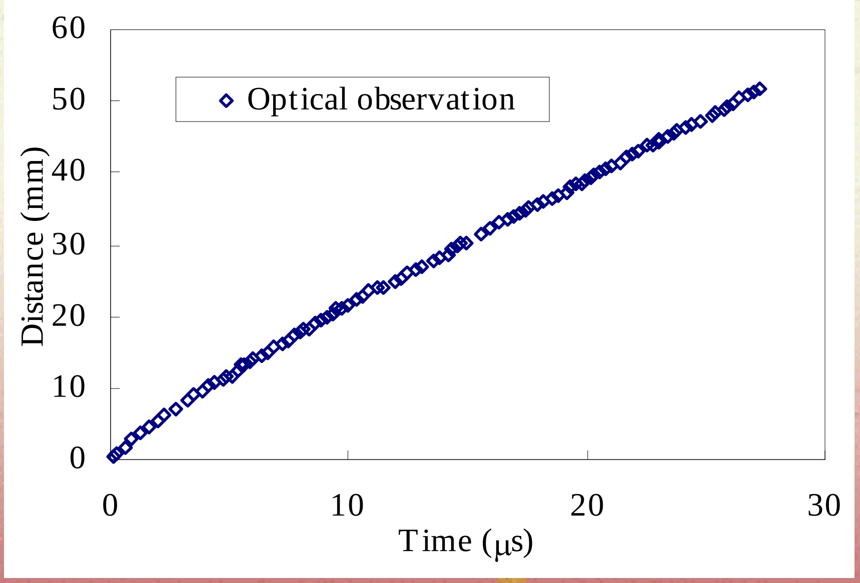


Framing photographs of underwater shock wave generated by the detonating fuse

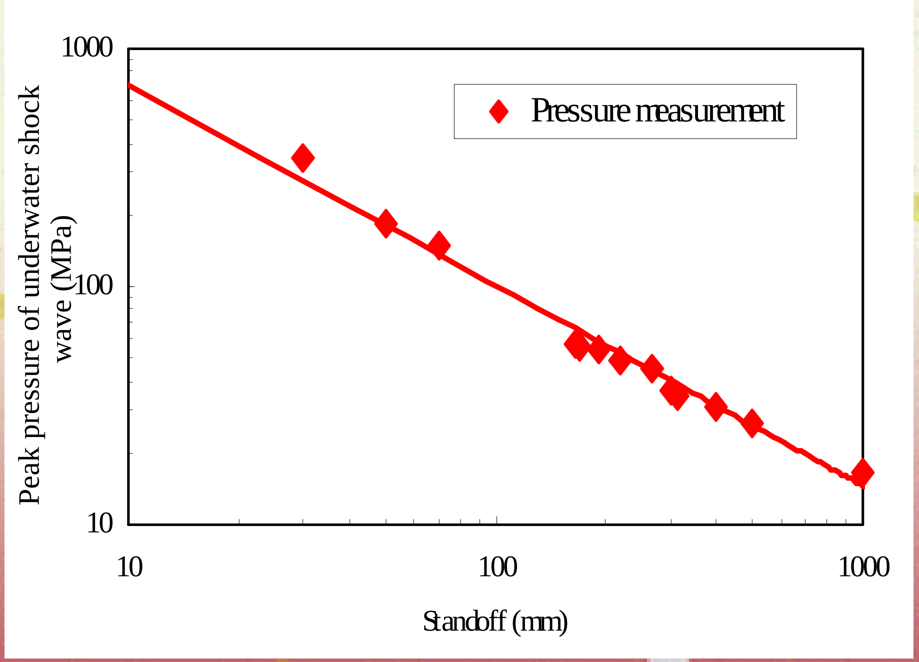


Streak photograph of underwater shock wave generated by the detonating fuse

Decay of the underwater shock wave

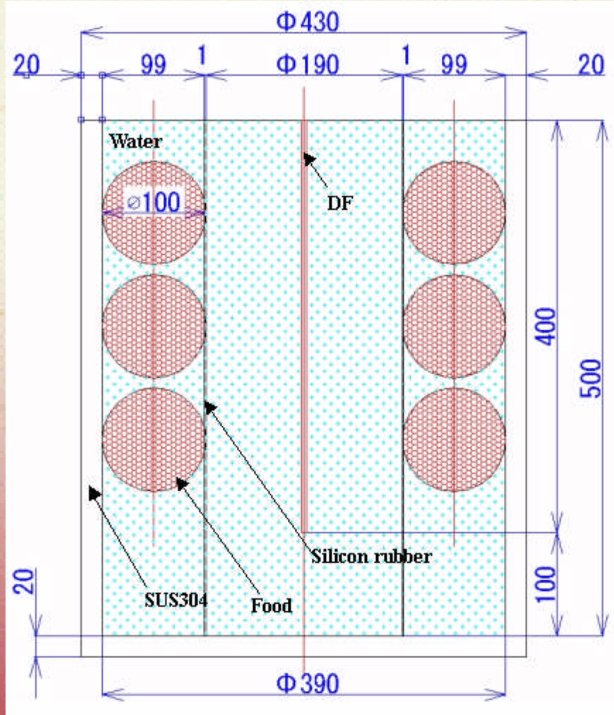


Relation between the time and the distance of underwater shock wave generated by the detonating fuse



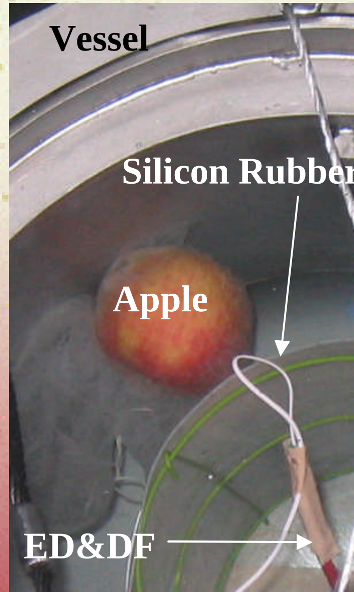
Pressure value of underwater shock wave

Food processing device



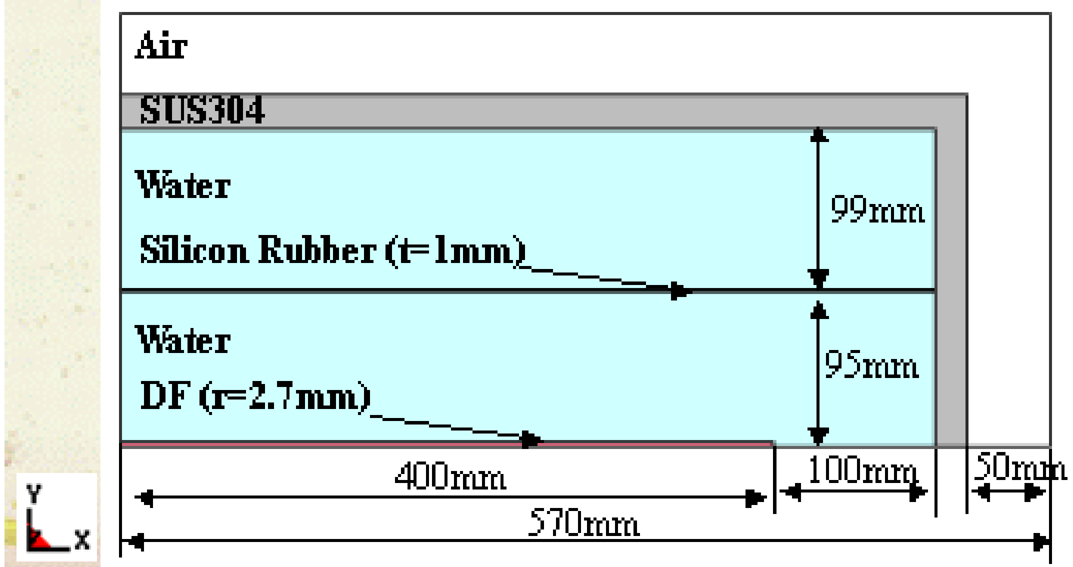
Schematic illustration of the vessel for food processing

Photograph of the vessel



Experimental setup in the vessel

Numerical Simulation



Fluid-Structure Interaction

The Euler method was applied to fluid (DF,Water,Air), and the Lagrange method was applied to structure (SUS304,Silicon rubber).

The interaction calculation was done to both by the FSI(Fluid Structure Interaction) algorithm.

PART	*METHOD*	*MATERIAL*	*E.O.S.*
DF	**Euler**	**High_Explosive_Burn**	**JWL**
Water	**Euler**	**Null**	**Mie-Grüneisen**
Air	**Euler**	**Null**	**Linear Polynomial**
SUS304	**Lagrange**	**Elastic_Plastic_Hydro**	**Mie-Grüneisen**
Silicon rubber	**Lagrange**	**Elastic**	**-**

Governing equation

The Euler method was applied to fluid (DF,Water,Air), and the Lagrange method was applied to structure (SUS304,Silicon rubber).

Eulerian method	Lagragian method
Equation of mass conservation $\frac{\partial \rho}{\partial t} = -\rho \cdot div(v) - v_i \frac{\partial \rho}{\partial x_i}$	
Equation of momentum conservation $\rho \frac{\partial v_i}{\partial t} = \sigma_{ij,j} - \rho \cdot v_i \frac{\partial v_i}{\partial x_j}$	Equation of momentum conservation $\rho \frac{\partial v_i}{\partial t} = \sigma_{ij,j}$
Equation of energy conservation $\rho \frac{\partial e}{\partial t} = \sigma_{ij} \cdot \varepsilon_{ij} - \rho \cdot v_i \frac{\partial e}{\partial x_j}$	Equation of energy conservation $\rho \frac{\partial e}{\partial t} = \sigma_{ij} \cdot \varepsilon_{ij}$

Computational method & Equation of state

Lagrangian formulation & Multi Material Eulerian formulation

Detonating fuse ; JWL

$$P_{JWL} = A\left[1-\frac{\omega}{VR_1}\right]\exp(-R_1V) + B\left[1-\frac{\omega}{VR_2}\right]\exp(-R_2V) + \frac{\omega e}{V}$$

	A(GPa)	B(GPa)	R_1	R_2	ω
DF	452.35	8.85	5.485	1.425	0.28

Water&SUS304; Mie-Grüneisen

$$P = \frac{\rho_0 c_0^2 \eta}{(1-s\eta)^2}\left[1-\frac{\Gamma_0\eta}{2}\right] + \Gamma_0\rho_0 e$$

	ρ_0(kg/m^3)	c_0(m/s)	s	Γ_0
WATER	1000	1490	1.79	1.65
SUS304	7900	4570	1.49	2.17

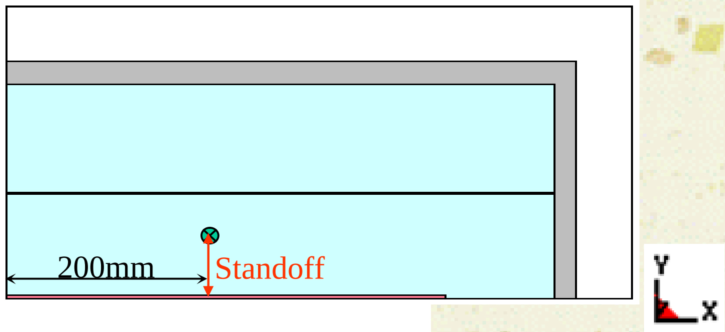
Air ; Linear Polynomial

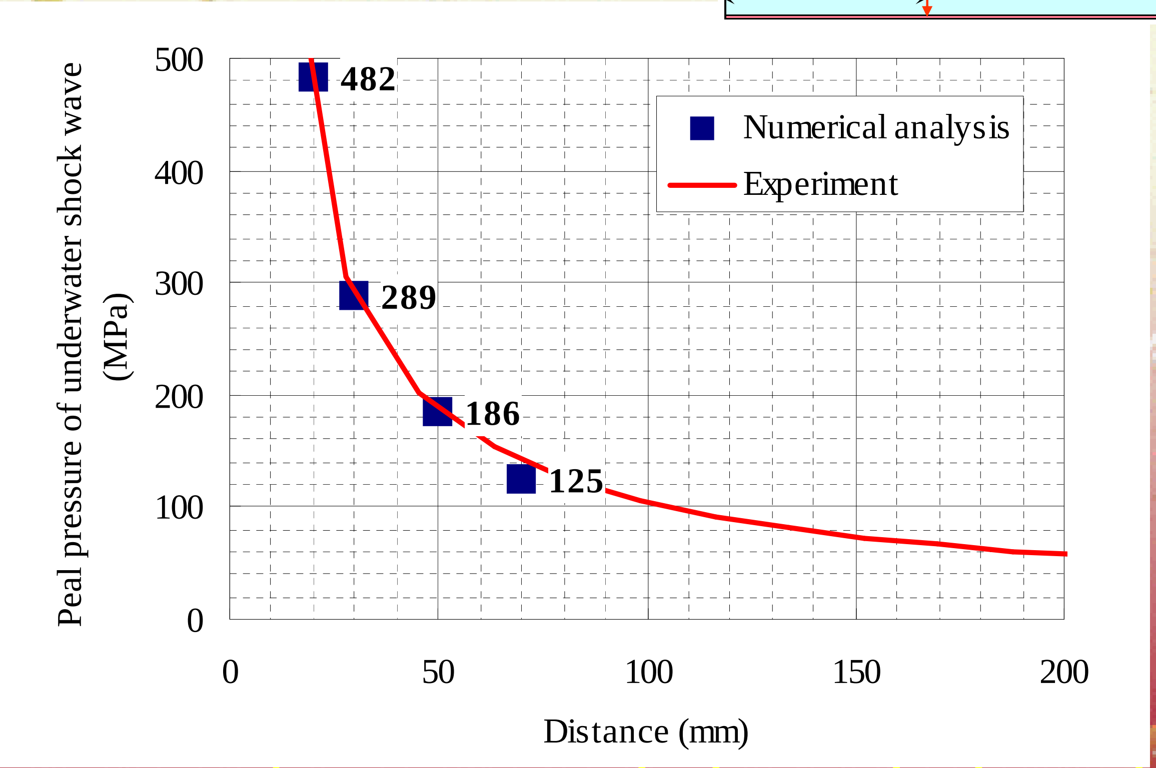
$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E$$

	ρ_0(kg/m^3)	γ	C_4	C_5
AIR	1.025	1.403	0.403	0.403

3. Burn technique ; C-J volume burn

Comparison of pressure

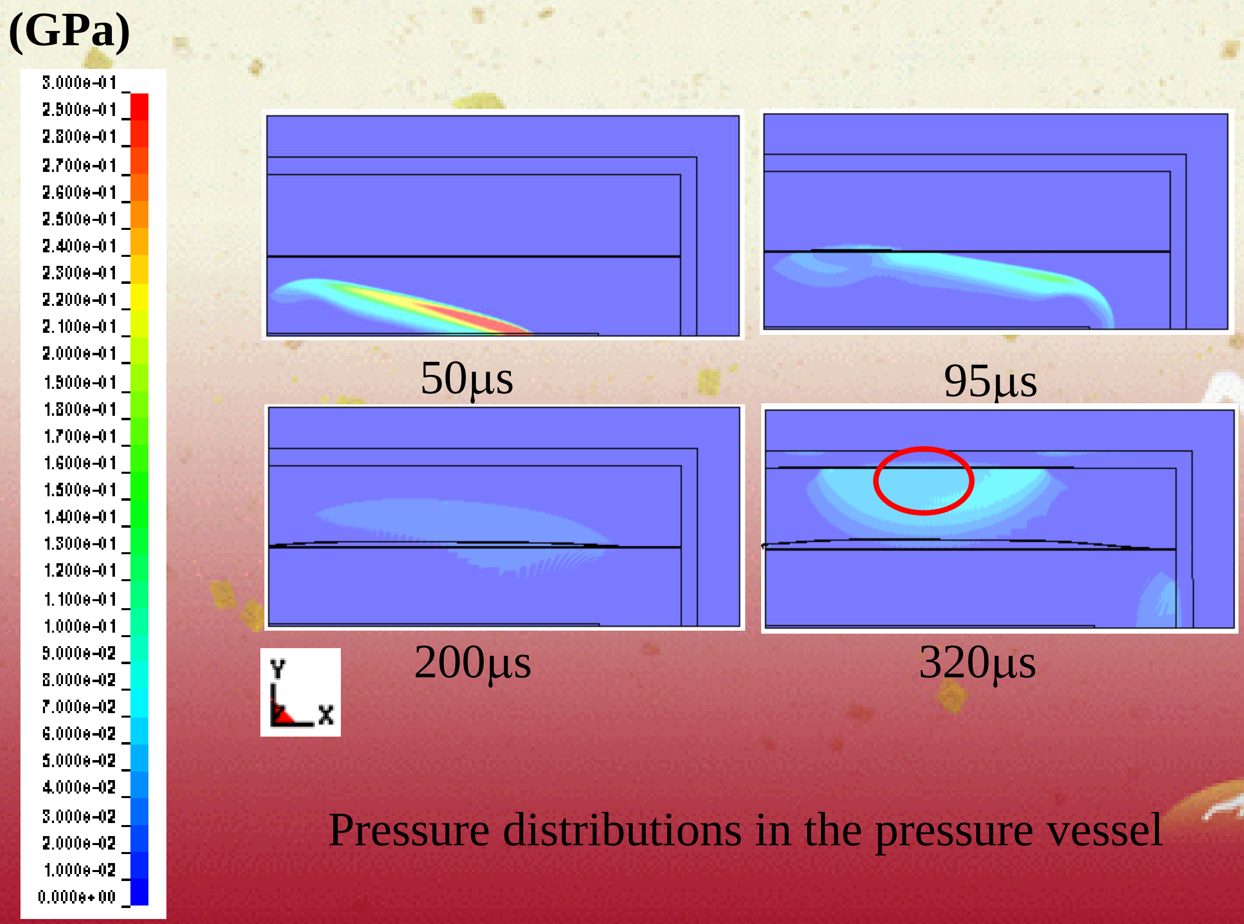




Comparison between experimental and numerical analysis results for the underwater shock pressure

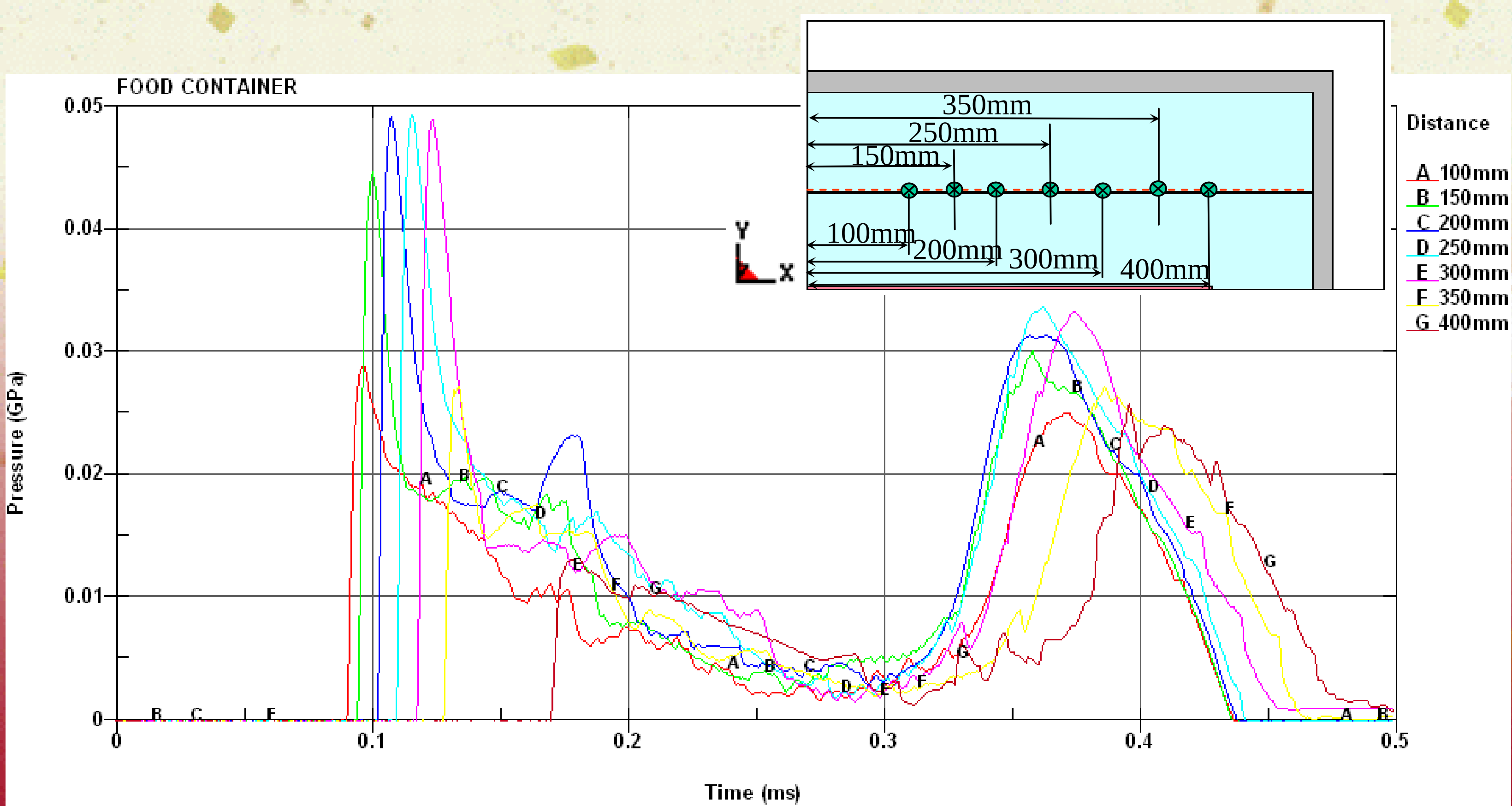
Pressure distribution

The reflected wave can be confirmed by boundary (A) of SUS304 and water. The reflected wave spreads as a shock wave because the impedance of SUS304 is higher than that of water.

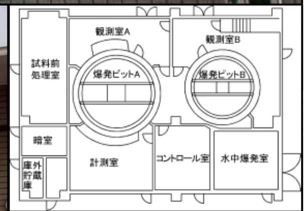


Pressure distributions in the pressure vessel

Pressure applied on food

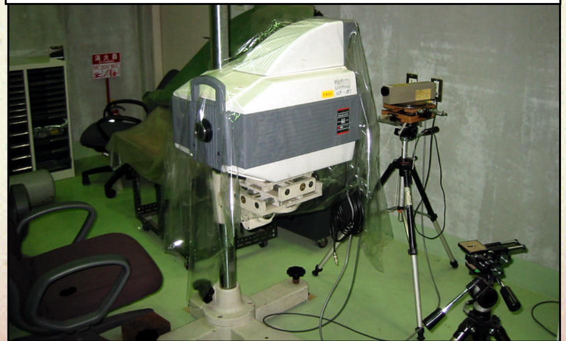



衝撃実験棟


観測室A
観測室B
試料前処理室
爆発ピットA
爆発ピットB
暗室
屋外貯蔵庫
計測室
コントロール室
水中爆発室

Equipments of the Centre

Image converter camera



1x10^{8}frames/s

Pit A

6mφ Explosive:10kg

Plasma Acoustic Blast

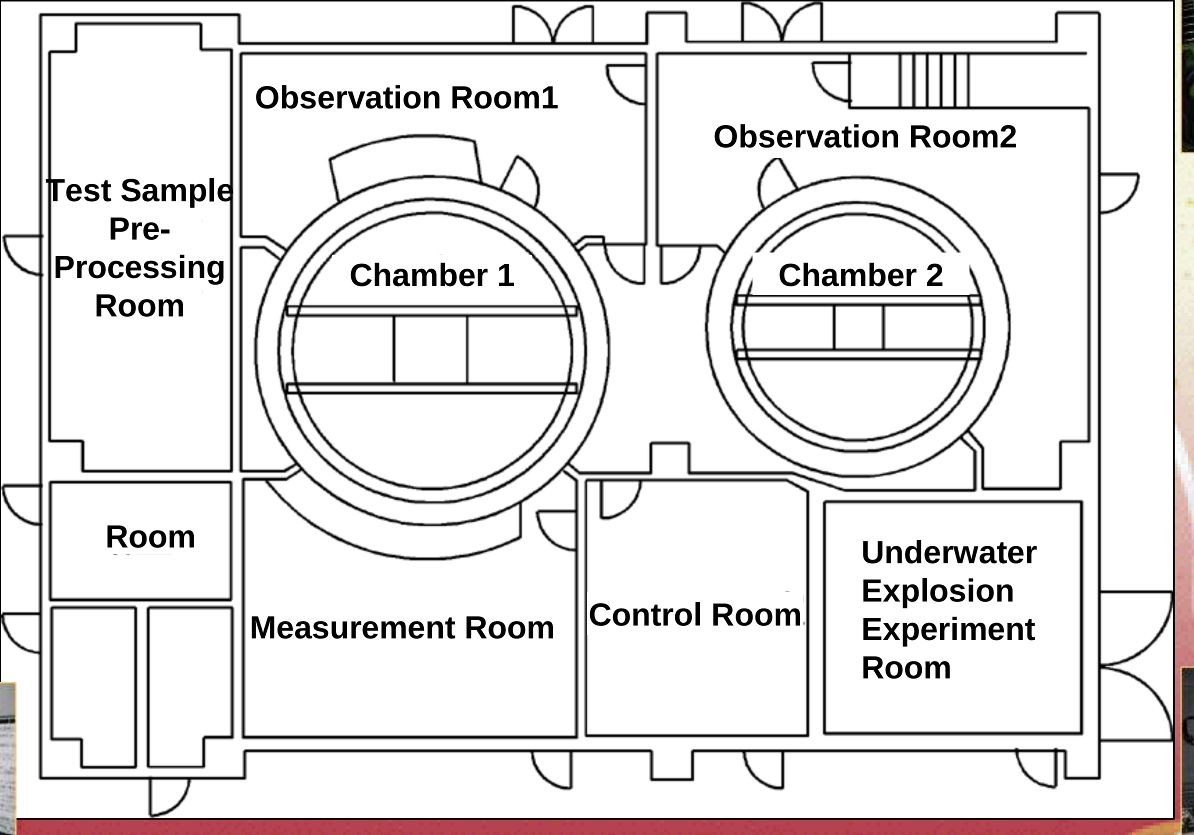
DC Max Voltage:22kV
Capacitance:200μF
Summit Current:75kA
Max Energy:50kJ

Control Room

Laboratory building

Explosion Chamber

Chamber 1



Observation Room1

Control Room

Underwater Explosion Experiment Room

Research Fields

Examples of food processing by shock waves

Effect	Food example	Comment
Softening	Pineapple	Edible part can be double
Improvement of exploitation	Apple	Easy to squeeze
Improvement of penetration	Japanese radish	Decrease penetrating time
Improvement of extractability	Coffee beans	Decrease extracting time
Pulverization	Tea leaves	Pulverize without friction heat

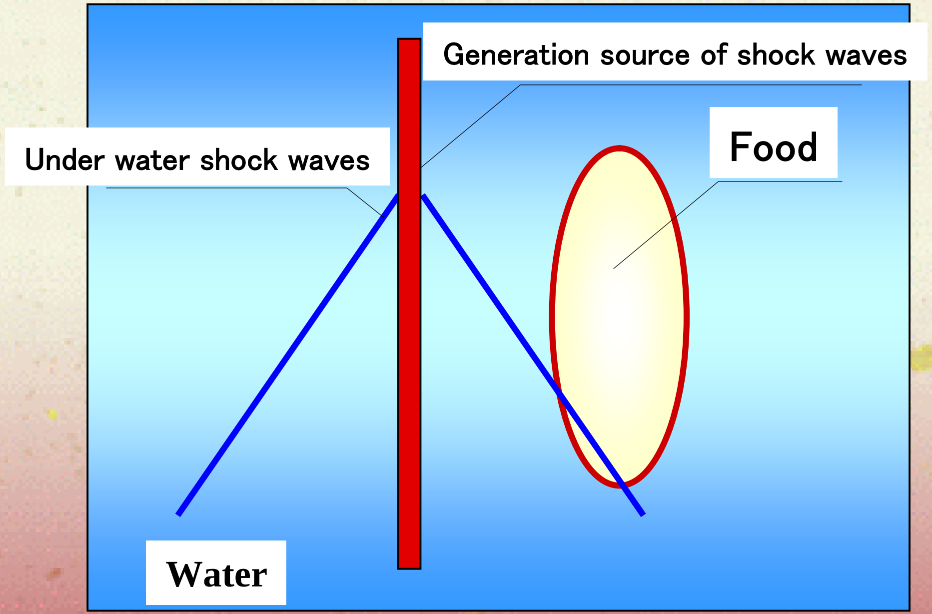
Features of food processing by shock waves

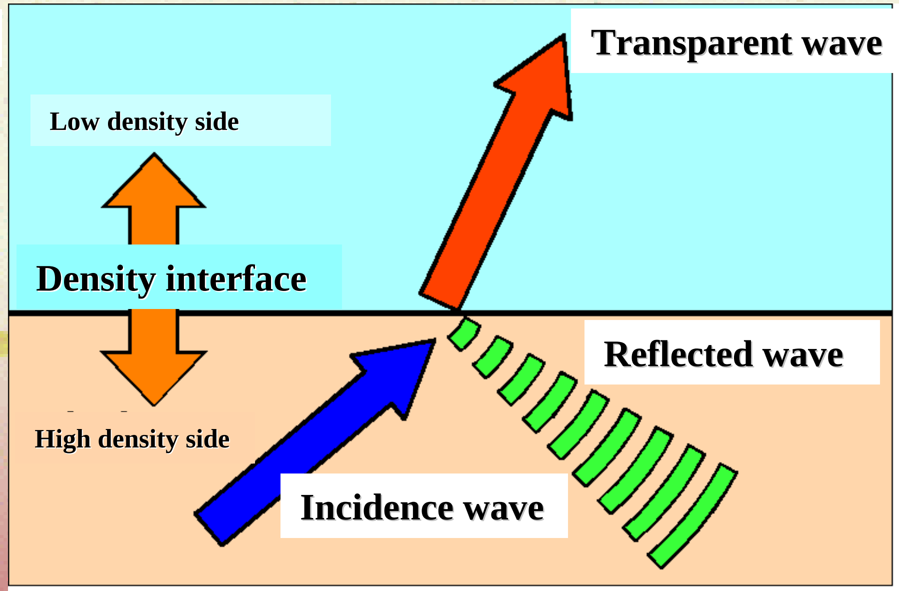
1. Shock wave processing for food is heatless.
2. Food processed by shock wave is almost in the raw
3. Shock waves is generated by explosive and electricpulse. The pressure is very high and reaches several MPa to several hundred.

Experiment of shock wave loading by explosives

Experiment of shock wave loading by electric pulse

Functions of shock waves for food

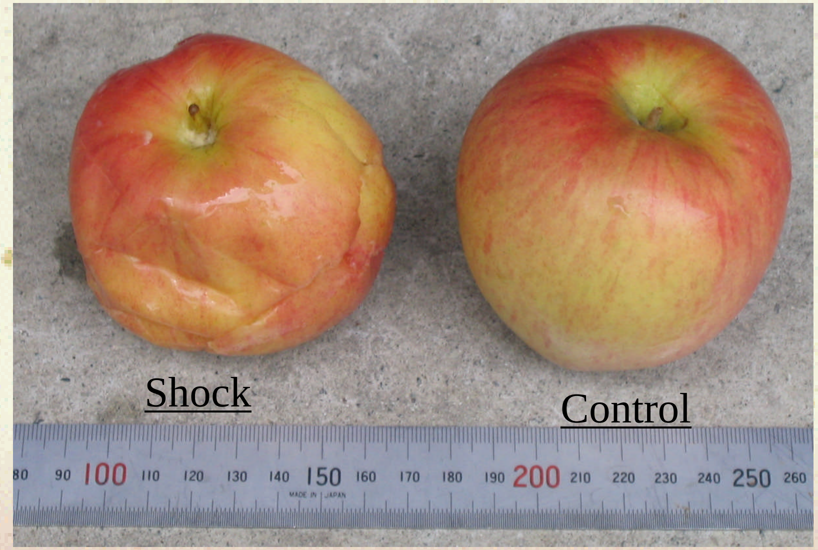




The shock wave is a momentary very high pressure at the MPa level (1MPa=100 atmospheric pressure) spreads at the speed that exceeds speed of sound. The heat denaturation action for food is almost none and only the pressure acts on food.

Shock waves cause the expansion wave and the reflection wave on food and it's possible to process food by taking this advantage.

Apple processed by underwater shock wave

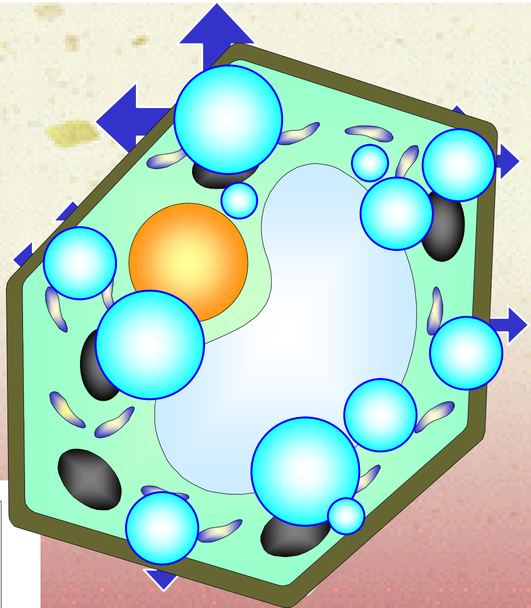


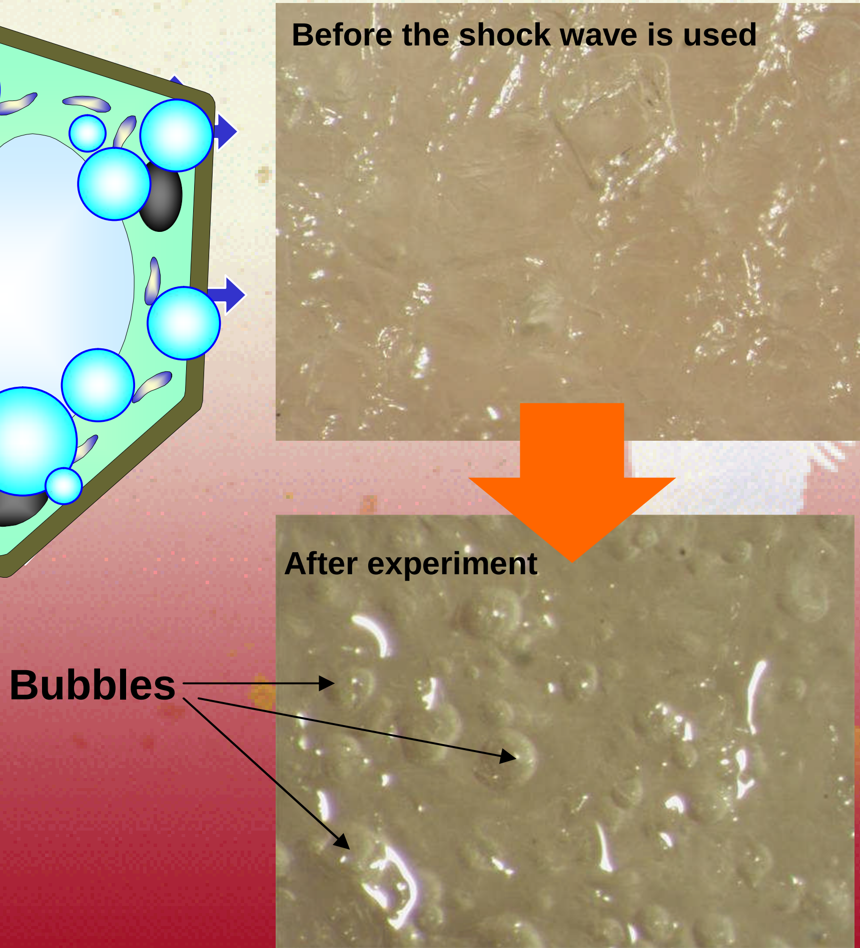
Apple processed by underwater shock wave

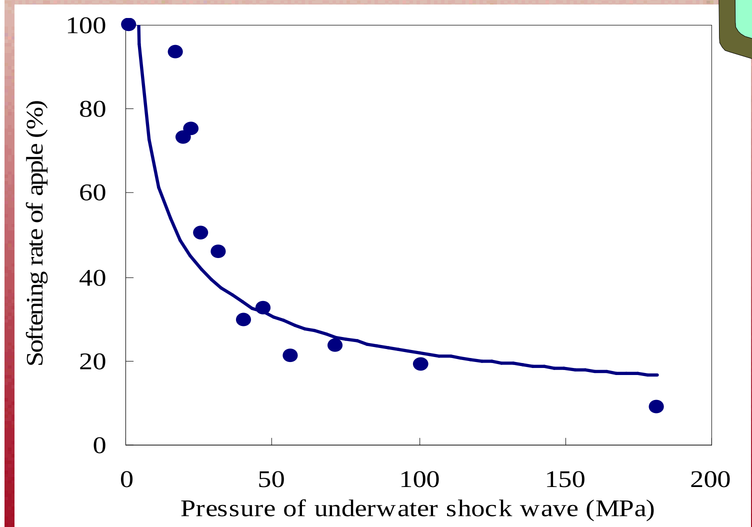
	P_{max} (MPa)	Hardness		pH
		Peel side	Center	
Control	-	80	79	3.5
DF	50	13	27	3.3
WE	50	20	33	3.3

Softening principle of Apple

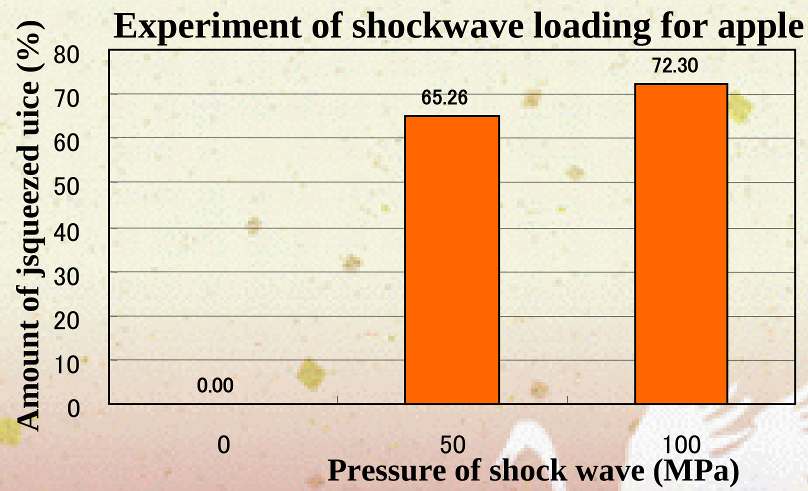
Food is soften because the cell walls (membrane) are destroyed by expansion of cell and bubbles which can be expanded by a reflected wave in the cellular tissue.





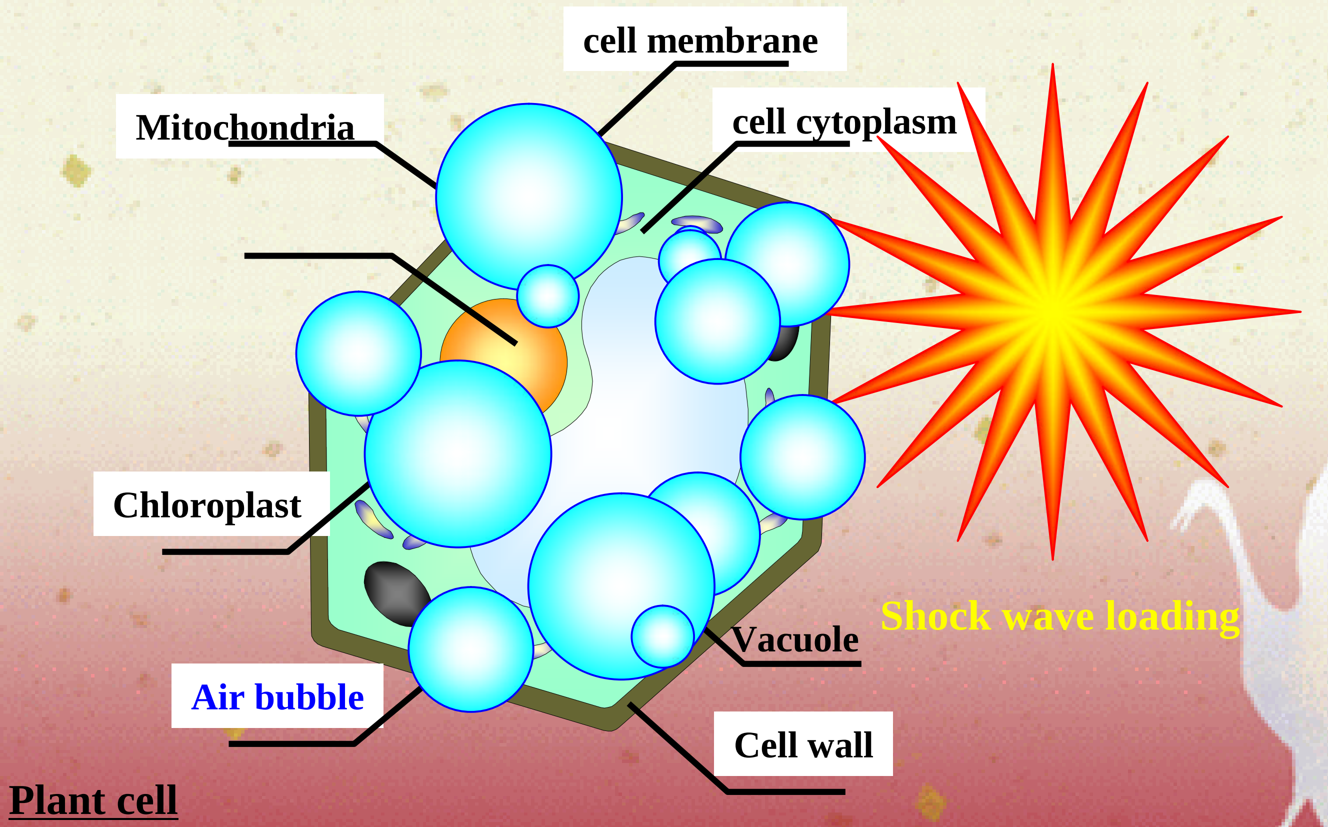


Softening by shock wave loading: apples



The apple flesh become soft by shock wave loading, and it's very easy to gain juice from the apple by putting weight on it and squeezing by hand as well.

Mechanism of softening



Mechanism of softening

Shock waves spreads at the more than 1500m /s and destroy cells in the apple.

Preparation before processing

Vacuum-Packed food

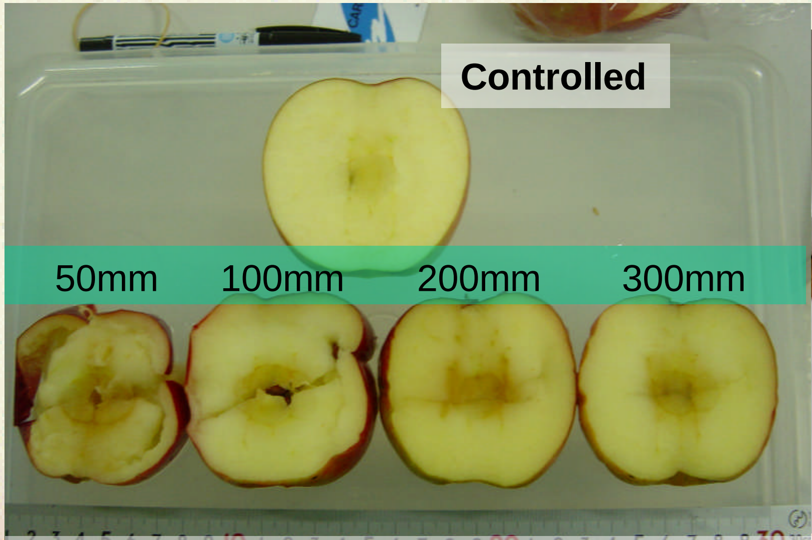
Detonating fuse as generation source of shock waves

Polycarbonate bottle provides

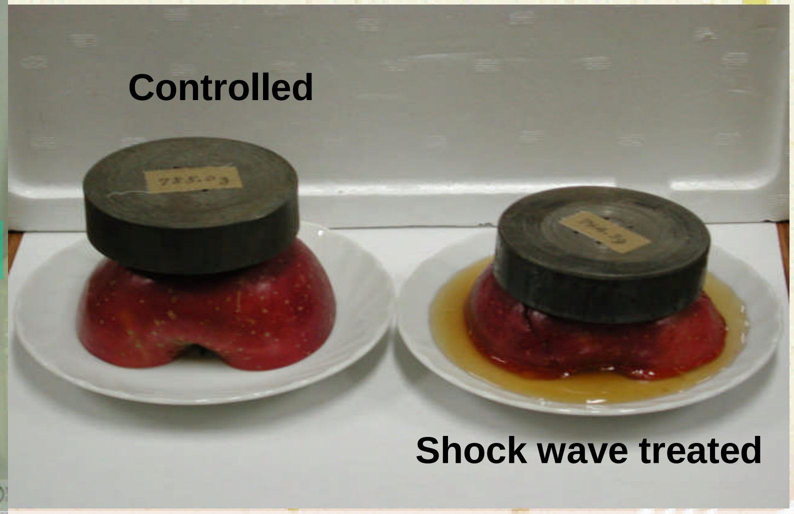
- High clarity
- High crashproof
- High heat tolerance

Image of shock wave loading

Before and after shock wave loading



Cross section of apples
after shock wave loading

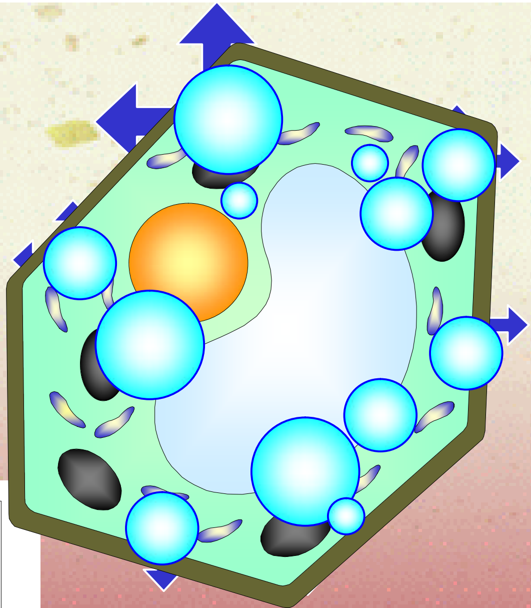


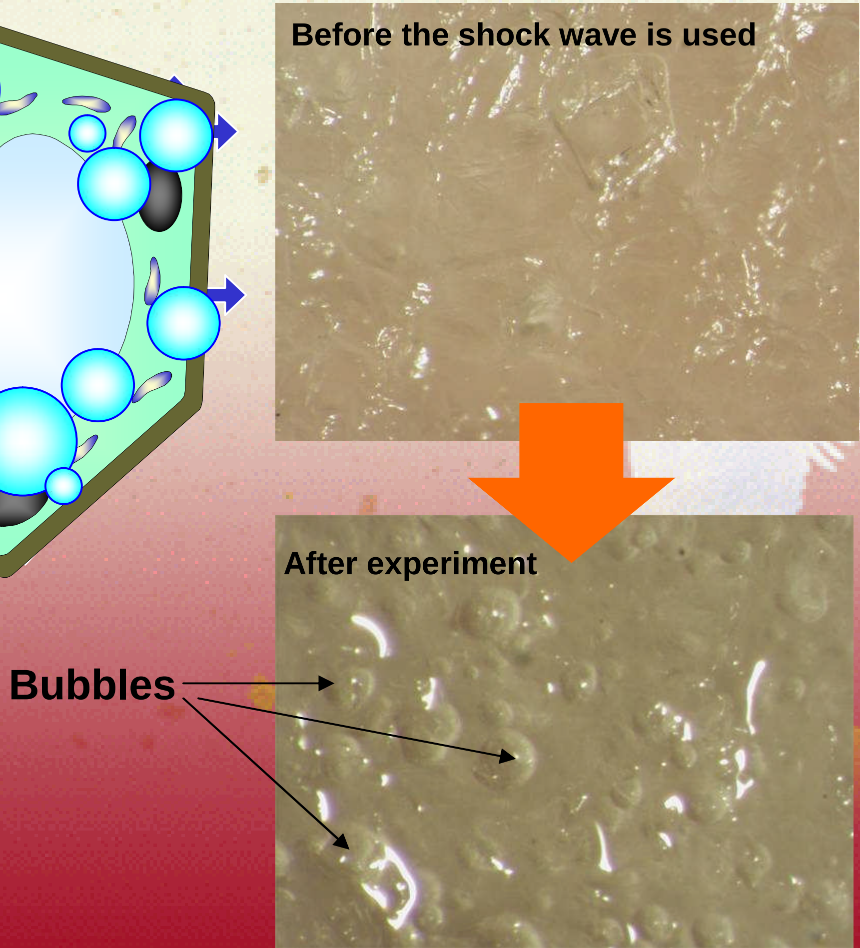
It's easy to gain apple juice

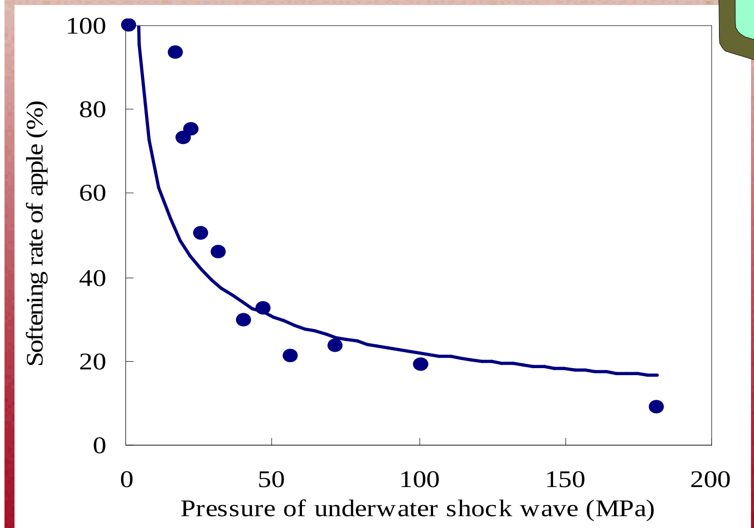
By shock wave loading it becomes like a sponge, and spills out easily. Moreover, it's possible to put a straw into the apple and drink directly.

Softening principle of Apple

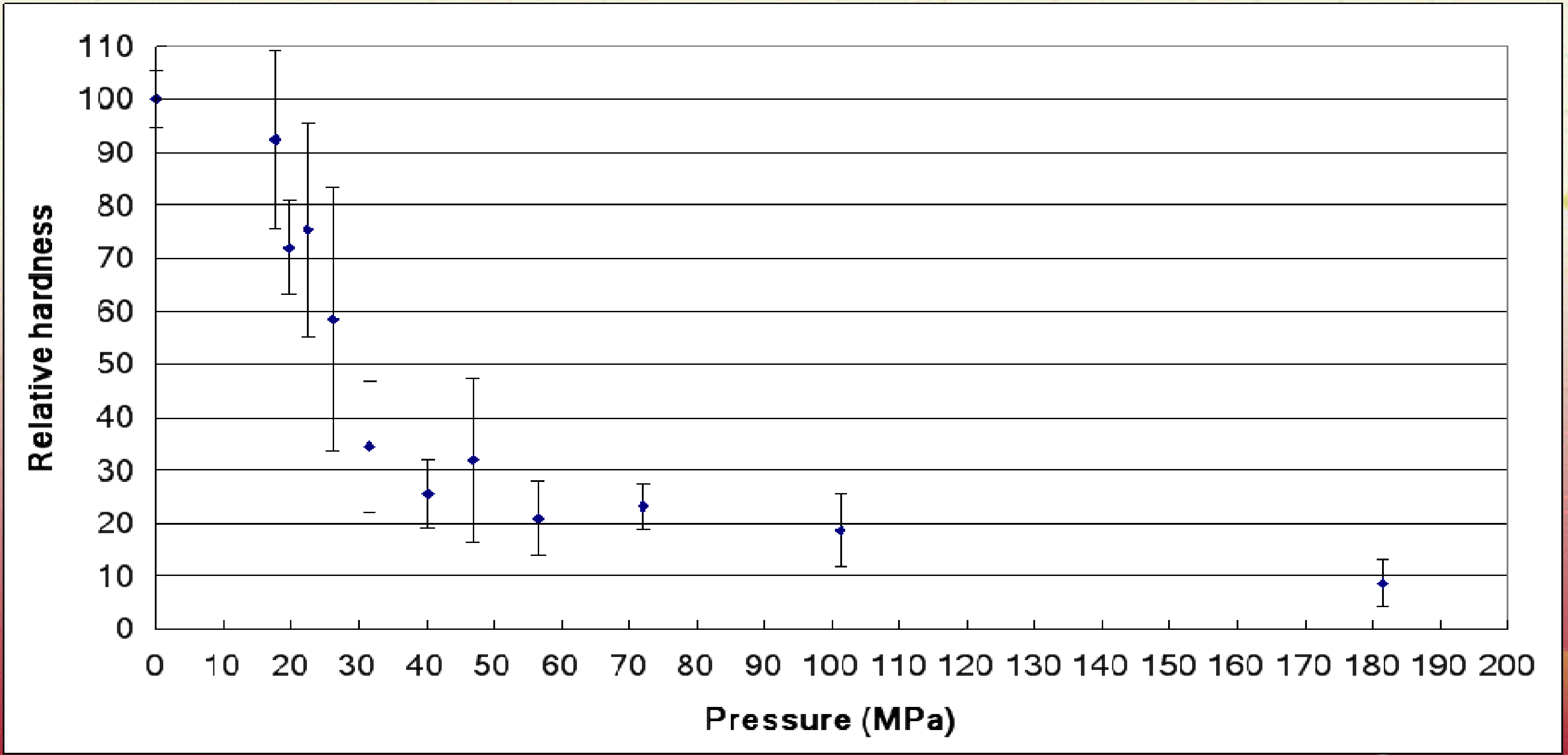
Food is soften because the cell walls (membrane) are destroyed by expansion of cell and bubbles which can be expanded by a reflected wave in the cellular tissue.







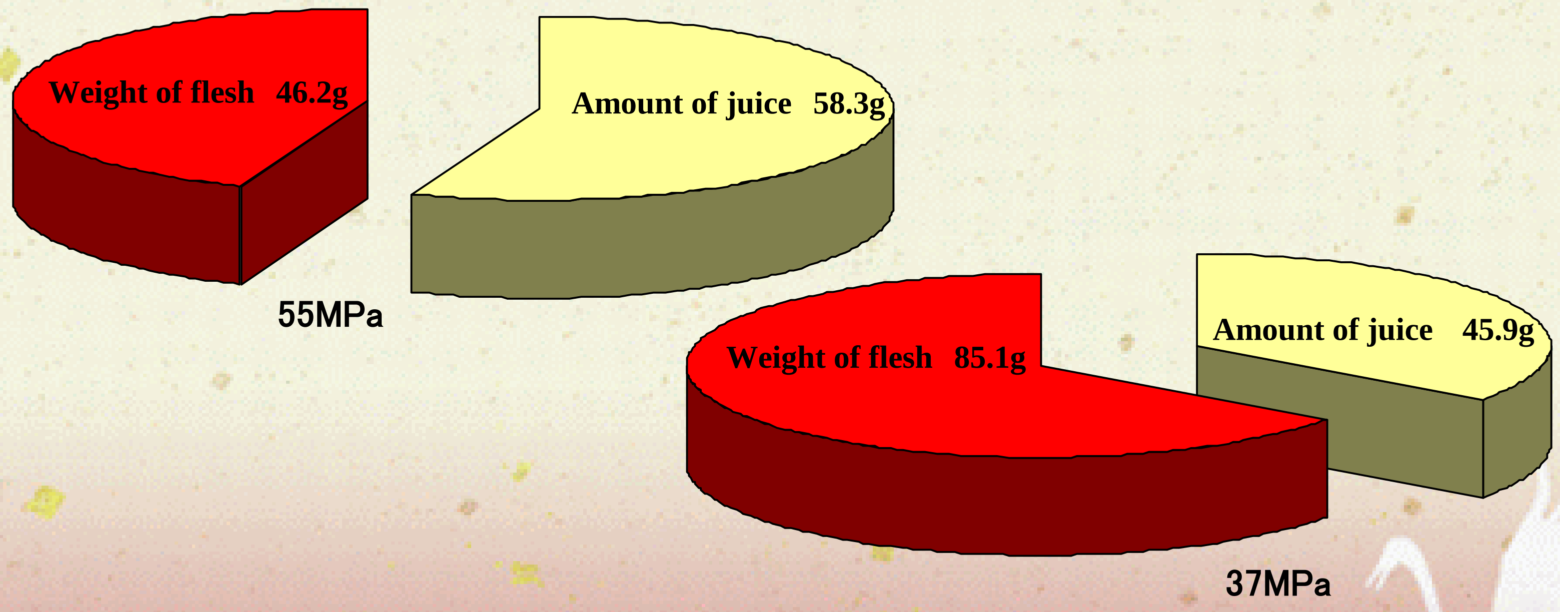
Hardness variation of apples by under water shock waves



Juice extraction by pressurization

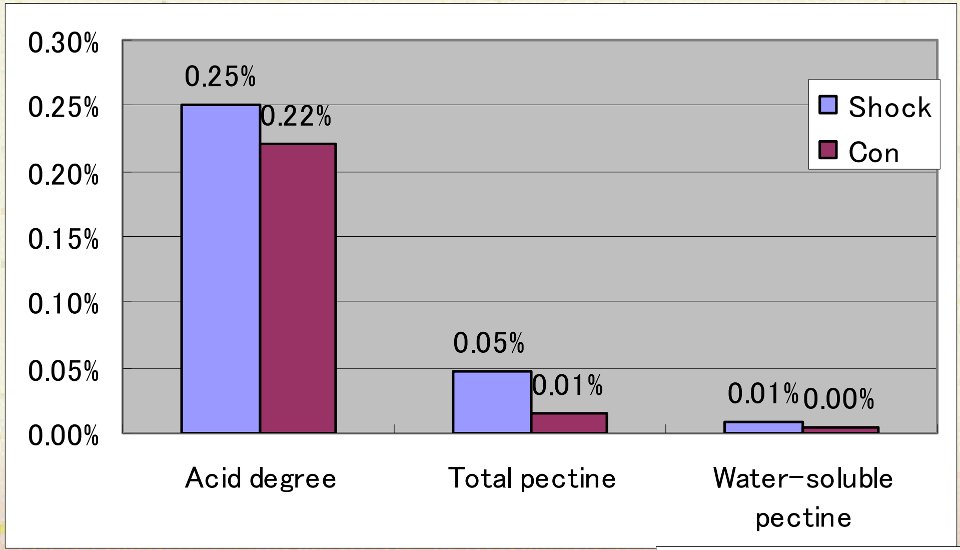
Squeezing by hand

Result of the pressurization



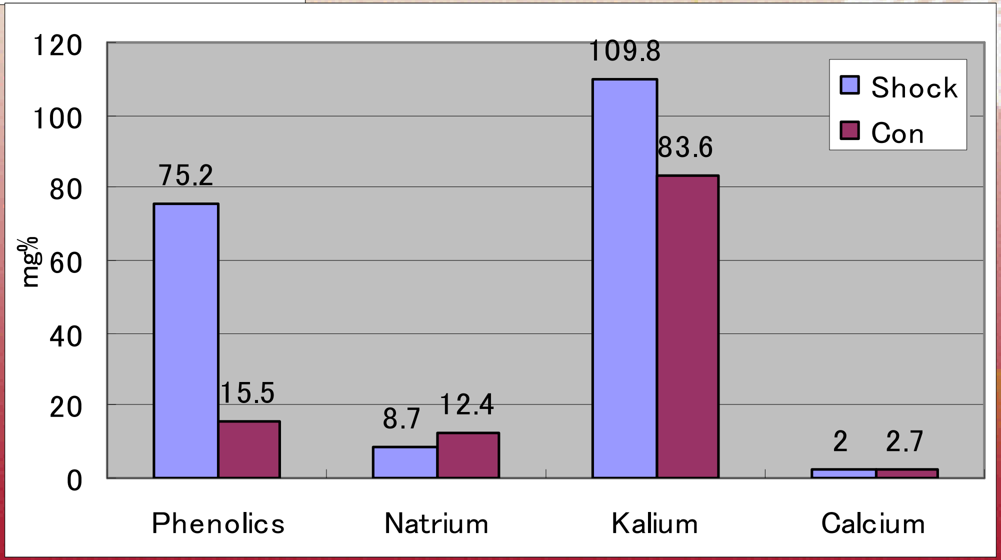
Pressure of shock wave	Amount of juice (g)	Weight of flesh (g)	Weight size(g)
37MPa	45.9	85.1	2477
55MPa	58.3	46.2	2437

Analysis of the nutrients of the apple

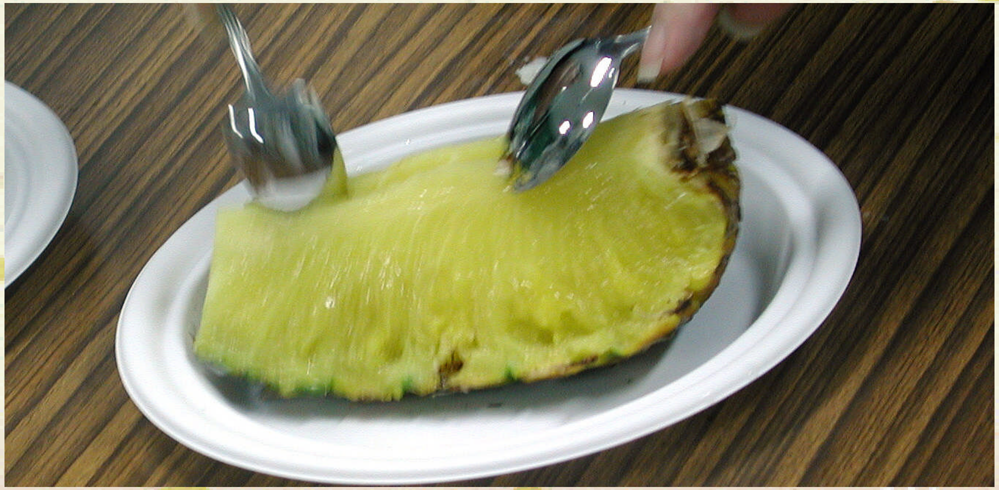


＜Component of examination＞

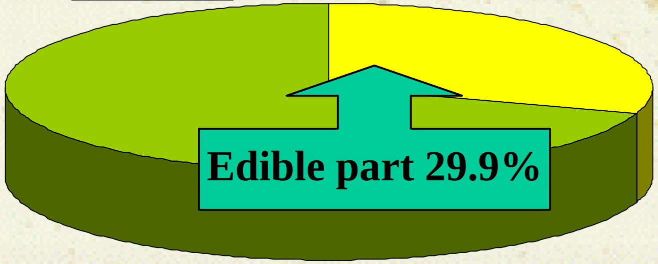
Acid degree
pH
Total pectine
Water-soluble pectine
Phenolics
Natrium
Kalium
Calcium



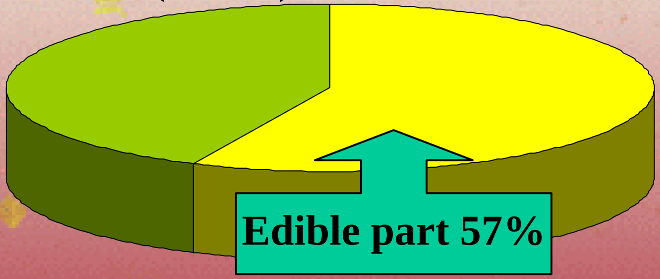
Hardness determination of pineapples



Untreated

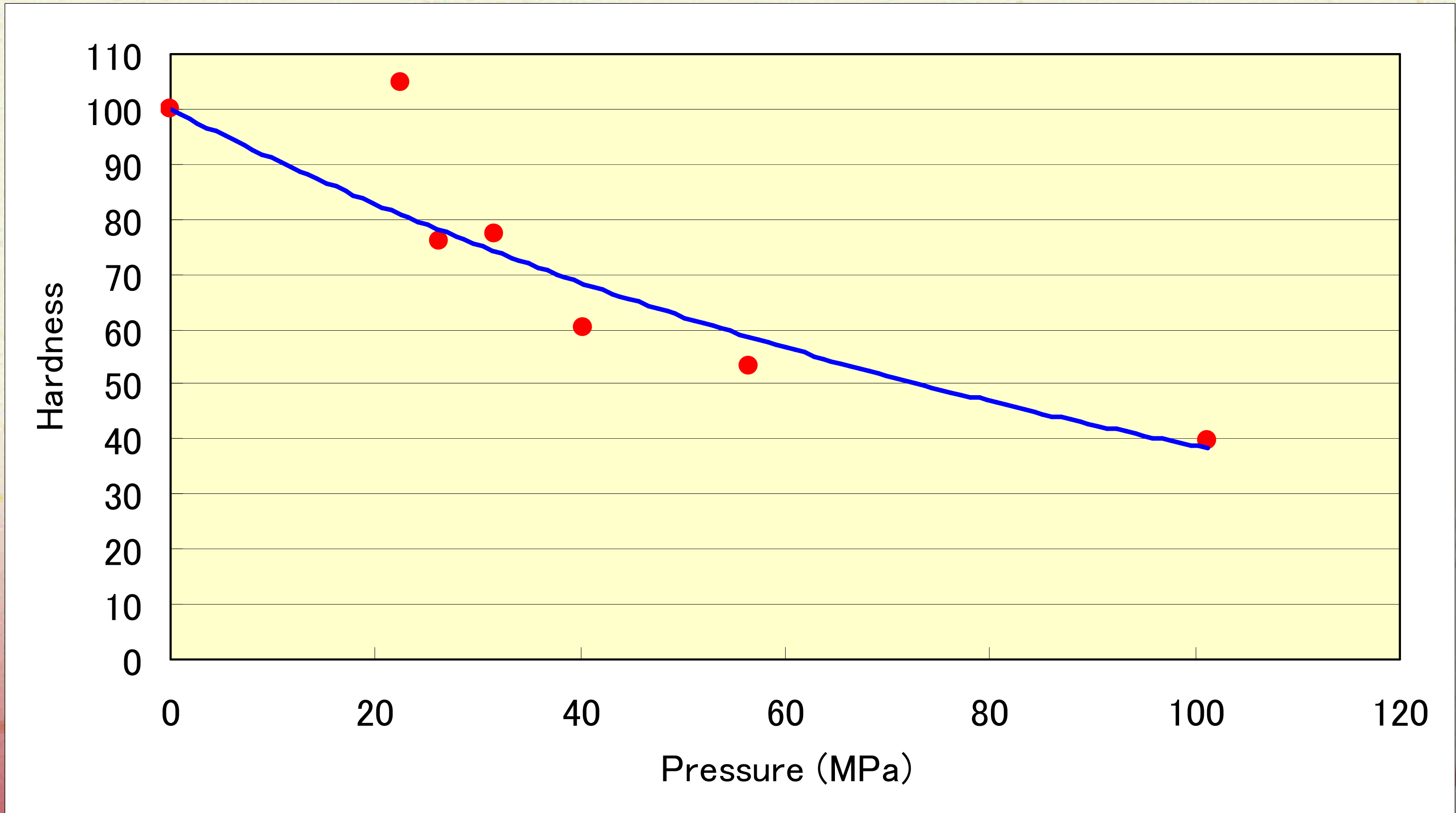


Shock wave treated (50MPa)



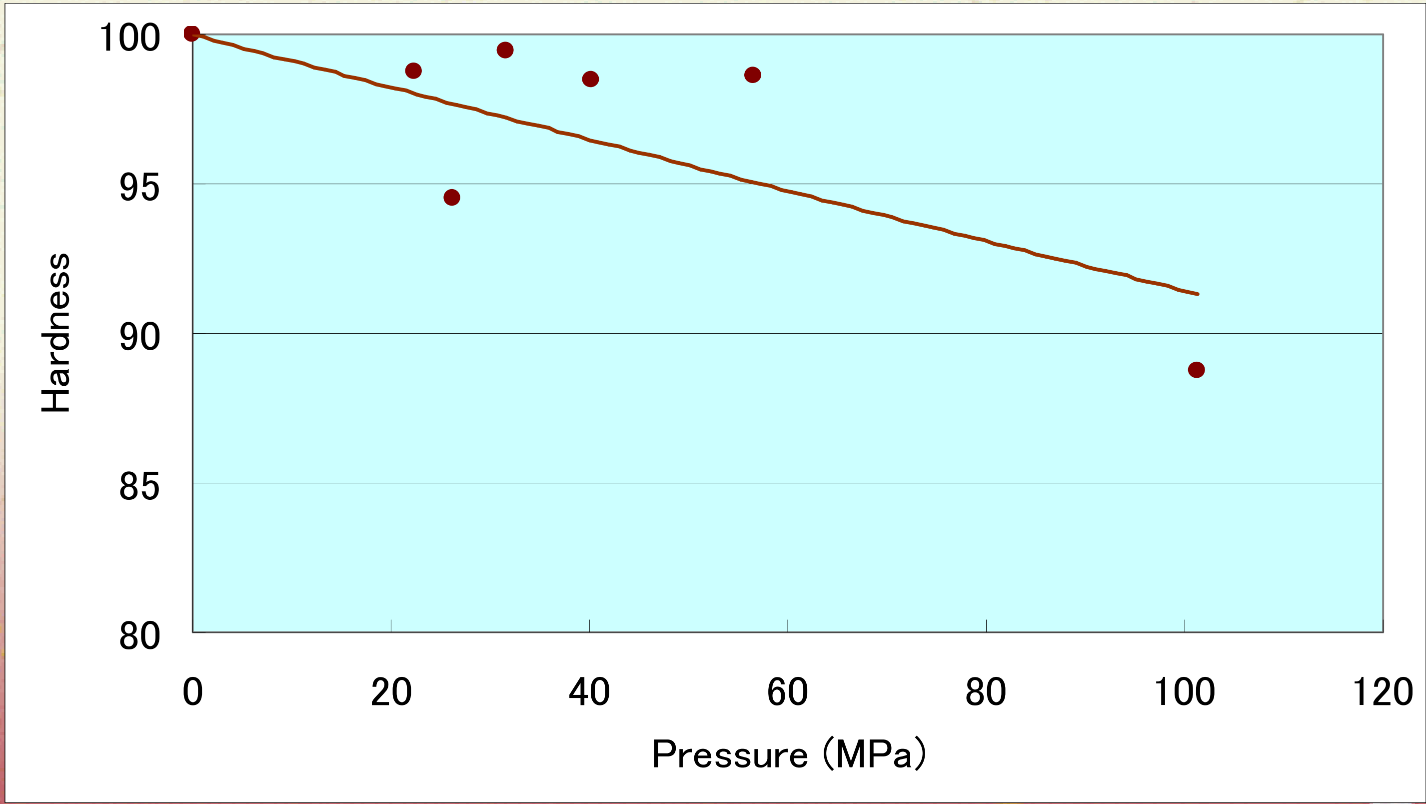
By shock waves loading, pineapple become completely soft and can be eaten with spoon easily.
Moreover, edible part of the pineapple become double comparing to untreated one. The flesh is fresh!

Hardness determination of pineapple flesh



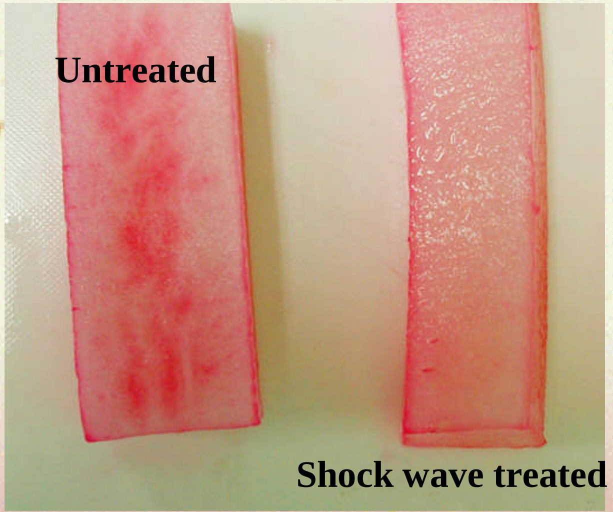
hardness variation by shock wave pressure (%) and the approximation

Hardness determination of pineapple core



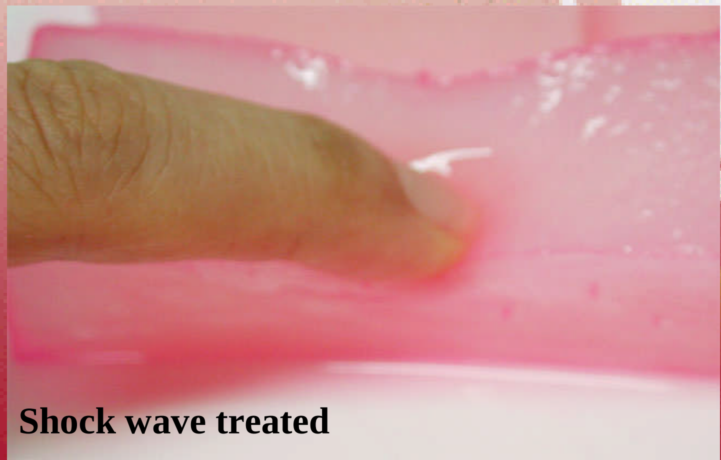
hardness variation by shock wave pressure (%) and the approximation

Softening by shock wave loading : Japanese radish



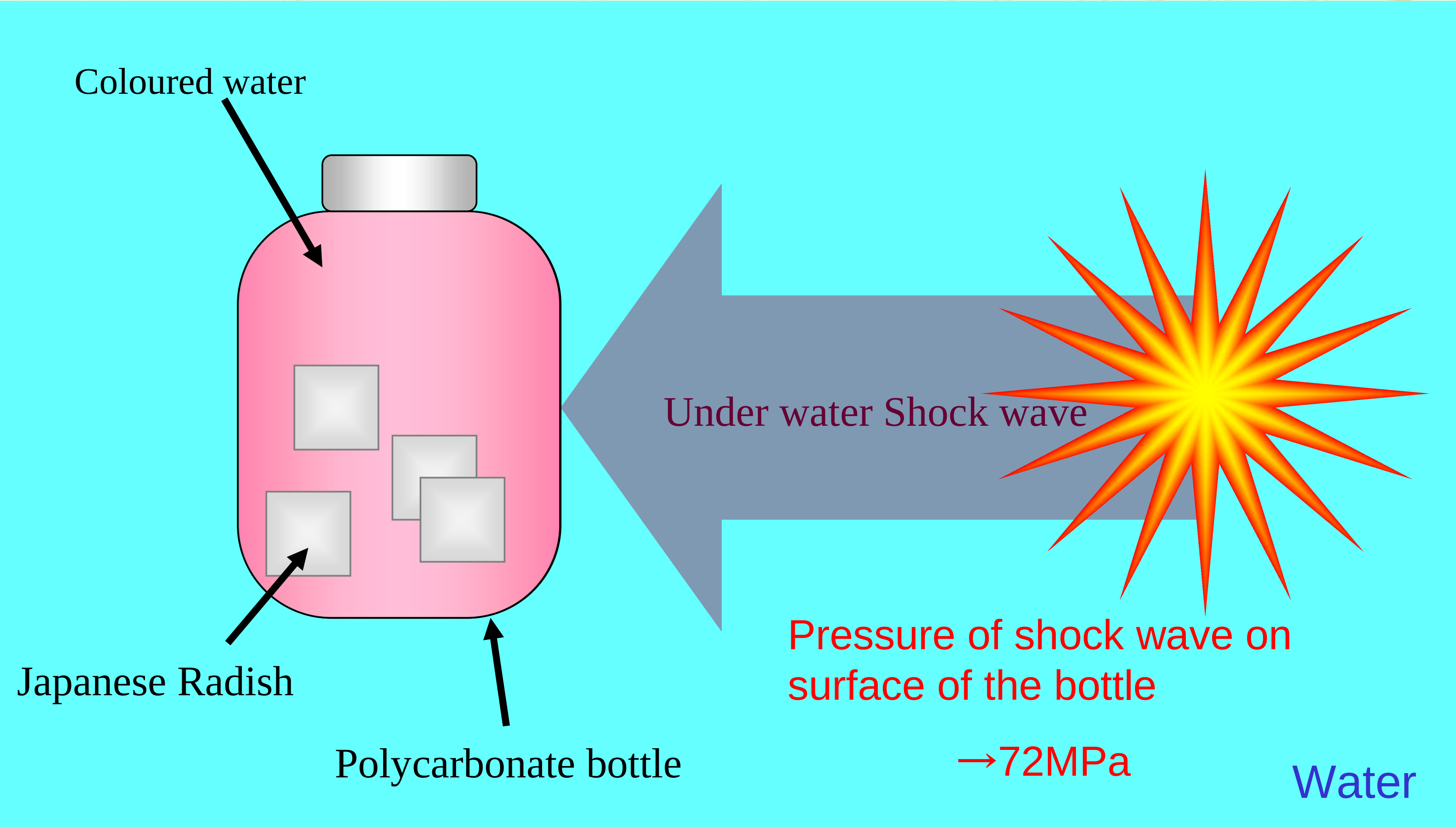
Experiment of red food colouring infiltration

Hard

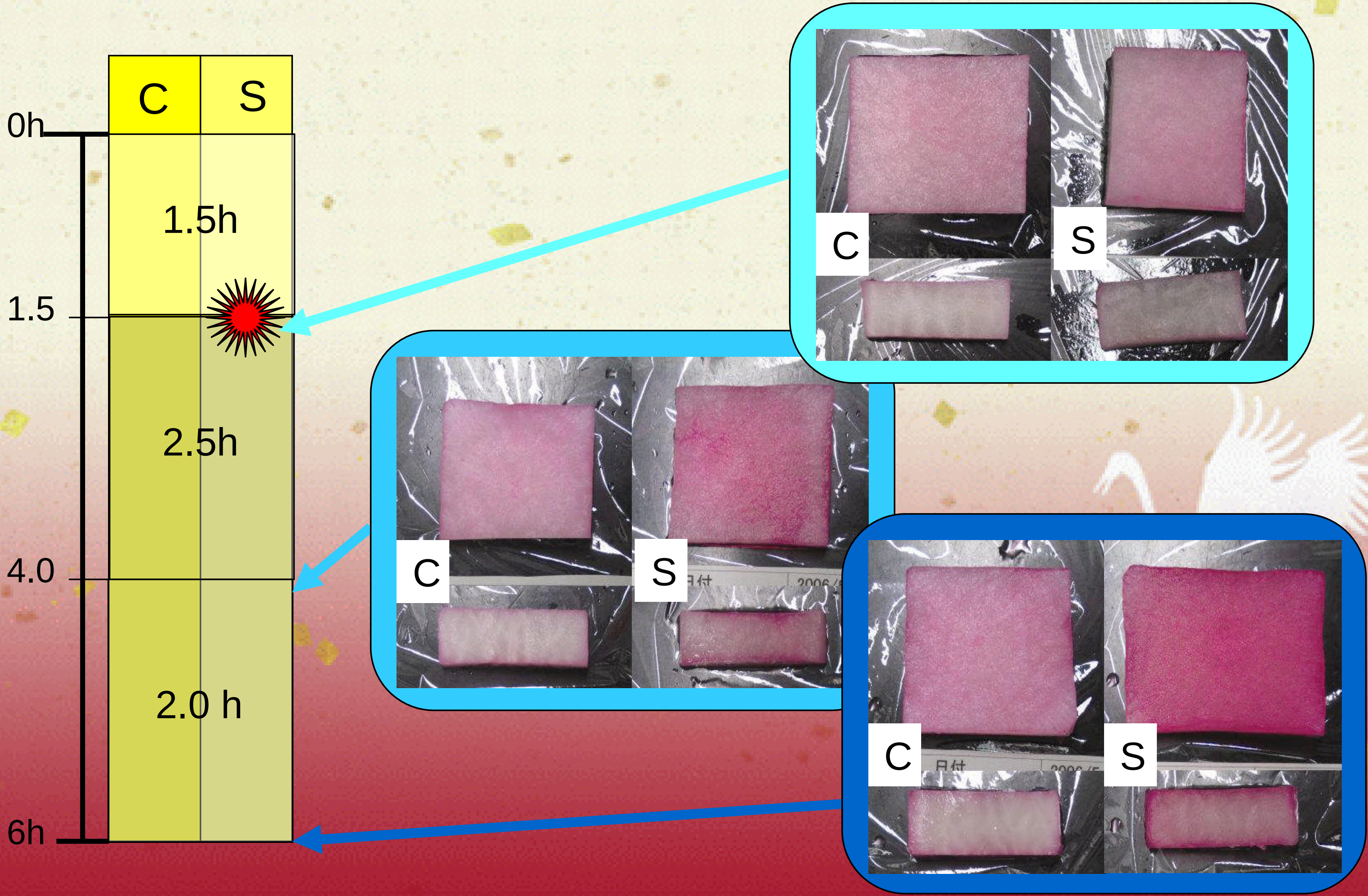


Very soft like stewed

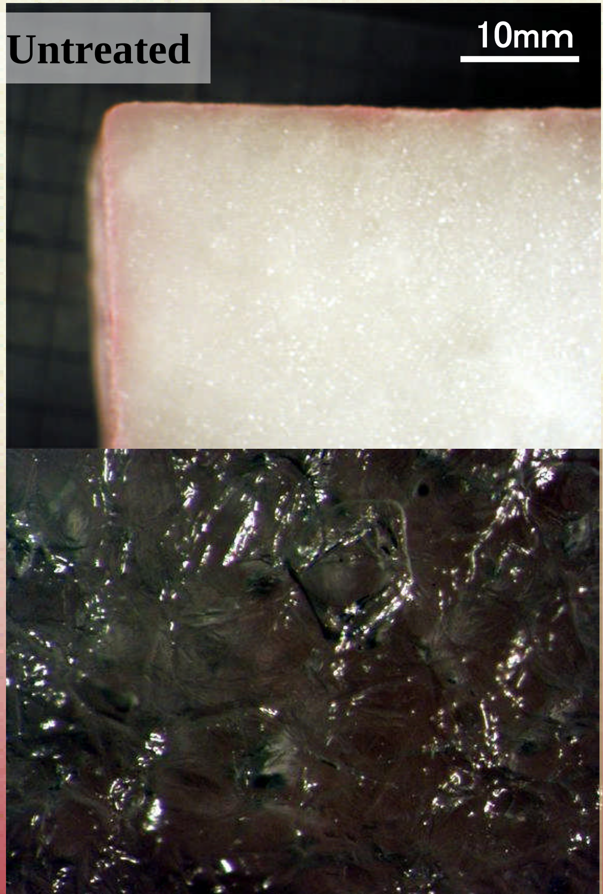
Colouring experiment of the radish

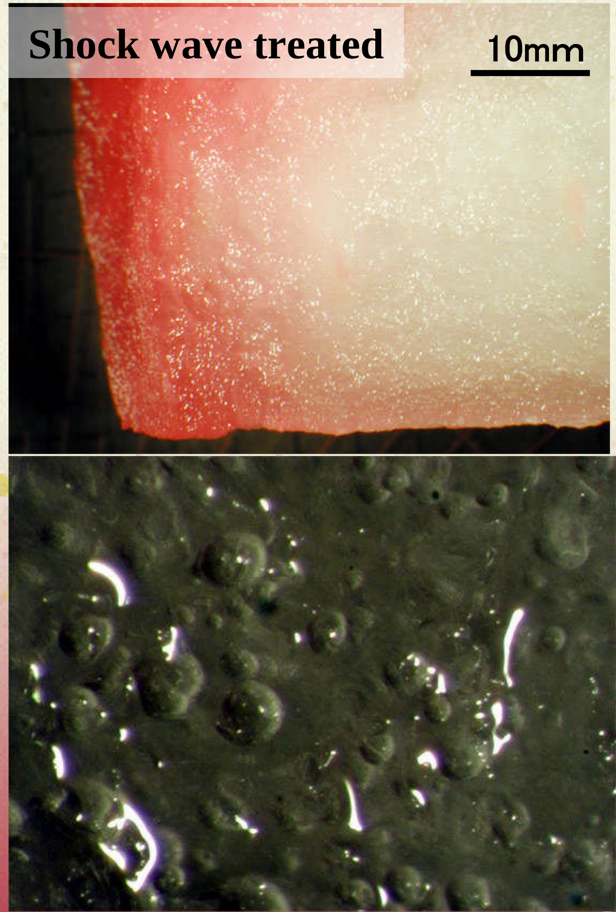


Analysis of the experiment



Microgram of surface of the radish





After shock wave loading for the radish, red food colouring infiltrates very well and a lot of air bubble are confirmed by microgram

Pulverization by underwater shock waves: walnuts

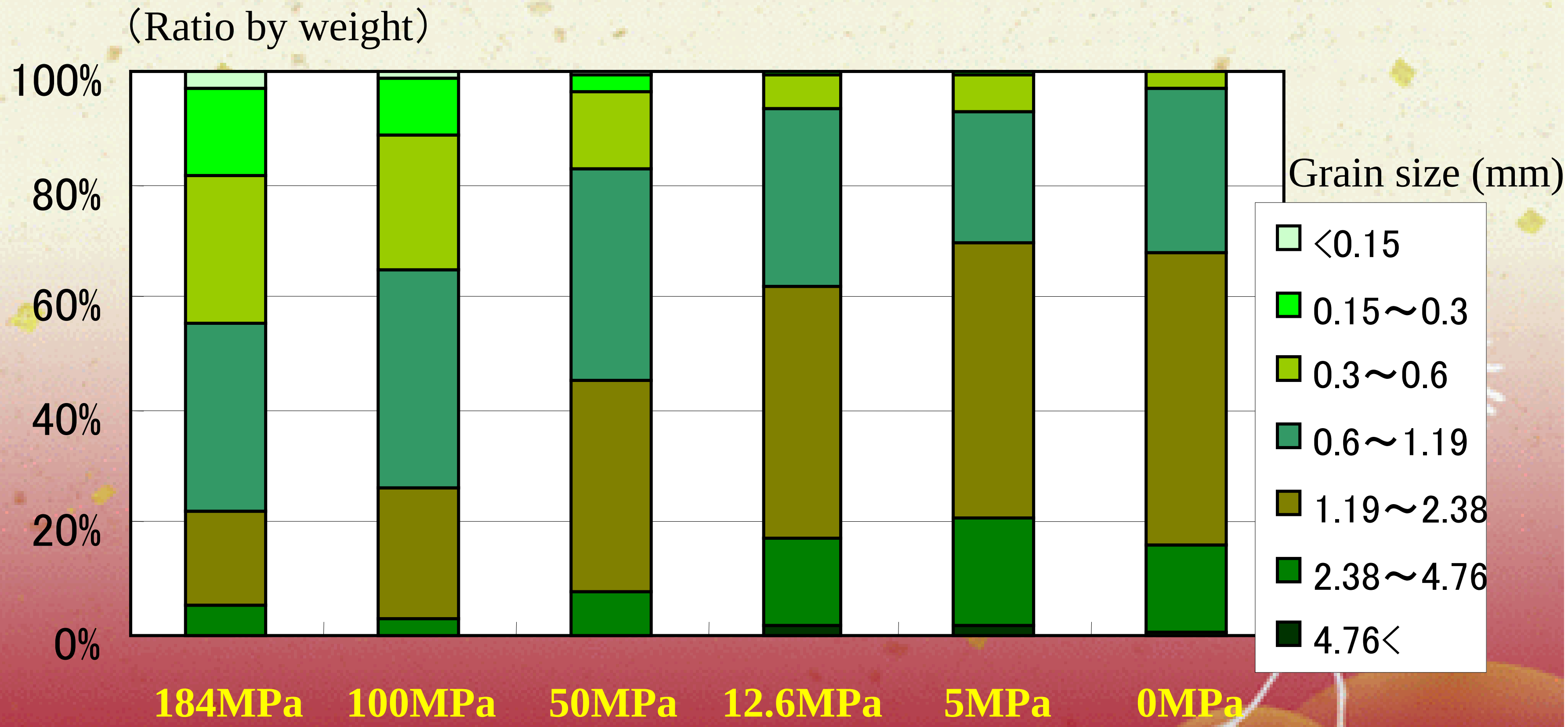


Low ⟷ Shock wave loading ⟷ High

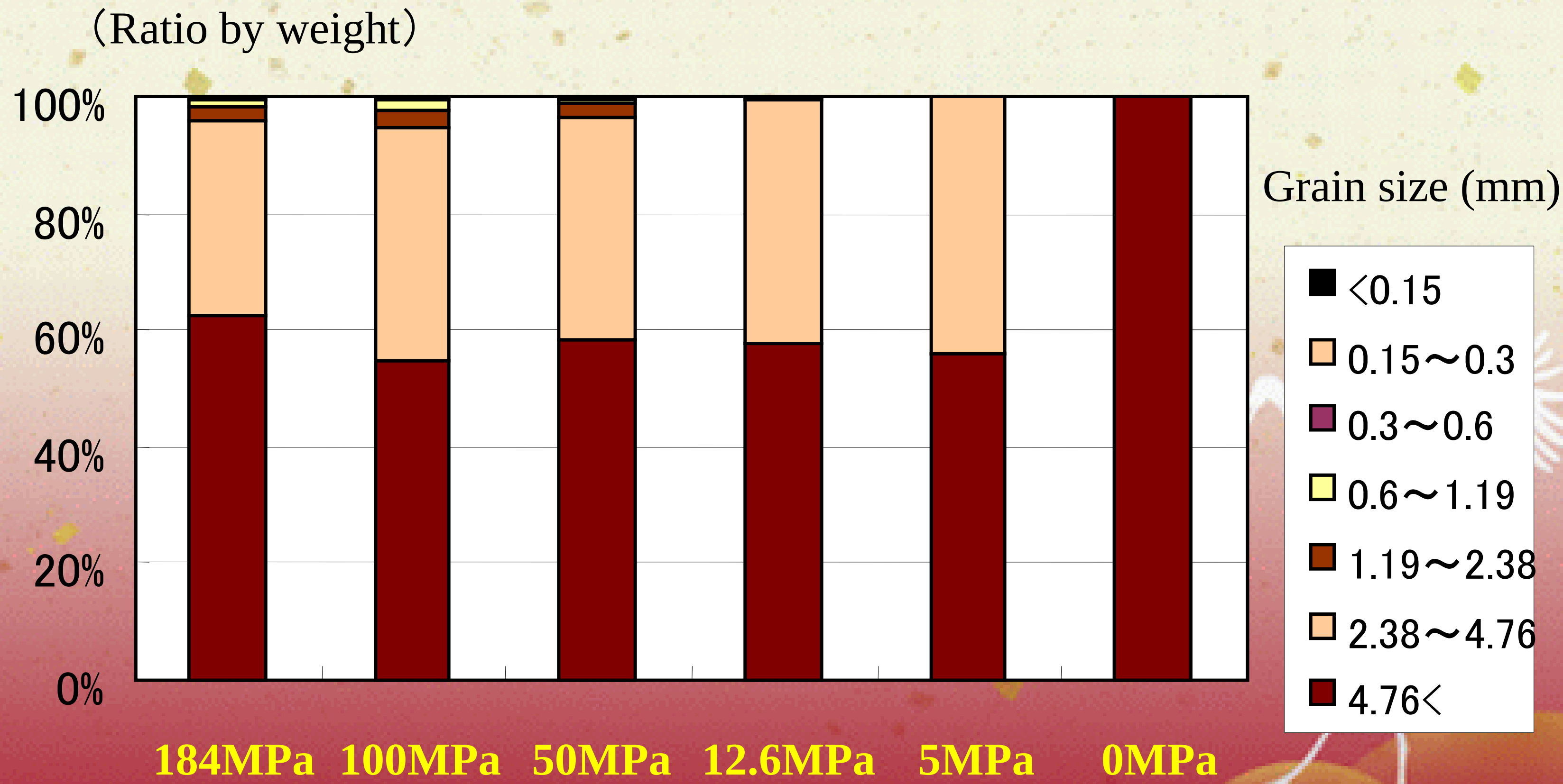
The damage of walnuts and husk become intense rising of the load pressure.
It’ s easy to divide walnuts and husk by the moderate loading pressure.

Pulverization by underwater shock waves: tea leaves

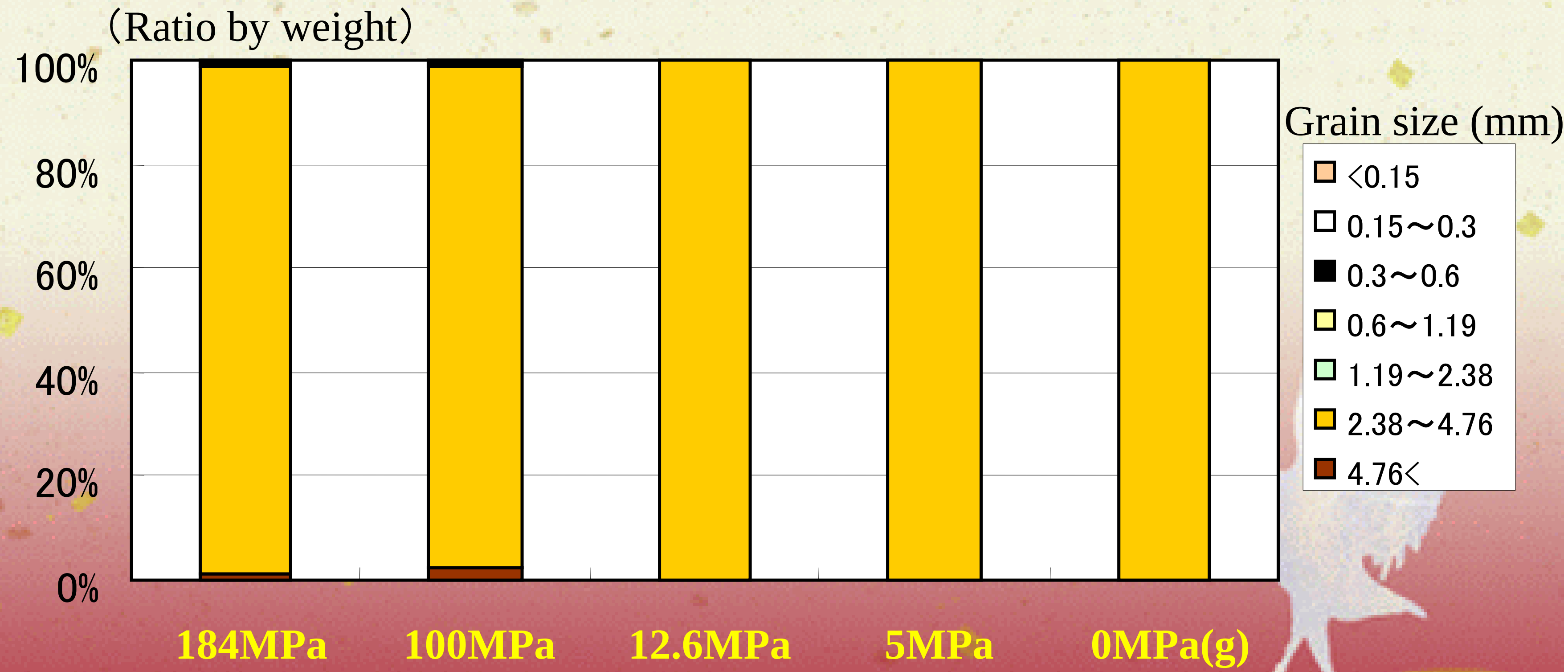
Particle size distribution data of tea leaves (ratio by weight)



Particle size distribution data of red beans (ratio by weight)



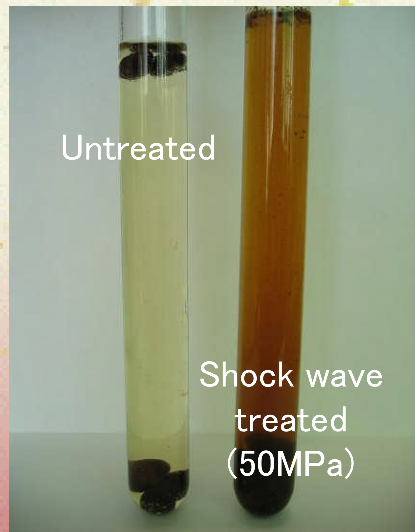
Particle size distribution data of wheat (ratio by weight)



Improvement of coffee extractability

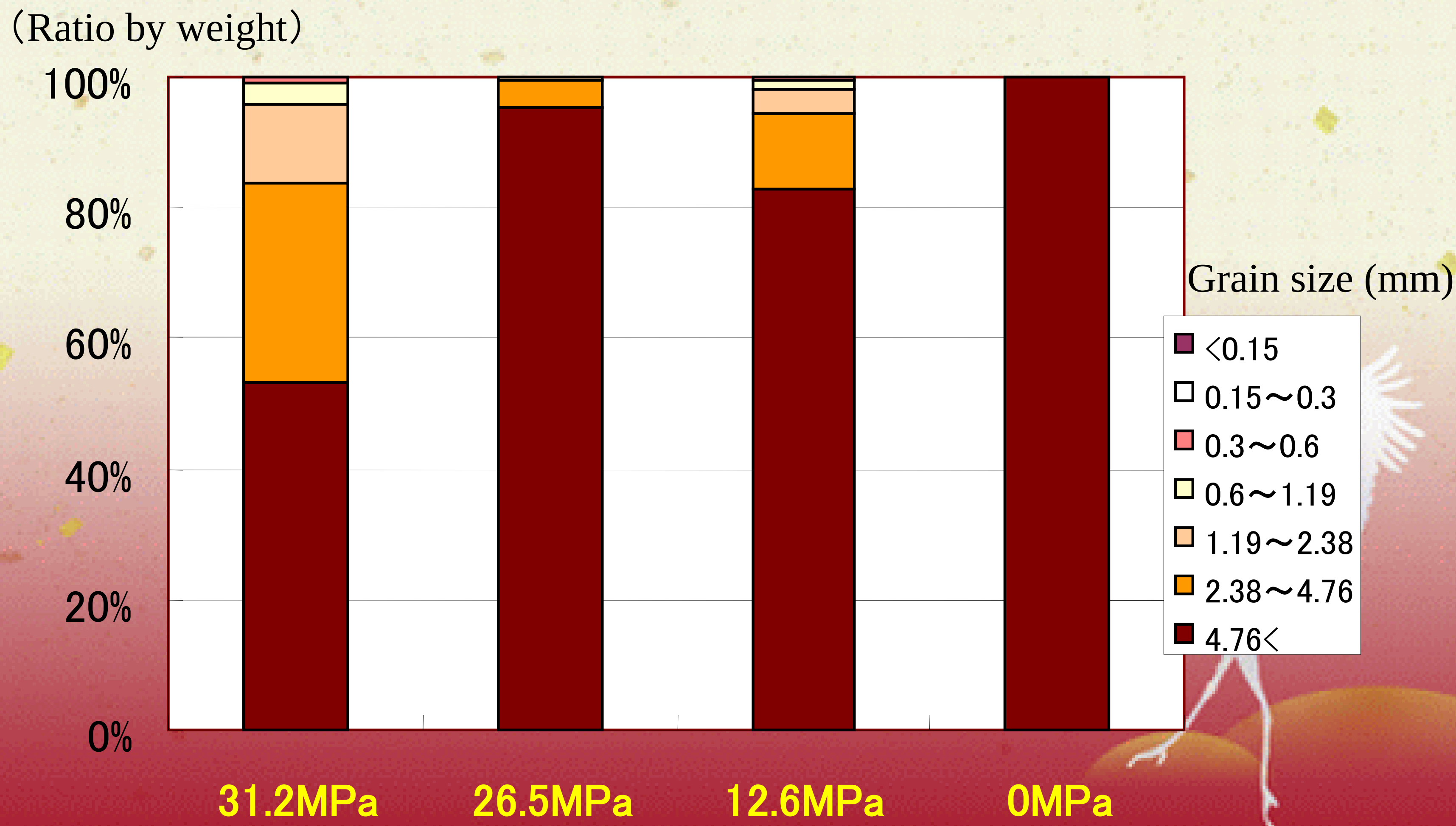
Untreated **Shock wave treated (50MPa)**

After 1hour

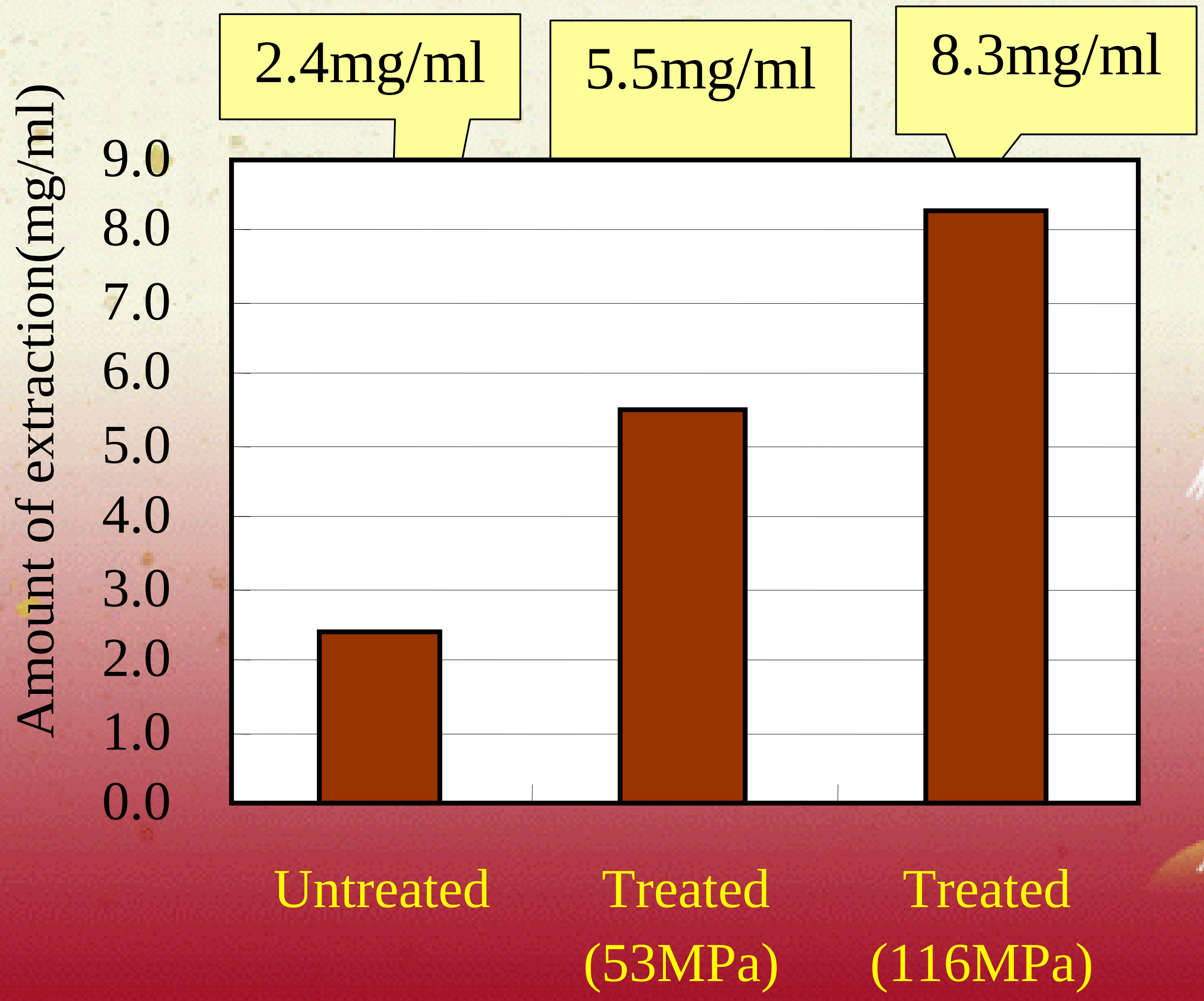


After 6hours

Particle size distribution data of coffee beans (ratio by weight)



Extracted volume of coffee



Principal ingredients of coffee

Peak No.	Time	Area	Conc.
1	0.573	4028	0.9143
2	0.875	2515	0.5707
3	1.192	1469	0.333
4	**0.467**	**116048**	**26.3384**
5	2.238	14977	3.3993
6	2.358	10820	2.4558
7	2.555	28885	6.5558
8	**3.118**	**126290**	**28.6629**
9	**4.507**	**107268**	**24.3457**
10	9.592	14844	3.3689
11	11.292	5370	1.2188
12	13.1	5103	1.1582
13	19.445	2987	0.678
Total		440605	100

Chlorogenic acid

$C_{16}H_{18}O_9$

Caffeine

$C_8H_{10}N_4O_2$

Niacin (Nicotine acid)

$C_6H_5NO_2$

Chlorogenic acid

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Niacin
(Nicotine acid)
$C_6H_5NO_2$

Peak data（mocha coffee）

Chlorogenic acid

		Control		Treated (53MPa)		Treated (116MPa)	
Peak No.	Time	Area	Conc.	Area	Conc.	Area	Conc.
1	0.855-0.857	5713	0.4937	2320	0.3758	2995	0.2895
2	1.173-1.188	10293	0.8896	25476	10.6062	18643	1.8023
3	1.458-1.463	2803	0.2422	-	-	1564	0.1512
4	1.66-1.685	14150	1.2229	52077	8.4358	25152	2.4317
5	2.21-2.22	48214	4.1669	-	-	55462	5.362
6	4.638-4.72	27261	2.3561	23293	3.7731	22109	2.1375
7	6.122-6.282	38405	3.3192	44925	7.2773	44344	4.2871
8	6.888-6.983	16482	1.4244	7513	1.2169	11724	1.1334
9	9.953-10.035	61956	5.3545	26592	4.3076	46816	4.5261
10	13.325-13.463	127039	10.9793	75811	12.2803	110624	10.6949
11	16.53517.037	192062	16.5989	-	-	35841	3.4651
12	18.707-18.712	461294	39.8673	107526	17.4178	226293	21.8777
13	21.742-21.847	127145	10.9885	199669	32.3437	417042	40.319
14	25.185-25.26	6706	0.5796	1555	0.2518	-	-
15	27.583-27.633	16327	1.411	10579	1.7136	15749	1.5226
TOTAL		1157075	100	617335	100	1034358	100

Caffeine

Niacin (Nicotine acid)

Peak data（blended coffee）

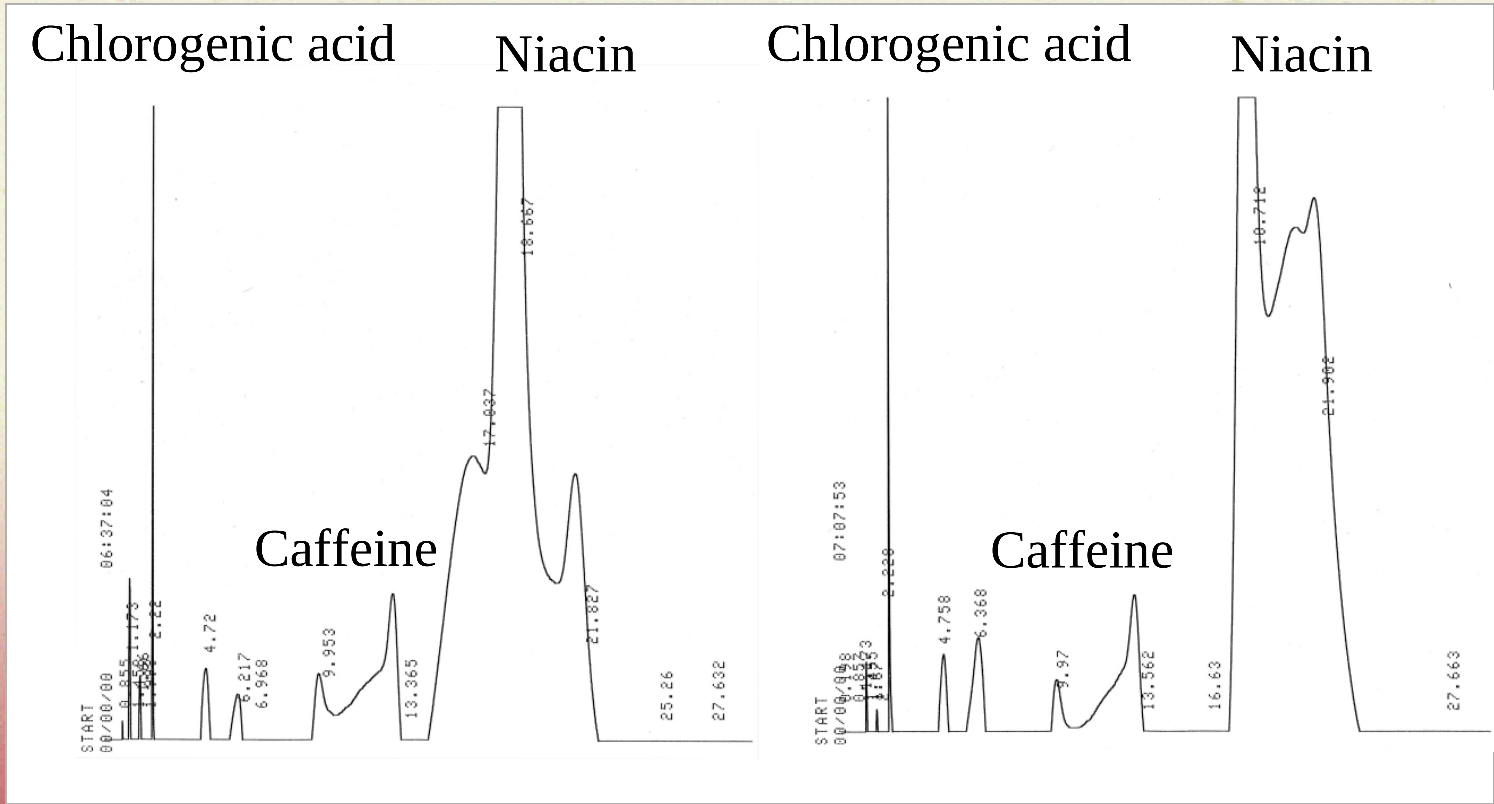
Chlorogenic acid

Peak No.	Time	Control Area	Control Conc.	Treated (53MPa) Area	Treated (53MPa) Conc.	Treated (116MPa) Area	Treated (116MPa) Conc.
1	0.192-0.198	1139	0.1016	1105	0.1122	-	-
2	0.853-0.857	3609	0.322	4401	0.4467	2202	0.2898
3	1.173-1.177	7517	0.6706	13602	1.3806	5485	0.7218
4	1.445-1.455	1994	0.1779	2224	0.2258	1442	0.1898
5	1.667-1.673	11727	1.0461	11722	1.1898	7350	0.9673
6	2.222-2.233	53295	4.7543	50201	5.0954	46421	6.1094
7	4.758-4.792	25908	2.3112	33775	3.4282	21057	2.7713
8	6.337-6.458	61842	5.7844	53286	5.4086	38662	5.0882
9	6.983	-	-	-	-	17111	2.2519
10	9.915-9.97	53875	4.8061	294948	29.9372	46458	6.1143
11	12.248	-	-	-	-	40553	5.3371
12	13.192-13.66	125190	11.168	70340	7.1395	53399	7.0277
13	16.402-16.63	35600	3.1758	-	-	7005	0.922
14	18.712-18.74	282205	25.1751	212591	21.5779	344925	45.3954
15	21.828-22.127	434963	38.8024	222466	22.5802	96652	12.7204
16	25.3	-	-	-	-	9825	1.2931
17	27.643-27.707	19106	1.7044	14562	1.478	21279	2.8005
TOTAL		1120970	100	985223	100	759824	100

Caffeine

Niacin (Nicotine acid)

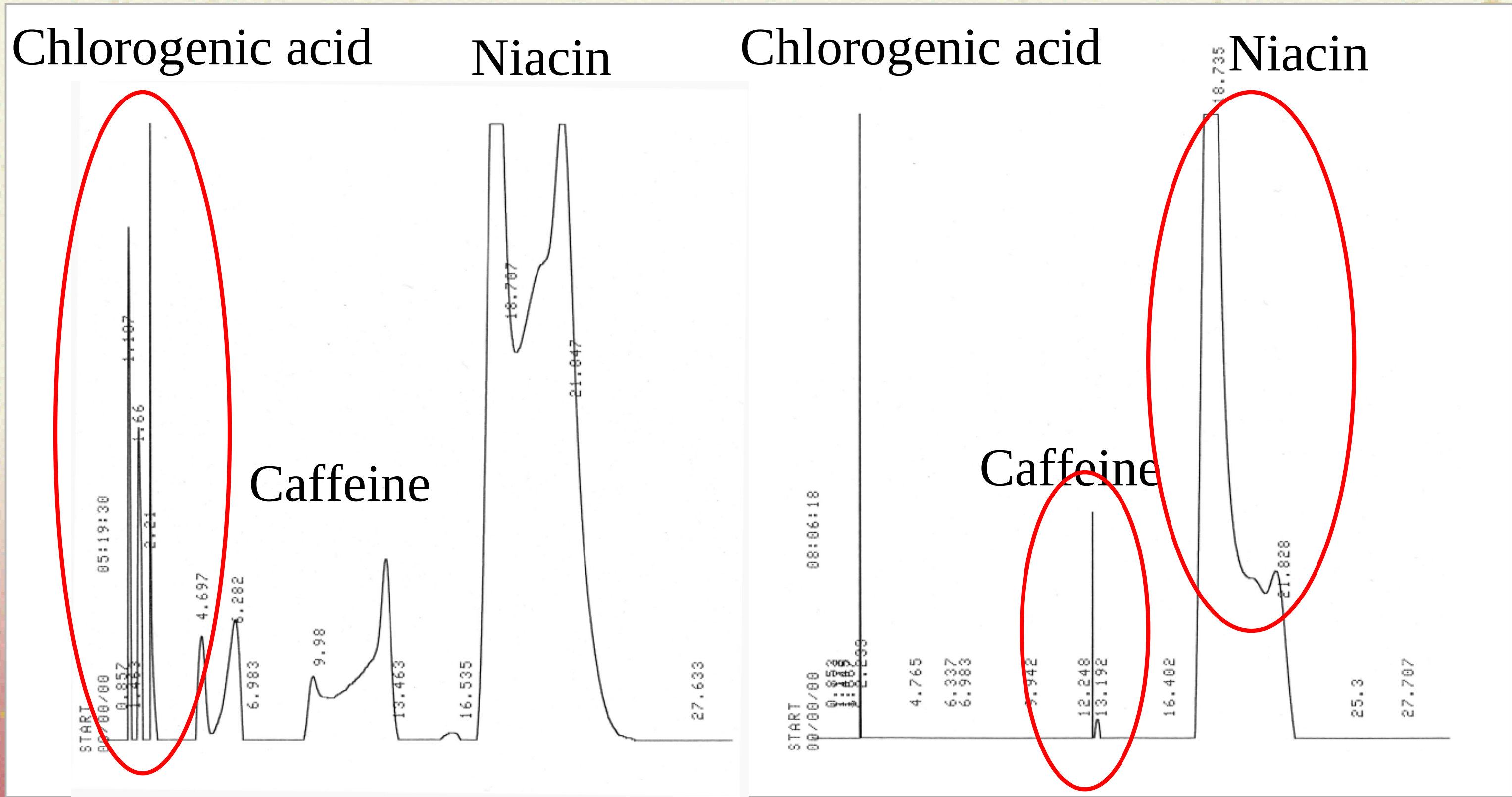
Dissolution curve (untreated)



Mocha coffee

Blended coffee

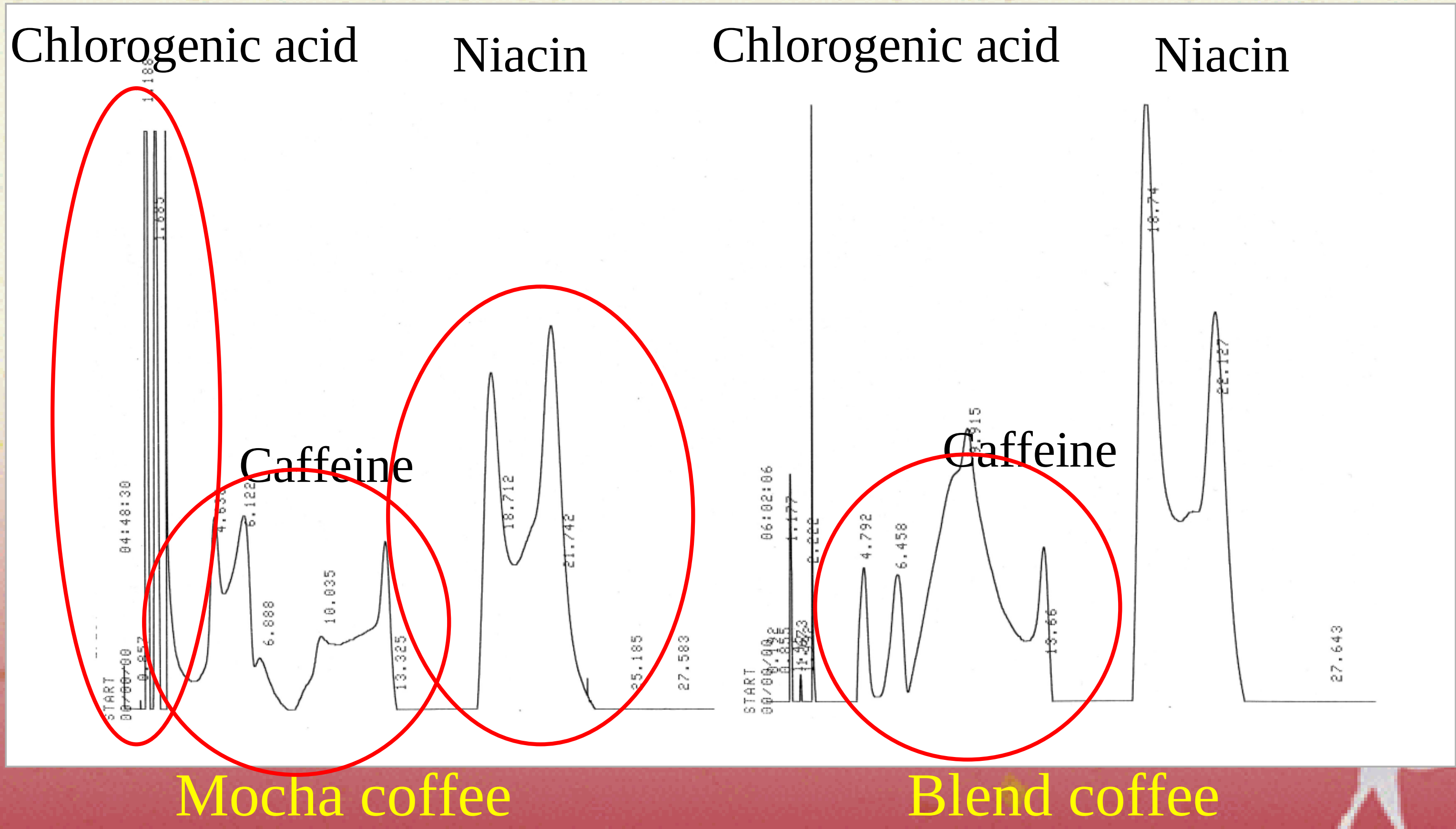
Dissolution curve (53MPa)



Mocha coffee

Blended coffee

Dissolution curve (116MPa)



Bakuha Range
-Purpose of cooking range by shock waves-

Shock wave processing by explosive

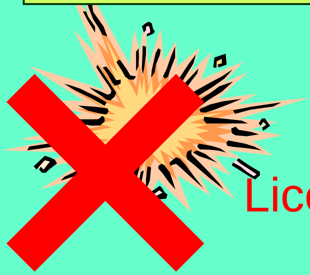
←old way

processed by
shock wave →

- **Processing in a flash**
- **No heating for softening**

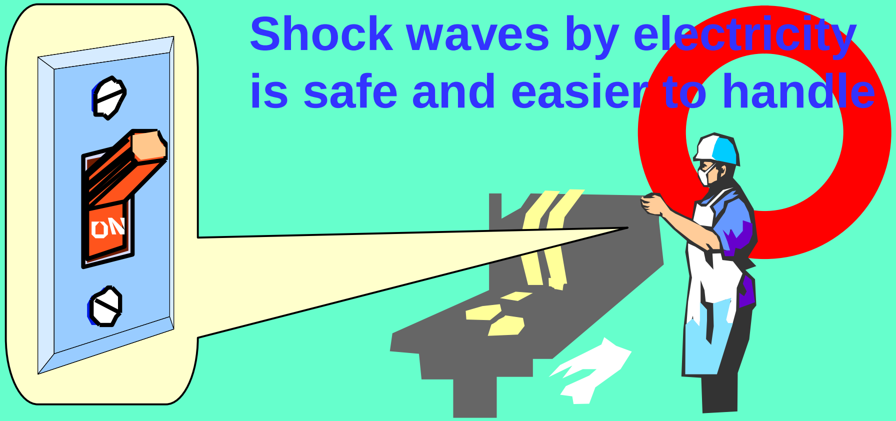
(patent 2005-077735 PCT/JP2006/305460)

Shock waves by electricity-based



Using explosive
requires
Licentiate and facilities

Shock waves by electricity is safe and easier to handle



Development of food processing device using electricity–based shock waves

original Bakuha range
(explosive)

Original model

New Bakuha range
(electricity)

New model

Introduction by Japanese TV program

Food processing technology by underwater shock wave was introduced.

World Business Satellite by TV Tokyo

broadcasted on April 28, 2008

”Food-Saving day”

-Science of Cutting Edge Food Processing-

Introduction by Japanese TV program

“Jekyll & Hyde” -Forecasting near-future- by TV Asahi
broadcasted on June 8, 2008

“Shock wave cooking range”
-Revolutionary future cooking device-

Introduction by Japanese TV program

Hi! He! Say!

Broadcasted on August 2th 2008

Thanks for your Attention!