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EXPERIMENTAL INVESTIGATION OF POOL BOILING HEAT TRANSFER ENHANCEMENT IN MICROGRAVITY IN THE PRESENCE OF ELECTRIC FIELDS

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Problem statement

The research carried out in the Heat Transfer Laboratory of the Johns Hopkins University was motivated by previous studies indicating that in terrestrial applications nucleate boiling heat transfer can be increased by a factor of 50 when compared to values obtained for the same system without electric fields. Imposing an external electric field holds the promise to improve pool boiling heat transfer in low gravity, since a phase separation force other than gravity is introduced. The influence of electric fields on bubble formation has been investigated both experimentally and theoretically.

Method of study and results

The research carried out within the framework of the NASA project focused on the analysis of bubble formation under the influence of electric fields. In the first phase of the research air was injected into the working fluid PF5052 through an 1.5mm diameter orifice located in the center of the circular ground electrode which is flush with the bottom wall of the test cell. The life cycle of the bubble was captured on videotape with a high-speed camera. Bubble shapes in terrestrial conditions and microgravity (microgravity experiments were carried out in NASA's KC-135 aircraft) with and without electric fields were visualized for a range of operating parameters. In addition to evaluating the effects of ***gravity***, ***the magnitude and polarity of the electric field***, the ***mass flow rate of the air*** injected into the test cell, as well as the ***level of heating*** applied to the bottom electrode were varied during these experiments. Typical bubble sequences for the uniform electric fields (0V and 25kV potential difference between the electrodes) recorded in terrestrial conditions are shown in Figure 1 and in microgravity in Figure 2.

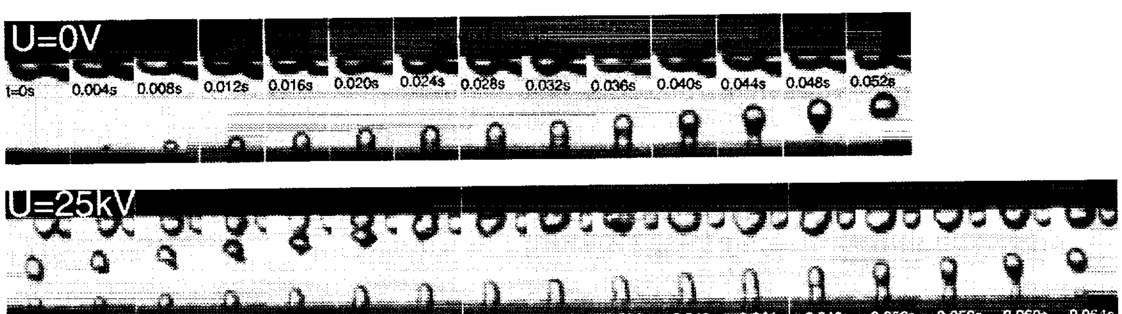

Figure 1. Bubble formation at an orifice without electric field (top) and with 25 kV applied to the electrodes as function time visualized under terrestrial conditions in the Heat Transfer Lab of the Johns Hopkins University.

Experiments were carried out for two ***configurations of the electrodes***. In the first series of experiments the two electrodes were ***parallel***, generating a uniform electric field. In the second series of experiments the shape of the ***high-voltage electrode*** was modified to a ***spherical shape*** (its diamater being one fourth of the diameter of the circular ground electrode) and positioned off-axis with respect to the bottom ground electrode. This electrode configuration yields a nonuniform electric field.

Bubble shapes and sizes were measured using digital image processing. A dedicated digital image processing code was developed for this purpose using the Matlab software. In the analysis, selected image sequences were converted into a digital format using a frame grabber. The images were then enhanced and sequentially read by the image processing code. The size of the bubble during bubble formation, its volume and key dimensions were extracted and stored in a file for further evaluation. Measured bubble shapes are currently being compared with predictions obtained using simplified analytical models.

In addition to the visualization of bubble shapes, **temperature fields** were visualized using **holographic interferometry**. Dedicated image processing codes for the evaluation of interferometric images of bubbles and tomographic algorithms for the tomographic reconstruction of 3D temperature distributions around the bubble were developed.

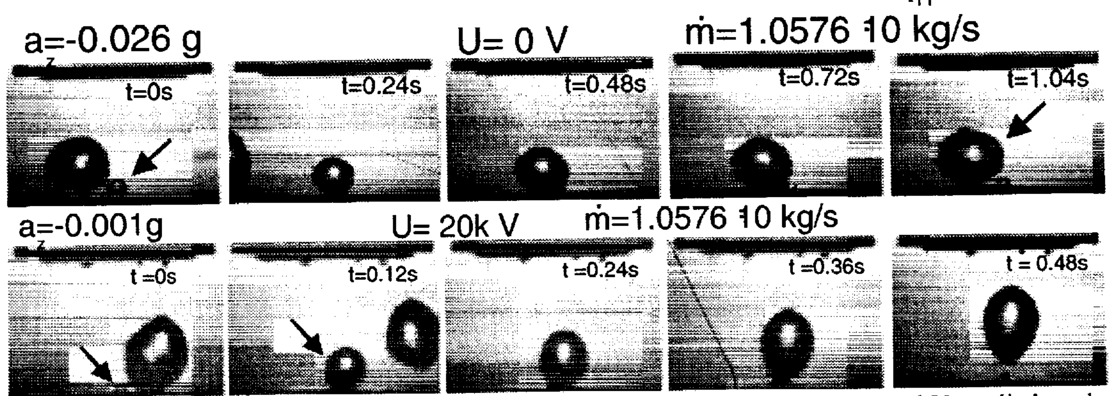

Figure 2. Bubble formation at an orifice without electric field (top) and with 25 kV applied to the electrodes (bottom) as function time visualized in microgravity conditions in NASA's KC-135 aircraft.

The results of visualization experiments clearly indicate that there are significant differences in bubble shape, size and frequency, caused by effects of gravity and electric fields. In terrestrial conditions the bubbles at detachment are much smaller and more elongated in the presence of the electric field than for the reference conditions without the electric field. Microgravity experiments have verified that in the presence of electric fields bubbles do detach from the orifice and move away from the surface as opposed to the situation when large spherical bubbles developing at the orifice remain motionless on the surface in the absence of acceleration. The bubble shape in microgravity is elongated when an electric field is applied between the electrodes, contrasted to the nearly spherical shape in the absence of the electric field. In addition to the change of shape, one key difference in the behavior of the bubbles in the presence of the electric fields is the significantly reduced tendency for coalescence.

Apart from the experimental studies, existing simplified analytical models describing bubble formation at an orifice and during boiling were evaluated and modified to accommodate the physical effects considered in the NASA study. Bubble shapes and sizes at detachment were evaluated for a range of working fluids as function of the magnitude of the electric field and the gravity level.

The influence of gravity level on bubble shapes in the performance fluid PF5052 for two values of the potential difference imposed between the electrodes, U=50kV and U=0V, is illustrated in Figure 3. Results obtained for terrestrial conditions show little difference in bubble shape due to the electric field. Bubble elongation in microgravity is pronounced, as illustrated in Figure 3. The elongation becomes more significant with increasing magnitude of the electric field (50 kV) both in terrestrial conditions and microgravity. The comparison of modeling data with experimental results is currently underway.

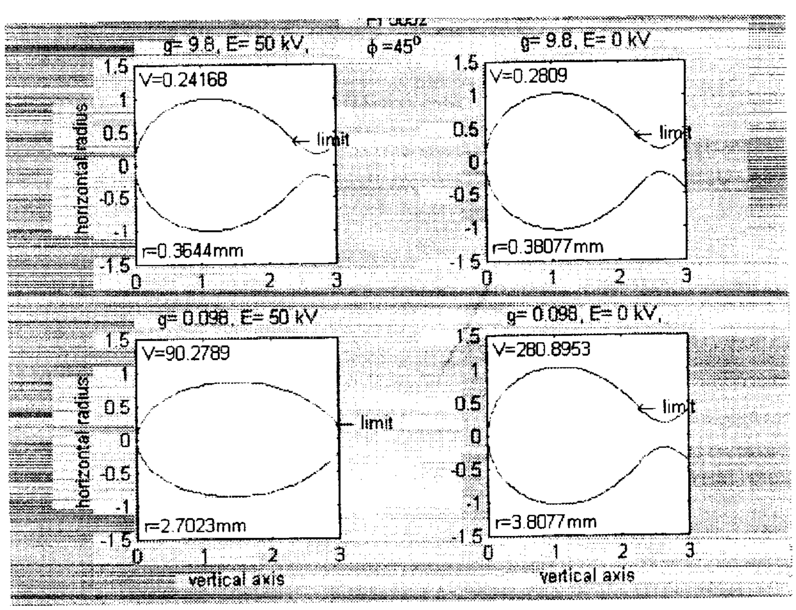

Figure 3. Bubble shapes at detachment for terrestrial conditions and 1/10g for a potential difference between the electrodes of 50 kV (left) and 0 kV (right)

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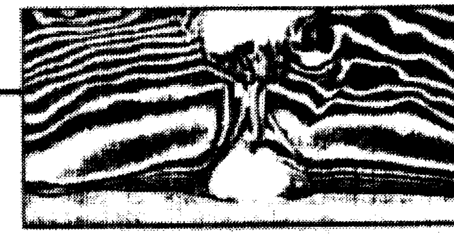
Fifth Microgravity Fluid Physics and Transport Phenomena Conference

August 9-11, Cleveland, OH



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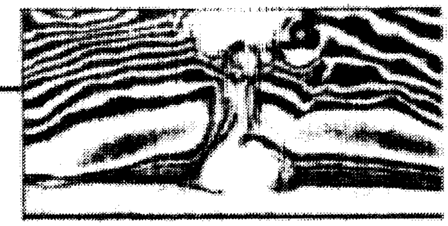
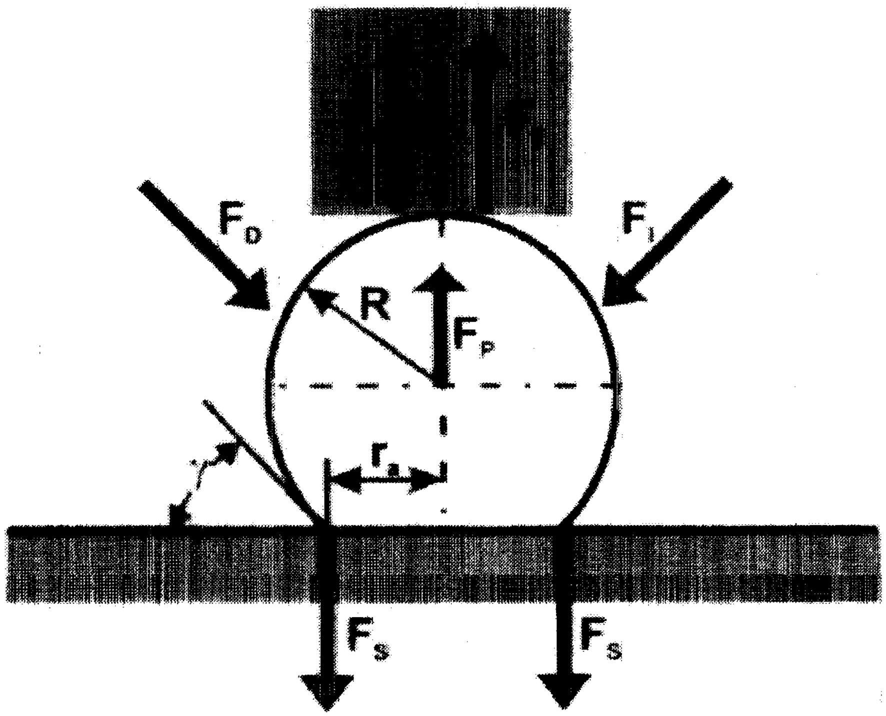
Ground support team for KC - 135 flights

OUTLINE

1. **Introduction and motivation**
2. **Summary of past research accomplishments**
3. **Bubble formation at an orifice in microgravity under the influence of electric fields**
   - Experimental approach
   - Experimental setup
   - Visualization images and results
   - Modeling efforts
4. **Outlook and future research**



FORCES ACTING ON A BUBBLE DURING DYNAMIC BUBBLE GROWTH



Force balance $F_D + F_S = F_I + F_P + F_B + F_E$

Drag $F_D = C_D \frac{\rho_L}{2}\left(\frac{dR}{dt}\right)^2 \pi r_a^2$

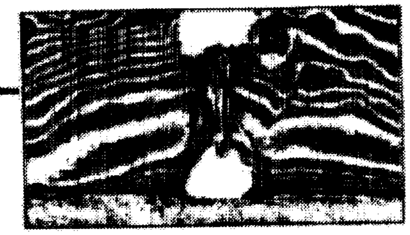
Surface tension $F_S = 2\pi\ r_a \sigma\ \sin\gamma$

Inertia $F_I = \frac{4}{3}\pi R^3 \rho_L \frac{d^2R}{dt^2}$

Pressure $F_P = \left(\frac{2\sigma}{R} + \Delta p_V\right)\pi r_a^2$

Buoyancy $F_B = \frac{4}{3}\pi R^3 (\rho_L - \rho_V) g$

Electric field F_E



FORCE CAUSED BY THE ELECTRIC FIELD

$$\vec{F}_E = \rho_f \vec{E} - \frac{1}{2} E^2 \nabla \varepsilon - \nabla \left[\frac{1}{2} \rho \; E^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \right]$$

Coulomb's force (electrophoretic) $\rho_f \vec{E}$

Dielectrophoretic force $\frac{1}{2} E^2 \nabla \varepsilon$

Electrostriction $\nabla \left[\frac{1}{2} \rho \; E^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \right]$

Gases: $\rho \left(\frac{\partial \varepsilon_G}{\partial \rho} \right)_T = \varepsilon_0 (\varepsilon_G - 1)$ Liquids: $\rho \left(\frac{\partial \varepsilon_L}{\partial \rho} \right)_T = \frac{\varepsilon_0 (\varepsilon_L - 1)(\varepsilon_L - 2)}{3}$

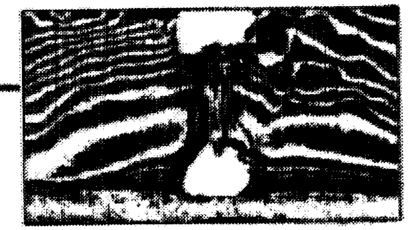
Relaxation time of electrical charges $\boxed{\tau_\sigma = \frac{\varepsilon}{\sigma}}$

Thermophysical and transport properties: $\boxed{k = k(E)}$ and $\mu = \mu(E)$

Electrical properties: $\boxed{\varepsilon = (\varepsilon)_0 (1 + a\Delta T)}$ and $\sigma = (\sigma)_0 (1 - b\Delta T)$

Pool Boiling in Microgravity

under the Influence of Electric Fields



GOVERNING EQUATIONS

Momentum equation
$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\rho\ \vec{g}+\boxed{\vec{F}_E}-\mu\ \nabla^2\vec{v}$$

Incompressibility condition
$$\nabla\cdot\vec{v}=0$$

Energy equation
$$\frac{\partial T}{\partial t}+\vec{v}\cdot\nabla T=\alpha\nabla^2 T+\boxed{\sigma\ E^2/\rho c_p}$$

Force of electrical origin
$$\vec{F}_E=\rho_f\vec{E}-\frac{1}{2}E^2\nabla\varepsilon-\nabla\left[\frac{1}{2}\rho\ E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right]$$

σ electrical conductivity
E electric field strength
ρ_f free charge density
ε dielectric permittivity

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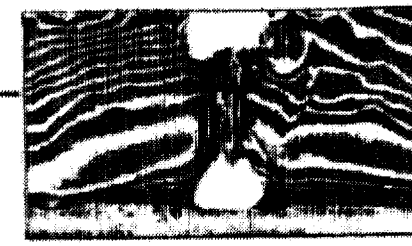
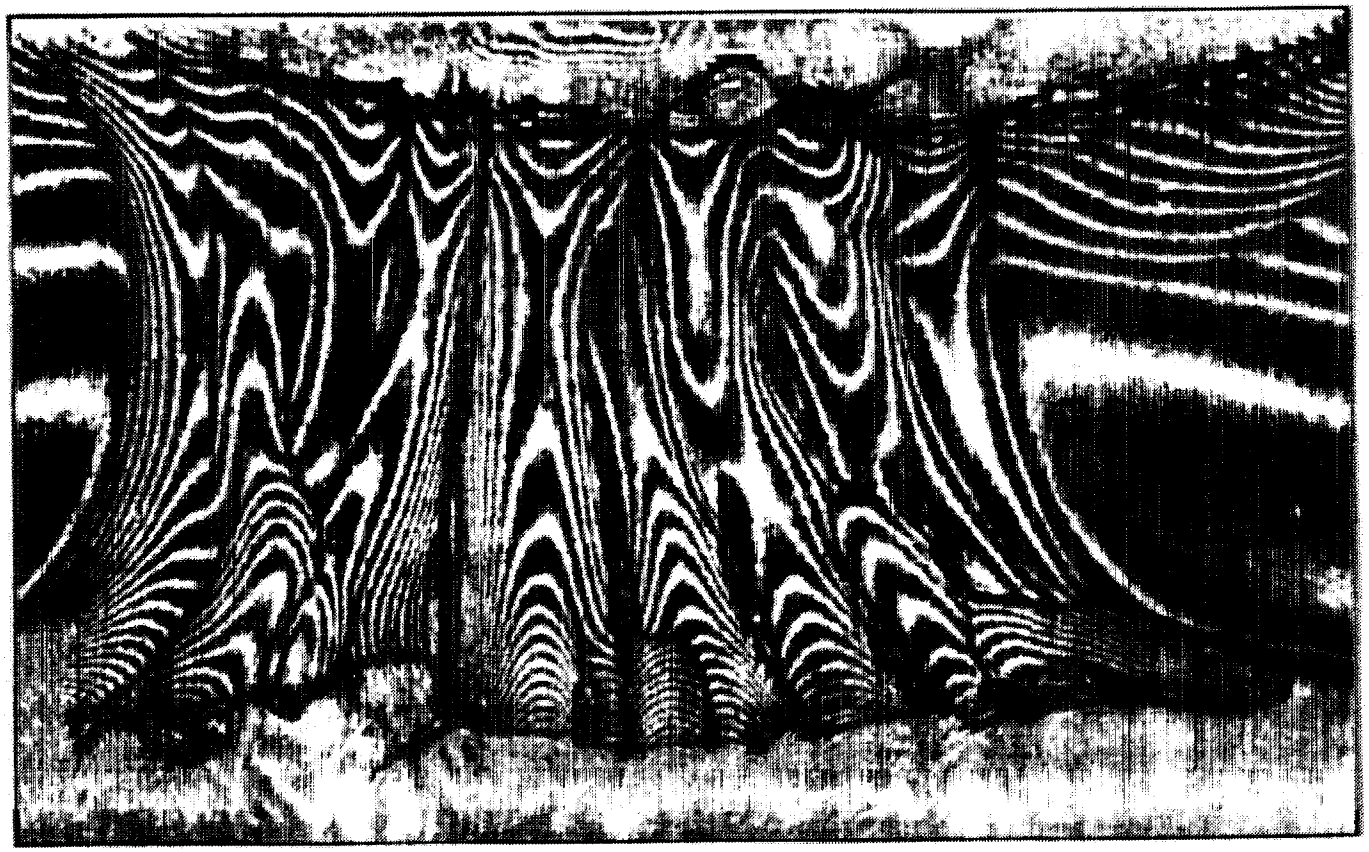
Past research accomplishments - measurement techniques -

- Visualization of unsteady temperature distributions around bubbles using real-time holographic interferometry
- Accounting for light deflection effects in the reconstruction of temperature distributions from interferometric images
- Reconstruction of axially symmetrical temperature distributions from interferometric images
- Reconstruction of 3D unsteady temperature distributions from interferometric images using tomographic techniques
- Measurement of bubble volume and dimensions using digital image processing

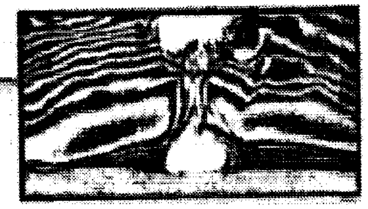


THERMAL PLUME ABOVE THE HEATED DISK VISUALIZED BY HOLOGRAPHIC INTERFEROMETRY

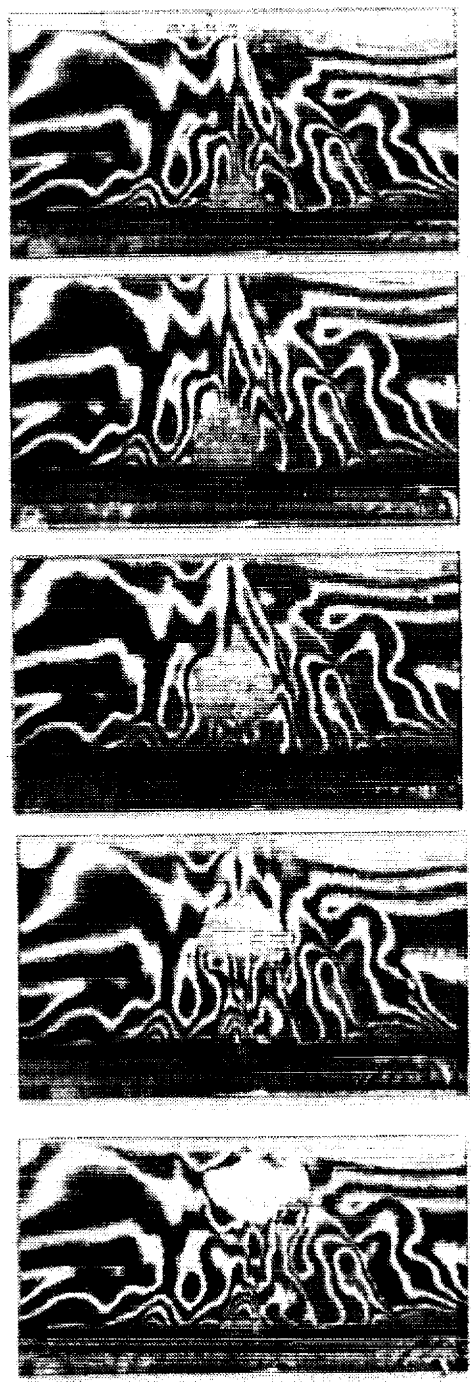


Working fluid: PF-5052
Saturation temperature: T_{sat}=50 °C
Pressure: p= 1 bar

Surface temperature T_s= 29 °C
ΔT/fringe pair=0.05 °C



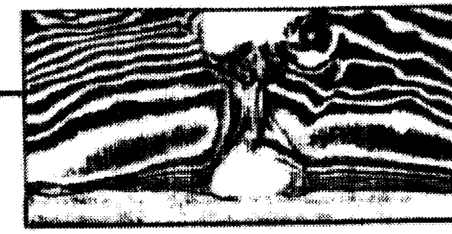
AIR BUBBLES INJECTED INTO THE THERMAL BOUNDARY LAYER THROUGH AN ORIFICE



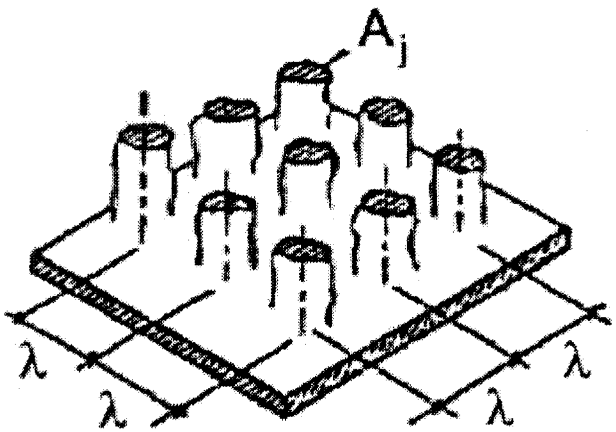
Working fluid: PF-5052
Saturation temperature: T_{sat} = 50 °C
Pressure: p= 1 bar

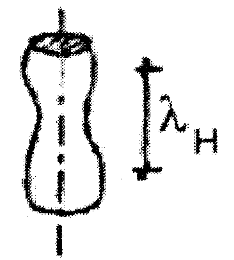
Surface temperature: T_s = 25 °C
ΔT/fringe pair = 0.05 °C

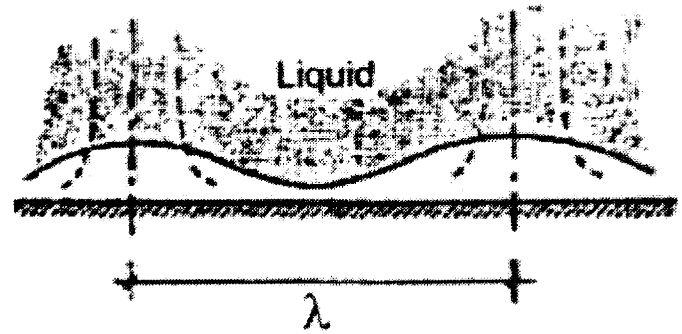
Time separation between images = 0.01 seconds



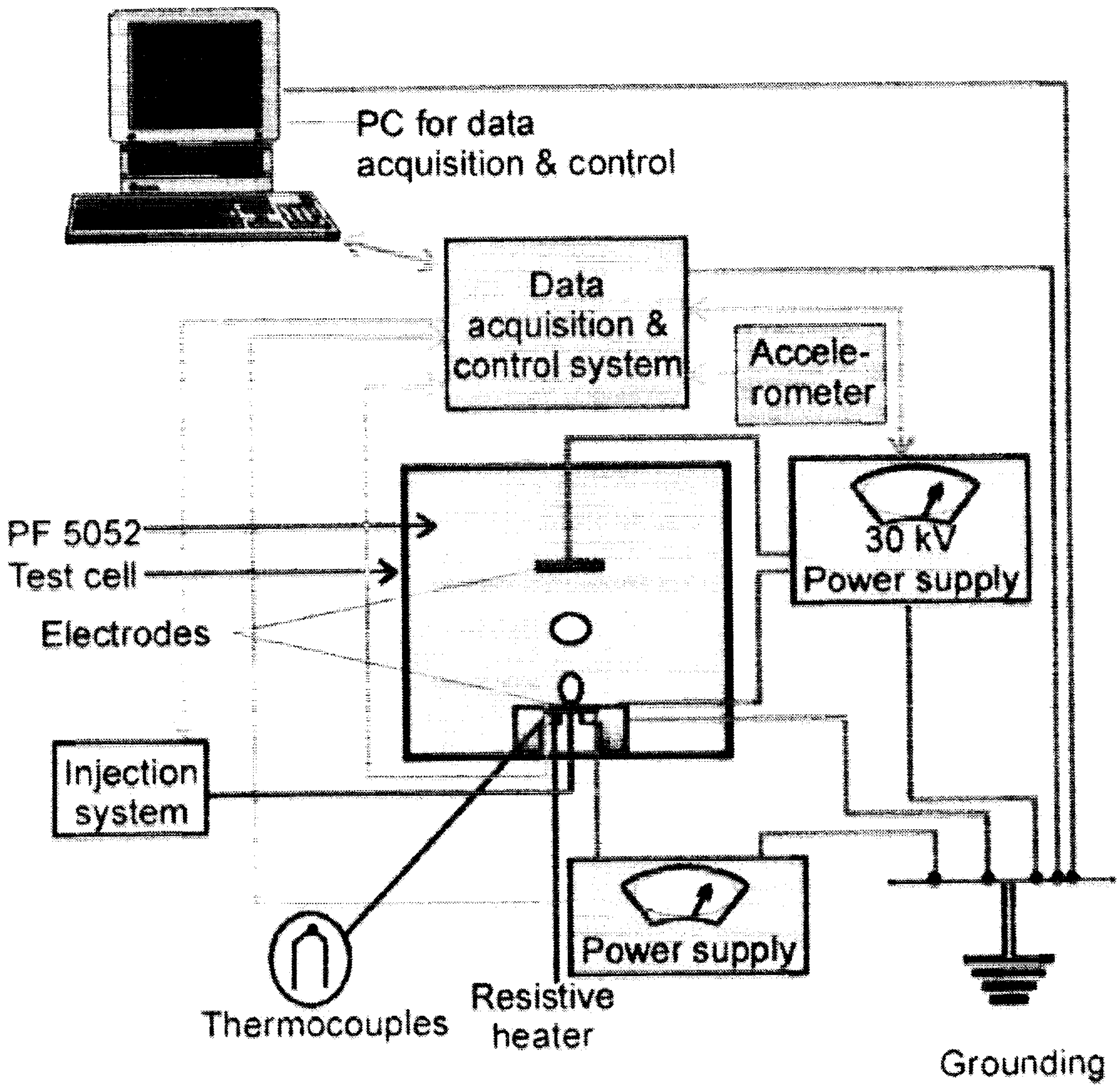
PHF VAPOR PATTERNS HYDRODYNAMIC THEORY



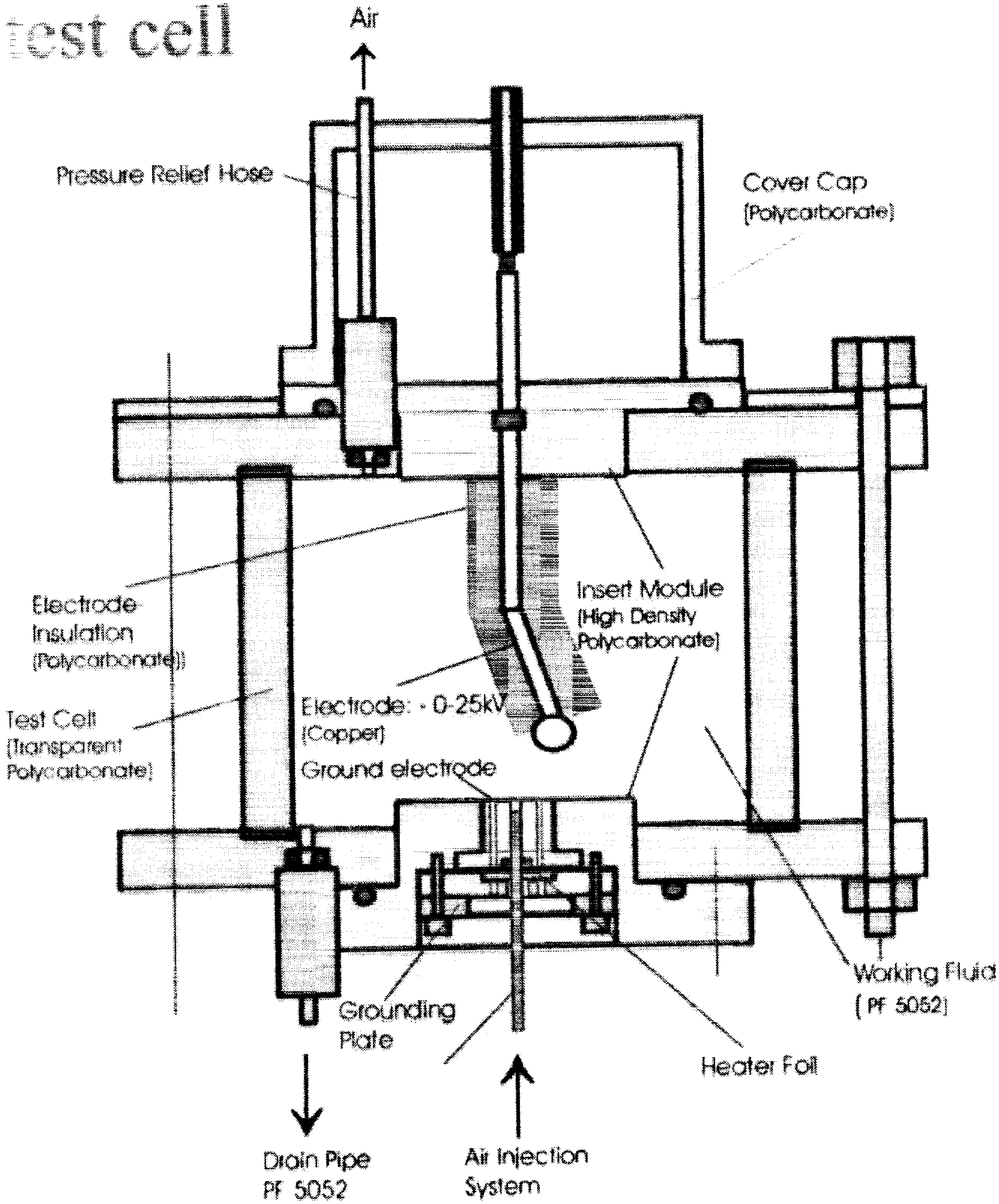


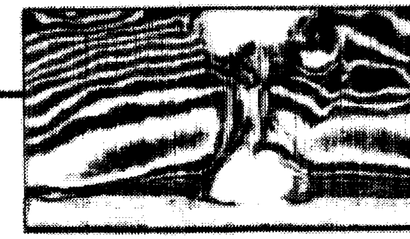


SCHEMATIC OF THE EXPERIMENTAL SETUP

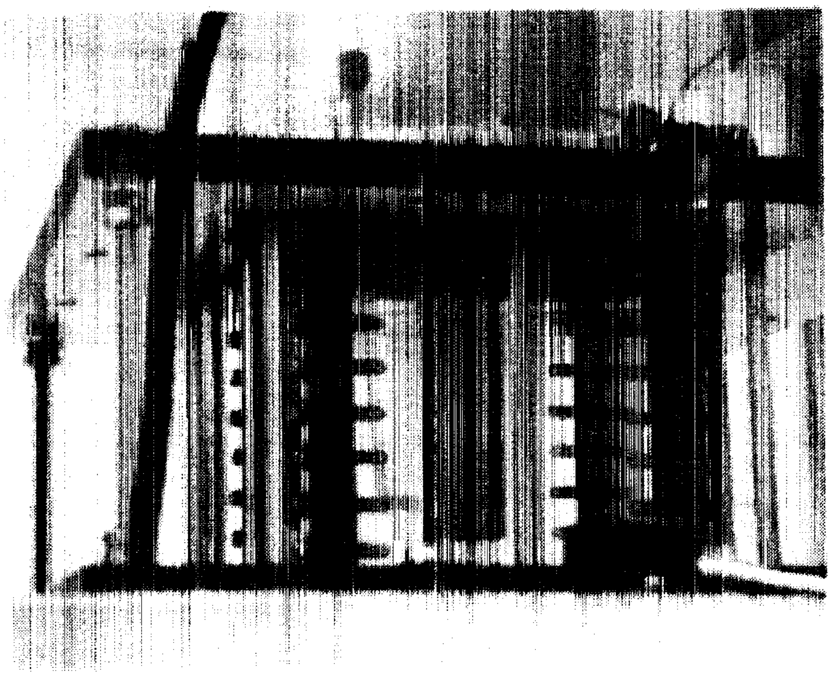


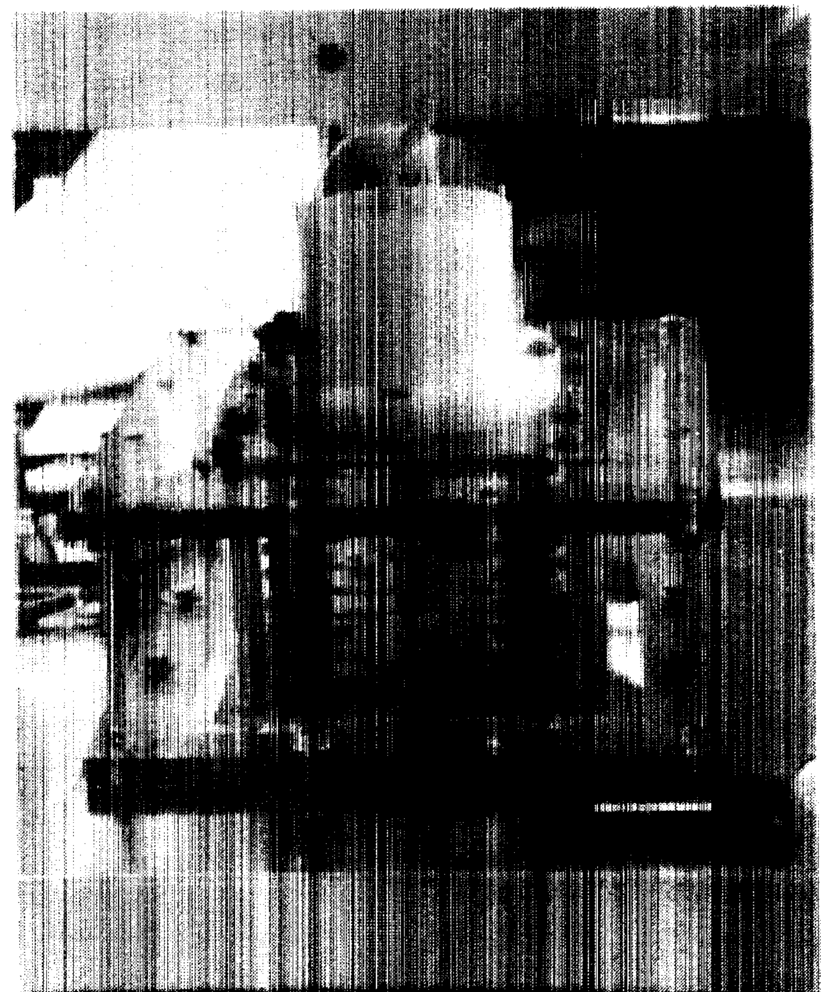
Schematic of the test cell





Details of the test cell





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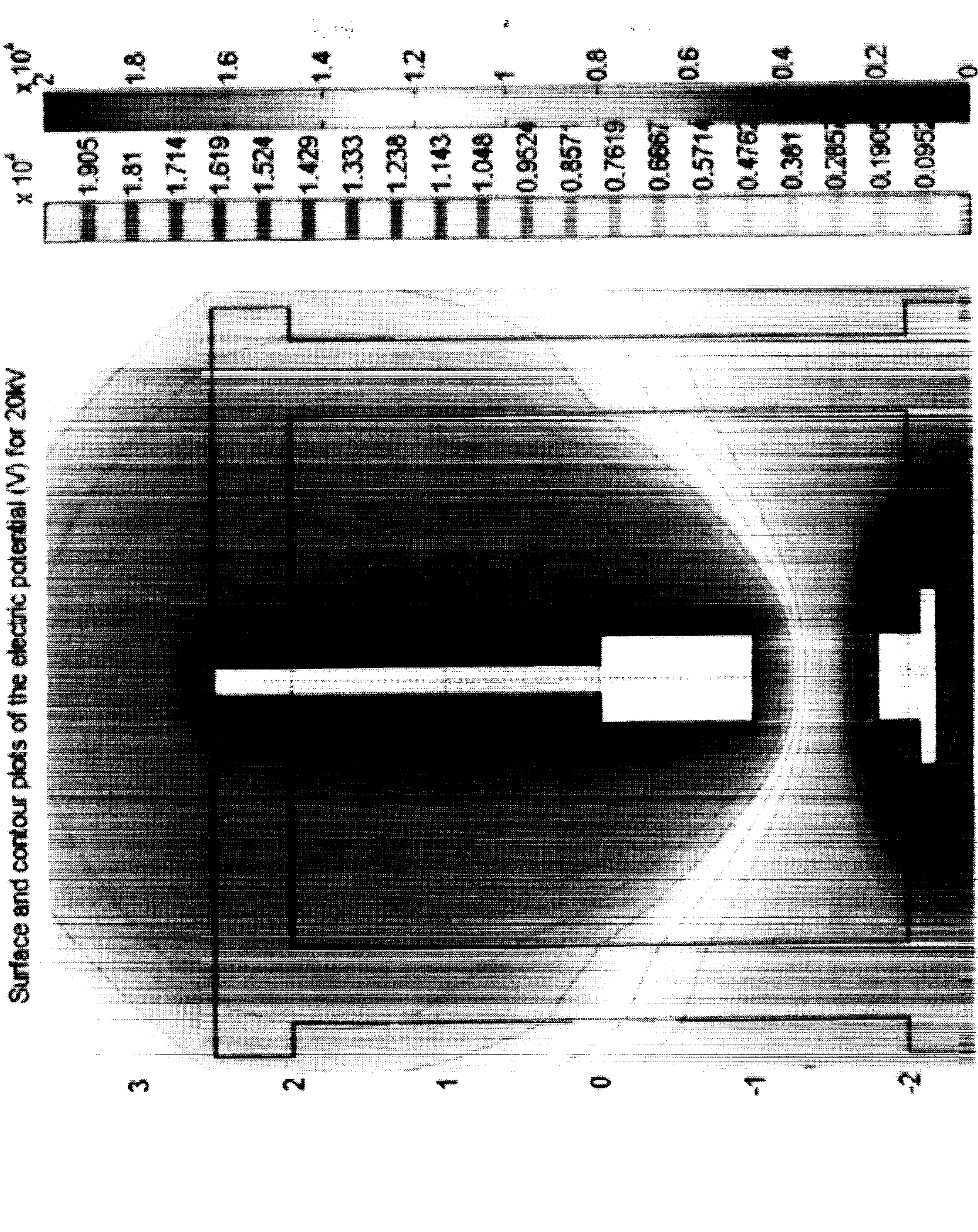
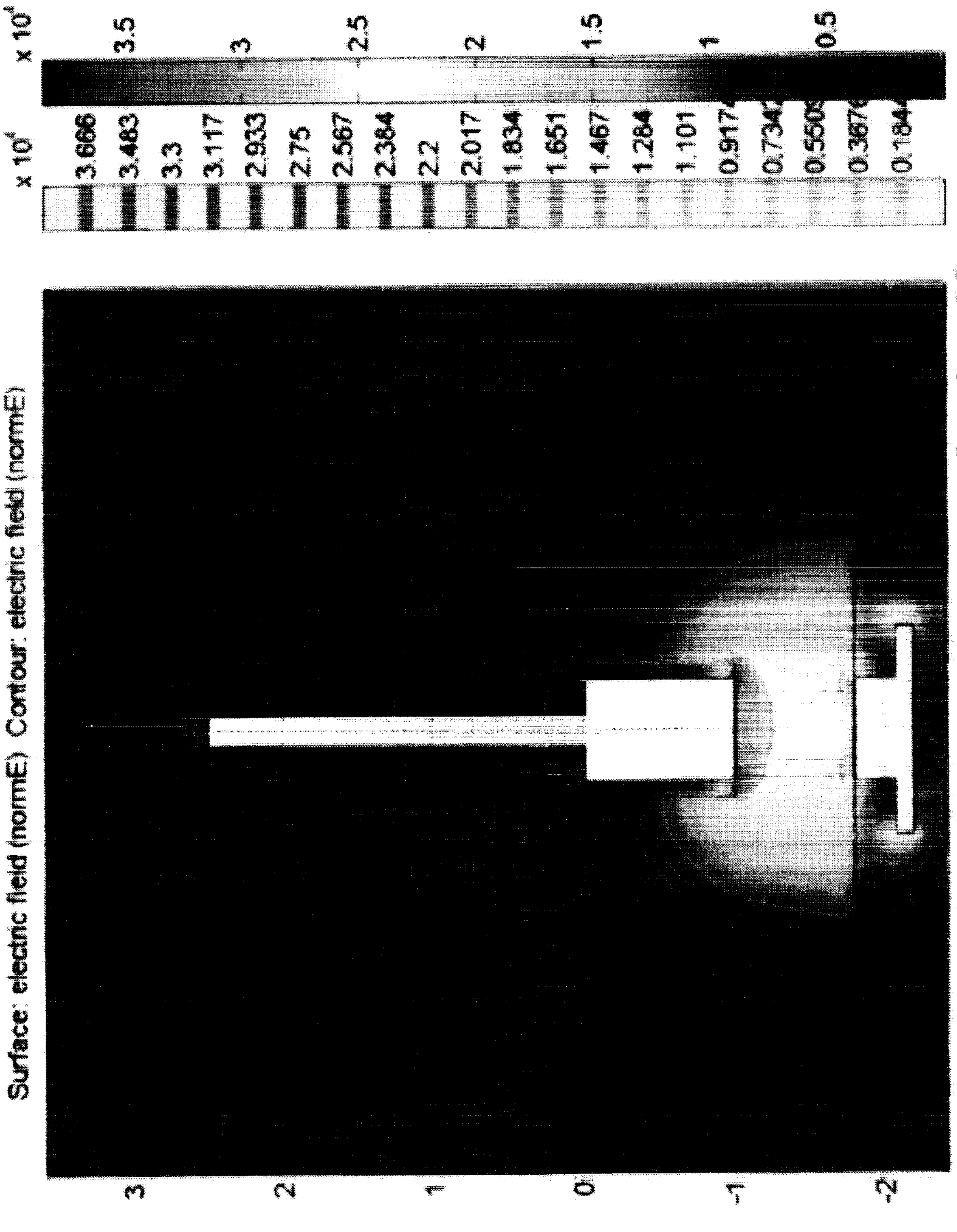
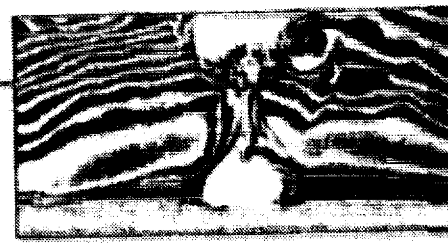
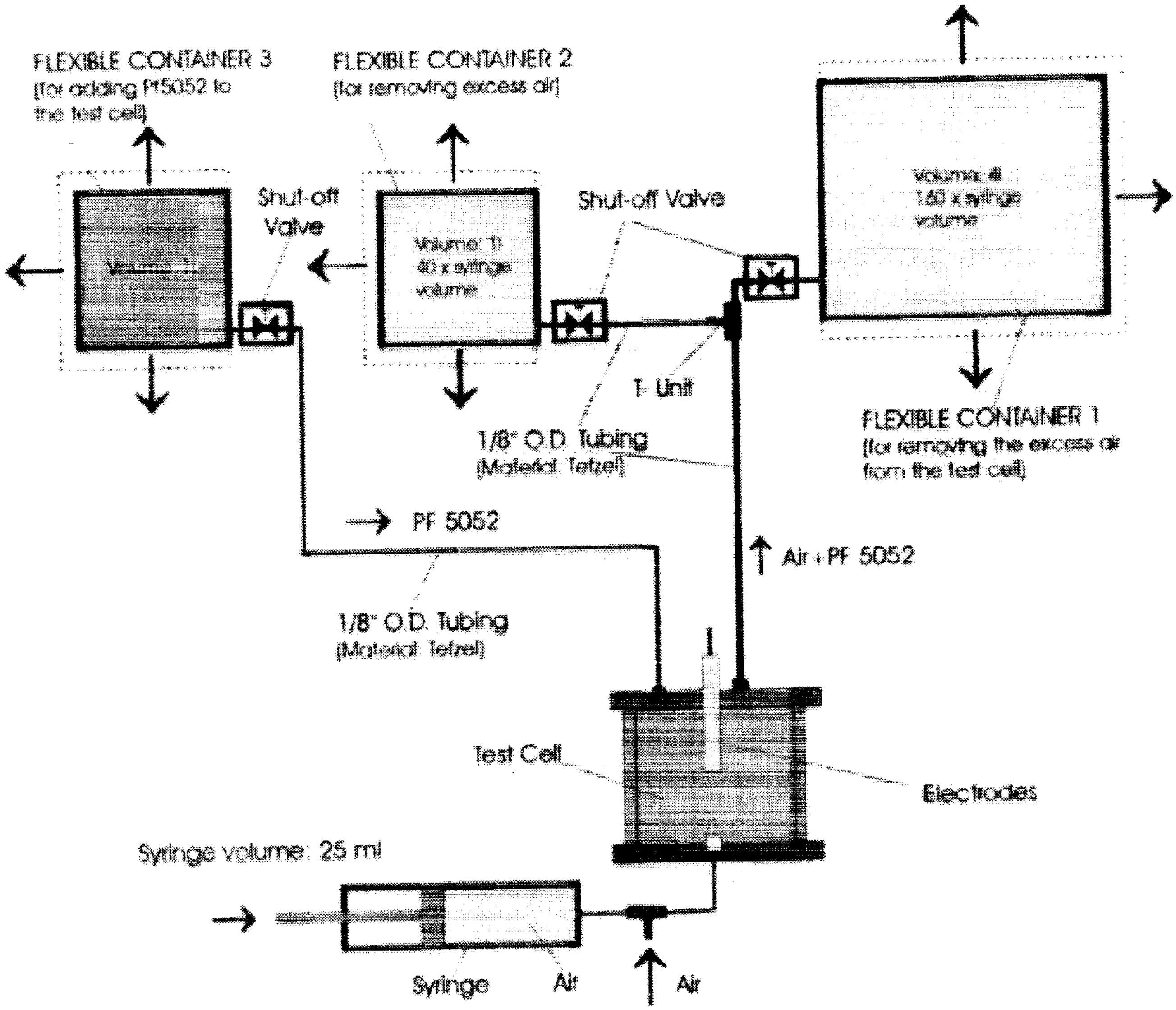
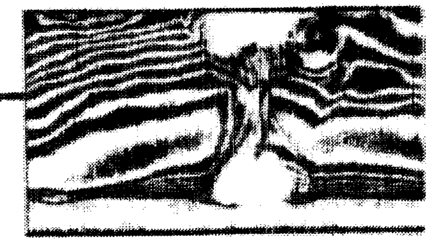

Surface and contour plots of the electric potential (V) for 20kV
x 10^4
1.905
1.81
1.714
1.619
1.524
1.429
1.333
1.238
1.143
1.048
0.9524
0.857
0.7619
0.6667
0.5714
0.4762
0.381
0.2857
0.1905
0.0952
x 10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
2
1
0
-1
-2


Surface: electric field (normE) Contour: electric field (normE)
x 10^4
3.666
3.483
3.3
3.117
2.933
2.75
2.567
2.384
2.2
2.017
1.834
1.651
1.467
1.284
1.101
0.9174
0.7341
0.5506
0.3670
0.1844
x 10^4
3.5
3
2.5
2
1.5
1
0.5

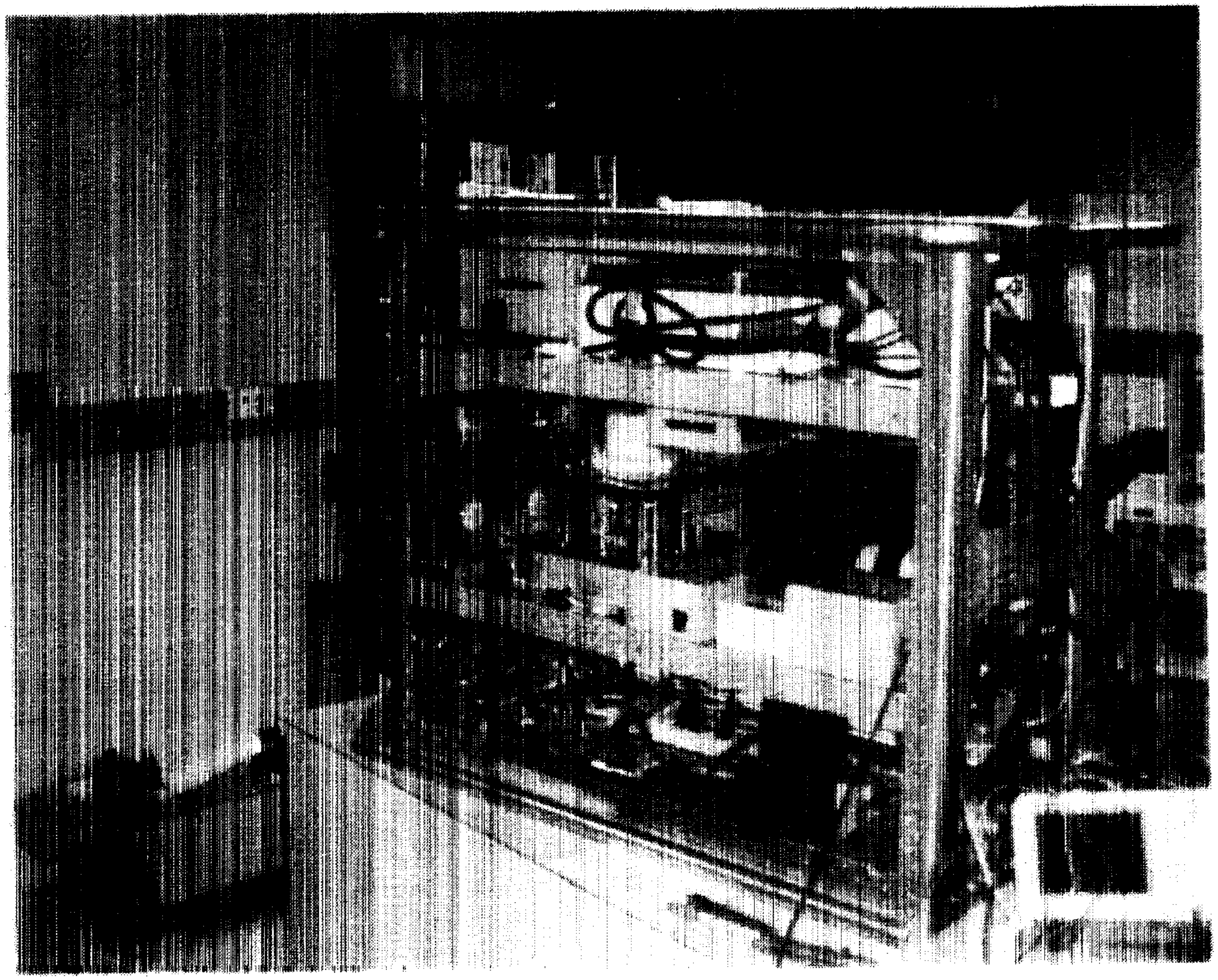


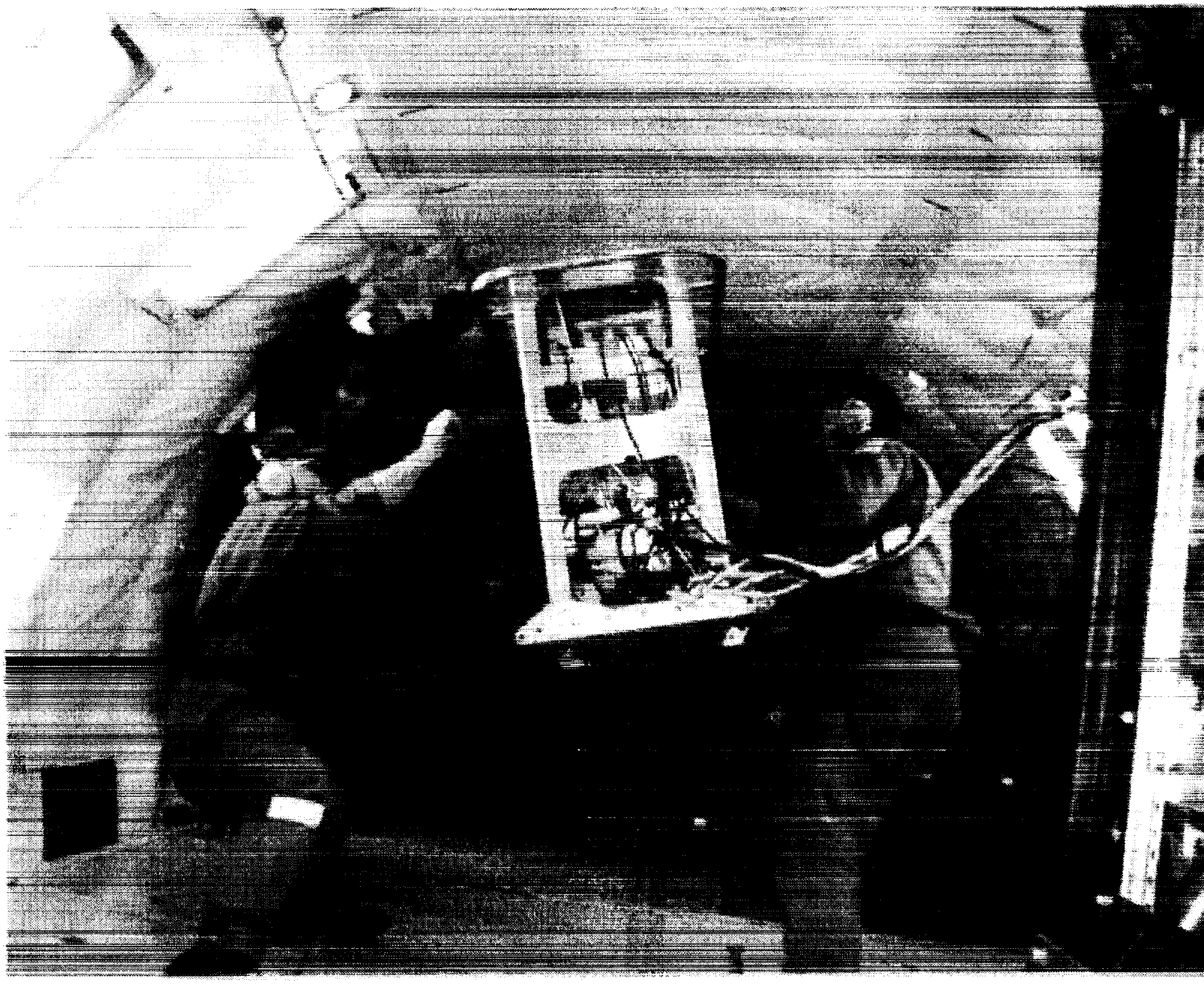
Pressure relief system





Experimental rack

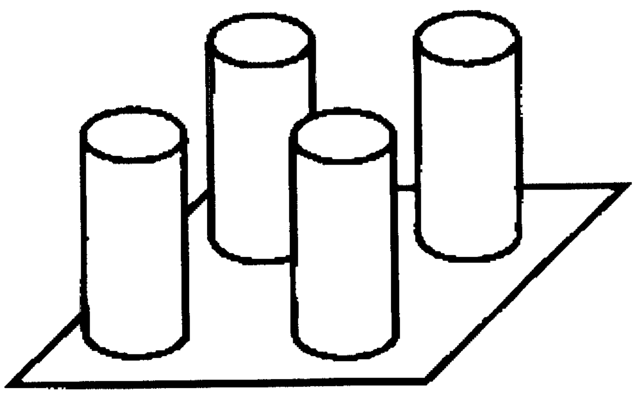




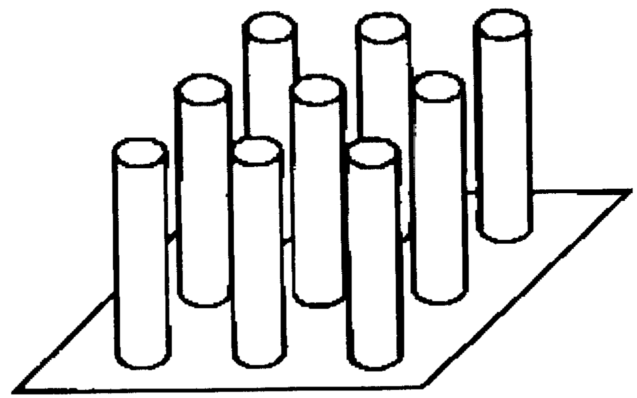
Experimental parameters

- Potential difference between electrodes: 0V, 5kV, 10kV, 15kV, 20kV
- Polarity
- Shape of the high-voltage electrode: cylindrical, spherical
- Heating applied to the ground electrode
- Gravity: 1g, 0g, 0.3g, 0.1g
- Mass flow rate of the injected air

PHF VAPOR PATTERNS



a) without electric field



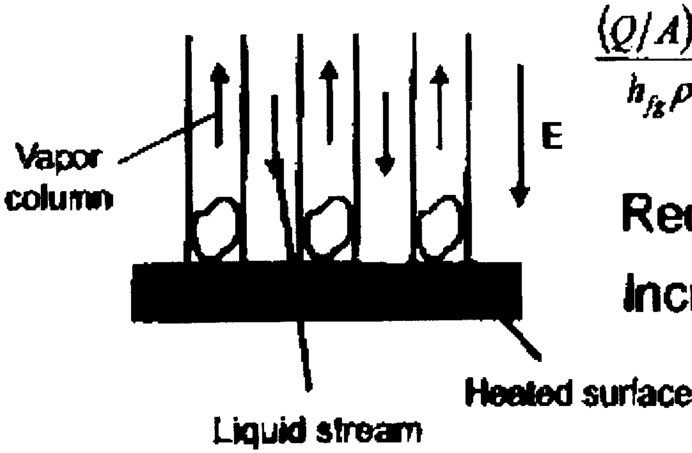
b) with electric field

HYDRODYNAMIC MODEL FOR PEAK HEAT FLUX

$$\frac{(Q/A)_{max}}{h_{fg}\rho_v} = 0.13\left[\frac{\sigma g(\rho_L - \rho_v)}{\rho_v^2}\right]^{\frac{1}{4}}$$ Zuber and Tribus (1958)

based on the Helmholtz - Taylor analysis

ELECTRIC FIELD EFFECT - ELECTROHYDRODYNAMIC APPROACH

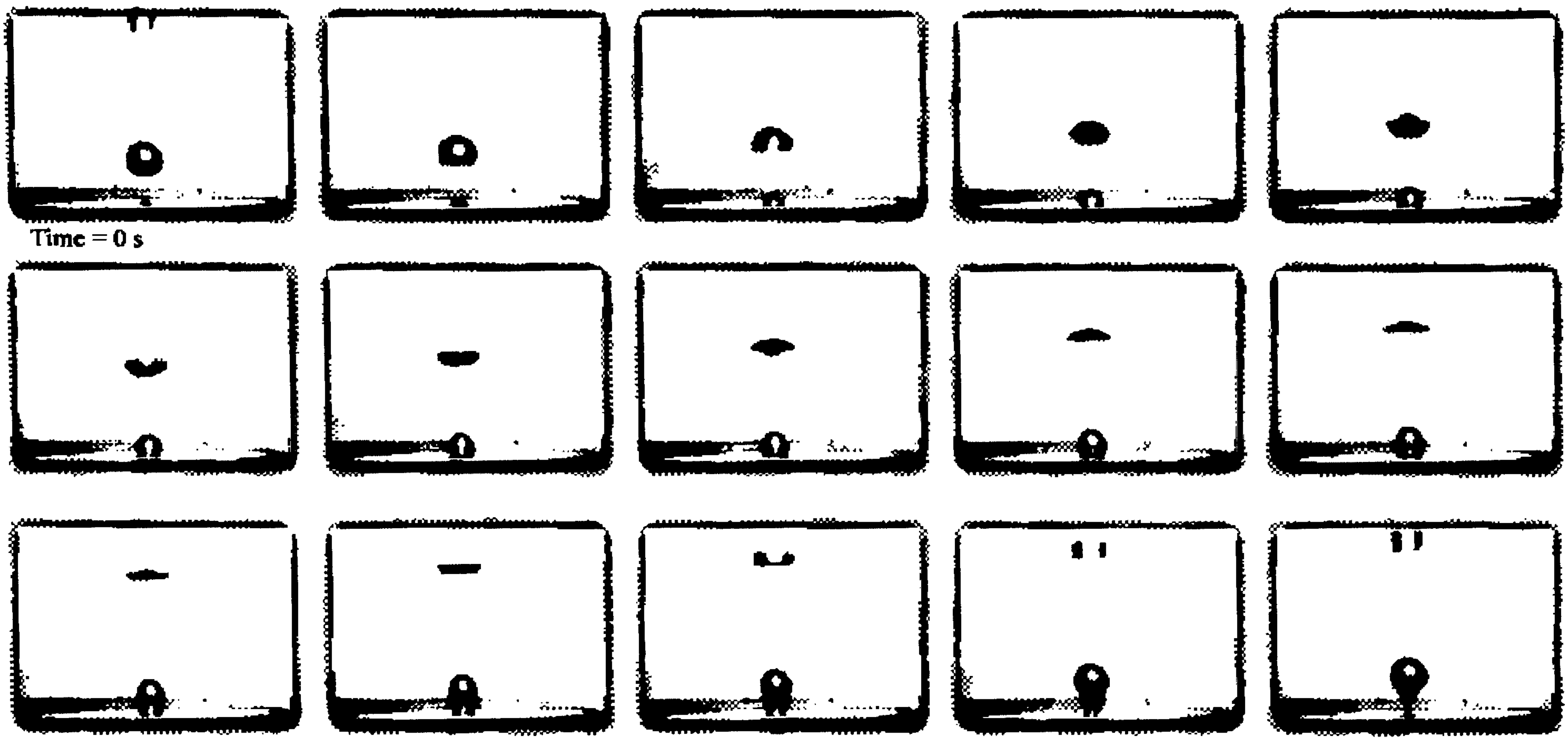


$$\frac{(Q/A)_{max}}{h_{fg}\rho_v} = C_1\left[\frac{(\sigma g(\rho_L - \rho_v))^{\frac{1}{2}}}{\rho_v}\left(\frac{\rho_L}{\rho_L + \rho_v}\right) + \frac{(\varepsilon - \varepsilon_0)^2 E^2}{\rho_v(\varepsilon + \varepsilon_0)}\right]^{\frac{1}{2}}$$ Melcher (1963)

Reduction of bubble departure size $DE = C_2$

Increase of bubble departure frequency $fD^2 = C_3$

Life cycle of an injected bubble in 1g



Time = 0 s

Time = 0.056 s
Volume = 4.22×10^{-3} cm^3

Experiment Parameters:

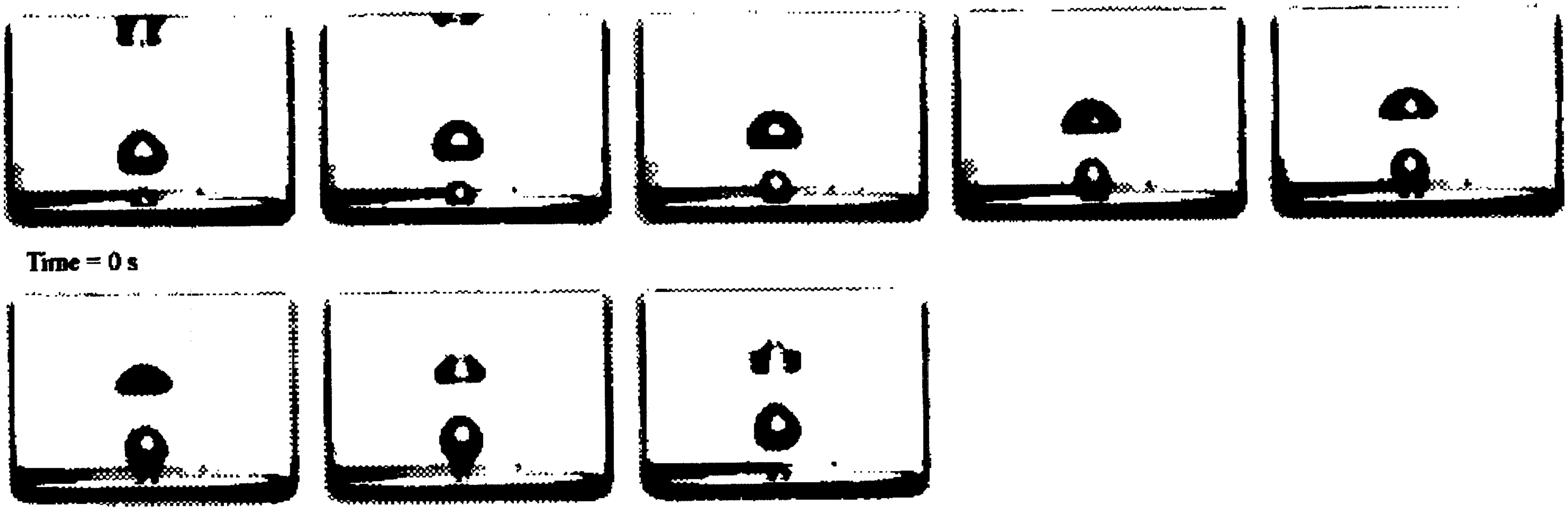
Potential Difference: 0 kV
Mass Flow Rate: 2.58×10^{-7} kg/s
Time Interval: 0.004 s

Terrestrial, Cleveland Matrix, Experiment No. 7

Average Acceleration:

Acceleration X: 0 g
Acceleration Y: 0 g
Acceleration Z: 1 g

Life cycle of an injected bubble in 1g, 20kV



Time = 0.024 s
Volume = 8.77×10^{-3} cm^3

Experiment Parameters:

Potential Difference: 20 kV
Mass Flow Rate: 2.58×10^{-7} kg/s
Time Interval: 0.004 s

Terrestrial, Cleveland Matrix, Experiment No. 11

Average Acceleration:

Acceleration X: 0 g
Acceleration Y: 0 g
Acceleration Z: 1 g

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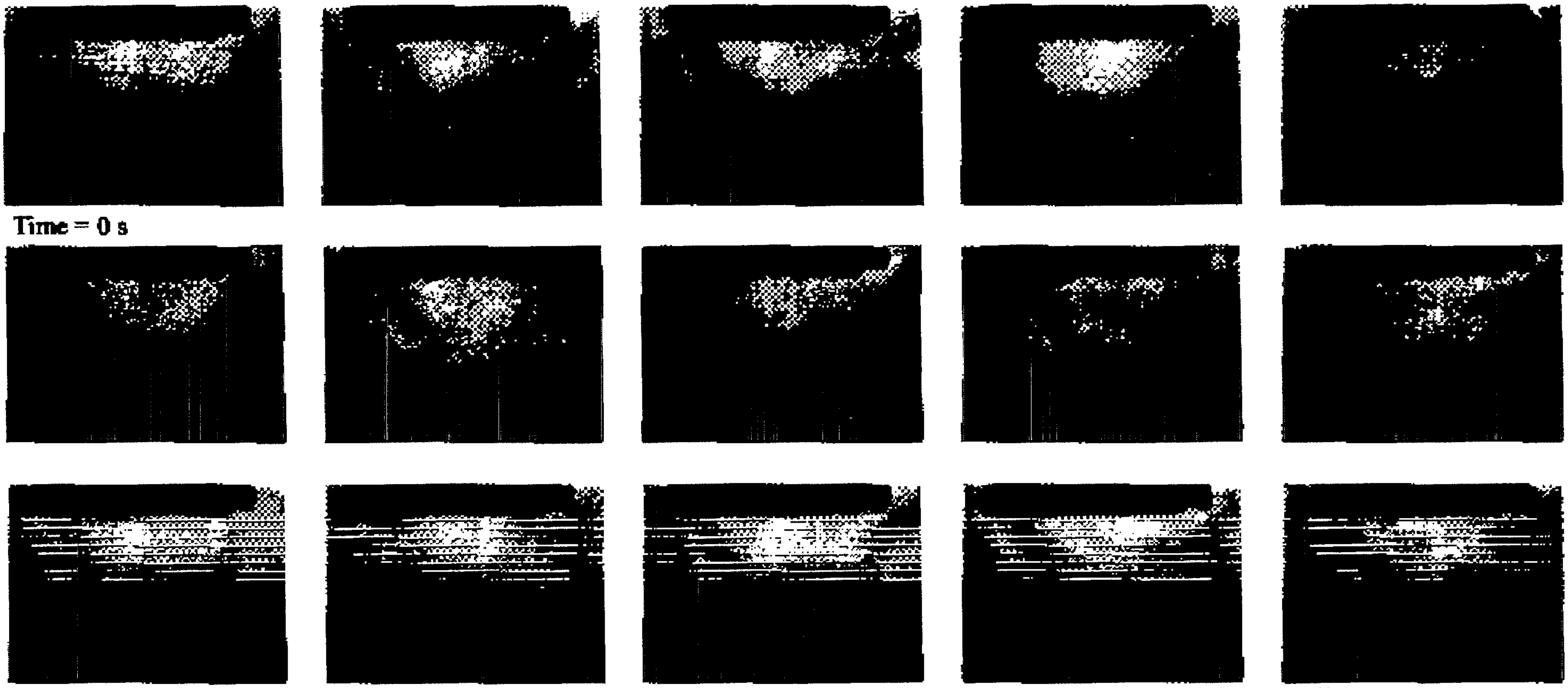
Pool Boiling in Microgravity

under the Influence of Electric Fields

Life cycle of an injected bubble in microgravity, 0V



Experiment Parameters:

- Potential Difference: 0 kV
- Mass Flow Rate: 2.58 x 10^{7} kg/s
- Time Interval: 0.048 s

Cleveland, Day 2: October 20, 1999, Experiment No. 7

Average Acceleration:

- Acceleration X: 0.02g
- Acceleration Y: 0.04 g
- Acceleration Z: 0.02 g

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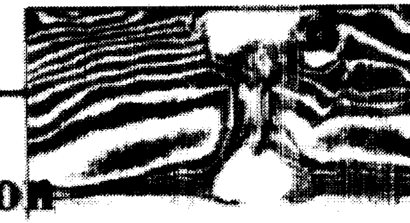
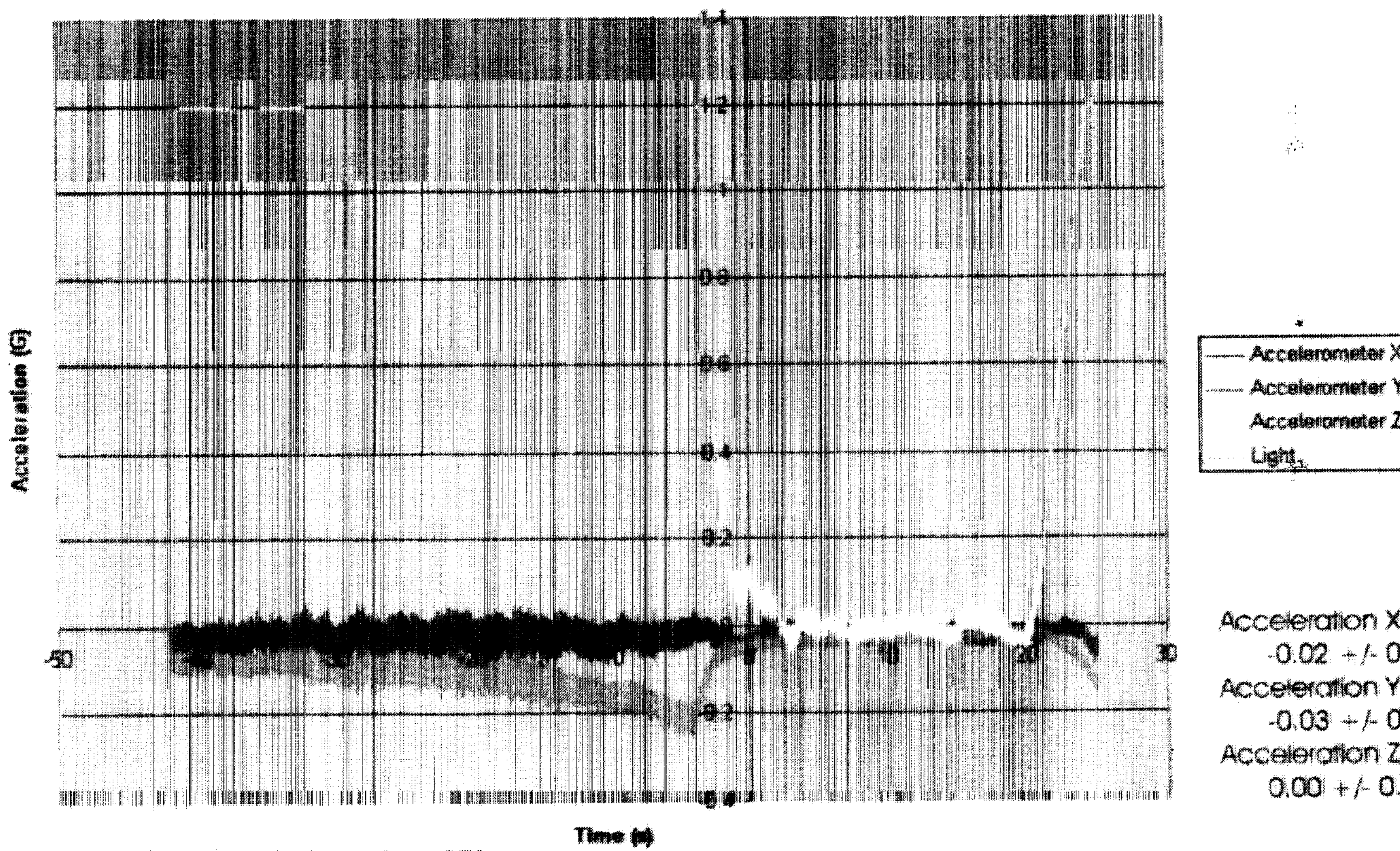
Pool Boiling in Microgravity

under the Influence of Electric Fields

Typical Acceleration Data: Bolted-Down Configuration





Acceleration X:
-0.02 +/- 0.(

Acceleration Y:
-0.03 +/- 0.(

Acceleration Z:
0.00 +/- 0.0

Cleveland Experiment Day 3 October 21, 1999

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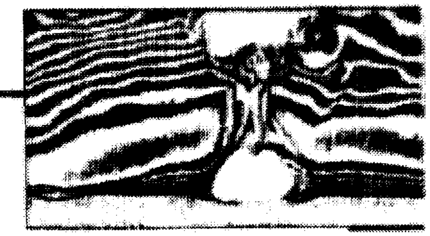
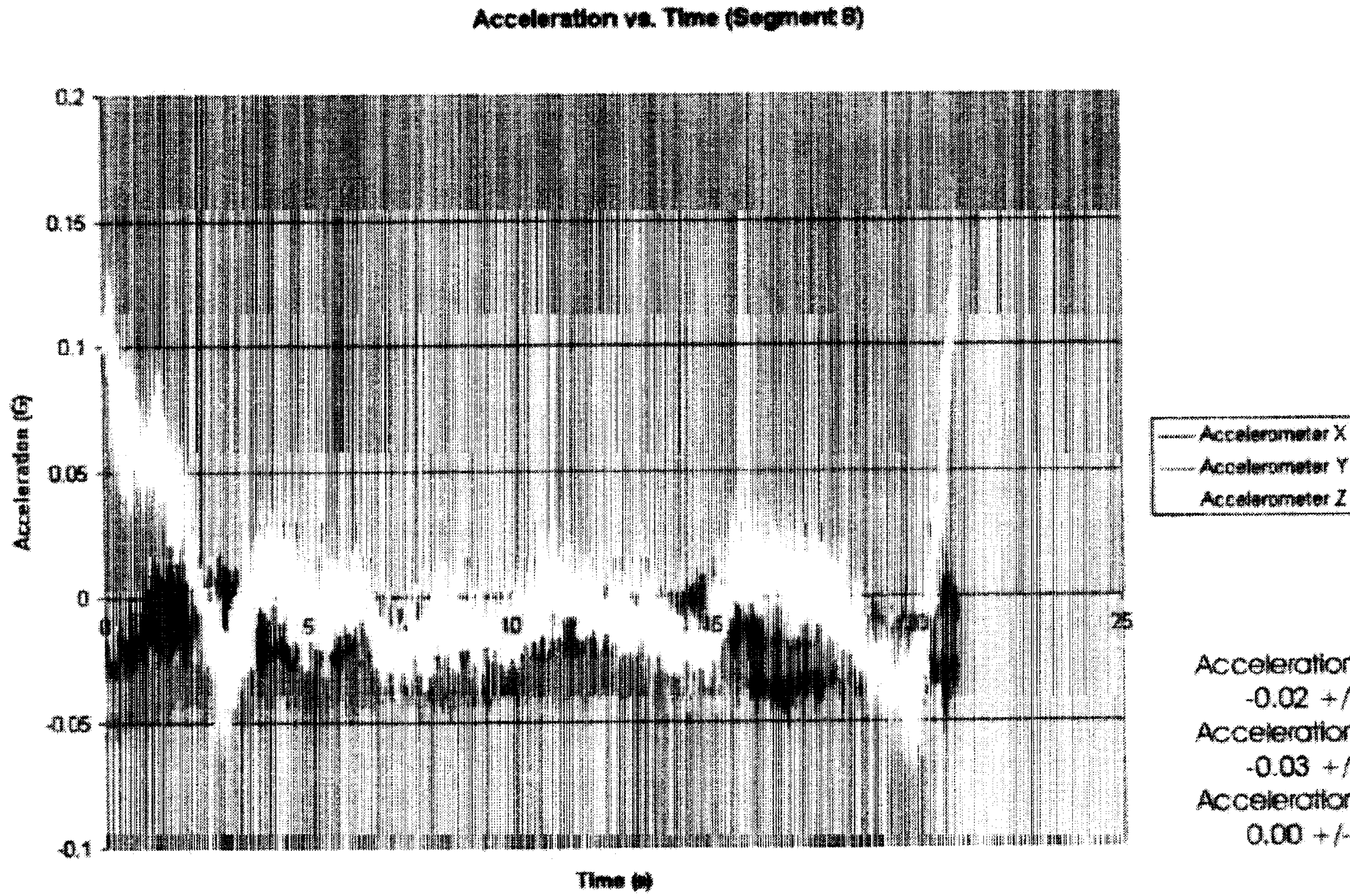
Pool Boiling in Microgravity

under the Influence of Electric Fields



Typical Acceleration Data -- 0G Portion



Acceleration X:
-0.02 +/- 0.01

Acceleration Y:
-0.03 +/- 0.01

Acceleration Z:
0.00 +/- 0.03

Cleveland Experiment Day 3 October 21, 1999

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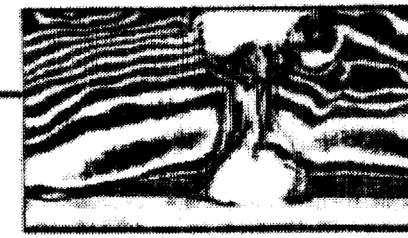
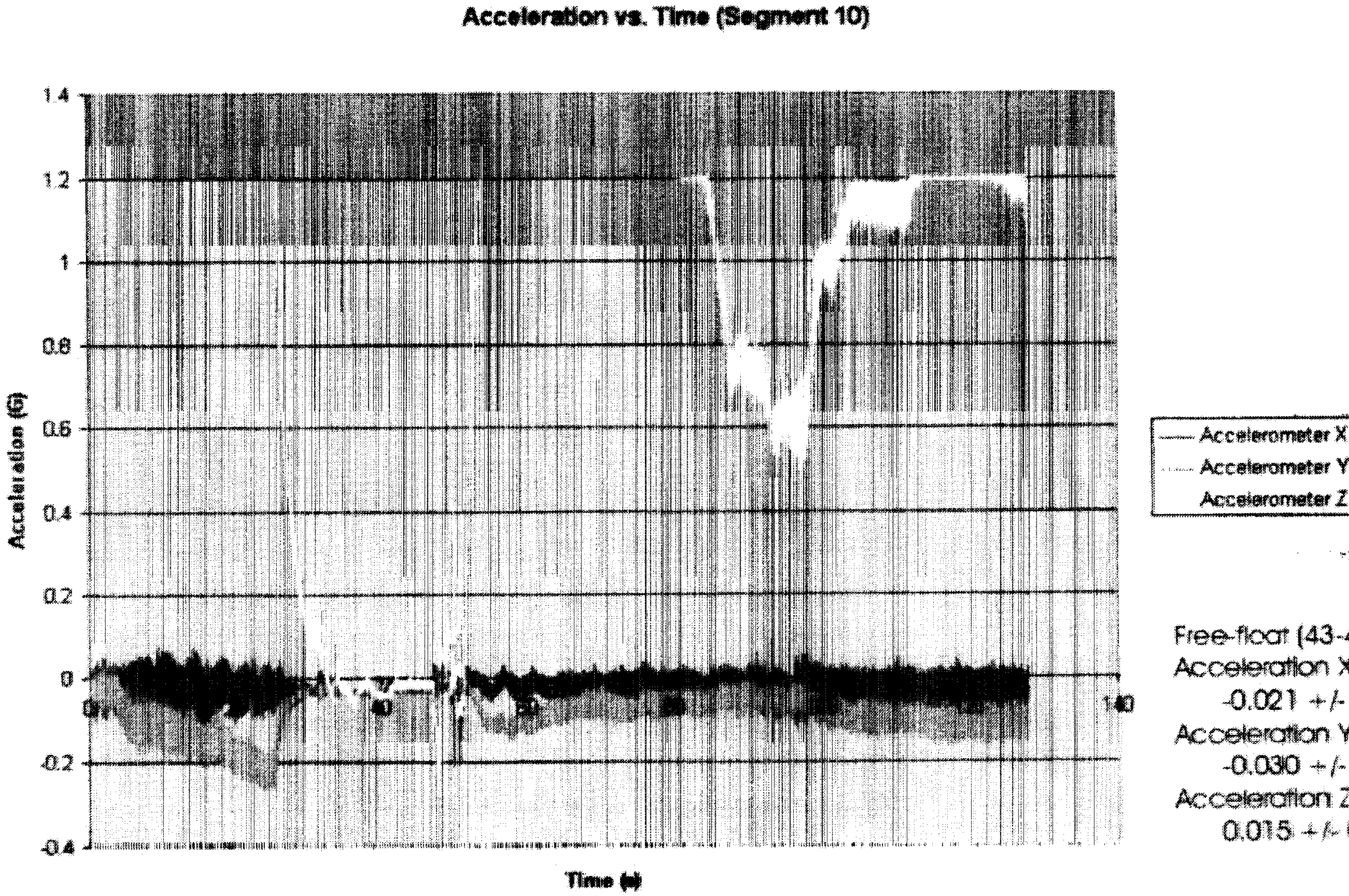
Pool Boiling in Microgravity

under the Influence of Electric Fields

Typical Acceleration Data





Free-float (43-47 s.
Acceleration X:
-0.021 +/- 0.0(
Acceleration Y:
-0.030 +/- 0.0(
Acceleration Z:
0.015 +/- 0.00

Houston Experiment: Day 3 February 3, 2000

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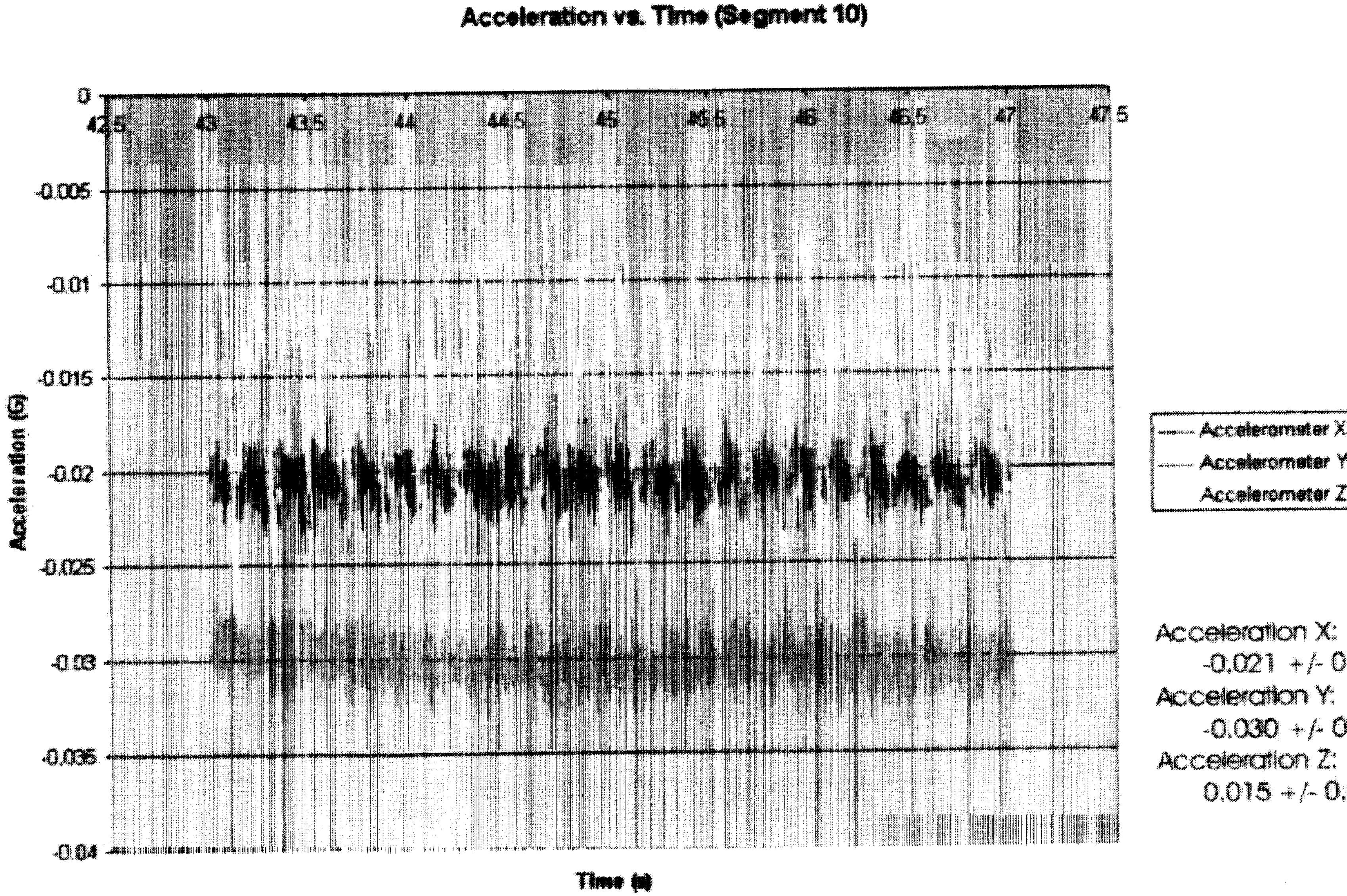
under the Influence of Electric Fields

Typical Acceleration Data -- Free-float Portion



Acceleration X:
-0.021 +/- 0.0(

Acceleration Y:
-0.030 +/- 0.0(

Acceleration Z:
0.015 +/- 0.00

Houston Experiment Day 3 February 3, 2000

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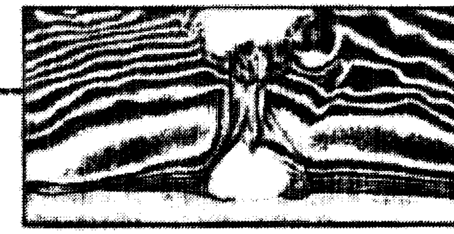
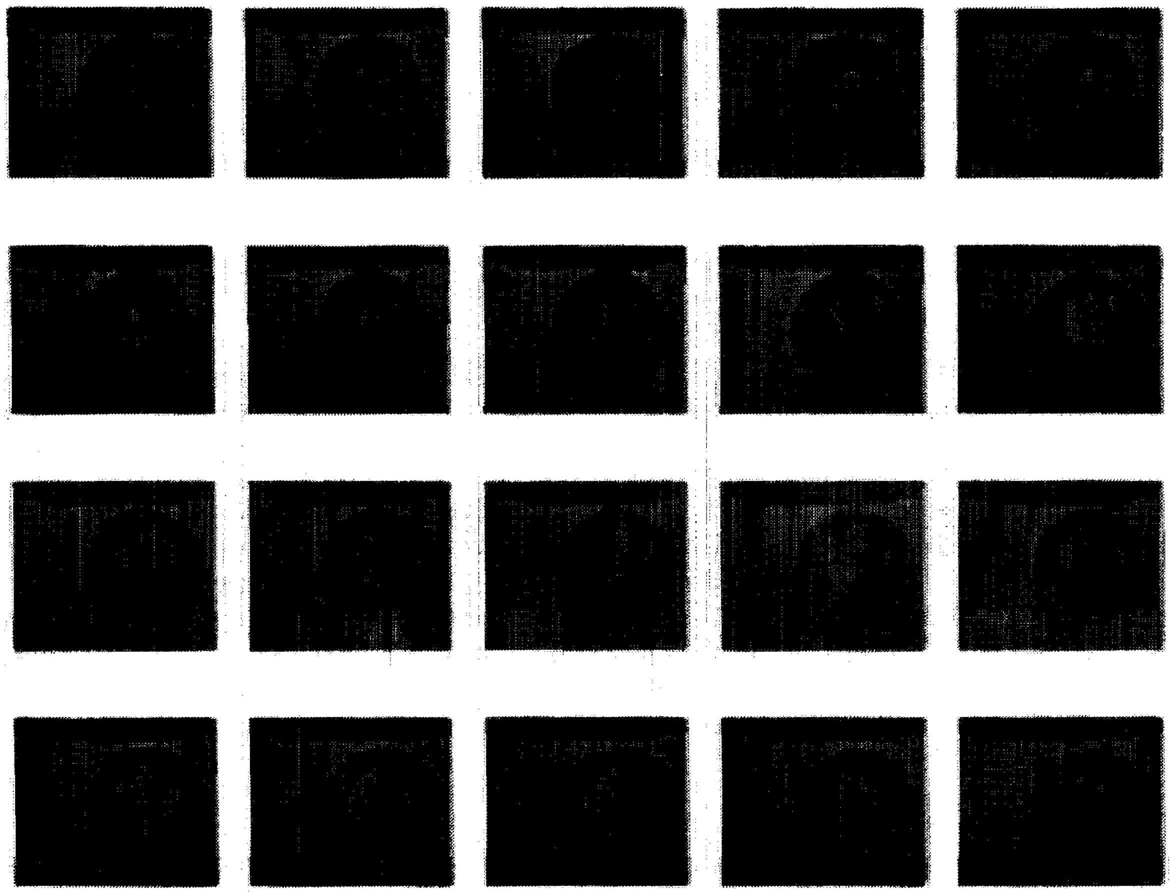


Interfacial instability on bubble surface in microgravity



Experimental Parameters:
Potential Difference: 0 kV
Mass Flow Rate: 4.09 x 10 ^ -7 kg/s
Time Interval: 0.004 s

Cleveland Experiment, Day 3, October 21, 1999

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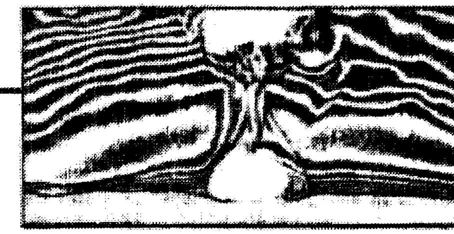
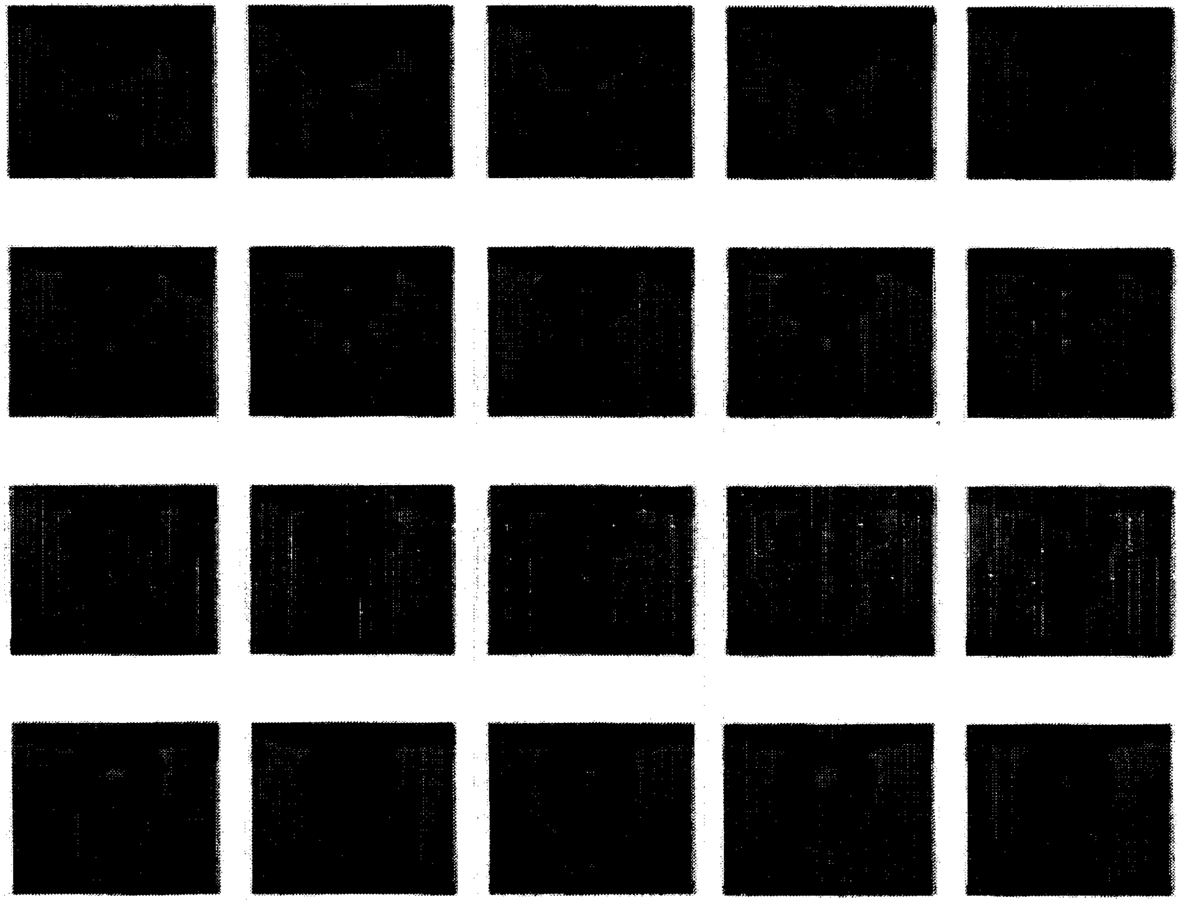
under the Influence of Electric Fields



Coalescence of Bubbles in Microgravity



Experiment Parameters:
Potential Difference: 0 kV
Mass Flow Rate: 4.09 x 10 ^ -7 kg/s
Time interval: 0.004 s

Cleveland Experiment, Day 3, October 21, 1999

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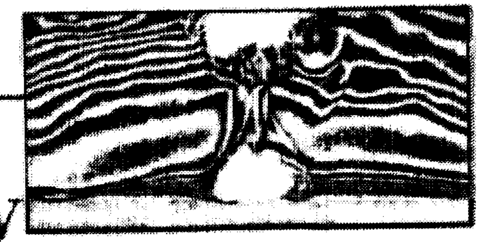
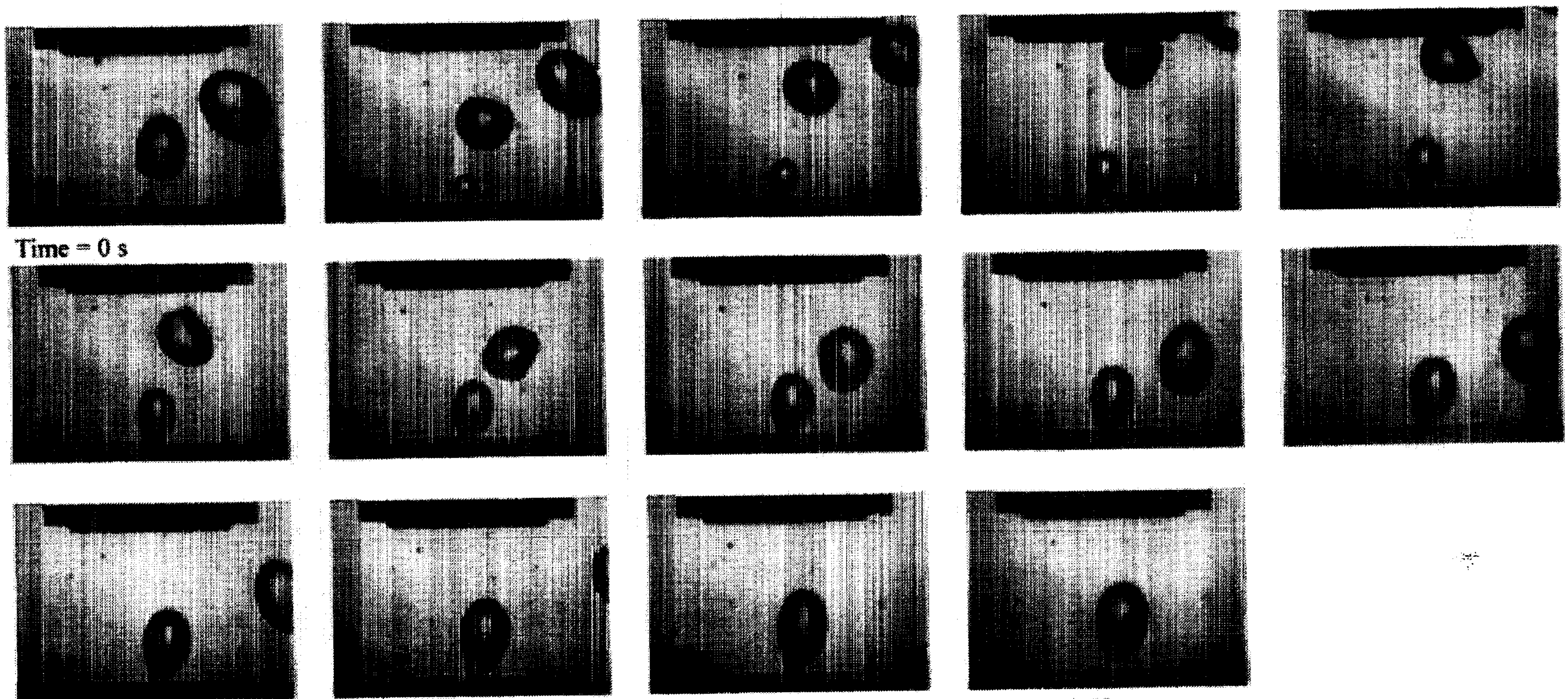


Life cycle of an injected bubble in microgravity, 20kV



Time = 0 s

Time = 0.52 s
Volume = 9.19×10^{-3} cm^3

Experiment Parameters:

Potential Difference: 20 kV
Mass Flow Rate: 2.58×10^{-7} kg/s
Time Interval: 0.040 s

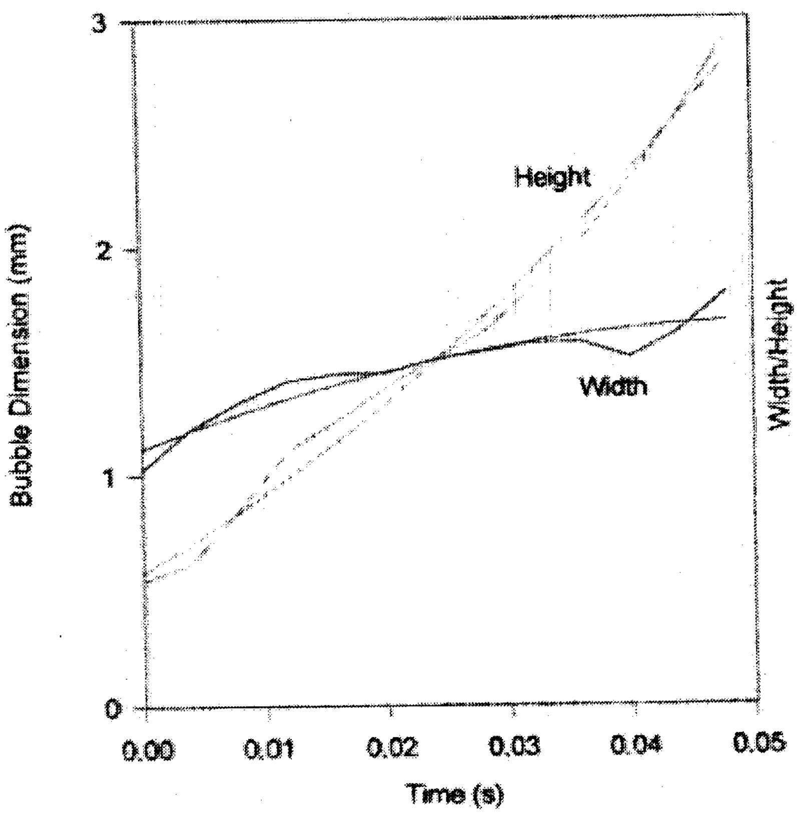
Average Acceleration:

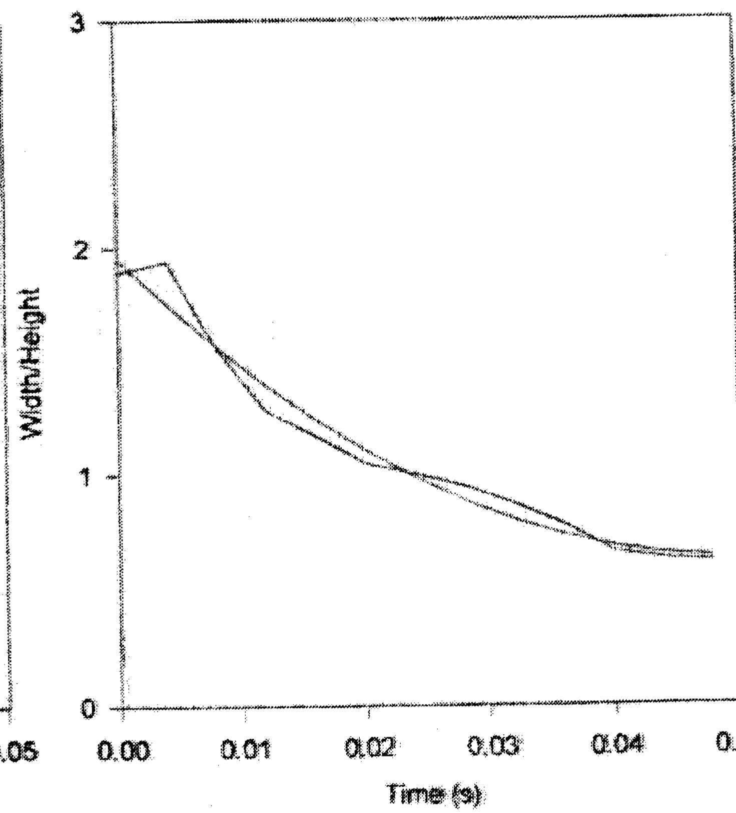
Acceleration X: 0.03 g
Acceleration Y: 0.02 g
Acceleration Z: 0.02 g

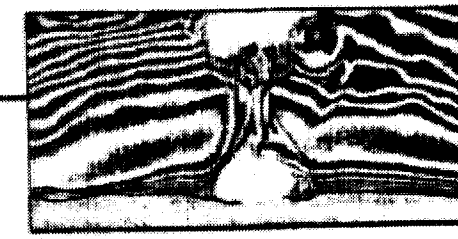
Cleveland, Day 2: October 20, 1999, Experiment No. 11

Bubble dimensions: terrestrial, 0V

Experimental Sequence
Terrestrial - Cleveland Matrix
0 kV, 1 g, 0.7 mm

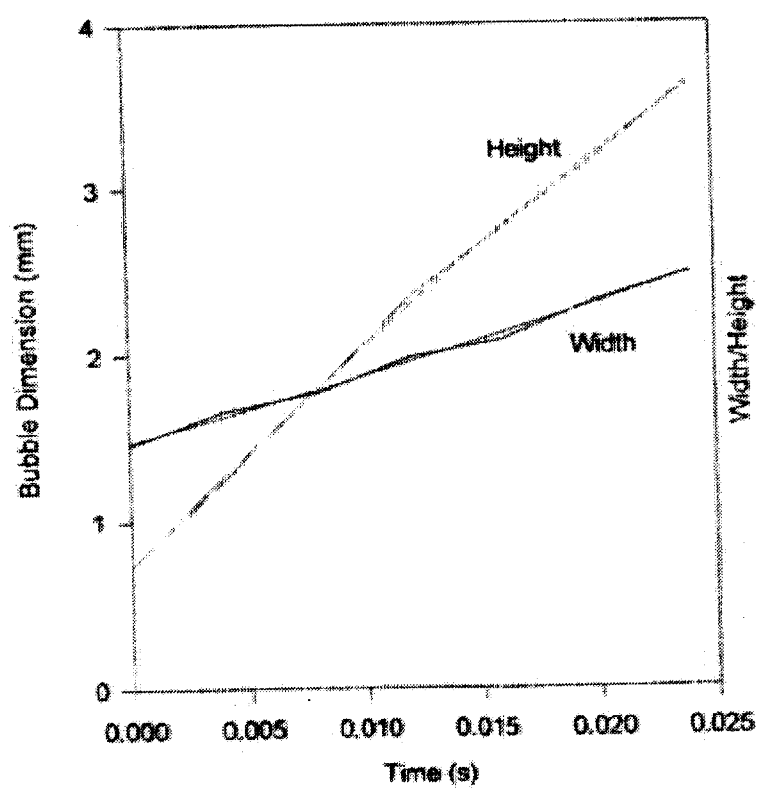


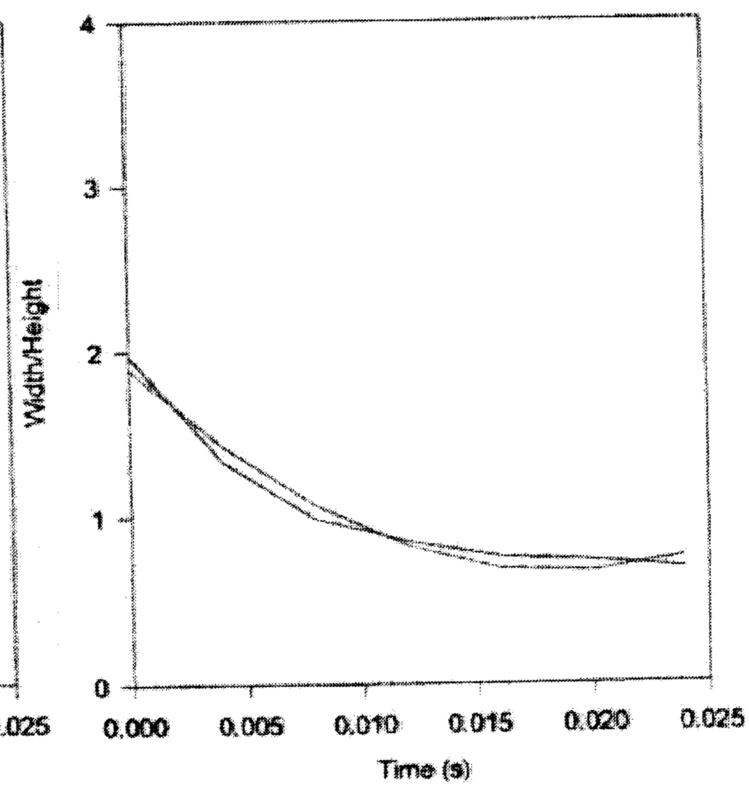


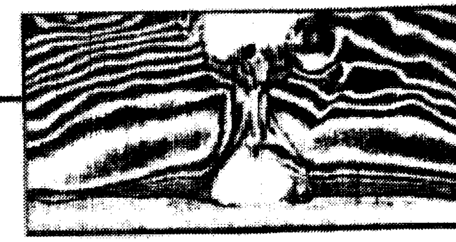


Bubble dimensions: terrestrial, 20kV

Experimental Sequence
Terrestrial - Cleveland Matrix
20 kV, 1 g, 0.7 mm/s

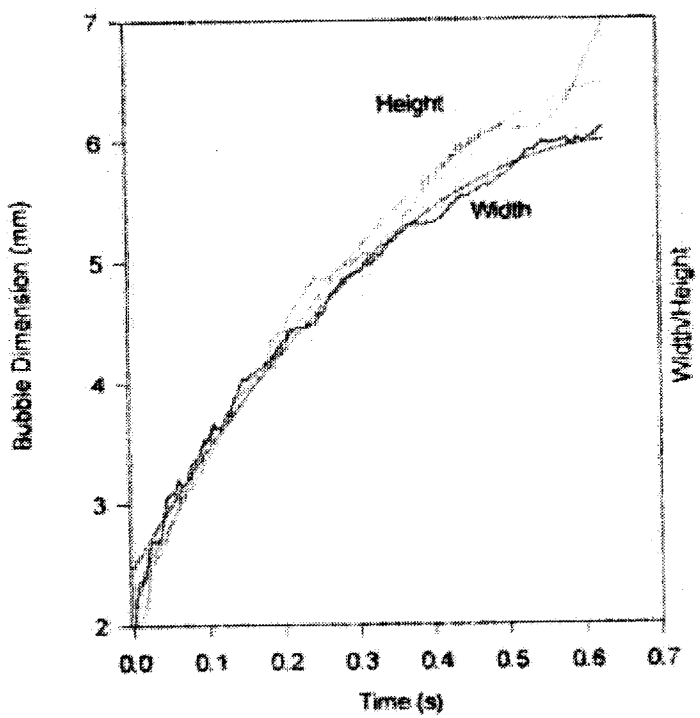


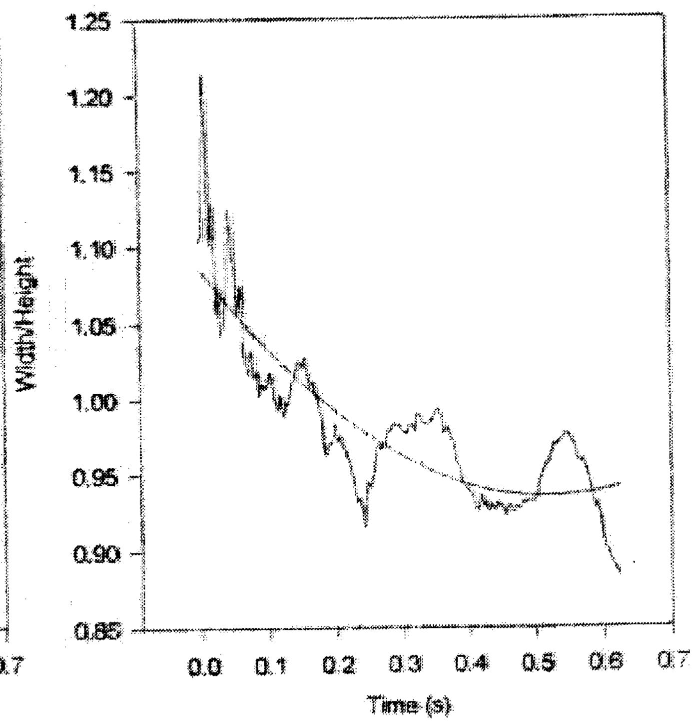


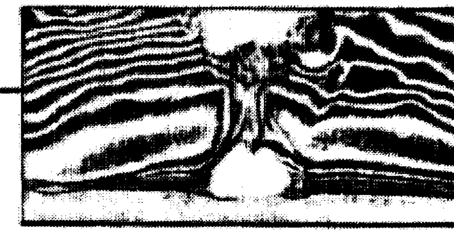


Bubble dimensions: microgravity, 0V

Experimental Sequence
Cleveland, Day 2 - October 20, 1999
0 kV, 0 g, 0.7 mm/s

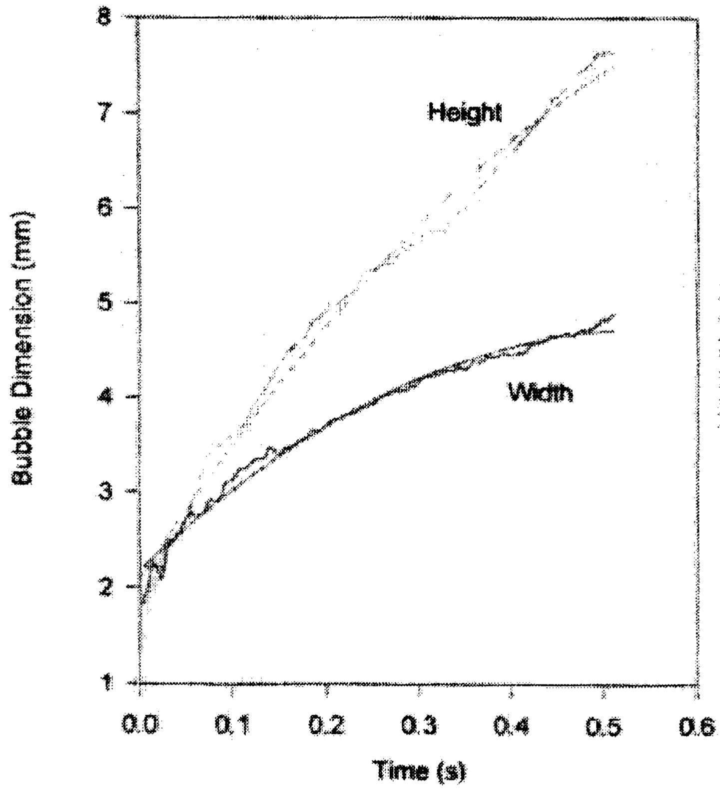


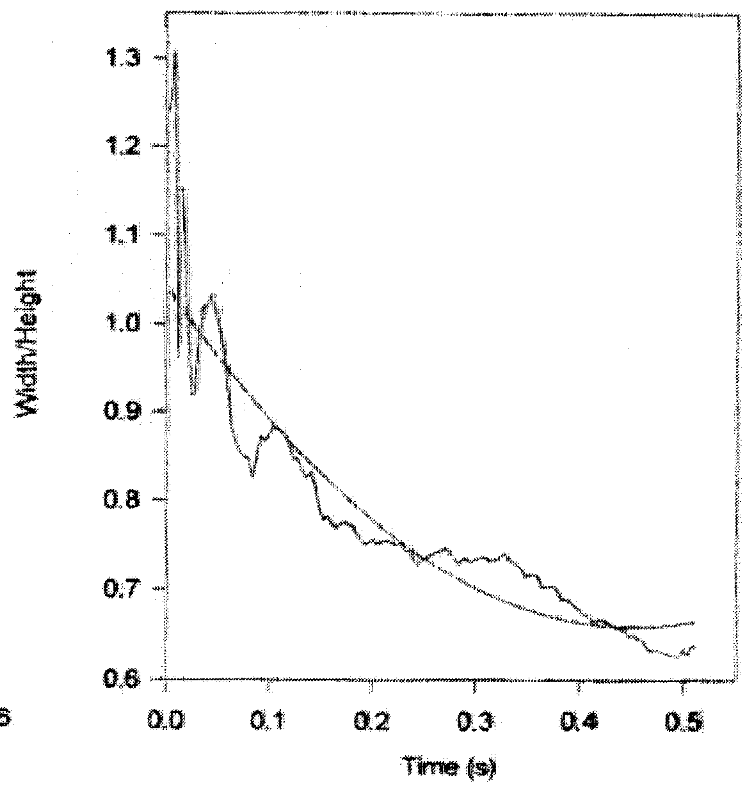




Bubble dimensions: microgravity, 20kV

Experimental Sequence
Cleveland, Day 2 - October 20, 1999
20 kV, 0 g, 0.7 mm/s





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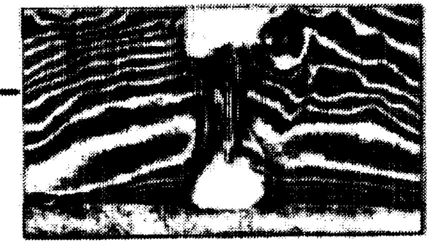
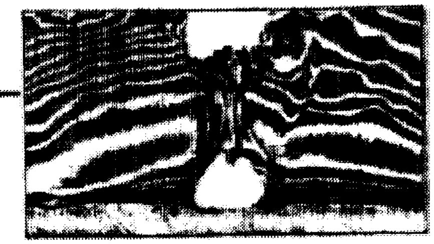


THERMOPHYSICAL PROPERTIES OF PF-5052 AND SELECTED WORKING FLUIDS

Fluid	Chemical Structure	Thermophysical Properties							
		Boiling Point	Critical Point		Density at 25°C	Thermal Conductivity		Specific Heat Capacity at 25°C	
		T	T_c	p_c	ρ_c	k_{liq}	k_{vap}	$c_{p\ liq}$	$c_{p\ vap}$
		[°C]	[°C]	[bar]	[kg/m³]	[W/mK]	[W/mK]	[J/kgK]	[J/kgK]
PF5052	$C_5F_{11}NO$	50.00	181.00	19.15	1700.0	0.062	0.010	975.2	
R123	$CHCl_2CF_3$	27.78	183.70	3.67	1463.0	0.081	0.011	965.0	721.0
R141b	CCl_2FCH_3	32.15	208.35	4.54	1230.0	0.091		691.4	775.3
Water	H_2O	100.	374.0	219	958.3	0.679	0.025	4220.0	2030.0



ELECTRICAL AND OPTICAL PROPERTIES OF PF-5052 AND SELECTED WORKING FLUIDS

Fluid	Chemical Structure	Optical Properties	Electrical Properties		
		Index of refraction at 25 °C	Permittivity	Electrical Conductivity	Relaxation Time
		n	ε_{liq}	σ	t
		-	[Farad/m]	[1/Ωm]	[ms]
PF5052	$C_5F_{11}NO$	1.2712	1.541 E-11	1.29E-08	1.20
R123	$CHCl_2CF_3$	1.329	3.984 E-11	4.72E-08	0.84
R141b	CCl_2FCH_3	1.36 (at 10 °C)	7.145 E-11	9.47E-09	7.55
Water	H_2O	100.	7.080 E-10	5.52E-06	0.12

MAXIMUM BUBBLE SIZE IN THE ABSENCE OF ELECTRIC FIELD (Fritz, 1935)

Basic assumptions:
1. Buoyancy balanced by surface tension forces
2. Orifice diameter much smaller than bubble diameter (?)

Governing differential equation: $\frac{1}{R}+\frac{\sin\Phi}{x}=\frac{2}{R_{tip}}+\frac{g(\rho_V-\rho_L)}{\sigma}\cdot z$

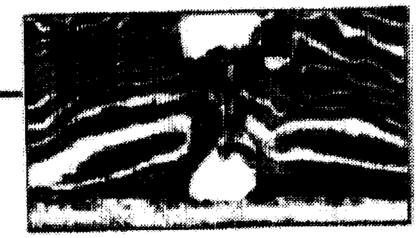
Maximum bubble volume: $V_{\max}^{\frac{1}{3}}\left(\frac{\rho\ g}{\sigma}\right)^{\frac{1}{2}}=0.01667\ \Phi$

Equivalent departure radius: $R_d=0.0103\ \Phi\left(\frac{\sigma}{\rho g}\right)^{\frac{1}{2}}$

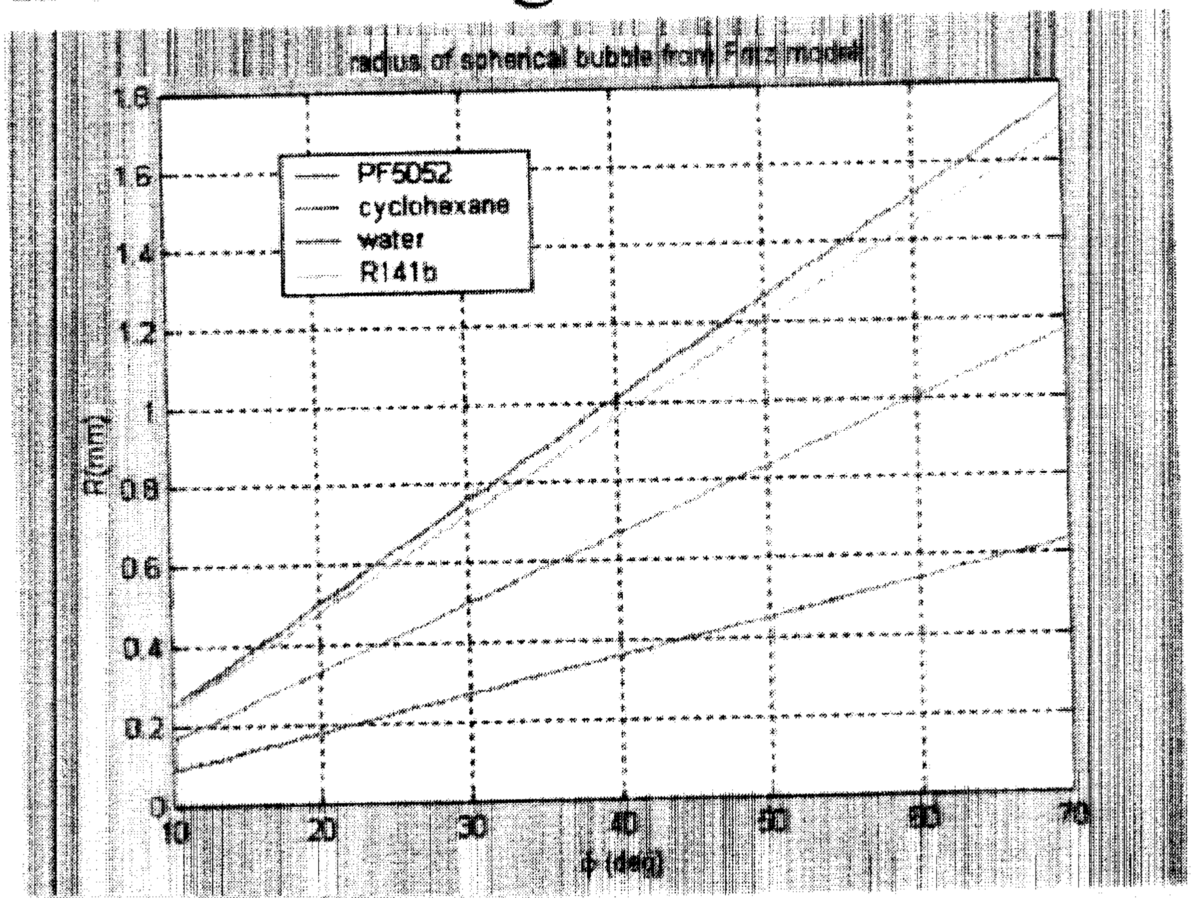
Fritz, W., 1935, *Berechnung des Maximalvolumens von Dampfblasen,* Physikalische Zeitschrift, Vol. 36, No.11, pp. 379-384.

Pool Boiling in Microgravity

Under the Influence of Electric Fields



Radius of spherical bubbles as function of contact angle: Fritz model



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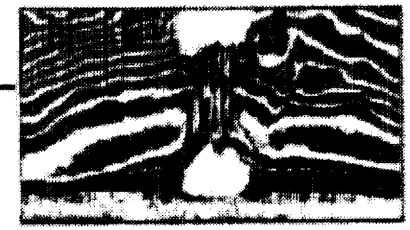


MAXIMUM BUBBLE SIZE IN AN ELECTRIC FIELD

Cheng and Chaddock, 1986

Assumptions:

- Relies on bubble volume and contact angle from Fritz model
- Buoyancy balanced by surface tension and the electric field force
- Orifice diameter much smaller than bubble diameter (?)
- Bubbles with spheroidal profiles

Governing equation:
$$\frac{\partial}{\partial x}\left(\alpha^{-\frac{2}{3}} + \alpha^{\frac{1}{3}}\frac{\sin^{-1} e}{e}\right) - \frac{\varepsilon_0 E^2 r}{3\sigma}\frac{\partial H}{\partial \alpha} = 0$$

Parameters:

$$e = \left(1 - \frac{b^2}{a^2}\right)^{\frac{1}{2}}$$ – eccentricity

$$H = \frac{(\varepsilon_V - \varepsilon_L)\varepsilon_L}{(1-n)\varepsilon_L + n\varepsilon_V},$$

$$\alpha = \frac{\text{major radius}}{\text{minor radius}}$$

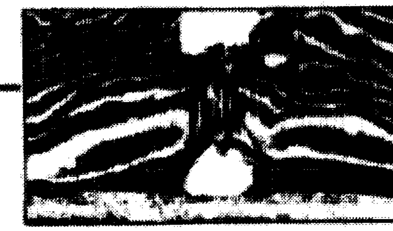
$$n = \frac{1-e^2}{2e^3}\left(\ln\frac{1+e}{1-e} - 2e\right)$$

Bond number $$Bo = \beta \equiv \frac{(\rho_L - \rho_V)R_{tip}^2 g}{\sigma}$$

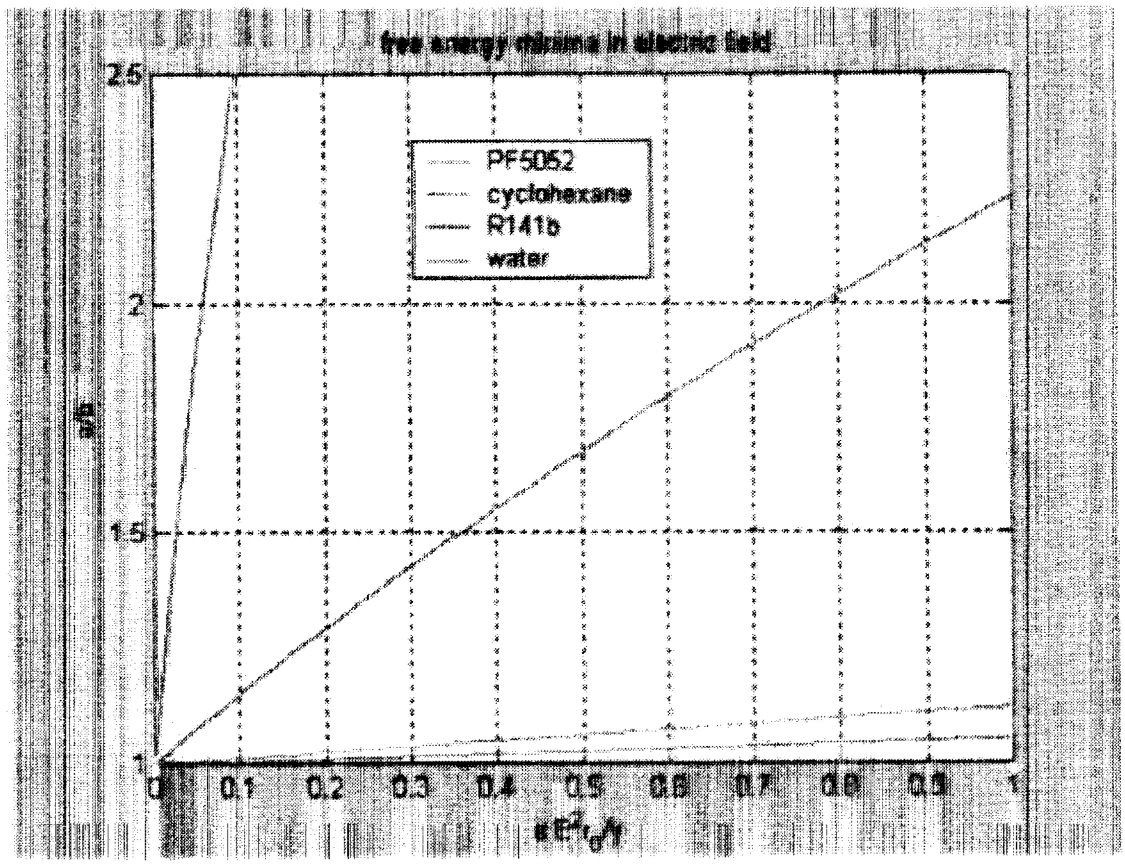
Cheng, K.J., Chaddock, J.B., 1986, *Maximum size of bubbles during nucleate boiling in an electric field*, , Int. J. Heat Fluid Flow, Vol, 7, No. 4, pp.278-282.

Pool Boiling in Microgravity

Under the Influence of Electric Fields



Elongation of the bubble in the electric field



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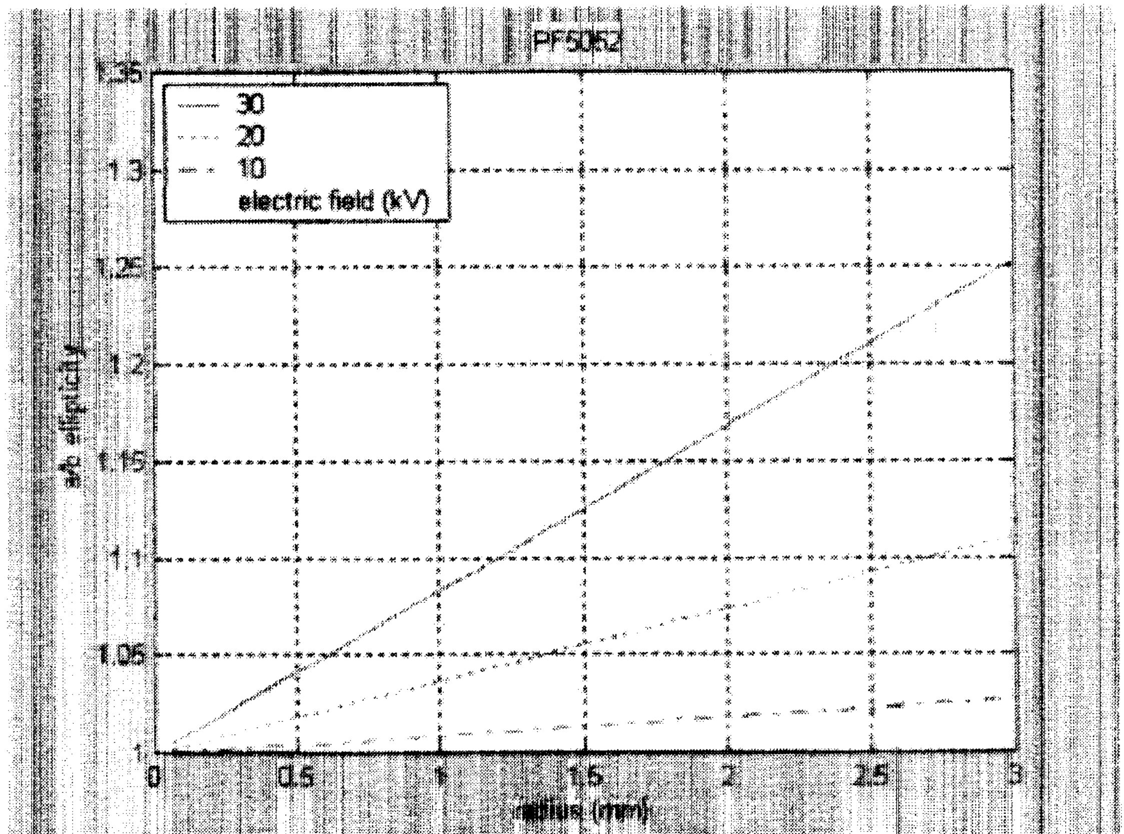
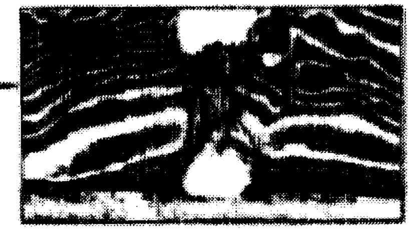
Pool Boiling in Microgravity

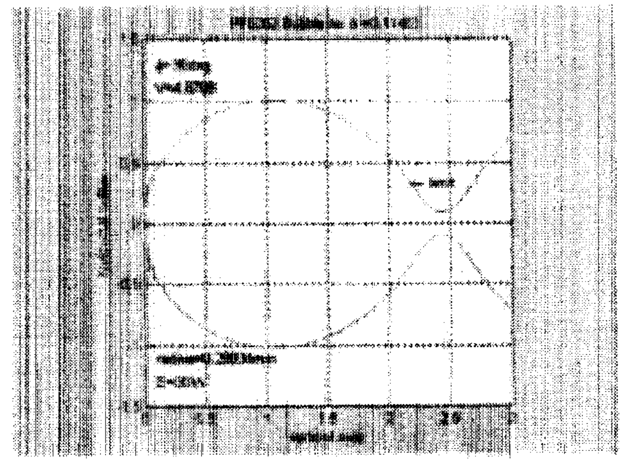
Under the Influence of Electric Fields

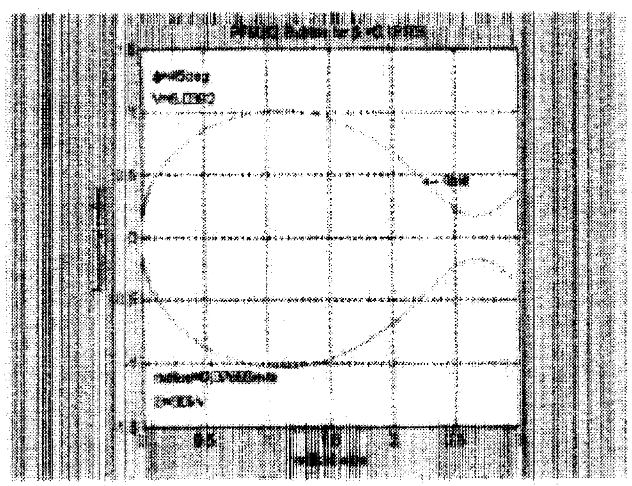
Elongation of the bubble as function of radius and electric field magnitude

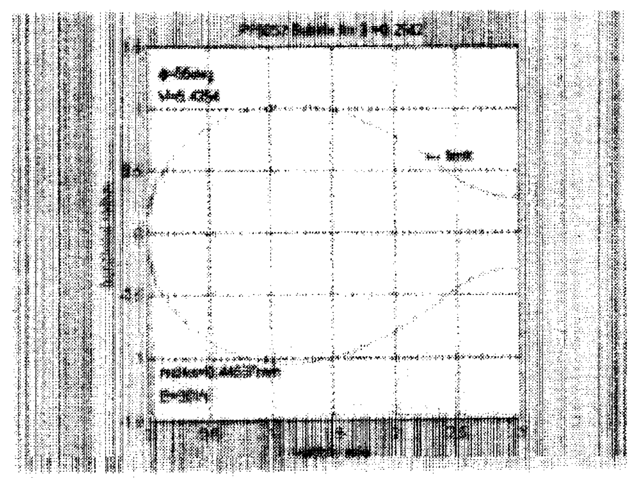




Bubble shapes in PF5052 as function of the parameter β

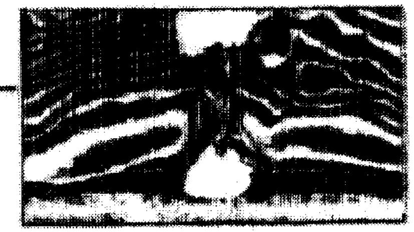




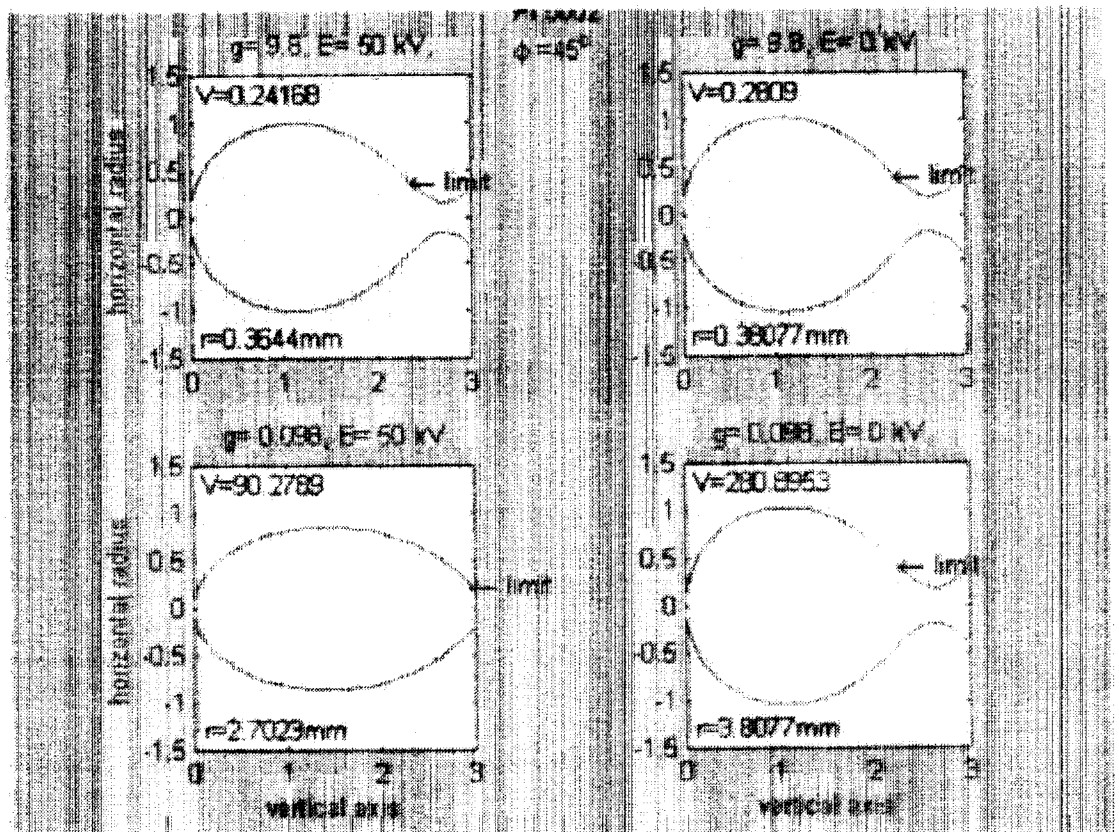


Pool Boiling in Microgravity

Under the Influence of Electric Fields



Bubble shapes in PF5052 as function of electric field and gravity



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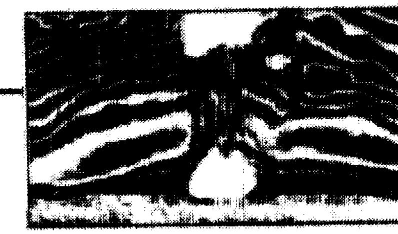
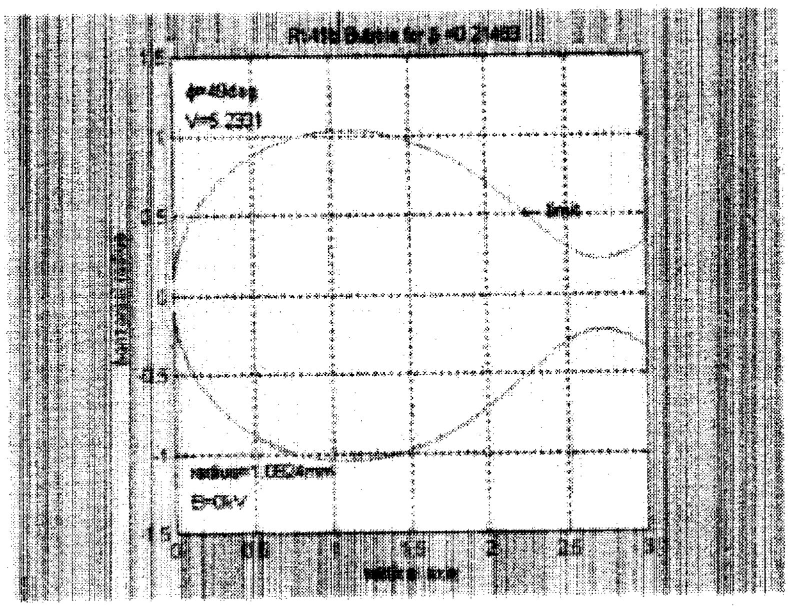
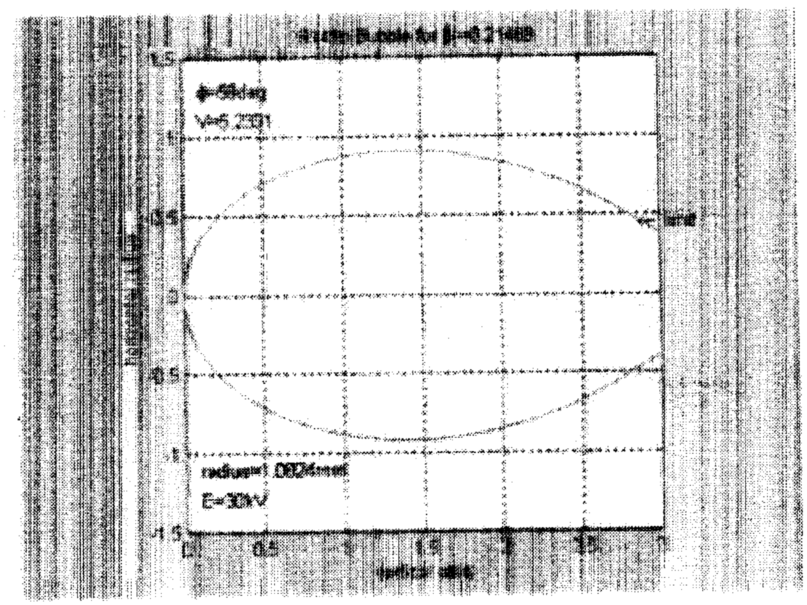
Under the Influence of Electric Fields

Bubble shapes in R141b as function of contact angle and electric field







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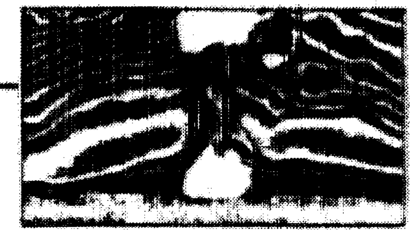
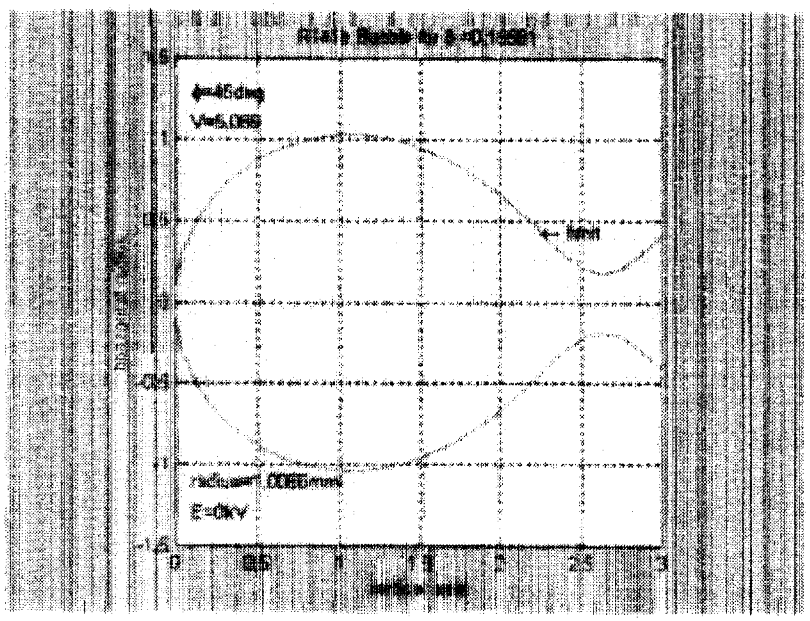
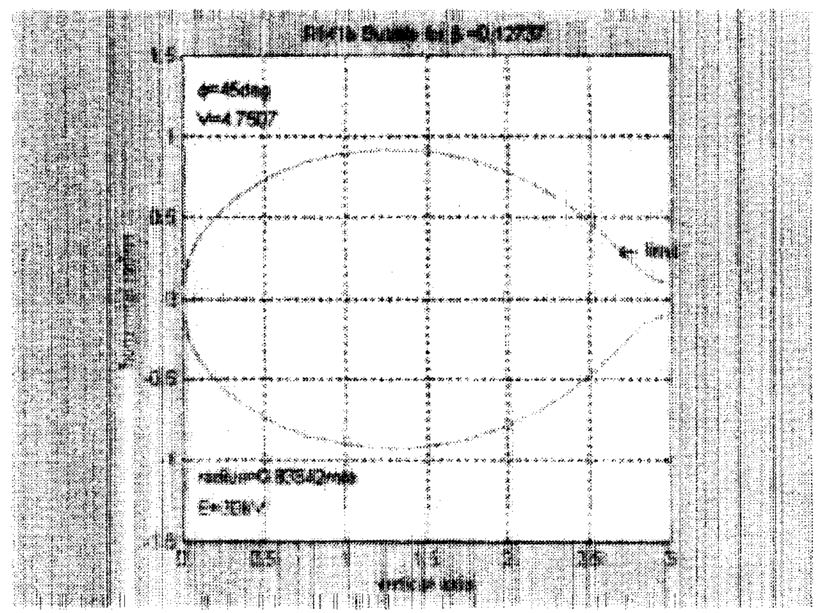


Bubble shapes in R141b





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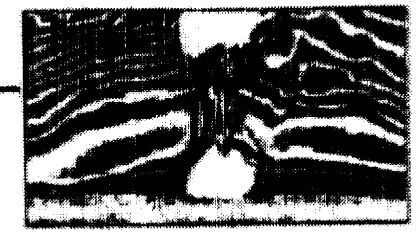
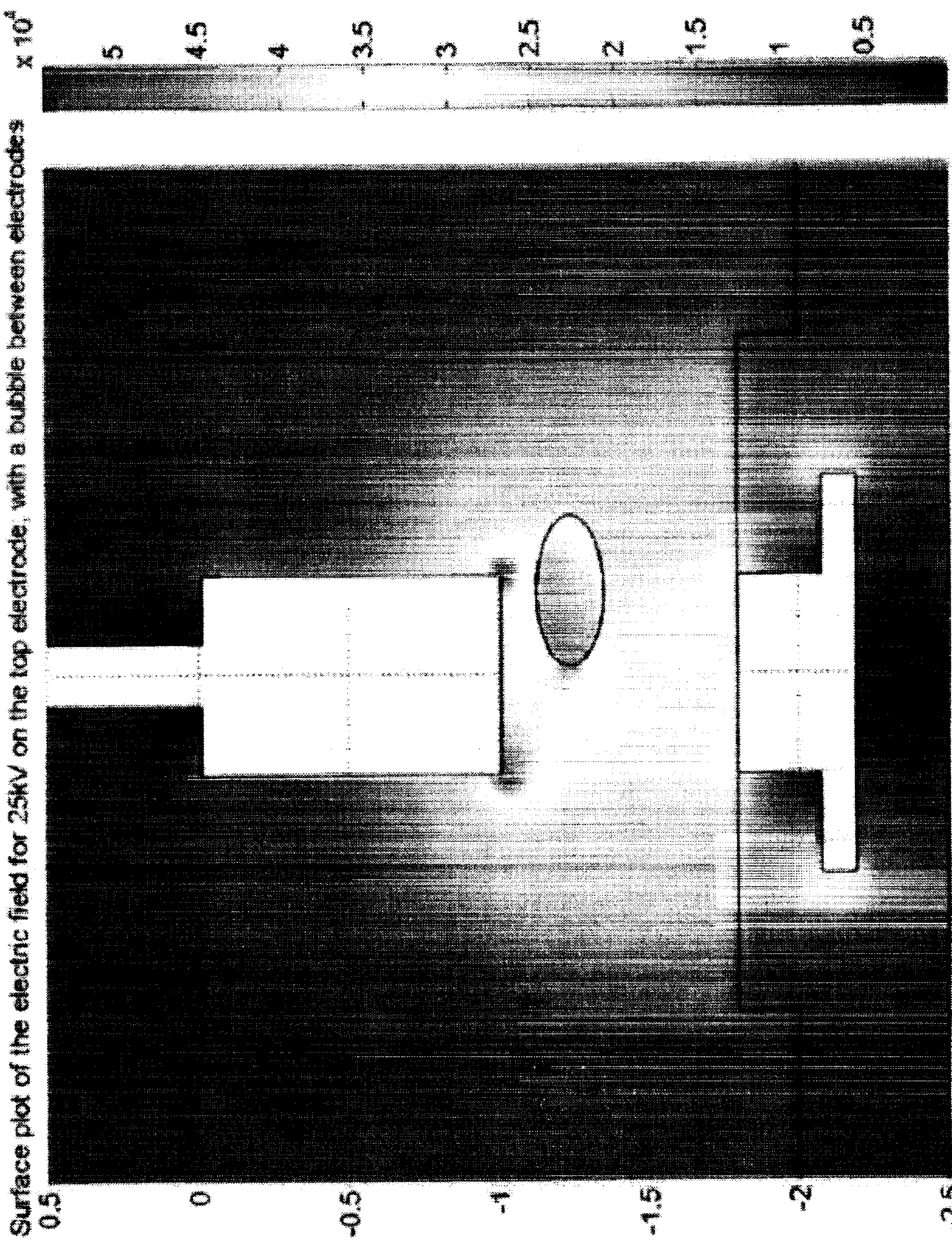


Future work

- Validation of the analytical model *
- Numerical determination of electric field force components for experimental sequences *
- Quantify the impact of electrode shape *
- Establishing the dependence on gravity level *
- Experiments with boiling on a single nucleation site
- Experiments with holographic interferometry


Surface plot of the electric field for 25kV on the top electrode; with a bubble between electrodes
x 10^4