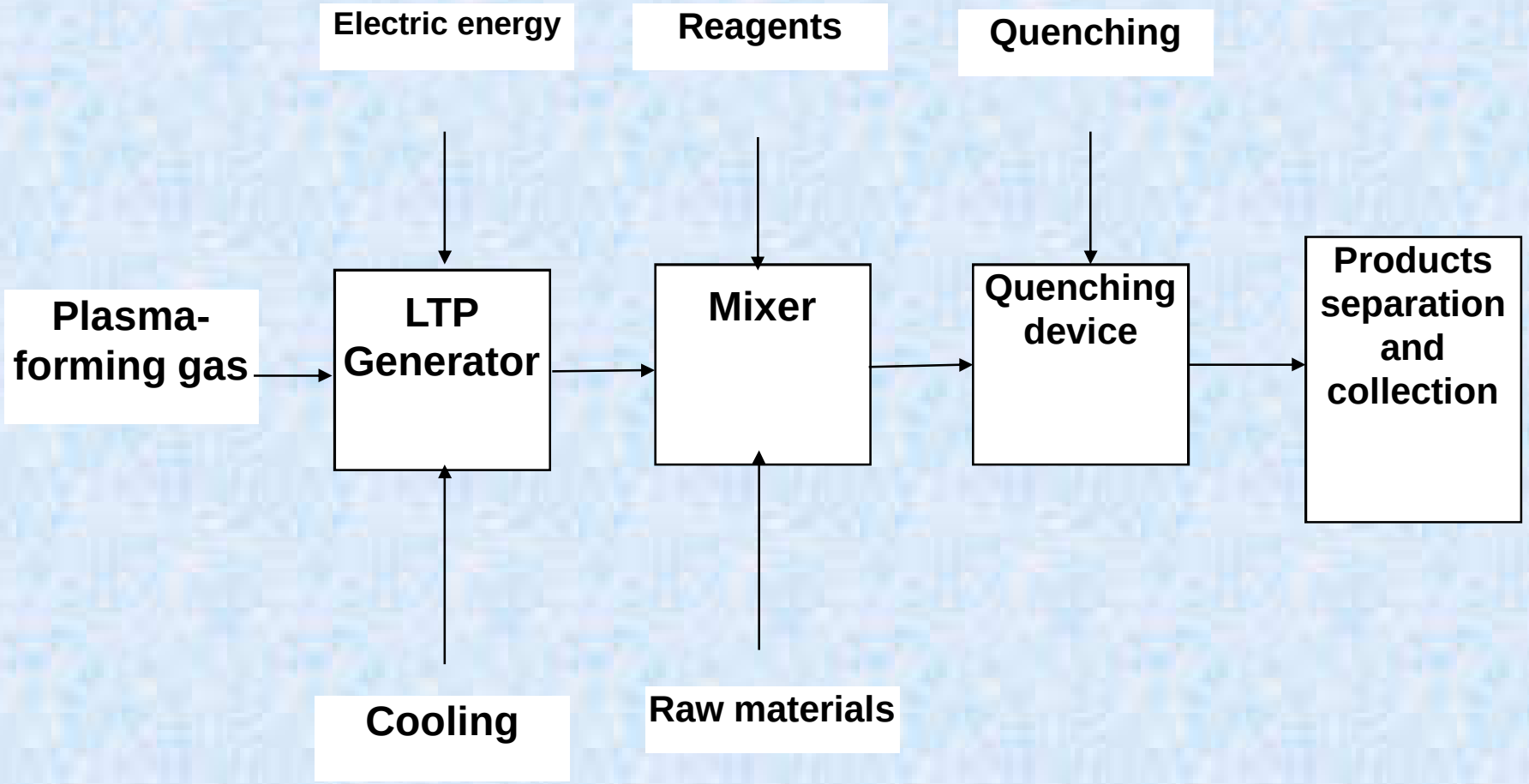
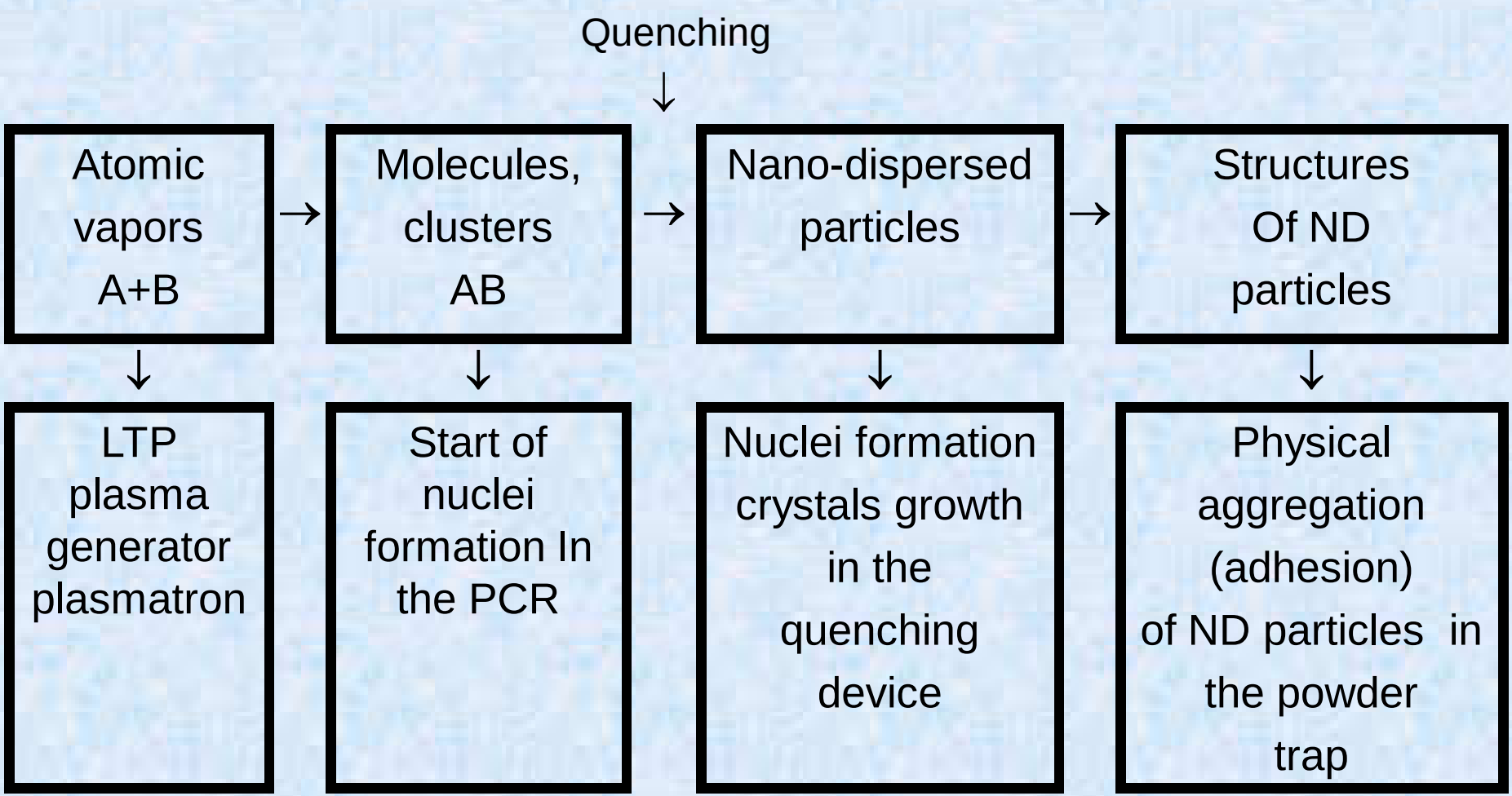
NANOPOWDERS – PLASMACHEMICAL SYNTHESIS AND PROPERTIES

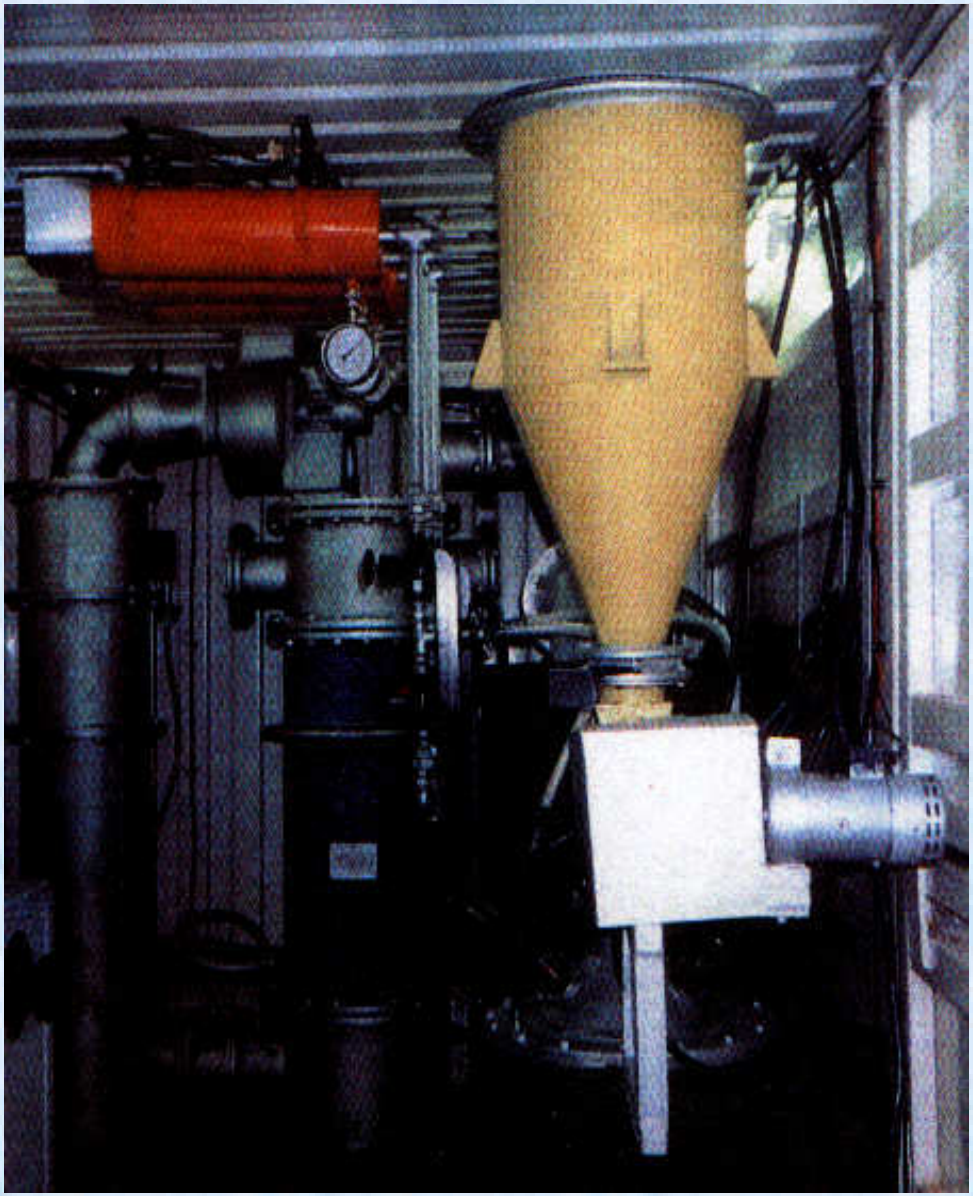
Prof. G.P. VISSOKOV, Ph.D, D.Sc.



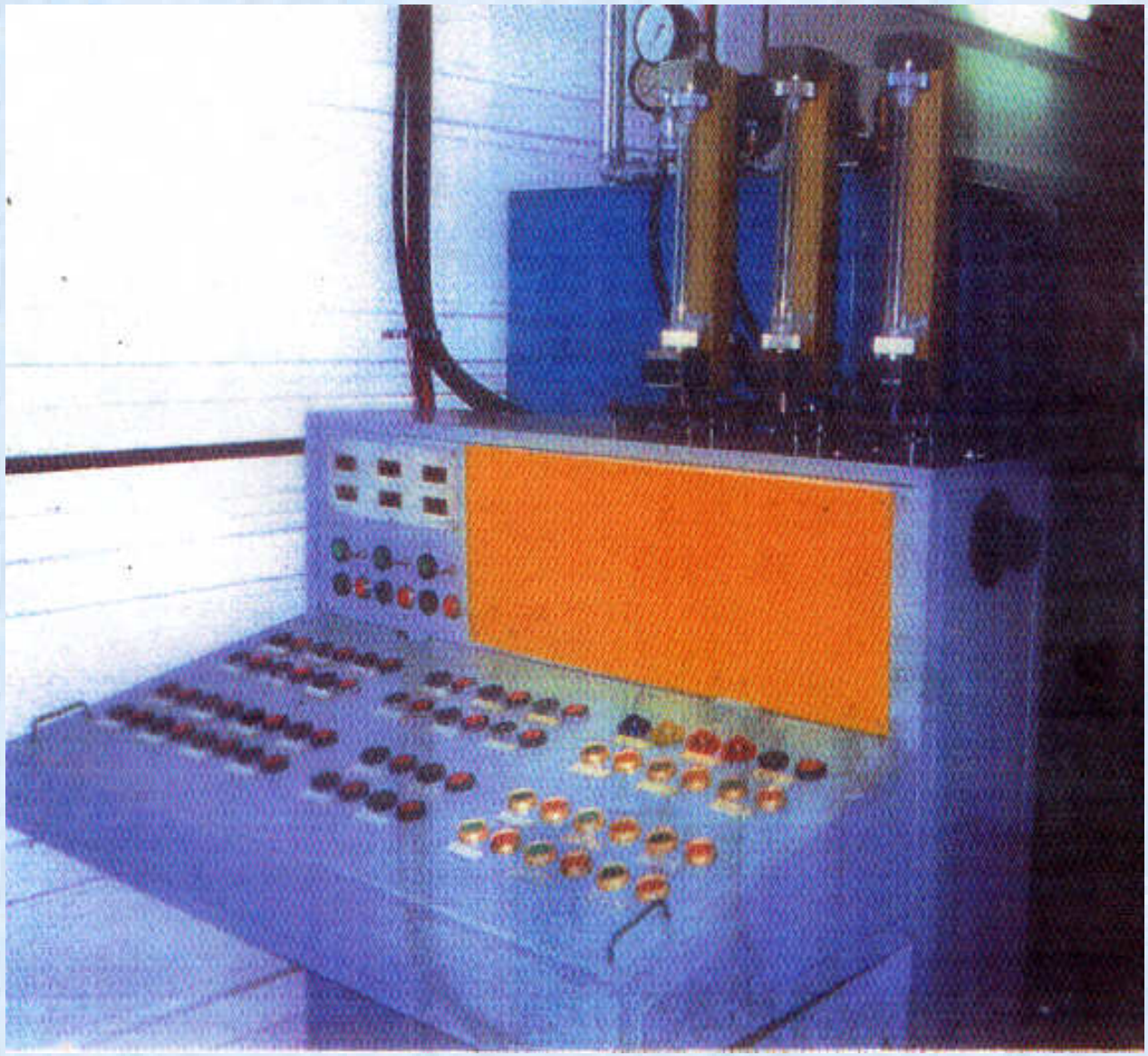
Schematic diagram of a plasma-chemical installation for ND powders preparation



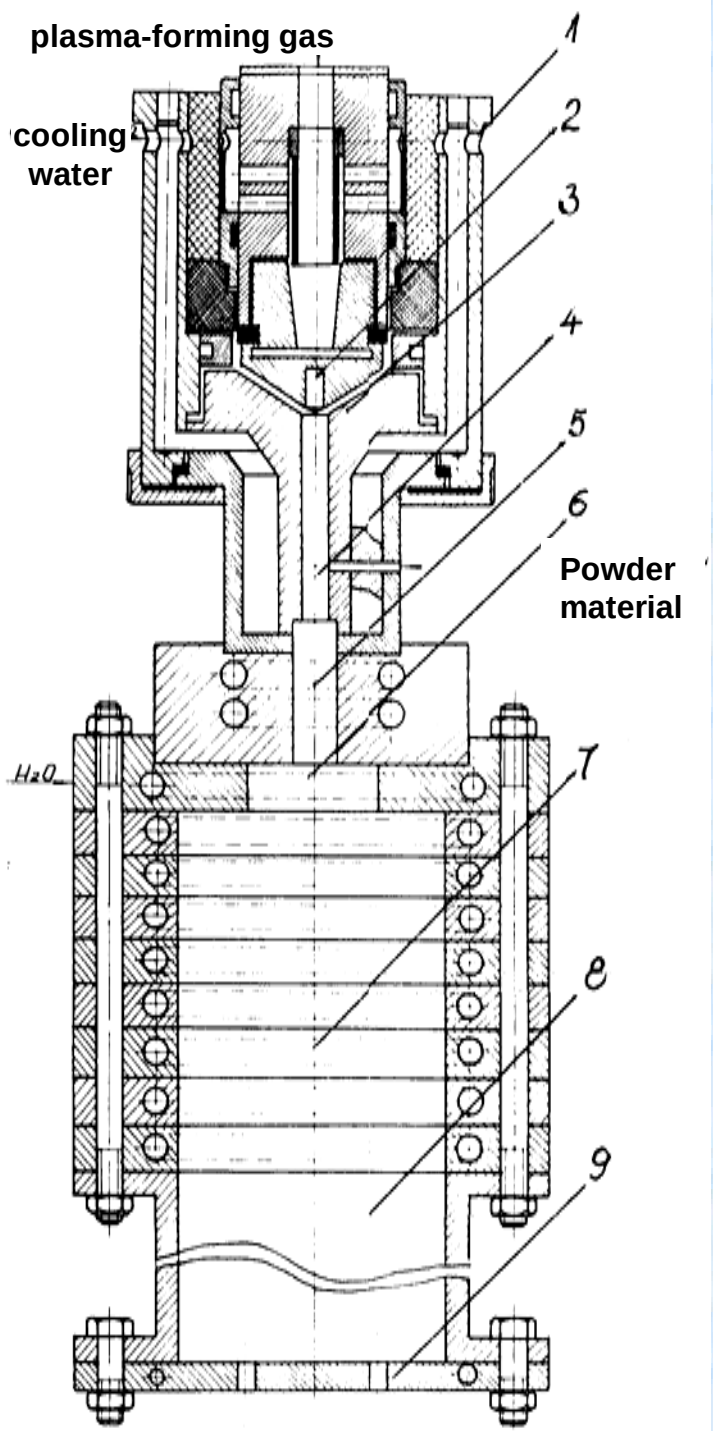
Scheme for formation of structures of ND particles



General view of plasmachemical instalation for preparation of NDP

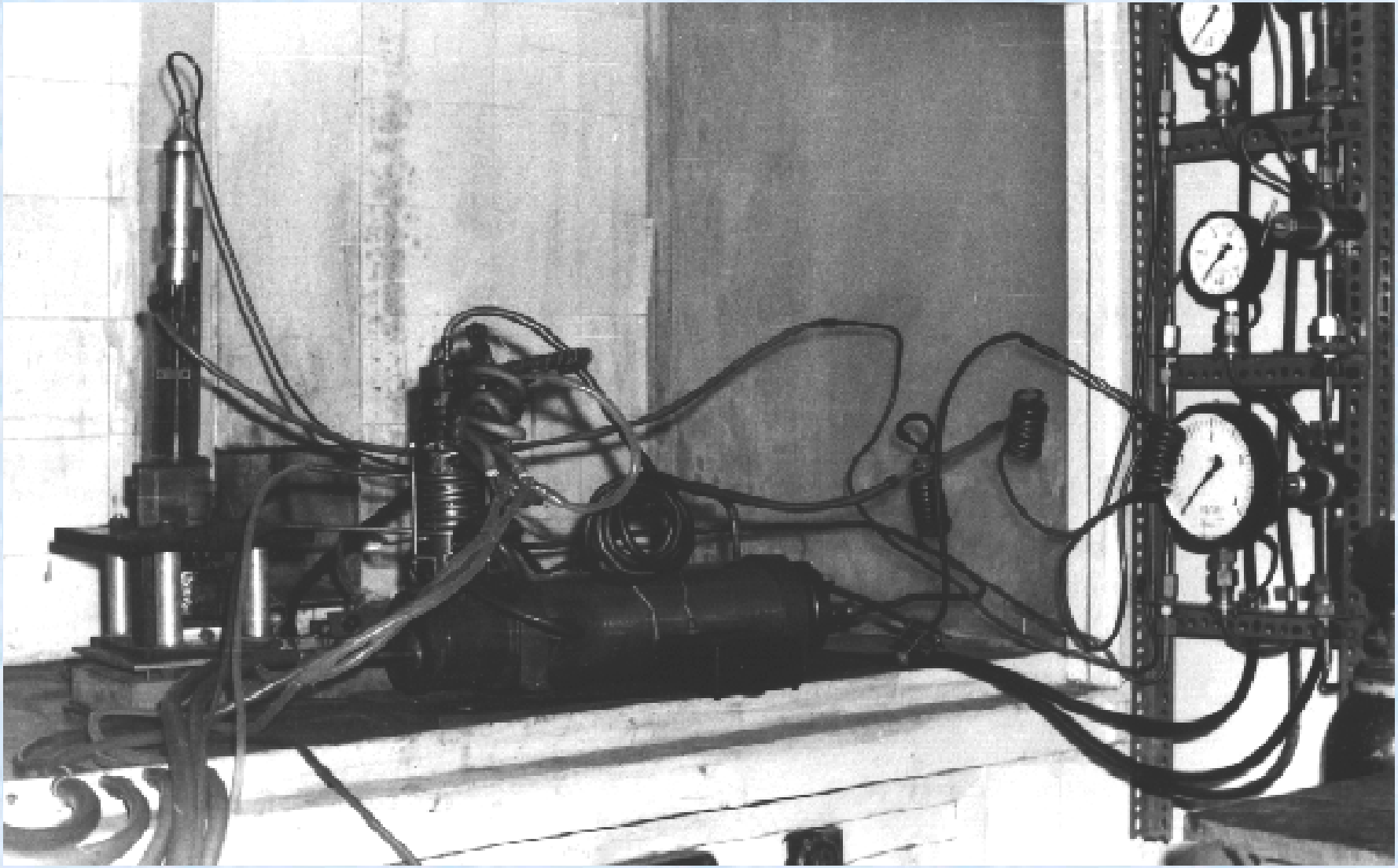


General view of plasmachemical instalation for preparation of NDP

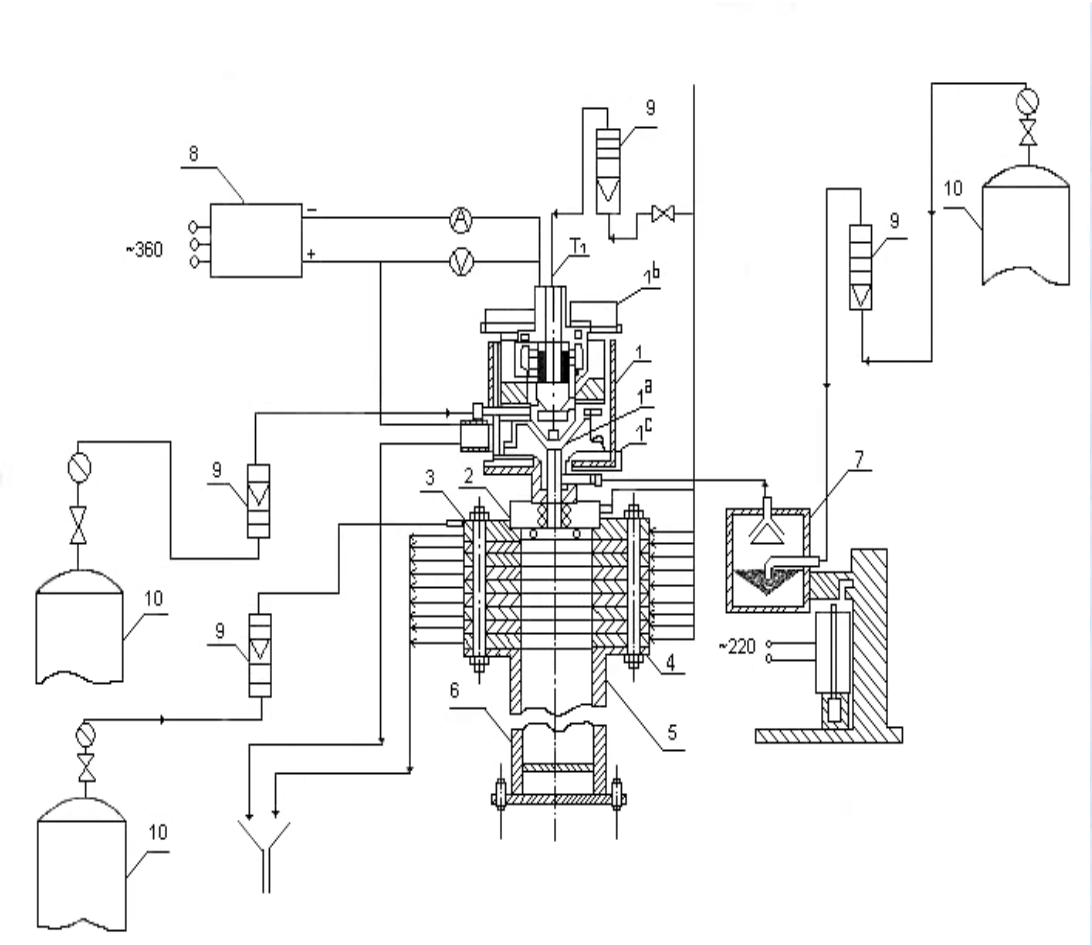


Schematic of a plasma-chemical installation

1 - electric-arc plasmatron; 2 - plasmatron's cathode; 3 - plasmatron's anode; 4 - anode nozzle and mixer; 5 - water-cooled copper PCR; 6 - cold gas quenching device; 7 - quenching device and powder-trapping chamber with cold water-cooled walls; 8 - powder-trapping chamber; 9 - filter



General view of plasmachemical instalation for preparation of NDP



Schematic diagram of plasma-chemical installation for synthesis and/or regeneration of nanodispersed catalysts for ammonia production

Electric-arc D.C. plasmatron; 1[a]. Thoriated tungsten cathode; 1[b]. Water-cooled copper anode; 1[c]. Plastic adjusting ring; 2. CW PCR; 3. Quenching device; 4. Water-cooled copper sections of the quenching device; 5. Powder trapping chamber; 6. Filter; 7. Vibration powder-feeding device (if necessary, a piston type vibration powder-feeding device can also be used); 8. Current rectifier; 9. Flow-rate meters; 10. Bottles with plasma-forming, powder-carrying and quenching gases; T_1 - temperature of inlet water; T_2 - temperature of outlet water

GENERALIZATIONS ON THE PLASMA-CHEMICAL PREPARATION AND CHARACTERISTICS OF NANO-DISPERSED INORGANIC POWDERS

Developed PCPs for preparation of NDP

No.	Main reaction	End product (yield, %)
I. Neutral medium - destruction, re-condensation		
1.	$MnO_2 \rightarrow Mn_2O_3 \rightarrow Mn_3O_4 \rightarrow MnO \rightarrow Mn$	Mn
2.	$MoO_3 \rightarrow MoO_2 \rightarrow Mo$	Mo
3.	$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$	α-Fe, γ-Fe
4.	$ZrSiO_4 = ZrO_2 + SiO_2$	$ZrO_2 + SiO_2$
5.	$\alpha\text{-}Al_2O_3 \rightarrow \gamma\text{-}, \delta\text{-}Al_2O_3$	γ-, δ-Al_2O_3

No.	Temperature interval, K	Particles size, nm	Specific surface m^2/g	Field of application
1.	3500-4000	<100	40-70	powder metallurgy, metal ceramics, pigments
2.	4000-5000	<100	up to 300	
3.	2000-3000	<100	up to 100	
4.	4000-5000	<500	up to 50	
5.	3500-4500	<500	30-50	

Developed PCPs for preparation of NDP (continuation)

No	Main reaction	End product (yield, %)
	II Reducing medium - reduction	
6.	$(MnO_2, Mn_2O_3, Mn_3O_4) + H_2 \rightarrow Mn + H_2O$	Mn (53 %)
7.	$MoS_2 + 2H_2 = Mo + 2H_2S$	Mo (90-93 %)
8.	$MoO_2 + 2H_2 = Mo + 2H_2O$	Mo (90-93 %)
9.	$CoO + H_2 = Co + H_2O$	Co (100 %)
10.	$ZnO + H_2 = Zn + H_2O$	Zn (100 %)
11.	$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$	α-, , γ-Fe (100 %)

No.	Temperature interval, K	Particles size, nm	Specific surface m^2/g	Field of application
6.	2500-4000	<100	up to 80	powder metallurgy, metal ceramics, chemical industry, microelectronics
7.	2500-4000	<100	20-380	
8.	3000-4000	<100	up to 300	
9.	3000-4000	<100	up to 160	
10.	3000-4000	<100	up to 160	
11.	2000-4000	10-100	up to 160	

Developed PCPs for preparation of NDP (continuation)

No.	Main reaction	End product (yield, %)
	III. Oxidizing medium - oxidation	
12.	$SiCl_4 + O_2 = SiO_2 + 2Cl_2$	SiO_2 (100 %)
13.	$SiCl_4 + 2H_2O = SiO_2 + 4HCl$	SiO_2 (100 %)
14.	$Fe \rightarrow FeO \rightarrow Fe_3O_4 \rightarrow Fe_2O_3$	Fe_2O_3, Fe_3O_4
15.	$4Al + 3O_2 = 2Al_2O_3$	γ-Al_2O_3 (100 %)
16.	$2CoS + 3O_2 = 2CoO + 2SO_2$	CoO (100 %)
17.	$(Ni,Al)+O_2 \rightarrow NiO+Al_2O_3+NiAl_2O_4$	catalysts for CH_4 reforming
18.	$(Cu,Zn,Al)+O_2 \rightarrow CuO(Cu_2O)+ZnO+Al_2O_3$	catalyst for CO convertion by H_2O
19.	$3Fe + 2O_2 = Fe_3O_4$	synthesized and/or activated (regene-rated) catalysts for ammonia synthesis
20.	$4Fe + 3O_2 = 2Fe_2O_3$	
21.	$2Fe + O_2 = 2FeO$	

No.	Temperature interval, K	Particles size, nm	Specific surface m^2/g	Field of application
12.	up to 10000	<100	60-200	chemical, pharmaceutical, rubber industries, metallurgy, pigments, catalysts for CH_4, CO conversion, ammonia synthesis, industrial catalysis
13.	up to 11000	<100	90-400	
14.	1200-2200	10-50	90-150	
15.	1200-7000	6-45	20-420	
16.	1000-3000	-	up to 60	
17.	2000-3000	10-30	up to 110	
18.	up to 5100	10-40	45-51	
19.	1100-3400	20-60	10-40	
20.	1300-3500	20-60	20-40	
21.	1500-3500	<100	up to 40	

Developed PCPs for preparation of NDP (continuation)

Main reaction		End product (yield, %)
IV. Nitrogen medium - nitride formation		
22.	$2Al + N_2 = 2AlN$	**AlN** (100 %)
23.	$3Si + 2N_2 = Si_3N_4$	**α-δ-Si_3N_4** (48%, **97% after purification**
24.	$3Mg + N_2 = Mg_3N_2$	**Mg_3N_2** (73 %)

No.	Temperature interval, K	Particles size, nm	Specific surface m^2/g	Field of application
22.	3300-3800	50-70	60-100	chemical industry, coatings,
23.	3000-3500	10-60	up to 250	
24.	2000-2500	10-60	up to 180	

Developed PCPs for preparation of NDP (continuation)

	Main reaction	End product (yield, %)
V. Reducing-oxidizing medium		
25.	$SiO_2 + C = SiO + CO$ (I)	SiO_2 (100 %)
26.	$2SiO + O_2 = 2SiO_2$ (II)	
27.	$NiO + H_2 = Ni + H_2O$ (I)	synthesized (regenerated) catalyst for CH_4 reforming
28.	$2Ni + O_2 = 2NiO$ (II)	
29.	$(CuO,ZnO,Al_2O_3) + H_2 \rightarrow (Cu,Zn,Al) + H_2O$ (I)	synthesized (regenerated) catalyst for CO by H_2O
30.	$(Cu,Zn,Al) + O_2 \rightarrow CuO(Cu_2O) + ZnO + Al_2O_3$ (II)	
31.	$Fe_3O_4 + 4H_2 = 3Fe + 4H_2O$ (I)	synthesized (regene-rated) catalysts for ammonia synthesis
32.	$3Fe + 2O_2 = Fe_3O_4$ (II)	

Developed PCPs for preparation of NDP (continuation)

No.	Temperature interval, K	Particles size, nm	Specific surface m^2/g	Field of application
22.	3300-3800	50-70	60-100	chemical industry, coatings,
23.	3000-3500	10-60	up to 250	
24.	2000-2500	10-60	up to 180	
25.	5000-10000	50-500	50-400	microelectronics, food industry, synthesis of catalysts for CH_4 and CO conversion, catalysts for ammonia synthesis
26.	10000-300			
27.	1000-4000	<100	up to 150	
28.	4000-300			
29.	1000-4000	<100	up to 40	
30.	4000-300			
31.	1000-4000	10-30	up to 50	
32.	4000-300			

Structural, phase and morphological characteristics of plasma-chemically synthesized ND powders of bulk materials

No.	Compound		Chemical content, %	Shape and size of the particles nm	Specific sur-face, m^2/g
1.	Silicon nitride	I	Si_3N_4- 100	bulk	-
	-bulk	II	Si_3N_4- 100	bulk	-
2.	Silicon Nitride	I	Si_3N_4- 95.6	spherical and hexagonal	181
	-plasma	II	Si_3N_4- 94.9	10-60	173
		III	Si_3N_4- 95.6	after sintering	
3.	Aluminum nitride-bulk		AlN -100	bulk	-
4.	Aluminum nitride-plasma		AlN - 99	spherical and hexagonal	82
	Aluminum nitride - plasma, sintering		AlN - 99	bulk, after sintering	-
5.	Titanium nitride-bulk		TiN -100	bulk	-
6.	Titanium nitride-plasma *		TiN - 92.4	cubic and tetrahedral 10-80	43
	Titanium nitride-plasma, sintering		TiN - 92.4	bulk, after sintering	-

Structural, phase and morphological characteristics of plasma-chemically synthesized ND powders of bulk materials (continuation)

No.		Phase	Crystal system	Crystal lattice constants	Relative change of the crystal lattice constants
1.	I	α-Si_3N_4	hexagonal	*a*=0.7818; *c*=0.5591; *c*/*a*=0.7151	-
	II	β-Si_3N_4	hexagonal	*a*=0.7595; *c*=0.2902; *c*/*a*=0.3821	-
2.	I	β-Si_3N_4	hexagonal	*a*=0.7592; *c*=0.2904; *c*/*a*=0.3825	*a*:0.04; *c*:-0.04
	I	α-Si_3N_4	hexagonal	*a*=0.7800; *c*=0.5572; *c*/*a*=0.7143	*a*:0.23; *c*:0.34
	II	β-Si_3N_4	hexagonal	*a*=0.7651; *c*=0.2877; *c*/*a*=0.3760	*a*:-0.74; *c*:0.86
	II	α-Si_3N_4	hexagonal	*a*=0.7822; *c*=0.5600; *c*/*a*=0.7159	*a*:-0.05; *c*:-0.16
	III	β-Si_3N_4	hexagonal	*a*=0.7660; *c*=0.2910; *c*/*a*=0.3799	*a*:-0.86; *c*:-0.27
3.		AlN	hexagonal	*a*=0.3111; *c*=0.4975; *c*/*a*=1.5992	-
4.		AlN	hexagonal	*a*=0.3100; *c*=0.4950; *c*/*a*=1.5968	*a*:0.35; *c*:0.50
		AlN	hexagonal	*a*=0.3119; *c*=0.4986; *c*/*a*=1.5986	*a*:-0.26; *c*:-0.22
5.		TiN	face-centered cubic	*a*=0.4243	-
6.		TiN	face-centered cubic	*a*=0.4235	*a*:0.19
		TiN	face-centered cubic	*a*=0.4253	*a*:-0.24

Structural, phase and morphological characteristics of plasma-chemically synthesized ND powders of bulk materials

No.	Compound		Chemical content, %	Shape and size of the particles nm	Specific surface, m^2/g
7.	Di-aluminum trioxide-bulk	I	Al_2O_3 - 100	bulk	-
		II	Al_2O_3 - 100	bulk	-
8.	Di-aluminum trioxide-plasma		Al_2O_3 - 100	spherical 5-40	145
9.	Iron-bulk	I	Fe - 100	bulk	-
		II	Fe - 100	bulk	-
10.	Iron-plasma	I	Fe - 50	spherical	150
	Iron-plasma	II	Fe - 50	10-50	150
11.	Iron oxide-bulk		FeO - 100	bulk	-
12.	Iron oxide-bulk		FeO	spherical 10-50	160
13.	Tri-iron tetraoxide-bulk		Fe_3O_4 - 100	bulk	-
14.	Tri-iron tetraoxide-plasma		Fe_3O_4 - 94	spherical 10-50	160
15.	Di-iron trioxide-bulk	I	Fe_2O_3 - 100	bulk	-
	Di-iron trioxide-bulk	II	Fe_2O_3 - 100	bulk	
16.	Di-iron trioxide-plasma I		Fe_2O_3 - 100	spherical	190
	Di-iron trioxide-plasmaII		Fe_2O_3 - 100	5-40	185

Structural, phase and morphological characteristics of plasma-chemically synthesized ND powders of bulk materials (continuation)

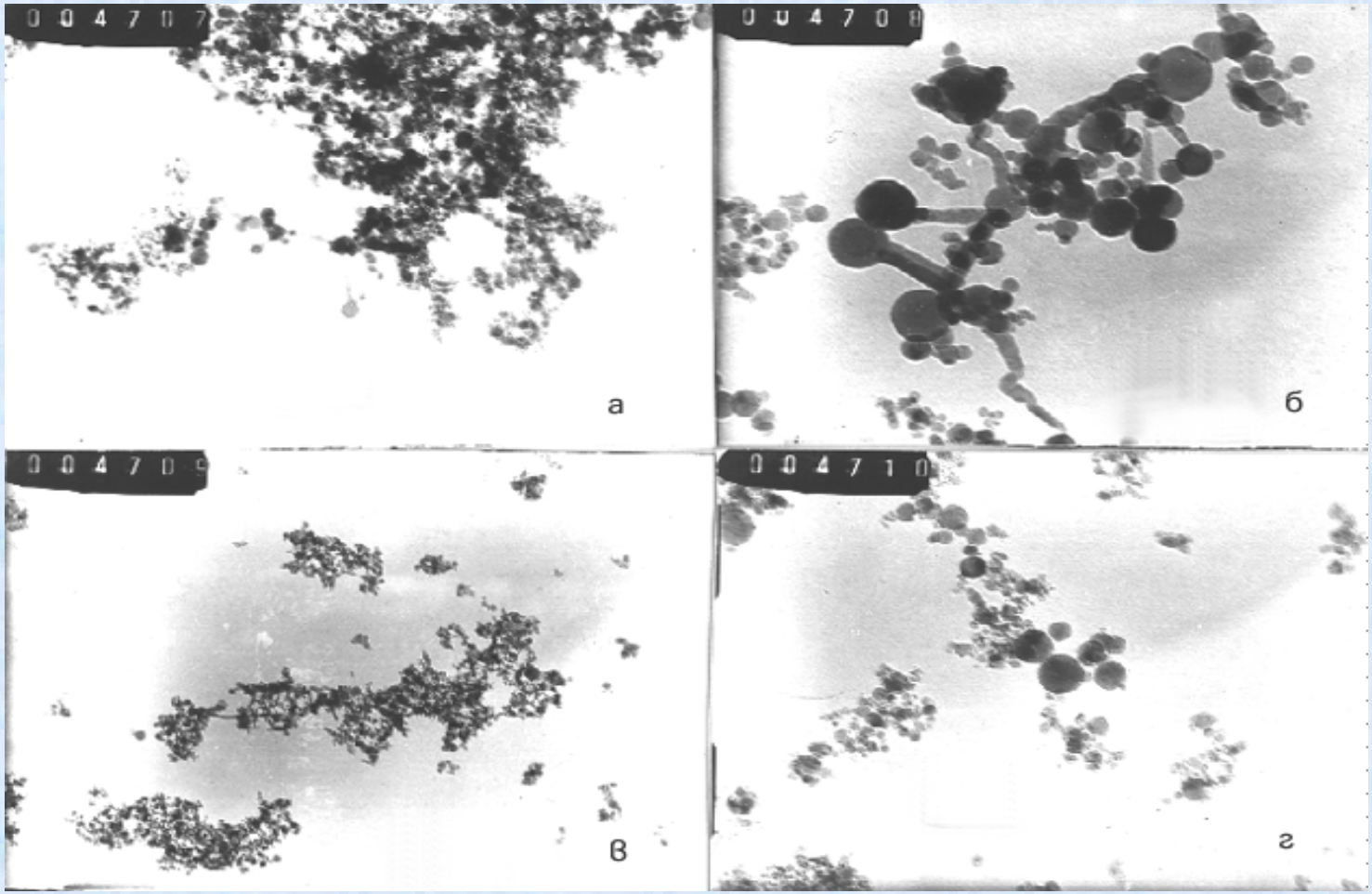
No.		Phase	Crystal system	Crystal lattice constants	Relative change of the crystal lattice constants
7.	I	α-Al_2O_3	rhombohedral	*a*=0.512; □=55.25°	-
	II	γ-Al_2O_3	tetragonal	*a*=0.5620; *c*=0.7800; *c*/*a*=1.3879	-
8.		γ-Al_2O_3	tetragonal	*a*=0.5570; *c*=0.7700; *c*/*a*=1.3931	*a*:0.89; *c*:0.51
9.	I	α-Fe	body-centered cubic	*a*=0.286645	-
	II	γ-Fe	face-centered cubic	*a*=0.3656	-
10.	I	α-Fe	body-centered cubic	*a*=0.2841	*a*:0.89
	II	γ-Fe	face-centered cubic	*a*=0.3631	*a*:0.68
11.		FeO	cubic	*a*=0.4357	-
12.		FeO	cubic	*a*=0.4336	*a*:0.48
13.		Fe_3O_4	cubic	*a*=0.8390	-
14.		Fe_3O_4	cubic	*a*=0.8360	*a*:0.36
15.	I	α-Fe_2O_3	trigonal	*a*=0.5420; □=55.28°	-
	II	γ-Fe_2O_3	cubic	*a*=0.8339	-
16.	I	α-Fe_2O_3	trigonal	*a*=0.5400	*a*:0.37
	II	γ-Fe_2O_3	cubic	*a*=0.8310	*a*:0.35

Structural, phase and morphological characteristics of plasma-chemically synthesized or regenerated type CA-1 catalysts for ammonia synthesis and of a bulk sample.

No.	Type of catalyst for ammonia synthesis	Chemical composition, mass % and Fe^{2+}/Fe^{3+} ratio	Particles shape and size, nm
1.	CA-1, standard, fraction below 50 μm	FeO- 29; Fe_2O_3 - 65; Al_2O_3 - 3.0; K_2O - 0.8; CaO - 2.O; SiO_2 - 0.2. Fe^{2+}/Fe^{3+} = 0.44	irregular, below 50 μm
2.	CA-1, regenerated in argon medium	FeO - 27-29; Fe_2O_3-64-65; Al_2O_3 -3.4-3.5; K_2O- 0.8; CaO- 2.0; SiO_2- 0.3; α-γ-Fe, Fe^{2+}/Fe^{3+} = 0.41-0.45	cubic 20-80
3.	CA-1, synthesized in air in CW PCR	(Fe_3O_4+Fe_2O_3+FeO) - 94; Al_2O_3- 3.0; K_2O - 0.8; CaO - 2.0; SiO_2 – 0.2; Fe^{2+}/Fe^{3+} = 0.26-0.30	spherical 20-60
4.	CA-1, synthesized in technical grade nitrogen (5% No.O_2)in CW PCR)	Fe_3O_4-75-80; Fe_2O_3-13-18; Al_2O_3-2.8-3.0; K_2O-0.8; α-γ-Fe; CaO-2.0; SiO_2 - 0.3; Fe^{2+}/Fe^{3+} = 0.32-0.41	spherical 20-60
5.	CA-1, synthesized in air in WW PCR	Fe_3O_4 - 49.6; Fe_2O_3 - 44; Al_2O_3 - 3.0; K_2O- 0.6; CaO- 1.8; SiO_2 - 0.6; MgO - 0.4; Fe^{2+}/Fe^{3+} = 0.26	spherical 20-45
6.	CA-1, synthesized in technical grade nitrogen (5% O_2)in WW PCR)	Fe_3O_4 - 70.5; Fe_2O_3 - 23; Al_2O_3 - 3.1; K_2O- 0.6; CaO- 1.8; SiO_2 - 0.6; MgO- 0.4; Fe^{2+}/Fe^{3+} =0.32; α-γ-Fe	spherical 20-45

Structural, phase and morphological characteristics of plasma-chemically synthesized or regenerated type CA-1 catalysts for ammonia synthesis and of a bulk sample (continuation)

	Specific surface, m^2/g	Main phases and crystal system	Crystal lattice constant of some of the main phases, nm	Relative change of the lattice constant: a: = $(a_b - a_p)/a_b.100$, %
1.	1,6	Fe_3O_4 - cubic	Fe_3O_4 - a = 0.840	a_{Fe3O4}: 0.12
2.	14-22	Fe_3O_4 - cubic	Fe_3O_4 - a = 0.83788	a_{Fe3O4}: 0.13
		α-Fe - body-centered cubic	α-Fe - a = 0.28657	$a_{\alpha\text{-}Fe}$: 0.03
		γ-Fe - face-centered cubic		
		FeO - cubic		
3.	21-33	Fe_3O_4 - cubic	Fe_3O_4 - a = 0.83761	a_{Fe3O4}: 0.17
		γ-Fe_2O_3 cubic		
		FeO - cubic		
4.	20-30	Fe_3O_4 - cubic	Fe_3O_4 - a = 0.8369	a_{Fe3O4}: 0.25
		α-Fe - body-centered cubic	α-Fe - a = 0.28664	$a_{\alpha\text{-}Fe}$: 0.00
		γ-Fe - face-centered cubic		
		FeO		
5.	45	Fe_3O_4 - cubic	Fe_3O_4 - a = 8373	a_{Fe3O4}: 0.20
		γ-Fe_2O_3 cubic		
		FeO - cubic		
6.	50	Fe_3O_4 - cubic	Fe_3O_4 - a = 8390	a_{Fe2O4}: 0.00
		α-Fe - body-centered cubic	α-Fe - a = 0.28655	$a_{\alpha\text{-}Fe}$: 0.03
		γ-Fe - face-centered cubic		
		Fe_2O_3 - cubic		
		FeO - cubic		



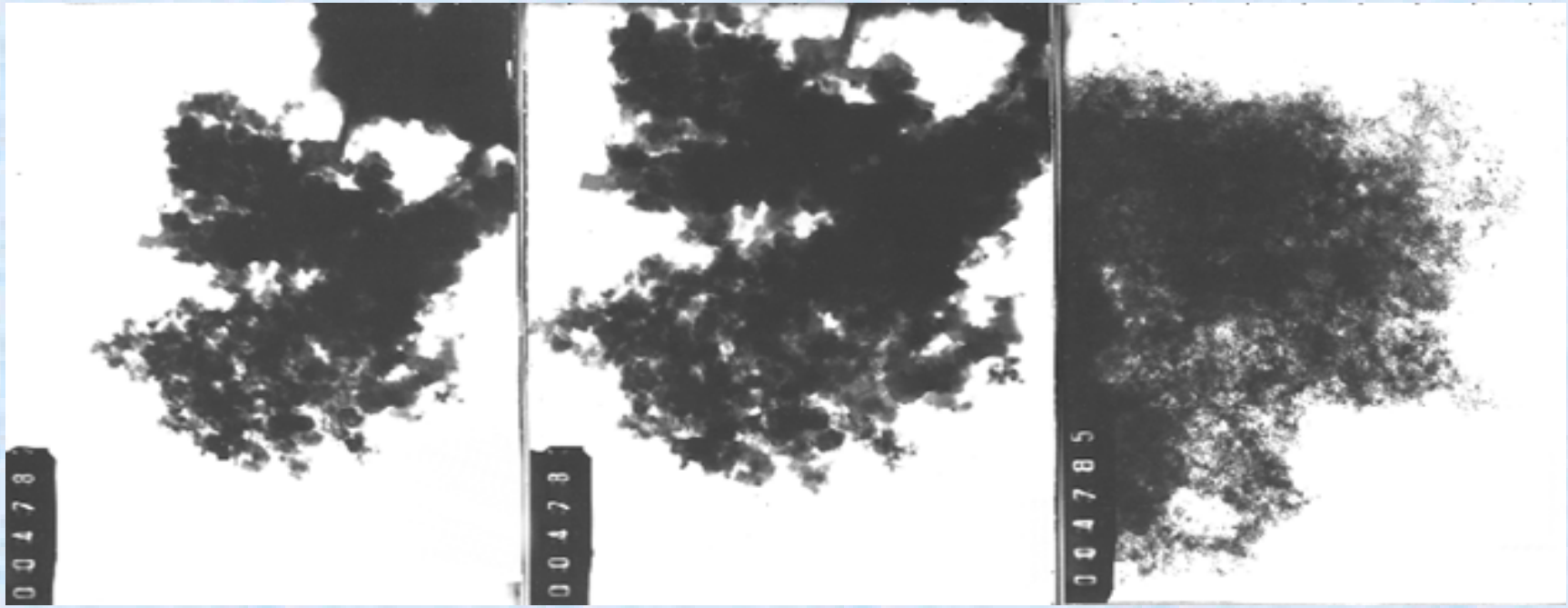
Electron-microscope photographs of plasma-chemically synthesized ND AlN.

a - magnification 43 000, 1 mm = 22 nm;

b - magnification 98 000, 1 mm = 10.2 nm;

c - magnification 43 000, 1 mm = 22 nm;

d - magnification 98 000, 1 mm = 10.2 nm



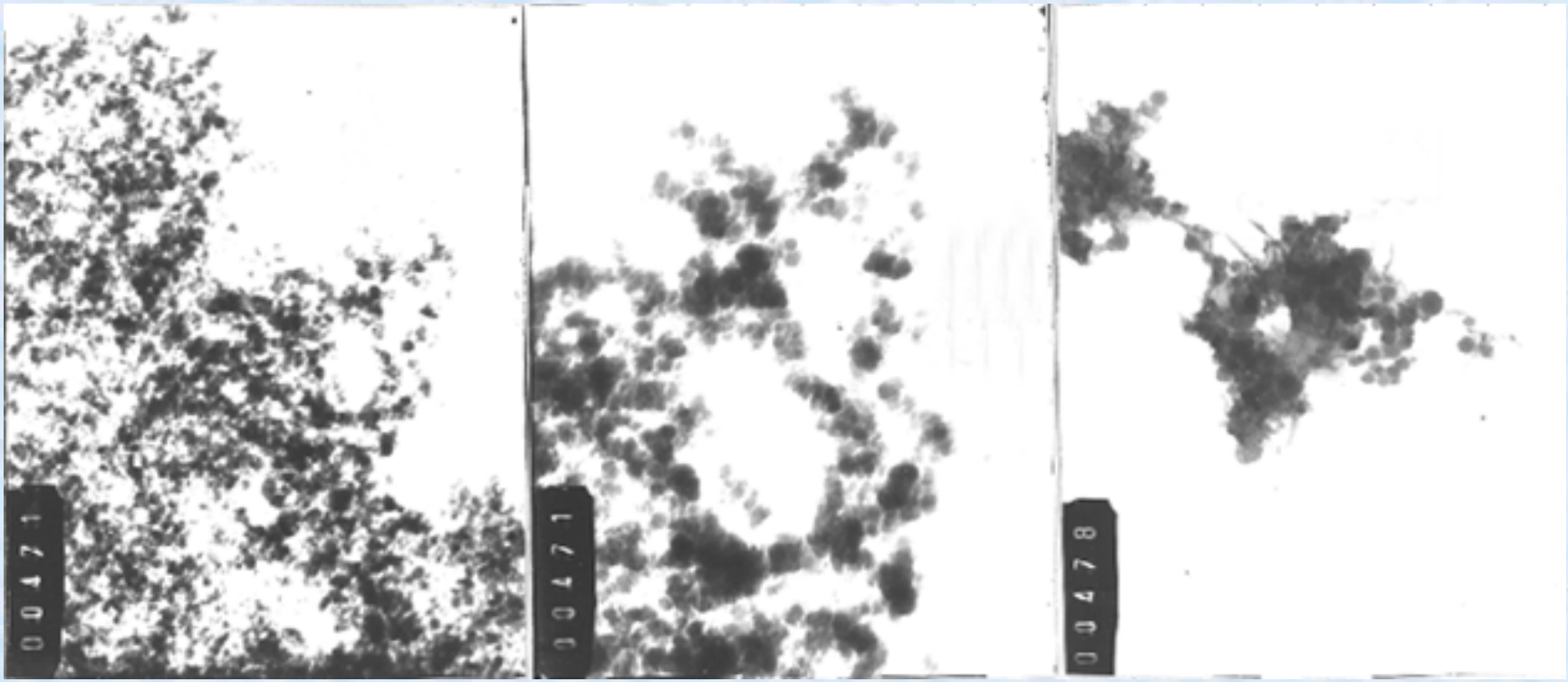
a **b** **c**

Electron-microscope photographs of plasma-chemically synthesized ND Mg_3N_2.

a - magnification 28 000, 1 mm = 38 nm;

b - magnification 36 000, 1 mm = 28 nm;

c - magnification 36 000, 1 mm = 28 nm



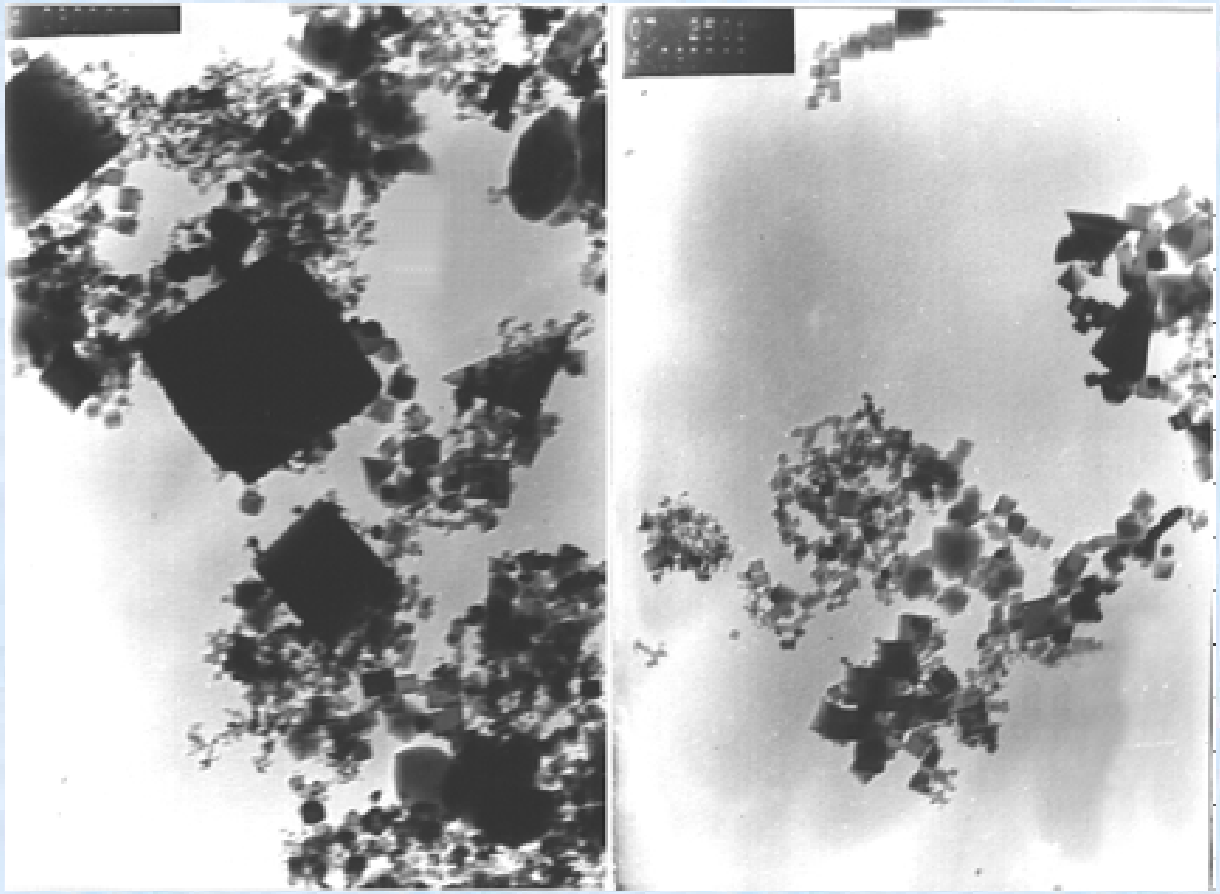
a **b** **c**

Electron-microscope photographs of ND Si_3N_4 plasma-chemically synthesized in a WW PCR

a - magnification 36 000, 1 mm = 28 nm;

b - magnification 98 000, 1 mm = 10.2 nm;

c - magnification 43 000, 1 mm = 22 nm



a b

Electron microscope photographs of PCS ND TiN

a - magnification 90 000; 1 mm = 10 nm; S = 32 m^2/g;

b - magnification 90 000; 1 mm = 10 nm; S = 80 m^2/g

$$T \geq \frac{E}{2R \ln \frac{A^{1/2} \Delta H m^{2/3} \gamma^{1/3}}{K \lambda \rho d \tau^{1/2}}}.$$

T- the self-ignition temperature;the activation, K;
E – the energy of oxidation, J/mol;
λ - the ND powder heat conduction, J/mK;
ρ - the density, g/m^3 of the ND particles;
d - the diameter of the ND particles, m;
τ - the heating duration, s;
in inversely proportional to pre-exponential factor;
ΔH - the thermal effect of oxidation, J/g;
m - the sample's mass, g;
γ - the bulk mass of the powder, g/m^3

Some technological characteristics and physico-chemical properties of chemically active and/or pyrophoric ND powders synthesized in electric-arc low-temperature plasma*

No.	Nano-dispersed substance	Main plasma-chemical reactions of synthesis	Temperature interval in the plasma-chemical reactor, K	Par-ticles size, nm	Speci-ficsur-face, m^2/g	Passivating agent	Protective layer compo-sition
1.	Mn	$Mn_xO_y+yH_2 \rightarrow xMn+yH_2O$	2000-4000	<100	up to 80	N_2	Mn_3N_2, Mn_4N, Mn_2N
2.	Mo	$MoS_2+2H_2 \rightarrow Mo+2H_2S$	2000-4000	<100	20-380	CO	$Mo(CO)_6$
3.	α-Fe, γ-Fe	$Fe_xO_y+yH_2 \rightarrow xFe+yH_2O$	2000-3000	10-100	up to 160	N_2 (0.5%, O_2), CO	Fe_xO_y $Fe(CO)_5$
4.	Catalyst for NH_3 synthesis, type CA-1	$3Fe+2O_2 \rightarrow Fe_3O_4$	1100-3500	20-60	10-40	N_2 (0,5-2% O_2) CO_2 (2% O_2)	Fe_xO_y Fe_xO_y

Some technological characteristics and physico-chemical properties of chemically active and/or pyrophoric ND powders synthesized in electric-arc low-temperature plasma* (continuation)

No.	Nano-dispersed substance	Main plasma-chemical reactions of synthesis	Temperature interval in the plasma-chemical reactor, K	Par-ticles size, nm	Speci-fic surface, m^2/g	Passivating agent	Protective layer compo-sition
5.	Catalyst for LTC of CO with H_2O	$(Cu,Zn,Al)+O_2\rightarrow$ $\rightarrow CuO(Cu_2O)+ZnO+$ $+Al_2O_3$	up to 5100	10-40	45-51	N_2 (1% O_2)	CuO, Cu_2O
6.	Catalyst for CH_4 reforming	$(NiAl)+O_2\rightarrow NiO+Al_2O_3$	2000-3000	10-30	Up to 110	N_2 (1-2% O_2)	NiO
7.	AlN	$2Al+N_2\rightarrow 2AlN$	3300-3800	50-70	60-100	annealing up to 1000 K	-
8.	Ng_3N_2	$3Mg+N_2\rightarrow Mg_3N_2$	2000-2500	10-60	Up to 180	annealing up to 900 K	-

* The Table is compiled on the basis of G. Vissokov's scientific publications.

SPECIFIC ENERGY OF SOME PLASMACHEMICAL PROCESSES

I. PLASMACHEMICAL THERMAL DESTRUCTION

No	Basic reaction	MJ/kg	kW.h/kg
1.	$ZrSiO_4 \Rightarrow ZrO_2 + SiO_2$	7.92	2.2
1[a]	for conventional	10.8 ÷ 33	12
2.	$MoS_2 \Rightarrow Mo + S_2$ (B = 48 ÷ 58 %)	36 ÷ 43,2	10÷12
3.	$Al_2O_3 \Rightarrow 2Al + 1.5O_2$	24.7	6.9
4.	$TlO_2 \Rightarrow Tl + 2O$	5.0	1.4
5.	$NiO \Rightarrow Ni + O$	9.0	2.5
6.	$CuO \Rightarrow Cu + O$	4.7	1.3
7.	$Ca_3(PO_4)_2 \Rightarrow 3CaO + 2PO + 3O$	20.68	5.74

II. REDUCTION PLASMACHEMICAL PROCESSES

No	Basic reaction	MJ/kg	kW.h/kg
1.	$Fe_xO_y + yH_2 \Rightarrow xFe + yH_2O$ (Theor.)	7.92	2.2
1a.	(when W = 100 kW)	17.4÷21.4	4.8÷5.9
1b.	(when W = 1000 kW)	15 ÷ 19	4.2÷5.3
1c.	(when $H_2 : CH_4 = 2 : 1$)	9.5	2.6
1d.	(ref.)	10 ÷ 37	2.8÷10.3
2.	$W_xO_y + yH_2 \Rightarrow xW + yH_2O$	~ 50	~13.9
3.	$MoO_x + xH_2 \Rightarrow Mo + xH_2O$	72	20
4.	$V_2O_3 + C(H_2) \Rightarrow V + CO_2(H_2O)$	22.4	6.2
5.	$Nb_2O_5 + 5H_2 \Rightarrow 2Nb + 5H_2O$	34.2÷41.8	9.5÷11.6
6.	$Fe_xO_y+zV_2O_5+5zH_2 \Rightarrow xFe.2zV+5zH_2O$	22.4	6.2
7.	Iron-based alloys	14.4	4
8.	$SnO_2 + 2H_2 \Rightarrow Sn + 2H_2O$	9.83	2.7
9.	$Fe_xO_y+zCr_2O_3+3zH_2 \Rightarrow xFe.2zCr+3zH_2O$	43.2	12
10.	$NiO + H_2 \Rightarrow Ni + H_2O$	14.4	4
11.	$Co_3O_4 + 4C \Rightarrow 3Co + 4CO$	10.8÷12.6	3÷3.5
12.	$Co_3O_4 + 4H_2 \Rightarrow 3Co + 4H_2O$	7.2÷9.0	2÷2.5
13.	$MgO + C \Rightarrow Mg + CO$	64.8	18

II. REDUCTION PLASMACHEMICAL PROCESSES (EXTENSION)

No.	Basic reaction	MJ/kg	kW.h/kg
14.	$FeO.TiO_2+CH_4 \Rightarrow Fe+TiO_2+CO+2H_2$	4	1.1
15.	$BCl_3 + 1.5H_2 \Rightarrow B + 3HCl$	~ 20	~ 5.6
16.	$TiCl_4 + 2H_2 \Rightarrow Ti + 4HCl$	31	8.6
17.	$SiCl_4 + 2H_2 \Rightarrow Si + 4HCl$	~ 20	~ 5.6
18.	$AlCl_3 + 1.5H_2 \Rightarrow Al + 3HCl$	45.36	12.6
19.	$ZrCl_4 + 2H_2 \Rightarrow Zr + 4HCl$	~ 25	~ 6.9

III. NITRIDING PLASMACHEMICAL PROCESSES

No.	Basic reaction	MJ/kg	kW.h/kg
1.	$2P + N_2 \Rightarrow 2PN$	11.6	3.23
2.	$6P + 5N_2 \Rightarrow 2P_3N_5$	11.7	3.26
3.	$TiCl_4 + NH_3 + H_2 \Rightarrow TiN + 4HCl$	35	9.7

CARBIDE PLASMACHEMICAL PROCESSES

No.	Basic reaction	MJ/kg	kW.h/kg
1.	$TiCl_4 + CH_4 + H_2 \Rightarrow TiC + 4HCl$	20 ÷ 60	5.6 ÷16.7
2.	$MoCl_5 + CH_4 + H_2 \Rightarrow Mo_2C + HCl$	~ 15	~ 4.2
3.	$WCl_6 + CH_4 + H_2 \Rightarrow WC + W_2C + HCl$	5 ÷ 10	1.4 ÷ 2.8

OXIDIZING PLASMACHEMICAL PROCESSES

No.	Basic reaction	MJ/kg	kW.h/kg
1.	$TiCl_4 + O_2 \Rightarrow TiO_2 + 2Cl_2$	1.8	0.5
2.	$SiCl_4 + O_2 \Rightarrow SiO_2 + 2Cl_2$	~ 2.0	~ 0.56

REDOXI PLASMACHEMICAL PROCESSES

No.	Basic reaction	MJ/kg	kW.h/kg
1[a].	$SiO_2 + C \Rightarrow SiO + CO$		
2[b].	$SiO + O \Rightarrow SiO_2$	~ 36	~ 10

CONCLUSIONS

1. For the first time we:

- proposed and developed a technique for plasma-chemical regeneration (and, in certain cases, synthesis) of spent deactivated catalysts used in the production of ammonia, such as catalysts for natural gas reforming (steam conversion of methane), for low-temperature conversion of carbon monoxide with water vapour and for synthesis of ammonia; in a number of cases, these catalysts exhibit catalytic activity and thermal stability higher than those of the conventional analogs;

- implemented a process for production of nano-dispersed silicon dioxide through hydrolysis of silicon tetrachloride in electric-arc low-temperature plasma;

- synthesized aluminium, silicon, and magnesium nitride, in high-frequency induction electrode-less cold plasma, achieving degree of nitride formation of 73 % (for magnesium nitride);

- proposed and developed a technique for preparation of ND metal powders (manganese, molybdenum, cobalt) by means of reduction of the respective concentrates (manganese-oxide, molybdenite and cobalt cake) in electric-arc low-temperature plasma with gas-phase reducing agents (hydrogen, butane, ammonia);

- proposed a technique for plasma-chemical preparation of nano-dispersed γ-iron with specific surface reaching 160 m^2/g by means of reducing iron oxides by hydrogen in electric-arc low-temperature plasma, with the possibility to control the ratio between the α- and γ-iron via the rate of quenching;

2. Furthermore, we performed a thorough physicochemical study of plasma-chemically synthesized and/or regenerated catalysts, using X-ray diffraction pattern analysis, electron microscopy, derivatography, Moessbauer spectroscopy, as well as chemical, thermo-magnetic etc. analyses; we also explored the dynamics and kinetics of the formation via reduction of the active surface (the "plasma" catalysts are reduced at a rate 2 - 5 times as high as that of the respective industrial analogs); The following was also established:

- for a catalyst for natural gas reforming: degree of methane conversion, efficiency, output;

- for catalysts for synthesis of ammonia (in the case of a stoichiometric nitrogen-hydrogen mixture, volume velocity of 30 000 h-1 and pressures of 0.1 and 30 MPa): activity (15 to 20 % higher than that of the SA-1 catalyst, relative degree of conversion, rate constants, activation energies, relative activity, degree of conversion during deactivation.

3. We analysed the characteristics of the quasi-equilibrium and non-equilibrium plasma-chemical processes employed in the technologies for production of nano-dispersed inorganic powders. From a technological and, to some extent, design point of view, we discussed the main component of the plasma-chemical installation, namely, the plasmatron (plasma generator) - electric-arc and induction, the plasma-chemical mixer and reactor, the quenching device.

4. We developed and built installations for plasma-chemical preparation of ultra-dispersed inorganic powders (metals, oxides, nitrides, pigments, catalysts, etc.) by processing ingredients with given purity (metals, oxides, salts) and/or raw materials or wastes of inorganic (metallurgical origin), such as mineral salts, deactivated (spent) catalysts, pyrite burnt, various concentrates and cakes, etc.

5. We designed and built different variants of various devices: high-frequency induction (quartz) plasmatrons and inductors, plasma-chemical mixers and reactors (cylindrical, conical, with “cold” of “warm” walls), power feeding devices (with boiling layer, piston, with pneumatic transport) power traps (chamber, with partitions, with settler, with filters - mechanical and electrical, cyclones), etc.

6. The plasma-chemical techniques are very promising, especially when there are no alternative methods for production of ultra-dispersed powders with specific properties.

7. The nano-dispersed powders have found extensive applications in various industrial branches as:

- reagents, fillers and catalysts - in the chemical industry;

- intensifying agents in the sintering processing, for production of materials with zero porosity and specific properties, for hardening of metals and alloys - in the powder metallurgy (metal ceramics);

- for production of artificial dielectrics with high dielectric constant, for production of ferrites, for production of materials with specific semiconducting characteristics, for production of high-temperature superconductors, for manufacture of cathodes for electro-vacuum devices - in the electronic industry;

- for alloying (modification) of metals and alloys - in the metallurgy, and many others.

8. The experimental results obtained on the technological parameters of the plasma-chemical processes for production of nano-dispersed powders can be applied to the design of experimental semi-industrial installations, when the modelling criteria are taken into account; in some cases (e.g., production of nano-dispersed silicon dioxide through vaporization of quartz sands, synthesis of nano-dispersed nitrides of silicon, aluminium titanium), these criteria can be used for the design of industrial equipment. The practical utilization of the techniques necessitates adjustment of some of the processes under industrial conditions.

This can be carried out in any chemical or metallurgical industrial enterprise that shows interest in the production of nano-dispersed powders with unique properties.

THANK YOU FOR YOUR ATTENTION !