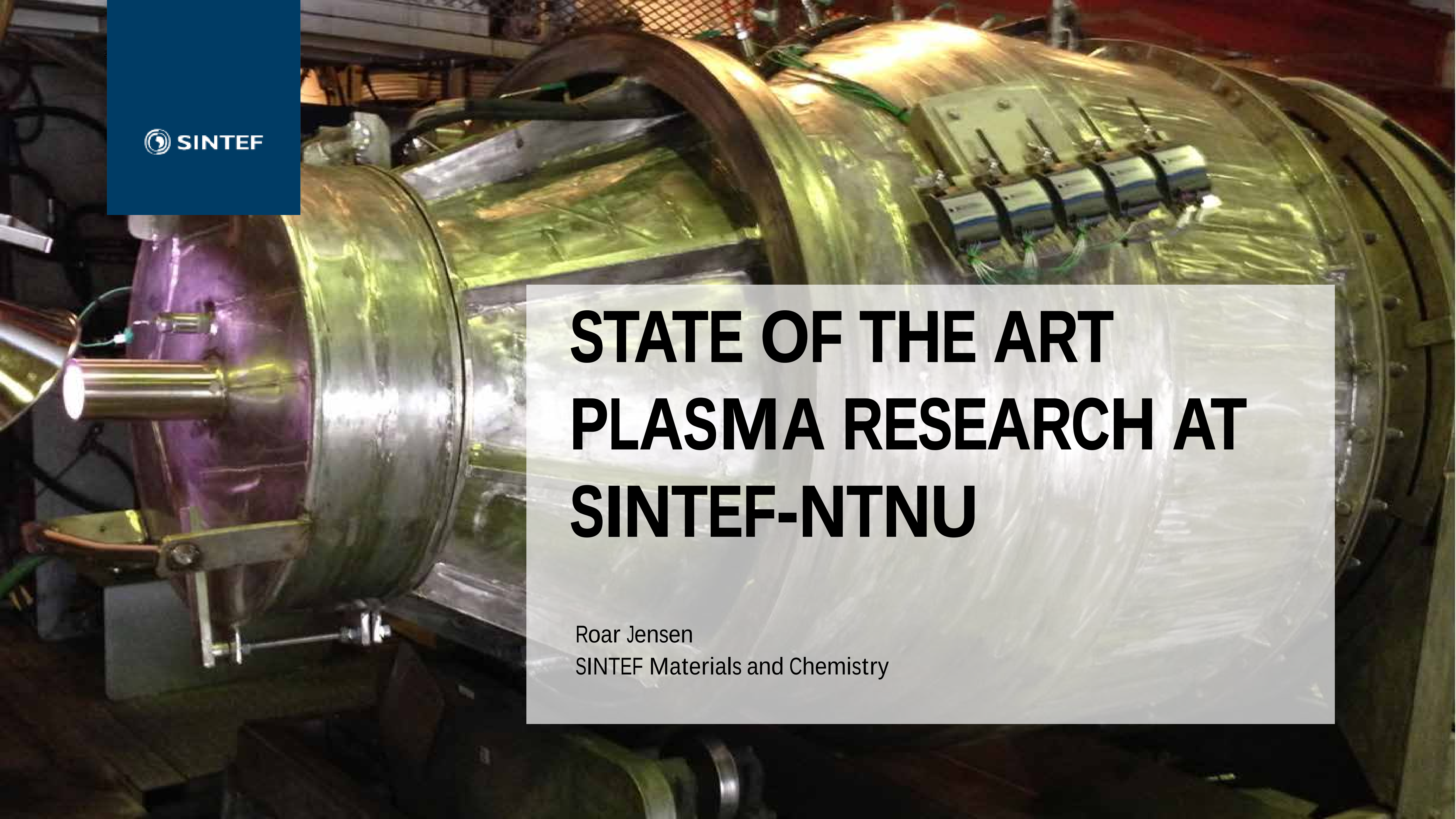

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STATE OF THE ART PLASMA RESEARCH AT SINTEF-NTNU

Roar Jensen
SINTEF Materials and Chemistry

Contents

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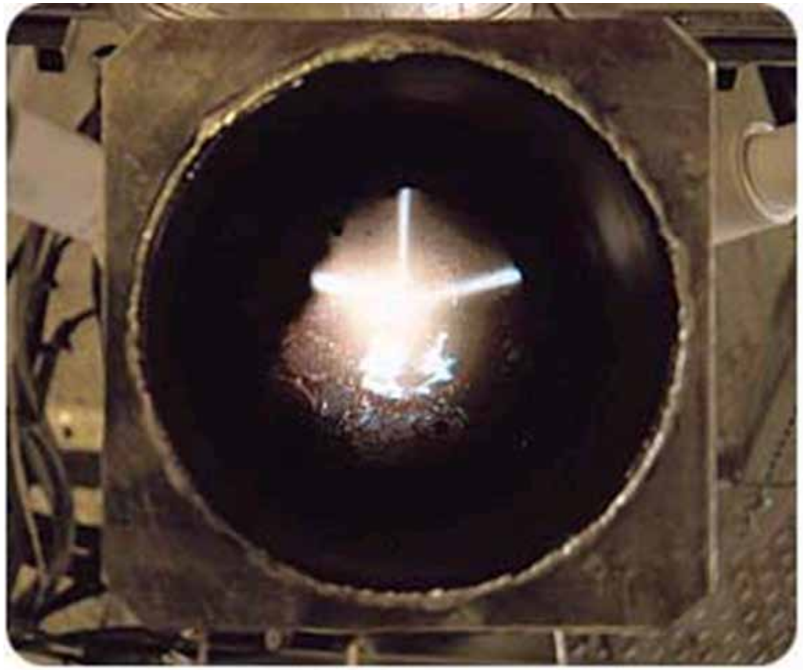
History of Plasma Research and High Temperature Process development at NTNU/SINTEF

Plasma research at NTNU - SINTEF was started in early 1960ies.

A graphite plasma torch invented at SINTEF in late 1970ies was first used as an immersed plasma lance in liquid metals.

In 1986 a thermal plasma research group was established with financial support from the Norwegian Research Council (NFR), the ferroalloy industry and other industrial companies.

The group has since been engaged in process development as well as in computer simulation of thermal plasmas.



Three Transferred Plasma arcs in the Plasma REactor for Smelting at SINTEF (PRESS)

Contract research

- The plasma research group at SINTEF Materials and Chemistry performs contract research and development for Norwegian and foreign industry in the field of thermal plasma technology.
- Our specialities include process development, computer modelling, plasma reactor design and experimental testing and verification.
- We perform consultant work to evaluate new plasma processes and compare with alternative technology.
- The basis is our competence within the areas of thermodynamics, plasma physics, metallurgy, practical experience, use of FLUENT, use of DAC, and our plasma laboratory.

Plasma and plasma technology

- Plasma is often referred to as the fourth state of matter. It is ionised gas containing free electrons and ions. Typical temperatures in plasmas at atmospheric pressure are 6.000 K to 30.000 K. Where as gas is a good insulator, plasma conducts electricity. This attribute is used to generate heat in electric arcs.
- Plasma arcs have some sort of stabilisation, as opposed to free-burning in alternating current (AC) arcs when used in submerged arc furnaces or electric steel furnaces. In plasma technology, plasma torches are used to generate plasma from electricity. Direct current (DC) is generally used and the arc is stabilised by using methods such as magnetic fields or gas injection.

Plasma process advantages

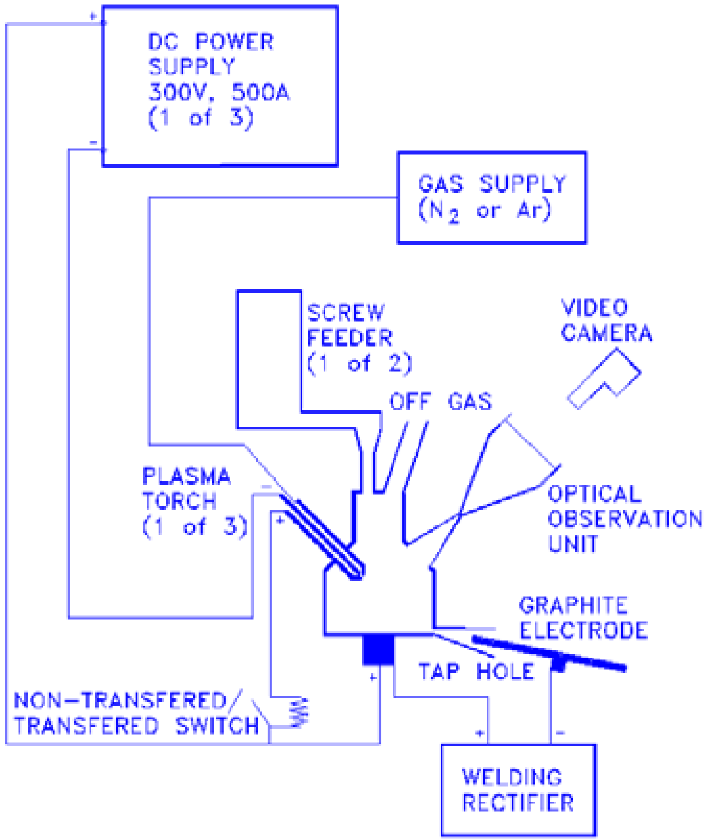
- The use of plasma technology offers new possibilities for high temperature production processes. Due to the very high heat content, using plasma is more energy efficient than using fossil fuels, especially for processes that demand high temperatures. The off-gas volume is also very low.
- Plasma processes are characterized by short response time, god process control, high yield, high and consistent product quality and high production per unit volume. Plasma technology meets the demands for more environmentally friendly processes.

DC power supply in SINTEF’s laboratory

- The DC power supply in SINTEF’s laboratory consists of three six-pulse controlled thyristor rectifiers with:
  - Current ratings of 500 A and maximum DC voltages of 300 V.
- Twelve-pulse controlled thyristor rectifier with:
  - Current rating of 1000 A and a maximum DC voltage of 1000 V.

The PRESS reactor

- The Plasma Reactor for Smelting at SINTEF (PRESS) is a multipurpose test facility with one or three 500 A plasma torches.
- The reactor consists of several modules which can be modified or replaced to suit the process requirements.
- Inert, reducing or oxidising atmosphere may be chosen depending on the reactor lining materials used.



Schematic diagram of the experimental facility, PRESS.

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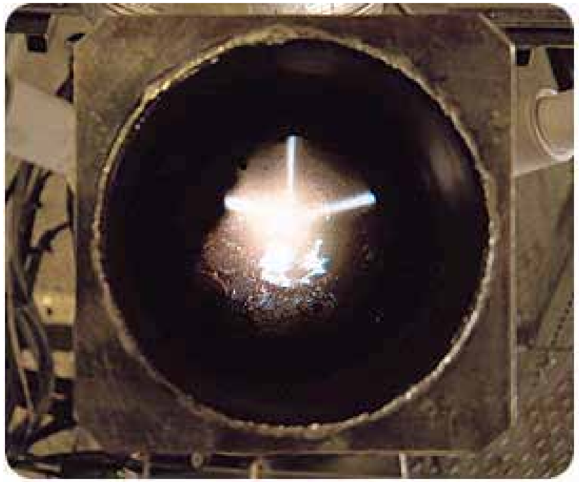
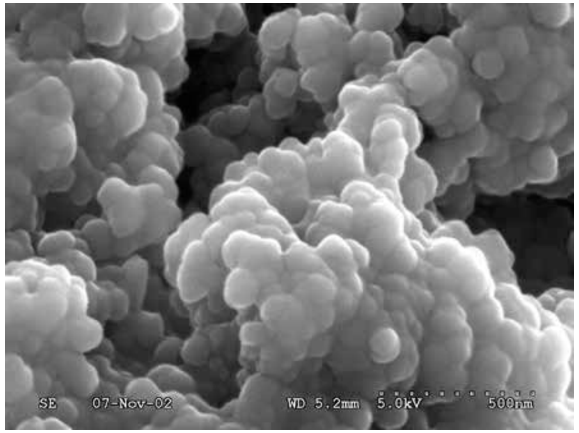
Experimental program in the PRESS-reactor

- An extensive experimental program has been run in the PRESS reactor. Some examples are; re-melting silicon metal fines, production of ultra fine silica particles and the treatment of hazardous wastes.
- Process development work in the PRESS-reactor has resulted in two patented processes for the Norwegian company Elkem ASA. These processes are for recovery of silicon and copper in residues from synthesis of organic chloro-silanes and chloro-silanes.
- An industrial plant for vitrifycation of used fluorescent tubes was operated by Miljøtek a/s in Meraker, Norway based on results from tests in the PRESS-reactor.





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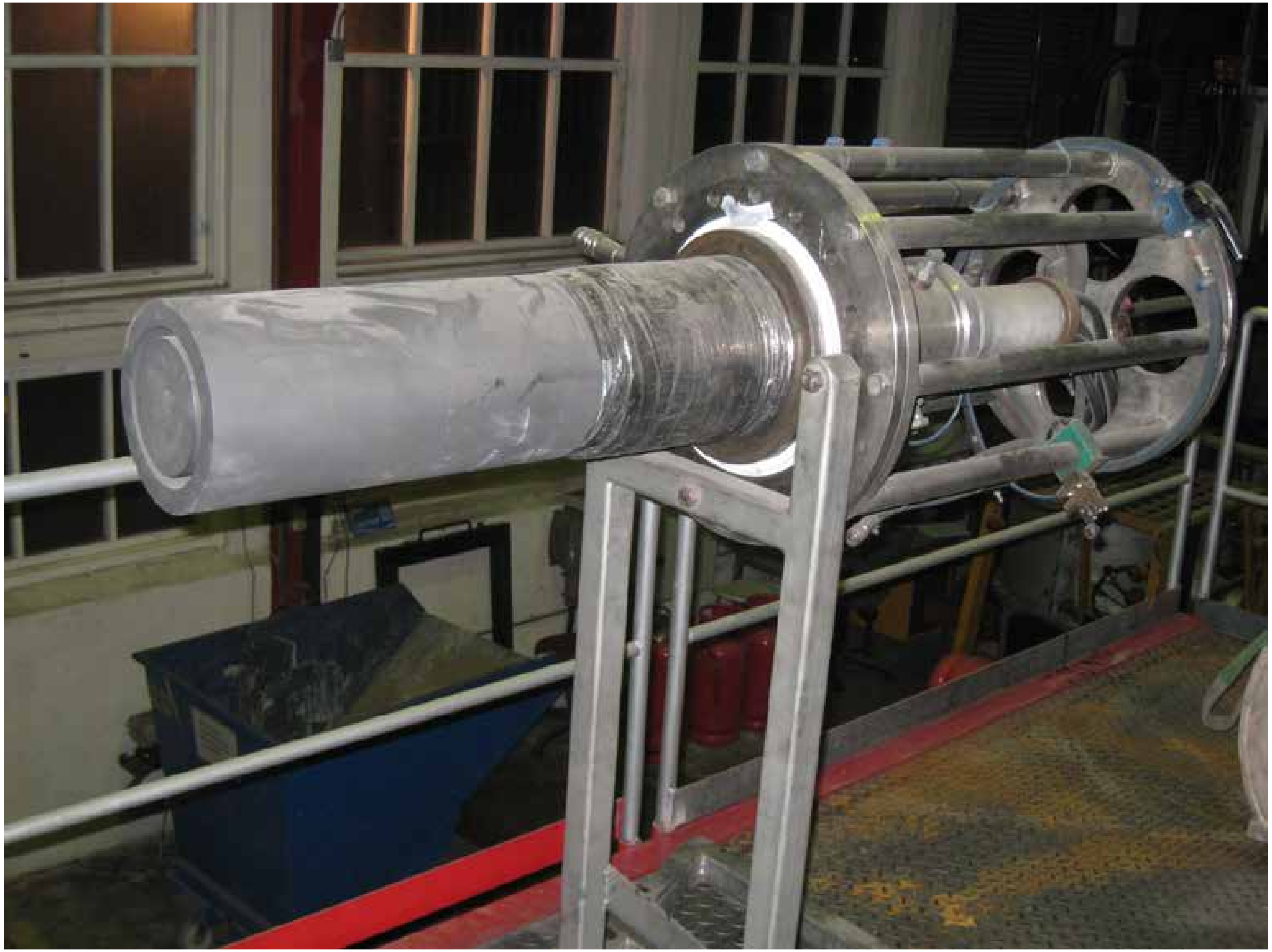
300 kW Graphite Plasma Torch



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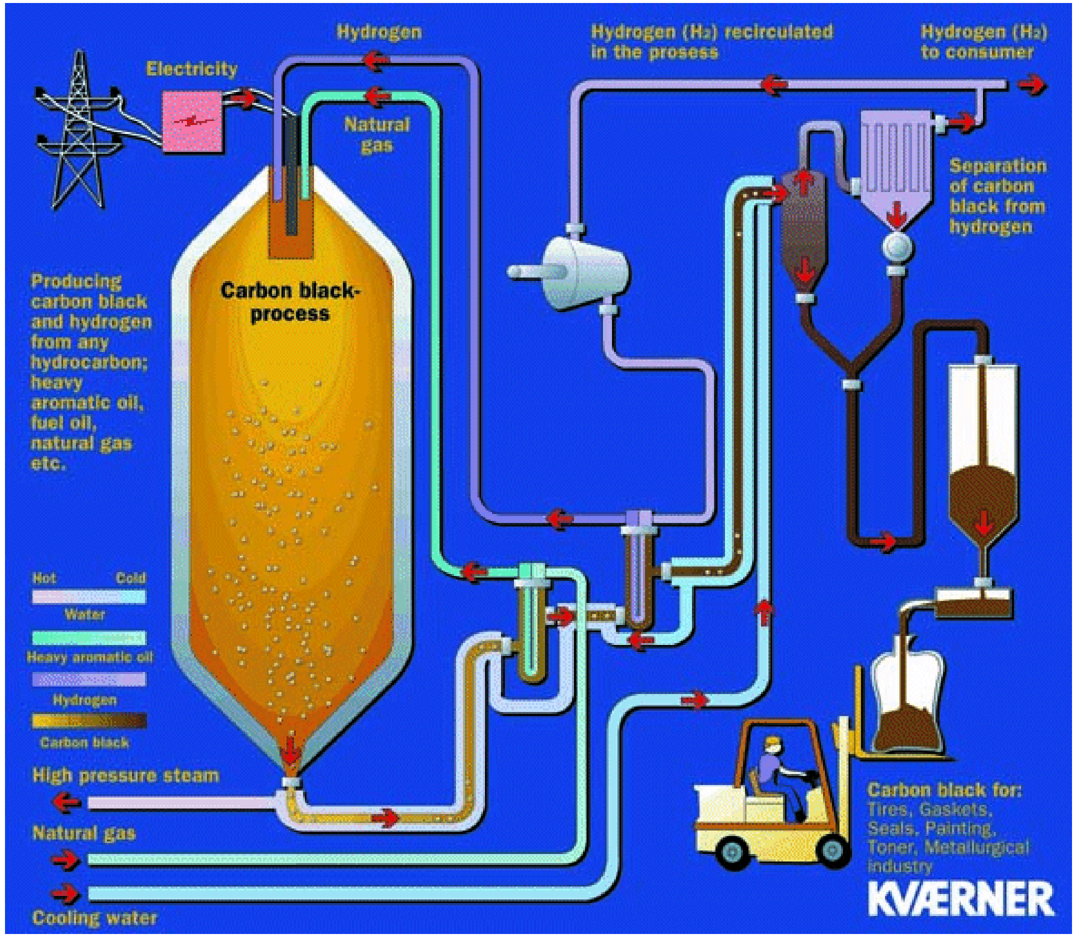
Carbon black (CB) and Hydrogen

- The graphite plasma torch is a robust and energy efficient heat source in reducing and inert atm.
- The plasma torch was used in a process for decomposition of hydrocarbons directly into CB and H2.
- Developed together with Kværner and ScanArc.
- A reactor(150 kW) was built at SINTEF (1989).
- Kværner (1992) built an industrial-scale pilot plant (ScanArc, Sweden 3 MW).
- A 20.000-ton/year CB plant of 6 MW was in operation in Canada (1998-2001).



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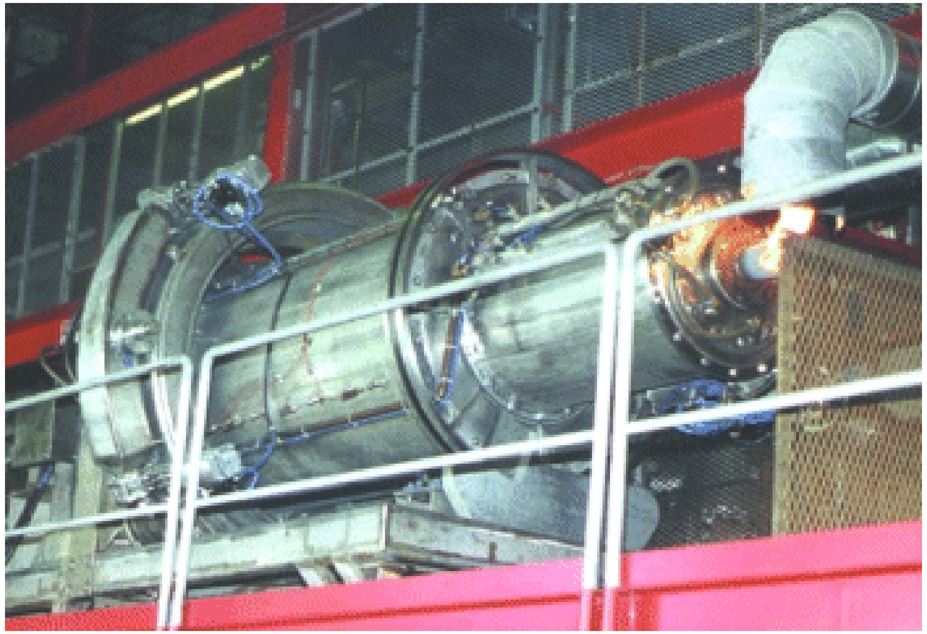
Plasma rotary furnace for production of SiC.

- A plasma rotary furnace with a 300 kW plasma torch, 2.75 m long and with 0.55 m inner diameter with a graphite inner lining.
- Used for processing with solid/gas reactions at temperatures up to 2200ºC in inert or reducing atmospheres.
- Used for production of silicon carbide of high purity as a intermediate product in the Solsilc process.



Plasma Production of Carbon Nanotubes (CNT)

Principle objective:

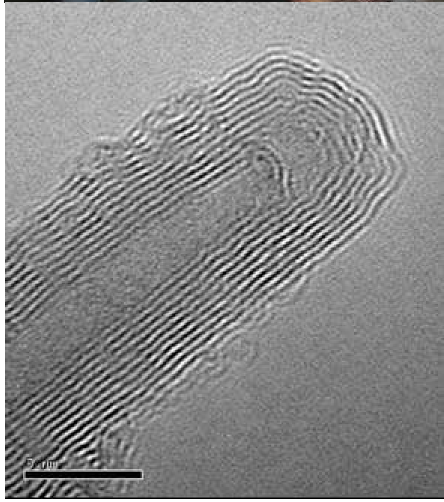
- Provide a new process for continuous production of high value CNT based on high temperature thermal plasma technology. Establish a business alliance with the aim of up-scaling the process to industrial scale.

Sub-goals:

- Patenting the process
- Achieve 20% share of CNT directly from the process
- Develop a separation method that gives 90% share of CNT
- Provide a CFD model for the continuous process

Results:

- A well functioning plasma reactor was designed and built based on our know-how of plasma technology, aided by CFD modelling.
- High purity product; MWNT with no ash or remains of catalysts.
- Straight tubes with low structural defects density.
- The concept can be scaled up to industrial scale.
- PhD thesis delivered March 2007: "modelling of dynamic arc behaviour in a plasma arc reactor"
- Magnetic field model and plasma arc model
- Norwegian patent approved 2009.01.12.
- US patent approved 2. October 2012.
- Patent in several countries.



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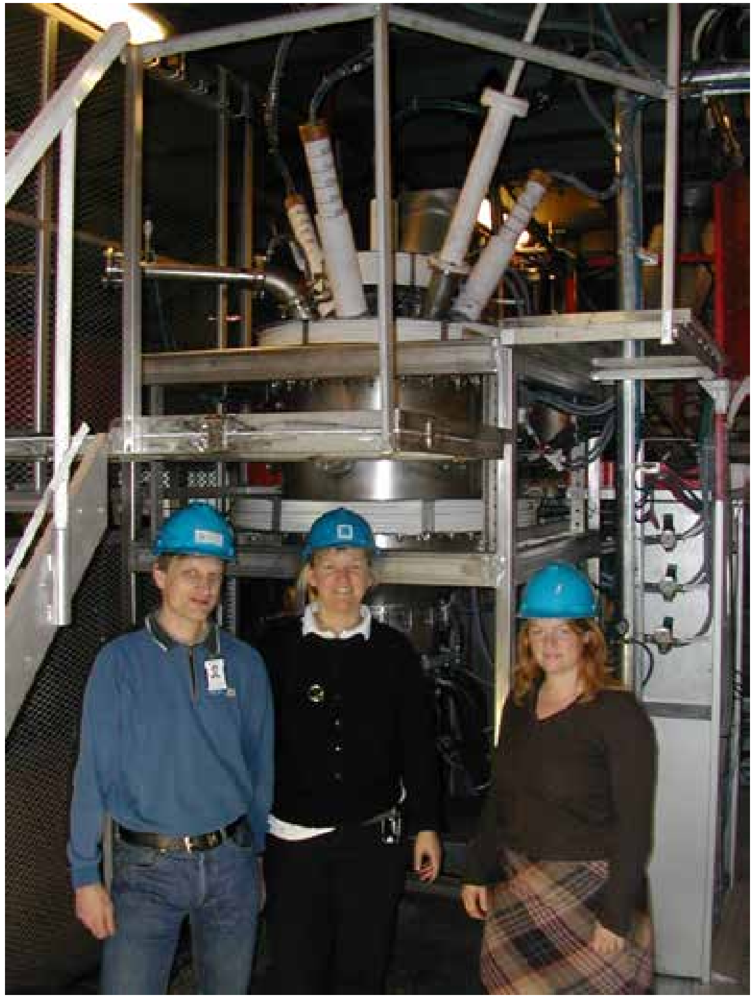
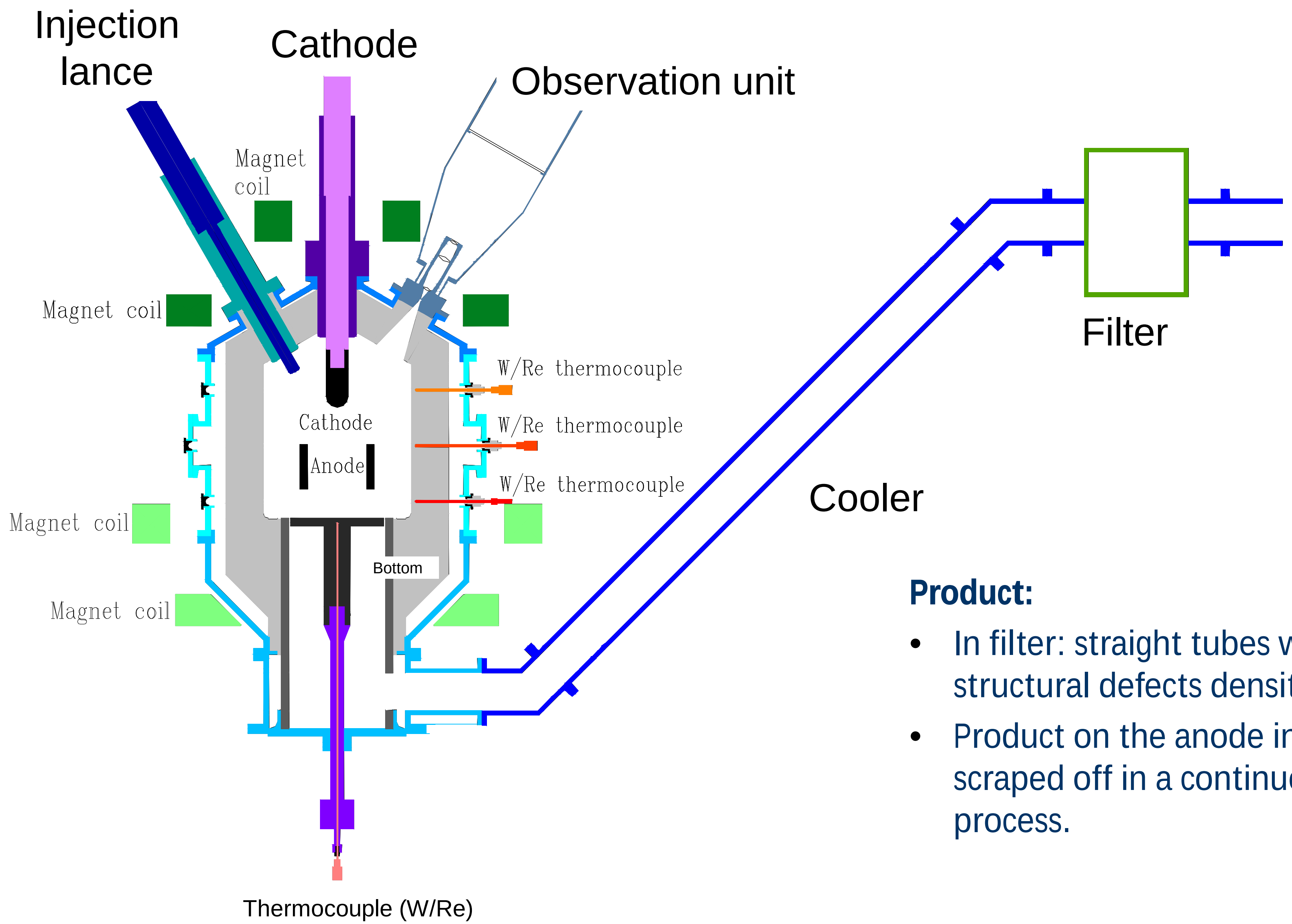
PPM-Reactor

Typical:

- Arc current 650 – 900 A
- Arc voltage 130 – 200 V
- Power 100 – 150 kW
- CH_4 carbon source
- Helium plasma gas (Ar/H_2)
- Reactor wall temperature 1800 - 2100 ºC

The reactor is very stable both with regard to electrical operation, arc control, temperature distribution and flow pattern

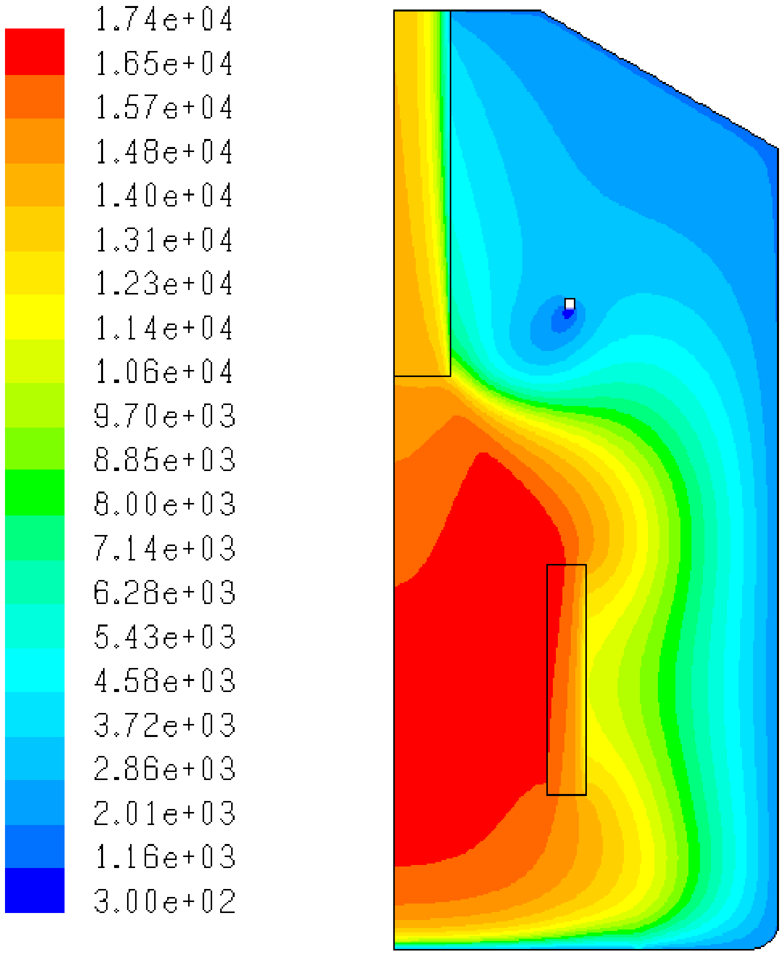




Product:

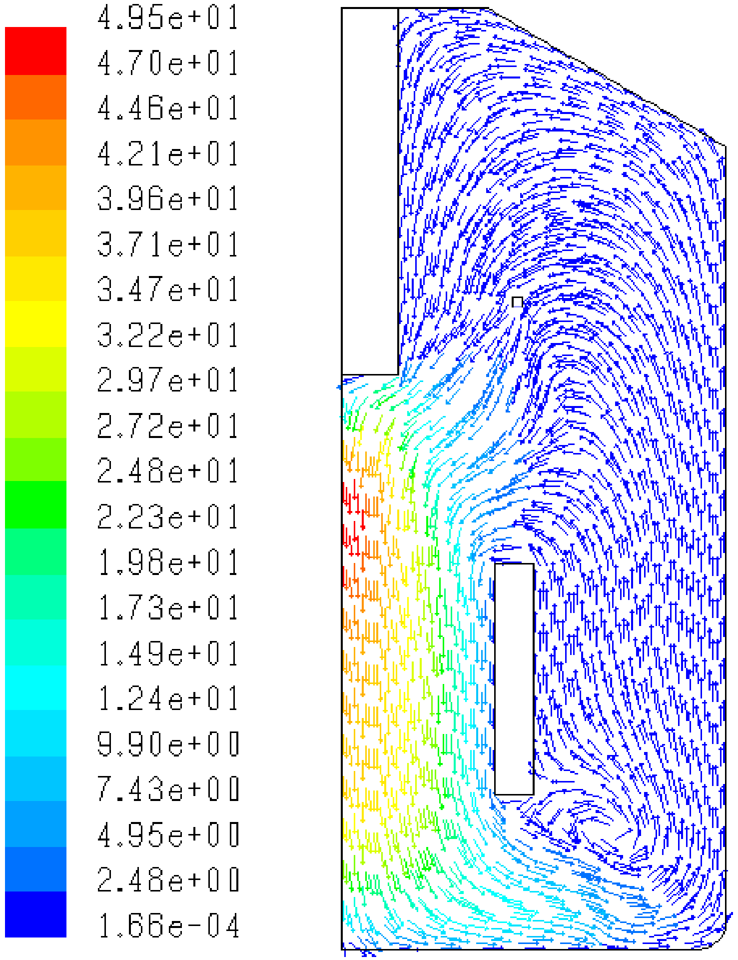
- In filter: straight tubes with low structural defects density
- Product on the anode inside, is scraped off in a continuous process.

Temperature distribution



Plasma gas 1: 0 l/min
Plasma gas 2:100 l/min

Velocity vectors



Gas 1: 0 l/min
Gas 2: 100 l/min
Residence time:1.6s
Loops:5.3

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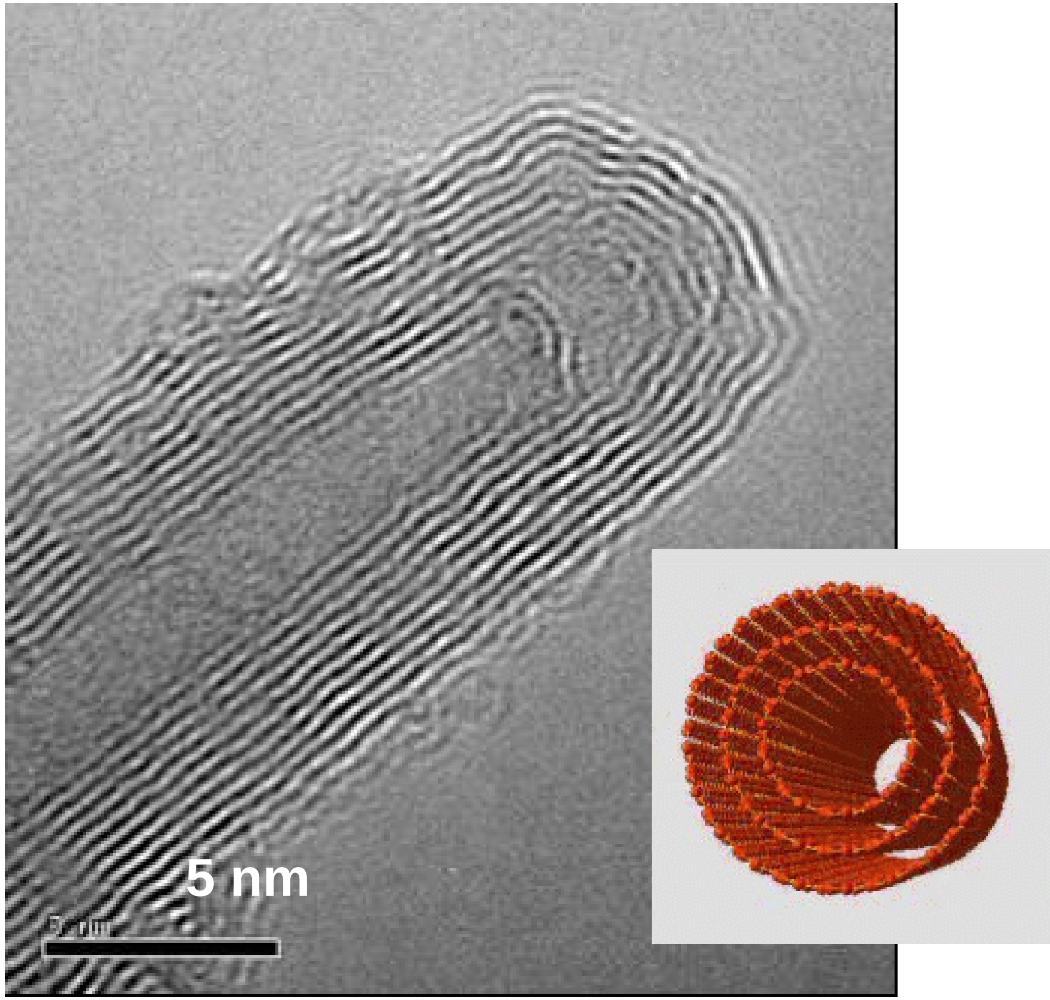
Carbon nanotube produced in the PPM reactor

FEG-TEM image of a MWNT

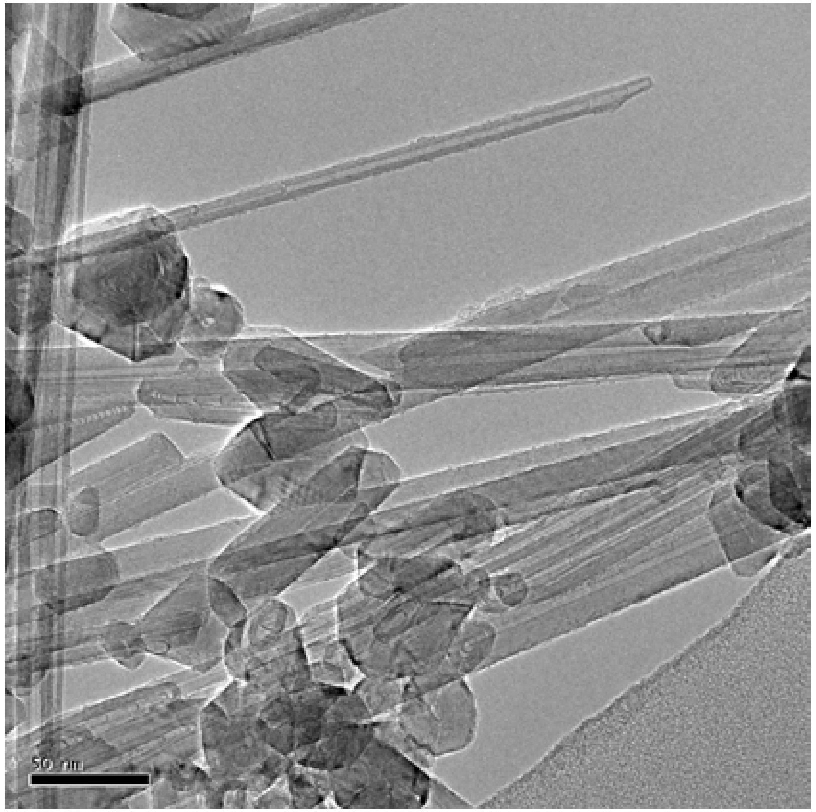
- diameter ≈ 10 nm
- 11 walls
- 0.34 nm between
- inner diameter 2 nm

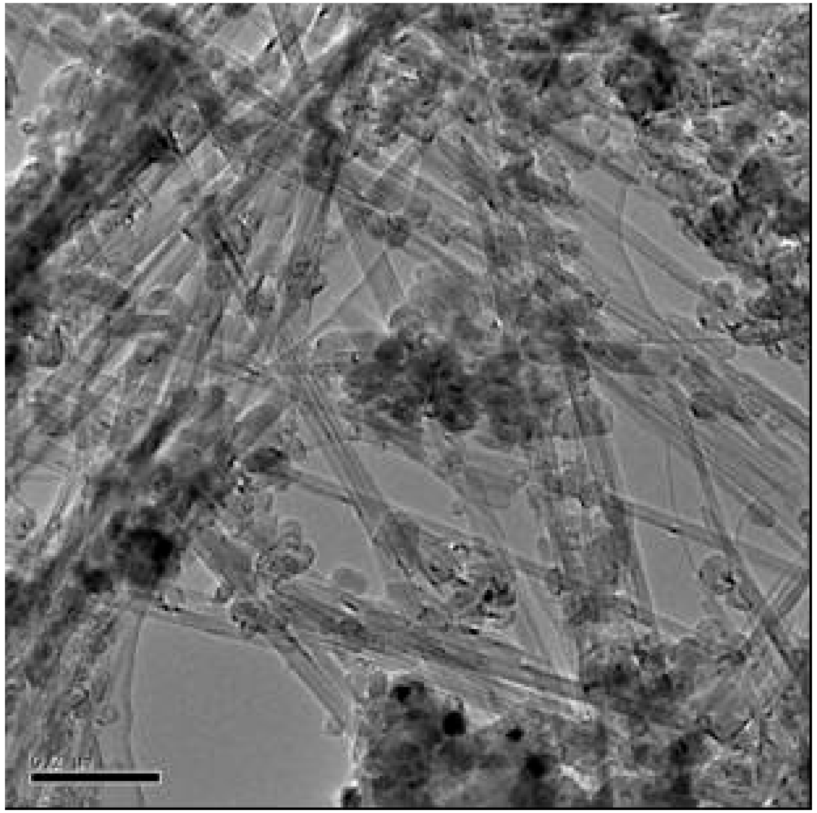
- Straight CNTs produced at high temperatures
- All observed CNT have closed ends.



TEM: Filter sample

Run 15; Mean diameter 14 ± 7 nm, Range 4 -37 nm

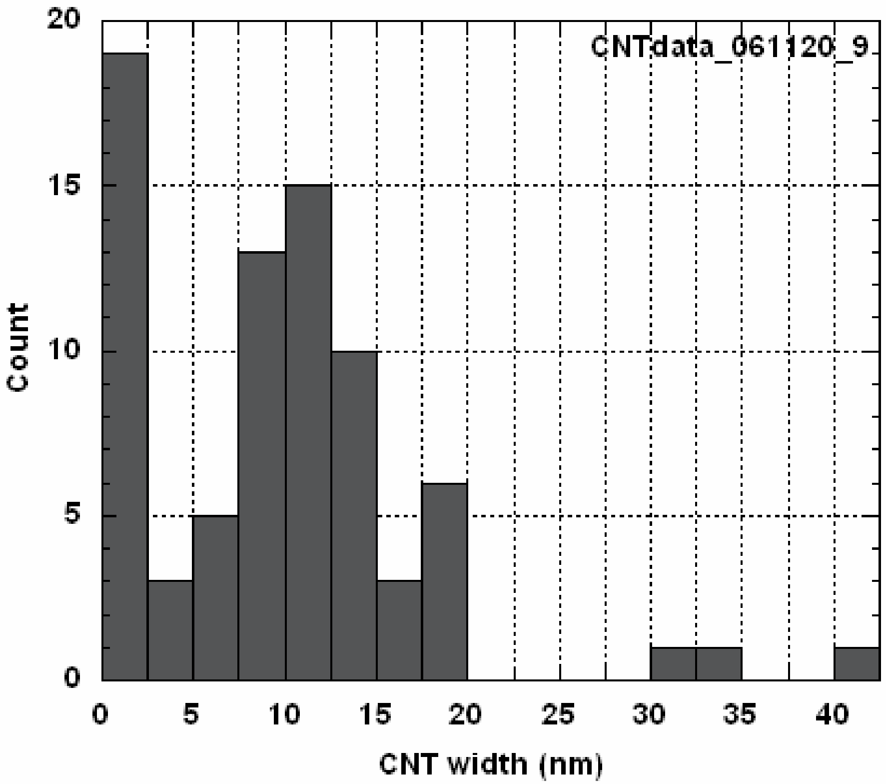


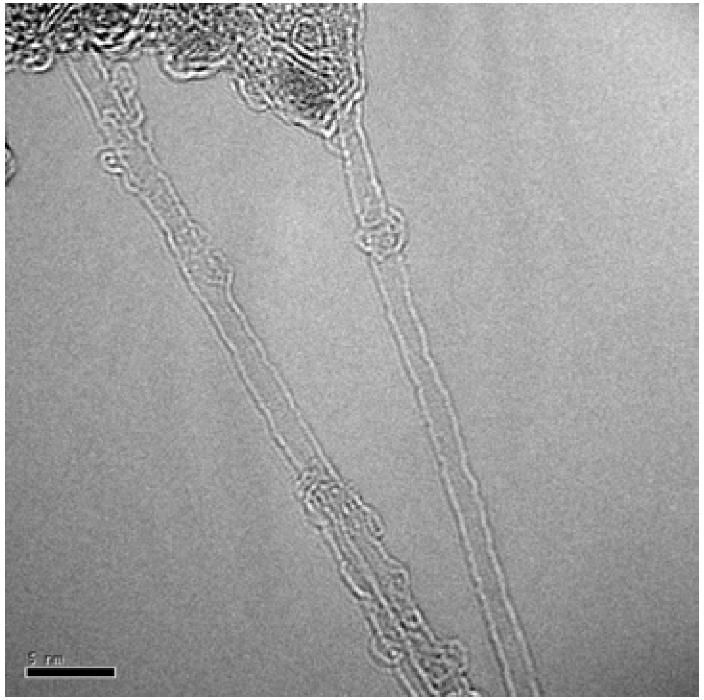


High shares of CNTs, using an injection rate of methane of 10 l/min. Photo: C. Marioara

PPM with catalyst: SWNT also produced

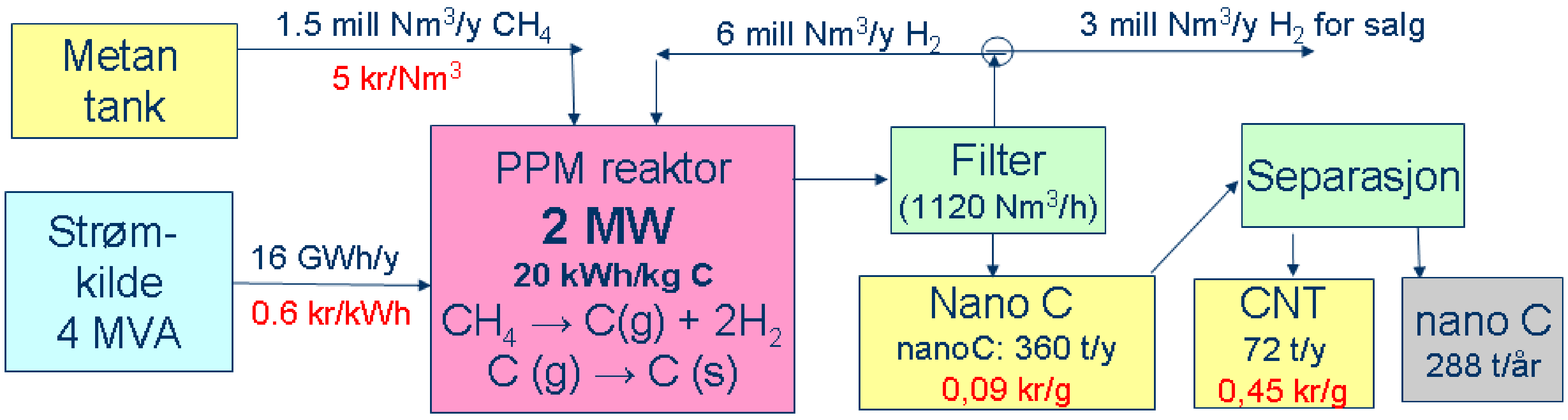
TEM: Filter sample





Size distribution of nanotubes: 10 ± 7 nm. Photo: C. Marioara

Industrial PPM process



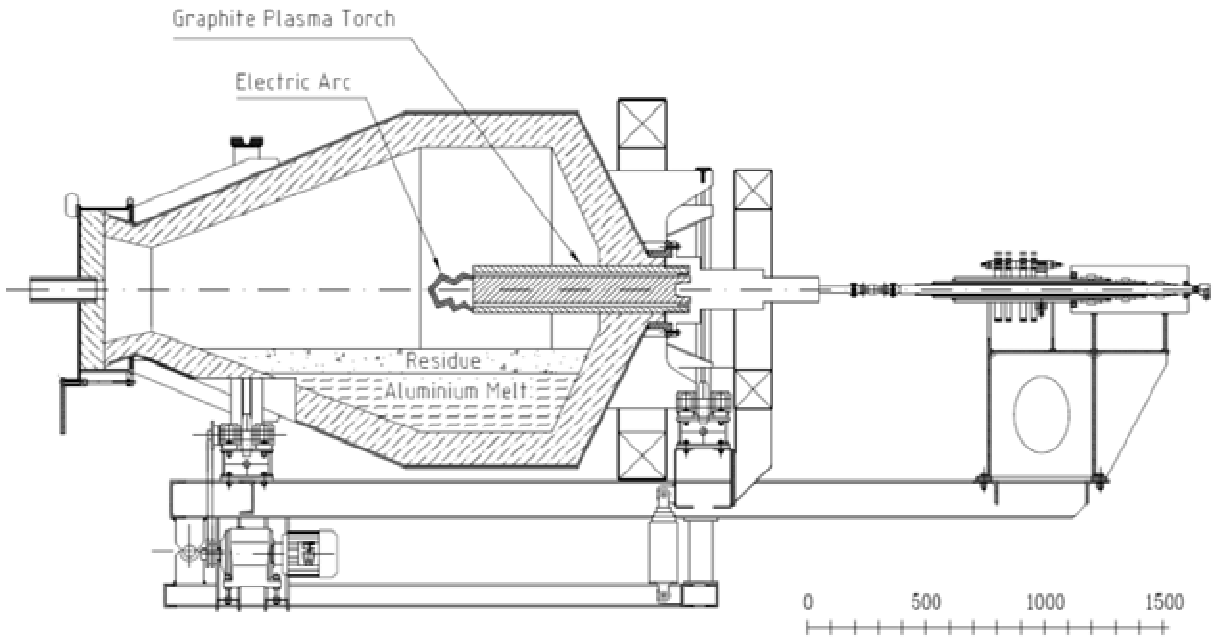
Production of CNT at low cost – with high quality

Properties: High strength, low weight, semi-conductor or conductor

Applications: batteries, field emission devices, composite materials

Salt Free Treatment of Aluminium Dross

- A plasma rotary furnace with a 300 kW graphite plasma torch and 500 kg batch capacity has been designed and used for separation of metallic aluminium from aluminium dross and difficult aluminium scrap without using any salt.
- Inert or reducing plasma gas flows between the electrodes.
- Arc movement is controlled by a magnetic field.
- Due to the furnace design and operation, only a small amount of plasma gas is needed.



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Experiment in the plasma rotary furnace

Feeding aluminium dross

Tapping aluminium

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Expected consumption and performance data for SINTEF Plasma Rotary Furnace and 3MW industrial furnace based on experimental results

	Operating power			
	110kW	140kW	225kW	3MW
Overall heat efficiency*	70%	75%	83%	90%
Tapping interval*	2h 20 min	1h 50min	1h 15min	3h 00min
Aluminium recovery in tapped metal	>96%	>96%	>96%	>96%
Treatment capacity per day [ton dross]	5.100	6.500	9.600	160
Electric energy consumption [kWh/ton dross]	425	400	370	320
Graphite electrode consumption [kg/ton dross]	0.25	0.25	0.25	0.25
Argon consumption [m3/ton dross]	23	15	10	3
Hydrogen consumption [m3/ton dross]	5	5	5	1.5

* Semi-continuous furnace operation with 30 minutes stop for tapping and charging included (1 hour for industrial furnace) .
750°C tapping temperature.
Charge containing 50% Al and 50% Al_2O_3.
0.5 ton (20 ton for industrial furnace) charge per batch.

Advantages of SINTEF Plasma Rotary Furnace Technology

- Low energy consumption
- High aluminium metal recovery
- Low off-gas volume
- Low refractory wear
- No use of salt in processing
- High process flexibility
- Excellent process control
- High degree of automation
- Easy to operate
- Low environmental impact

Conclusions

- SINTEF Materials and Chemistry can performs contract research and development for Norwegian and foreign industry in the field of thermal plasma technology.
- The SINTEF graphite plasma torch is a robust and energy efficient heat source that can be used for many applications in reducing and inert atmosphere.
- The graphite plasma torch have been successfully used in an industrial process for decomposition of hydrocarbons directly into CB and H2, developed together with Kværner.

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