SYNTHESIS REPORT
FOR PUBLICATION

CONTRACT N°: BRE2 - CT92-0263

PROJECT No: BE P5646

TITLE:
“PLASMA TREATMENT FOR TEXTILES: NEW PRODUCTS AND ENVIRONMENT PROTECTION”

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REFERENCE PERIOD FROM 01/02/93 TO 31/01/96

STARTING DATE: 01/02/93 DURATION: 36 MONTHS

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME
Plasma treatment for textiles: new products and environment protection

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Abstract

Textile finishing is a great consumer of water, power and products, and contributes to the pollution of the environment. Decreasing of the effluents emission has to be done, taking into account the difficulties encountered in the European textile industry (competition with developing countries). The obtention of high quality products using a clean process with guarantees of safety for the firm and the customers is necessary.

An alternative to the conventional techniques is given by plasma treatments. A plasma is produced by applying an electrical field in a gas. This forth state of the matter (after solid, liquid and gas) is characterised by a high density of reactive particles (electrons, ions, radicals and metastable molecules) and W-visible radiations. Plasma treatments modify only the surface of materials and all other characteristics are not changed: aspect, touch, mechanical properties,... Many properties of textiles (e.g. adhesion, dyeability, nettability, ...) are more related to the surface layer than to the bulk of the material. Depending on the nature of the excited gas, plasma treatments can induce different modifications of the fibres surface:

- etching for cleaning the surface,
- fictionalization for activation (e.g. nettability, adhesion),
- crosslinking for stabilisation (e.g. solvent resistance),
- radicals creation to initiate a post-grafting,
- polymer deposition to fix a highly crosslinked thin layer.

The methodology used for this study has two phases:
1) In a first step, plasma treatments that could substitute traditional treatments or create new products have been scientifically and technically studied at laboratory scale.
2) Then, the best treatments selected during the first phase, have been tested at industrial scale using the best available plasma machines for tops or fabrics treatment. Treatments in industrial conditions were then used for the evaluation of the impact on the productive cost.

Different fibres were treated by plasma:
- wool (shrink-proofing),
- polyamide (dyeability, flame retardancy),
- cotton and cotton/polyester (antibacterial),
- aramide and polyester (adhesion promotion).

Laboratory scale experiments gave very promising results on all materials and demonstrate the technical interest of plasma treatments applied to textiles. Optimal treatment conditions for each application have been determined.

For treating tops and fabrics at industrial scale, a state of the art on existing plasma machines has shown that the best available equipments are:
- wool tops treatment: LTP5 from the Shanghai Textile Research Institute (China) and the pilot of the Polish Textile Institute of Lodz (Poland),
- fabrics treatment: KPR 180 from NIEKMI (Russia) / TECNOPLASMA (Switzerland).
Industrial scale trials demonstrate the economic interests of such technology for the European textile industry. But, the existing equipments need to be improved and/or rethink for a full integration in the productive line.

I) Introduction

Two main problems are at the origin of this study: competitiveness of European textile industry and environment protection.

1) The difficulties encountered in the European textile industry are mainly caused by the competition of developing countries. European strategy has to be the development of new high-added value products that are able to create new markets.

2) Wet technologies are traditionally used in preparation, colouring and finishing of textiles. Chemical treatments used in the industry need high quantities of water: 330 l/kg of wool and 380 l/kg of cotton produced. Limitation or elimination of water consumption during finishing is economically justified by the continuously increasing costs of supplying water and purifying effluents and by the high energy costs induced by the after treatment’s drying. Other factors, such as environment legislation and safer working conditions, are also explaining the interest of European textile industry in new dry processes. From a legal viewpoint, the pollution generated in Europe by the textile finishing has to be solved in a near future (Ecolabels such as OEKO-TEX 100 and 1 000).

The objectives of this work is to demonstrate, by using plasma equipments at laboratory scale and then at industrial scale, the potentialities and the limits of such processes for the European textile industry.

Properties like shrink-proofing, flame retardancy and adhesion of textile materials are typically obtained by introduction of conventional additives by impregnation, mixing with melt polymer before spinning or impregnation with resin and thermal fixation. All these traditional processes induce pollution, consume a lot of energy, modify the physical properties (touch, aspect, mechanical properties,...) and are limited for production of new materials. Textile industry is looking for soft and non-polluting technologies that could open new markets. Plasma treatments functionalize or polymerise only a thin layer on fibre surface by using excited gases. This dry process gives access to a new chemistry for the obtention of new products.

Plasma technology brings solutions to textile industrial problems:
- suppression of liquid or gaseous effluents,
- decrease of water consumption,
- obtention of new materials,
- improvement of working conditions,
- increase of the competitiveness.
II) **Technical description**

II.A) Materials/ application fields

Depending on the materials, four different properties are expected:
- shrink-resistance (wool),
- flame retardancy (polyamide),
- antibacterial properties (cotton and cotton/polyester),
- adhesion promotion (aramide and polyester).

II.B) Objectives

II.B.1) **Wool**

Wool felting could be described as the ability to irreversible change in dimensions under simultaneous influence of water, heat and mechanical action. The reasons for this phenomenon are the chemical structure of the fibres and the very developed scale structure leading to a preferential movement into the scale direction. In chemical terms, oxidation by chlorine is the preferred method used for traditional shrink-proofing treatment. This technique induces negative changes in other wool properties and generate a lot of AOX.

<table>
<thead>
<tr>
<th>Process step</th>
<th>AOX concentration (mg/l)</th>
<th>AOX percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorination</td>
<td>176</td>
<td>69</td>
</tr>
<tr>
<td>first rinse</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>second rinse</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>sulphite bath</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>rinse</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>softener</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>total</td>
<td>258</td>
<td>100</td>
</tr>
</tbody>
</table>

Plasma treatment of wool has three main goals:
- solution to the environment problems (bring AOX to zero),
- improvement of the product quality,
- improvement of the process productivity and decrease of the process cost.

II.B.2) **Polyamide**

As with other thermoplastic fibres, polyamide has some natural flame retardant properties due to its ability to shrink away from a source of ignition and the fact that the melting of the polymer removes energy from the burning textile material. However, the melting is often accompanied by dripping the molten flaming polymer that can transfer the flame to a second site. The traditional flame retardant finishing of polyamide has had little commercial success due to the poor durability of these finishes during laundering. The use of a back coating technique using antimony oxide - organobromine combinations has shown some success but has found limited commercial use due to toxic effects. The main method of making polyamide
flame retardant is the use of additives to the polymer melt. These include aromatic bromine, cycloaliphatic chlorine and melamine derivatives. According to US, no successful commercial exploitation could be mentioned. For polyamide, the objective is to produce a new material.

II.B.3) Cotton and co#on/polyester

Antibacterial cotton and cotton polyester concern two different markets:
- Hygiene in hospital: bed sheet, pillow, blouses, sanitary masks, . . .
- Comfort (anti odours): underwear, undershirts, socks, . . .

The antibacterial properties are currently given by the impregnation in active solution. This process induce pollution and the washing resistance of the product is low. Plasma treatment is a totally new concept for the obtention of antibacterial property.

II.B.4) Aramide and polyester

Since the sixties, tyre manufacturers tried to replace more and more rayon carcass by polyester or aramide. This goal has primarily been set to produce an equivalently durable tyre with less material. Second reason is that rayon production causes effluent pollution. Third reason is the existence of a monopoly on the cellulose from which rayon is produced. An increasing share of the world tyre market is being taken over by Japanese tyre manufacturers operating primarily from Japan. New ecological process has to be found for using polyester and aramide as rubber reinforcement in Europe. Traditional treatment for adhesion promotion involved two steps which induce a high pollution: epoxy and RFL (resorcinol-formol-latex) coatings. The objectives of plasma treatment are:
- in a first phase, plasma treatment will be designed to enhance nettability of the fibre surface to enable direct reaction with traditional RFL dip (substitution of epoxy coating),
- in a second phase, the plasma development will be oriented towards full substitution of epoxy and RFL coating. The cords should then be able to bond directly to a curable rubber matrix.

II.C) Plasma treatments

According to the properties to be obtained the following ways have been prospected:

\[
\begin{array}{ccc}
\text{natural or synthetic fibres} & \rightarrow & \text{plasma deposition} \\
& \rightarrow & \text{plasma etching} \\
& \rightarrow & \text{functionalization} \\
\end{array}
\]

\[
\begin{array}{ccc}
& \rightarrow & \text{flame retardancy} \\
& \rightarrow & \text{adhesion} \\
& \rightarrow & \text{shrink-resistance} \\
& \rightarrow & \text{adhesion} \\
& \rightarrow & \text{antibacterial}
\end{array}
\]
II.D) Methodology

The methodology used for each couple textile/application field has two phases:

1) In a first step, plasma treatments that could substitute traditional treatments or create new products have been scientifically and technically studied at Laboratory scale.

2) The best treatments selected during the first phase, have been tested at industrial scale using the best available plasma machines for tops or fabrics treatment. Materials treated in industrial conditions were then used for the evaluation of the impact on customers.

III) Results

III.A) Laboratory scale plasma treatments

III.A.1) Shrink-proofing of wool

As most of the chlorination treatments, plasma treatments have been done on wool tops.

III.A.1.a) Chemical changes of the wool surface

Plasma treated wool surface shows a significant increase in oxygen content, as well as a variation in the concentration of other elements presents (S, F?). Carbon and sulphur are oxidised.

Plasma treated wool top was analysed to investigate the homogeneity of the plasma treatment throughout the wool top: fibres were taken outside and inside the top. The homogeneity of the plasma treatment is acceptable.

The increase of the oxygen and nitrogen concentrations onto the surface induces a modification of the surface energy, even after a short exposure time. Treated surface retains its hydrophilicity over at least 6 weeks. Some loss in properties is observed for samples treated for a short duration at low power.

III.A.1.b) Physical changes of the wool surface

Etching of the surface by plasma increases the friction coefficient but no descaling is observed. Fibre/fibre friction coefficient is higher after plasma treatment, whatever the nature of gas used for plasma generation.

SEM analysis of several traditional treatments of wool tops show that chlorination treatments cause considerable surface damage by a smoothing as well as a loosening of the scales. Kroy-Hercosett treatment is the most damaging process and samples showed almost a complete loss of the surface scales. In comparison, surface damage during plasma treatment is negligible.

III.A.1.c) Mechanical properties of single fibres after plasma treatment

For all plasma treatments, diameter and tensile strength of single fibres are not changed. For comparison, chlorination induces a decrease of about 5% of the single fibres tensile strength. Improvements of elongation (+2 to 4% against -15% for traditional treatment) are observed.
III.A.1.d) Colour, softness, roughness and touch tests
These tests were made in a subjective way by 5 people. Results and opinions obtained from these 5 technical people have been similar and uniform. After plasma treatment, good results are obtained for ductility and colour but roughness has to be decreased to keep the natural wool touch of the wool.

III.A.1.e) Variation of weight during and after plasma treatment
Drying phase and vacuum during plasma treatment induce a weight loss of 10%. This weight loss corresponds mainly to water elimination. After moisture regain, plasma treatment induces an increase of 1% of the weight: more water is incorporated in WOOF after plasma treatment (high hydrophilicity). Moisture regain needs 5 hours after plasma treatment to be achieved (12 hours after chlorination/drying treatments).

III.A.1.f) Traditional shrink-proofing treatment of weaved and knitted fabrics
After chemical degradation of the scales, shrinkage of knitted fabrics is quite more important than weaved fabrics (22% to 8% after 5 x 5A). Those results point out the differences existing between a fixed structure (weaved) and a sliding structure (knitted).

III.A.1.g) Plasma treatment for shrink-proofing of wool fabric
After 5 x 5A launderings, chlorination reduce the shrinkage to 14% and plasma treatment to 18%. These values have to be compared with the 40% of shrinkage of untreated samples.

III.A.2) Fire retardant polyamide

III.A.2.a) Plasma functionalization of polyamide
After treatment by Ar or O₂, plasmas, water absorption time is nearly zero. This good nettability comes from the plasma fixation of polar groups. CF₄ plasma treatment of polyamide cause a decrease in hydrophilicity and the time of water absorption increased from 12 seconds to approximately 70 seconds. The polyamide fibres etching after plasma appeared as grooves rather than pits. The flaming characteristics of polyamide (70 to 240 g/m²) are significantly affected by plasma treatments. Plasma treated polyamide 70 g/m² did not ignite, even if the time of flame application is 20 seconds. Samples were seen to melt with the heat of the flame, but no flaming droplets are observed. For heavier fabrics (120 to 240 g/m²), the ignition occurs but, compared to the untreated sample, longer time of flame application is required.
III.2. b) Plasma deposition on polyamide

Different kinds of chemical have been tried: synthesised and commercial products. All of them can be divided into four families: fluorinated monomers, acrylamide derivatives, guanidine salts and phosphate derivatives. From this study, remarks concerning the design of molecule for plasma deposition treatment for flame retardancy can be made:

- carboxylic groups are more efficient than ketone,
- nitrogen and hydroxyl groups give good results,
- for phosphate derivatives, a short alkyl chain between the unsaturated bond and the phosphate group and presence of ammonium improve the performance.

Best results are obtained with butane tetracarboxylic acid and guanidine cyanurate. But, performances obtained after plasma deposition are lower than those obtained after CF₄ plasma treatment.

III.3) Antibacterial cotton and cotton/polyester

III.3a) Antibacterial properties of plasma treated cotton

The antibacterial test used is a qualitative test. A mix of gelatine, bacteria and red dye is put in a petridish. Samples are placed over the gelatine. After 24 hours at 37°C, development of bacteria appears as red spots (colonies of bacteria).

Three types of textile behaviour can be observed:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Petri dish</th>
<th>Bacteria’s colonies</th>
<th>Inhibition zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-antibacterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antibacterial without inhibition zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antibacterial with inhibition zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

On a non-active textile, the sample is covered by red spots. On active textile, there is no red spot on the sample. Sometimes, around the sample, an inhibition zone may be observed, meaning that a diffusion of the active chemical in the gelatine occurred.

Best samples are antibacterial textile without inhibition zone: good activity and good fixation of the antibacterial product.

Before testing, treated and untreated samples are washed one time at 40°C to eliminate chemical additives that could be present. Untreated samples become pink revealing the development of a high quantity of bacteria.
After chlorine plasma treatment, the pink colour is very weak meaning that the bacteria development is highly decreased. No inhibition zone is observed: the antibacterial products (chlorine atoms grafted on polyamide) are well fixed on the textile. Absence of inhibition zone and washing resistance point out that:
- the chlorine plasma treatment is permanent,
- the antibacterial chemicals will not desorb during use (wet skin=> no toxic effect),
- the antibacterial mechanism occurs by contact between bacteria and treated textile.

III.A.4) Adhesion promotion of aramide and polyester cords

For the Laboratory scale experiments, aramide and polyester cords have been plasma treated. Materials used are:
- two polyester cords from Toray and Teijin,
- two aramide cords from Akzo and Dupont de Nemours.

III.A.4a) Chemical and mechanical changes of the aramide and polyester cords

The plasma fixation of polar groups induces a modification of the surface energy. As a good compatibility of fibres with the matrix is in favour of adhesion, surface energy is an important parameter.

The two kinds of PET show different reactivities between plasmas: Teijin PET surface is less modified than the one of Toray PET.

Similar differences are observed for the aramide: Akzo Twaron surface energy is more sensitive to the plasma than the one of Dupont Kevlar.

Polyesters with finish show a chemical composition with a high carbon percentage. After plasma treatment of polyester with finish, the surface composition is closed to theoretical one (degradation and/or oxidation of the finish).

The mechanical performances of polyester and aramide cords are not modified by the plasma treatment.

III.A.4. b) Adhesion of plasma functionalized polyester

Toray PET gives higher adhesion than the Teijin candidate. High adhesion level is reached for short plasma treatment duration: up to 150 °/° compared to Epoxy treated samples.

III.A.4. c) Adhesion of plasma functionalized aramide

Plasma treated Twaron shows high adhesion level whereas Kevlar shows lower and about equal adhesion for plasma treated and control samples (epoxy treated). The different nature of the finish is supposed to be responsible of the lower performance of Kevlar (this has been checked: following paragraph).

III.A.4. d) Influence of the finish

The spin finish causes a substantial difference in the surface chemical composition for both PET and aramide. In both cases the true chemical surface structure is hidden below an oxygen containing surface layer.
Plasmas have a **cleaning action** on the surface: etching of the finish layer and revelation of the polymer structure. The chemical composition of the finish is a very **important** parameter for the adhesion level obtained after plasma treatment.

**IV.E.2.e - Adhesion of plasma deposited samples**

The objective of the plasma deposition is to substitute both epoxy and RFL treatments. Very promising results are obtained on aramide: plasma deposited samples reach the adhesion level of epoxy-RFL treatment. Adhesion level of plasma deposited polyester is lower than its control (epoxy+ RFL).

### 111.13) State of the art on industrial plasma machine for tops and fabrics treatment

The existing industrial plasma machines for tops and fabrics treatments are described below.

#### III.B. 1) Industrial machines for wool tops treatment

<table>
<thead>
<tr>
<th>Country</th>
<th>Inventors or Patent Assignee</th>
<th>Number of patents</th>
<th>Dates of Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland</td>
<td>Witold RAKOWSKI</td>
<td>0</td>
<td>Works for more than 20 years</td>
</tr>
<tr>
<td></td>
<td>(Polish Textile Institute - Lodz)</td>
<td>(lot of publications)</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>Shanghai Textile Research Institute</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>NIEKMI</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>WTZ Baumwollind</td>
<td>1</td>
<td>1978</td>
</tr>
</tbody>
</table>

The best available machines for wool tops treatment are:

- **Origin**: Polish Textile Research Institute (Poland)
  - **Process**: continuous
  - **Plasma pressure**: 1 mbar
  - **Capacity**: 30 kg/h
  - **Top speed**: 1.5 to 20 m/min

- **Origin**: Shanghai Textile Research Institute (China)
  - **Process**: continuous
  - **Plasma pressure**: 1 atmosphere
  - **Capacity**: 20 kg/h
  - **Top speed**: 1 to 15 m/min

These two machines have been used for trials and the tests done have been compared to the two main traditional treatments (Basolan and Kroy-Hercosett).
### III.B.2) Industrial machines for fabrics treatment

<table>
<thead>
<tr>
<th>country</th>
<th>Inventors or Patent Assignee</th>
<th>Number of patents</th>
<th>Dates of Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>Ivanovo Power Research</td>
<td>1</td>
<td>1984</td>
</tr>
<tr>
<td>Russia</td>
<td>Bast. Fibres Industrial Research</td>
<td>1</td>
<td>1991</td>
</tr>
<tr>
<td>Russia</td>
<td>NIEKMI (Tecnoplasma)</td>
<td>4</td>
<td>1992-1993</td>
</tr>
<tr>
<td>Japan</td>
<td>Unitika</td>
<td>14</td>
<td>1988-1993</td>
</tr>
<tr>
<td>Japan</td>
<td>Hitachi</td>
<td>3</td>
<td>1985, 89, 91</td>
</tr>
<tr>
<td>Japan</td>
<td>Toray</td>
<td>5</td>
<td>1984-1987</td>
</tr>
<tr>
<td>Japan</td>
<td>Kuraray</td>
<td>1</td>
<td>1987</td>
</tr>
<tr>
<td>Japan</td>
<td>Kanebo</td>
<td>1</td>
<td>1989</td>
</tr>
<tr>
<td>Korea</td>
<td>11 Sung Machinery Ind. Co</td>
<td>2</td>
<td>1993</td>
</tr>
</tbody>
</table>

The **best** machines for fabrics treatment are:

- **Origin**: Hitachi (Japan)
  - Process: continuous
  - Plasma pressure: 1 mbar
  - Cloth width: 160 cm
  - Machine speed: 0 to 20 m/min

- **Origin**: Unitika - **Sando** Iron Works (Japan)
  - Commercial application: Japanese uniforms
  - Process: batch
  - Plasma pressure: 0.1 to 2 mbar
  - Cloth width: 150 cm
  - Machine speed: 0 to 50 m/min

- **Origin**: Niekmi (Russia) - Tecnoplasma (Switzerland)
  - **Commercial** application: printing of wool in Russia
  - Process: batch
  - Plasma pressure: 1 mbar
  - Cloth width: 100 to 280 cm
  - Machine speed: 8 to 80 m/min

The Hitachi machine is more adapted for films treatment and its efficiency on textiles is very limited (**degassing** and high specific surface of textiles). Unitika equipment is not available to European industry. The best available machine, the KPR 180 from Russia, has been used for **pre-industrial** trials.
III.C) Pre-industrial plasma treatments

III.C.1) Shrink-proofing of wool

Tests done on plasma treated wool have been compared to traditional treatments of wool (Basolan and Kroy-Hercosett treatments). The aim of the Basolan treatment is to obtain the hand washing level.

The two main advantages of the Chinese machine are the working pressure (atmospheric) and a potential low price of an industrial machine. But, the efficiency of these machine is not acceptable for the market trends.

The efficiency of the Polish machine was really higher than the Chinese one. Good results are obtained after plasma treatments done at the Polish Textile Institute:
- very good strength and elongation properties of the fibres,
- for the first time, the regularity of the yarn is very uniform,
- colour absorption is very good,
- the superwash level is reach for fine counts and single twist yarns.

The only result to improve is the touch without affecting the shrink-proofing properties. Other properties are equal or better than traditional treatments (Basolan or Kroy-Hercosett).

III.C.2) Traditional fabrics: polyamide, cotton and cotton/polyester

The Russian machine, the KPR 180, induced very uniform modifications of the fabrics: uniformity on the width and on the length. Gases that can be used in this machine are air, nitrogen and oxygen. Therefore, the only effect that can be obtained at industrial scale on polyamide, cotton and cotton/polyester, is an increase of nettability. But, the main interesting treatments obtained at laboratory scale require the used of other gases. Main important improvements on existing equipment is to allow a larger choice of gases: change of joints, different oil for pumping, . . .

III.C.3) Adhesion promotion of aramide and polyester cords

All the materials treated in different conditions in the KPR 180 have lower performance (close to untreated materials) than the ones treated at laboratory scale (higher performances than traditional treated material). The low efficiency of the KPR 180 for the treatment of technical fabrics comes probably from to points: high quantities of water content in the fibres and insufficient electronic density of the plasma.

Solutions could be:
- resorption of the material by multiple pass in the machine before plasma treatment,
- distribution of the same power on half of the electrodes, this will increase the electronic density.
III.D) Economical aspects of industrial scale plasma treatments

The cost of plasma treatments have been estimated for wool tops and for fabrics using data presented on the top of each tables.

### III.D.1) Tops treatment cost (Polish machine)

<table>
<thead>
<tr>
<th></th>
<th>1 shift</th>
<th>2 shifts</th>
<th>3 shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours/Year</td>
<td>2000</td>
<td>4000</td>
<td>6000</td>
</tr>
<tr>
<td>Depreciation cost (Ecu/1000 kg)</td>
<td>0,326</td>
<td>0,163</td>
<td>0,109</td>
</tr>
<tr>
<td>Electricity: 0,054 Ecu/kW (Ecu/1000 kg)</td>
<td>0,040</td>
<td>0,040</td>
<td>0,040</td>
</tr>
<tr>
<td>Water: 3,33 Ecus/m³ (Ecu/1000 kg)</td>
<td>0,020</td>
<td>0,020</td>
<td>0,020</td>
</tr>
<tr>
<td>Salary: 22 Ecus/h (Ecu/kg)</td>
<td>0,367</td>
<td>0,367</td>
<td>0,367</td>
</tr>
<tr>
<td>Treatment cost with account of water (Ecu/kg)</td>
<td>0,753</td>
<td>0,590</td>
<td>0,536</td>
</tr>
<tr>
<td>Treatment cost without account of water (Ecu/kg)</td>
<td>0,733</td>
<td>0,570</td>
<td>0,516</td>
</tr>
</tbody>
</table>

These values have to be compared to the average chlorination treatment cost: 0,700 Ecu/kg.

For this study, the gas used for plasma generation is air: the cost of purification of air has no incidence on the cost per square meter. Air is an efficient gas for shrink-proofing of wool by plasma treatment.

### III.D.2) Fabrics treatment cost (Russian machine : KPR 180)

<table>
<thead>
<tr>
<th></th>
<th>1 shift</th>
<th>2 shifts</th>
<th>3 shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours/year</td>
<td>2000</td>
<td>4000</td>
<td><strong>6000</strong></td>
</tr>
<tr>
<td>Depreciation cost (Ecus/1000 m)</td>
<td>72</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td>Electricity: 0,054 Ecu/kW (Ecus/1000 m)</td>
<td>2,3</td>
<td>2,3</td>
<td>2,3</td>
</tr>
<tr>
<td>Water: 3,33 Ecus/m³ (Ecus/1000 m)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Salary: 22 Ecus/h (Ecus/1000 m)</td>
<td>29,3</td>
<td>29,3</td>
<td>29,3</td>
</tr>
<tr>
<td>Treatment cost with account of water (Ecus/m²)</td>
<td>0,071</td>
<td>0,048</td>
<td>0,041</td>
</tr>
<tr>
<td>Treatment cost without account of water (Ecus/m²)</td>
<td>0,065</td>
<td>0,042</td>
<td>0,035</td>
</tr>
</tbody>
</table>
These values have to be compared to with the average price of a finishing operation: 0.110 Ecu/m².

The gas used for this economical study of plasma treatment for fabrics is air. Depending on application, other gases may be used. In this hypothesis, the price of the considered gas must be added: from 0.001 Ecu/m² to 0.06 Ecu/m², depending on the gas.

IV) Conclusion

The technical, economic and environmental interests of plasma technology are now obvious for textile industry. But, no adequate plasma machine exist for a large scale production in an industrial environment. Good concepts have been developed during the last ten years (Polish and Russian machines), but European textile industry needs a full automated, reproducible and efficient process. From the work done, keeping the best concepts of the Russian and Polish machines, and improving or changing all the weak points, a development of ready to used industrial plasma machines is now possible.

Acknowledgements

The authors acknowledge the European Commission for the financial and organisational supports under the Brite EuRam Project BRE2 - CT92 -0263.