Some aspects of tyre impact on environment: production, service and recycling**

The natural processes follow their natural course in a balanced manner of cause and effect while the human manufacture of products is ultimately a one-way course i.e. a production-consumption cycle utilising raw materials and energy and, in return, these are replaced with residues, waste products, more or less hazardous effluents.

The modern civilisation, as far as we are able now to forecast, is and will be largely dependent of motorization in transportation and in everyday life and a vehicle provided with its own engine cannot do its work without tyres. Next logical step will be to approach the potential tyre impact on environment. In a common sense, this impact is perceived only in relation with dumps of used tyres but the purpose of present lecture is to call your attention on the entire assembly of interference of tyres with the environment:

• in production (consuming raw materials as well as significant amount of energy based mainly on fossil resources and generating more or less polluted effluents);
• in service (by fuel consumption in rolling associated also with CO₂, CO and NO₂ generation; by noise and debris and gases generation in the abrasion process on road);
• in recycling of used tyres (by retreating, reclaiming, production and use of crumb tyre rubber, generation of steam and/or energy, etc.).

Today, we are far away from fulfilling requirements for a real sustainable development. Neither the genuine recycling approach nor sustainable development is likely in the foreseeable future. Such a step forward, regarding tyre production-service-recycling, undoubtedly requires some fundamentally new ideas and, at the same time, a more responsive approach of the problem within the frame of our society.

Key words: tyre, impact on environment, manufacturing of tyre, exploitation of tyres, recycling of used tyres

Wybrane aspekty wpływu opon na środowisko: produkcja, użytkowanie i recykling

Procesy naturalne zachodzące w przyrodzie znajdują się w stanie równowagi, podczas gdy działalność produkcyjna człowieka zmierza ostatecznie w jednym kierunku, tzn. stanowi cykl produkcji i zużycia, w którym surowce i energia zamieniane są na śmieci, odpady i mniej lub bardziej niebezpieczne ścieki.

Nowoczesna cywilizacja, tak daleko, jak można to przewidzieć, jest i będzie w znacznym stopniu zależna od motoryzacji, tak w transporcie, jak i w życiu codziennym, a pojazdy silnikowe nie będą mogły spełniać swojego zadania bez opon. Logiczną konsekwencją tego powinno być określenie potencjalnego wpływu opon na środowisko. Ogólnie rzecz ujmując, wpływ ten został dostarczony tylko w przypadku składowisk zużytych opon, jednak celem niniejszego artykułu jest zwrócenie uwagi na złożony zespół interferencji opon ze środowiskiem:

• podczas produkcji (zużycie surowców oraz znaczny wydatek energii pochodzącej przeważnie z zasobów mineralnych i związane z nim mniejsze lub większe zanieczyszczenie środowiska),

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* Tofan Grup S.A., Bucharest, Romania
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1. Introduction

The modern civilisation in its last essence consists in the manufacture and use of artefacts. They make, to a certain extent, the man of present days independent of his natural environment, ease his physical effort, enhance his health, security and welfare. In fact, human beings have developed their own artificial world which coexists and interferes with the nature. The processes of the nature follow their natural course in a balanced manner of cause and effect while the human manufacture of products is ultimately an one-way course. In its most general aspect a production-consumption cycle utilises raw materials and energy and, in return, these are replaced with residues, waste products, more or less hazardous effluents.

Our environment is close to reach the point of being unable of recovering unaided from the localised and more diffuse attacks the human society make on it. A responsible judgement should eliminate the throwaway approach achieving a sustainable development, sparing the exhaustible resources and recovering, recycling as more as possible of consumed material and/or energy [1-3].

Now, looking more closely to the production-consumption cycle of tyres (Figure 1) we have to distinguish the area of the production of raw materials (rubbers, fillers, textile cord, steel cord, chemicals etc.) which has features in common with other industries including their ways of impact on the environment. Starting with tyre manufacture we enter the area of the specific interaction with this indispensable product of the modern life.

2. Tyre manufacture

The examination of the individual phases of the life cycle starts logically with tyre production. An input/output model (Figure 2) looks quite general and specific features appear discussing each category.

Saving of raw materials is a first economic requirement for reducing cost but we remember that many raw materials in tyre manufacture are from non-renewable sources we are in position to observe that we are miles away from fulfilling the fundamental requirement: non-renewable resources may only be used for the creation of renewable resources. Sparing of raw materials is a problem of everyday management and, at the same time, it is a challenge for technicians aiming for:

- reducing the tyre weight;
- using more recycled materials;
- reducing scrap and waste.

Energy saving means reducing CO₂ emission but it cut processing cost as it is commonly welcomed. There are two distinct categories of problems in connection with technology and with machinery/equipment which interact mutually.

The technological approach is focused in two area which are big energy consumers: mixing and curing. Energy efficient equipment, computer-enhanced processing procedures, elimination and/or recycling of waste heat can energy savings of 20-30%. R&D is expected to increase these savings by optimisation of the production (mixing, curing) cycles, using mixers and mills with variable speed drives (VSD), extending the use of rheomodifiers in compound formulations, introducing modern accelerator+activator groups [4] etc.).

Monitoring and targeting only of the energy use for curing, according to the UK Energy Efficiency Office [5], can reduce energy consumption by 10-15%.

Another direction for sparing energy includes: sound design of machinery, equipment and the layout of the factory as a whole, good practice in machinery/equipment operation and maintenance. Only few examples are quoted here [3,6]:

- use of VSD for mixers and mills but also for cooling fans, delivery pumps and so on;
- design the system to give consistent flow rate and appropriate inlet temperature;
- use chilled water systems/heat pumps as a last resort for refrigeration they should be used for warming rooms;
- make use of heat from elsewhere in the plant.

Table 1 [2] presents for illustration the nature and size of the impact on the environment associated with the production of a typical passenger car tyre. There are rather small amounts of pollutants but multiplication by the huge number of tyres produced world-wide allow to observe the real impact on the environment.
Fig. 1. Production – consumption cycle of tyres

Fig. 2. The input/output model of the tyre manufacturing plant
Table 1. Impact on the environment associated with manufacture of a typical passenger car tyre*

<table>
<thead>
<tr>
<th>Material consumption</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural rubber</td>
<td>1.165</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>1.553</td>
</tr>
<tr>
<td>Active fillers</td>
<td>1.618</td>
</tr>
<tr>
<td>Oils (plasticizers)</td>
<td>0.518</td>
</tr>
<tr>
<td>Chemicals</td>
<td>0.582</td>
</tr>
<tr>
<td>Steel</td>
<td>0.776</td>
</tr>
<tr>
<td>Rayon</td>
<td>0.226</td>
</tr>
<tr>
<td>Polyamide</td>
<td>0.032</td>
</tr>
<tr>
<td></td>
<td>6.670</td>
</tr>
</tbody>
</table>

2. Energy consumption

<table>
<thead>
<tr>
<th>Energy source</th>
<th>MJ/kg (tyre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal energy</td>
<td>5.815</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>3.771</td>
</tr>
<tr>
<td>Total</td>
<td>9.586</td>
</tr>
</tbody>
</table>

3. Emission to the atmosphere during tyre production

<table>
<thead>
<tr>
<th>Emission</th>
<th>g/kg tyre</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>0.00**</td>
</tr>
<tr>
<td>NOₓ</td>
<td>48</td>
</tr>
<tr>
<td>CO</td>
<td>0.06</td>
</tr>
<tr>
<td>CO₂</td>
<td>429</td>
</tr>
<tr>
<td>Total organic carbon</td>
<td>0.50</td>
</tr>
<tr>
<td>Dust</td>
<td>0.08</td>
</tr>
</tbody>
</table>

4. Emissions to water during tyre production

<table>
<thead>
<tr>
<th>Emission</th>
<th>l/kg tyre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of cooling water</td>
<td>20</td>
</tr>
<tr>
<td>Temperature</td>
<td>-30 °C</td>
</tr>
<tr>
<td>PH value</td>
<td>7.8</td>
</tr>
<tr>
<td>COD</td>
<td>~20 mg/l</td>
</tr>
</tbody>
</table>

5. Waste volumes

<table>
<thead>
<tr>
<th>Waste type</th>
<th>g/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>General refuse</td>
<td>76</td>
</tr>
<tr>
<td>Miscellaneous waste</td>
<td>47</td>
</tr>
<tr>
<td>Hazardous waste (solid waste, chemicals, liquid waste solvents, mineral oils, sludges)</td>
<td>5</td>
</tr>
<tr>
<td>Rubber waste</td>
<td>29</td>
</tr>
<tr>
<td>**Total</td>
<td>157</td>
</tr>
</tbody>
</table>

* Passenger car tyre 175/70 R 13 CT 22
** Steam and energy generated in gas power station

To be more specific some peculiar aspects will be shown later on. Traditionally, rubber manufacture is associated with a dusty-black environment.

The are several kinds of submicron particulate matter including carbon black, silica and other mineral fillers. Decreasing the dust emission in factory and in surrounding area can include: good equipment and good practice in material handling (in storehouse but also in transporting, weighing and mixer supplying systems), dust recovery with high efficiently systems, modern forms of powders (e.g. microgranules, dust suppression pre-blends etc.). Many interesting approaches already exist in this area, but the cost factor is frequently prohibitive; however, it is expected, that new technical solutions decreasing the production costs of pre-blends will become attractive in near future. VOCs can be emitted during rubber processing and curing but their concentration in air is usually very low and generally not exceed the accepted limit (10 mg C/m³).

The situation is dissimilar if solvents are used in some processes, and problems arise for tyre factories. The EC environmental solvent directive may yet put severe restrictions on industrial practices that means now it is a good time to be prepared for the diminution and hopefully elimination of solvents in many adhesives and other liquids used in tyre manufacture. R&D efforts are indeed focused on two directions: moving to water-based adhesives and/or improving the formulation, processing and practice in producing and manipulation of the semifinished products in order to ensure enough tackiness without application of solvents or adhesive.

During last years a special attention was paid to aromatic mineral oils used as plasticizers [7,8]. Based on long-term experiments on animals, several petroleum extracts are classified (and labelled) as carcinogenic. CONCAWE, the Health and Safety organisation of the European mineral oil industry proposed to classify mineral oil products according to IP 346-method (based on DMSO extraction); if the DMSO extract exceeds 3%, the product has to be labelled. It is very probably that EU legislation will incorporate this proposal.

In fact, any classification of the aromatic plasticizers should be done according to their content of PAH but experimental data reveal [9] that DMSO extract has nothing to do with the real PAH content: e.g., for a typical aromatic process oil the DMSO extract was about 20% while the sum of the individual PAHs was 0.03%. However, based on results on laboratory animals (skin cancer of mice was produced with mineral oil application) it is obvious that skin contact to the aromatic process oil has to be avoided by appropriate protection equipment and automatic dosage of this plasticizer. Now, focusing the attention on oil-containing rubber blends, the results of extraction tests (carried out with artificial sweat), the PAHs in rubber blends are not bioavailable [10] and relevant epidemiology results indicate no excess of skin cancer in rubber workers. As far as airborne concentration are concerned, the amounts of total PAHs are under the limits given by legislation of various countries.

Curing fumes represent another object of concern for long time ago and many investigations have been done in laboratories and at workplace (e.g.[11-13]). RAPRA has developed a fume data base to enable rationalisation and control of rubber fume [14]. Tests cou-
ucted by Aarts and Davies [15] revealed that weight loss of typical rubber compounds during vulcanisation is of the order of 5 g/kg, containing maximum 10 per cent of organic materials. In spite of the great effort done up to present it is obviously that analytical techniques still need further improvement in an attempt to know the hazardous substances present in curing fume and to help in their elimination.

Nitrosamines are known as carcinogenic for rather long time ago; probably the first hint of a toxic problem with nitrosamines came with two severe cases of liver damage in workers on a pilot plant in UK. Since then, much toxicological work has been done and is still in progress: of some 300 N-nitroso compounds tested, over 90 per cent have been shown to be carcinogenic. Nitrosamines may be formed in the tyre industry. Great efforts have been made in tyre industry worldwide to decrease airborne nitrosamine concentrations at workplaces by replacing nitrosamine forming accelerators and by better ventilation and other technical and organisational measures. A comprehensive overview (even it is concerned with German rubber industry) was given by WdK [16]. Means of reduction of nitrosamines in tyre industry suppose a systematic R&D effort and a cooperation of the producers of rubber chemicals with the users bearing in mind the ways known till present [17-21]:

- replace the short chain dithiocarbamates and thiurams with their long chain homologs;
- use of synergistic mixtures of conventional accelerators in order to diminish the quantities of each to be employed;
- use of inhibitors (ascorbic acid, α-tocopherol) to brake nitrosamine formation;
- use of alternative, nitrogen-free cure accelerators (phosphorus-based, xantogen-type);
- use alternative curing systems, sulphur-free; in association with a good ventilation of the workplace and stock-room areas.

There are sundry ways of encountering hazardous substances in tyre production for a rather recent overview the reader can consult [22] an only some prominent examples have been discussed here. In industrial practice every employer is required to determine whether employees are exposed to hazardous materials in workplace and he must verify that the maximum tolerance limits are being adhered to and, if necessary, ascertain what technical and/or organisational protective measures must be taken in accordance with respective national statutes.

3. Tyre in service

Tyres are rather expensive products: in cost for car exploitation, tyres come just after fuel. On another hand, like all rubber goods, they are not easily recyclable and there are serious ecological problems with waste management. Prolongation of service life reduces the amount of used products left for disposal. Redesigning tyres to use less material and running for higher mileage without sacrificing other specific requirement like road grip and skid resistance, for safety and fuel economy became, the co-ordinates for developing the philosophy of tyre industry nowadays.

In spite to the fact that tyre is present everyday and everywhere, the lay public is always surprised to learn how great an impact the use of a tires has on the environment, compared with its manufacture and disposal. Figure 3 [2] shows that the most significant effect comes from the amount of energy consume just to overcome the tyre rolling loss. By comparison, the energy incorporated (as raw materials and manufacture) in a new tyre is around ten times lower while the amount of energy which can be recovered by combustion is under one third of this last. Starting from the above presented data it is comprehensible the major concern of the tyre manufacturers in improving performances and durability of tyres that means reducing rolling loss, reducing abrasion loss, reducing noise generation, etc. Rolling loss is the result of the energy dissipated by tyre itself in service leading to supplemental fuel consumption of the vehicle. Tyre rolling loss is influenced by many factors [23]: tyre size, tyre construction, tread pattern, tyre material structure, road texture and roughness, temperature, etc.

Rys. 3. Energy balance for a typical passenger car tyre (tyre weight – 8 kg; car fuel consumption 10 litres for 100 km): (a) material and manufacture; (b) fuel consumption to overcome rolling resistance over a distance of 50,000 km; (c) energy production; (d) material and manufacture for retreading.

All major tyre producers are very active in introducing fuel saving “green tyres” through the auto manufacturers as original equipment tyres on new vehicles in EU as well as in USA; they have also lobbying the governments to pass legislation requiring labelling of tyres according to their fuel economy. Vehicle manufacturers as well as tyre manufacturers are realising that “eco-tyre” is set to become the norm for the next future [24]. The estimated effect of switching all tyres to the new “green tyres” (replacing standard tyres) is pre-
sented in Table 2 (adapted from [25]). The potential savings of fuel and the reduction in carbon dioxide (claimed by tyre manufacturers are very large numbers: compared to the total consumption of fuels world-wide, it is a small but significant change toward improving the future environment. The substantial R&D effort in reducing tyre rolling loss resulted in many scientific papers and patents from which only few, more recent examples are quoted here: for improvement of tyre tread compounds using silica/silane filler [25-27] and/or use of new types of polybutadienes and solution-SBR [28], improvement of dynamic characteristics by adjustment of compound morphology [29], laboratory assessment of the dynamic characteristics in correlation with service performance of the tyre [30, 31, 32].

Table 2. Potential annual effects from switch to "green" tyres

<table>
<thead>
<tr>
<th></th>
<th>Fuel savings, million fitters</th>
<th>Reduction of CO\textsubscript{2} emission, million kilograms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>6 600</td>
<td>16 100</td>
</tr>
<tr>
<td>Trucks</td>
<td>1 500</td>
<td>4 000</td>
</tr>
<tr>
<td>Total</td>
<td>8 100</td>
<td>20 100</td>
</tr>
<tr>
<td>World-wide</td>
<td>32 000</td>
<td>81 000</td>
</tr>
</tbody>
</table>

For agricultural tyres, fuel consumption and traction force are also important economical and ecological characteristics which have been improved introducing radial construction for this family of tyres. For this special case a specific requirement is important too – tyre pressure on the ground. Figure 4 – extra illustrates new agricultural/implement tyres applies less pressure on the soil, with more superficial action in modification of the biosystem and less compaction.

Noise generation by tyre in service is another aggression on the environment as well as on the vehicle user (driver and accompanying persons).

Analyzing tyre contribution to vehicle noise generation we must remember the mechanism through which the tyre is able to generate vibration (Figure 5) tyre as a source of vibrations (mainly due to presence of blocks and grooves on the tyre external surface), and tyre as a filtering item able of transmitting as low an amount of vibration generated by contact with road surface irregularities. The vibrations to be taken in consideration are in the domain 30 – 60 Hz mainly responsible for tactile comfort and the domain 80 – 90 Hz the most important one from acoustic point of view; either resonance exists in the range of kHz. Considering now the whole vehicle-tyre system, two main areas must be taken into account: the noise perceived by the passenger inside the vehicle and the noise generated around the vehicle, external noise, in which the tyre plays an important role (together with other traditional noise sources – mainly engine) because it is relevant in the total acoustic emission but also because of the changes in regulatory area [33].

The increase in vehicle circulation in urban areas and on highways and the growing demand for a better
quality of life are pushing EU and USA legislators to introduce very tight limits to the total level of noise generated by the vehicles.

Table 3. Emission of materials by tyre in service

<table>
<thead>
<tr>
<th>Materials</th>
<th>Quantity per one passenger car tyre, per km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles 30-70 μm</td>
<td>15-20 mg</td>
</tr>
<tr>
<td>Particles remaining in suspension &lt; 30 μm</td>
<td>0,25-1,25 mg</td>
</tr>
<tr>
<td>Gases (CO, CO₂, CS₂, COS, SO₂, hydrocarbons)</td>
<td>0,25-1,25 mg</td>
</tr>
</tbody>
</table>

The fact that rubber compound is worn away from the tyre surface during the service is obvious and is rather easy to quantify. The emission of the tyre on road can be classified as presented in Table 3 [2] with p. 8. If we take as an illustration that the amount of debris generated in surroundings is 75 kt/year in Germany and 6 – 10 kt/year in Sweden it is obvious that concern for this polluting source is by far not negligible [32-34]. Various studies have shown [2] that biological (bacteria and fungi) and chemical (oxygen, ozone, enhanced by light) decomposition take place with a rate of 0.7% a day (in California area) or a half-life of 16 month (resulting in laboratory simulations). The content of inorganic substances, with special mention for Zn, (which can be deduced starting from its average content in rubber compounds) as well as for Cd and Pb (present along by Zn in a ratio of 1/1000) is presumed to end up in the ground and their influence on the balance of the microelements contained in soil remains to be investigated.

4. Recycling/recovering and disposal

Displacing our attention in the post-consume area of the tyre life, we have to pay first attention to the retreading which means indeed reusing the tyre casing after its first use and vulcanising on a new tread. That is an actual recycling, with all advantages of a circuit system designed to keep the product in service for as long as possible. Retreading industry has a tradition comparable with the tyre industry itself and now there are two well developed technologies: hot-cure and cold-cure (Figure 6). Every technology has advantages and disadvantages [35] and also specific features exist under ecological aspect [36]. It is important that special care be exercised, particularly having in view that tyre and carcass parameters vary from one manufacturer to another as well as the exploitation circumstances during first life of the tyre. Only retreaded tyres optimised for the dimensions [37], for durability and rolling loss may be designate as “ecologically compatible”.

For the developed countries, the proportion of the tyres recycled by retreading, are situated close to the
percentages presented in Figure 8: the portion of retreaded truck tyres is in line with technical viability while the amount of car tyres could be expanded significantly from purely technical view, customer acceptance playing a major role here.

Rys. 7. Share of retreads in the tyre replacement market of developed countries

Implementation of modern retreading technologies associated with appropriate quality assurance systems [37a] should lead to a significant reappraisal of retread tyre’s image.

It is important to observe that retreading, in comparison with other recycling ways, is most attractive having a sound margin of profit. Its future depends on ability in adaptation to new vehicles and handling characteristics by short development cycles in order to obtain market acceptance supported by service life and money saving. For the next century it appears an enhanced tendency [38]: a partnership of big tyre producers with professional tyre retreaders.

In the domain of recycling/recovering, a sound policy of waste management make optimum use of materials, and to endeavour to obtain maximum environmental benefit. In array of decreasing efficiency, a four-level strategy can be represented as follows:

- use less material in the product/increase service life of the product;
- recycle waste where possible;
- recover energy where waste cannot be recycled;
- dispose of waste by the best environment-friendly option.

Concern for recycling/recovering of used tyres is for long time ago and only some reviews published in last decades are quoted here [39-47] dedicated to tyre or tyre/rubber good problem or in a large connection with used car disassembling/recycling/recovering [48]. Figure 8 presents the main ways of tyre recycle recovering.

Energy generation based on rubber waste (Table 4) has its roots in the simple observation that 1 kg used tyre (with/without steel cord) can generate 9.5/8.3 kWh while 1 kg coal generates ca 8.5 kWh. In spite to the fact recovered energy is less than a third of the energy consumed with materials and manufacture of the tyre energy recovery from rubber waste is considered a valid option, where other recovery methods are not useful for economic and/or ecological reasons. Compliance with existing EU legislation confirms that fuel treatment technology used in modern energy recovery (for electric energy, for steam or for co-generation) are consistently safe, even for products containing halogenated rubbers.

Another energy recovery option is cement manufacture where part of the energy needed could be sup-
Table 4. Energy recovery from waste tyres

<table>
<thead>
<tr>
<th>Input material(s)</th>
<th>Combustion in power stations</th>
<th>HT combustion with preliminary pyrolysis</th>
<th>Combustion in cement kilns</th>
<th>Garbage incineration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tyres</td>
<td>Fluid</td>
<td>Household garbage, scrap tyres</td>
<td>Scrap tyres, TDF, crumb rubber</td>
</tr>
<tr>
<td>Products</td>
<td>Steam and/or electric power</td>
<td>Steam and/or electric power</td>
<td>Cement</td>
<td>Steam and/or electric power</td>
</tr>
<tr>
<td>Thermal efficiency, %</td>
<td>84</td>
<td>92</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>Specific emissions, kg per ton of input material</td>
<td>8-19</td>
<td>15-16</td>
<td>4-5</td>
<td>1-1.5</td>
</tr>
</tbody>
</table>

Table 5. Thermochemical processes for recovering of used tyres

<table>
<thead>
<tr>
<th>Input material</th>
<th>Pyrolysis</th>
<th>Gasification</th>
<th>Gasification with preliminary stage</th>
<th>Hydrogenation with preliminary stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed fraction with ca. 20% scrap tyre</td>
<td>Pyrolysis</td>
<td>Depolymerization</td>
<td>Pyrolysis</td>
<td>Depolymerization</td>
</tr>
<tr>
<td>Lignite briquettes with 20% scrap rubber</td>
<td>Scrap tyres</td>
<td>TDF Base oil</td>
<td>Scrap tyres</td>
<td>TDF</td>
</tr>
<tr>
<td>Products</td>
<td>Pyrolysis gas, pyrolysis oil</td>
<td>Synthesis gas, sulfur, (steam) (HCL)</td>
<td>Syncrude (HCL)</td>
<td></td>
</tr>
<tr>
<td>Thermal efficiency, %</td>
<td>70</td>
<td>76</td>
<td>77</td>
<td>84</td>
</tr>
<tr>
<td>Specific emission, kg per ton of input material</td>
<td>1-2</td>
<td>&lt; 1</td>
<td>2-3</td>
<td>1-3</td>
</tr>
</tbody>
</table>

For reprocessing oriented to material recycling, and for some processes of energy (co)generation too, waste tyres should be previously shredded, chopped, separated from foreign materials (textiles, steel wires) and, eventually ground. The equipment for shredding and fragmentation was extensively developed during past decades [56] and chopped tyres became a standard commodity on American market as TDF (Tire Derived Fuel) or as a starting material for production of rubber powders in various finesse.

Grinding can be realised at room temperature [57-60] or at low temperatures [61-65], using liquid nitrogen as refrigerating agent and working media. A good review, even it is not a very good one, was published by Solovev [66] and comparisons of grinding at low temperature against grinding at room temperature were published more recently [67,68]. Special methods realise very fine fragmentation in liquid media with/without addition of chemical reagents and in this field an important contribution have Zachesova and co-workers (a review on the subject was published [69]). The particles resulting in a grinding process are characterized by their average diameter and distribution of diameters but the usefulness of the obtained rubber powder depends also on the form of particles and of topography/topo-
rubber crumbs and their coatings form a homogeneous system;
- the process can be applied to all rubbers;
- the manufacturing process is not environmentally detrimental;
- obtained treated crumb rubber can be added in increased amounts in virgin stocks without undesired influence and offering incentive cost saving.

The use of recovered tyres scrap in civil engineering is also presented in Table 6: liners, mats for high wear areas, roofing tiles and many other find application in private houses, livestock stalls, isolation of irrigation canals etc. [67,83-86].
Nevertheless, the huge amount of the waste tyres cannot be used by tyre and rubber industry, neither the other applications presented up to now; other users will have to play a part and between them, rubberized asphalt in road building is a potential major user because the addition of crumb rubber (by an appropriate technology) in asphalt mixtures offers the following advantages [87,88]:

- increased resistance at high and low temperatures;
- improved aging resistance;
- resistance to cracking;
- higher wear resistance;
- higher elasticity;
- decrease of permanent deformations;
- reduction of the vibration induced by vehicle circulation;
- increase of service-life of asphalt covering;
- decrease of maintenance cost.

The use of ground rubber in rubber modified asphalt is well known in Europe and USA. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required states to begin using prescribed quantities of rubber modified asphalt in federally assisted highways promising a potential market demand of 80 million scrap tyres by 1997. Never funded, the law did not fulfill its potential but it did forced states to act fast and helped launch a significant crumb rubber infrastructure of companies which are driving market today [89,90]. In parallel, investigations are conducted different companies in many countries [91-94] enhancing the progress toward higher performances at lower costs.

Reclaiming is a rather old industry working in tight connection with tyre and rubber manufacture as user of scrap and waste and as supplier reclaim, improperly named sometimes “devulcanized rubber”. The progress in reclaiming and reclaim use was reviewed recently [95] but during last decade this approach is more reconsidered as a viable alternative in recycling and environment protection [96,97]. Consumption of the reclaim suffered a dramatic decline after ‘60s for two main reasons: decrease of the price of virgin rubbers and low performances of the reclaim-containing vulcanizates. Both these lead to the observation that technologies in use are obsolete for production cost as well as for product performance. It become obvious that it is a lack of the technology and non-classical ways were approached; by association of fine milling with chemical reclaiming in a liquid medium (a review of the subject [69]), biochemical splitting of sulfur bridges in vulcanizates [74], microwave conversion of scrap tyres [98] and, during last years, an enhanced attention is paid to the utilization of ultrasonic waves in devulcanization [99-102]. Another promising approach is based on De-Link reactant which, according to the inventors [103], uncouples the polysulfide bonds; the recommended process is very simple, just to put ground tyre rubber with the reagent De-Link on the mill and mix for 10-15 minutes the obtained devulcanized product looks like a rubber compound and is processible and can be re-vulcanised without the addition of any curative. Association of thermal and mechanochemical action is a possible approach able to offer a general solution for recycling waste vulcanised rubber [104].

### Table 7. U.S. Market demand of scrap tyres (millions of tyres)

<table>
<thead>
<tr>
<th>Market segment</th>
<th>1996*</th>
<th>1998*</th>
<th>2002**</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDF (Tyre Derived Fuel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cement kilns</td>
<td>45.5</td>
<td>58</td>
<td>68</td>
</tr>
<tr>
<td>pulp &amp; paper mills</td>
<td>35.0</td>
<td>39</td>
<td>44</td>
</tr>
<tr>
<td>utility boilers</td>
<td>29.5</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>dedicated tyre to energy</td>
<td>15.0</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>industrial boilers</td>
<td>20.5</td>
<td>25</td>
<td>31</td>
</tr>
<tr>
<td>Resource recovery facilities</td>
<td>6.0</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Lime kilns</td>
<td>1.0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Copper smelters</td>
<td>0.0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Iron cupola foundries</td>
<td>0.0</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total Fuel</strong></td>
<td>152.5</td>
<td>186</td>
<td>222</td>
</tr>
<tr>
<td>Products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>size-reduced rubber</td>
<td>12.5</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>fabricated products</td>
<td>8.0</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Civil engineering</td>
<td>10.0</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>0</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Agricultural</td>
<td>2.5</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>Export</td>
<td>15.0</td>
<td>15.0</td>
<td>10</td>
</tr>
<tr>
<td>Miscellaneous uses</td>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td><strong>Gros Total</strong></td>
<td>202</td>
<td>249</td>
<td>288</td>
</tr>
<tr>
<td>Annual generation of scrap tyres</td>
<td>286</td>
<td>275</td>
<td>313</td>
</tr>
<tr>
<td>Scrap tyre markets as % of total generation</td>
<td>76</td>
<td>90</td>
<td>92</td>
</tr>
</tbody>
</table>

* STMC data
** Estimation

Many other utilisations of scrap tyres (without sectioning) were presented in papers, patents and commercial literature, including construction of reefs and floating reefs, floating breakwaters, resilient protectors on highways, soil stability enhancement and others.

The Scrap Tyre Management Council, USA (STMC) periodically publishes a review of scrap tyre use and disposal and Table 7 [105] shows that utilisation for energy generation represents the major market for scrap tyres (ca.75%) and total market demand was reached in 1998 that means ca.90% of annual generation, while for current year the expectation is for about 92%. Concerning the quantity of used tyres resulting each year, USA represents ca.40% and EU represents 28.5% of the world total. The recycling and recovering
ratio is the highest in USA, followed by EU. At the same time, in USA there are currently one billion used tyres in stockpiles, either legal or illegal. Waste tyres at landfills, because of their size and shape, took up a disproportionate amount of space relative to their weight. Addition of waste tyres to stockpiles is an expedient and health and environmental problems associated with waste tyres stockpiling arrive with our everyday news. Tyre fires burning weeks and month became serious concern, and disease problems associated with waste tyres stockpiling arrive with our every day. Waste tyres recycling is a business with tight margins and companies entering into this arena need to have a firm market for their products; at the same time they need to produce consistently good materials/products in order to maintain and increase their market share. Obviously, the main raw materials - scrap tyres - are abundant and a source of an environmental headache; as long as this situation continues, tipping fees will encourage investment and involvement in the business. With more and more companies designing and installing manufacturing plants dedicated to waste tyre processing, the demand for scrap tyres increases, this places pressure on their availability and also upon tip fee structure as they slide to a point where the companies will pay for waste tyres. It is rather difficult forecasting the period of existence of tipping fees, but it is quite clear that, in the countries not applying such fees, the problem of scrap tyres remains unsolved and it exercises an increasing pressure on the environment [106, 107]. At the same time, a good management of waste tyres should be associated with technical development in an attempt to approach a total recyclability of tyre derived materials [108].

In this connection, the legislation of various states has direct influence: at present in, USA, 48 states have some form of scrap tyre regulations, either through specialised scrap tyre legislation, or through regulations adopted under broad solid waste laws. The European legislation is considered “soft” and a substantial improvement is expected either by generalization of tipping fees [105] or by other facilities offered to the companies dedicating to scrap tyres recycling. The EC recommendations are very pertinent in this respect:

- an agreement will be made between Commission and tyre manufacturers obliging manufacturers to continue to increase tyre life and to guarantee that tyres are produced with retreating in mind;
- action will be taken to ensure that drivers treat their tyre properly;
- member states’ governments will have to ensure close to 100% collection of used tyres;
- retreads will have to be ISO 9000 certified and common standards will be introduced;
- use of retreads will be promoted;
- standards for granulating plants will be set up;
- research into new uses of rubber powder will be promoted;
- use of tyres as fuel will be promoted as long as it does not restrict supply of waste tyres for crumbing;
- use of tyres in landfill will be banned from 1998.

The implementation of the above presented recommendations is expected to contribute substantially to the accomplishment of the EC programme and in reaching of the targets proposed for the end of the century [109 – 112]:

**EC scrap tyre programme**

The programme needs to deal with:

- 2000 kt of tyres currently;
- 2500 kt by the year 2000;
- Currently:
  - 23% are retreated,
  - 30% are recycled,
  - 46% disposed off

**Objectives by 2000**

- To reduce the amount produced by 10%, to 2300 kt
- To increase retreading to 25-30%
- To increase recycling to 60%
- Hence to reduce disposal to zero

... and beyond

- After 2006, whole and shredded tyre disposal will be banned
- A rapidly evolving market for recycled materials requires implementation of appropriate standards/specifications.

More recently, remembering that the tyre is a part of the automobile, it seems quite appropriate to approach the problem of waste tyres in connection with disassembling of used vehicles [108-110].

5. About next future

Technological breakthroughs in the recycling of waste tyres (as surface modified crumb, as reclaim) are pushing growth in existing and new applications. The automotive industry publicly announced its commitment to using recycled rubber in automotive products and they teamed up with Michelin Co. to continue research increasing the use of recycled rubber in new modern tyres [82, 90, 111]. But, thinking about the tyres for the beginning century, we have to think also about the car of the future [48, 109].

Today, we are far away from fulfilling the requirements for a real sustainable development. Neither a genuine recycling approach nor sustainable development is likely in the foreseeable future. Such a transformation undoubtedly requires a few fundamentally new ideas and some fundamental changes within the frame of our society. Nowadays one cannot imagine that will be making tyres much different in principle to what we do now, i.e. from rubber, carbon black, chemicals, textiles and steel. And so, the subject of present paper was not to speculate on the distant future but to show what we can already do now, in the next future. In line with such an approach we are in position to make some assertion:
• tyre service life and rolling loss will be improved step by step;
• retreating will develop improving the performance/cost ratio;
• waste tyre recovery will find a good way via TDF and use in cement kilns;
• use of rubber fine powder will increase due to implementation of new grades and of new surfaced treated sorts;
• reclaiming technology is expected to realise a significant progress to be in position to offer reclaim grades usable in modern radial tyres;
• professional and ecological education of vehicle owners and drivers is expected to improve tyre service life.

These developments associated with the extension of total quality management to the environment and safety systems seems a good way to a better future.

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111. Xxx, Neue Reifenzeitung, No.1 (2001), p.62
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Appendix – some additional sources of information

XXX
Rubber Recycling (A Bibliography periodically updated),
Compiled by Joan C. Long
XXX (Malcolm Pirnie, Inc)
Air Emissions Associated with the Combustion of Scrap Tires for Energy Recovery
XXX
Tires as a Fuel Supplement: Feasibility Study
XXX (STMC)
Scrap Tire Market Development Conference, Dallas, TX
XXX (Office of Engineering / Office of Technology Applications)
State of the Practice – Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier
XXX (EPA & DOT)
Engineering and Environmental Aspects of Recycled Materials for Highway Construction – Final Report
XXX
Proceedings of Scrap Tire 94 – Scrap Tire Business Development Conference, Tacoma, Washington
XXX (Texas Transportation Institute)
XXX
Scrap Tire Use / Disposal Study
1996 Update
XXX (EPA)
Illegal Dumping Prevention Guidebook, EPA 905-B-97-001
XXX
Recycled Rubber. STMC Products Catalog