THE INTRODUCTION OF ENVIRONMENTALLY FRIENDLY INSULATION SYSTEMS FOR MEDIUM VOLTAGE APPLICATIONS

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Abstract

This is the first in a series of articles. It describes the initial methods and techniques used in order to introduce alternative dielectric materials into electrical equipment. A circuit breaker has been used as a demonstrator to define the design performance requirements and develop the procedures of material selection while the environmental characterisation has been performed using an Eco-design tool known as the Environmental Information Management Explorer (EIME) software system. Material selection has been principally based upon their ability to reduce their impact on the environment during their full life cycle and yet maintain both their technical and commercial performance.

Keywords

Electrical Insulation, Environment, Eco-design, Circuit breaker, tie rod, bushing, AREVA T&D SDR (Switch Disconnector Railway)

1. INTRODUCTION

During the past 20 years there has been a general acceptance by the industrial nations of the world that the depletion of natural resources has important environmental, economic and political implications. Legislation has become more prohibitive and as a result many governments have introduced policies to encourage sustainable economic and social development within their societies. Many companies are now trying to address these issues, not only to reduce costs based upon the full life cycle of their products but also to reduce the long-term impact on the environment.

2. BACKGROUND

The Medium Voltage Switchgear Business (MVB) of AREVA T&D use certain materials within their products, which are environmentally unfavourable and have a desire to replace them with alternative materials, which would neither pose an environmental nor an economic threat to their future prosperity. In order to introduce environmentally friendly electrical insulation systems in a systematic approach within their products, it was decided to select a demonstrator to pursue this design philosophy, develop the methodology and maximise the benefits from this strategy.

3. DEMONSTRATOR

A pole-mounted SDR (Switch Disconnector Railway) switch employed on the railway network was selected as the ideal demonstrator as it offered three different types of electrical insulation systems in one unit.

- A static and structural insulation system
- A dynamic and structural insulation system
- A static and non-structural insulation system

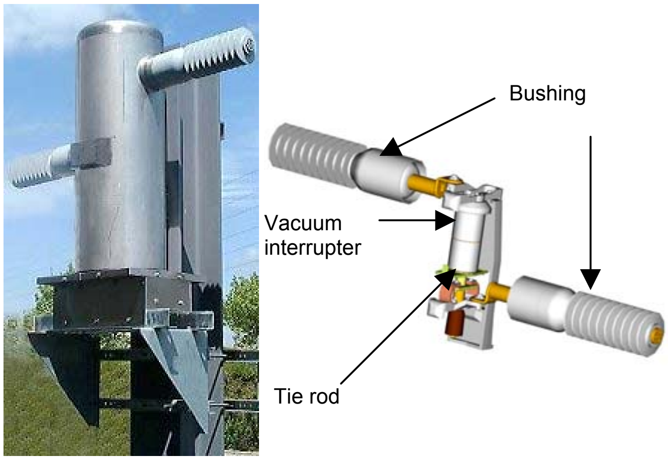

Figure 1: Illustration showing a single pole version of the SDR Circuit Breaker

This single pole switch disconnector is used for load-breaking and fault making duty on feeders and catenaries supplied at 15 kV and 25 kV. It is compact, easy to install and free from maintenance. It is constructed from a hermetically – sealed stainless steel tank and has two synthetic bushings (static and structural insulation system) diametrically attached from

opposing sides of the tank which provide the electrical input and output connections.
Internally the switching mechanism is operated by a magnetic actuator, which axially moves an insulation shaft/tie rod (dynamic and structural insulation system) and separates the contacts within a vacuum interrupter bottle. The tank is filled with sulphur hexafluoride gas (static and non-structural insulation system) at a relative pressure of 0.5 bar. The electrical, mechanical and environmental characteristics for the equipment, which incorporates both the tie rod and the bushing are specified in Table 1.

	Units	SDR 25
Electrical		
Rated Voltage	KV	25
Rated Frequency	Hz	50/60
Power Frequency Withstand Voltage – 1 min	kV$_{rms}$	95
Lightning Impulse Withstand Voltage	kV	250
Rated Current	A	1250
Rated Breaking Current	KA$_{rms}$	8
Short Circuit XXX Current	kA$_{peak}$	20
Mechanical/Environmental		
Installation		Outdoor
Ambient Temperature	°C	-40 to + 40
Storage Temperature	°C	-40 to + 70
Altitude	M	1000
Degrees of Protection – Switch		1P67
Endurance – Mechanical and Electrical	Cycles	10,000
Pollution Withstand Level to IEC 60815		IV
Creepage distance	mm	1069

Table 1: The electrical and environmental characteristics of the SDR Circuit Breaker (Demonstrator)

3.1 Tie Rod

The insulating shaft /tie rod fulfils two roles:

- as an electrical insulation barrier between the vacuum interrupter bottle and ground
- as a means to transmit the mechanical movements of the actuator to the mobile contact of the vacuum interrupter.

The insulating shaft/tie rod configured in the shape of a cone has metal inserts moulded at either end. The casting is a silica filled epoxy resin.

3.2 EPDM Bushing

The two synthetic bushings provide the high voltage to ground external insulation for the circuit breaker. Their design consists of an alumina trihydrate filled EPDM rubber compression moulded onto an aluminium conductor. Embedded with the moulding adjacent to the steel tank is a steel cone which relieves the electrical stress field in this area and provides mechanical and sealing integrity to the tank.

3.3 Sulphur Hexafluoride

The hermetically sealed tank is filled with SF6 at a relative pressure of 0.5.bar to provide additional electrical insulation. The insulating properties of the gas prevent flashover either around the outside of the vacuum interrupter bottle.

4. TECHNICAL APPROACH

The introduction of any new material or product is governed by constraints that fall within the general methodology framework for life cycle product design (Ref1).

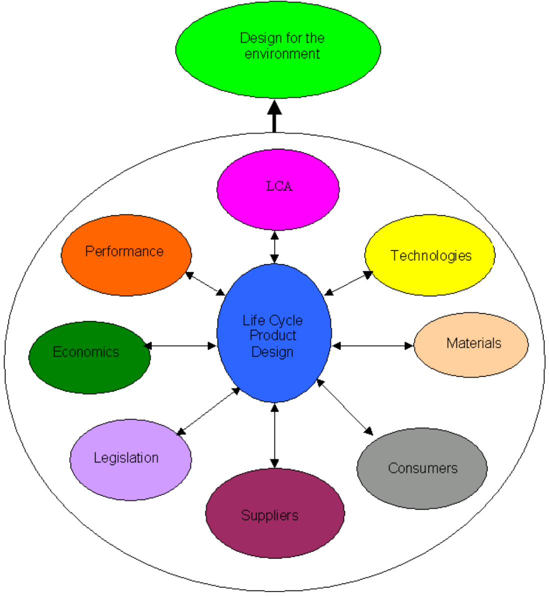

Figure 2: A general methodology framework for life cycle product design (LCPD)

Constraints that normally have to be applied without exception are that the product must:

- maintain its technical performance
- be economically viable
- satisfy the relevant legislation

Most of the present legislation being introduced is concerned with the effects on the environment.

4.1 Functional Performance Requirements

4.1.1 Specification

Design specifications are normally available for any component used within a switch disconnector as it clearly defines and states the minimum performance requirements that must be maintained. Clearly the overriding importance is that any alternative material selected for either the tie rod or the bushing must still be capable of satisfying all these functional requirements without the possibility of failure in service.

4.1.2 Evaluation Criteria

Each of these functional requirements will have an order of merit or degree of importance depending upon the component and its application. Therefore a weighing of 1 to 5 was specified for each of the functional requirements to denote its relative importance (W_i). The highest value being the most critical for service operation.

Suppliers and manufacturers market their product range by giving the intrinsic properties of their materials tested to an International Standard. Each of the functional requirements corresponds to an appropriate intrinsic property and an example of this is given in Table 2 for the tie rod and Table 3 for the bushing.

Functional Requirements of Tie Rod in Circuit Breaker (F)	**Relative Importance by Weighting (W_i)**	**Materials Property Dependant Upon Function F**
Mechanical		
Tension Dynamic Shock	W_1 5	Tensile Strength Tensile Modulus
Compression Dynamic Shock	W_2 5	Comp. Strength Comp. Modulus
Torque	W_3 5	Flexural Strength
Compressive creep behaviour at elevated temperatures	W_4 5	Creep Behaviour at elevated temperatures
Contact operations	W_5 5	Notched Impact Strength
Electrical		
Voltage Withstand	W_6 5	Loss Tangent Dielectric Strength Permittivity Vol. resistivity
Lightning Impulse	W_7 5	
Geometry		
Insulation dimensions	W_8 3	CTI Arc resistance
Thermal		
Thermal Cycling	W_9 5	Continuous Service Temperature
	W_{10} 3	Glass Transition Temperature
	W_{11} 3	Thermal Conductivity
	W_{12} 3	Linear Expansion
Physical & Chemical		
	W_{14} 3	Density
	W_{15} 3	Moisture Absorption

Table 2: The functional requirements of the tie rod

4.1.3 Principle of Ranking

In order to determine whether any replacement materials selected for each of the applications would be technically better or worse than the existing materials a principle of ranking was devised based upon a mathematical model known as a fuzzy performance summation. This was also to classify materials into a preferential order for selection. Needless to say, it is not the intention of this paper to describe this technique in detail but just to demonstrate the methodology.

Functional Requirements of Bushing in Circuit Breaker (F)	**Relative Importance by Weighting (W_i)**	**Materials Property Dependant Upon Function F**
Mechanical		
Static Bending Forces	W_1 3	Stress at rupture Elongation at rupture
	W_2 3	Tear Strength
Electrical Withstand		
Voltage Withstand	W_3 5	Loss Tangent, Dielectric Strength, Permittivity Surface and volume resistivity
Lightning Impulse	W_4 5	Loss tangent Permittivity Dielectric strength Surface and volume resistivity
Geometry		
	W_7 5	Tracking and Erosion Resistance
Thermal		
Temperature Cycling	W_8 3	Glass Transition Temperature,
	W_9 3	Coefficient of Thermal Shrinkage
Physical & Chemical		
	W_{10} 1	Hardness
	W_{11} 1	Density

Table 3: The functional requirements of the bushing

The intrinsic property of a material was taken from the manufacturer's data sheets, which was then used to calculate a number for that particular property known as the Relative value (R_i). The existing materials were given an intermediate value of 3, while an improvement (4 or 5) or decline (1or 2) in performance was reflected by the value. As the data for each of the intrinsic properties for different materials varied enormously with a wide distribution, the property change was classified by a "best fit" curve according to the following three conditions:

1. A change in the cumulative distribution curve for each property, which was either linear, Ln function or Lg function.
2. A bench mark defined by the existing material property value.
3. A boundary value denoted by a lower limit, which was a safety factor and excluded the material from use.

The property values for the existing materials fabricated for the tie rod and bushing were used to define the bench mark and to denote the boundary conditions. These parameters for the various intrinsic properties for the tie rod are shown in Table 4 for the rod.

Properties		Principle of ranking			
	Unit	Bench Mark	Boundary Value	Distribution Curve	Relative Function Formula (R_i)
Mechanical					
Tensile Strength	MPa	75	50	Ln ()	R=7.5×Ln (0.036×x)-4.5
Tensile Modulus	GPa	9.5	3	Ln ()	R=2.6×Ln (2.718×x/9.5)+0.4
Flexural Strength	MPa	110	60	Ln ()	R=5×Ln (2.71828x/110)-2
Compressive Strength	MPa	135	70	Ln ()	R=4.61×Ln (2.71828x/135)-1.61
Impact Strength Notch	kJ/m^2	7	4	Ln ()	R=5.34×Ln (2.71828x/7)-2.34
Thermal					
Glass Transition Tg	℃	100	80	Linear	R=0.15x-12
Thermal Conductivity	W/mK	0.8	0.2	Linear	R=5x-1
Linear Expansion	10^{-5} 1/K	3.5	10	Linear	R=-0.46x+4.6
Heat Deflection Temp.1.8MPa	℃	120	100	Linear	R=0.15x-15
Electrical					
Insulation Resistance	Ω.cm	1.00E+14	1.0E+9	Lg()	R=0.6Log(x)-5.4
Loss Tangent 1kHz		0.01	0.1	Lg ()	R=3×Log(1/x)-3
Permittivity 1kHz		3.5	5.5	Linear	R=-3×x+16.5
Dielectric Strength	kV/mm	18	10	Ln()	R=5Ln(2.718x/18)-2
Physical					
Density	kg/cm^2	1.75	3	Linear	R=-2.4x+7.2
Water Absorption	%	0.1	0.4	Linear	R=-10x+4

Table 4: The boundary conditions and their respective relative formula to calculate the relative values for each property of the tie rod.

The generation of a relative function formula (last column) then enabled a Relative value to be calculated for all the different materials examined.

An overall value for each material, known as the weighted average, was then calculated based upon the sum of the product of each functional design weighting (W_i) and its corresponding Relative value (R_i) for each property.

$$Z = \frac{\sum_{i=1}^{n} W_i\ R_i}{\sum W_i}$$

This formula was used to process the data because it has two advantages: it reflects the importance of the weighting and it minimises the errors brought about by the fact that some of the material data is either not provided or available from the manufacturers. The calculation method is best illustrated by considering a particular material for the tie rod. This is illustrated below by the evaluation of a glass filled polyphenylene sulphide (PPS) given in Table 5.

Properties	Unit	PPS	Relative Value (R_i)	Weighting (W_i)	PPS Relative Value x Weighting	Weighted Average (Z)
Mechanical						
Tensile Strength	MPa	195	5	5	25	
Tensile Modulus	GPa	14.7	4	5	20	
Flexural Strength	MPa	285	5	5	25	
Compressive Strength	MPa	265	4	5	20	
Impact Strength Notch	kJ/m^2	10	4	5	20	
Thermal						
Glass Transition Tg	℃	90	1	3	3	
Thermal Conductivity	W/mK	0.2	1	3	3	
Linear Expansion	10^{-5} 1/K	6.2	1	3	3	
Heat Deflection Temp.1.8MPa	℃	270	5	3	15	
Electrical						
Insulation Resistance	Ω.cm	E+13	2	3	6	
Loss Tangent 1kHz		0.0002	4	5	20	
Permittivity 1kHz		4	3	5	15	
Dielectric Strength	kV/mm	28	3	5	15	
Physical						
Density	kg/cm^2	1.65	5	3	15	
Water Absorption	%	0.02	4	3	12	
Total				61	217	3.56

Table 5: The weighted average for a glass filled polyphenylene sulphide.

The glass filled PPS has a weighted average of 3.56 compared to the existing silica filled epoxy tie rod of 2.85 and is based upon the evaluation of 15 properties. This process was carried out on numerous insulation materials, which ranged from synthetic man-made materials i.e. thermoplastics and thermosets to the natural materials of wood, ceramics and glasses.

4.2 Environmental Life Cycle Assessment

A life cycle assessment assumes a very broad view of normally complex issues dealing with products, processes and activities and also a wide range of environmental impacts. Environmental management on this subject has been published by the International Standards Organisation (ISO) who has defined four phases of the life cycle assessment. (Ref 2-4)

Any life cycle study examines the use of materials and energy extracted from the environment to generate product and services and identifies the emissions and waste products that are associated with the full life cycle before their eventual return to the environment.

4.2.1 Evaluation Criteria

In order to comply with the standards, legislation and to simplify many of the tasks, the environmental performance of materials was analysed used a computer software tool known as Environmental Information and Management Explorer (E.I.M.E.) (Ref 5). This was jointly developed by ADEME (French Environmental Agency) with the assistance of a number of French electrical companies particularly AREVA T&D Ltd.

This tool is based on the product Life Cycle Assessment, which permits a quantitative environmental evaluation and allows a comparison of the environmental performances for different designs. The model examines the product description process and its associated pollution on the environment by using eleven different pollution burdens or impacts, which act as an indicator or “warning”.

No particular preference is given to any of the environmental indicators. In order to aid the material selection procedure for each of our applications an order of priority was given for each of the environmental burdens by attributing a weighing to each one (W_e). It was recognised that these preferences could alter in the future due to changes in legislation, political influence and customer’s criteria but that this was our accepted position now as it was considered unlikely that there would be major changes in future legislation prior to 2007. Two different mathematical methods were considered to categorise the various materials using these defined weightings.

Environmental Burdens	**Weighting (W_e)**	**Environ. Impact value (E_n)**	**Impact Assessment Value (W_e x E_n)**
Hazardous Waste Production **(HWP)**	5	3	15
Ozone Depletion **(OD)**	5	3	15
Global Warming **(GW)**	5	3	15
Energy Depletion **(ED)**	5	3	15
Water Depletion **(WD)**	3	3	9
Raw Material Depletion **(RMD)**	3	3	9
Water Toxicity **(WT)**	3	3	9
Air Toxicity **(AT)**	1	3	3
Air Acidification **(AA)**	1	3	3
Photochemical Ozone Creation **(POC)**	1	3	3
Water Eutrophication **(WE)**	1	3	3
	Total impact assessment value = 99		

Table 6: Environmental burdens – Weighting and impact assessment value (Method 1.) for epoxy

4.2.1.1. Method 1: The EIME value for each environmental burden with respect to the existing material was attributed an intermediate value of three. Materials with better or worse EIME values were given an environmental impact value (E_n) on a scale of 1 of 5 respectively.

A final impact assessment value was calculated from the sum of the product of each individual environmental impact value and its weighting ($\sum W_e \times E_n$). This is illustrated in Table 6. Materials with the lowest environmental impact values i.e. below 99 were the preferred choice for selection.

4.2.1.2. Method 2: The EIME values for each environmental burden for both the existing and alternative materials were converted to logarithm_{10} values (E_l), subtracted and a final impact assessment value determined from the sum of the product of each individual environmental impact value and its weighting ($\sum W_e \times E_l$). Negative values indicate an improvement in selection of materials whereas positive values were worse. An example using a glass filled Polycarbonate (A) compared with the existing material (B) is illustrated in Table 7.

Environmental Burdens	**Weighting (W_e)**	**Log A – Log B (E_l)**	**Impact Assessment Value (W_e x E_l)**
Hazardous Waste Production **(HWP)**	5	-0.14	-0.70
Ozone Depletion **(OD)**	5	-4.60	-23.0
Global Warming **(GW)**	5	-0.18	-0.90
Energy Depletion **(ED)**	5	-0.08	-0.40
Water Depletion **(WD)**	3	-0.17	-0.51
Raw Material Depletion **(RMD)**	3	-0.10	-0.30
Water Toxicity **(WT)**	3	-0.66	-1.98
Air Toxicity **(AT)**	1	-0.30	-0.30
Air Acidification **(AA)**	1	-0.32	-0.32
Photochemical Ozone Creation **(POC)**	1	-0.08	-0.08
Water Eutrophication **(WE)**	1	-0.64	-0.64
	Total impact assessment value = -29.1		

Table 7: Environmental burdens –Weighting and impact assessment value (Method 2.)

5. SURVEY AND POTENTIAL CANDIDATES

Extensive surveys were carried out on a wide range of materials and included, thermosets, thermoplastics, ceramics and natural materials. Each material was categorised using the principle of ranking in order to place them in a preferential order of merit.

5.1 Tie Rod

Some of the materials reviewed are displayed in Table 8 to illustrate the selection procedure of the combined technical and environmental approach. The values displayed have been normalised so a direct comparison can be made with the existing tie rod. The selection of materials with a functional performance >1 and an environmental value < 1 for Method 1 and a negative value for Method 2 are preferred.

Generic type	**Normalised Functional performance (Weighted average)**	**Environmental Performance #**	
		Normalised Method 1	**Method 2**
PC-GF 20%	1.39	0.54	-29
PC	1.30	0.54	-5
PET-GF30%	1.22	0.62	-33
PBT -GF30%	1.25	0.58	-28
PPS- GF40%	1.25	0,78	-24
PES -GF30%	1.35	1.50	-7
PPO -GF30%	1.29	1.02	-17
PEI -GF 30%	1.09	1.46	-9
PEI	0.94	1.5	-5
PBT	0.92	0.58	-27
PA66	1.22	1.24	11
PI	0.70	1.50	4
Glass ceramic	1.19	0.54	-52
Wood*	0.81	0.54	-45
SMC	1.33	1.30	-12
Epoxy tie rod	1.00	1.00	0

** wood similar to beech wood*

*# **Note:** a value for ozone depletion (OD) is not available for the epoxy material in the EIME software model. A hypothesis has been implemented that assumes all the materials selected as potential replacements for epoxy and have ozone depletion impact values that are larger than epoxy.*

Table 8: Material environmental performance values for the tie rod

An examination of the Table shows:

- The glass filled thermoplastics have higher functional and environmental performances than their unfilled counterparts.
- The thermosets, typically SMC, satisfy the functional performance but fail on the environmental values.

When the thermoplastics are compared to the thermosets they offer many advantages. These are:

1. Weight reduction –they have lower relative densities and therefore use less material per unit component.
2. Recycling – they can be remoulded to form new components as a cost-effective operation. However at the higher glass contents (>50%) recycling becomes less efficient as some of the glass filler has to be removed.
3. Volatile solvent emissions – the processing of thermosets can involve the presence of solvents harmful to the environment not associated with thermoplastics.
4. Economical – the unit cost of the thermoplastic can be cheaper on the overall manufacturing cycle with faster moulding cycles, greater production yields and fewer subsidiary operations.

Some thermoplastics for example the Polyimide (PI) and the Polyamide (PA66) fail both the functional and environmental performances.

The environmental advantages of wood and a glass ceramic are clearly displayed in Table 6 and show their attractive environmental performance values. However caution is necessary to confirm they satisfy the qualification specification. An in depth study of the various environmental burdens for the most favourable candidates i.e. the glass filled thermoplastics (PC, PPS, PE and PBT), wood, glass ceramic is illustrated in Figure 3. It reflects also the fact that the ozone depletion impact values are not available for epoxy.

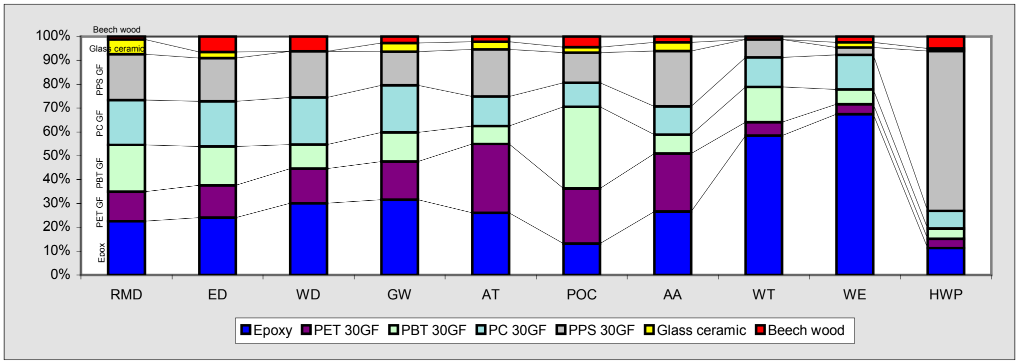

Figure 3 : Illustration showing the various environmental burdens for the different materials

In all of the environmental burdens the wood, glass ceramic, glass filled Polycarbonate (PC) and glass filled Polybutylene Terephthalate (PBT) have significant lower impact values than the existing epoxy tie rod. The glass filled Polyphenylene Sulphide (PPS –30GF%) also has less impact except for the hazardous waste production (HWP). The glass filled Polyethylene Terephthalate (PET- 30GF%) has less impact for most of EIME indicators but has slightly greater impact on air toxicity (AT) and photochemical ozone creation (POC).

To further demonstrate the major improvements on the environment that can be achieved by a change in material, a comparison of wood, polycarbonate and the epoxy for the various EIME indicators is illustrated in the form of a radar diagram displayed in Figure 4.
Here the epoxy material is normalised to a value of 100% and the relative percentage values for the other two materials found within the inner perimeter.

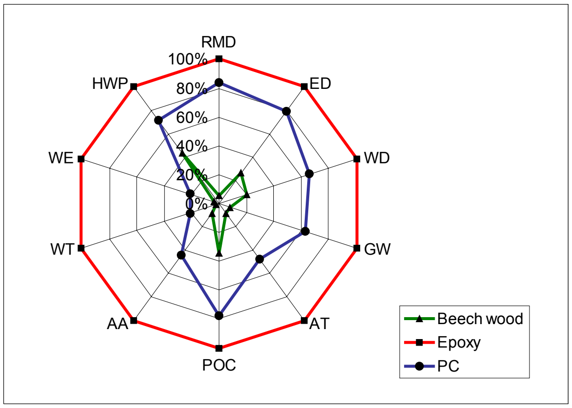

Figure 4: Comparison between wood, thermoplastic (PC) and epoxy environmental impacts.

5.2 Bushing

Many of the rubbers assessed to replace the EPDM bushing material and which gave a technical advantage on their functional performance were rejected because of their environmental characteristics. The only exception was the different types of silicone systems. The values for one of the most favourable silicones is shown in Table 9.

Generic type	Functional performance (Weighted average)	Environmental Performance	
		Method 1	Method 2
Silicone rubber	1.47	0.54	-23
EPDM rubber-bushing	1.0	1.0	0

Table 9: Material performance values for the bushing

The Life Cycle Assessment gained from using the EIME computer software for both the silicone and EPDM materials during their full life cycles is again shown in the form of a radar diagram (Figure5). This time, for the purpose of comparison, the EPDM material is set to the relative value of 100% for each of the factors except for the ozone depletion burden. The silicone shows a significant improvement in every one of the environmental factors except ozone depletion (OD). However, this impact is still low for both materials (EPDM: 3.6 x 10^{-4} g and silicone: 6.8 x 10^{-3} g for the ~CFC-11 CCl_3F)

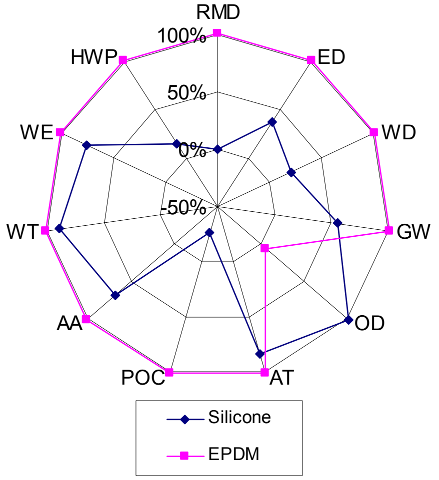

Figure 5: Comparison between silicone and EPDM environmental impacts.

A limitation of the EIME software tool is that it evaluates the generic type but it is unable to differentiate between the different types based on their silicone polymerisation mechanisms. A decision on the preferred silicone was based upon the overall cost of product manufacture for the room temperature vulcanisation (RTV), liquid silicone rubbers (LSR) and heat vulcanisation rubbers (HTV) as illustrated in Table 10.

	Raw material	Processing	Performance
RTV	High	Low	Medium
LSR	Medium	Medium	Medium
HTV	Low	High	High

Table 10: Costs for silicone elastomers relative to service performance

6. CONCLUSIONS

It has been clearly demonstrated that the use of this type of approach using a combination of the technical requirements and Eco-design methodology has been successful in the selection of favourable candidates to satisfy the overall product design for the tie rod and bushing.

However, this route gives an initial assessment and not a definitive answer and other determining factors may have to be addressed and checked. The commercial viability of the basic raw material and its fabrication route can still be the major issues in the decision to use a particular material.

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