Developing a new compatibility table for design for recycling

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Abstract: Design Engineers take use of various tools and methods to aid on decision making on end-of-life of products, including techniques such as Design for Disassembly, Design for Environment, Design for Recycling, Design for End of Life, and so on. Among the Design for Recycling techniques there are specific tools regarding to the reprocess of product components, including some compatibility tables for plastic materials. These tables list possibilities of compatibility of commonly employed plastics, however not providing further information about how compatible they are. On the other hand, material engineers study reprocessing strategies like polymer mixture in a more specific way, evaluating all blend properties. So, to the polymer engineering, compatibility is a technological term that is related to desired final properties of the mixture. Furthermore, the wide range of plastic grades available implies greater difficulties on using these tables due to the presence of additives in some grades, such as fillers, fibber glass and flame retardants. The limitations of these compatibility tables are evaluated in this paper and some background is provided for developing a new compatibility table. Compatibility concept is evaluated both under the view of the design and the polymer engineering, different polymer mixtures and blends are gathered from literature, and a new compatibility table, based on compatibility concept adopted by materials engineering, is presented for some commonly employed polymers.

Keywords: compatibility table, design for recycling, design for reprocessing, polymers, end-of-life strategies.

1. Introduction

The end-of-life of products has been a growing concern to the industry, the academy and the government. They continuously develop new strategies for reuse, remanufacturing and recycling, aiming a more sustainable way to produce goods.

However, this scenario is still not a reality for a great number of small and medium enterprises (SMEs), as well as to some large companies. Beyond economical issues, there are some technical factors involved. First, in industry there are a great number of engineers that does not have a proper environmental education since this subject is relatively new at graduation schools. Second, there is a maturity factor that must be considered when evaluating environmental actions taken by industry. As presented by Brezet (1997), and illustrated in Figure 1, there are four levels of maturity for environmental innovative actions taken by the industry:

- Product improvement: The improvement of existing products as regards pollution prevention and environmental care. Products are made compliant;
- Product redesign: The product concept stays the same, but parts of the product are developed further or replaced by others. Typical aims are increased reuse of spare parts and raw materials, or minimising the energy use at several stages in the product life cycle;
- Function innovation: It involves changing the way the function is fulfilled. Examples include a change from paper-based information to e-mail, or private cars to 'call-a-car' systems; and
- System innovation: New products and services arise from requiring changes in the related infrastructure and organizations. A changeover in agriculture to industry-based food production, or changes in organization, transportation and labour based on information technology.

Nevertheless, for some industries it could be technical and economical demanding to achieve Level 2 or, even, Level 1. This scenario is more usual on SMEs, since they have fewer resources available. In these cases it is more common for enterprises to follow easier paths. For example, it is more likely to a design team to develop a product that is fully and easily recyclable than to investigate possibilities of remanufacturing and reuse, since it is easier to think and detail a product based on only one lice cycle than various.

So, when considering the first 2 levels of Ecodesign maturity, it is possible to notice different sub-levels of maturity. Initially there is a tendency to adopt recycling as the main end-of-life strategy, since it is closer to more traditional engineering tasks. This strategy usually results on

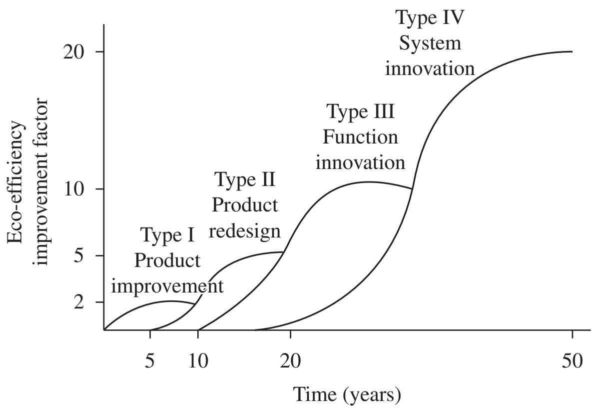

Figure 1. Four Stage model of Ecodesign innovation (BREZET, 1997).

recycled materials with low value added to other products, and more degraded when compared with neat materials.

On the higher level of Type II stage of innovation there are strategies for remanufacturing and reuse, which could be more cost and engineering demanding. These strategies usually imply costs for testing and maintenance for the returned products, which implies better planned product and life-cycle.

Before achieving reuse and remanufacturing expertise, it is possible for design teams to consider recycling strategies that leads to more value-added materials, with properties that could be used to improve products competitiveness. This way of thinking could be considered a middle-level between the two previous ones.

This paper is regarding to the mixture compatibilities for plastic materials. Metals are not included since the metallurgical aspects for combining materials is well known. However, when considering plastics, there are a greater number of technical aspects to be considered, including level of recycling, origin of the materials, number of recycling and, for mixtures, viability of blending.

Blending plastics is particularly an interesting solution to providing value-added products after recycling mixtures, since it is possible to obtain improved properties that could be commercially explored. A key concept for making plastics blends is the compatibilization. It is necessary since the simple mixture of two polymers is frequently not possible, needing a third element to bind them together. This element is called compatibilizer on materials engineering.

The compatibility concept is not particularly clear in the design engineering literature. In this knowledge field, it is common to take use of some design tools to make decisions during the development effort. Among these tools are found some compatibility tables, which address possibilities for combining two or more materials.

It is important to notice that the reliability of these tables is essential for the design process. Otherwise, additional design effort will be necessary, rising project costs.

This paper describes two points of view of plastic recycling: materials engineering and design engineering. Three compatibility tables found on literature are evaluated based on these two engineering areas. A new compatibility table for polymer materials is presented, which was build based on literature data about polymer mixture and blending.

2. Recycling plastics – methods and techniques

Slow natural environmental degradation, enhanced by the growing production and consumption of polymeric materials has contributed to the increased amounts of plastic waste. Thus, management and recycling of plastic waste is an economic priority of the more developed countries of the world.

Plastic recycling can be classified in four categories (BRANDRUP, 1992; EHRIG; CURRY, 1992; SPINACÉ; DE PAOLI, 2005):

- Primary recycling: consisted in industrial plastics waste conversion into new plastic products; for example, processes shreds are reintroduced into the process;
- Secondary recycling: polymeric waste from urban solid waste are changed back into plastic raw materials for further processing into new plastic products, for example polypropylene packing recycling to obtain garbage bag;
- Tertiary recycling: consisted in technological production process of chemical raw or fuels from polymeric waste. This type of recycling is also called as chemical recycling; and
- Quaternary recycling: technological process of energy recover from polymeric waste by controlled incineration is also called energetic recycling.

The primary and secondary recycling are known as mechanical recycling. The difference between them is the primary use post-industrial polymers and secondary post-consume materials. Table 1 compare the usefulness of the different options available for plastic recycling.

In Table 1 it can be observed that mechanical recycling is preferred when plastic waste consists exclusively of one pure plastic completely uncontaminated and without a paint coating, the material could be recycled without problems and virtually there is no loss of quality. Generally, functional combinations of materials, aging and contamination change the composition and the properties of the new materials obtained through recycling (BELLMANN; KHARE, 1999).

Separation process of different industrial wastes can be very complex and expensive (VILLALBA et al., 2002).

Table 1. Comparative of various methods of plastic recycling (BELLMANN; KHARE, 1999).

Type of plastic waste	Mechanical recycling	Chemical recycling	Energy recovery
Single plastic waste	++	+	+
Mixed plastic waste	+	++	++
Mixed plastic waste plus paper etc.	–	–	–

(-): not applicable (+): suitable (++): preferred.

Some separation processes based on physical and chemical properties of materials have been proposed, but they are difficult to be applied to industrial level in most cases (PAPPA et al., 2001). Recycling of different wastes by blending techniques is a feasible solution for most engineering plastic waste to obtain synergetic properties and upgrade polymer wastes (BALART et al., 2005). However, this method has some limitations, including thermodynamic immiscibility of most polymers, which results in inferior mechanical properties of a material obtained from blends of various plastics. Sometimes, immiscible blends can be compatible, that is, they have more than one phase but have good mechanical properties. Moreover, most of polymer mixtures lead to immiscible and incompatible blends. Improvement on mechanical properties of these blends may be accomplished by application of suitable compatibilizers, cross-linking additives, and/or electron radiation, which leads to an increase on the interfacial adhesion of macromolecules of the polymers forming a given blend. In this way, for example, impact strength of such materials can be enhanced (ULTRACKI, 1990).

Compatibility is often poorly defined qualitative term and it can drive to different interpretations (ZENKIEWICZ; DZWONKOWSKI, 2007). Usually the term compatibility is used to a mixture of polymers that reaches a desired property, for example, good impact resistance and/or high tensile strength (PAHL; NEWMAN, 2000).

This definition leads to a deeper sense of compatibility, which will be the basis of the analysis of the compatibility tables on topic 4.

3. Recycling on product development

Recycling in engineering design could be seen by different forms, including, but not restrict to, marketing needs to be fulfilled, design requirements to be pursuit or, at least, enterprise environmental responsibility. Still, independently of the company aim, there is ample literature to support design engineers on decision making regarding to this subject.

Ijomah et al. (2007) discussed some design guidelines for product remanufacturing. Among the ten golden rules (LUTTROPP; LAGERSTEDT, 2006) there are two explicitly related to materials recycling. Among the twenty three opportunities present on the Ecodesign Checklist (TICHNER et al., 2000) there are three that is directly related to recycling. Kriwet et al. (1995) demonstrate an approach for incorporating recycling considerations into product design, which includes guidelines to aid the development of recycling friendly products. The relationship between recycling and product disassembly is discussed by Kroll and Hanft (1998).

Pahl and Beitz (1996) describe a series of guidelines aiming to improve the product design in means of recycling, covering aspects from product disassembly (essential to minimizing the cost of product end of life), the need for a facility of separation of different materials, and proper planning of the destination given to materials of high value and dangerous, and the specification of a compatibility table for plastic materials. A slightly simple compatibility table is presented by Hundall (1997), which also presented compatibility tables for metals, glass and ceramics. In both cases the compatibility table is derived from VDI 2243. From these tables is possible to notice that few thermoplastics are considered compatible with others. However, for the compatible ones, it is not described in the tables the kind of compatibility that exists and how to obtain it. It is recommended (PAHL; BEITZ, 1996) for the design engineers to check the materials compatibility with experts in order to get through this problem.

It is interesting to notice that some authors (LUTTROPP; LAGERSTEDT, 2006; TICHNER et al., 2000; KROLL; HANFT, 1998) recommend to avoid materials mixtures. However, the presence of a compatibility table in VDI2243 is still a clear example of the need of materials combination in certain products or process.

Then, it is necessary to provide a more detailed description of the compatibilities possibilities and potential results in terms of technical properties to simplify the interaction with experts, speed-up the development process, and allow design engineers to define recycling strategies that results on more value added products.

In the next topic it is discussed some divergences found between the information provided by these tables and the specialized literature, as well possibilities for providing a more detailed information for design engineers.

4. Comparing current compatibility tables

Compatibility Tables, such as the ones previously discussed, are decision tools for the design engineers use to select materials. A wrong choice of a material could lead to the redesign of the product and, consequently, more costs for the enterprise. Furthermore, it is not possible for every company, principally for the SMEs, to consult materials experts on every situation, since it could lead to prohibitive costs. Therefore, it is important for these compatibility tables to provide more trustworthy and complete information possible.

To evaluate these aspects it will be considered the compatibility table provided by Pahl and Beitz (1996), illustrated in Figure 2 containing some common families of polymer materials.

In a first analysis, it is possible to notice two interesting points: the compatibility table does not explore the different existing compositions of plastics, and all their grades. For example, all polyamides (PA) are treated together, regardless the specific characteristics of which type, such as PA6 and PA66, and which procedures should be adopted to combine them. Furthermore, there is a wide range of plastic grades available, approximately 65.000 different grades (KMETZ, 2006), and the presence of additives in some grades, such as fillers, fibber glass and flame retardant implies greater difficulties in using these tables.

A deeper evaluation, based on the compatibility concept, shows some divergences between the mixture compatibility in literature and the index presented on the table. One example of this divergence is polyethylene (PE) and polypropylene (PP) mixtures. In the table they are considered fully compatible. However, the incompatibility between low density polyethylene (LDPE) and PP has been reported by Teh et al. (1994) e Bertin and Robin (2002). In LDPE rich blends, a heterogeneous PP dispersion in the LDPE matrix produces two phases in the melt. The low interfacial adhesion between the phases is responsible for a decrease in mechanical properties especially related to its morphology, including impact strength, strain at break and ductile to brittle transition. According to Shanks (2000), the immiscibility between the phases makes the rule of mixtures ineffective in predicting some properties of interest. To overcome this difficulty, the use of various compatibilizers has been reported. Yang et al. (2003) showed that the addition of a commercial ethylene/propylene block copolymer improved the ductility of LDPE/PP blends, particularly for PP rich blends. Bertin and Robin (2002) studied and characterized virgin and recycled LDPE/PP blends and the use of compatilizing agents, such as ethylene-propylene-diene monomer copolymer (EPDM) or PE-g-(2-methyl-1,3-butadiene)graft copolymer, to enhance their impact strength and elongation at break. Although this may solve the compatibility problem, the use of compatibilizers adds cost to the recycled product, usually resulting in loss of interest from the recycling sector (STRAPASSON et al., 2005).

Other example of divergences found in the compatibility table is polycarbonate/acrylonitrile-butadiene-styrene copolymer (PC/ABS) mixtures, which mechanical properties depend on the PC molecular weight, blend

Basic material	Important synthetic design materials	Additive											
		PE	PVC	PS	PC	PP	PA	POM	SAN	ABS	PBT	PET	PMMA
	PE	●	○	○	○	●	○	○	○	○	○	○	○
	PVC	○	●	○	○	○	○	○	●	◉	○	○	●
	PS	○	○	●	○	○	○	○	○	○	○	○	○
	PC	○	⊙	○	●	○	○	○	●	●	●	●	●
	PP	⊙	○	○	○	●	○	○	○	○	○	○	○
	PA	○	○	⊙	○	○	●	○	○	○	⊙	⊙	○
	POM	○	○	○	○	○	○	●	○	○	⊙	○	○
	SAN	○	○	○	●	○	○	○	●	○	○	○	●
	ABS	○	◉	○	●	○	○	⊙	○	●	⊙	⊙	●
	PBT	○	○	○	●	○	⊙	○	○	⊙	●	○	○
	PET	○	○	⊙	●	○	⊙	○	○	⊙	○	●	○
	PMMA	○	●	⊙	●	○	○	⊙	●	●	○	○	●

● Compatible
◉ Limited compatibility
⊙ Compatible in small quantities
○ Not compatible

Figure 2. Compatibility of plastics materials (PAHL; BEITZ, 1996).

processing conditions, and type, size and content of ABS rubber. In this case, compatibilization with appropriate additives is considered to exhibit beneficial effects to achieve better mechanical properties of this blend (ELMAGHOR et al., 2004).

On the other hand, it is important to notice that there are a great number of mixtures considered compatibles on the table which have their compatibility demonstrated in literature. It includes all PC/poly(butadiene tereftalate) (PBT) mixtures (TJONG; MENG, 2000), the poly(methyl methacrylate)/styrene-acrylonitrile copolymer (PMMA/SAN) mixtures, when the weight fraction of AN monomeric units in SAN copolymers is within the range of 9% and high limit around 30% (CAMERON et al., 2002), the poly(vinyl chloride) (PVC)/PMMA mixtures, when there are contents of PVC greater than 60% w/w in the blend (AHMAD et al., 2008).

Other compatibility tables are found in the literature. Figure 3 presents the compatibility table from Renault standard 00-10-0-060/1994 and Figure 4 presents the table from Hensen (1988). These three tables (Figure 2, 3 and 4) present differences on data concerning polymer compatibility. For example, PC and ABS mixture on Renault's table are compatible in special conditions, but does not have any information about these conditions. On Hense's table PC and ABS have good compatibility and on Pahl and Beitz's they are compatible. A clear example is presented by PP and PE mixture. In Hense's table, which consider the division on High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE), consider both incompatible with PP, but on Renault's table PE was compatible in special conditions with PP and on Pahl & Beitz table they are compatible.

5. Development of the new compatibility table

To develop a new compatibility table it was adopted a matrix structure similar to the ones employed by the previous works. However, to fill up its contents was performed a

	ABS	PA	PC	PE	PMMA	POM	PP	PBT	PVC	PC + PBT	ABS + PC
ABS	1										
PA	2	1									
PC	2	3	1								
PE	3	3	3	1							
PMMA	1	3	2	3	1						
POM	3	3	3	3	3	1					
PP	3	2	3	2	3	3	1				
PBT	2	2	1	3	3	2	3	1			
PVC	2	3	3	3	1	2	3	2	1		
PC + PBT	2	2	1	3	2	2	3	1	2	1	
ABS + PC	1	2	1	3	2	3	3	2	2	2	1

Figure 3. Compatibility Table from Renault standard 00-10-0-060/1994. 1: good compatibility; 2: compatible in special conditions; and 3: incompatible.

	PS	PSAI	SAN	ABS	PA	PC	PMMA	POM	PVC	PP	LDPE	HDPE	PBT
PS													
PASI	1												
SAN	6	6											
ABS	6	6	1										
PA	5	4	6	6									
PC	6	5	2	2	6								
PMMA	4	4	1	1	6	1							
POM	6	6	6	5	6	6	5						
PVC	6	6	2	3	6	5	1	6					
PP	6	6	6	6	6	6	6	6	6				
LDPE	6	6	6	6	6	6	6	6	6	6			
HDPE	6	6	6	6	6	6	6	6	6	6	1		
PBT	6	6	6	5	5	1	6	6	6	6	6	6	
PET	5	5	6	5	5	1	6	6	6	6	6	6	6

Figure 4. Compatibility Table from Hense (1988). The compatibility decreases from 1 to 6. Number 1 is very good compatibility and number 6 incompatible.

review in literature to gather results of compatibilization studies on polymer blends. For this initial proposal it was focused on plastics usually studied on materials engineering, such as PP, PE and PA-6. It was also focused four mechanical properties usually adopted on engineering design: impact strength, Young's Modulus, Yield strength and Elongation at break. The results of the gathering of information are presented on Table 2.

To include the four mechanical properties in to the compatibility table, it was inserted a four cell matrix for each materials pair. Each quadrant of this matrix is related to a specific mechanical property, as could be seen on Figure 5. It was also adopted the symbols presented on Figure 6 to describe the mechanical properties resulted of the mixture of two polymers, with or without compatibilizers. The obtained Compatibility Table is presented on Figure 7.

Compatibility data for some mixtures, such as ABS/LDPE and ABS/PA6, were not found on the literature. However, these mixtures are considered not interesting for commercial use. It is also important to notice that the compatibility data present on the proposed compatibility table is only part of the compatibility information, since the specific conditions and degree of compatibility obtained via literature, such as described on Table 1.

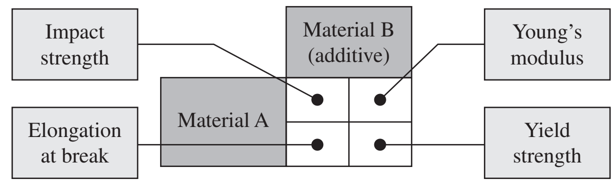

Figure 5. Mechanical properties on the compatibility table.

	Improve mechanical properties	Maintain mechanical properties	Worsen mechanical properties
With compatibilizers	⇧	⇔	⇩
Without compatibilizers	⇧	⇔	⇩

Figure 6. Mechanical properties after mixture.

Table 2. Compatibility in literature.

Blend	Author	Conditions	Properties
PP/HDPE	Bartlett et al. apud Castilhos (2004)	Compatibilizer: EPR	Decrease tensile strength, Young's Modulus and increase break elongation and impact strength.
	Castilhos (2004)	Compatibilizer: EPR	Decrease yield strength, Young's Modulus and increase elongation at break and impact strength.
HDPE/PP	Carvalho et al. (2004)	Without compatibilizer; composition up to 25% PP	Maintain yield strength and Young's Modulus and increase elongation at break
HDPE/LDPE	Kukaleva (2003)	Without compatibilizer; composition: up to 23% LDPE	Improve impact strength, Young's Modulus and Yield strength
LDPE/PP	Bertin and Robin (2002)	Compatibilizer: (5%) EPDM ou EPM.	Maintain yield strength, decrease Young's Modulus and improve impact strength and elongation at break
LDPE/PA6	Filippi et al. (2005)	Compatibilizer: HDPE-g-MA Composição: (75/25)	Maintain Young's Modulus and Yield strength and increase elongation at break
PA6/LDPE	Filippi et al. (2005)	Compatibilizer: HDPE-g-MA Composição: (75/25)	Increase Young's Modulus and Yield strength and decrease elongation at break
PA6/ABS	Kudva et al. (2000)	Compatibilizer: SAN-MA	Improve impact strength and decrease Young's Modulus
PA6/HDPE	Agrawal et al. (2008)	Compatibilizer: PE-g-AA	Decrease Young's Modulus, maintain Yield strength and increase impact strength and elongation of break
HDPE/PA6	Vallim (2007)	Without compatibilizer; composition up to 25% PP	Decrease Yield strength and impact strength and increase Young's Modulus
ABS/PP	Yang and Katy (2007)	Compatibilizer: 8% hydrogened SEBS	Increase impact strength, yield strength and elongation at break
PP/PA6	González-Montiel et al. (1995)	Compatibilizer: SEBS-g-MA EPR-g-MA	Increase impact strength and decrease yield strength and Young's Modulus
PA6/PP	González-Montiel et al. (1995)	Compatibilizer: SEBS-g-MA EPR-g-MA	Increase impact strength and decrease yield strength and Young's Modulus

Compatibilizers: EPM = ethylene-propylene copolymer; EPR = ethylene-propylene random copolymer; EPR-g-MA = ethylene-propylene random copolymer grafted with maleic anhydride; HDPE-g-MA = high density polyethylene grafted anhydride maleic; PE-g-AA = polyethylene grafted acrylic acid; SAN-MA = styrene acrylonitrile copolymer grafted anhydride maleic; and SEBS-g-MA = styrene-ethylene/butylene-styrene triblock copolymer grafted with maleic anhydride.

Additive / Material	LDPE		HDPE		PP		PA6		ABS	
LDPE	⇔	⇔			⇧	⇩		⇔		
	⇔	⇔			⇧	⇔	⇧	⇔		
HDPE	⇧	⇧	⇔	⇔	⇧	⇔	⇩	⇧		
		⇧	⇔	⇔		⇔		⇩		
PP	⇧	⇩	⇧	⇩	⇔	⇔	⇧	⇩	⇧	⇧
	⇧	⇔	⇧	⇩	⇔	⇔		⇩	⇧	
PA6		⇧	⇧	⇩	⇧	⇩	⇔	⇔	⇧	⇩
	⇩	⇧	⇧	⇔		⇩	⇔	⇔		
ABS					⇧	⇧			⇔	⇔
					⇧				⇔	⇔

Figure 7. Compatibility Table based on compatibility concept.

6. Conclusions

This paper presented two different points of view on recycling. The first, based on the side of materials engineering, shows that it is not necessary that recycled material shows the same properties as virgin resins. However, a good balance between properties and processing which allow its reuse and upgrading is absolutely necessary to a recycled material. Recycling of different wastes by blending techniques is a feasible solution for most engineering plastic waste to obtain synergetic properties and upgrade polymer wastes but they are limited by compatibility considerations.

On the other hand, by the side of design engineering, recycling is seen as the fulfilment of customer needs, legal issues, and so on. It is important to notice that a great part of the design effort to provide a well planned end-of-life strategy relies on the use of DfX tools, such as the Design for Recycling, which includes the compatibility tables.

It is interesting to notice that the compatibility tables are bridges between these two engineering fields. So, it is important that these tools provide information as accurate as possible. The evaluation presented on this paper shows that there is some weak points in the tables available, including the absence of different compositions on polymer families. It was also possible to identify some divergences on the table, which indicates some mixtures as fully compatible; however some of them need compatibilizer agents to be truly compatible.

Despite the fact that some authors consider making materials blends undesirable, it is better for the environment to return a product to the marketing than to dispose these materials. This strategy will be even more interesting if, during the design of the new product, it was considered the technical benefits made available by any particular blend. By this way it is possible to add value to the product and, possibly, increase the use stage of its life-cycle. In this context, the compatibility tables play an important role in integrating design teams with such different expertises.

The new compatibility table presented on this paper was developed based on the compatibility concept employed by the materials engineering, and it is result of the gathering of scientific literature data. This is an ongoing work, since other important families, such as poly(ethyl tereftalate) (PET) and PC, are not mapped yet. However, the methodology adopted for building the proposed compatibility table is easily replicated, allowing to the design engineers to fill up its own information needs for specific mixtures.

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