Evaluation of the Ecological Costs and Benefits of Fire Safety – A Case Study of Brominated Flame Retardants

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Abstract

A novel Life-Cycle Assessment (LCA) model has been defined for the determination of the environmental cost of measures taken to attain a high level of fire safety. This study represents the first full application of this LCA model. This case study concentrates on a comparison between a TV with an enclosure manufactured from V0 rated High Impact Polystyrene (HIPS, typical for the US market) and one with HB rated HIPS (typical for the European market). A fire model has been defined based on international statistics, which indicate that use of V0 rated enclosure material essentially removes the risk of TV fires while approximately 165 TV fires occur per million TVs in Europe each year (where the enclosure material is breached).

The full application of the model indicates that emissions of some key species (such as dibenzodioxins and PAH) are actually lower for the TV with the FR enclosure than for the TV with the NFR enclosure. This has direct repercussions for the assessment of the environmental impact of the FR TV relative to that of the NFR TV.

Finally, when considering the risk associated with the use of flame retardants it is important to also consider the risk associated with fires. Based on the indepth analysis of available fire statistics conducted as a part of this study, it has been estimated that as many as 160 people may die each year in Europe as a direct result of TV fires and as many as 2000 may be injured in the same period.

1. Introduction

For the past 5-10 years there has been an ongoing discussion of possible environmental effects associated with flame retardants. In most cases the focus has been on specific brominated flame retardants but at times the whole group has been considered environmentally questionable by association. Within this context the opinion that ”it is better to let things burn more often than to use flame retardants” has been voiced (Letter to editor, Sirenen, 1996). Upon closer inspection it quickly becomes apparent that there is no work published that would support (or refute) this opinion. Up until recently there has been no way to quantify such a qualitative statement and thereby make a valid comparison between the ecological costs and benefits of fire safety.

In response to this lack of information a new life-cycle assessment model, the so called “Fire-LCA” model, was developed (Simonson *et al*, 1998). This model aims at weighing the environmental benefit of a high level of fire safety, in terms of a reduction in the size and number of fires, against the environmental cost of the production and use of the flame retardant by which this fire safety is achieved.

The Fire-LCA model includes emissions associated with the production of the flame retardant and its introduction into the product and juxtaposes these with emissions associated with fires due to the product in question. In this way, it is possible to obtain a realistic measure of the environmental impact of including the flame retardant in the product. Further, the effect of the flame retardant on the recyclability of the material used and on the emissions associated with energy recovery and Landfill are, of course, also considered explicitly.

The product chosen for the first full application of the Fire-LCA model is a TV set (Simonson *et al*, 2000). This choice has been governed by the fact that fire statistics are abundant concerning TV fires, and that different levels of fire safety are adopted for TV enclosures in Europe and in the US. This latter point is due to differences in the fire safety standards that are required in these two parts of the world. Another fact that makes TV sets ideal for the first application, is that the flame retardant generally used in the TV enclosure is decabromodiphenyl ether (deca-BDE). This is one of the flame retardants which has been specifically investigated, and should therefore be a stringent test for the model.

The effect of the presence of a flame retardant in the TV enclosure, on the size and frequency of fires, is a crucial part of this new model. A detailed investigation of European and US fire statistics provides the basis for this part of the study. The application of results of this investigation of fire statistics, in terms of the input to the fire part of the Fire-LCA model, is presented here while details of the full statistical investigation are presented elsewhere (De Poortere *et al*, 2000).

2. TV Fire Statistics

Most developed countries keep detailed statistics over the frequency and source of fires. Variations in statistics between different countries and different sources within any given country provide information concerning the size and type of fire. Statistics from fire brigades tend to focus on large fires as the fire brigade is generally not called in to deal with a very small fire. In contrast, statistics from insurance companies generally contain both small and large fires, as one is likely to report even a small fire to an insurance company in order to make a claim. In the case of TVs, where different safety standards govern enclosure material internationally, differences in TV fire statistics between Europe and the US give an indication of the benefit of the flame retardant in reducing the frequency of fires.

Based on the results of a previous investigation (De Poortere *et al*, 2000) one can define the number of TV fires in Europe (normalised per million TV sets each year) as: 100 TV fires due to internal ignition; 65 TV fires due to external ignition; and, 160 TV fires where the TV enclosure is not breached in the incident. This makes a total of 165 TV fires/million TVs where the TV enclosure is breached and 160 TV fires/million TVs where the TV enclosure is not breached, for a TV set with non-flame retarded enclosure material. Further, information is available which enables a division of the TV fires where the enclosure is breached according to the probable size of the fire.

An investigation of US statistics has revealed that TV fires are quite uncommon in the US. A total of 5 TV fires/million TVs occur each year in the US (Hall, 1997). These fires are classified as ”minor” in the LCA model as the US TV was found through experimentation to be extremely difficult to ignite. US statistics for TV fires when the enclosure is not breached have not been forthcoming and so the model assumes that the number of such fires is essentially the same in Europe and the US. It has been estimated, both in Europe and the US that approximately one third of these 160 TV fires /million TVs (where the enclosure is not breached) will be replaced while the remaining two thirds will be repaired.

The results are summarised in Table 1 for the TV fires where the enclosure material is breached in the case of TVs with HB enclosure material and V0 enclosure material.

Table 1: Fire-LCA input for European TV (HB enclosure) and US TV (V0 enclosure) denoting all fires where the enclosure is breached.

European TV	US TV
58 minor	5 minor
88 TV only	
8 full room	
11 full house	

3. LCA Model

A schematic flow chart describing the Fire-LCA model is also shown in Fig. 1. In essence the Fire-LCA model represents a modification of a conventional LCA in that it includes emissions from fires.

The fire emissions data for the “TV only” and “full room” categories in Table 1 were obtained through full scale experiments. In these experiments a large variety of species were measured including HCl, HBr, HCN, NO_x, SO_2, CO, CO_2, PAH, dibenzodioxins and furans, TBBP A, deca-BDE, and PCB. Full emissions results from these experiments are summarised elsewhere (Simonson *et al*, 2000).

An LCA evaluates the environmental situation based on ecological effects and resource use but does not cover the economical or social effects. In an LCA, a model of the system is designed which is, of course, a representation of the real system with various approximations and assumptions.

In a conventional LCA the risk factors for accidental spills are excluded. Thus, in the LCA data for the production of a chemical, only factors during normal operation are considered. There can, however, also be emissions during an accident in the factory. Those emissions are very difficult to estimate due to a lack of statistical data and lack of emission data during accidents. The same type of discussion exists for electric power production in nuclear power plants. Fires are slightly different to industrial accidents of the type described above, as a wealth of statistics is available from a variety of sources (such as the Fire Brigades and Insurance Companies). As shown in the previous section differences in these statistics between countries and different sources in the same country provide information concerning the frequency of fires and their size and cause.

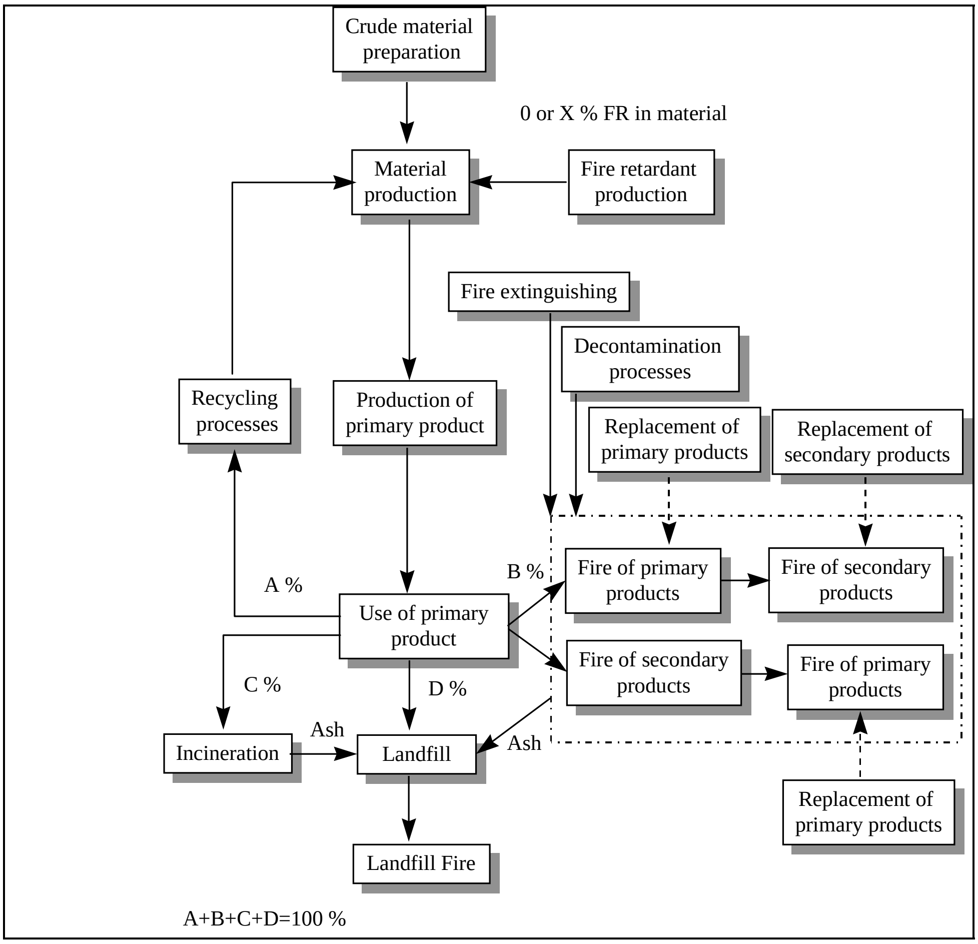

Fig. 1: Schematic representation of the Fire-LCA model.

A great deal of data is needed as input to this LCA model. Not only do we need well defined fire statistics to define flow into the fire part of the model, we also need basic input for the production of all raw material and the manufacture of the TV. Similarly, we require input information concerning energy requirements and emissions from the various end-of-life scenarios available, i.e., recycling, energy recovery and landfill. A fourth alternative would be possible in the case of brominated flame retardants, i.e. bromine recovery. Too little is known at present about this alternative so it has not been included in this TV LCA.

4. Results and Discussion

A large number of results are available due to the large number of input parameters present in the model and complex flows through the entire life cycle. Results are presented for a present day scenario and a future scenario. In the present day scenario 1% of TV sets go to incineration, 2% go to disassembly (for recycling) and the rest go to landfill (with the exception of those involved in fires). In the future scenario 1% go to incineration, 89% to disassembly and the rest to landfill. The future scenario has been modelled based on possible future waste treatment system, designed for the year 2010. It should be noted that the TV enclosures from disassembly are directed to incineration. It is assumed that all incineration is run with energy recovery.

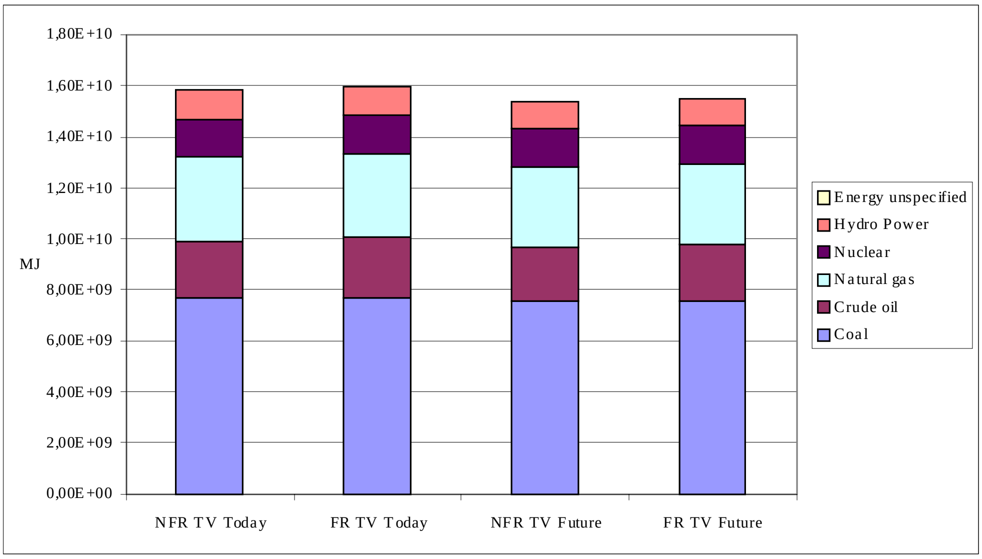

Fig. 2: Comparison between the different scenarios shows only small differences in the energy use.

The energy requirements (see Fig. 2) throughout the whole life-cycle come from many parts of the model. The majority of the energy requirement comes from the “USE” module. This corresponds to the energy requirements for running the TV during its functional lifetime. The mixture of energy in the “USE” module corresponds to the standard OECD mixture for the production of electricity. This is based on data available for 1997.

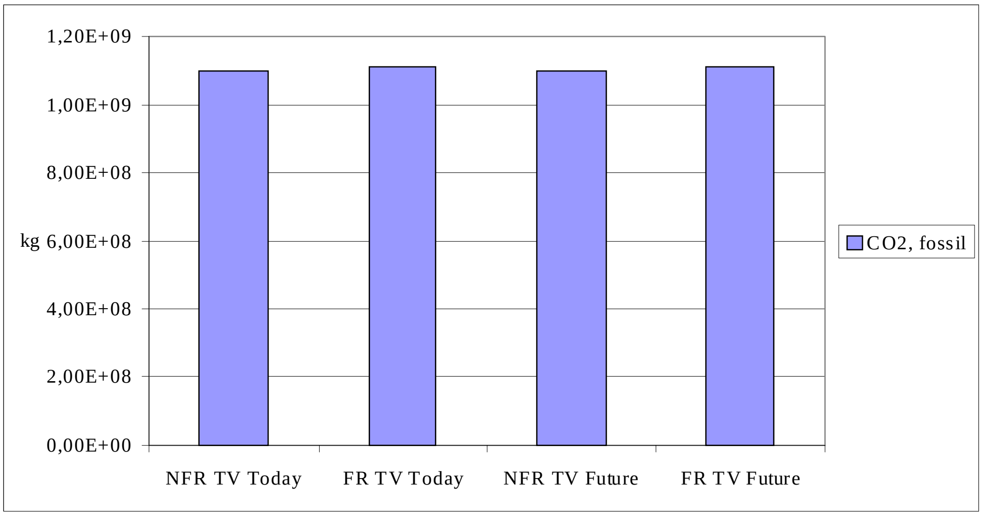

Fig. 3: Comparison of CO_2 emission for 10^6 TV set over their 10 year life cycle.

Fires represent a small part of the total emissions of carbon dioxide (CO_2) in the TV life-cycle. The majority of the CO_2 emissions come from the production of energy during the TV USE and PRODUCTION modules. The emissions of CO_2 from the fire part of the model cause the total CO_2 emissions for the FR TV to be slightly lower than those for the NFR TV (see Fig. 3). The effect is, however, in the region of the uncertainly of the LCA input.

The results for emission of polycyclic aromatic hydrocarbons are very different to those for CO2. A significant decrease is seen in the PAH emissions for the flame retarded (FR) TV relative to the non-flame retarded (NFR) TV (see Fig. 4), for both the present day and future scenarios. This is a direct effect of the fact that the NFR TV is involved in a greater number of fires.

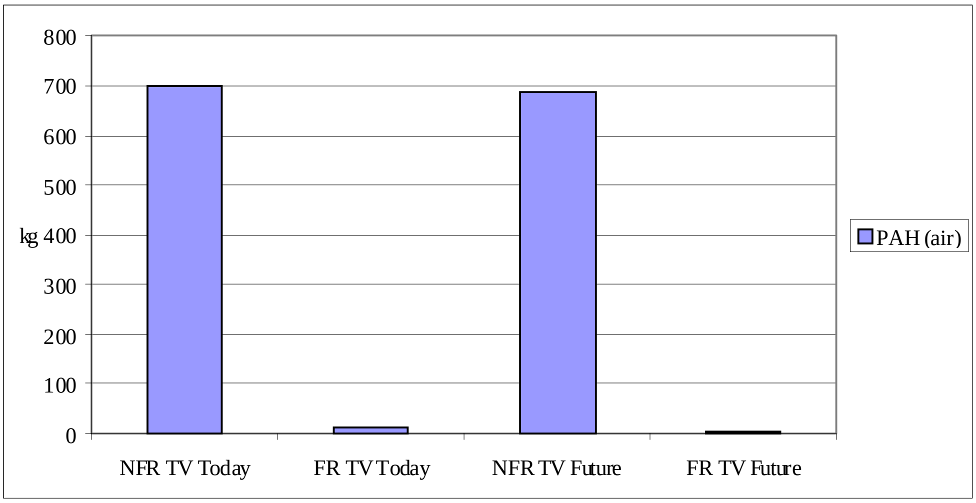

Fig. 4: The emission of PAH to the air for 10^6 TV set over their 10 year life cycle.

Similarly, a significant decrease is seen in the TCDD-equivalents for the FR TV relative to the NFR TV (see Fig. 5), for both the present day and future scenarios. The TCDD-equivalents are based on EADON factors as the majority of other input information from other sources throughout the life-cycle cite EADON values. In the full report of this study more recent factors are also considered.

There is presently no accepted international method of defining TBDD-equivalents. For the sake of simplicity we have assumed that the same factors can be used to define the toxicity of the various members of the PBDD-equivalents as those used for the chlorinated variety. As in the case of TCDD-equivalents, a significant decrease is seen in the TBDD-equivalents for the FR TV relative to the NFR TV (see Fig. 5), for the present day scenario. This is changed to an increase in the future scenario.

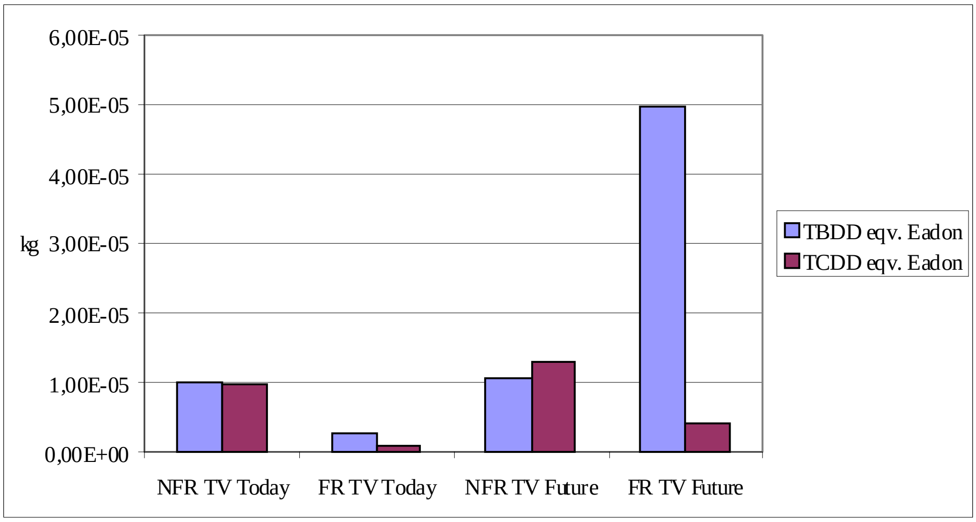

Fig. 5: The emission of TCDD and TBDD equivalents to the air for 10^6 TV set over their 10 year life cycle.

Again the result for the present day scenario is a direct effect of the fact that the NFR TV is involved in a greater number of fires than the FR TV. The fact that the TBDD-equivalent emissions increase for the FR TV in the future scenario is a direct result of the allocation of a small amount of TBDD-equivalent emissions to all FR TV enclosures sent to incineration and energy recovery. The TBDD-equivalents are allocated according to bromine content and in our model it is assumed that the dioxin emission limit proposed in the waste directive, i.e., 0.1 ng TCDD eq./Nm^3, is met. Thus, the maximum emissions can be estimated to this value for a normal chlorine content in the waste. Assuming an average halogen content of 5000 mg/kg waste and a flue gas flow of 5 Nm^3/kg waste at 11% O_2, the dioxin emission is estimated to be 0.50 ng TXDD equiv./kg waste or 0.10 ng TXDD-equivalent per g halogen input. The amount of TBDD-equivalent produced is then calculated in direct relation to the amount of bromine input to the energy recovery facility in the form of TV enclosures.

One should also note that the production of PAH is many times higher than the production of all types of dibenzodioxins and furans. In light of the large amount of PAH produced throughout the TV life-cycles relative to dibenzodioxins and furans it is reasonable to conclude that PAH emissions represent a much greater risk to health and the environment that TCDD-equivalent and TBDD-equivalent emissions. A model is available for the comparison of different pollutants based on the assignment of “Unit Risk Factors” (Spindler, 1997). Using this “unit risk” model one can compare the risk that a person exposed to the same quantity of different substances over their lifetime would develop cancer. The application of the model requires that the PAH emissions be reduced to a single toxicity equivalence factor in essentially the same manner as that for dibenzodioxins and furans. In the case of PAH the species benzo(a)pyrene, or BaP, that has been defined as the most toxic species and assigned a toxic equivalence factor of 1. All other species are then assigned toxic equivalence factors relative to BaP, allowing the calculation of BaP-equivalents (Nisbeth and LaGoy, 1992).

It has not been possible to do this for the majority of PAH emissions as we do not have information concerning the specific species emissions hidden behind the general term “PAH”. A reduction of the amounts of the various PAH emitted from our room fire experiments, however, indicate that the BaP-equivalent of our room fire gases is approximately 3% of all the PAH emissions. Thus, the BaP-equivalents for the full LCA models have been estimated as 3% of the total PAH production.

Table 2: Cancer risk of PAH relative to TCDD-equiv. for each scenario.

Species	Unit Risk factor (URF)	NFR today	FR today	NFR future	FR future
BaP-equiv. (kg)	7×10^{-2} μg/m^3	1.46	3.05×10^{-2}	1.44	7.60×10^{-3}
TCDD-equiv. (kg)	1.4 μg/m^3	1.36×10^{-5}	1.01×10^{-6}	1.82×10^{-5}	5.71×10^{-6}
Cancer risk factor*		108000	30200	79200	1300

*(BaP-equiv.$\times$URF$_{BaP}$) / (TCDD-equiv.$\times$URF$_{TCDD}$), the values have been rounded to the nearest 100.

Based on the toxicity analysis presented in Table 2 it is clear that PAH emissions from the whole life-cycle of one million TVs represents a far greater risk than that of dibenzodioxins and furans. This risk is significantly higher in the case of NFR TVs relative to FR TVs, both in the present day scenario and the future scenario. This effect is largely due to the increased number of fires in the NFR TV models relative to the FR scenarios. This confirms results recently presented concerning PAH and dibenzodioxin emissions from large fires in Germany (Troitzsch, 2000).

5. Conclusions

Results from a comparison between the LCA of a TV with V0 enclosure material to that with HB enclosure material indicate that the original postulate that ”it would be better to allow things to burn more often rather than use flame retardants” is questionable. In the case of a number of key emission species there is a markedly higher total emission over the whole life cycle from the NFR TV than from the FR TV in the present day scenario, although the picture becomes more complicated in the future scenario.

The emissions with the most marked difference between in FR and NFR TV sets reflect those species that can be minimised from all controlled combustion sources. These include PAH and TXDD-equivalents. The emission of PAH dominates over the emission of TXDD-equivalents. Thus, the PAH emissions represent a far greater cancer potential that the TXDD-equivalent emissions.

Fires are not, however, the dominant source of those species (such as CO, CO_2, NO_x etc) that are given off in abundance from controlled combustion. Controlled combustion, as in the case of energy production, gives rise to large amounts of CO and CO_2. In this case the differences in total emission due to fires is marginal. This has been predicted previously (Persson and Simonson, 1998) and is a confirmation of the fact that the emission of organic compounds such as PAH and dibenzodioxins and furans is perhaps the major environmental problem associated with fires.

Finally, in a risk analysis it is important to consider all potential risks. In this context it should be emphasised that according to European statistics at least 16 people die each year and 197 are injured as a direct result of TV fires. This number is a conservative estimate from a study conducted by the UK Department of Trade and Industry (DTI, 1996). A true estimate may be up to 10 times this number. In the US, however, there is no record of people dying as a result of a TV fire. Thus, the risk to human lives of a fire should not be neglected in an overall assessment of the risk of flame retardants.

6. Acknowledgements

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