EVALUATION OF THE RISK TRADE-OFF CONCERNING BROMINATED FLAME RETARDANTS IN EU
– PHASE OUT OF DECA-BDE AND INCREASE OF TV FIRES -

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Abstract
We focused on Decabromodiphenyl ether (DecaBDE), which is known as cost-effective brominated flame retardant used in TV enclosure components, for the evaluation of risk trade-off caused by the avoidance of its use. Risk trade-off framework, which enables to evaluate and compare the different type of risks, such as human health risk and fire risk is constructed. To date, several governments, especially in EU, made clear that their approach against environmental issue is based on the precautionary principle. Thus, there observed a tendency to place more value on human health risk than physical risk (i.e. fire risk in this case). In the current study, we tried to quantify and compare these risks. At first, we conducted a Cost Benefit Analysis (CBA) considering human health impacts of DecaBDE use and both economic and health damage by TV fires. The results suggested that net benefits of DecaBDE use were positive under all the five scenarios considered. Secondly, we tried to re-evaluate the net benefits of DecaBDE use by replacing the rate of TV fires with more stringent one. Although it diminished fire rate by 75%, under the most realistic two scenarios, results showed positive net benefits of DecaBDE use.

Introduction
The brominated flame retardants (BFRs) have been used in various applications for its good flame retardancy, cost-effectiveness and good mechanical property. In the 1980s, however, it had become clear that BFRs were unevenly distributed in various environmental media. BFRs have been reported to have various types of environmental issues due to their PBT/vPvB property, conversion to lower brominated compounds, and long-range transport, thus, they are now under international regulations such as Stockholm convention.

1. Human health effects of DecaBDE are not quite significant presently but more researches are ongoing. Decabromodiphenyl ether (DecaBDE) is one of BFRs mainly used as additives in High Impact Polystyrene (HIPS) of Cathode Ray Tube Television (CRT-TV) enclosure for preventing TV fire. Nowadays, non-negligible human exposures to DecaBDE are reported to occurring. However, results of many risk assessment reports indicated that no adverse health effects were expected due to the satisfactory margins of safety. European Chemicals Bureau (ECB) concluded that there were at present no need for further information and/or testing, and no need for risk reduction measures beyond those which had been taken already to protect both human health and the environment[1].

2. There is a certain relationship between the elimination of DecaBDE use in TV enclosure components and increase of TV fires. In the early 1990s, the anti-halogen stance of some environmentalist groups in Europe did a number of legislative activities to restrict the use of certain halogenated flame retardants. In middle of the 1990s, TV fire suddenly increased to a higher level in EU countries, because many TV manufacturers had voluntarily called off using DecaBDE in HIPS in accordance with some environmental labeling systems like Blue Angel. Monitoring results of composition of TV enclosure reported in magazines showed a strong trend away from the use of halogenated additives in plastics[2]. This phenomenon is represented as a typical case of risk trade-off of environmental risk and fire risk. It is important to consider risks from various view points; the TV manufacturers

should have considered reducing the sum of all kinds of risks, but not just reducing one risk which are focused on environmental risk. Although almost all the literature reported the usefulness of flame retardants, the benefits of flame retardants, which increase human health risk as well as reduce TV fire risk, were just qualitative[3, 4, 5, 6].

3. What we want to do is not qualitative comparison but quantitative CBA. In the current study, we tried to evaluate the relationship of risk trade-off of those risks quantitatively. Benefits of DecaBDE use in TV enclosure components are 1) preventing deaths and injuries, and 2) protecting properties. On the other hand, costs of DecaBDE use in TV enclosure components cause 1) consuming cost of DecaBDE, and 2) social cost of human health effects (in the current study, we presumed "cost" was nearly equal to "risk"). In addition, we tried to answer the following questions; Do the benefits, which obtained as reducing number of TV fires, overweigh the human health risks caused by exposure to DecaBDE, and how much the margin of benefits are there?

Methods

In 2006, Simonson et al. had conducted CBA concerning the DecaBDE use in TV enclosure components for the first time[7]. However, critical error in their process and limitation of its CBA model were suggested (especially following 1), 2)). Thus, we repaired their problems and developed a new CBA model. The improved points are as follows: 1) Assuming the costs and benefits as non-steady state, 2) Excluding the cost for deposition of TV, 3) Taking adverse effects to human health of DecaBDE used in TV enclosure components into account, and 4) Taking uncertainties of several parameters into account, using Monte Carlo Simulation. The ranges of uncertainties obtained from the results were calibrated by sensitivity analysis.

Analytical scheme: we assessed the costs and benefits of DecaBDE use in each stage of life cycle of TV, i.e. manufacturing, usage (exposure to DecaBDE, occurrence of TV fires), deposition stages (these scenarios are based on the CBA by Simonson). And we estimated the costs and benefits of DecaBDE use, comparing the cases for flame retarded TV (FR-TV) use and non-flame retarded TV (NFR-TV) use (Fig. 1). Noted that we assumed very simple case, in which FR-TV had changed to NRF-TV by avoiding DecaBDE in EU.

Widespread pattern of FR-TV: We can assume two scenarios concerning widespread usage of TV, steady state and non-steady state in purchase behavior of TV. The former state means "gained benefits from FR-TV is saturated", because this scenario assumes the TV has already well-distributed and additional benefits from purchasing FR-TV could not be expected (formula (1) and Fig. 2,). Meanwhile the latter means "gained benefits from FR-TV are developing", because this scenario assumes the FR-TV is gradually spreading at constant rate x% (x is derived from life cycle of TV) (formula (2) and Fig. 3). It is clearly apparent that gained annual benefits in steady state scenario are larger than non-steady state one. The formulas deriving respective annual benefits are as follows (in this formula, we assumed life cycle of TV is uniformly 10 years);

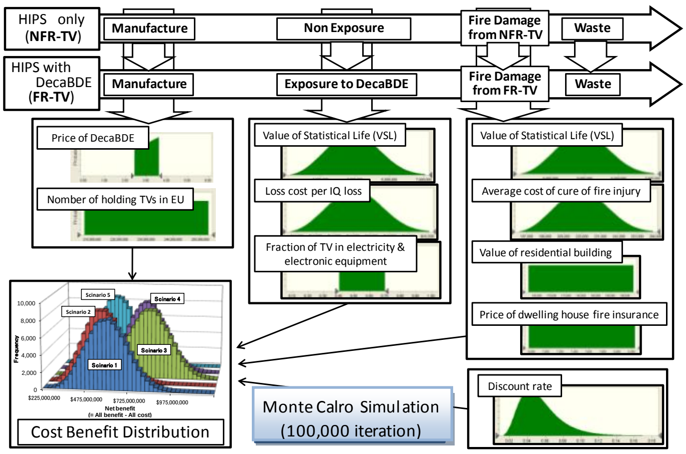

Fig. 1 Schematic of DecaBDE CBA
(Only the parameters with distribution are shown)

Steady state: $$\sum_{n=1}^{10}\frac{\overline{B}}{(1+r)^{n-1}}=\sum_{n=1}^{10}\frac{10B}{(1+r)^{n-1}}$$

$$\therefore\ \overline{B}=10B \qquad (1)$$

Non-steady state: $$\sum_{n=1}^{10}\frac{n\times B}{(1+r)^{n-1}}=\sum_{n=1}^{10}\frac{\overline{B}}{(1+r)^{n-1}}$$

$$\therefore\ \overline{B}=\frac{r}{(1+r)-(1+r)^{-9}}\sum_{n=1}^{10}\frac{n\times B}{(1+r)^{n-1}} \qquad (2)$$

(B : gained annual benefits at present when 10% FR-TV of all possessed TV have been replaced in EU (US$/year); $\overline{B}$: gained annual benefits (US$/year); r : discount rate; n: year)

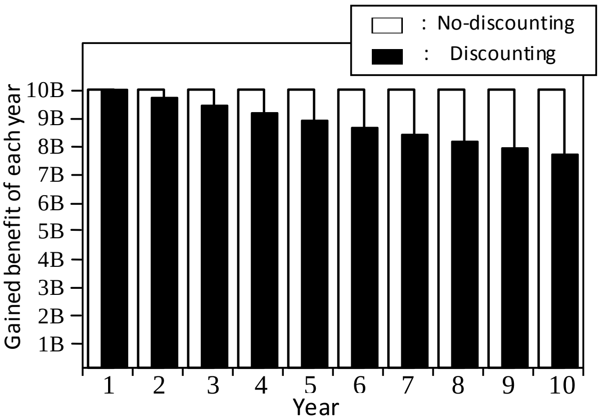

Fig. 2 Conceptual diagram for gained annual benefits (steady state, present value)

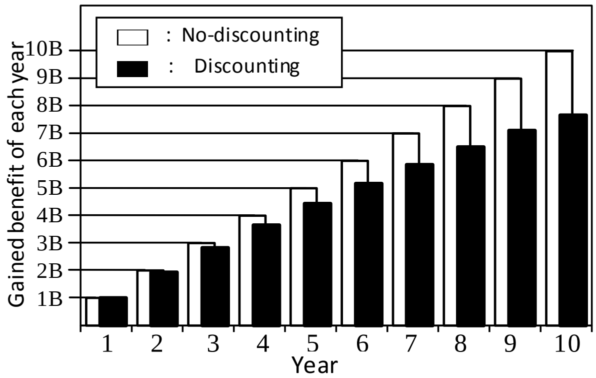

Fig. 3 Conceptual diagram of gained annual benefits (non-steady state, present value)

The method used by Simonson is different from both formulas (1) and (2) (formula (3)). Formula (1) should have been used in the CBA by Simonson, because Simonson assumed steady state.

Equation used by Simonson: $$\overline{B} = \sum_{n=1}^{10} \frac{B}{(1+r)^{n-1}} \qquad (3)$$

We chose formula (2) (non-steady state scenario), because 1) for the estimation of worst case scenario, and 2) for realistic consideration, such as gradual phase-out of DecaBDE in HIPS in EU. Our scenario would underestimated the benefit, compared with scenario chosen by Simonson et al., and the order of gained annual benefits would be as follows; formula (1) > formula (3) > formula (2).

Estimation of human health risks caused by DecaBDE use: Simonson et al. did not consider human health risk, which caused by exposure to DecaBDE in their CBA model with a great trust to EU risk assessment report submitted by ECB[4]. In Japan, the National Institute of Advanced Industrial Science and Technology, Research Center of Chemical Risk Management, equally concluded that there was no significant human health risk by

Table 1 Extrapolating the human health risks by DecaBDE estimated in Washington State model into EU

	Lifetime health impact	Case number	Unit value	Time conversion index	Converted value (2005 price)
Parameters in Washington-model[8]	Annual Cancer	5	$US\$_{2004}$ 26,976	1.034	US$139,466
	Annual Cancer Mortality	4	$US\$_{1990}$ 4,800,000*	1.495	US$28,704,000
	Annual Hypothyroid Case Entering Treatment	2,400	$US\$_{2004}$ 7,940	1.034	US$19,703,904
	Annual Subclinical Hypothyroid Pregnancies	30	$US\$_{2004}$ 7,940	1.034	US$246,299
	Annual IQ impacts	210	$US\$_{2000}$ 14,500**	1.134	US$3,453,030
	Delay to replace electronics [-][8]				0.87
	Delay to disorder timing [-][8]				0.91
Extrapolating Washington to EU	$Deca_{E\&E}/Deca_{All}$	Range: 0.8~0.9, uniform distribution derived from Lassen et al.[9]			
	$Deca_{TV}/Deca_{E\&E}$	Range: 0.97~0.98, uniform distribution derived from Lassen et al.[9]			
	TV_{WA}	Median: 26.8 million TV, Range: ±10%, uniform distribution (to reflect on sensitivity analysis.)			
	TV_{EU}	Median: 230 million TV[7], Range: ±10%, uniform distribution (to reflect on sensitivity analysis.)			
	Annual costs in EU by loss of human health (median value)				$US\$_{2005}$ 25,726,392

* Median value. Detail is shown in Table 3, "VSL" column. Shaded column means the parameter with distribution (Same manner are used hereafter).

** Using Washington model's adoption; Range: US$12,700~US$17,000, Weibull distribution, type 3.

Table 2 Scenarios for our CBA calculations

Scenario	Discount rate	Human health risk	House fire
1	No	Yes	No
2	Yes	Yes	No
3	Yes	No	Yes
4	Yes	Yes	Yes
5	Yes	Yes	Indirectly (Insurance)

DecaBDE use in Japan. However, we assumed that adverse human health effects caused by DecaBDE to gain an understanding of margin of net benefits (total benefits minus total costs). Thus, we chose the model of Washington State Departments of Ecology and Health (Washington-model), which estimates potential social benefits generated by banning the DecaBDE use[8] (Table 1). We are concerned here only about four health impacts because we can get only their unit values which convert health impacts to costs.

At this moment, let us try roughly some amount of investigation about DecaBDE's human health effects estimated in Washington-model. We can estimate cancer risk from the number of "annual cancer mortality" and population in Washington State, resulting $4.5x10^{-4}$. If this estimate is true, then, it may lead directly to ban of DecaBDE not only in Washington State's region, but also at the global level. Consequently we thought it was easy to say that Washington-model was overestimating the human health risks by DecaBDE use. In the current analysis, we extrapolated Washington-model to EU by estimating that it is in proportional relationship to both the number of possessed TV and human health risks by DecaBDE used in TV enclosure components (formula (4)). Their parameters are indicated in Table 1. In the current analysis, we use the change fraction of Consumer Price Index (CPI) for converting old value into present value, and Gross Domestic Product (GDP) rate based on Purchasing Power Party (PPP) per capita for integrating circulated money into US dollar.

$$Effect_{EU} = Effect_{WA} \times \frac{Deca_{E\&E}}{Deca_{All}} \times \frac{Deca_{TV}}{Deca_{E\&E}} \times \frac{TV_{EU}}{TV_{WA}} \qquad (4)$$

($Effect_{EU}$, $Effect_{WA}$: Health impacts of DecaDBE use in EU and Washington State, respectively; $Deca_{All}$: Amount of DecaBDE consumption in EU; $Deca_{E\&E}$: Amount of DecaBDE usage in electrical and electronics equipments in EU; $Deca_{TV}$: Amount of DecaBDE usage in TV enclosure components in EU; TV_{EU} , TV_{WA} : The numbers of TV possessed in EU and Washington State, respectively)

Exclusion of deposition stage: Simonson took the cost for destruction of TV into account, considering the differences of FR- and NFR-TV's life cycle[3]. But we did not believe that there was difference in waste cost between FR-TV and NFR-TV. Thus, we did not take this cost into account.

Table 3 Parameters for calculation, and their distributions for Monte Carlo Simulation

Parameter	Value used in this analysis	Reference
Cost of DecaBDE	Min: US$0/TV, Max: US$3.30/TV, Maximum likelihood value: US$3.30/TV, Triangle distribution [US$2.00/TV, US$3.30/TV]	Ref. 5, 7, 10
Value of Statistical Life (VSL)	Av: US$$_{2005}$7.2 million, SD: US$$_{2005}$4.84 million, Weibull distribution, type 3	Ref. 11
Social costs of DecaBDE's health impact	cf. Table 2	—
Average cost for treatment of fire victims	Median: US$180,000, 90%tile: US$225,000, Normal distribution	Estimation based on Ref 7, 12
Discounting rate	5%tile:3%, 95%tile:10%, Lognormal distribution	Ref. 13
TV life-cycle	10 year	Estimated value
Number of deaths avoided per year	160 persons/year	Ref. 7
Number of injuries avoided per year	2,000 persons/year	Ref. 7
Number of full fire-damaged houses avoided	11 /million TV/year	Ref. 7
Average cost of restoring full-damaged house	Median: US$ 180,000, Range: ±10%, Uniform distribution (to reflect on sensitivity analysis.)	Ref. 7
Number of TV fires avoided (including housing fire)	107 /million TV/year	Ref. 7
Average cost per fire (based on statistics from Swedish fire insurance)	Median: US$ 7,500, Range: ±10%, Uniform distribution (to reflect on sensitivity analysis.)	Ref. 7

Results and Discussion

Results: We estimated and compared 5 scenarios based on CBA by Simonson using parameters shown in Table 2 and 3. We conducted Monte Carlo Simulation (100,000 iteration) and the results are shown in Fig. 4. The result of the sensitivity analysis is shown in Fig. 5. Fig. 4 suggested that the benefits gained by adding inflammability overweighed its costs (= risk) even when human health impacts were included. In addition, it was strongly suggested that human health risks were too small to be ignored (comparing the Scenario 3 and 4), and that one parameter, which was average cost per housing, affected the result considerably (comparing the Scenario 3, 4 and other scenarios).

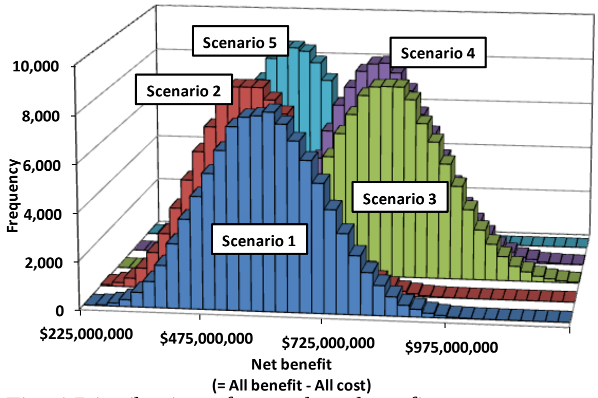

Fig. 4 Distribution of annual net benefits (before VSL was re-evaluated)

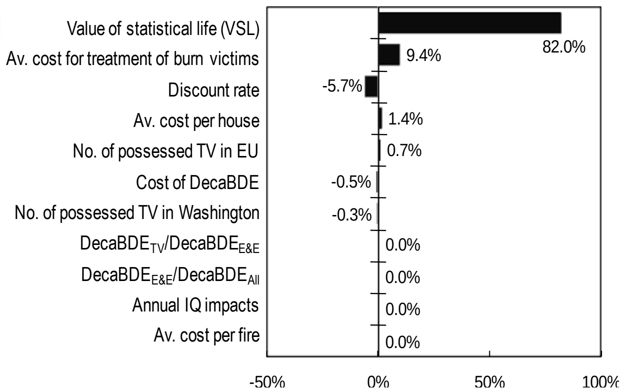

Fig. 5 Sensitivity Analysis between net benefits and parameters (Fig. 4, scenario 4)

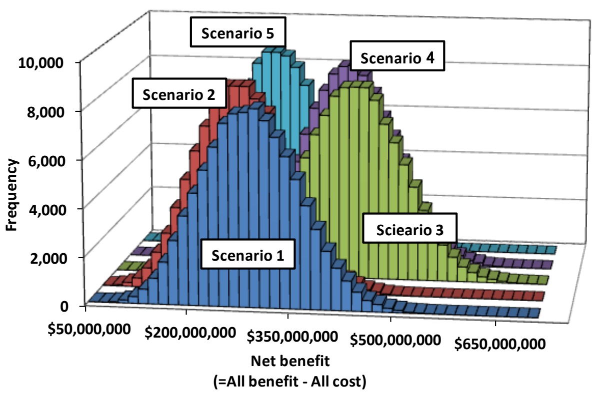

Fig. 6 Distribution of annual net benefits (after VSL was re-evaluated)

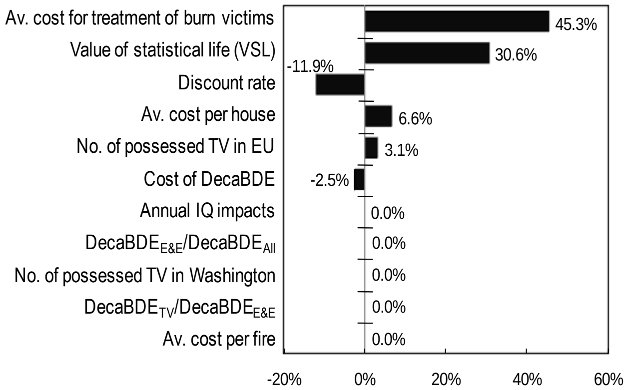

Fig. 7 Sensitivity Analysis between net benefits and parameters (Fig. 6, scenario 4)

Re-evaluate VSL as realistic value: We re-evaluated the distribution of VSL and re-calculated by our CBA model, because the uncertainty of VSL significantly influenced net benefit distribution (Fig. 5). Table 4 represents official VSL in several EU countries and that it had the following distribution; Av.: US$$_{2005}$1.77 million and SD: US$$_{2005}$0.38 million. We re-evaluated our CBA by adopting lognormal distribution using official VSL in several EU countries for unifying official VSL in EU (Fig. 6, 7). Official value of VSL in EU, incidentally, is covered into this distribution[18]. Fig. 7 represents that the sensitivity of VSL clearly decreased and sensitivity of other parameters increased. The results shown in Fig. 6 suggested that all the

Table 4 List of official VSLs in several EU countries

Country	Official VSL of every country	VSL(US$$_{2005}$)
United Kingdom	£$_{1997}$ 1.00~1.60 million[14]	1.60~2.56 million
	£$_{1998}$ 1.05 million[15]	1.94 million
Sweden	SEK$_{1997}$ 14.3 million[16]	1.56 million
Finland	FIM$_{1999}$ 11.26 million[17]	1.98 million
Germany	¥$_{2004}$ 177 million[13]	1.20 million
Netherlands	¥$_{2004}$ 296 million[13]	2.02 million

scenarios assumed distribution was reconstructed with relatively narrow ranges, and the median shifted to lower net benefit. And ($Median_{Scenario3} - Median_{Scenario4}$) / $Median_{Scinario3}$ equaled 0.0036; it could be deduced that human health impacts affected net benefits only by 0.36% increase.

Re-evaluation of TV fire using more stringent data in our CBA: T. Muir raised questions regarding the method to expand the data, number of TV fires, from local town in Sweden to entire of EU, which conducted by Simonson, and he did this extrapolation from same raw data[19]. He estimated that the number of annual deaths avoided were 20-89 persons/year (median: 46), and the number of annual injuries avoided as 242-1,097 persons/year (median: 565), meanwhile estimation by Simonson is in Table 3. Clarke also quantified the benefit obtained from BFR use in the USA[20]. His analysis was conducted based on the data of TV fires in US. Table 5 shows TV fire rates which were normalized by dividing by number of TVs in the estimated area, respectively (Table 5). In the current study, the data estimated by Muir was chosen as worst case. The result is shown in Fig. 8. There is a possibility that the net benefits of Scenario 1, 2 and 5 were under zero (respectively 15%, 10%, 2%), although these scenarios were unrealistic. In contrast to them, it was impossible for the net benefits of Scenario 3 and 4 to be under zero. Thus, it is summarized as follows: although we decreased TV fire rate by 75% (Muir's estimation), the results even showed positive net benefits of DecaBDE use at the very least under the most realistic scenarios.

Table 5 Data of fire damage rate
(Unit: person/year/million TV)

	Deaths avoided	Injuries avoided
Simonson	0.696	8.70
Clarke	0.415	5.18
Muir	0.200 (0.087-0.387)	2.50 (1.05-4.77)

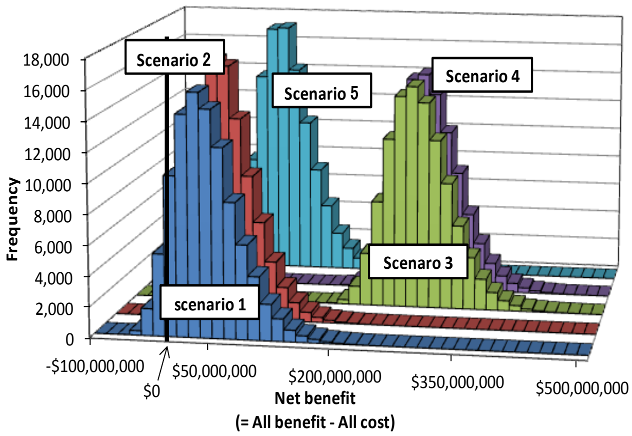

Fig. 8 Distribution of annual net benefits by using Muir's estimation of TV fire's data

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