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Environmental Balances of Thermal Superinsulations[1]

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This paper introduces environmental balances for three different thermal insulation concepts (evacuated multi-foils, evacuated glass fibers, and a conventional foam insulation) of a 300 L LN_2 storage tank. The calculations are based on material consumptions in the manufacturing phase and thermal losses of the tank during the use phase. Materials consumption is identified from the design of the tank taking into account stainless steel containers, thickness of container walls, mechanical supports, bellows, getter, and insulation materials. Thermal losses are calculated using finite element methods. It is demonstrated that evacuated multi-foil insulation is, from energetic *and* environmental considerations, by far superior to evacuated glass fibers and to conventional foam insulation. Its environmental "amortization time" (a return on investment when outbalancing environmental impacts by corresponding savings) is in the order of 80–160 weeks of operation. This also demonstrates that it is important to apply an environmental life cycle perspective, and not analyze only the energetic and materials aspects, when new technologies are assessed.

KEY WORDS: efficiency; finite elements, life cycle assessment; thermal superinsulations.

1. INTRODUCTION

Thermal superinsulations have a permeability to heat flow significantly below that of air. Minimum heat losses are achieved with evacuated,

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highly reflecting metal foils. This type, with a discontinuous structure, also includes Dewar (thermos) flasks, and locally supported multilayer insulations. Another means to achieve very small heat losses is to evacuate beds of finely divided solids (e.g., glass fibers or ceramic powders).

A very large variety of papers, and some traditional textbooks, describe experimental determinations of heat losses and analysis of heat loss components at cryogenic and high temperatures in superinsulations; for a survey, see, e.g., Refs. 1 and 2 and the literature cited therein. However, few investigations have been presented for environmental load balances (life cycle assessment (LCA)) of superinsulations. It is important to conduct such investigations for standard and new technologies to keep up with the demand for a sustainable society.

As for all industrial products, the LCA of superinsulations comprises an analysis during manufacturing (including material extraction and production), use, and disposal phases. Energy savings by superinsulations during the use phase considerably reduce, e.g., CO_2 emissions to the atmosphere. We present an analysis to what extent these energy savings will outbalance emissions during manufacturing, in comparison to a conventional thermal insulation. This immediately leads to the question whether (like *energetic* break-even points identified, e.g., for power plants) an *environmental* break-even point can be defined for thermal superinsulations.

2. DESCRIPTION OF THE INVESTIGATED INSULATIONS

The following analysis is applied to the insulation of a 300 L LN_2 storage tank. Three insulation concepts are considered:

- evacuated, highly reflecting multi-foils,
- evacuated glass fibers,
- a conventional polyurethane foam insulation.

Dimensions of the tank, neck, and bellows and corresponding thicknesses of the wall materials (mostly stainless steel) are given in Table I (the same dimensions as for the tank described in Ref. 3, where thermal and fluid resistance networks were introduced to calculate heat losses and residual gas pressures in a multi-foil insulation). In the present paper, heat losses are calculated from two-dimensional (2D) finite element (FE) calculations (exploiting cylindrical symmetry of the tank) using a commercially available computer program. For the case of the multi-foil insulation, the total mass of the empty tank (144.5 kg, including mechanical supports and three wheels) and storage volume (294.5 L) approaches the Messer Cryotherm Apollo 300 tank.

Table I. Dimensions of the Insulated Tank (all in mm)

	Insulation concept 1	Insulation concept 2	Insulation concept 3
Height of inner container	1500	1500	1500
Inner diameter	500	500	500
Thickness of side walls	3	1.5	1.5
Thickness of top/bottom walls	4	1.5	1.5
Thickness of insulation space	20	60	400
Outer container: thickness of side walls	2.5	0.8	1.5
Thickness of top walls	3.5	1	1.5
Length of the neck	400	400	400
Thickness of outer walls	2	0.8	1.5
Effective length of the bellow	800	600	600
Inner diameter	30	30	30
Thickness of side walls	0.5	0.5	0.5

As for the Apollo 300 tank, daily evaporation losses shall not be larger than 0.5%. Assuming the tank is filled to 95% of its volume (a rather high filling level), this means permanent heat losses must not exceed 2.66 W.

2.1. Concept 1: Evacuated Multi-foils

The tank is insulated with 30 highly reflecting radiation shields (6 μm Mylar foils metallized with 40 nm Al on both sides), with spacers in-between, wrapped around the inner container and the bellows, over their lengths and on upper and lower front sides of the tank. At the top and bottom of the tank, complete overlap of the foils is assumed. A tissue, with a thickness of 55 μm (knit woven from monofilament polyester yarn), is used as spacer material. Getter material is supplied to the tank to maintain the vacuum (clearly below 10^{-2} Pa). Re-evacuation, and exchange of the getter material, is assumed every 5 years of operation. The width of the insulation space is 20 mm. The inner and outer containers, neck, bellows, and mechanical supports of the tank yield a material consumption of 140.9 kg stainless steel.

We will not duplicate calculation of the total (pseudo-) thermal conductivity through the multi-foil insulation (details are described in Ref. 3). Addition of all thermal conductivity components (radiation, residual gas pressure, contact conductivity) yields a total (pseudo-) thermal conductivity of 4.482×10^{-5} $\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$ through 30 foils and spacers *normal* to the shield and wall surfaces; this value yields rough agreement (within 10%)

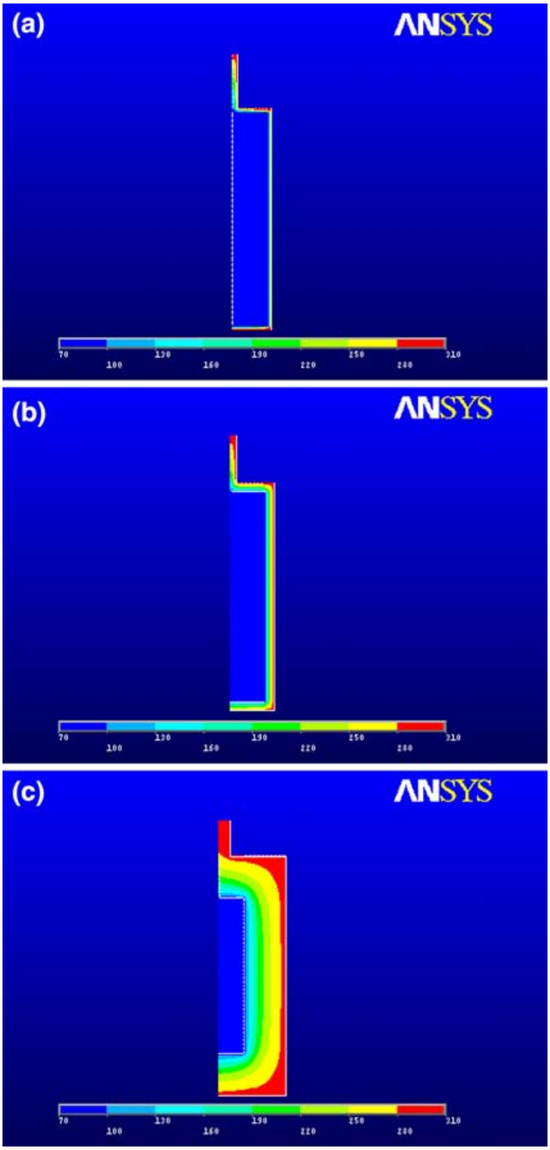
between experimental and calculated total heat losses of the storage tank (see end of this subsection).

A numerical analysis of temperature profiles on each of the discrete foils and spacers would neither be reasonable (from numerical efforts) nor is it required for the present purpose. Instead, we have considered a *continuous* filling of the insulation space using the (pseudo-) thermal conductivity for heat flow *normal* to foil surfaces, while a corresponding (pseudo-) thermal conductivity for heat flow *parallel* to the 30 foil surfaces was estimated from another thermal resistance network resulting in 5.57 $\mathrm{mW{\cdot}m^{-1}{\cdot}K^{-1}}$ (with the same accuracy as before). Furthermore, temperature-dependent thermal conductivities of wall materials and of nitrogen vapor above the boiling liquid, and free convection on the outer container with a heat transfer coefficient of 6 $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ to ambient, have been used in the FE calculations. The total heat loss of the tank then amounts to 2.578 W, slightly lower than the 2.73 W resulting from the thermal network in Ref. 3. Both results roughly meet the 0.5% evaporation loss criterion (2.66 W). The temperature profiles resulting from the FE-calculation for this insulation concept are shown in Fig. 1a.

2.2. Concept 2: Evacuated Glass Fibers

The width of the insulation space is now 60 mm to, at least, approach the 0.5% evaporation losses within a factor of 10 while keeping the total volume of the tank within an acceptable size (although the tank is used for stationary applications, too thick an insulation would lead to intolerable mass increase). Since glass fiber boards (made from glass fibers by a thermo-fixation process) are mechanically load-bearing, the thickness of the metallic walls of the inner and outer containers can be reduced; compare Table I. This results in only 99.9 kg stainless steel consumption. The density of the glass fiber boards is 240 $\mathrm{kg{\cdot}m^{-3}}$. Fine magnetite powder (15% of glass fiber mass) is used as an opacifier to the glass fibers, and again the getter material is introduced to the insulation space. The lifetime of the vacuum (1 Pa) in the glass fiber insulation is assumed to be 10 years, before re-evacuation and new getter material would be necessary. The total mass of the empty tank (same volume as before) including neck, bellows, glass fibers, mechanical supports, and wheels is about 157.2 kg, which does not substantially exceed the mass (144.5 kg) of the superinsulated tank when using Concept 1.

The thermal conductivity of the evacuated glass fiber boards is between 2 and 4.7 $\mathrm{mW{\cdot}m^{-1}{\cdot}K^{-1}}$ at 77 and 373 K; within this temperature interval, the thermal conductivity values were linearly interpolated. These values are representative for glass fibers with a density of 240 $\mathrm{kg{\cdot}m^{-3}}$


(a)
(b)
(c)
70
100
130
160
190
220
250
280
310

◄

Fig. 1. Cross sections of the tank for insulation concepts 1 (a), 2 (b), and 3 (c), respectively, showing temperature profiles calculated from 2D finite elements (only half of the cross section is given). Calculations use dimensions as given in Table I, thermal properties of the insulations (Concepts 1–3) as given in the text and a finite element computer program. Horizontal bars identify temperature intervals between 70 and 310 K. Thin dashed line in (a) indicates the symmetry axis of the tank.

density; compare, e.g., Ref. 4. The thermal conductivities of the other materials are taken as before.

The total heat loss of the tank from 2D FE-calculation amounts to 31.6 W. This is a factor of about 12 more than the losses achieved with Concept 1. Due to the logarithmic dependence of heat losses on insulation thickness, under cylindrical geometry, even with an insulation thickness of 400 mm, it would not be possible to meet the goal of daily 0.5% evaporation losses, 2.66 W. Calculated temperature profiles for the glass fiber insulation are shown in Fig. 1b.

2.3. Concept 3: Conventional Polyurethane (PU) Foam Insulation

For this concept, the outer stainless steel container is replaced by a fiber reinforced polymer (polyurethane) mantle, to mechanically protect the PU-foam insulation. This reduces the mass of the consumed stainless steel to 73.9 kg for the inner container, bellows, and mechanical supports. However, since the thermal conductivity of PU-foam between 77 and 373 K ranges from 15 to 45 $\mathrm{mW \cdot m^{-1} \cdot K^{-1}}$ (compare, e.g., Ref. 5), the thickness of the insulation has to be increased strongly. In the present calculations, we have assumed a thickness of 400 mm. With a density of the PU-foam of 90 $\mathrm{kg \cdot m^{-3}}$, this results in 255 kg foam and a total mass of the tank of 341 kg including inner container, bellows, mantle, mechanical supports, and wheels.

Although the insulation thickness is very large, the total heat loss, again from the 2D FE-calculation, cannot be reduced below 60.89 W. This is about twice as much as achievable with evacuated glass fibers (with an insulation thickness of 60 mm) and accordingly exceeds the 0.5% daily evaporation losses by a factor of about 23. Temperature profiles in the insulation are shown in Fig. 1c. Note the enormous thickness of the PU-insulation, in relation to the stored $\mathrm{LN_2}$ volume; yet this thickness is not enough to yield a thermal performance of the tank comparable to evacuated glass fiber insulation.

So far, the differences in the heat losses clearly identify concept 1 (evacuated multi-foils) as the best solution from a purely *energetic* point of view focussed on the operational period. The key question now is, whether this remains true also from an *environmental* standpoint. It is clear, on the one hand, that the large thermal losses of Concepts 2 and 3 will lead to a strong increase of CO_2-emissions to the atmosphere, because thermal losses of the tanks have to be compensated by additional liquefaction of nitrogen in cooling cycles; operation of a cooling machine thus will consume additional energy. On the other hand, the larger consumption of stainless steel of Concept 1, and fabrication of metallized foils for this concept, could lead to increased environmental impact in the manufacturing phase.

3. ENVIRONMENTAL BALANCES FOR THE THREE INSULATION CONCEPTS

3.1. Survey

Life cycle assessment (LCA) is a method for estimating the environmental impact during the whole life cycle of a product, from raw material extraction to until the product turns into new raw materials, or is scattered as waste. LCA is often used to compare different alternatives for materials selection, production methods, recycling and such, in an effort to reduce pollution, health hazards, and resource depletion. The aim is a sustainable society. The LCA method has been developed extensively and condensed in a variety of ISO standards (ISO 14040 to 14043, Ref. 6). Basically, the LCA method consists of the following four steps:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

The first of these items, goal/scope of the present study, has been defined in previous sections: for the goal, which insulation concept is best, from environmental standpoints? For the scope, Table II summarizes the most important materials consumed during fabrication of the tank and insulations, and during use of the tanks insulated with Concepts 1–3.

In the inventory analysis, all environmentally relevant inputs and outputs of the product system are collected, allocated to the studied product, and summarized into a life cycle inventory profile. The inputs to be considered are raw materials and energy, the outputs are wastes and emissions to land, water, and air.

For the present analysis, the energy input related to heat losses of the tank has to be corrected according to the efficiency of the cooling cycle.

Table II. Flow of Materials Used for Manufacture of the Tank (all in kg)

Insulation concept 1	
Stainless steel, total	140.6
Tombak metal or stainless steel	0.323
Polyester foil, 6 μm thickness	0.877
Tissue, 55 μm thickness, knit woven from monofilament polyester yarn (spacer)	0.530
Al 99.999% target, effective mass	0.114
Zeolite or other getter used during manufacture phase	0.090
Ethanol for cleaning of the tank	1
Rubber material for wheels	2
Permanent total mass (empty tank)	144.5
Insulation concept 2	
Stainless steel, total	99.7
Tombak metal or stainless steel	0.242
Glass fibers	47.8
Fe_3O_4-powder, mean grain diameter below 0.1 mm (opacifier)	7.17
Zeolite or other getter used during manufacture phase	0.299
Ethanol for cleaning of the tank	1
Polymer material for wheels	2
Permanent total mass (empty tank)	157.2
Insulation concept 3	
Stainless steel	73.6
Tombak metal or stainless steel	0.323
PU-foam	255.4
Fiber reinforced PU envelope (mantle)	9.14
Adhesive tape	0.761
Adhesive	0.2
Ethanol for cleaning of the inner container	1
Polymer material for wheels	2
Permanent total mass (empty tank)	341.4

The Carnot efficiency, $77/(T_a - 77)$, where T_a denotes ambient temperature, has to be reduced to the fraction by which the Carnot cycle can be realized under real conditions. Experimental values for the percentages of Carnot efficiencies obtainable with cooling machines are listed, e.g., in the traditional Strobridge charts (see Ref. 7) from which a rough estimate can be taken: even for a very large cooling power, e.g., 10^3 kW, the real efficiency does not exceed 40% of the Carnot efficiency. Accordingly, every energy input related to heat losses of the tanks during the use phase has to be multiplied by a factor of about seven. This large penalty leads to the expectation that as in other industrial products, the performance of which is subject to energy conversion efficiencies (power stations, turbines, motors, generators, etc.), the whole environmental balance of the tank will be dominated by the *use* phase where the heat losses occur.

On evaluation of the data, one could directly use the life cycle inventory profile showing the total use of material and energy as well as emissions and wastes generated. A more common way of evaluating the data is, however, to conduct an impact assessment. The three main stages in impact assessment are classification, characterization, and weighing. In classification, the resources and emissions of the system under study are assigned to a number of environmental impact categories or effect classes, e.g., global warming, ozone depletion, and acidification. An emission can in some cases belong to several impact categories. A number of different substances may have an impact on each category, and they are therefore all related to one specific substance to allow addition of their effects. For example, for calculation of the greenhouse effect (global warming potential, GWP) in the characterization step, all substances like CH_4, N_2O, CFCs, and HCFCs are associated with CO_2 while for the acidification potential, all substances are converted to the impact of SO_2. In the next step, characterization, calculation of the total impact within each impact category is carried out.

In the final step, the weighing, all the impacts are summarized to give one single value. There are several methods, some of them are based on the national political goals for pollution reduction and some on the willingness to pay for either impact on human health or to restore/protect certain safe-guard objects.

The EPS 2000 weighing method (Ref. 8) used in this study includes five safeguard objects: human health, biological diversity, biological production, resources, and aesthetic values. All of these are valued in a medium- to long-term perspective, and therefore local effects are not considered as serious as global effects. This is represented by environmental load units (ELU) used to estimate the impact. A monetary value is attributed to each effect (ELU = Euro), based on studies of the importance of different safe-guard objects to society, and people in general. Impacts of all processes involved in the life cycle of a product on each of the safeguard objects are then combined to give a final ELU value for the product. The total environmental impact of a product is thus expressed as an integral *monetary* value (in Euro) that describes the cost that would have to be spent, or that a society would be willing to pay, if the corresponding environmental loads could be avoided by alternative measures.

Other evaluation models include, e.g., ECO NL and Eco-Indicator 99 models. The ECO NL model belongs to ecological scarcity methods and represents an evaluation according to the ratio between annual anthropogenic load and critical annual load and results in a country-specific eco-factor. The Eco-Indicator 99 is a weight factor based on two ecological safeguard objects (human health, ecosystem impairment) and delivers a total amount of indicator points as a measure for environmental damage. In the next subsection, we will compare results from the EPS 2000 with the Eco Indicator 99 method.

All LCA calculations reported in the next subsection have been made using a commercially available computer software (EcoLab, from Nordic Port) with a database developed by ABB Corporate Research. The possibility to evaluate at different levels of aggregation and subjectivity serves the purpose of presenting unbiased life cycle inventory data, data coupled to environmental impact, and data evaluated according to a specific weighing method.

3.2. Results

Figure 2 shows, for the three insulation concepts, the emissions affecting global warming; the data represent the sum over manufacture, use, and end of life phases. Insulation concepts 1–3 are identified from the

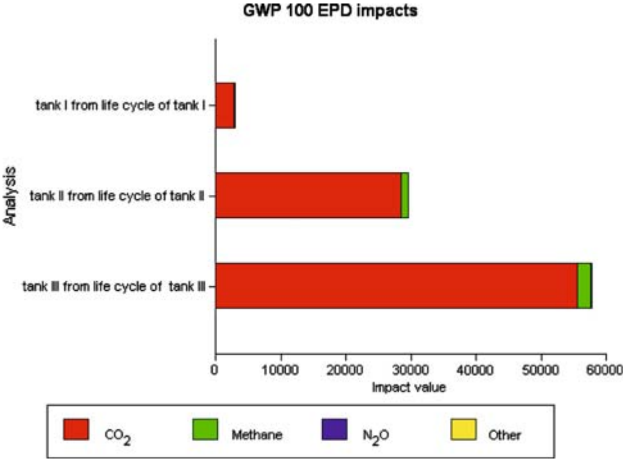


Fig. 2. Global warming potential impacts, GWP, calculated for insulation concepts 1–3. Data are presented for the different types of emission contributing to the global warming impact, and are given as the sum taken over the manufacture, use, and end of life-phases of the insulations and for a life time of 20 years. Insulation concepts 1–3 are identified from the descriptors tanks I–III, respectively, of the ordinate of the diagram. Quantities are given in kg CO_2 equivalents.

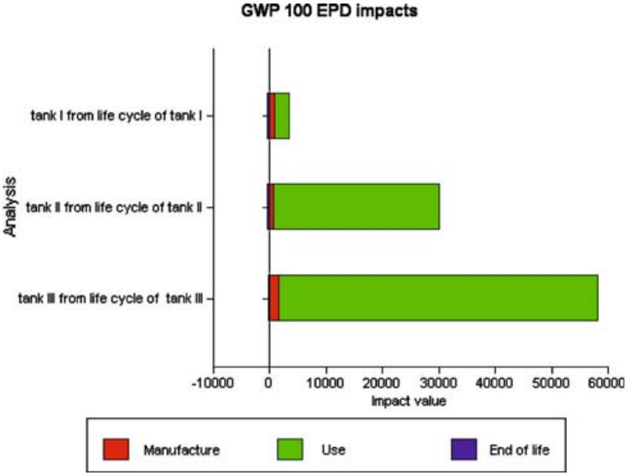


Fig. 3. Global warming potential impacts, GWP, calculated for insulation concepts 1–3. Data are presented for the different life cycle phases (manufacture, use, end of life) contributing to the global warming impact, and are given for a life time of 20 years. Quantities are given in kg CO_2 equivalents.

descriptors "tanks I to III," respectively, of the ordinate of this and the following diagrams. The total GWP values, taken over the lifetime of the tanks (20 years), amount to 2922, 29,640, and 57,820 kg CO_2 equivalents of which "true" CO_2 emissions constitute 97, 96, or 96%, respectively. This means contributions from CH_4 and N_2O, relative to CO_2 emissions, are small.

In Fig. 3 the global warming potential, GWP, calculated for insulation concepts 1–3 over the lifetime of 20 years, is split into contributions from the different life cycle phases. This figure shows that the major impact from Concept 2 and 3 comes from the use phase. From both Figs. 2 and 3, and under the GWP perspective, Concept 1 (evacuated multi-foils) seems to be the most benign to the environment.

As a next step, two weighing methods, Eco-Indicator 99 (Fig. 4) and EPS 2000 (Fig. 5), were applied to confirm the conclusion about which alternative is the best from an environmental perspective. The impact from the manufacturing phase is comparatively equal for alternatives 1–3 (neglecting for the moment that concept 1 shows the largest value, as is to be expected from its increased stainless steel consumption). But the impact from the use phase is conclusive for the total results: from a life cycle perspective and from both weighing methods taken over the lifetime

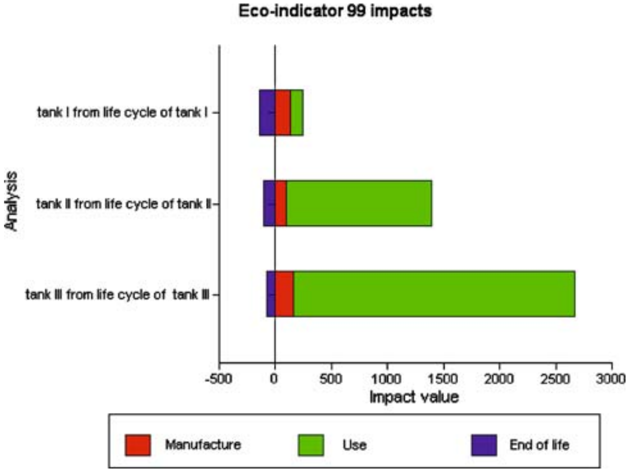


Fig. 4. Result evaluation using the Eco-Indicator 99 weighing method. Quantities are given using average weighing factors expressed in "indicator points" representing a measure for the total environmental damage potentially caused by the product.

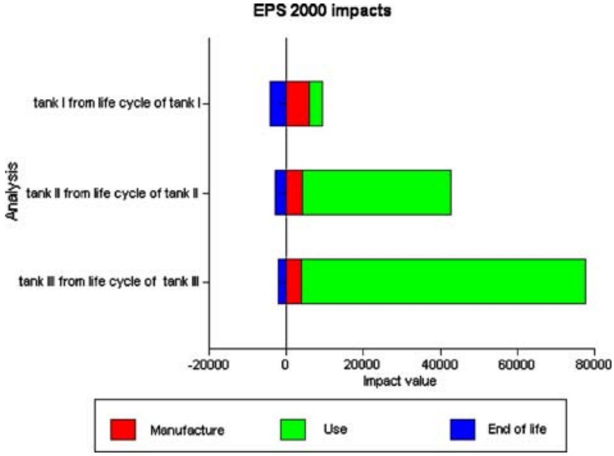


Fig. 5. Evaluation using the EPS 2000 weighing method representing a measure, as a monetary value, for the total environmental damage. Quantities are given in ELU (environmental load unit, 1 ELU $\approx$ 1 Euro).

of 20 years of each insulation concept, evacuated multi-foils prove to be about a factor of 10 or 20 better than Concepts 2 or 3, respectively.

In summary, the GWP as well as both EPS 2000 and Eco-Indicator 99 evaluations confirm that the overwhelming part of the environmental impact results from the use phase of the three LN_2 storage tanks and that Concept 1 is the best from an environmental point of view.

As with other products, the energetic performance of which is subject to thermodynamic efficiency, it is again the use phase that dominates the environmental performance. Selection of construction materials thus could have serious environmental impacts only if short-living products would be considered.

3.3. Environmental "Amortization Time (ROI)"

For identification of *energetic* amortization times, e.g., of a power plant, diagrams are usually prepared that in the manufacturing phase, consider all consumptions of energy as negative input while electrical energy produced by the new power station in its use phase is considered as positive output. Energetic amortization (the return on investment, ROI) is obtained as soon as the electricity energy produced in the use phase outbalances the energy consumed during the construction phase. In the following, we will propose a similar estimate: identify an *environmental* amortization time by which savings obtained during the use phase will outbalance environmental loads resulting from the manufacturing phase. Since thermally insulated objects unfortunately do not produce, but consume, energy, this identification can be made only by comparison of a particular insulation concept with a reference system: here we compare Concept 1 with Concepts 2 and 3.

Let us denote the evaluation results obtained with the EPS method as a function $\mathrm{EPS}_{i,k}(t)$. This function depends on time, t (the life-time of the insulation concepts). Let t_0 denote the start time of the use phase of the LN_2 storage tank. At $t \leqslant t_0$, the calculated EPS-values accordingly are taken as negative, while for $t > t_0$, they are taken as positive. So we have at t_0 for Concepts 1, 2, and 3 from the manufacturing phase EPS-values of -5947, -4276, and -3805 units, respectively.

In the expression $\mathrm{EPS}_{i,k}(t)$, the index i denotes the insulation concept index ($1 \leqslant i \leqslant 3$) and k is the index for the three life cycle phases (manufacture, use, end of life, $1 \leqslant k \leqslant 3$) of the insulations. With this convention, we are able to calculate differences (i.e., savings of environmental impacts during any of the phases) as

$$f_1(t) = \mathrm{EPS}_{2,k} - \mathrm{EPS}_{1,k} \text{ and } \tag{1}$$

$$f_2(t) = \mathrm{EPS}_{3,k} - \mathrm{EPS}_{1,k} \tag{2}$$

as a function of time, t. In the following, we will restrict this comparison to the use phases ($k = 2$), and it is assumed that the EPS-values in this phase increase linearly over the lifetime of the insulation. Re-evacuations, with corresponding additional material flows (new getter materials) and energy (operation of a vacuum pump, heating of glass fibers during evacuation), although included in the calculations, will not be considered explicitly in this diagram. Recycling efforts (recycling of stainless steel, incineration of polymeric materials) are neglected in this diagram because these are only small corrections to the whole balance, in view of the impacts arising from the use phase. The results of this calculation are shown in Fig. 6.

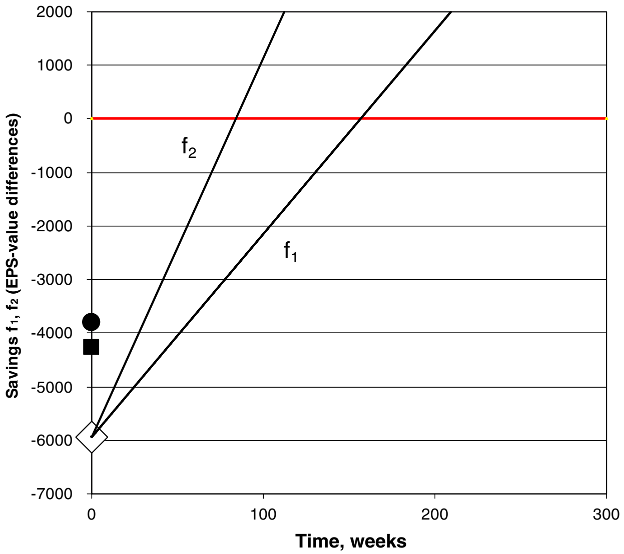


Fig. 6. Determination of *environmental* amortization times from EPS-values of insulation concept 1, in analogy to *energetic* amortization times (return on investment, ROI) of thermodynamic cycles such as power plants or turbines, when comparing Concept 1 with Concepts 2 (curve f_1) and 3 (curve f_2). Open diamond, solid square, and solid circle indicate EPS-values (taken negative in this diagram) obtained for the manufacturing phase of insulation concepts 1, 2, and 3, respectively. Amortization time is extracted from the points of intersection of the two curves f_1 and f_2 with the horizontal red line. Efforts for re-evacuation of insulations 1 and 2 and recycling are omitted in this diagram (but are integrated in the calculations).

The evacuated multi-foil insulation, with respect to concepts 2 and 3, has compensated its (slightly larger) environmental impacts from the manufacturing phase by substantial savings in the use phase after 84 or 157 weeks of operation, respectively, when used in a super-insulated 300 L LN_2 storage tank. For comparison, the environmentally related (energetic) amortization time of a steam turbine operating under full load is much shorter (less than 10 weeks), which reflects the considerably higher energetic efficiency of this thermodynamic cycle.

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