ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF GAS DISTRIBUTION SYSTEMS

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ABSTRACT

Environmental aspects tend to be increasingly important in designing gas distribution systems and in selecting gas distribution materials. Therefore the environmental aspects of various materials options for gas distribution networks were analyzed by means of a quantitative life cycle assessment. This paper describes the methodology used and presents the quantitative endresults to indicate the potential environmental effects caused by the various materials options. In general, substantial differences are found between the individual piping systems analyzed in this study. No piping system, however, can be said to score significantly better or worse on all environmental themes relative to the other systems analyzed. Under the assumptions made, it turns out that, in general, the metal systems give higher scores than the plastics ones. Especially polyvinylchloride scores low. Gas leakages during the period of 'use' of the piping system turned out to have an important and direct effect on two of the environmental themes analyzed.

INTRODUCTION

Energy utilities invest a lot in their gas distribution networks. Cost-effectiveness, safety and operational reliability all play a major role in designing gas distribution networks and in selecting gas distribution materials. Environmental considerations, too, tend to be increasingly important. As part of the overall evaluation of various alternatives, the energy utilities in the Netherlands needed a quantitative environmental tool to support the design of gas distribution networks. In making a well balanced choice of materials to be used in a gas distribution network, all environmental impacts should be taken into account 'from the cradle to the grave'. In formulating a responsible environmental policy, life cycle assessment (LCA) of distribution networks has proved to be a valuable tool for supplying environmental information.

Two years ago GASTEC finished an LCA study[1)] on piping systems for gas distribution, under the authority of the Netherlands energy utilities. In performing the LCA, GASTEC has cooperated with CML, the Centre of Environmental Science of the Leiden University. GASTEC has been aiming at a quantitative assessment of the total environmental load caused by the various materials options for natural gas distribution networks in the Netherlands. The study aimed to provide environmental information capable of helping decisions on gas distribution networks, and ultimately aimed to improve the environmental performance of the energy utilities. The study involved materials such as modified polyvinyl chloride (PVC), polythene (PE) and cross-linked polythene (PEX), steel and ductile iron.

This paper describes the methodology used and presents the quantitative endresults to indicate the total environmental load caused by the various materials. The endresults might be relevant for other distribution networks, e.g. for water distribution and sewage, although direct transposition of the conclusions would be inappropriate.

THE LCA METHODOLOGY

Life cycle assessment (LCA) deals with the environmental impact of a product in its entire life cycle. It summarizes all environmental effects to generate a certain product. In the EU LCAs are considered to be the official basis for eco-labelling. LCA is the most suitable way to analyze and evaluate the environmental aspects of a product during its entire lifespan. In 1992 CML published a general method for conducting LCAs[2]. A life cycle consists of all the processes related to the functioning of a product: from the extraction of resources, the production of materials, the production of components, transmission, the use of the product through reuse and disposal of all final waste (including the discarded product itself) and finally the disposal of that product, and the final production waste. The environmental impacts througout the entire life cycle comprise all the extractions from and emissions to the environment. This method has also been used for the presented study in this paper. The terminoly however is modernized, along the lines emerging in the Society for Environmental Toxicology And Chemistry (SETAC) and the International Organisation for Standardization (ISO).

Five individual components can be distinguished in LCA: objective and scope definition, inventory analysis, life cycle impact assessment, Interpretation an improvement analysis. Each component in turn can be subdivided in several steps necessary to operationalize a LCA. In the sections to follow, these components are described separately.

OBJECTIVE AND SCOPE DEFINITION

The purpose of this study was to gain insight into the environmental aspects of various materials options for gas distribution networks by conducting a quantitative LCA. All stages in the life cycle of a network were included in this study, from the extraction of basic resources to the final disposal of the used materials. This study has been restricted to the 4 - 8 bar feeder systems and the 100 mbar distribution networks operated by the energy utilities. Not included in this study are the high pressure transmission grids (i.e. 40 bar grids) and city gate and distribution stations. Also the service pipes and all gas utilization equipment in households like central heating have been excluded. In figure 1 a schematic view of the boundaries of the gas distribution networks analyzed is given.

An overview of the environmental aspects of the various options makes it possible to draw a rational picture of the environmental impacts associated with the use of these materials. Because of the unique history of gas distribution in the Netherlands, the choice of materials used in gas distribution networks is wider than in most countries. The total length of these gas distribution networks amounted to 110.000 km on a total area of 36,000 km^2 in the year 1998. The networks may be divided into a number of subsystems based on the internal pressure class and the materials used. In the high pressure 'feeder system', steel (8 bar) and PE (4 bar) are most widely used. In the low pressure 'distribution network', rigid PVC (until the early 70's) and impact-modified PVC (100 mbar) are dominantly used, in total 60.000 km, and also some ductile iron and PE.

In principle all currently installed pipe materials in the Netherlands were included in this LCA study. Furthermore PEX has been included as a potential new material in the near future.

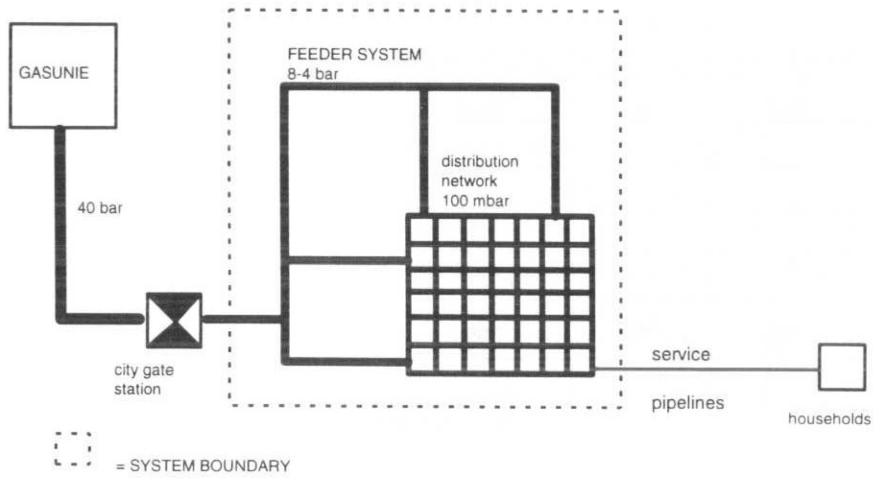

Figure 1: The place of the gas supply systems analyzed in this study. The rectangle indicates the system boundaries, in which both feeder system and distribution network are included.

The various gas piping materials which were compared in this study are therefore:

- *For the 8 bar subsystem: steel, polythene PE-100, polythene PE-80 (4 bar) and cross-linked PE (PEX);*
- *For the 100 mbar subsystem: ductile iron, modified PVC, and polythene PE-80.*

To structure the analysis the alternatives were compared on the basis of a functional unit, based on the assumption that they are equally fit for purpose. The functional unit was kept constant for each type of network under consideration. The functional unit is defined as the annual supply of 20 million m^3 natural gas to clients, from a city gate station to 10,000 services. This definition was based on the following considerations. A typical Dutch household consumed in the early 90's 2,000 m^3 gas annually. Furthermore the maximum capacity of this gas distribution network is based on a peak load of 1.5 m^3 gas per household per hour, i.e. 15,000 m^3 gas per hour for all branches. The gas distribution networks compared consist of a high pressure feeder subsystem (4 or 8 bar) and a low pressure distribution subsystem (100 mbar). Together they make up the gas distribution networks considered. The total length of the feeder subsystem is 12.7 km, and the total length of the 100 mbar distribution subsystem is 100 km. In figure 2 a schematic view of the standardized system is given.

All networks analyzed in this study are defined specifying all components, their required numbers and their weights in kg. A distribution network has many different components, whereas a feeder system is mainly straight pipeline. A distribution network contains numerous bends and joints, because all 10,000 households have to be connected to this system. The pipes for the standardized feeder subsystems come in 2 or 3 different diameters. For the standardized distribution subsystems, pipes of 4 different diameters have been used. For each type of network involved a lifespan of 70 years is assumed.

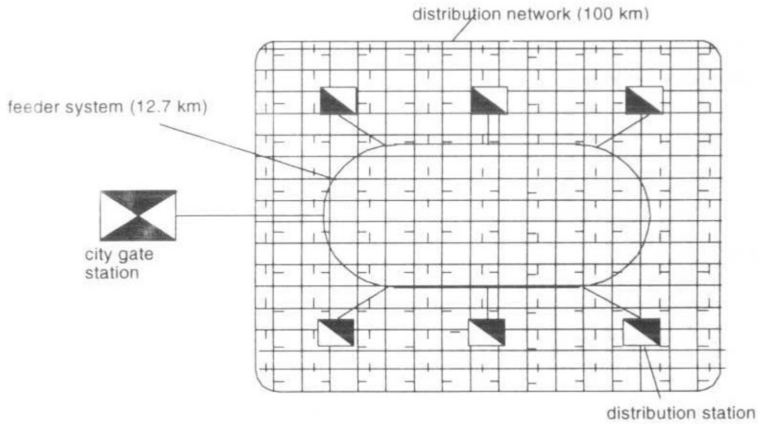

Figure 2: The standardized system considered in this study.

INVENTORY ANALYSIS

This component includes an inventory analysis of environmental interventions during the entire product life cycle associated with the fulfilment of the functional unit. The life cycles of the networks selected consist of a number of economic processes, which are directly linked together: each input into a process is either an output from other economic production, consumption or waste processes or an environmental resource. All these economic production, consumption and waste processes concern the production of raw materials (oil, gas, coal, iron ore, rock salt), the production of materials (raw iron, steel, PE, chlorine and PVC), the production of components (pipes, elbows, T-pieces), the construction of a network, the use of the network and finally its disposal. In addition to the economic processes directly related to the life cycle of a network, all kinds of additional support processes are required concerning electricity, transportation, capital goods and all other possible ancillaries. All these economic processes produce certain products or services. These services are the inputs to other economic processes in the life cycle of a network, which cause environmental interventions. Examples of these environmental interventions are emissions to air, water and soil, space used, resources used and radiation.

Originally, company specific data were preferred. However only for PVC, where company specific data from the Netherlands were used, this turned out to be possible. If no company specific data were available, process data were taken from the database published by ETH, Eidgenössische Technische Hochschule, Zürich: 'Environmental Life Cycle Inventories for Energy Systems'[3]. In general this has been the case for all other materials examined. Some other processes involved data from CML databases and other sources. The ETH database is mainly concerned with the modelling of different energy systems in an unaggregated transparent and consistent 'cradle to grave' approach.

An important parameter in the operational phase of the life cycle constitutes the amount of gas that leaks from the systems. In the gas leakage figures for both the feeder system and the distribution system no distinction has been made between materials. The figures used give an estimate that is based on the best available figures. The figure for the feeder systems is estimated to be 0.0011 % and for the distribution system 0.050 % relative to the transported amount. This is assumed to be valid for new networks, since it is relatively low. For lack of empirical data it was not possible to discriminate between the various piping materials.

At the end of the life cycle of the various networks three different outputs can be identified:

- *the transported gas during its use;*
- *reusable scrap or regranulate;*
- *possible energy recovered from waste incineration.*

It is not correct to allocate all the environmental impacts to the transport function of the gas networks only, so for the purpose of this study a calculation was made of the allocation factors. Based on the environmental interventions caused by all processes necessary to fulfil the predefined functional unit, inventory tables have been generated for the various networks. These lists provide quantitative overviews of all resources used and substances emitted to air, water and soil originating from the fulfilment of the functional unit as modelled in this study. These inventory tables are based on the allocation factors explained above and represent the quantified environmental interventions of 20 million m^3 natural gas transported by the various networks analyzed.

LIFE CYCLE IMPACT ASSESSMENT

This component includes the choice and modelling of environmental interventions, thus specifying their potential environmental effects. Here a potential environmental effect means a consequence of the environmental interventions, due to processes (often of a highly complex nature) in the environment. The link between the the environmental interventions and the environmental effects is described with models. These models enable an analysis of the contribution of a functional unit network to these environmental effects. The classification leads to a list of all environmental effects, specified for the product studied. This list is known as an environmental profile. In the characterisation, the environmental profile is quantified for each product system investigated. In this study the environmental profile is the basic environmental indicator on which the comparision of the various product alteratives is based. The environmental profile, used to compare the various product alternatives consists of the following nine environmental themes:

- *Global Warming Potential **(GWP)***
- *Ozone Depletion Potential **(ODP)***
- *Photochemical Oxidant Creation Potential **(POCP)***
- *Acidification Potential **(AP)***
- *Nutrification Potential **(NP)***
- *Ecotoxicity Aquatic **(ECA)***
- *Human Toxicity Potential **(HTP)***
- *Abiotic Depletion Potential **(ADP)***
- *Odour Threshold Limit **(OLT)***

This is a fairly complete set of well defined environmental effects that may result from the existence and use of the various networks. However, environmental effects such as noise, waste heat, depletion of biotic resources, number of victims of accidents, terrestrial ecotoxicity and damage to landscapes are not included.

In the classification step, the environmental inventory table is quantified, with the aid of models, according to nine environmental effect scores. This list is known as an environmental profile, or eco-balance. In this study, the environmental profile is the basic environmental indicator on which the compariosion of the various product alternatives is based.

In the characterisation step the effect scores are normalized. So the contribution made by a given network to an environmental effect is linked to the contribution made by a given community to the same problem over a given period of time. In this study the world annual effect scores[4] were used to normalize the specific effect scores related to the functional unit. The ratio between each effect score and the global contribution to that effect score over a year provided the normalized environmental profile consisting of normalized effect scores, all of which were expressed in years.

INTERPRETATION

The environmental profile was subjected to sensitivity analysis on reliability and validity of the results. In this study, the environmental profile is the basic environmental indicator on which the various product alternatives were compared, all equally capable of fulfilling the same function in society. The product assessment was executed by evaluating the environmental profiles. This means that the environmental profiles of the various types of networks and materials were compared. Ideally the scores for the various environmental effects of which these environmental profiles consists, should be weighted and combined into a single environmental index. Considerations about the actual importance of these environmental effects depend on subjective, personal opinions, which may benefit from a public discussion. Since objectively constructed weighting factors are not available at present, the elaboration of an environmental index will be one of the future developments.

IMPROVEMENT ANALYSIS

The insights obtained in performing this LCA study may be suitable inputs for an improvement analysis. Actually, the knowledge gained will allow to identify areas where technical change would be most desirable from an environmental point of view. Conducting an improvement analysis of the main problem areas over the total life cycle of a network would pinpoint the most likely candidates for effective reductions in environmental loads. Reliable environmental information may also be helpful to authorities dealing with national and international standards, rules and regulations for gas pipes.

RESULTS PER SUBSYSTEM

In table 1 and in figure 3 the normalized environmental profiles for the 4 - 8 bar feeder subsystems are given.

(yr × 10^{-10})	Steel	PE-100	PE-80	PEX	max/min
POCP	5.8	5.8	6.3	5.8	1.1
ECA	11	3.2	4.9	3.2	3.4
GWP	3.0	1.6	2.2	1.6	1.9
AP	1.8	1.2	1.8	1.2	1.5
ADP	0.53	0.50	0.76	1.7	3.3
HT	1.5	0.91	1.4	1.1	1.6
NP	0.59	0.28	0.43	0.26	2.3
OTL	2.7	0.20	0.30	0.19	14
ODP	0.04	0.09	0.13	0.09	3.5
EC (GJ)	208	153	234	151	1.5

Table 1: Final results for the feeder system. Scores on environmental themes related to the world's yearly scores, expressed in yr·10^{-10}. The right column gives the relation to the minimum and the maximum score for all themes.

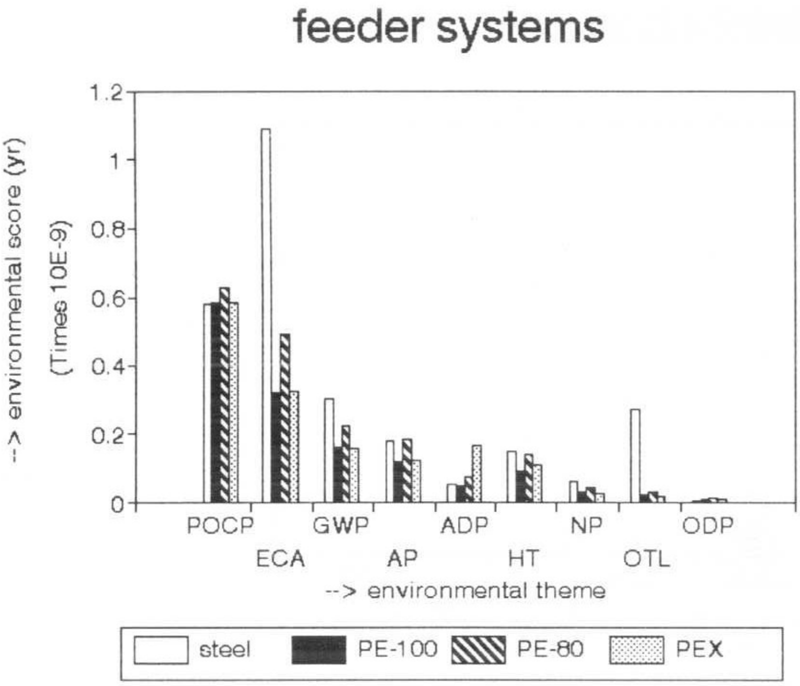

Figure 3: *Environmental profiles for the 4 - 8 bar feeder systems.*

Considering the general heights of the normalized figures per environmental theme, it can be seen that the scores for POCP are rather high in relation to the other scores. This is mainly due to the emission of methane during gas leakage.

As a ranking of the alternatives it can be said that steel has the highest scores, followed by PE-80. The best scores are found from PE-100 and PEX, which two materials show little differences. When dividing the maximum score through the minimum score per environmental theme, the figures do not differ more than a factor 3.5, except for the smell score (OTL) where the highest and lowest scores differ a factor 14. This large difference is caused by the relatively high smell score for steel. This score in turn, is caused by the emission of H_2S during coal coke production, which is a raw material for the steel production.

Exceptions on the ranking of the materials are formed by the smog formation score (POCP), as this one is almost completely caused by gas leakages. For the acidification score (AP), steel and PE-80 score about the same. The score for abiotic depletion (ADP) forms an exception: the raw material iron ore is not considered to have a depletion score in contrary with the raw material oil for the plastics. Apart from that, PEX uses a rather large amount of copper for the brass fittings, which largely influence the abiotic depletion (ADP) score.

Also an exception is formed by the ODP score, as steel does have less influence on ozone depletion than the plastics. Finally, for steel, the scores aquatic ecotoxicity (ECA) and odour threshold limit (OTL) have a considerably higher score than the others, for ECA due to the rather high amount of freighter transport involved (emitting the anti fouling tri-butyl-tin salts), for OTL due to the use of coal during production of the raw iron (emission of H_2S).

In figures 4 and 5 and table 2 the normalized environmental profiles for the 100 mbar distribution networks are given.

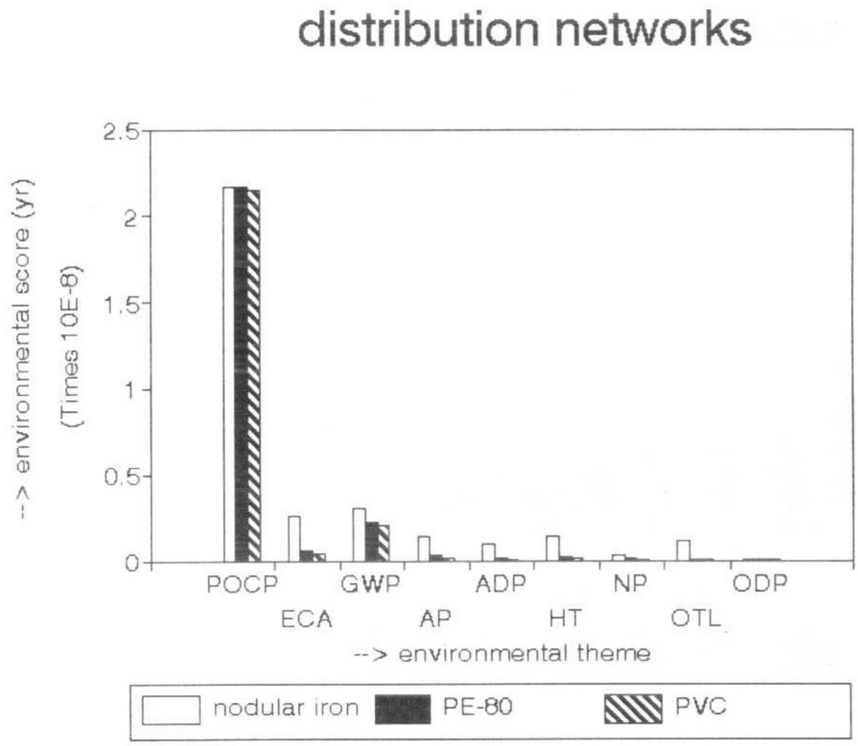

Figure 4: Environmental profiles for the 100 mbar distribution networks, overview.

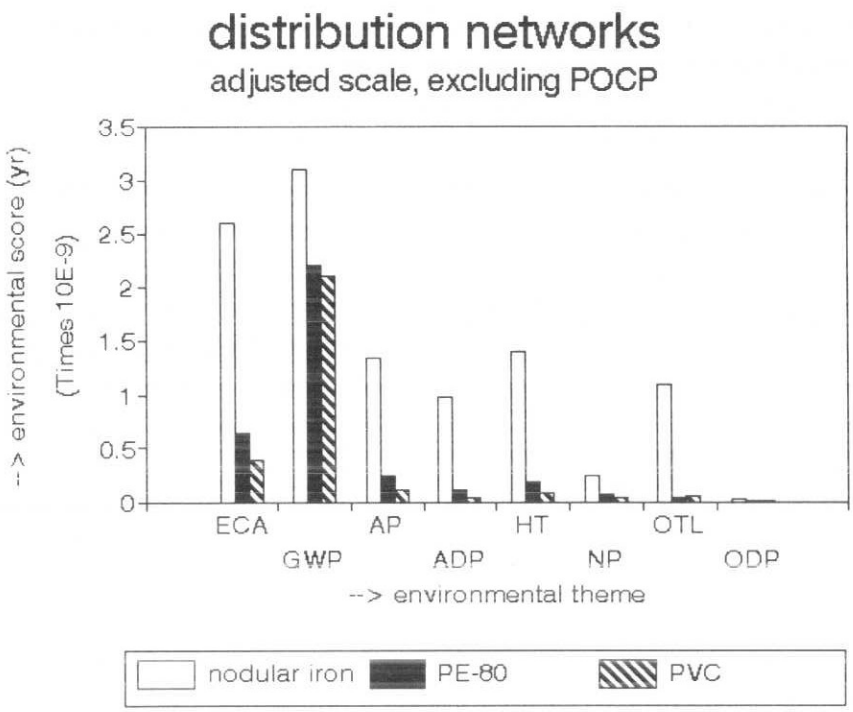

Figure 5: Environmental profiles for the 100 mbar distribution networks, adjusted scale.

(yr × 10^{-10})	nod. iron	PE-80(100)	PVC	max/min
POCP	216	216	215	1.0
ECA	26	6.4	3.9	6.7
GWP	31	22	21	1.5
AP	13	2.5	1.1	12.7
ADP	9.7	1.0	0.45	21.3
HT	14	1.9	0.76	18.5
NP	2.5	0.61	0.33	7.6
OTL	11	0.39	0.48	27.8
ODP	0.25	0.17	0.07	3.3
EC (GJ)	748	303	139	5.4

Table 2: Final results for the distribution network. Scores on environmental themes related to the world's yearly scores, expressed in yr·10^{-10}. The right column gives the relation between the maximum and the minimum score.

Considering the general heights of the normalized figures per environmental theme, it can be seen that the scores for smog formation (POCP) are very high, compared to the other scores, which is caused by gas leakages. The gas leakages also influence the global warming score (GWP), making this also rather high. The aquatic ecotoxicity (ECA) score for nodular iron is rather high compared to the other materials. The scores for smell (OTL) and ozone depletion (ODP) are rather low (except for nodular iron's smell, which is relatively high).

When dividing the maximum score through the minimum score per environmental theme, the figures differ with a factor up to 28. Obviously, the max/min-factor for smog formation (POCP) and global warming (GWP) are about 1, since the scores on these themes are completely or almost completely caused by the gas leakages. Very high differences (factor >20) exist for abiotic depletion (ADP) and odour threshold limit (OTL). For all themes, the maximum scores are formed by nodular iron.

In general, nodular iron scores worst. On a large distance PE-80 and PVC follow, where PVC scores the best. The exceptions are found in the smell (OTL) score: PVC scores slightly higher than PE-80. As the POPC (smog) score is completely caused by gas leakage, this score is about the same for all materials.

CONCLUSIONS

In general, substantial differences are found between the individual piping systems analyzed in this study. No piping system, however, can be said to score significantly better or worse on all environmental themes relative to the other systems analyzed. Besides, the scores turn out to be strongly dependent on assumptions, such as the estimated life-span.

Under the assumptions made, it turns out that, in general, the metal systems (steel and nodular iron) give higher scores than the plastic ones. Especially polyvinylchloride scores low.

Since no evaluation of the relative importance of the individual effect scores in the environmental profiles has been developed yet, no general conclusion can be drawn on the ranking of the pipeline systems analyzed in terms of environmentally 'better' or 'worse'.

Another interesting result is that gas leakages during normal operation dominate the Photochemical Oxidant Creation Potential and the Global Warming Potential scores.

Therefore these scores are very sensitive to changes in the amount of gas leakage into the atmosphere during the period of 'use' of the piping system. This is a somewhat surprising result, since at the outset of this study it was expected that the period of use of a piping system would not have such an important and direct effect on one or more of the environmental themes analyzed.

Environmental improvements for gas piping systems mainly have to be found in the decrease in material use and in the decrease in gas leakages.

LITERATURE

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