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A QUALITY MANAGEMENT APPROACH TO THE LIFETIME PROBLEMS OF NON-METALLIC STRUCTURAL MATERIALS

(The Abstract of the PhD Dissertation)

The dissertation develops new principles for lifetime analysis of water-purifying membrane filters, as no adequate method exists for identical assessment of parts failing under differing conditions.

To supply commensurable exposure values, it introduces the concepts of "*Lifetime chlorine exposure*", "*Equivalent operating time*" and "*Equivalent lifetime*" (lasting until final breakdown) based on analogies. Filter module lifetime analyses are performed with the creation of a "*Lifetime database*" to prove the calculation method in practice.

"*Stress profile*" objectively assessing the utilisation environment's straining and damaging factors is first time defined, as well as "*Lifetime profile*", taking into account the material and manufacturing parameters. *Decision tree* known form other fields is first time adapted for the selection of crucial lifetime factors (*"KO" factors*) and a methodology is suggested for their monitoring.

1. Introduction

The primary aim of the research is to adapt the lifetime-analysis method – more advanced in the field of machine industry, electronics and the manufacturing and maintenance of light sources – in a field where analysis is impeded by complex maintenance and failure processes and difficult to interpret concepts. Interpretation problems result in inaccuracy and therefore, in some cases, in unusable lifetime predictions. In the case of equipment under non-constant exposure levels and changing conditions, levels of impairment with time might differ widely after the elapse of identical calendar time.

In this present research numerically definable (i.e. objectively assessable) concepts and calculation methods are introduced that are suitable for solving the problem. It is also necessary to develop a database enabling the collection of data and the calculations.

Questions concerning lifetime can be answered in an exact manner if beside the product's original characteristics, the composition of the different kinds of stresses and the stress characteristics, that is, the "Stress profile", the materials used and the construction are also known. Another new concept is "Lifetime profile", which is the whole set of information that can be known about breakdown forms and their probabilities in a well defined use environment of one single product from a set of products.

2. Formulation of the Scientific Problem

The dissertation elaborates the problem of the lifetime analysis of membrane filters used in water purification. A manufacturing company, classified among the leading enterprises of the world, provided opportunity for the recognition and analysis of these problems. Although this present analysis is solely concerned with ultrafiltrating membrane tubes, its statements and methods can be considered valid and applicable in every field of lifetime analysis, after the necessary adaptations.

Lifetime analyses of the above mentioned membranes are based on three information sources:

- *Complaints*, informing about details of the most important problems, the breakdown events. The problem concerning this type of information is that a relatively small amount of information is gathered about one version of a specific product, and they reflect only catastrophic failures caused by more serious manufacturing or maintenance defects, not the normal operation.

- *Feedback from Operators* concerning final breakdown, and, in state of art practice, the tracking of operation with measurable parameters in relocated factories. Most information concerns operation conditions and not deterioration. It provides a large amount of data, however, the less problematic the operation is, the longer is the feedback time towards product manufacturing and maintenance.

- *Testing with Accelerated Testing Equipment.* It provides exact information concerning deterioration, the problem is, however, that it is only economical with limited sample numbers. A further problem is that the "acceleration method" and the excessively

regulated conditions resulting in a distorted deterioration process out of the ordinary one, might lead to incorrect conclusions.

The solution would be to process the results of the three information sources in a newly developed database and to develop exact calculation methods for the transformation of the data together with ensuring adequate instrumentation of the process.

Moreover, it is necessary to develop and introduce a methodology adequate for the selection of parameters critical for the given product's lifetime and the creation of a unified concept system concerning its stress characteristics.

A further aim of the present research is to ensure that, observing the deterioration process in any given environment, the calculation of exposures converted into equivalent units directly ensure comparability concerning the products' breakdown.

3. Research Objectives

The objective of the research is thus firstly the definition of concepts reflecting a new approach:

- Lifetime chlorine exposure,

- Equivalent operating time,

- Equivalent lifetime

and the development of methods for making them numerically definable. These are followed by the concepts

- Stress profile,

- Lifetime profile

adequate for summarising and recording the exposures and other harmful effects of the process of use.

The allocation method of critical lifetime factors was adopted as a new method from a different field and the allocation itself was performed by a group of specialists in team work.

For the calculation of the concepts and characteristics created in the first chapters, the basics of the database tracking the entire lifetime and documenting the main environmental parameters are laid. In this database it will be necessary to record data and variables, factors and remarks beside the calculation and actuator functions. The final objective is the definition of equivalent lifetime of filter elements, real-time tracking and archiving of data.

4. Research Methods

The research aims at methodological development and therefore applies analytical and explorative methods. It explores the material structure mechanisms resulting in deterioration, as well as the calculation methods of proven value in the quantification of lifetime, and their scientific background.

The literature search concerning the exposure and degradation of filters used in water purification ensures the sound technical foundations of the calculations used for the development of transformation methods for lifetime data.

Due to the quality management approach stated in the title, the application and development of relatively simple and easy to use calculation and analytical methods – that still required the contribution of expert teams – was preferred. Therefore, the dissertation integrates knowledge from different fields of expertise.

The introduction of process data, its assignment to a given product, its assessment, and its transformation into lifetime characteristic (based on its effect on the product) plays a significant role in the development of the *database*. Another function expected from the database is the summary of the transformed characteristics based on the cumulative effect, and its archiving that can be supplemented with quality related data.

In the last chapter, relationships between the conditions and the lifetimes defined with the developed calculation methods as well as failure statistics are analysed. The directions of further development are also appointed that may serve effective practical use.

5. New Research Results

5.1. Critical Factors in the Lifetime of Membrane Filters

Similarly to the definition of *Critical Control Points* in food safety systems, a process for the selection of parameters critically influencing lifetime has been developed. The basis of the method is that with a series of yes/no answers to closed logical questions the questions of a decision tree – similar to the question series recommended for HACCP analyses – have to be answered. (Fig. 1.)

The team selected the following parameters with the adapted decision tree in organised teamwork:

- **Sodium-hypochlorite concentration** during normal operation, in maintenance and recovery cycles.

- Mostly **hydrodynamic exposure** of the filter, based on pressure amplitude – maintained flux – regulation system.

- **Temperature**, and in connection with it viscosity and the rate of harmful reactions.

- **Coagulation propensities** of certain materials in untreated water (mainly Ca, Mg, …, responsible for water hardness, possibly other materials facilitating coagulation).

Both continuous monitoring, recording of time series of the quantified parameters, and feedback in case of deviations, i.e. the well known routine process is necessary.

With the monitoring developed during the present research it has been made possible that the demonstrated significant degradation effects be regulated in order to achieve longer lifetime, safer operation and schedulable maintenance treatments.

Thesis 1

For the completion of this work a new method concerning the lifetime tracking of modular filter elements has been introduced. This method enables the group performing the analysis to select the lifetime characteristics, with a claim of objectivity.

As for the first time a formerly used method was reworked and adopted for the purpose of selecting the factors crucially influencing lifetime ("KO" factors) with the help of a series of closed questions and a special "decision tree". A theoretical process of monitoring the selected factors was also created.
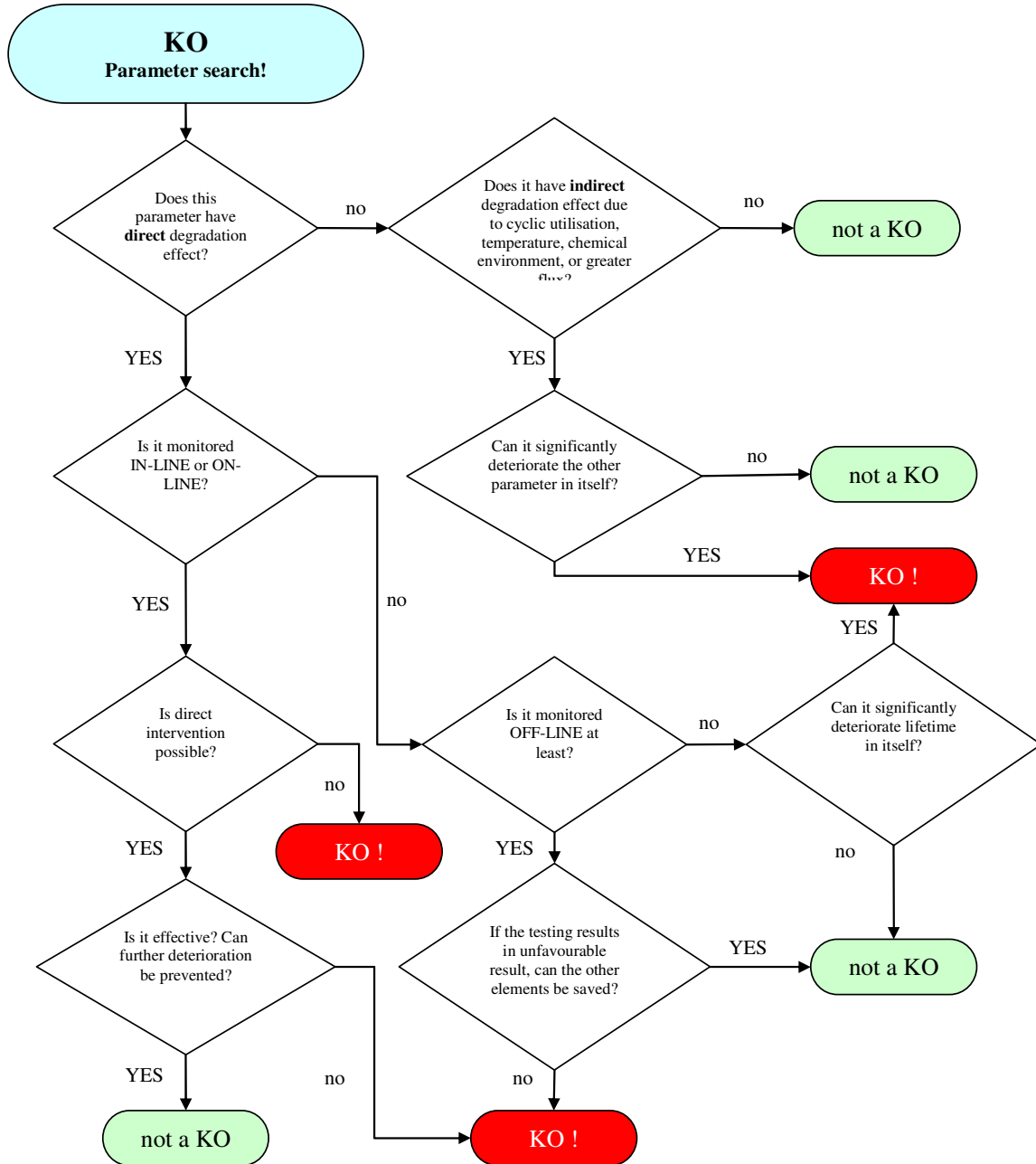
Figure 1 Special decision tree for the selection of "KO" parameters

5.2. New Methods for the Characterisation of Membrane Filter Deterioration and Standardised Definition of Lifetime

The lifetime reducing effect of chlorine – applied either occasionally in small amounts or in greater amounts for maintenance or recovery purposes – accumulates during the membranes' lifetime, which can be expressed with the total dose suffered during these processes and can be characterised with the numerical value *Chlorine exposure* as deteriorating factor. Chlorine exposure (LCl), already introduced as an expression can be quantified with the below equation:

$$LCl(ppmh) = conc(ppm) \cdot time(h)$$

As the temperature and chlorine concentration of the treatments deteriorates the polymer materials at a differing rate, the expression "lifetime chlorine exposure" (LCl$_{total}$) was introduced for this exposure factor. Research also necessitated a more exact method of quantification. The method differentiates between three working states of the membrane filters in the below equations, and summarises the doses suffered during their total working time. These are the normal operation *(LCl$_0$)*, maintenance treatments performed approximately monthly *(LCl$_K$)*, and the recovery treatment performed approximately twice a year *(LCl$_F$)*. Reactions caused by chlorine content – like aging – are greatly influenced by the temperature in the different working states. Chlorine exposure is, therefore, modified by a "temperature factor" (T*) that does not carry any dimension. The calculated chlorine exposure based on the three working states is accordingly:

$$LCl_{total} = \sum LCl_o + \sum LCl_K + \sum LCl_F \text{ , [ppmh]}$$

Thesis 2

For the tracking of the cumulative damaging effect of the sodium hypochlorite treatment used for the cleaning and maintenance of membrane filters, a numerically definable calculation method requiring computer data connection or other effective data flow was developed. The calculation applied to the entire life cycle and performed along the different working positions is a novelty.

For the numerical definition of chlorine exposure during the entire lifetime the concept and calculation method of "LIFETIME CHLORINE EXPOSURE" is introduced, which has been proven by experiments to be suitable for use in membrane filter technology using chlorine at water-purification plants.

$$LCl_{total} = \sum T_0{}^* \cdot cc_0 \cdot t_0 + \sum T_K{}^* \cdot cc_K \cdot t_K + \sum T_F{}^* \cdot cc_F \cdot t_F \text{ where:}$$

LCl – **lifetime chlorine exposure**

T* – temperature factor – a weighting factor taking into consideration the damaging effect of chlorine, depending on the temperature; it can be unified for the individual treatment types

cc – *Cl* concentration value at the given treatment type

t – cumulated time of exposure to the individual treatment types; the total time of exposure to the medium with the given state parameters

o – as subscript denotes normal operation, when chlorine was added to untreated water

K – as subscript denotes maintenance treatment

F – as subscript denotes repair treatment

Lifetime data calculated this way have advantages in product planning, operation and maintenance, moreover, renders the lifetimes of products working in different environments comparable.

Cumulative damaging factors cause the membrane filters' structure wear down, or bring final breakdown nearer in other ways. However, recurring effect types can be identified, that are caused by the working states of operation and cleaning. Filter cassettes used in water-purification plants and the membranes they contain are characterised by identical environmental conditions and stress characteristics (see "*Stress Profile*" later).

As listed below, the filters' lifetime consists of five types of stress phases. Based on their regular recurring frequency and duration, the quantitative proportion of the individual phases can be calculated. These phases are the following:

- Stress phase consisting of almost identical filtration and backwash cycles under winter operation conditions.

- Stress phase consisting of almost identical filtration and backwash cycles under summer operation conditions.

- All of the above operation conditions in particular cases: feeding to drinking water, with the addition of a moderate amount of chlorine (1-2 ppm).

- Stress phase characteristic for aeration during rest.

- **K** (maintenance) periods, with temperature relatively low, low chlorine content (but higher than normal operation, approx. 500 ppm), flow-free conditions, duration: 2-5 hours

- **F** (recovery) periods, with temperature relatively high, high chlorine content (approx. 1000 ppm), flow-free conditions, duration: 20-30 hours

During real deterioration and in the case of accelerated tests, determination of the deterioration time – or aging time – affecting the product will not be possible only by the determination of the total chlorine exposure (LCl) during lifetime, but by taking into account other deteriorating factors (e.g. filter load, dynamic effects, viscosity, the coagulation propensies of materials in untreated water, etc.) as well.

Based on the deteriorating factors that can be considered general for a certain period, the determination of "*equivalent operating time*" will be necessary. By tracking and summarising the data from these periods a transformed lifetime can be calculated, which, if calculated based on durations weighted with different degrees of stress, can provide a more realistic picture about the exposures of the product during its lifetime. This transformed time is "*equivalent lifetime*". Its calculation permits a more exact comparison of the performance of products used in accelerated tests and working under easier or more difficult conditions.

Thesis 3

An extendable method is developed in the field of membrane filtration that continuously takes into account some operational parameters. A prerequisite of this method is the transport and processing of operational variables via a computer network.

New terms of "EQUIVALENT OPERATING TIME" and "EQUIVALENT LIFETIME", as well as calculation method for them were created, and applied in the experiments, thus taking into account the accumulation of the lifetime reducing factors and their combined effect more precisely than formerly, and making them comparable within operation under differing conditions.

$$\tau_e = \sum_{i=1}^{n} t_{e_i} = \sum_{i=1}^{n} t_i \cdot \Phi_i \cdot TCl_i \cdot h_i \quad \text{where}$$

τ_e – equivalent lifetime

t_e – equivalent operating time

t – calendar time elapsed under identical circumstances

ϕ – hydrodynamic exposure factor necessary for maintaining the flux

TCl – combined factor simultaneously taking into account temperature and chlorine exposure

h – factor taking into account the coagulation propensities of the medium's individual components

The above calculation can provide more exact input information for product planning, and for the planning of operation, maintenance, or even greater investment processes.

Research was also directed to the determination and systematic description of quality parameters describing stress-bearing capabilities of the individual products and stress characteristics. A system of concepts was created for the description of exposures of a given product. "*Stress profile*" encompasses the scope of characteristics adequate for this description:

- the set of known exposures undoubtedly affecting the product while functioning,

- the set of exposures caused by outside factors, handleable by probability-theory,

- the set of contingent conjunctions between the outside environment and the exposures, quantifiable on a probability basis.

The group of "KO factors" discussed in Thesis 1, helping in the determination and care of the critical lifetime factors, can be selected from these three sets.

As shown by the next picture, the stresses, the life expectancy of the product, resulting from its material and construction, and the complex factors acting during installation, operation and maintenance, constitute the "lifetime profile" of a product operating in a given location.
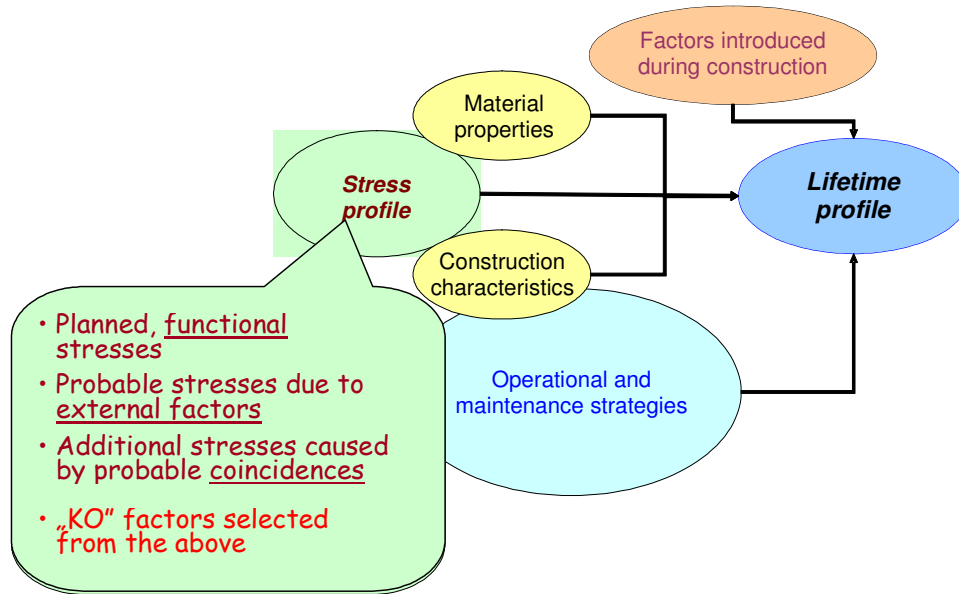
Figure 2 Critical factors of lifetime profile

5.3. Development of Database Structure for the Calculation and Tracking of Lifetime Combined with Exposures

The database created for data recording and calculations includes the following types of information for the tracking of lifetime:

DATA	*operational and generated VARIABLES*
for the identification of individual products	for the tracking of current **filter loads** affecting the individual product and the factors calculated from it
for the identification of plants where the product is located	for the tracking of current **chlorine exposure** affecting the individual product and the factor calculated from it
for the identification of technical units where the product is located and the installation position	for the tracking of current **temperature** affecting the individual product and the factor calculated from its effects
for the recording of the date of installation (and perhaps resetting) and of final breakdown	for the tracking of the harmful **coagulation propensities** of the **medium** and of the factor calculated from it
for the recording of non-numerical data concerning the products	for the calculation of **equivalent operating time** and as a summary, of **equivalent lifetime**

Besides recording data and variables, the database also

- calculates factors from operational data,

- knowing the factors, it calculates equivalent operating time and equivalent lifetime

- automatically generates transcripts, deletions, disables

- archives

Thesis 4

A data structure suitable for industrial use has been developed, which requires at least daily information acquisition, computer connection, and a database management subsystem. The data structure enables product development with respect to planning, production and facility management.

A "LIFETIME DATABASE" structure was created and applied in the experimental phase for equivalent lifetime calculations. This structure, in its content and functions, performs the collection, processing and archiving of data. This can give useful feedback via the tracking of product lifecycle for product planning and development, manufacturing technology, maintenance and operation processes, as well, as for related investment decisions.

Information concerning operation and breakdown essentially comes from three fields, and carries three different types of information and representation quality:

- Information acquired with the aftercare of products delivered to **operation sites** concern operation characteristics, lifetime, utilisation particularities and forms of breakdown. This source of information might be plentiful but shows a rather heterogenic picture. Firstly, operation conditions might differ significantly in different parts of the world. Secondly, technological discipline might be widely different, which might have a significant effect on lifetime data. Thirdly, the difference in the amount, structure and reliability of the data received renders their evaluation and the drawing of general conclusions more difficult. Information is provided by local operators, automatic equipment with signal transmitters and data transmission units, daily or weekly e-mails and maintenance protocols.

- **Complaints** concerning the breakdown of products provide valuable information; however, their representativeness is doubtful. Compared to the two other sources, they give information about significantly less products. It might be stated that only products that break down within an exceptionally short time or due to rarely occurring problems occur in these sources. Basically only quality related information might be won from the observance of impairments and their conditions, and these generally relate to manufacturing defects.

- In **factory testing equipment** representative products from a given production batch are "aged" and deteriorated. Data collection during the aging tests is performed with detailed observations and disciplined technology, but under accelerated conditions

(HALT and HASS testing), with reproducibility in sight. The data source is relatively small compared to the manufactured amount; nevertheless, this is the most important scene of aimed observations and experiments.

Only two of the above mentioned sources, data from **operation sites** and **testing equipment** is eligible for statistical processing, and they result in lifetime data lines somewhat differing in their distribution. Our aim is to make the results from the two information sources comparable and, most importantly, that the lifetime data of water-purification plants may be forecasted in advance, based on deterioration research.

Maintenance and operation treatments should be plannable with the development of the lifetime database, and it should provide input information for investment decisions. Moreover, using objective facts, supported by qualitative and quantitative data will enable to formulate expectations and provide information towards product planning and development as well as manufacturing.

One of the dissertation's objectives is to create a database from the identically structured data flows, with which lifetimes and the particularities of their distribution can be examined together. The result of this would render it possible to establish the connections between data from the three sources, based on the below theoretical functions:

In an ideal case not only statistical data but also a significant amount of text data is available that enable the researcher to connect the reasons and consequences of an occurrence with products, periods, locations and changes in production.

The picture below depicts the bridge that has the task to provide links between information sources, feedbacks and feedforwards, via the calculation methods linked to the introduced concepts and the creation of the database.
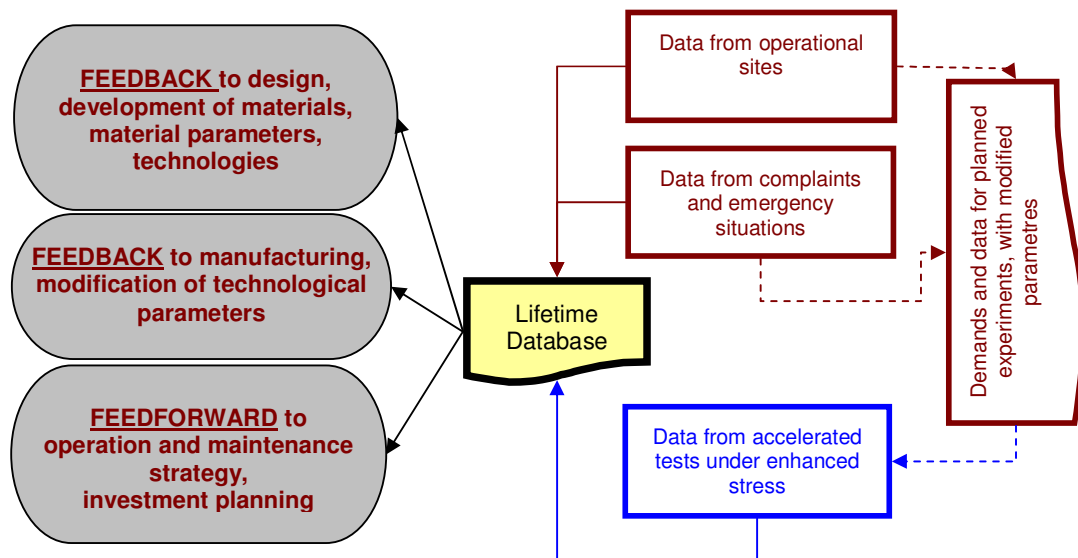
Figure 3 Aim and environment of the creation of lifetime database

The above picture shows the system of information sources and the database's possible uses.

Thesis 5

In order to achieve commensurability and integration of the – now isolated – data from accelerated tests, ad hoc data from failure statistics and mass data generated during usage, the LIFETIME DATABASE was complemented with data elements that enable the numerical time interval data to be converted into equivalent lifetimes (thesis 3).

The "LIFETIME DATABASE" thus developed is capable of combining the qualitative and quantitative data about the product's operational performance received from the operators, the analysts of the cases of damage and the service test equipment, to perform the relevant calculations, as well as to provide and archive quality-related information.

5.4. Analyses Based on the Data Won by the New Calculation Methods

Research was made in two directions. Firstly, the real relationship between chlorine exposure and lifetime had to be established. For this purpose, a correlation analysis was performed between "*lifetime chlorine exposure*" and "*equivalent lifetime*", introduced earlier. The established weak negative (but not significant) correlation indicates that equivalent lifetime is influenced by other factors as well; anyhow, greater chlorine exposure probably results in shorter lifetime.

The damaging effect of chlorine is better demonstrated by a second correlation analysis, in which a specific value was examined. Here, the connection between the chlorine dose specified for one month of the lifetime and the equivalent lifetime was statistically significant.
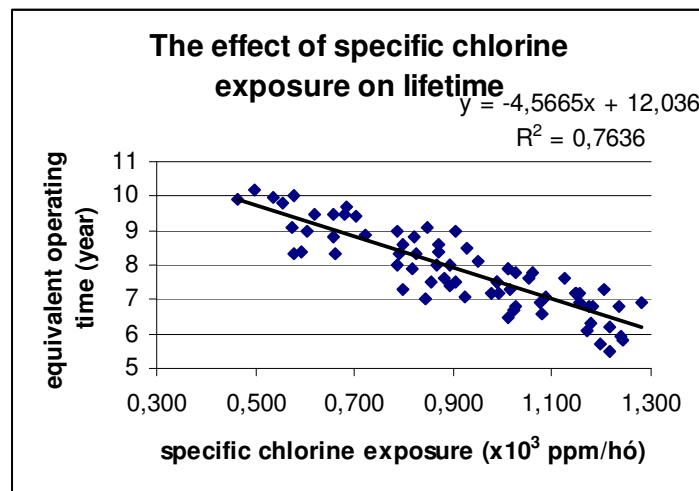
*Figure 4 Equivalent operating time calculated on the modules
with chlorine exposure specified for one month*

The second part of the research consisted of the study of the distribution of lifetime data. According to the examinations, if the 2-Parameter Weibull Distribution calculated with equivalent lifetime data is projected on the transformation plot, the resulting character will be according to the parameters below:

Chart 1 Weibull distribution calculated with equivalent lifetime data

	shape parameter per phase – b	characteristic lifetime per phase – T_K
first phase (2000-18000 hours)	1.15	550 000 hours *
second phase (18000 hours –)	4.7	75 000 hours *

When analysing equivalent lifetime data, it becomes apparent that the distribution greatly differs from the distribution calculated on a calendar time basis. This difference results from the weighting of the damaging effects caused by exposure levels and thus, from the differences in aging processes.

The two phases can still be recognized on the diagram, however, the shape parameters show an opposite tendency to the values calculated on a calendar time basis. This results in the return of the bathtub curve, i.e. the failure rate grows with the progress of deterioration, that is, the harmful effects enhance the structural damages, and the ratio of failures among the operable products is growing. It is possible that later, based on comprehensive routine analyses, the phases' intersection might present a basis for the transformation of statements based upon equivalent lifetime back to calendar time.

This permits the comparability of data if the products are used in plants functioning under different conditions, or become unusable under the "accelerated" conditions of aging tests.
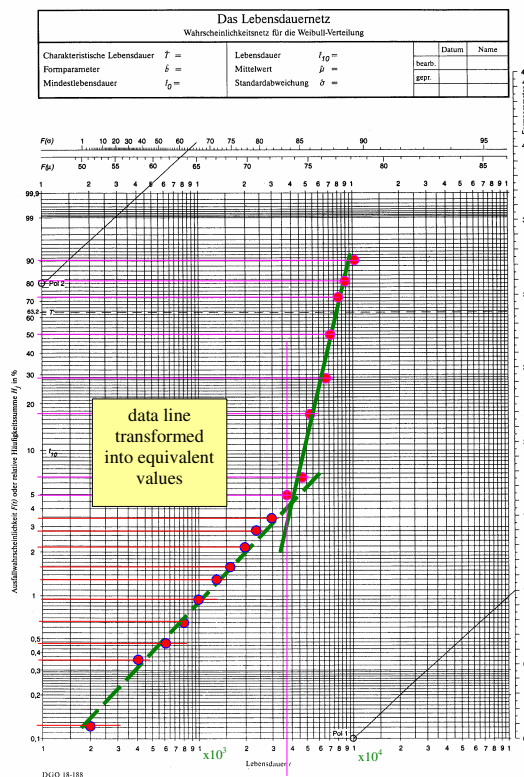
Figure 5 Lifetime plot for real values, taking into account equivalent operation time

Thesis 6

Based on the LIFETIME DATABASE filled with real operational data, data collected from separable production batches, and starting from well-defined factors, a lifetime analysis was conducted, which demonstrated that an interrelationship suitable for the feedbacks indicated in Thesis 4 can be confirmed.

> **From the EQUIVALENT LIFETIME values of the membrane filters a mixed Weibull distribution can be established, which is suitable for the description of product lifetime with the help of the calculation methodology even in case of operation under differing circumstances, thus ensuring the conditions necessary for the regulation of the maintenance system.**

6. Further Research Possibilities

The experts of the company supporting the present study considered the above approach to the question adequate, and they hope that it will bring the solution of their problems. A calculation method applicable to the given product and taking into account the described factors has not been used by the company till now. The evaluation system developed in the dissertation is in technical respect superior to the analyses applied till now. Analogies of the train of thought described in the present dissertation can be found in specialized literature; however, solutions and results for the data environment similar to the product have not been published. If the tracking of operation, maintenance and recovery periods will be more exact and isolable, the calculation of lifetime chlorine exposure will better approximate real values as well. Similarly, if information technology of entering the data (arriving in-line or on-line) into the database, automatic averaging, and refreshing is developed, the accuracy of the characteristic captured as equivalent operating time will increase.

Another field for development is the addition of further modifying factors to the database, should new critical lifetime factors be discovered. If the factors' values are rendered more exact by experiments and the clarification of the conditions, the method will be further developed and even better usable.

The methodology and lifetime database developed for membrane filters used for water purification can be placed along a development line – as can be observed in other fields as well – and as such can be considered an important step in the process. The essence of this "instinctive" process is that the information about the lifetime, damage and breakdown of the products shows all the more precisely the lifetime expectations of the products and the groups of constructions including them, and may serve as a basis for maintenance treatments and aid product development activities.

A special tendency can be observed in the field of membrane filters, given the industry field's instrumentation and documentation (e.g. information technology background). The development of the databases for tubular membrane filters fitted in modules permits and necessitates an integrated approach to data processing.

With hope in all these process potentials and further scientific research tasks I am awaiting the observations from practical implementation.

7. Scientific Contributions Related to the Topic

7.1. Conference Lectures

[1]   Gregász Tibor: **Az élettartam vizsgálatok adaptációs kérdései membránszűrőknél**
(*„Jövőbe mutató technológiák a környezetvédelemben és a könnyűiparban"* című BMF konferencián elhangzott előadás – 2009, és a megjelenésben levő kiadvány)

[2]   Koczor Z., Göndör V., Gregász T.: **Mérési rendszer fejlesztése technológiai sorba épített mérőeszközök esetében**
(*„Jövőbe mutató technológiák a környezetvédelemben és a könnyűiparban"* című BMF konferencián elhangzott előadás – *2009* és a megjelenésben levő kiadvány 2010-ben*)*

[3]   Gregász Tibor – Fekete Beatrix: **R&R vizsgálatok fejlesztése trendes jellemző mérési rendszerére**
(Anyagvizsgálat a Gyakorlatban (4. AGY) Szakmai Szeminárium 2008. Kecskemét)

[4]   Koczor Z., Göndör V., Gregász T.: **Gyakorlatorientált módszer a mérési bizonytalanság folyamatos csökkentésére**
(Magyarországi Tanúsított Cégek XIII. NEMZETI KONFERENCIA 2006. Balatonfüred, ISBN 963 06 0730 1, "A" szekció A3 1-12 oldal)

[5]   Gregász Tibor – Keszei Adrienn: **Az autóipari elvárások adaptálása textilipari környezetre mérőeszközök R&R vizsgálatainál**
(konferencia előadás IN-TECH-ED Budapest, BMF 2005 / Konferencia kiadvány: ISBN 963 9397 067, 2005. Textiltechnológiai szekció 171. oldal)

7.2. Written Contributions

[6]   Tibor Gregász, Endre Korondi: Influence of Maintenance Strategies on Envinromental Load
Acta Polytechnica Hungarica Vol. 5. No.3. 2008 page: 29-37.

[7]   Koczor Z., Göndör V., Gregász T.: A mérési tevékenység folyamatos fejlesztése
(Magyar Minőség – 2005/5