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EVALUATION OF OPERATING EXPERIENCE: THE PRECURSOR STUDY (GPS) PERFORMED IN THE FEDERAL REPUBLIC OF GERMANY

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EVALUATION OF OPERATING EXPERIENCE: THE PRECURSOR STUDY (GPS) PERFORMED IN THE FEDERAL REPUBLIC OF GERMANY

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FOREWORD

Probabilistic Safety Assessment (PSA) can provide important information related to the spectrum of possible accidents for a particular Nuclear Power Plant or other industrial installation. Such information, when based upon reliability data obtained from experience with that particular plant, concerns the accidents leading to core damage, the human system and component failures which constitute these accidents and the safety level of the plant. Following the accident at Three Mile Island in the USA (TMI-2) and more recently at Chernobyl in the USSR, PSA was used to understand how these accidents happened.

The demand for activities within the Agency's PSA programme has increased, particularly in the area of application of PSA insights to safety decisions. Consequently, an Advisory Group Meeting (AGM) was held on "Development of Manual for Probabilistic Risk Analysis and its Application to Safety Decisions", in Vienna, Austria, on 14 - 18 May 1984. The AGM has identified as a need documented experience with application and utilization of Probabilistic Safety Assessment. It was recommended that a series of case studies be written documenting actual experience where PSA has been used to give guidance in safety decision making. The first peer review on each of the case studies was to be carried out by technical experts and a high level peer review would be carried out by a senior oversight group. Based on the recommendation of the AGM a programme to publish a series of case studies on the use of Probabilistic Safety Assessment for safety decisions was initiated.

The Agency requested a number of scientists and engineers to document, in a uniform and suitable format actual experience with the application of PSA to safety decisions. A number of institutions' analysts such as NRC, NSF, EPRI, Argonne National Laboratory in the US, GRS (FRG), EdF (France), CSN (Spain), SRD (UK), AEA (UK) and OECD/NEA participated in the programme. To ensure the quality of case studies peer review was needed. A number of highly qualified experts in the field of Probabilistic Safety Assessment agreed to participate in reviewing case studies developed within this programme. The experts met on a number of occasions under the title of Oversight Committee to review and comment on the draft versions of various case studies as they were completed. The review comments were sent to the authors and incorporated in the case studies. In some cases this process was repeated more than once.

Probabilistic Safety Assessments (PSAs) are systematic and quantitative predictions of possible accident scenarios at technical installations on the basis of data gained from the past experience on similar technical installations. For supporting PSAs by operational experience as far as possible Precursor studies are performed. An Accident Sequence Precursor is defined as an observed event which could result, in coincidence with additional postulated events, in a potential severe core damage accident. In the presented case study the procedure of such Precursor studies is explained. Particularly, the methodology and the results of the plant-specific Precursor Study (GPS) performed in the Federal Republic of Germany are shown in detail.

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ABBREVIATIONS

ASP: Accident Sequence Precursor
BWR: Boiling Water Reactor
CMF: Common Mode Failure
ET: Event Tree
FT: Fault Tree
GPS: Precursor Study
LER: Licensing Event Report
LOCA: Loss of Coolant Accident
NPP: Nuclear Power Plant
PORV: Power Operated Relief Valve
PRA: Probabilistic Risk Assessment
PSA: Probabilistic Safety Assessment
PWR: Pressurized Water Reactor

1. PROBLEM DEFINITION

Nuclear power plant risk assessments have concluded that public health risk is dominated by accidents involving severe core damage as well as early containment failure. However, such an event scenario would require an initiating event and the failure of the protective safety features designed first to prevent radioactive release and second to mitigate consequences for the environment. In order to predict the corresponding event scenarios Probabilistic Safety Assessment (PSA) is a well established and powerful tool. A PSA can be characterized, in this context, as a fully systematic tool for identification and quantification of possible accident scenarios modeled on the basis of the design and operating characteristics of the facility and on data gained from the past experience at similar technical installations.

For a PSA operational experience should be used as far as possible in order to generate a realistic prediction of the future plant behavior because various models, data and assumptions used in PSA tasks include subjective judgements and have significant uncertainties associated with them.

The recommendation to use available operational experience more was first made by the 'Lewis Committee' after reviewing the Reactor Safety Study (WASH 1400) /1/. One of the possibilities for supporting PSAs by operational experience is the use of Precursor studies /2, 3, 4, 5, 6/. Such studies are based on the "Precursors" reported in reactor operation and use probabilistic methods for the prediction of the safety-related importance of these Precursors.

An "Accident Sequence Precursor" (ASP) or "Precursor" is an observed event, which resulted in a severe core damage or could lead, in coincidence with additional postulated events, to a potential severe core damage accident.

The Precursor methodology is based to the highest possible degree of event combinations observed in operational experience. The Precursor methodology has a particular strength in that it can use data on combinations of events instead of the single basic event data normally used in a PSA. Thus, while a PSA synthesizes the frequency of event combinations from the frequencies of the different initiating events and the failure probabilities of individual components, a Precursor study can directly take combinations of events into account, as far as observed, without making assumptions on the synthesis process.

Within the Precursor investigations different time periods of the past (e.g. periods of 1 year) may be studied, which allows us to detect and judge effects over time like system improvements or learning of the plant personnel because of mistakes. Precursor studies are also a powerful tool to obtain a deeper understanding of the safety-related importance of the Precursors collected in abnormal occurrence reporting systems or to optimize these systems using such insights. Events which rarely happen and have not been observed so far, naturally can not be verified using the Precursor methodology.

2. OBJECTIVES

The objectives of the U.S. Accident Sequence Precursor (ASP) Program were /7, 8/:

- From operational events identify significant or important sequences that, more likely than others, could have led to severe core damage.

- Search operational events for the elements or Precursors of severe core damage accident sequences which are not predicted or poorly predicted in current Probabilistic Risk Analyses (PRA).
- Analyze operational events to estimate the frequencies and trends of system failures, function failures, and overall frequency of severe core damage as an alternate data source to compare to frequencies estimated in PRAs.

The U.S. Accident Sequence Precursor (ASP) studies /2, 3/ expected to achieve these objectives by using the Licensing Event Report (LER) file to identify those events that were selected as Precursors. The ASP studies estimated an overall core damage frequency for specified operational periods of all U.S. commercial nuclear power plants with PWRs and BWRs, respectively. Additionally, trends of system failure and function failure probabilities for the population of the operating U.S. plants were assessed.

Considering the critiques and comments concerning the U.S. ASP study /9, 10, 11, 12/ on the one hand and the smaller scope of the existing German operational experience on the other hand, the method of the ASP Program was not directly used for the German Precursor Study (GPS) /4, 5, 6/. The GPS was carried out plant-specifically using the nuclear power plant Biblis /13, 14/ with the two units A and B as the reference plant.

Different from Biblis A (Fig. 1) there exists for Biblis B (Fig. 2) a complete separation of the redundant trains of the intermediate coolant system (component coolant system) and of the secondary coolant system (service water system).

The main differences between the ASP study and the GPS are summarized in Table 1.

Objectives of the GPS investigations are:

- to gain a deeper understanding of the safety-related importance of the event scenarios, reported during the operation of the plant,

- to identify and valuate possible weak points as well as,

- to compare the results with those of the German Risk Study /15, 16, 17/.

3. OVERVIEW OF THE ANALYSIS

When the analysis of the GPS was started, 7 PWR and 4 BWR were in operation in the Federal Republic of Germany, excluding prototype plants. The corresponding operational experience was 56 PWR and 24 BWR reactor years. This corresponds to approximately 20% of the U.S. operational experience between 1969 and 1979, as used in the ASP Study /2/. In total 1300 LERs were documented in the Federal Republic of Germany.

Because of the comparatively high degree of redundancy in the safety systems, total system failures occurred only for a few types of systems and only in a few cases. Partial failures of safety systems are not required to be reported in LERs in all cases, with the exception of emergency diesel generator and control rod failures. Therefore, it was not possible to derive system unavailabilities from the reported events. Thus, the following strategy was chosen concerning the plant-specific evaluation of the operational experience of Biblis nuclear power plant:

- Plant-specific frequencies of occurrence of initiating events were estimated for the time period between the beginning of commercial plant operation and the end of 1983 as well as for the corresponding half time periods.

- Using the reliability data bank for Biblis B /18, 19/ estimates for plant-specific train unavailabilities were calculated.

- System failures, multiple failures and potential system or multiple failures were evaluated when plant-specific operational experience was available.

- Operator errors were quantified on the basis of plant-specific operational experience.

The above mentioned reliability data bank for Biblis B contains for 39 selected systems the information from all repair and maintanance sheets filled out during approximately 3½ years of plant operation.

Initiating events, which occurred during start-up and cool-down, during hot stand-by or partial load, were in general evaluated as if they were initiating events during full load operation. Data for estimating train unavailabilities was treated in the same way. The same minimum requirements for the system functions were used as in the German Risk Study /15, 16, 17/. No initial screening of events was performed, but all selected events were analyzed. As Precursors to potential severe core damage accidents all plant-specific events and event sequences were selected,

- which led as initiating events not only to a reactor scram but also to a demand on further safety systems or safety-related systems*)

  or

- where, in connection with a simultaneous initiating event or a postulated initiating event,

  - ° a system failure or multiple failures occurred, or
  - ° a potential for system failure or multiple failures existed.

Potential system and multiple system failures were conservatively treated as if actual failures occurred. Failures of single system trains were not selected as Precursors.

An example for the Precursor with initiating event is the "loss of main feedwater" (Fig. 3); when such a transient occurs additionally to reactor scram the auxiliary feedwater system will be demanded. An example for the Precursor with a system failure or a multiple failure are the failures

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*) Examples of safety-related systems which are not safety systems are the pressurizer relief system and the secondary steam relief system.

of 2 emergency diesels which were present at the same time; the diesels will be demanded in case of a "power failure" (Fig. 4).

Manual interventions were treated in the following way:

- Manual actions which were not successful were not taken into account;
- Manual actions which were successful were taken into account with a probability of failure calculated on the basis of the field experience;
- Unplanned manual actions, which could allow failed safety systems or system trains to be recovered after the demand were conservatively not considered.

An example with respect to the first case is the "loss of main feedwater" were the system was not restored to operation. If the system was restored in the available time frame a probability of recovery was assigned to the event.

For each Precursor the plant-specific frequency of severe core damage was estimated. This was performed on the basis of the event trees (ETs) and fault trees (FTs) of the German Risk Study /15, 16, 17/. For each Precursor the event trees and fault trees were modified taking into account the actual system configuration at the time of occurrence ("Living ETs and FTs"). Estimates for the mean values were used and uncertainties of these mean values were calculated.

The Precursors without initiating event were evaluated on the basis of the frequencies of the corresponding initiating events for each half of the observation period. Also, the probabilities of failure of the operational systems (no recovery of main feedwater main heat sink etc.) were calculated for the appropriate half of the observation period. Because of the system modifications performed during the years of operation and because of the increasing experience of the plant personnel

- the frequencies of the initiating events as well as
- the probabilities of system failures

were reduced with the increasing operating time.

In order to show the impact of system improvements and of learning effects, the frequencies of the initiating events, the unavailabilities of system functions and the frequency of potential severe core damage accidents were not only documented for the total time period of operational experience (16 reactor years), but also on the basis of the half time periods.

For the reference plant of the study /13, 14/, the following information was used:

- system diagrams and descriptions
- detailed information about all operational transients
- specific reports to special occurrences
- detailed system information and fault trees from the German Risk Study
- train unavailabilities
- component unavailabilities in a few special cases
- description of system changes performed for the units Biblis A and B in the years 1975 to 1983.

The flow chart of Fig. 5 and Fig. 6 shows the major steps of the plant-specific Precursor assessment performed in the German Precursor Study (Phase 1). Additionally, a plant-type assessment which has not yet been started is also illustrated in this diagram (Phase 2). In the corresponding steps the question of transferability of data should be handled carefully. It should be distinguished between vendor-specific, plant-type specific as well as component-type specific field experience etc. Non-plant-specific data will be used as a supplement to the plant-specific information.

4. CALCULATION METHODS AND PROCEDURES

4.1. Frequencies per Reactor Year of the Initiating Events

Following the criteria of Chapter III, 64 events were selected as Precursors in the reference plant during a period of about 16 reactor years. The corresponding format for reporting and evaluation of these events is shown in Table 2. 53 Precursors were associated with initiating events, which resulted not only in a reactor scram but also in the demand of safety systems or safety-related systems. Four main categories of initiating events were found:

-	loss of main feedwater	29 events
-	loss of main heat sink	12 events
-	loss of preferred power (power failure)	6 events
-	opening of pressurizer valves.	16 events

Loss of preferred power means loss of off-site power and failure of the turbine generator to run back to house load. That means, in the case of this transient that the emergency Diesels are demanded for electric power supply. (In the English translation of the German Risk Study /16/ this transient was called "power failure".)

Frequencies of these initiating events and combinations between them were calculated for both the total time period of operational experience (16 reactor years) and the two half time periods (first and last 8 reactor years).

4.2. Average Unavailabilities of System Trains

The average unavailability $\hat{m}$ of a system train is given by:

$$\hat{m} = \frac{\text{sum of down-times during observation period}}{\text{observation time}}$$

For the down-times, both

- the failures of components where demanded during operation or during functional tests

  and

- the maintenance time intervals of components

which resulted in an unavailability of the train have to be considered. In the case of a component failure the down-time consists of the failure detection time and the repair time. Assuming random failures, i.e. considering the constant failure rate model as the best description of the failure behavior /18/, the average failure detection time is just half the time interval between the time of the last functional demand before the component failure occurred, and the time of the component failure.

If only the failure detection time of components, which are tested every 4 weeks, contribute to the mean value, $\hat{m}$, of the average unavailability of the trains:

$$\hat{m} \cong \frac{\hat{\lambda}\, T}{2} \quad ,$$

where
$\hat{\lambda}$ = estimator of the train failure rate and

T = 4 weeks, test interval

The estimator $\hat{p}$ of the system unavailability from random failures can be approximated by:

$$\hat{p} = \frac{251}{7680}\,(\hat{\lambda}\ T)^4 \;\cong\; \frac{16}{31}\left(\frac{\hat{\lambda}\ T}{2}\right)^4 \qquad \text{for a 1-out-of-4}$$

$$\hat{p} = \frac{3}{8}\,(\hat{\lambda}\ T)^3 \;=\; \frac{3}{4}\cdot 4\left(\frac{\hat{\lambda}\ T}{2}\right)^3 \qquad \text{for a 2-out-of-4}$$

when staggered testing of the trains is performed. The factors are calculated in /20/ on the basis of the exact formula (see also /21/).

If $\lambda T/2$ is replaced by $\hat{m}$, as was the case in the German Precursor Study, this results in an overestimation of the system unavailabilities by a factor of 31/16, i.e. nearly 2 (1-out-of-4 system) and 4/3 (2-out-of-4 systems), resp.

Because the constant failure rate model may not be valid in all cases, additional calculations were performed on basis of constant failure probabilities per demand. In this case the pessimistic assumption was made that the down-time is the complete time interval between the time of the last functional demand before the component failure occurred and the time of the component failure.

The average unavailabilities of system trains and of component groups demanded at the same time were evaluated for the following systems:

- pressurizer relief system
- secondary steam system
- auxiliary feedwater system
- emergency feedwater system
- demineralized water system (de-ionising system)
- emergency core cooling and residual heat removal system
- nuclear component coolant system (nuclear intermediate coolant system)
- nuclear service water system (nuclear secondary coolant system)
- chilled water system
- emergency Diesel system

The train unavailabilities were calculated using the records of the reliability data bank on repair and maintenance work performed within 3 1/2 years of reactor operation for Biblis B. For the emergency Diesel system, additional calculations were performed on the basis of all German LERs (see p. 5, first paragraph); the results were used for comparison with the plant-specific train unavailabilities of the emergency Diesel generators.

The pressurizer safety valves and the secondary steam safety valves were treated differently. Because plant-specific experience for these components was not sufficient, component-type information from conventional power plants was utilized /22, 23/. In a few further exceptions in which no train data was available, probabilities were calculated using plant-specific estimates of component unavailabilites.

The treatment of human error is explained in section III on p. 6.

4.3. Frequency of Severe Core Damage

The frequency of severe core damage was calculated with the following formula:

$$\begin{matrix}\text{Frequency of}\\ \text{severe core}\\ \text{damage}\end{matrix} = \sum_{\substack{\text{Precursors } i\\ \text{with}\\ \text{initiating}\\ \text{events}}} \begin{pmatrix}\text{frequency}\\ \text{of Precursor}\\ \text{event } i\end{pmatrix} \times \begin{pmatrix}\text{probability}\\ \text{of subsequent}\\ \text{severe core}\\ \text{damage associated}\\ \text{with event } i\end{pmatrix} +$$

$$\sum_{\substack{\text{Precursors } i\\ \text{without}\\ \text{initiating}\\ \text{events}}} \ \sum_{\substack{\text{corresponding}\\ \text{initiating}\\ \text{events } j}} \begin{pmatrix}\text{frequency}\\ \text{of Precursor}\\ \text{event } i\end{pmatrix} \times \begin{pmatrix}\text{probability}\\ \text{of initiating}\\ \text{event } j\end{pmatrix} \times \begin{pmatrix}\text{probability}\\ \text{of subsequent}\\ \text{severe core}\\ \text{damage associated}\\ \text{with events } i \text{ and } j\end{pmatrix}$$

The frequency of each Precursor i is always 1/16 reactor-years because the were treated separately.

The probability of subsequent severe core damage associated with each precursor was estimated on the basis of the event trees (ETs) and fault trees (FTs) of the German Risk Study /15, 16, 17/. Examples of such event trees are shown in Figures 3, 4 and 7. Observed Precursor event sequences are indicated in the corresponding event trees with bold lines. An example is the observed Precursor "loss of main feedwater" is indicated in Fig. 4. If the observed Precursor is a multiple failure which results in a partial failure of a system function, then the Precursor event sequence is indicated in the corresponding event tree with dashed bold lines. An example is the Precursor "failure of 2-out-of-4 Diesels" is shown in Fig. 3.

The fault trees were reduced to the level of trains and groups of components demanded at the same time. The event trees and fault trees were modified taking into account the actual system configuration for each Precursor ("Living ETs and FTs"). The mean values of the average unavailabilities (see section IV.2) were used for calculation of point estimates. These calculations were performed by means of the RALLY computed code package /24/ using the fault trees of the German Risk Study /15, 16, 17/.

For the Precursors without initiating event, corresponding initiating events were postulated, for which multiple failures or a system failure were important.

The probabilities of the initiating events, given a Precursor without initiating event, were calculated taking into account the Precursor duration and the frequencies of the initiating events in the corresponding half time period of operational experience.

Additional calculations were performed assessing common-mode failure probabilities on the basis of plant-specific system failures and multiple failures. These common-mode failure probabilities were introduced in the calculation of the probabilities of subsequent severe core damage in the first term of the above formula. For these additional calculations the second term of the above formula was neglected to avoid overestimation. No noticeable differences in the results between these additional calculations and the standard calculation procedure represented by the above formula were found.

The uncertainty analysis performed within the German Precursor Study will be explained in detail in /6/.

5. INTERPRETATION OF THE RESULTS

Before interpreting the results of the German Precursor Study (GPS) it seems to be useful to consider the differences with respect to over- or underestimation of results between the plant-specific GPS and the generic U.S. Accident Sequence Precursor (ASP) Program /2, 3/. A comparative listing of the sources of over- and underestimation is shown in Tables 3, 4 and 5.

The following discussion of results gained by the GPS is subdivided into the following categories:

- Overall results,
  i.e. results describing the overall frequency (in units of per reactor year) of potential severe core damage accidents.

- Specific findings,
  i.e. partial results of the GPS, which are discussed in more detail especially in comparison with results gained in the German Risk Study /15, 16, 17/.

- Results of the human error analysis,
  i.e. results which specifically address the human error influence on initiation of events selected as Precursors or the human error influence on coping with the subsequent accident sequence.

- Conclusions,
  i.e. general conclusions which can be drawn from the experience in performing a plant-specific Precursor study especially compared to generic Precursor studies.

5.1. Overall Results

The trend in the overall frequency of events selected as Precursors in both units of the Biblis NPP is shown in Fig. 8 and the trend in the overall frequency of potential severe core damage accidents is shown in Fig. 9. The main contributions to the severe core damage frequency occurred in the first years of plant operation. The decrease of the severe core damage frequency with increasing operating time is due to various system improvements. The estimated mean value of the overall frequency of potential severe core damage accidents is 5×10^{-5} per reactor year. The uncertainty analysis shows that the estimated 95 % confidence limit for this mean frequency is 5×10^{-4} per reactor year (Fig. 10). These results are based on the assumption that the failure mechanisms of the system trains can be described by constant failure rates. Under the pessimistic assumption of constant failure probabilities per demand the estimated mean frequency of potential severe core damage accidents would increase only by a factor of 2.

The above mentioned results fit into the 90 % confidence interval (1×10^{-5} to 3×10^{-4} per reactor year, with a mean value of 9×10^{-5} per reactor year) for the core melt frequency which was obtained by the German Risk Study /15, 16/. One reason for the lower mean value in comparison to the German Risk Study is the limited existing operational experience, i.e. the German Precursor Study evaluates only initiating events, system and multiple failures as well as human errors which actually occurred during the observation period.

The comparison of initiating events observed in the operational experience of Biblis NPP with those postulated in the German Risk Study has not revealed any new types of initiating events.

5.2. Specific Findings

The analysis of the individual contributions to the calculated severe core damage frequency shows some discrepancies between the German Risk Study and the GPS (see Table 6) which are worth noting.

In contrast to the German Risk Study there is no contribution to the total result from a "small leak in a reactor coolant loop" or from ATWS, because these were not observed in the operational experience.

The results for the "loss of preferred power" are in accordance with the results of the German Risk Study. The agreement is satisfactory for the "small leaks in pressurizer". These results were derived from the frequency of demands on the pressurizer relief valves and the probability of failure of the PORVs and the redundant block valves to reclose. It should be noted that, for these initiating events, larger frequencies were gained than in the German Risk Study. On the other hand lower probabilities of failure of the demanded systems were obtained.

The assumption of the German Risk Study that each "loss of preferred power" would lead to a demand of pressurizer relief valves has not been supported by the operational experience.

The train unavailabilities of the safety systems estimated from operational experience are generally lower (factor 2-3), but otherwise in good agreement with the values from the German Risk Study. For the high pressure safety injection, the accumulator injection, the nuclear component cooling system, the nuclear service water system and the chilled water system, the train unavailabilities calculated on the basis of the plant-specific experience are even lower (by a factor 6 up to 2 orders of magnitude). Naturally, these differences distinctly influence the unavailabilities of the system functions.

During the observed time period a significant improvement of the plant behavior was observed. At the beginning of commercial operation the dominant contribution was from the "loss of main feedwater and main heat sink" due to a actuation of the main steam line break-signals. This initiating event was only observed in the first half time interval (up until end of 1979) and can be interpreted as an initial problem, leading to improvements of the actuation devices, of the control of the main steam by-pass valves and of the operational instructions.

In the second half time period (1980-1983) the most important contributions came from the potential multiple failure of three residual heat removal pumps (in 1983 only) and from the "loss of preferred power". Meanwhile, the electric power supply of Biblis NPP was improved by the installation of a second independent grid connection to each unit. Therefore, the expected contribution of this initiating event will be much lower now.

The frequency of the opening of the first pressurizer relief valve decreased from 0.9 per reactor year in the first half time interval to 0.5 per reactor year in the second half time interval, the frequency of the opening of both pressurizer relief valves remained constant at 0.25 per reactor year.

A considerable reduction of the contribution of a "small leak in pressurizer" to the frequency of potential severe core damage results almost exclusively from several improvements to the pressurizer system, especially of the control devices for the pilot valves of the PORVs and for the block valves.

Summarizing the results, one can say that the plant-specific German Precursor Study supports the PSA performed for Biblis A /25/ and especially the German Risk Study for Biblis B /15, 16/.

5.3. Results of the Human Error Analysis

Nearly half of the Precursors that occurred in the Biblis NPP have been influenced by human errors (Fig. 11). For the contributions of the shift and the technical personnel see Fig. 12. These Precursors contribute 64% to the estimated frequency of severe core damage accidents (Fig. 13). The trend of the Precursors influenced by human errors corresponds well to the observed overall tendency. The frequency of Precursors influenced by human errors has decreased significantly and has now reached a very low level.

The analysis of human errors has revealed, that specific error modes were associated with shift personnel and maintenance personnel, resp. For the classification of the different error modes a proposal of Hacker /26/ was used, which proved to be useful in the practical application (Table 7). For the technical personnel mainly misidentification (e.g. insertion of an electronic module in a wrong slot position in the cabinat) and forgetting occurred, whereas for the shift personnel misjudgment (e.g. to put on a control oil supply neglecting the effect on the main steam by-pass valve) was the dominant error mode. The qualitative analysis has also demonstrated that a cause-oriented human error analysis requires a lot of very detailed information, which is in many cases not included in the available documents. The utility has achieved a significant reduction of the frequency of human errors by systems improvements and by enhanced training of its personnel. This supports and emphasizes the importance of a cause-oriented human error analysis.

For the documentation and analysis of the human error contribution to the Precursors a specific format (Table 8) was developed. This format was designed to provide a rough task analysis on which the quantitative and qualitative analysis could be based. Such a task analytic approach is especially useful for event scenarios in which more than one human error occurred.

5.4. Conclusions

The following general conclusions have been drawn from the plant-specific German Precursor Study.

The probabilistic results of PSAs, mainly obtained by analytic computation on the basis of failure rates of single components, could be verified by the plant-specific experience with system trains. The main advantage of this plant-specific Precursor study was that it pointed out the importance of plant-specific experience of (potential) system failures and (potential) multiple failures. Using the Precursor methodology, an annual trend could be derived for the frequency of potential severe core damage accidents. For the current system status, weak points in the systems were not identified. The impact of erroneous manual actions was significant, mainly in the frequencies of initiating events.

The application of system-analytic tools and especially probabilistic methods on the evaluation of LERs and other records of operational experience can contribute to:

- a deeper understanding of the safety-related importance of the events reported in reactor operation,
- the importance ranking of the different safety features,
- the identification of possible weak points in the plant,
- the expansion of the scope and content of the abnormal occurrences reporting systems.

Furthermore, the results from Precursor studies can be compared with those of PSAs. This gives more confidence in PSAs regarding the reliability figures and the completeness.

Both, generic and plant-specific Precursor studies have their advantages. Generic Precursor studies, based on a large number of LERs, expand the general knowledge about possible events and event sequences in NPPs. In generic Precursor studies the classification of initiators and the analytic calculation of postulated propagation to severe core damage is much more difficult because the system information in LERs is less detailed, and therefore more subjective judgements are necessary. On the other hand a greater number of events of the same type are available, and consequently the statistical basis for initiating events and system failures is better. Obviously, plant-specific Precursor studies give more representative insights for particular NPPs.

6. PEER REVIEW PROCESS

The work for the plant-specific German Precursor Study (GPS) has to be seen in conjunction with the U.S. Accident Sequence Precursor Program. Some of the experience with that generic Precursor study and especially the critique of that study could be utilized for the GPS.

The methods, data and results of the GPS have been extensively discussed with different experts. Discussions with the experts from the utility led to minor corrections with respect to operator errors. For a few Precursors a subjective judgement by the authors was required; for these events conservative interpretation was performed.

A formal peer review process, as discussed and partly performed for PSAs and Precursor studies in the U.S.A. was not applied to the GPS. But it is felt that the extensive discussion of the methods, data and results with experts inside and outside the company has achieved the goals of a peer review process to great extent.

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Table 1: Major differences between the ASP Study and the GPS

	U.S. Accident Sequence Program	German Precursor Study
Data Source	LER's	Detailed plant-specific information
Assessment of frequencies of initiating events	Mean frequencies for the population of PWR and BWR plants, resp., within the observation period	Mean frequencies for the reference plant within the half observation periods
Failure probabilities of systems and system functions	Mean failure probabilities based on system failures and multiple failures which occurred	Probabilities based on train unavailabilities and taking into account system modifications, quantification of system failures and multiple failures which occurred, consideration of potential system and potential multiple failures as actual failures.
Manual actions	Consideration of potential manual recovery actions	Quantification of operator errors on basis of the plant-specific experience. No consideration of potential manual recovery actions

Table 2: Format for reporting and evaluation of events

PRECURSOR:			No.: LER No.:
Corresponding initiating event:			NPP unit: Hour: Date:
Precursor contains initiating event: Yes/No			Operating conditions at onset of event:
Comparable Precursors:		Event tree No.:	Involved Systems:
Literature:			Diagnosis: Event undetected since:
TIME AFTER ONSET OF THE EVENT:	DESCRIPTION OF THE PRECURSOR:	OPERATING STAFF ACTIONS:	EVALUATION OF THE PRECURSOR^2. Frequency of the Precursor of the initiating event $\hat{h}$ [1/yr]: initiating event with Precursor postulated Average unavailability $\hat{m}$ of the system functions coping with the initiating event:
DESCRIPTION OF THE HUMAN ERROR:		INDICATION TO CMF:	Conditional probability $\hat{w}$ for core damage given the Precursor:
PRECAUTIONS (including system modifications):			Frequency of severe core damage: $\hat{h} \cdot \hat{w}$ [1/yr]:

Table 3: Potential sources of over- or underestimation in the ASP study acc. to /3/ and its comparison with the GPS

ASP study	German Precursor study
only actual event sequences are provided	
generic event trees	plant-specific event trees
generic data base	plant-specific data base
engineering judgement on recovery credit	plant-specific recovery factors
test interval of 1 month	plant-specific Tech. Specs. and operational demands
consideration of shut-down events	no consideration of shut-down events

Table 4: Potential sources of overestimation in the ASP study acc. to /3/ and its comparison with GPS

ASP study	German Precursor study
failure prob. per demand	failure rates per time (failure prob. per demand in an additional investigation)
overcounting of observed failures	only overcounting of observed single train failures

Table 5: Potential sources of underestimation in the ASP study acc. to /3/ and its comparison with the GPS

ASP study	German Precursor Study
only events reported in LERs (exception: loss of main feedwater)	all plant-specific events
only operationally observed events (e.g. no Large LOCA)	
no single train failures	also single train failures
no potential failures	also potential failures
no failures of containment cooling	also failures of containment cooling
no events prior to initial critically	no events prior to commercial operation
no train separation taken into account	actual train separation taken into account

Table 6: Contributions to the frequency of potential severe core damage accidents

CONTRIBUTIONS TO THE FREQUENCY OF POTENTIAL SEVERE CORE DAMAGE ACCIDENTS (1/yr)

Types of Initiating Events	German Precursor Study		German Risk Study
	Initiating Events	All Precursors	
Loss of main feedwater	2.1×10^{-5}	2.1×10^{-5}	3×10^{-6}
Loss of preferred power	1.6×10^{-5}	1.8×10^{-5}	1.3×10^{-5}
Loss of main heat sink without loss of main feedwater	1×10^{-8}	1×10^{-8}	3×10^{-8}
Small leak in pressurizer during loss of preferred power	8×10^{-7}	3.1×10^{-6}	7×10^{-6}
Small leak in pressurizer during other transients	2.4×10^{-6}	2.6×10^{-6}	2×10^{-6}
Small leak in pressurizer due to spurious opening of pressurizer valves	1.5×10^{-6}	4.2×10^{-6}	-
Small leak in a reactor coolant loop	-	-	5.7×10^{-5}
ATWS	-	-	1×10^{-6}

Table 7: Human Error classification scheme acc. to Hacker /26/

Human Errors due to lack,

nonuse or wrong processing of information

Required information objectively not available	Required information available but not used	Required information available but incorrectly used
	• oversight • forgetting • omission • stereotyped behaviour • ignoring	• misidentification • wrong remembering • misjudgment • wrong decision • incorrect motoric output • time or sequence errors

Table 8: Task analysis data sheet

PRECURSOR: No.: Page:

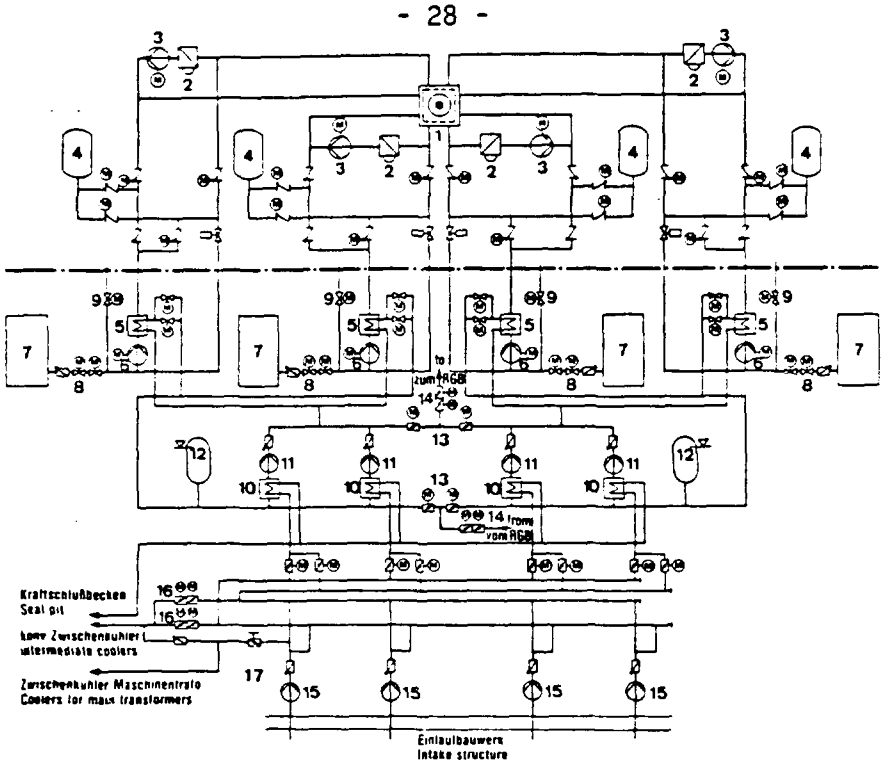
NPP unit: Date: Hour: Reactor Power at onset of event:

Brief event sequence description:

Job of operating personel:

Time:	Duration:	Location:	System/ Component:	Parameter:	Status:	Task of operating personnel:	I & C-devices involved:	Comments:

Evaluation:



1 reactor, 2 steam generator, 3 main coolant pump, 4 accumulator, 5 RHR-cooler, 6 RHR-pump, 7 flood tank, 8 flood tank valve, 9 sump valve, 10 intermediate heat exchanger, 11 intermediate coolant pump, 12 compensation tank, 13 valves for disconnection of systems, 14 containment closure for nuclear intermediate coolant system, 15 secondary coolant water pump, 16 disconnection valves.

Figure 1: Cooling chain for emergency core cooling (Biblis A) /25/

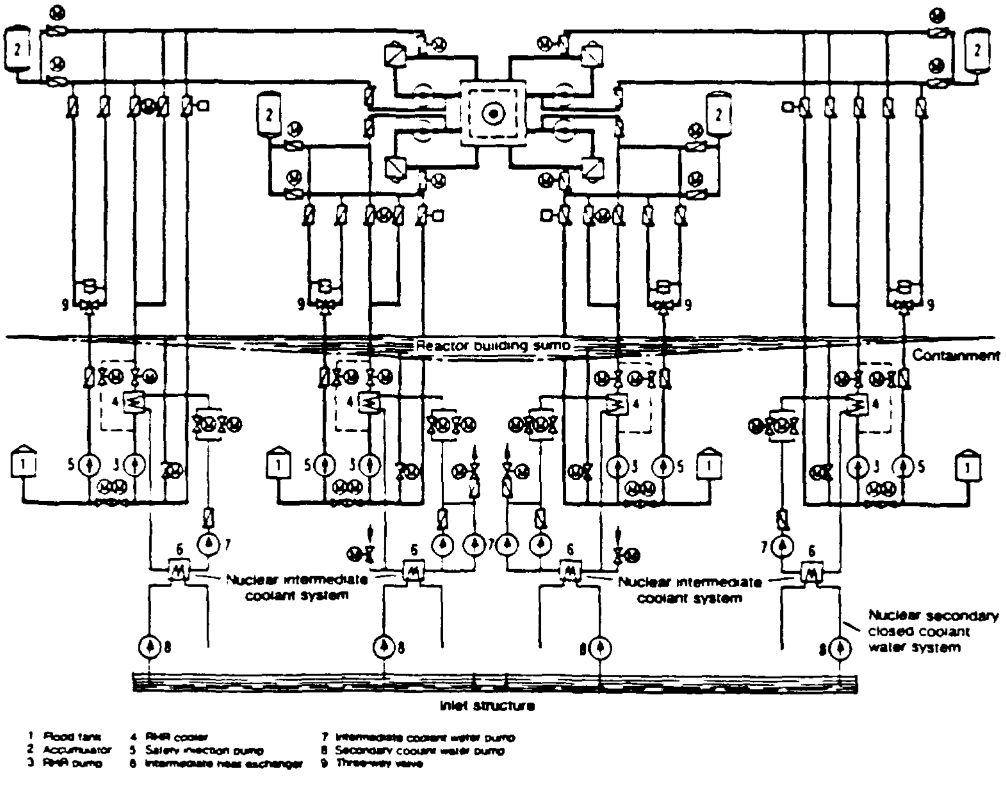
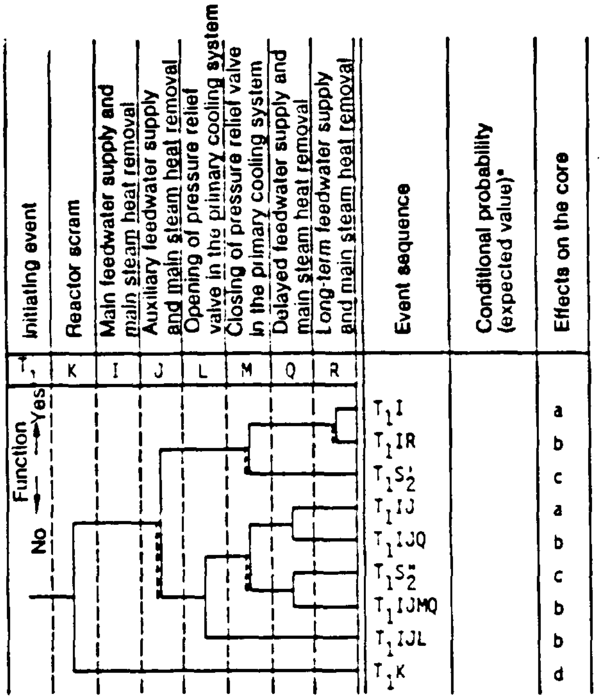


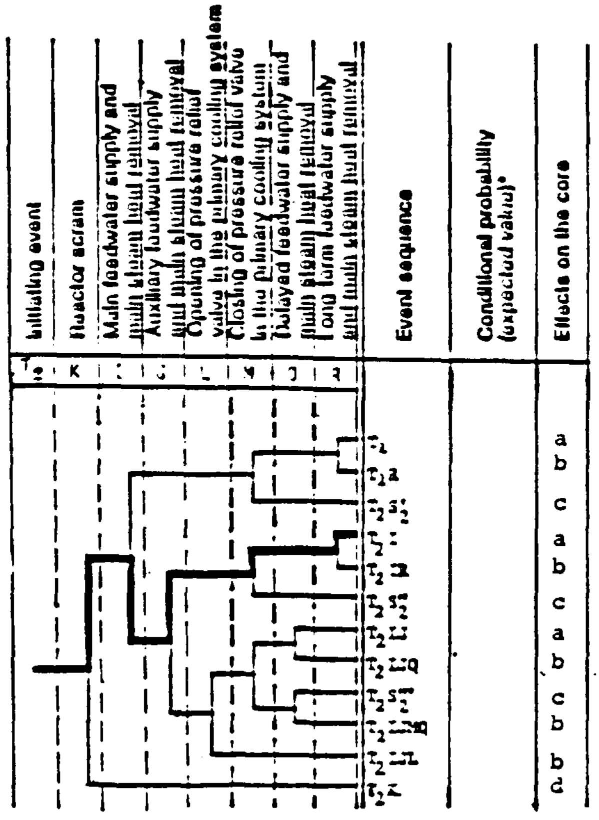
Figure 2: Cooling chain for emergency core cooling (Biblis B) /16/



a No core melt
b Core melt
c Continuation "small leak at pressurizer during power failure"
d Continuation "ATWS" accidents

*Probability of the individual event sequence assuming that the initiating event has occurred. The frequency of the individual event sequence is obtained by multiplication with the frequency n of the initiating event

Figure 3: Event tree for a "power failure"



a No core melt
b Core melt
c Continuation "small leak at pressurizer during power failure"
d Continuation "ATWS" accidents

Figure 4: Event tree for a "loss of main feedwater"

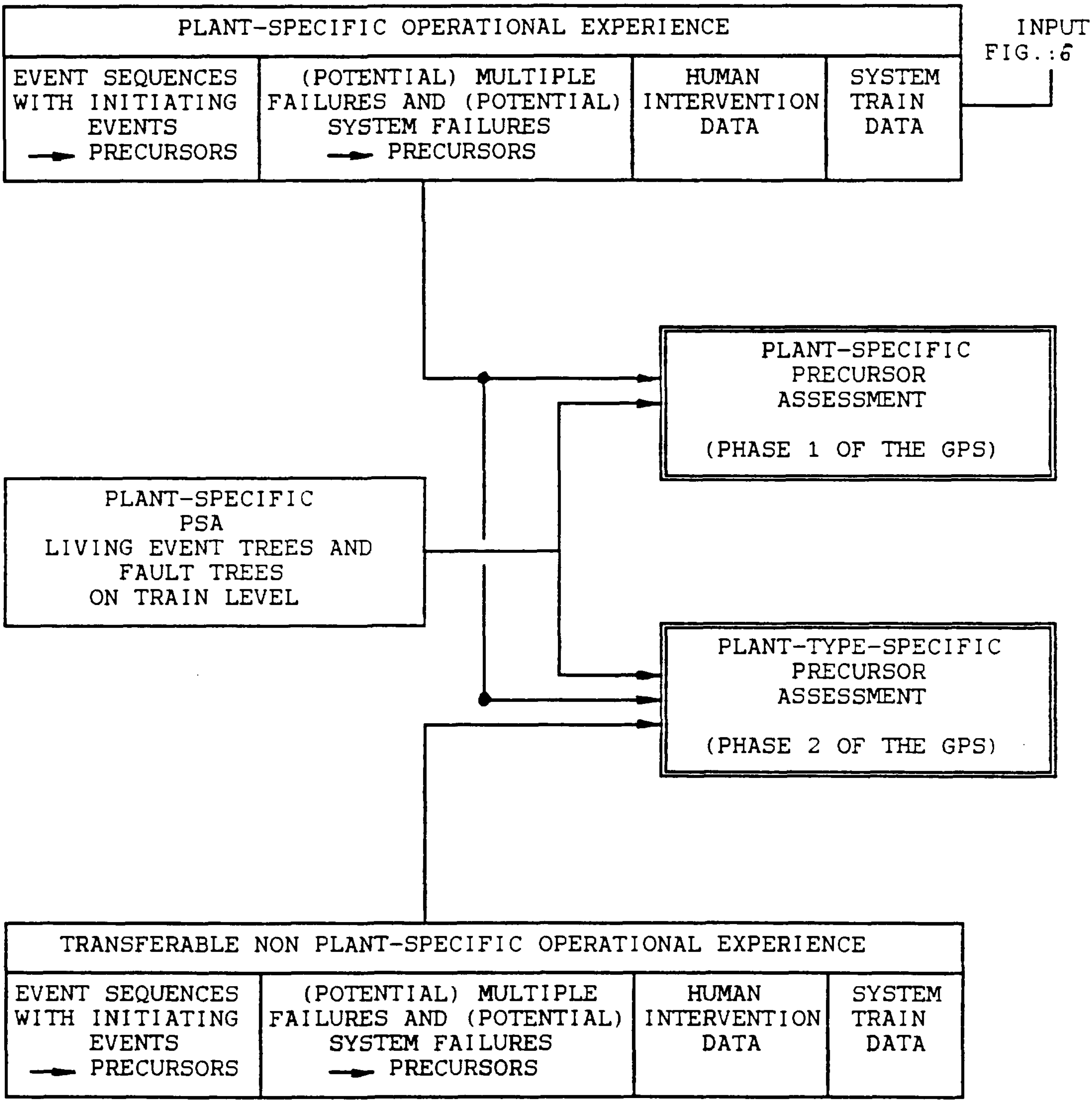


Figure 5: Flow chart of the major steps of the German Precursor Study

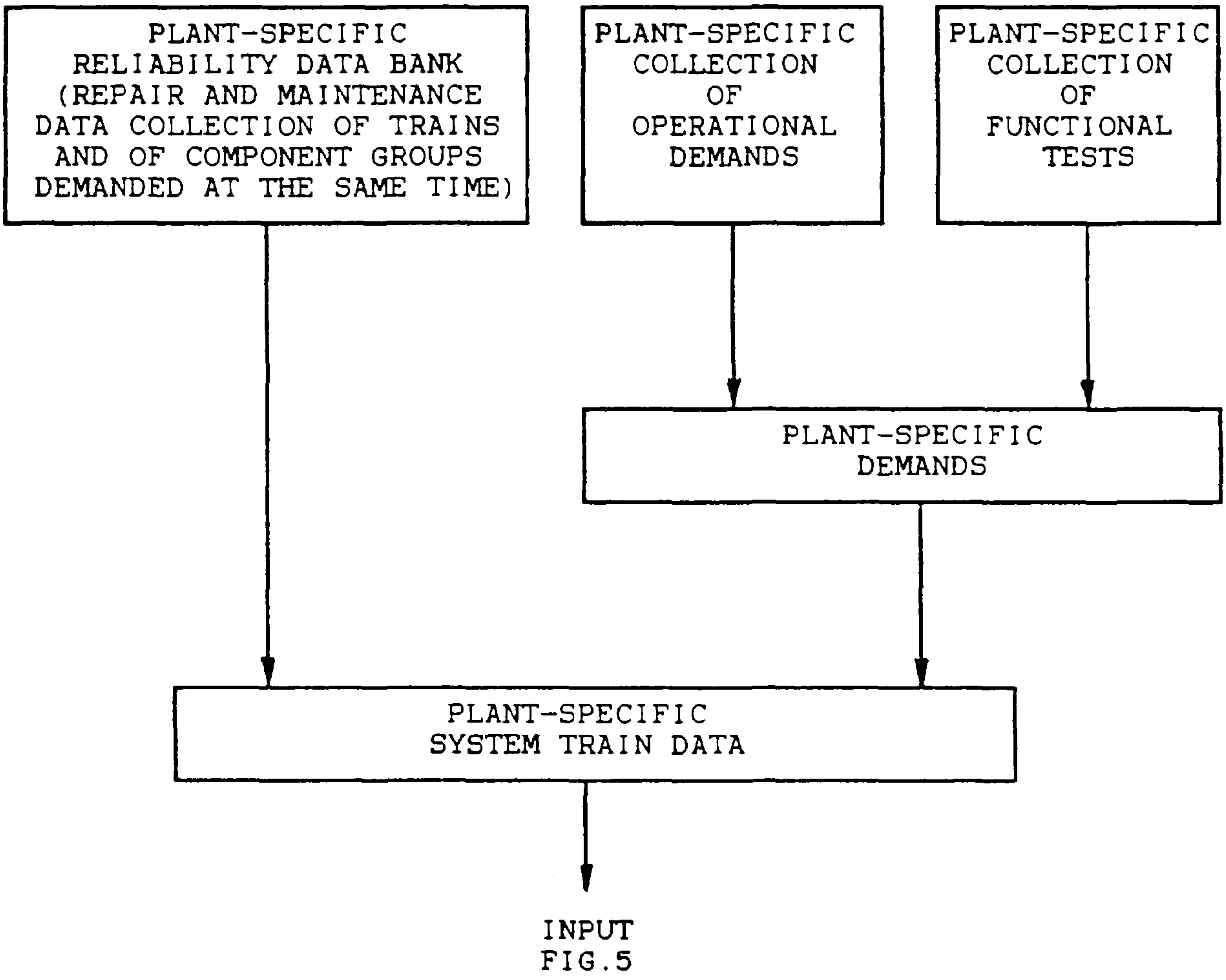
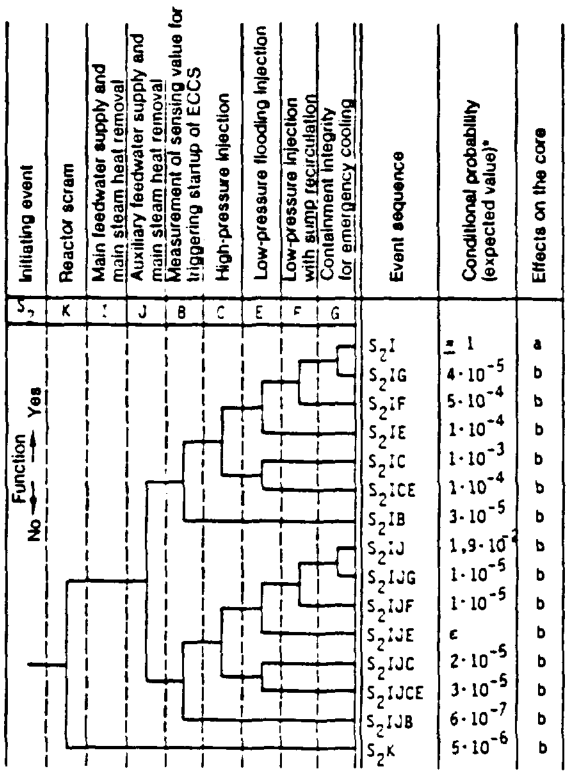


Figure 6: Input for the plant-specific system train data



a No core melt
b Core melt

*Probability of the individual event sequences assuming the initiating event has occurred. The frequency of the individual event sequences is obtained by multiplication with the frequency of h of the initiating event $h(S_2) = 2.7 \times 10^{-3}$/year (expected value)

Figure 7: Event tree for a "small leak"

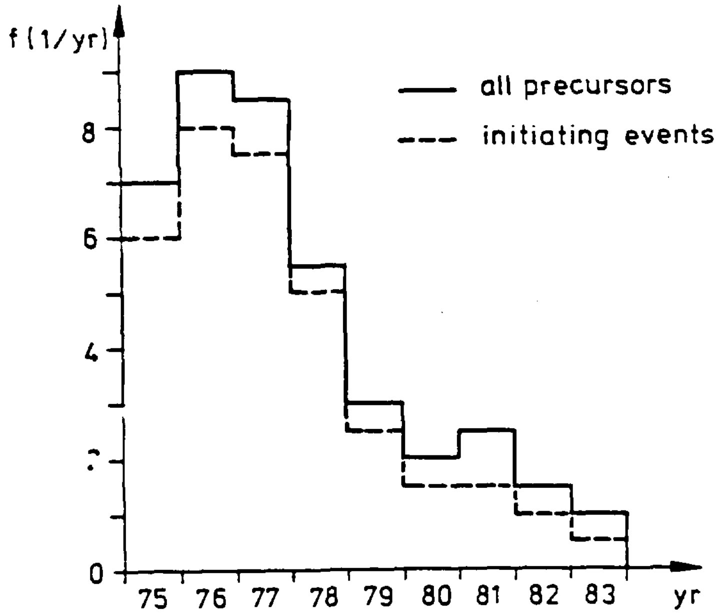


Figure 8: Frequency of events selected as Precursors vs. operating year

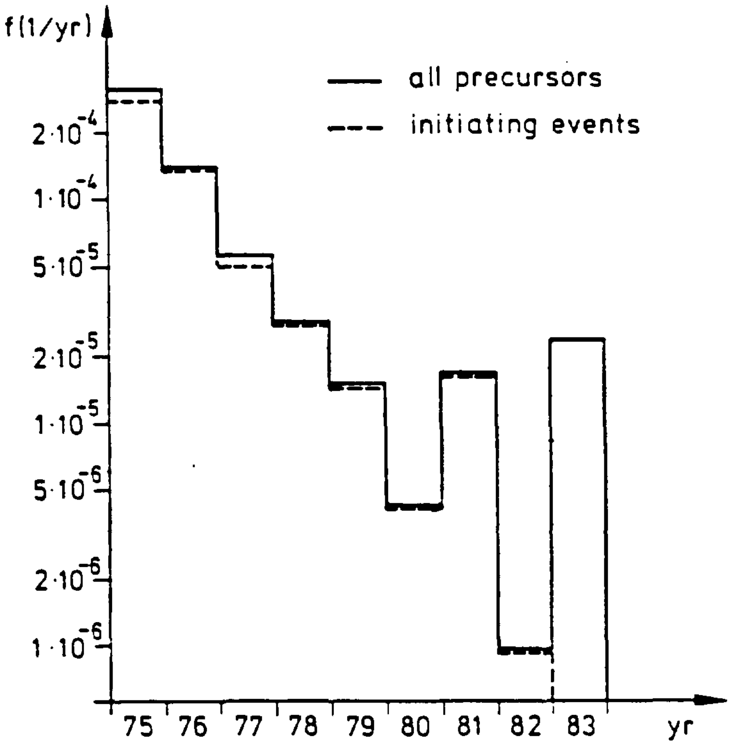


Figure 9: Frequency of potential severe core damage accidents vs. operating year

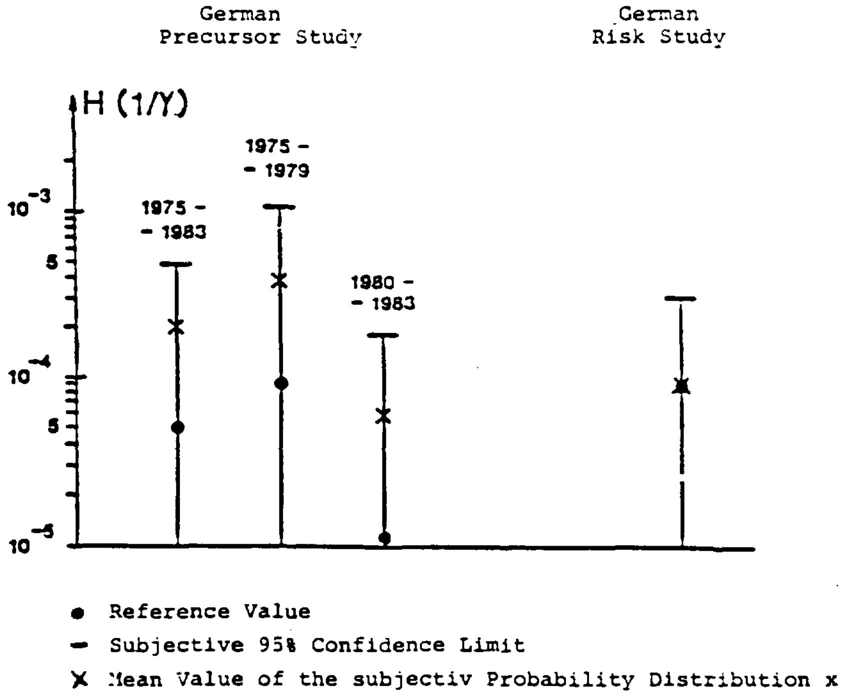


Figure 10: Estimated values and uncertainties for frequency of severe core damage accidents

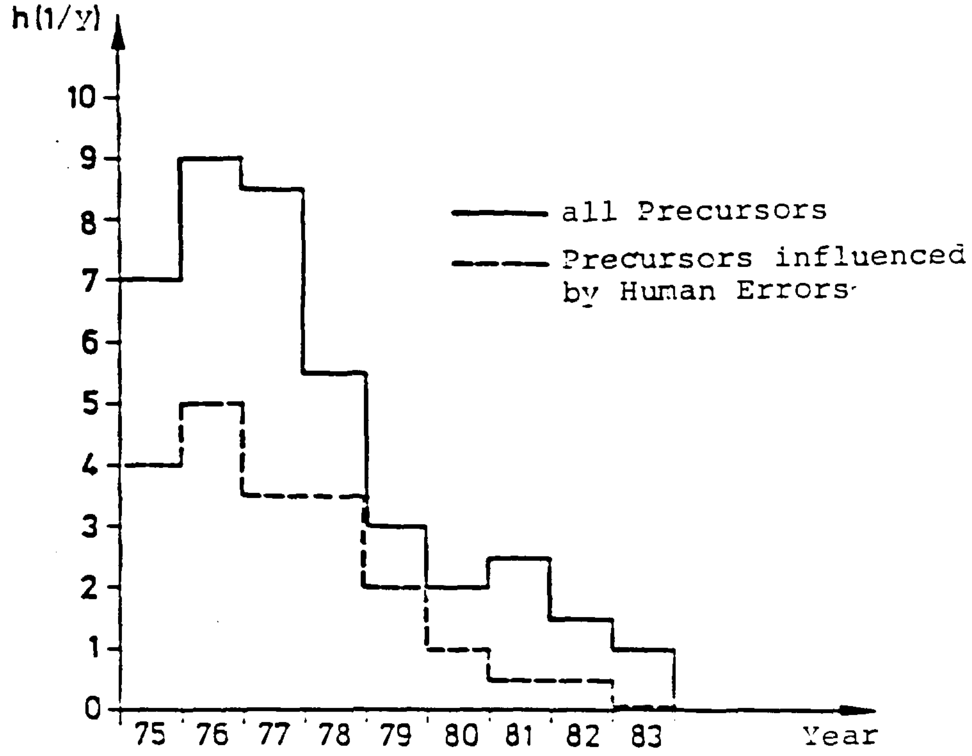


Figure 11: Frequency of Precursors influenced by human error vs. operating year

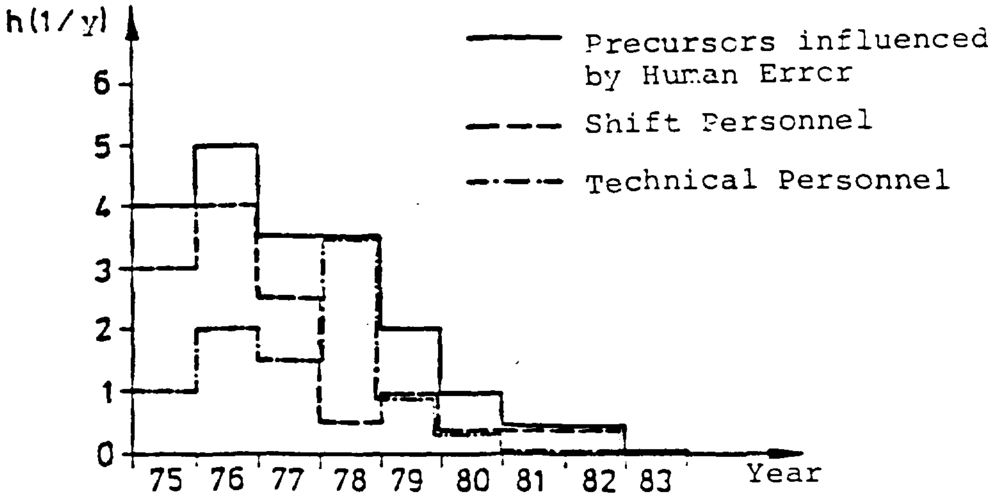


Figure 12: Frequency of precursors influenced by errors of the shift and technical personnel vs. operating the year

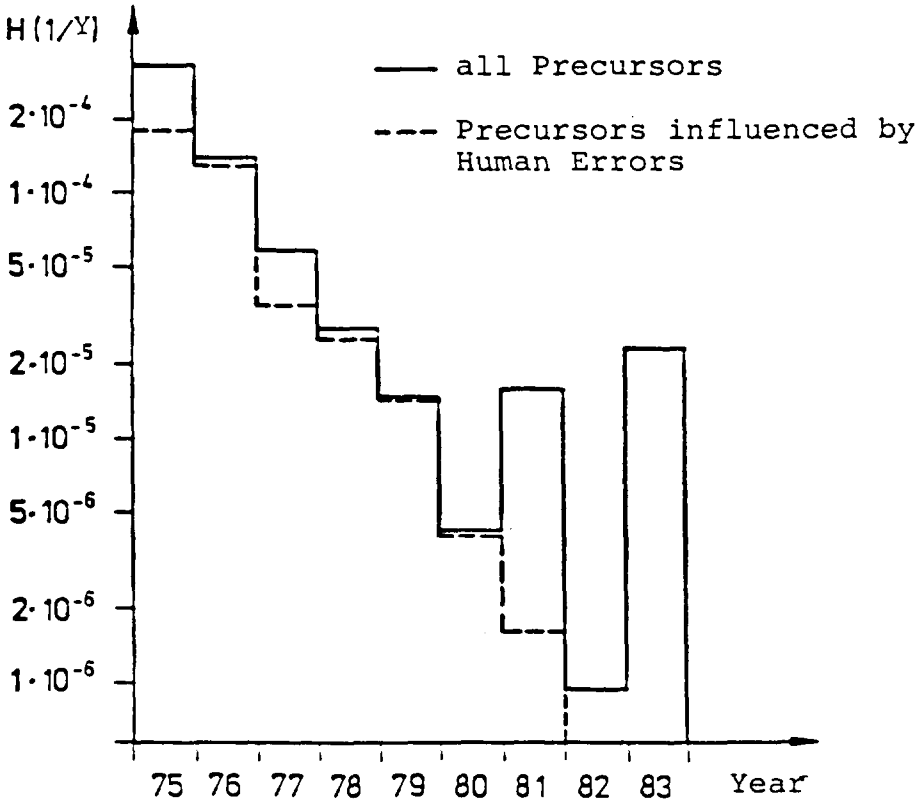


Figure 13: Frequency of potential severe core damage accidents influenced by human error vs. operating year

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