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Safety of Nuclear Power Plant : Human Reliability Analysis (HRA)

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Human influence on operation and safety of a system such as a NPP

- Regular operational actions including:
  - Maintenance and testing
  - Initiating of abnormal scenarios
  - Response to plant and human induced scenarios
  - Control of small disturbances, termination of an ongoing disturbance, as well as mitigation of its consequences.

⇨ Human actions include planned (trained) actions and unplanned actions; they may also trigger undesired events or worsen accident scenarios. Their importance strongly depends on the plant design and operation requirements.

Not considering human failures results in

- a disregard of essential factors,
- unrealistic results as human factors significantly contribute to accidental risks,
- analysis rejection, e.g. by regulatory body.

⇨ There are specific analytical methods needed for the consideration of intentional, malicious actions like sabotage (not part of this lecture).

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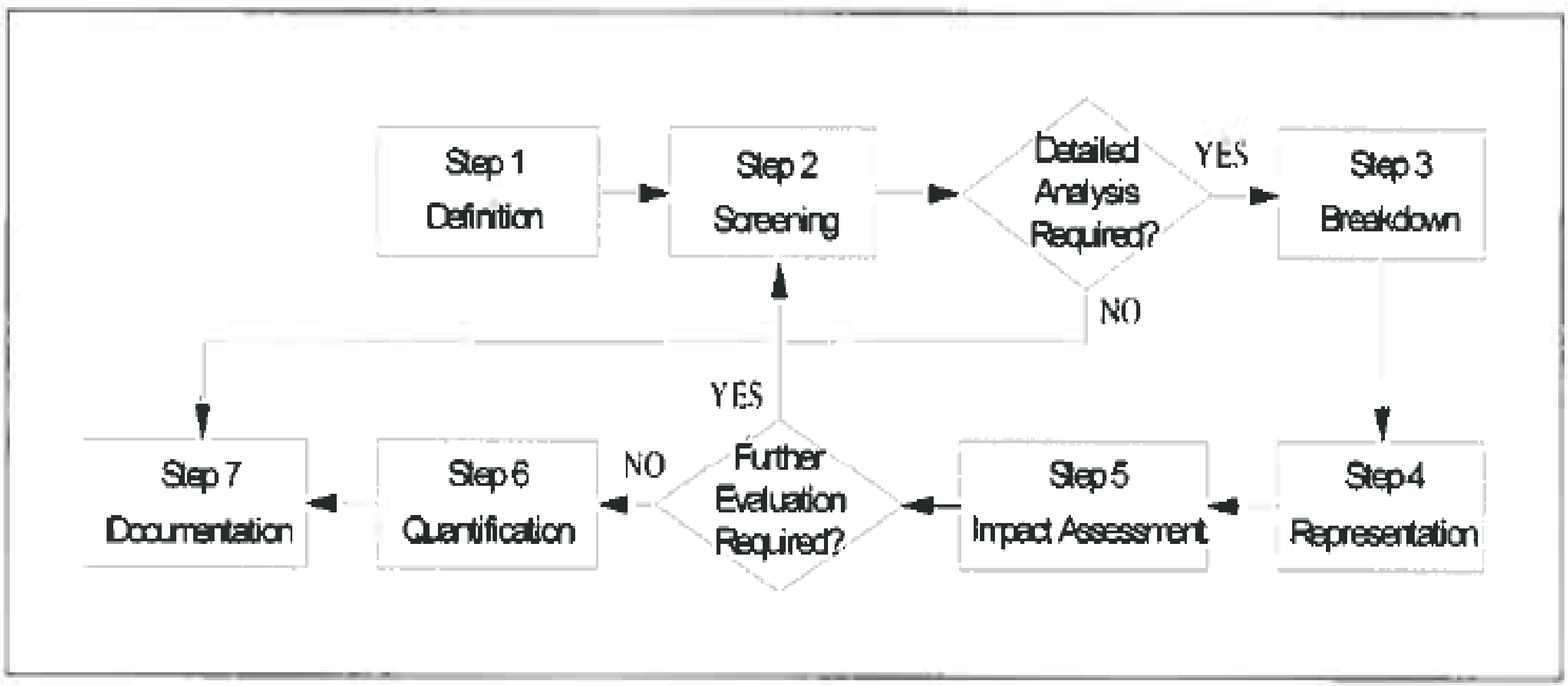
Framework for incorporating human-plant hardware interactions (sharp* steps)



* Systematic Human Reliability Procedure of EPRI

Representation of human failures

Human Reliability Analysis (HRA)

Considering the human failure as an integral part of a fault tree or event tree analysis.

Example fault tree analysis

- Covers interactions "man-machine" (or system), explicitly and implicitly,
- models human failures like failures of components,
- can help identify the most important impacts of human failures to a system.

Requirements

- Detailed knowledge of the system and the required actions / duties (handbooks).
- Taking into account additional factors such as action and duty chains.

Performance Shaping Factors

Group	Subgroup	Examples of PSFs
External PSFs	Situational Characteristics	Lighting, Noise and vibration, Work hours, Organisational structure
	Job and Task Instructions	Procedures, Work methods
	Task and Equipment Characteristics	Decision-making complexity, Human-machine interface factors, Team structure
Stressor PSFs	Psychological Stressors: factors that directly affect mental stress	Task speed and load, Threats of failure or loss of job, Monotonous work
	Physiological Stressors: factors that directly affect physical stress	Fatigue, Temperature extremes, Movement constriction
Internal PSFs	Organismic factors: characteristics of people	Training and experience, Skill level, Motivation, Group identification

Source: V. Dang, S. Hirschberg , PSI

Preparation of a HRA

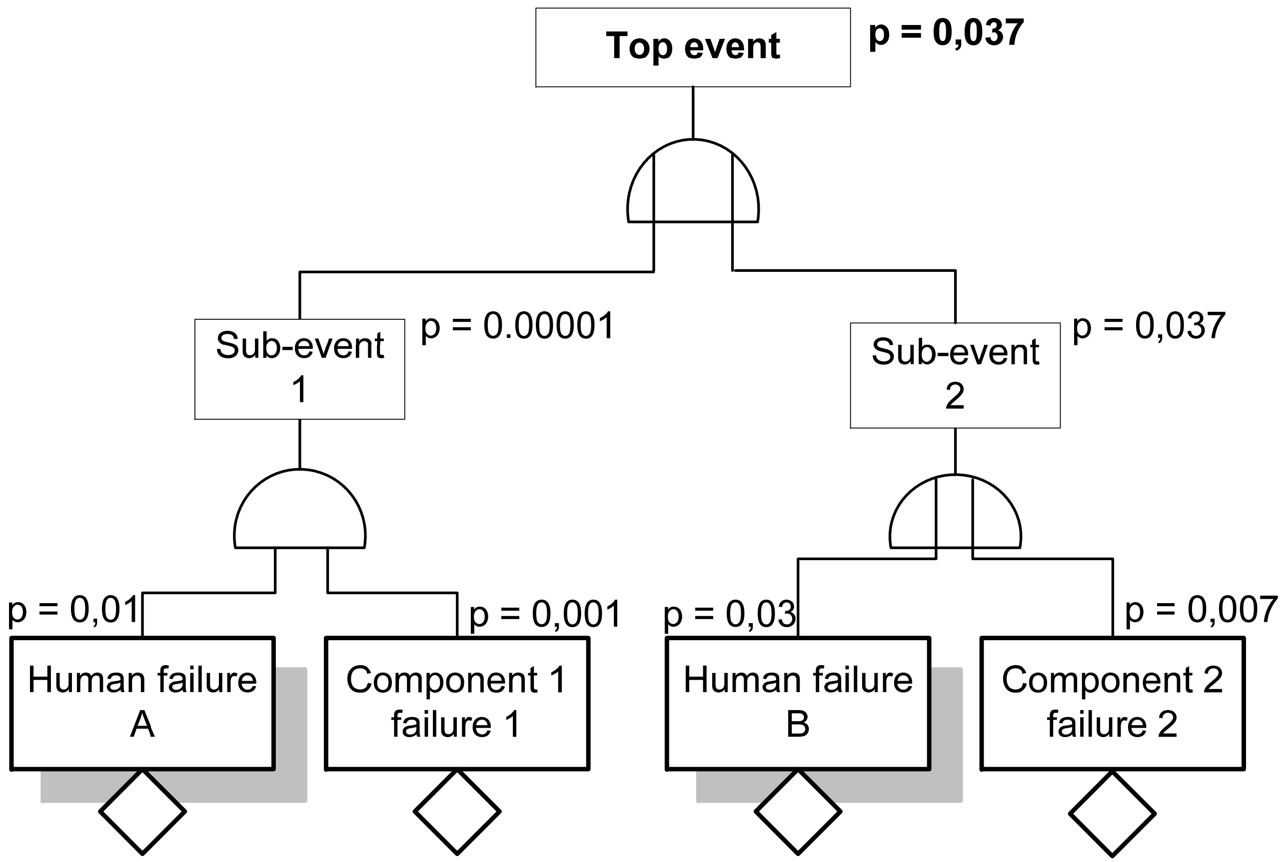
1. **Analysis of actions and tasks**
- Evaluation of required information
- Identification of state before and after task execution
- Identification of information transmission
- Identification of an adequate classification
- Identification of interconnections among staff and actions
2. **Analysis of the impact of actions on system safety**
- Screening of important actions
3. **Quantification of behavior**
- Practice oriented methods for the identification of failure probabilities:

THERP: breakdown	SLIM: expert based
Breakdown of actions into simple sub-actions until estimators are available (like FTA), which consider a.o. the influence of time; consideration of interdependencies between actors and actions afterwards.	Questioning of experts in order to assess "performance shaping factors" influencing human failure probabilities. The identification of the probability is then based on a calibration of the expert opinions by means of experience.

4. Representation of the behavior within a logical framework

- Building a quantitative fault / event tree with component failures and human action failures and performing a dominance analysis

Fault Tree



Technique for Human Error Rate Prediction (THERP)

Phase 1: Familiarization

- Plant visit
- Review information from system analysts

Phase 2: Qualitative Assessment

- Talk- or walk-through
- Task analysis
- Develop HRA event trees

Phase 3: Quantitative Assessment

- Assign nominal HEPs
- Estimate the relative effects of PSFs such as training
- Assess dependence
- Determine success and failure probabilities
- Determine the effects of recovery factors

Phase 4: Incorporation

- Perform a sensitivity analysis, if warranted
- Supply information to system analysts

Example: Diagnosis of an "Abnormal" Event

- The failure of the main feed water supply and – in addition – of the emergency water feed of a steam generator are assumed.
- Control room staff has to diagnose this event correctly and trigger recovery reactions within 20 min.
- The staff has to be aware that a corrective action must be in time; otherwise the "feed & bleed cooling" has to be initiated. Inadequate reactions may result in core meltdown.

Assignment of probabilities:

- The assessment of human error probabilities (HEP) needs "models and rules" (see next page)
- Assessment: If rule 2a is applied to the given situation then the probability of wrong diagnosis is given by Pr(F) = 0.01.

Guidelines for adjusting nominal HEP

1. Use upper bound of **Fig. A** if:
   a) the event is not covered in training **or**
   b) the event is covered but not practiced except in initial training of operators for becoming licensed **or**
   c) the talk-through and interviews show that not all the operators know the pattern of stimuli associated with the event.
2. Use lower bound of **Fig. A** if:
   a) the event is a well-recognized classic (e.g., Three Mile Island incident, 1979), and the operators have practiced the event in the simulator qualification exercises **and**
   b) the talk-through and interviews indicate that all the operators have a good verbal recognition of the relevant stimulus patterns and know what to do or which written procedures to follow.
3. Use nominal Human Error Probability (HEP) of **Fig. A** if:
   a) the only practice of the event is in simulator re-qualification exercises and all operators have had this experience **or**
   b) none of the rules for use of upper or lower bound apply.

Nominal Model of Estimated HEP for Diagnosis within Time t of an Abnormal Event by Control Room Staff

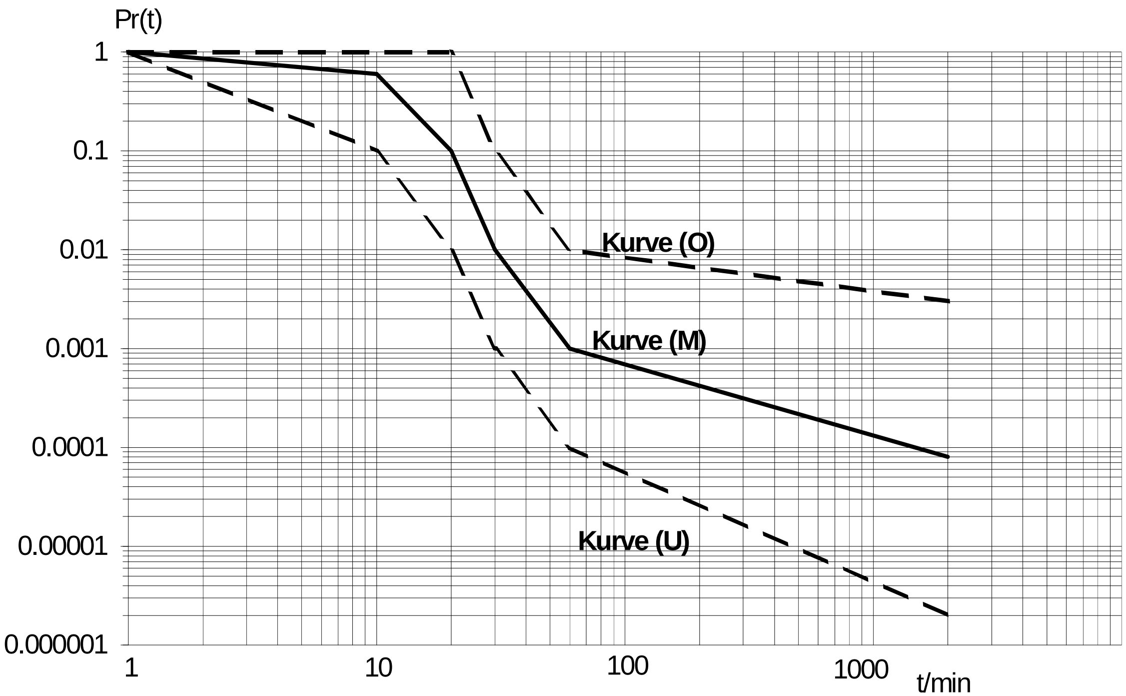


Fig. A: time t in minutes after a compelling signal of abnormal situation.

The probability of a false diagnosis Pr(t) by the operation staff in dependence of the time t after the recognition of an exceptional event.

The diagnosis contains the interpretation and, if necessary, the decision making: determination of the causes of the event to find out the system and/or components capable of reducing or eliminating the occurred problems.

The given probabilities are not appropriate for a single operator. They already include the redundancies of a typical operator team.

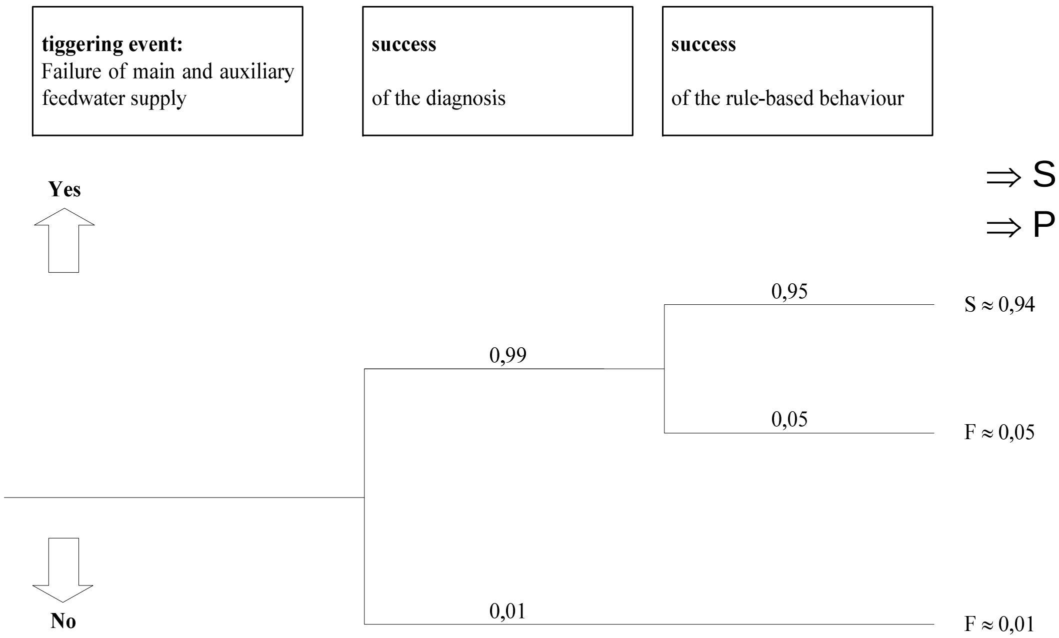
Overall assessment of human actions:

To assess the human actions the “diagnosis” and “behavior” are combined. Rule-based behavior is also quantified by the application of tables.

Example:

Probability of false diagnosis: p50 = 0.01

Probability of false behavior: p50 = 0.05



⇒ Sum of probabilities of failure paths: $Pr_{50} = 0.06$

⇒ Pr(system failure) = Pr(triggering event) · 0.06

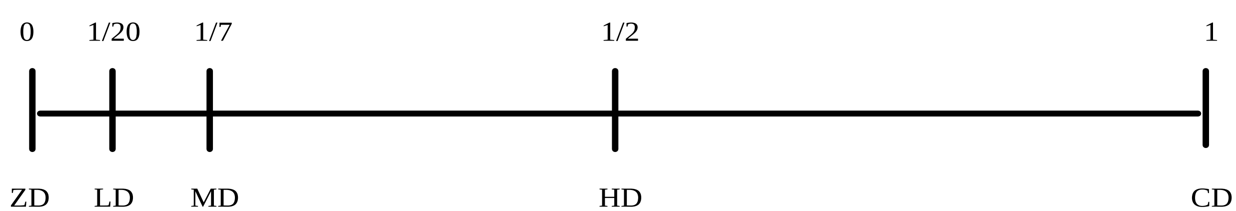
S – success path

F – failure paths

Dependence of human actions in the THERP-model:

Problem: Determination of probability of failure/success of a task may be related to failure/success of other tasks. Application to specific degrees of dependencies:

Degree of coupling	Median
ZD: Zero Dependence (no coupling)	x
LD: Low Dependence (weak coupling)	(1+19x)/20
MD: Moderate Dependence (medium coupling)	(1+6x)/7
HD: High Dependence (strong coupling)	(1+x)/2
CD: Complete Dependence (complete coupling)	1
x: base value of the failure- or success probability	



Redundancy of human actions and conditional failure probabilities in dependency of the degree of coupling (illustrated by the number ray).

Success Likelihood Index Methodology (SLIM)

The aim of SLIM is to quantify the human error probability (HEP) for taking “actions” or fulfilling tasks.

Performance Shaping Factor (PSF):

Factors that considerably affect the practicability of an “action” and influence HEP, like

- Adequacy of time
- Human-machine interface and indications of conditions
- Procedural guidance
- Training and experience
- Task complexity, stress

Procedure

1. Defining the “actions”
2. PSF rating and weighting
3. Grouping the “actions”
4. Calibrating the SLI
5. Transforming the SLI into human error probabilities

Step 1: Defining the “Action”

The operation staff characterizes and defines the “actions” in collaboration with “Human Reliability Analysis” experts and systems analysis experts.

Step 2: Rating and Weighting the PSF

Interviewing the operation staff in order to rate the PSF for certain “actions”. The PSF rating indicates to what extent the PSF assists or prevents its accomplishment.

A scaled ranking list ranging from 0 to 10 has to be compiled for each PSF in order to obtain consistent results from the various experts (Tab. 1)

Step 2: PSF Rating

Definition: This example of PSF represents the extent to which operating instructions enhance the ability of an operator to conduct a certain “action”.	
Scaling guidance r_k	
Rating	Example of a fictitious process with the following rating:
0	Instructions are precisely defined. Operators are able to easily follow the instructions.
1	-
2	Instructions are precisely defined. Operators are able to easily follow the instructions but the clarity could be affected by prior changes or modifications.
3	-
4	-
5	Instructions are available. Some interpretations by the operator are necessary to take certain “actions”.
6	Several steps in the procedure may require the operator to return to a previously completed step (e.g. continuous “action” or keeping ahead skipped tasks)
7	Instructions are being used but due to an urge to act the operator is only capable to use them as check-up.
8	The “action” is a coincidental event for which the instructions can only give a vague advice.
9	Instructions are poorly composed and may lead to wrong actions
10	No instructions exist for this “action”

Step 2: PSF Weighting

PSF "plant-human-machine interface and gauges system": scaled on the possibility of a human-machine interface to provide information to successfully take an "action"

Weighting w_k	**Example of a fictitious process**
0: insignificant	Other factors are so dominating that I do not care about how good or bad these indicators are because they will not change the human error probability of this specific "action"
1: low	This is an "action" based on the experience of responding to many alarms that require little or no diagnosis. I can easily prove the correctness of my "action" in various ways.
2: normal	Patterns of indicators absolutely force an "action" and check the correct response of the facility but they do not require a thorough checking or assessment.
4: high	A successful "action" is not possible without an adequate response to the facility's gauges. We have to consider specific parameters to diagnose the problem and/or checking the facility.

Step 3: Summary of the Weighting

Failure Likelihood Index (FLI)

$$\text{FLI} = \sum_{k=1}^{n} w_k \cdot r_k$$

whereas

k= PSF (k=1, 2, …, n) w_k: weighting; r_k: rating.

w_k and r_k are averaged expert opinions

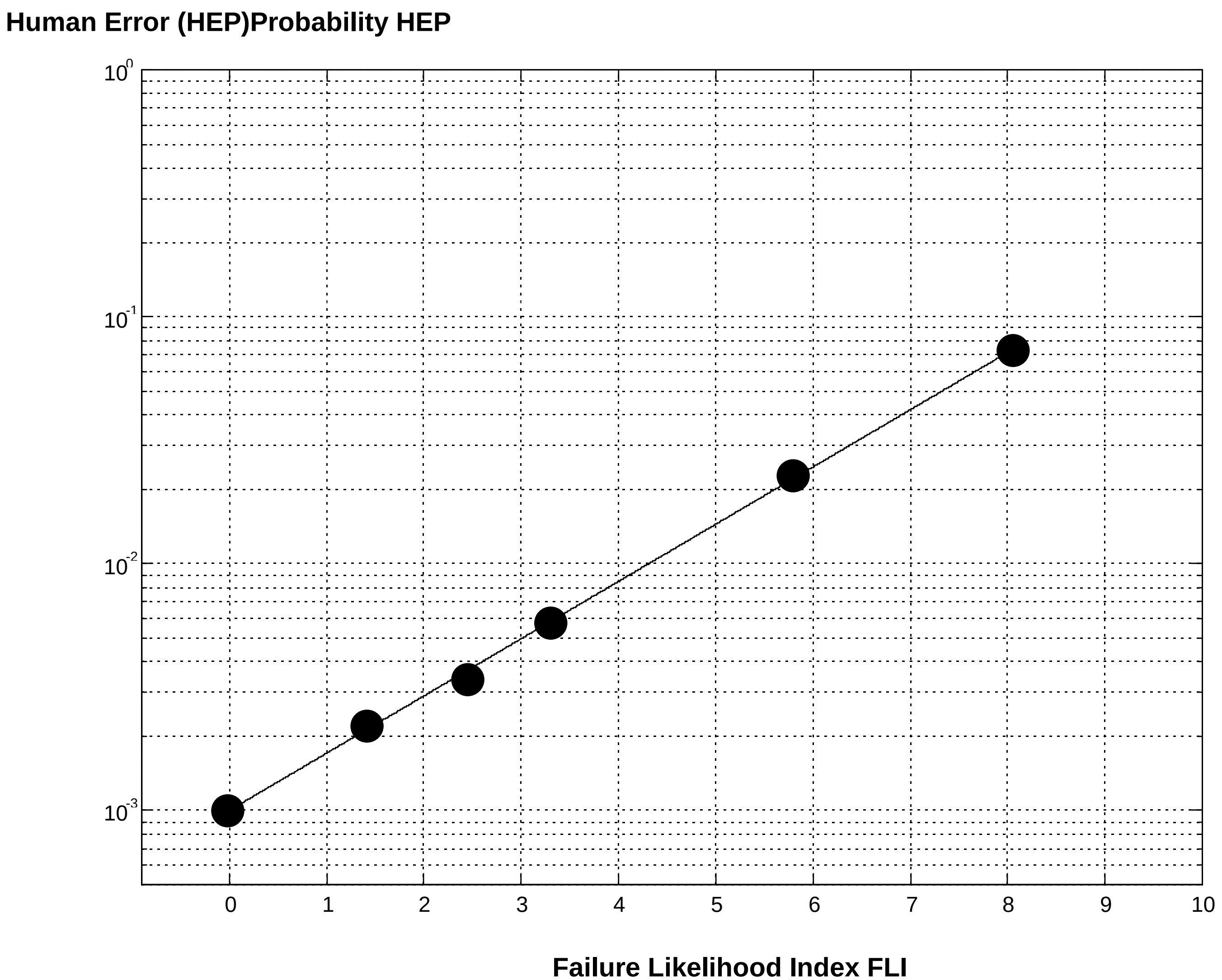
Step 4: Calibration and Transformation

Transformation of FLI into the requested HEP: the calibrated FLI scale is a quantitative relationship between FLI scale and the human error probabilities HEP:

$$\log_{10}(\text{HEP}) = a \cdot \text{FLI} + b$$

- whereas
- *a:* slope; *b:* intersection of axes.

Example of a Calibrated Scaling



SLIM key questions

- How the experts should be consulted, i.e. individually, all together or in groups?
- How the process of grouping should be structured, and at which SLIM working step the assessment should be weighted and summarized?
- How the PSF should be selected, especially if dependencies and correlations can disturb the ranking?
- How "actions" should be grouped and how the variability of the expert judgments should be considered?
- How can uncertainties arising from calibration and transformation be kept minimal?

A Technique for Human Event Analysis (ATHEANA)

- Designed to support the understanding and quantification of Human Failure Events (HFEs) in NPP,
- assuming that HFEs occur when the operators are placed in an unfamiliar situation where their training and procedures are inadequate or do not apply, or when some other unusual set of circumstances exists.

ATHEANA is a second generation HRA methodology designed to search for an error-forcing context (EFC) providing a possibility of enhancing the initial PRA model.

ATHEANA can be summarized by the following steps:

1. Define and interpret the issue, define the scope of the analysis
2. Describe the PRA accident scenario and its nominal context
3. Define the corresponding HFE which may affect the task in question
4. Assess human performance relevant information and characterize factors that could lead to potential vulnerabilities
5. Search for plausible deviations of the PRA scenario
6. Evaluate the potential for recovery
7. Estimate the HEPs for the HFEs
8. Incorporate each HFE and corresponding HEP into the PRA

ATHEANA contains two important loops:

- The first is from the characterization of the EFCs to the identification of the HFEs
- The second is from characterization of the EFCs to the PRA model
- The outcome of the qualitative part of HRA may be used to modify the underlying PRA model, for instance by pointing to conditions or human-system interaction that have been missed in the first place

- The final quantification step is express by the following equation:

$$P(E/S) = \sum_{\substack{unsafe \\ action\_i}} \sum_{\substack{error \\ forcing \\ context\_j}} Pij(S)$$

- where
  - P(E/S) is the probability of the HFE in the scenario S
  - Pij(S) is the probability of the unsafety action i resulting from EFCj in scenario S

ATHEANA's advantages and disadvantages:

- It is a focused prediction of the specific error that might be made and the most influential factors affecting that specific error,
- it increases assurance that the major risk associated with the HFE has indeed been captured,
- it is able to estimate HEPs for all sorts of combinations of factors and various conditions,
- it helps to identify the key risks associated with the HFE in question.

On the other hand

- The primary shortcoming is that no HEP produced. As a result, the ease with which this analysis can be fit into a predictive quantitative risk assessment is reduced,
- it fails to prioritize or establish details of the causal relationship between these factors,
- the outcomes of the human errors under consideration are constrained by previously defined sequences of PRA.

A comprehensive comparison between the methods

Methods	Strengths	Weaknesses
THERP	▪ overall, well-used in practice ▪ powerful methodology which can be made auditable by the assessor ▪ quite accurate	▪ highly judgemental based on assessor's experience ▪ relatively unstructured ▪ interaction between certain PSFs is unknown
SLIM	▪ flexible technique ▪ good theoretical method ▪ need no task decomposition ▪ deal with the total range of human errors forms	▪ complex method ▪ arbitrary PSFs choice ▪ sujective method ▪ lack of valid calibration data
ATHEANA	▪ able to estimate HEPs for all sorts of combinations ▪ increases assurance risk has been captured ▪ focused prediction of the specific potential error	▪ no HEP produced ▪ fails to prioritize or establish details of causal relationships ▪ outcomes of human errors are constrained by previously defined sequences of PRA

Summary

- Human errors can influence the reliability of and risk caused by technical systems considerably.
- HRA delivers the methods to model and quantify human errors within a comprehensive probabilistic analysis. However the analyses are associated with large uncertainties.
- By inclusion of human factors analyses become more realistic but also more complex and extensive.
- The proposed "methods" are substituting unavailable empirical data.
- HRA is only a segment in the domain of human factors (knowledge management, errors of, influence of safety culture, malicious attacks, etc.).