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International Atomic Energy Agency
Atoms for Peace and Development

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P10. Experience in use PSA for inspections, tests, and maintenance optimization

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Outline

- Introduction
- PSA application in:
  - Risk-informed regulatory inspection
  - Risk-informed surveillance test interval verification
  - Maintenance Effectiveness Monitoring (using PSA insides)
- Conclusion

Introduction

Background

In the early years of the world's nuclear power plant development and operation, the traditional approach to ensure nuclear safety was based primarily on a deterministic approach where a set of rules and requirements were defined (based on deterministic calculations and engineering judgement) that aimed at achieving a high level of safety.

- adequate design,
- inspection,
- maintenance of equipment,
- surveillance of equipment, etc.

Introduction

Deterministic vs Probabilistic

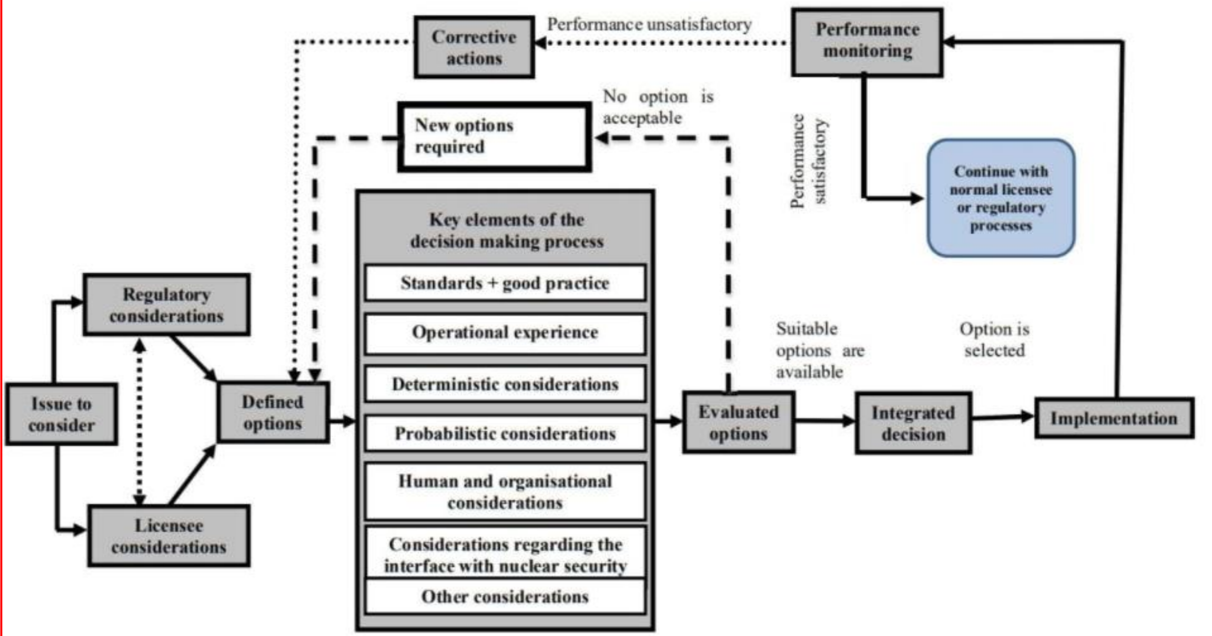
By using deterministic approach for Identified shortfalls it's hard to determine which of the possible plant improvements would give the greatest reduction in risk and hence which of them need to be given the highest priority for implementation.

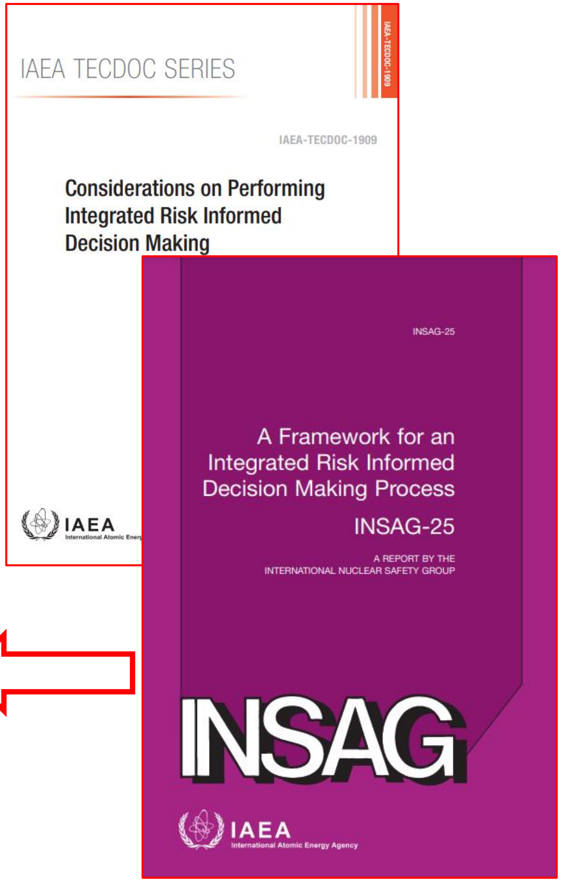
Meanwhile, use of PSA gives numerical risk metrics which contribute to a more explicit consideration of risk in the decision making process by giving probabilities or frequencies to specific consequences.

Introduction

Not risk based but risk-informed!

Main components of the Integrated Risk Informed Decision Making Process





Risk-informed regulatory inspection

Risk-informed regulatory inspection

Inspection:

In-service inspection. Inspection of structures, systems and components undertaken over the operating lifetime by or on behalf of the operating organization for the purpose of identifying age related degradation or conditions that, if not addressed, might lead to the failure of structures, systems or components.

Regulatory inspection. Inspection undertaken by or on behalf of the regulatory body.

Risk-informed regulatory inspection

Inspections are one of the primary functions of RB, that is performed to ensure that the safety regulations and rules the license is given by RB are adequately addresses and the required safety level is maintained. The overall inspection process consist of:

- Planning
- Implementing and recording the observation
- Finding evaluation and prescription
- Verifying proper implementation of prescription

Objective: by using risk-informed approaches by the Regulatory Body (RB) in the inspection process as effective tool to:

- save time and
- optimize resources of RB and
- Inspection efficiency improvement

by concentrating efforts on issues that can have high impact on safety.

Risk-informed regulatory inspection

Inspection Planning

In the planning stage of the inspection process main efforts were spent to develop risk-informed inspection routes.

- Studying existing inspection routes
- identifying risk-significant components
- Assigning components to corresponding compartments
- New risk-informed inspection routes, based on this compartment list and the existing inspection routes.

For the newly developed inspection routes, the recommendations are made for updating the inspection checklists to improve efficiency.

Risk-informed regulatory inspection

Inspection Planning

- Studying existing inspection routes:
  - Components in the compartments of existing routes
  - Importance of this components
  - Estimating the efficiency of the existing routs
  - Studying the check lists

Inspection route and check list #16			
Number of walkdown:		Date:	Total number of identified non-conformities:
Route: БЩУ 2 (Э305/2) → ЩПР(Э314/2)→ Э317/1→Э313/2(ЛК)→Э118/2(ЛК)→ Э108/4→Э108/5→Э108/6→Э119→Э105→Э103/4→ Э103/5→Э103/6→Э119→Э109/3→Э113/2→Э109/1→ Э108/3→ Э108/1→Э117/1→Э107→Э103/2→Э103/1→Э104		Time:	
object of control:	Non-conformity (Yes/No)	object of control:	Non-conformity (Yes/No)
Compartment: БЩУ-2 (Э305/2)		Compartment: ЩПР (Э314/2)	
Порядок, чистота и отсутствие посторонних предметов на рабочем месте.		Порядок, чистота и отсутствие посторонних предметов на рабочем месте.	
Состояние рабочего/аварийного освещения.		Состояние рабочего/аварийного освещения.	
Эксплуатационное состояние помещения в соответствие с требованиям ПТБ/ПРБ/ППБ.		Эксплуатационное состояние помещения в соответствие с требованиям ПТБ/ПРБ/ППБ.	
Ведение оперативной документации.		Положение двери/дверей помещения в соответствии с требованиями.	
Наличие и состояние тех. документации.		Наличие маркировок оборудования.	
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Compartment: Э313/2(ЛК)		Compartment: Э118/2(ЛК)	
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Risk-informed regulatory inspection

Inspection Planning

Quantification & Interpretation

- Importance measures

The purpose of an importance evaluation is to identify the important basic events, parameters, systems with regard to the occurrence of the undesired event.

Based on importance measures a ranking can be established to find the most critical events in the risk or reliability model.

Fussell-Vesely importance

$$\text{F-V} = \frac{\text{[sum of all CDF cut-sets containing the basic event]}}{\text{[total CDF]}}$$

F-V < 1, The F-V is a measure of the risk associated with a given basic event, it shows how much component or event contributing to the CDF

Risk reduction worth (RRW)

$$\text{RRW} = \frac{\text{[CDF when component is assumed working (P=0)]}}{\text{[total CDF]}}$$

RRW < 1, The RRW is a measure of the risk reduction that would be achieved when the unavailability of a component is reduced to zero, i.e. the event certainly does not occur.

Quantification & Interpretation

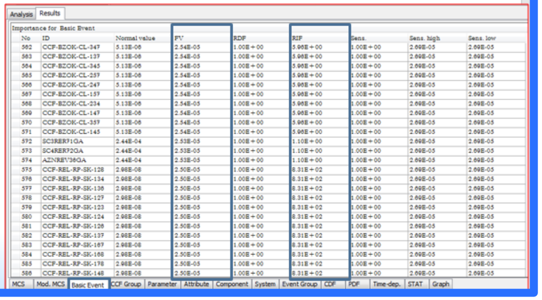
- Importance measures

Risk achievement worth (RAW)

$$\text{RAW} = \frac{\text{[CDF when the component is assumed failed (p=1)]}}{\text{[total CDF]}}$$

RAW > 1, The Risk Achievement Worth measure is expressed as a ratio giving the factor by which the top event probability increases due to a component not being available (p=1). It is the change of the outcome in a worst case scenario.

Importance measures are widely used in PSA applications



584	CCF-REL-RP-SK-168	2.98E-08	2.50E-05	1.00E+00	8.31E+02	1.00E+00	2.69E-05	2.69E-05
585	CCF-REL-RP-SK-178	2.98E-08	2.50E-05	1.00E+00	8.31E+02	1.00E+00	2.69E-05	2.69E-05
586	CCF-REL-RP-SK-148	2.98E-08	2.50E-05	1.00E+00	8.31E+02	1.00E+00	2.69E-05	2.69E-05

MCS | Mod. MCS | Basic Event | CCF Group | Parameter | Attribute | Component | System | Event Group | CDF | PDF | Time-dep. | STAT | Graph

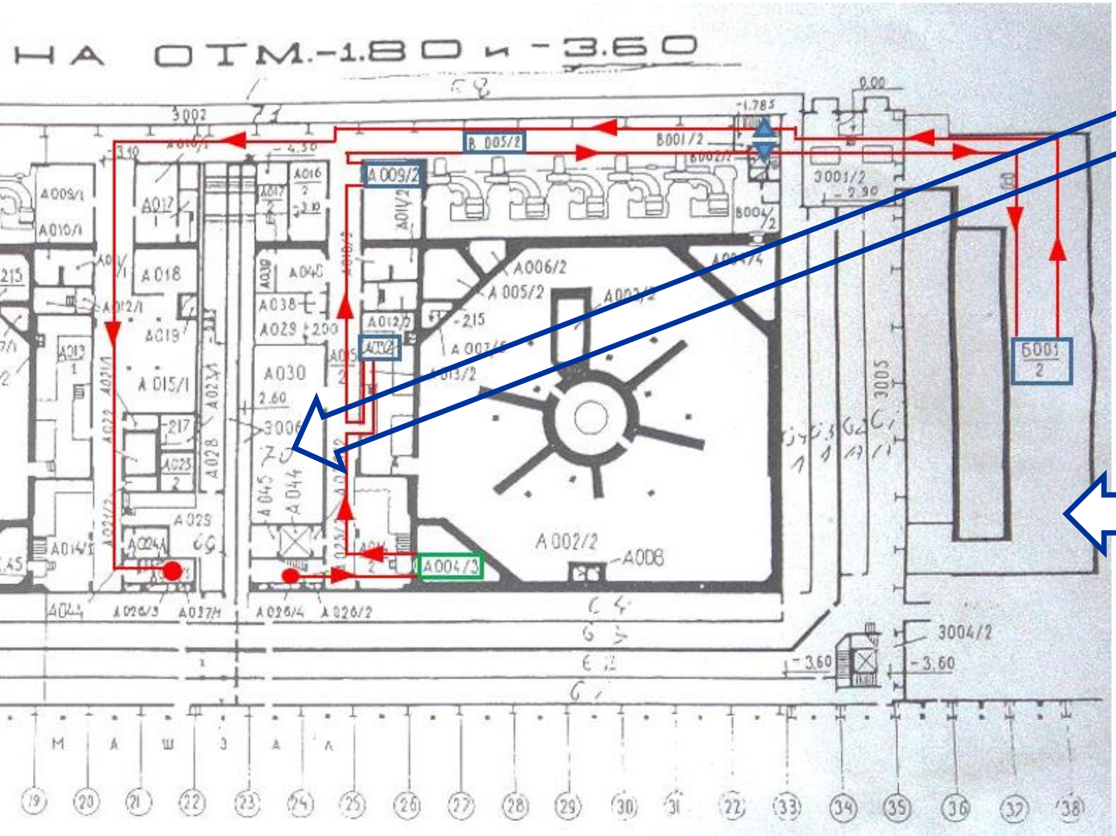
Importance of BE

Importance of components

Risk-informed regulatory inspection

Inspection Planning

- Assigning components to corresponding compartments



Compartment 2		
#	Component name	Importance
1	Component 1	Low
2	Component 2	Low
…	…	Low

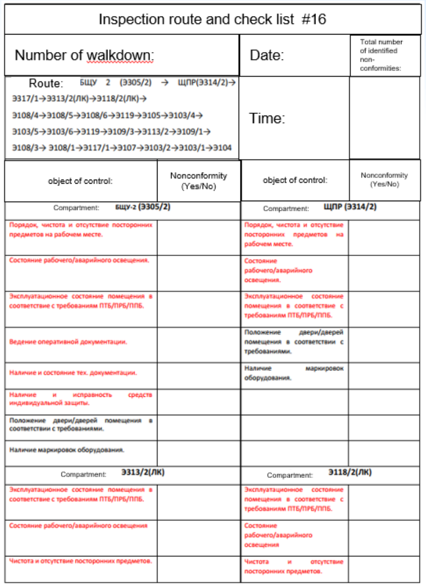
Compartment 1		
#	Component name	Importance
1	Component 1	High
2	Component 2	High
3	Component 3	High
4	Component 4	Medium
5	Component 5	Medium
6	Component 6	Low
	…	Low

Risk-informed regulatory inspection

Implementing inspection and recording the observations:

- Communications during the inspection
- Inspector requests for additional information
- Discussion of observations with the licensee

In this process the presence of PSA specialist will be beneficial.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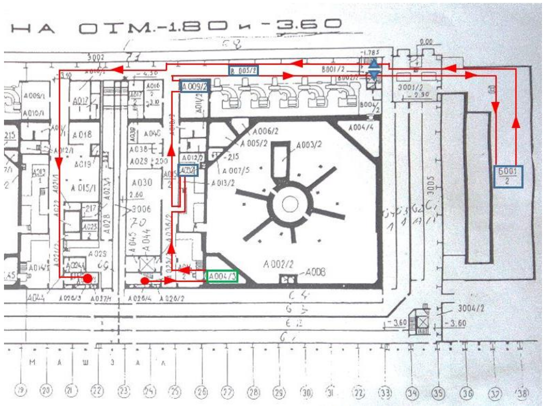
Updated the inspection checklists



Risk-informed inspection routes

Risk-informed regulatory inspection

example: inspection results

Hypothetic finding № 1. During the inspections the ECCS components were checked. It was identified that following testing or repair, the manually-driven valve on the pressure head of an ECCS pump had been left closed due to a human error. (**results from pre-Initiator human errors**)

Hypothetic finding № 2. During the inspections the components of the Primary Circuit Water Make-up System were checked. It was identified that the manually driven valve on the pressure head of a Make-up pump had been left closed following testing or a repair. (**results from pre-Initiator human errors**)

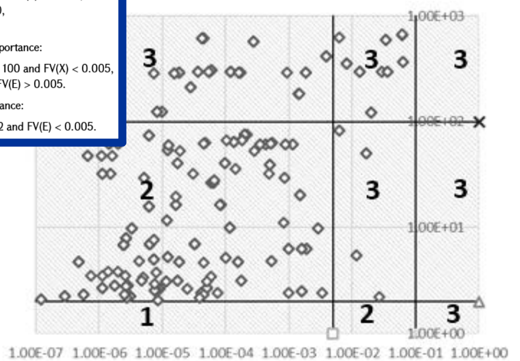
Hypothetic finding № 3. During the inspections it was identified that because of a missing indication of the direction to close the manually-driven valve on the pressure head of an Emergency Feedwater pump, it had been left closed following testing or a repair. (**This is typically a result of imperfect housekeeping**)

Hypothetic finding № 4. During the review of documents in the framework of inspections, some inconsistencies have been identified in the description of the Essential Service Water System and the job instructions of the operating personnel. The requirement of changing the position of the Interlock switch of the Essential Service Water System's pump into the right position following the completion of testing was omitted in the job instruction of the Main Control Unit (MCU) operator. (**inconsistencies in the documents or wrong instructions**)

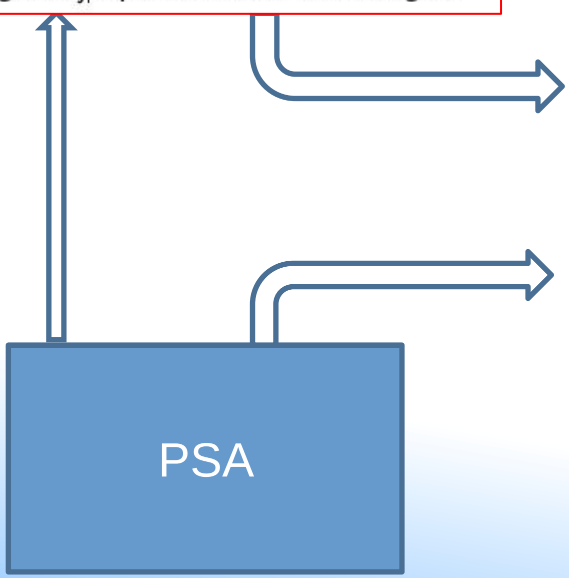
Risk-informed regulatory inspection

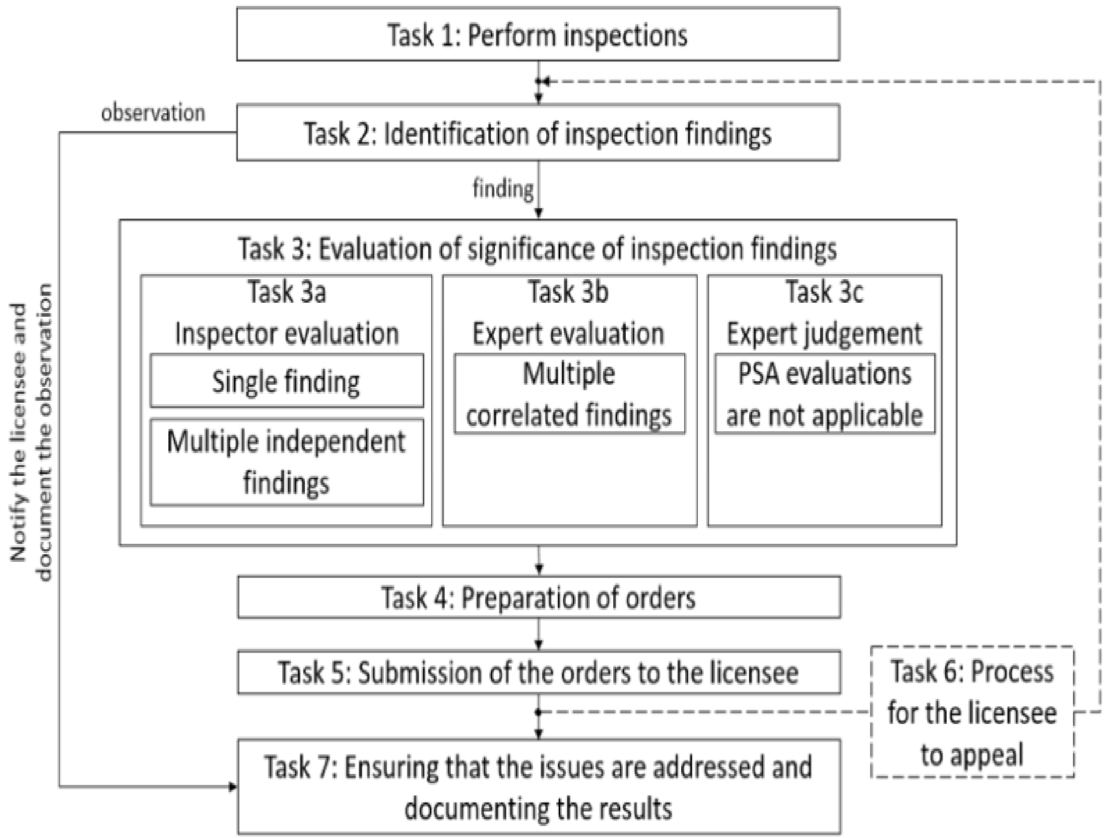
Finding evaluation:

- High safety importance:
  - RAW(E) > 2 and FV(E) > 0.005,
  - RAW(E) > 100,
  - FV(E) > 0.1.
- Medium safety importance:
  - 2 < RAW(E) < 100 and FV(X) < 0.005,
  - RAW(E) < 2, FV(E) > 0.005.
- Low safety importance:
  - RAW(E) < 2 and FV(E) < 0.005.



Distribution of ANPP systems' components with medium and high safety importance on the FV-RAW diagram





Risk-informed regulatory inspection

- **Finding evaluation:**

Case	Hypothetic finding №	Hypothetic finding №	Hypothetic finding №	ΔCDF
1	1	-	-	2.93E-07
2	4	-	-	8.31E-07
3	1	4	-	1.1E-06
4	2	3	-	1.7E-06
5	2	3	4	2.51E-06

Qualitative assessment is performed based on the evaluation of potential findings impact on:

- initiating event frequency;
- safety functions;
- potential consequences.

Finding significance	ΔCDF, 1/reactor×year	ΔLERF, 1/reactor×year
Very low	<1E-06	<1E-07
Low	<1E-05	<1E-06
Medium	<1E-04	<1E-05
High	>1E-04	>1E-05

Risk-informed surveillance test interval verification

Risk-informed surveillance test interval verification

Objective: re-evaluate the surveillance program of ANPP equipment using probabilistic safety assessment methods.

The project consisted of two phases:

1. Development of methodology;
2. Application of methodology proposed.

The project aimed to create bases for the Armenian regulatory body to verify proposed changes in surveillance test by the licensee.

Risk-informed surveillance test interval verification

The overall procedure for surveillance analysis by PSA is based on the US experience. The over all procedure have four elements:

Element 1: Define the proposed change;

Element 2: Perform engineering analysis;

Element 3: Define implementation and monitoring program;

Element 4: Submit proposed change.

To verify proposed changes by the licensee general procedure was slightly modified. The first two elements from the list above remained the same and a specific new Element 3 was added:

Element 3: Perform engineering analysis of alternatives and make final decision;

Risk-informed surveillance test interval verification

Element 1: Define the proposed change:

- Definition of the scope of analysis;
- Collection of supporting information for the analysis and treatment of the subjects of interest;
- Definition and description of the context, goals and impacts of the proposed changes.

Risk-informed surveillance test interval verification

Element 2: Perform engineering analysis:

- Collection of all information related to the change;
- Deterministic examination of the proposed change;
- Checking PSA status regarding the components selected to be addressed by surveillance analysis;
- Checking PSA status regarding all aspects of modeling and quantification which are related to surveillance analysis in some way;

Risk-informed surveillance test interval verification

Element 2: Perform engineering analysis:

- PSA model up-date in accordance with the results of points above;
- Quantification of verified PSA model;
- Modification of PSA model to address new surveillance strategy;
- Quantification of up-dated PSA model and presentation of comparison results.

Risk-informed surveillance test interval verification

Element 3: Perform engineering analysis of alternatives and make final decision:

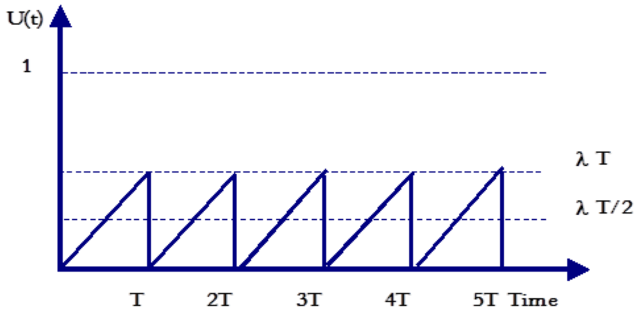
- Further analysis and interpretation of the results of Element 2 activities;
- Definition of compensating measures and supporting them with deterministic analysis;
- Addressing compensatory measures in PSA;
- Quantification of modified PSA model;
- Final interpretation of results of the analysis and providing them for decision making.

Risk-informed surveillance test interval verification

Aspects of using PSA for surveillance analysis and justification of changes in this area:

1. Conclusions related to the time period between consecutive surveillance acts;
2. Conclusions related to the length of surveillance.

The first case, the conclusions of the analysis have got always some safety impact because of the common assumption adopted that the surveillance strongly decreases probability that the given component/system could be found unavailable when demanded to act due to some reason in the next time period.



Unavailability of the component is given by the expression

$$U(t) \approx \lambda t$$

the maximum value of "t" is "T" where this represents the interval between proof tests

The second, it is just important that the surveillance act makes the component unavailable *(not always the case)

Risk-informed surveillance test interval verification

Application of developed methodology

The **developed** methodology was applied to ANPP. It covered:

- Selection of systems,
- Collection of plant specific information,
- Adaptation of ANPP PSA model
- Re-evaluation of ANPP surveillance postulated periodicity change impact on the overall CDF.

Risk-informed surveillance test interval verification

Selection of systems:

During the system selection, combination of FV and RIF importance measures was used for ranking the systems for the purpose of scoping the study. Based on the combination of FV and RIF importance measures, the ANPP high risk importance systems were selected for re-evaluation of surveillance test strategy. The systems for further investigation were identified as follows:

- Emergency core cooling system (ECCS);
- Normal make-up system;
- Spray system.

- High safety importance:
  - RAW(E) > 2 and FV(E) > 0.005,
  - RAW(E) > 100,
  - FV(E) > 0.1.
- Medium safety importance:
  - 2 < RAW(E) < 100 and FV(X) < 0.005,
  - RAW(E) < 2, FV(E) > 0.005.
- Low safety importance:
  - RAW(E) < 2 and FV(E) < 0.005.

Risk-informed surveillance test interval verification

Adaptation of ANPP PSA model

In the early phase of checking and adaption of PSA model for surveillance analysis, there may be two situations:

1. considered surveillance act - is already represented by some BE(s) in the PSA model;
2. BE(s) have to be added to PSA model to reflect the surveillance act of the given component.

Representation of surveillance act by BEs in the PSA model is twofold:

- surveillance act impacts time related parameter of stand-by component reliability model (time between tests);
- if the component is unavailable due to surveillance act, this unavailability can be modeled by specific BE.

Risk-informed surveillance test interval verification

Collection of plant specific information

- Operation and maintenance procedures
- site-specific information was collected in cooperation of NPP,
- Information for components of selected systems,

System Component	Periodicity of the surveillance test	Duration of the surveillance test
System: Normal make-up system **Pumps:** 2PN1-4	1 per month	30 min
System: ECCS **Pumps:** 2APN1-6	1 per month	40 min
System: Spray system **Pumps:** 2NBS1-3	1 per month	30 min

represents the minimum required time periods for stabilization of the monitored parameters

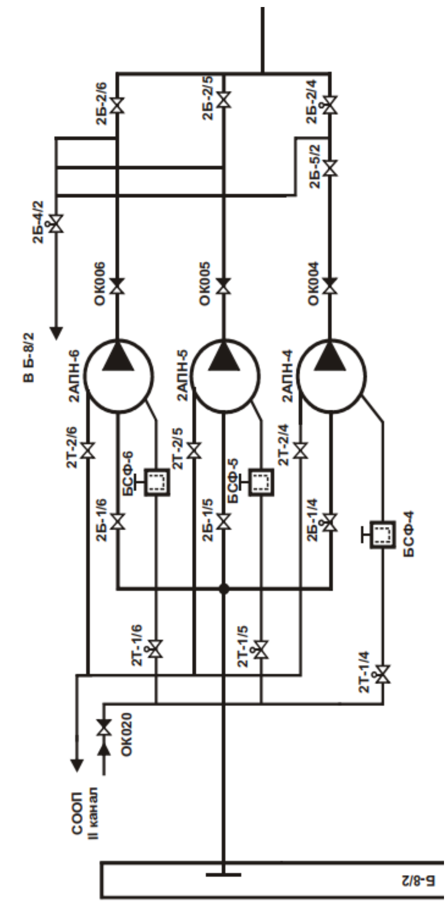
Risk-informed surveillance test interval verification

The objective of implementing analysis for selected systems is to estimate the impact of possible changes of the intervals between the regular surveillance tests. For this reason, two cases were considered:

- Case 1: twice more surveillance tests per year;
- Case 2: twice fewer surveillance tests per year.

For all selected systems, the following assumptions were made:

- if during the surveillance test of a pump some other components are used or checked, then it was considered that these components become also subject of the test;
- regardless of how many times the component is used or checked during the single surveillance test, it was considered as tested just once.



Risk-informed surveillance test interval verification

Considered case	CDF Mean	ΔCDF	% CDF from original CDF	Increase/ Decrease
CDF Original surveillance program	3.686E-05	-	-	-
ECCS				
Case 1: Twice more surveillance tests per year	3.619E-05	6.70E-07	1.82%	**Decrease**
Case 2: Twice fewer surveillance tests per year	3.806E-05	1.20E-06	3.26%	**Increase**
Normal make-up system				
Case 1: Twice more surveillance tests per year	6.70E-07	1.00E-08	0.03%	**Decrease**
Case 2: Twice fewer surveillance tests per year	1.82%	1.00E-08	0.03%	**Increase**
Spray system				
Case 1: Twice more surveillance tests per year	3.574E-05	1.12E-06	3.04 %	**Decrease**
Case 2: Twice fewer surveillance tests per year	3.974E-05	2.88E-06	8.06 %	**Increase**
ECCS, normal make-up system and spray system				
Case 1: Twice more surveillance tests per year	3.506E-05	1.80E-06	4.88 %	**Decrease**
Case 2: Twice fewer surveillance tests per year	4.095E-05	4.09E-06	11.10%	**Increase**

Risk-informed surveillance test interval verification

Insights

- Justification of the surveillance program should be executed on quantitative and qualitative basis.
- In case multiple changes are proposed in the surveillance program, they should all be addressed simultaneously.
- Acceptability criteria should be developed to verify the adequacy of proposed changes to the surveillance program.
- PSA model should be verified on applicability for this application.
- Change of active component’s reliability due to increasing running time should be considered and reflected in the model.
- components’ unavailability BE due to surveillance should be revised.

Maintenance Effectiveness Monitoring

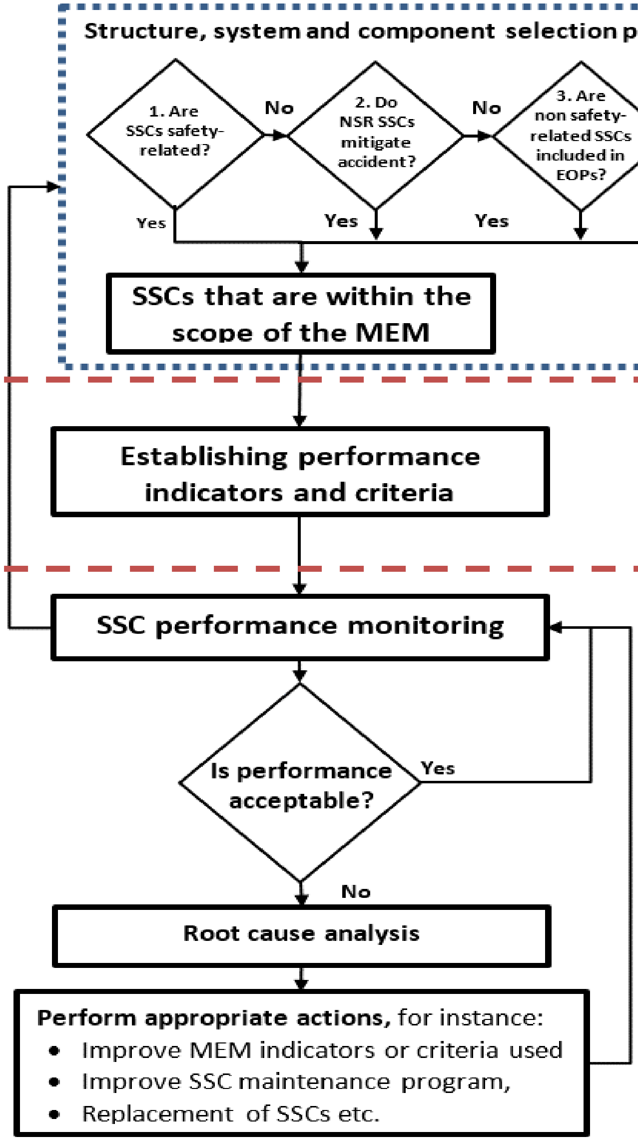
Maintenance Effectiveness Monitoring

(using PSA insides)

- Maintenance activities play a significant role in safe operation of the nuclear power plant. The function of the plant maintenance program is to preserve and restore the inherent safety, reliability and availability of plant structures, systems and components for reliable and safe operation.
- Continuous monitoring of maintenance program effectiveness ensures that safety related and certain non-safety related SSCs are capable to perform their intended functions.

Maintenance Effectiveness Monitoring

(using PSA insides)

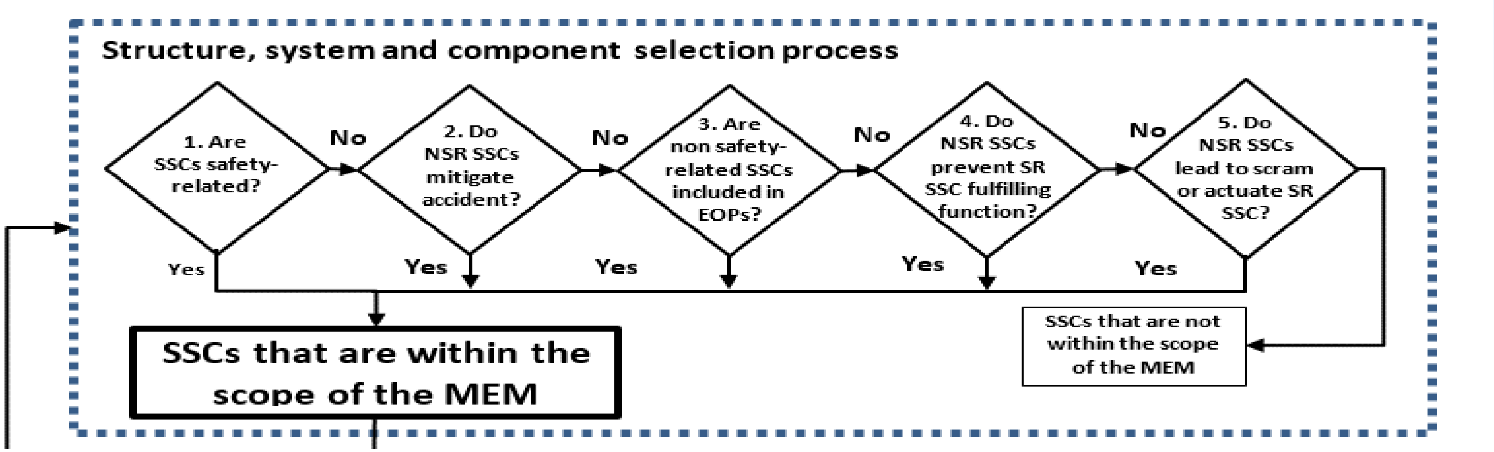


Selection of SSCs for maintenance effectiveness monitoring (MEM).

Establishing performance indicators and criteria for selected SSCs.

Evaluation of SSCs performance against selected indicators monitoring process.

Maintenance Effectiveness Monitoring
(using PSA insides)



1. Are SSCs Safety-Related?

Safety related systems are defined as systems whose failures impair normal operation of the NPP or impede elimination of deviations from normal operation and can lead to DBA and BDBA.

2. Do non safety-related SSCs mitigate accidents / transients?

This criterion implies determination of non safety-related SSCs which are needed to mitigate accidents or transients.

Maintenance Effectiveness Monitoring

(using PSA insides)

3. **Are non safety-related SSCs used in emergency operating procedures?**

This criterion implies determination of non safety-related SSCs that provide a mitigating function in plant EOPs. The available EOPs should be revised for SSC selection for ANPP.

4. **Do non safety-related SSCs prevent safety-related SSCs from fulfilling their safety-related function?**

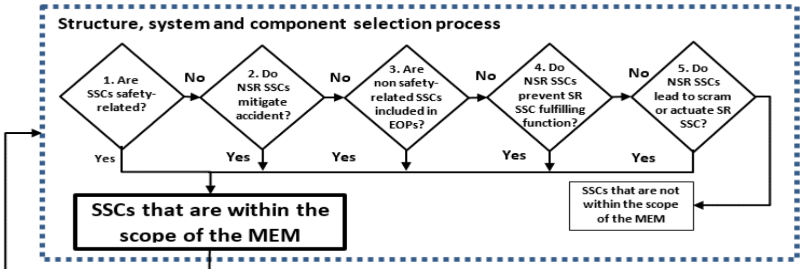
This criterion implies investigation of the systems interdependencies to determine failure modes of non safety-related SSCs whose failure prevents a safety function from being fulfilled. Analysis should be based on actual plant-specific and industry wide operating as well as on engineering evaluations such as PSA, Failure Mode and Effects Analysis (FMEA), environmental qualification (EQ) and others.

5. **Do non safety-Related SSCs Scram or Actuates Safety Systems?**

This criterion implies determination of non-safety related SSCs whose failure could cause a reactor scram or actuation of a safety related system.

Maintenance Effectiveness Monitoring

(using PSA insides)



Selection of SSCs for maintenance effectiveness monitoring (MEM).

#	ANPP systems, structures and components	1. Are SSCs safety-related?	2. Do NSR SSCs mitigate accident?	3. Are NSR SSCs in EOPs?	4. Do NSR SSCs prevent SR SSC to fulfill function?	5. Do NSR SSCs scram or actuate SR systems?	PSA SSCs
1.	Reactor pressure vessel and internals	♦[1]					+
2.	Steam Generator (SG)	♦					+
3.	Control Road intermediate cooling circuit system					♦	+
4.	RCP intermediate cooling circuit system				♦	♦	•
5.	RCP oil system				♦	♦	+
6.	Demineralized water system		♦	♦			•
7.	Scram system (control road mechanical part)	♦					•
8.	Primary emergency makeup system	♦					•
9.	Primary overpressure protection system	♦					•
10.	Heating network [2]						
11.	Clean condensate System						
12.	Deactivation system						
. .	… …	…	…	…	…	…	..
92	Diesel driven SG make-up system	♦					•

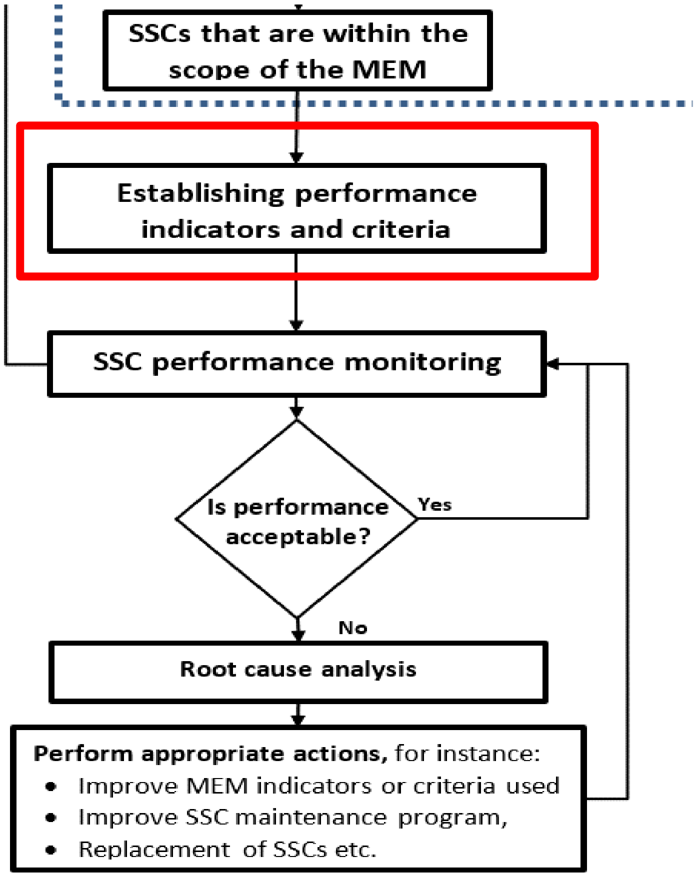
The SSC are adequately represented in the PSA

75 SSCs were found to satisfy defined criteria. The efforts were focus on the 42 SSCs for which reliability indicators could be derived from PSA study.

Maintenance Effectiveness Monitoring

(using PSA insides)

- The probabilistic reliability indicators used for inspecting effectiveness of maintenance are based on numerical evaluation of risk and safety.
- The principle of this approach is based on the fact that the risk estimated by level 1 PSA is acceptable
- If PSA is not adequate or the risk is not acceptable, the obtained target values, accordingly, will not be adequate and acceptable



Maintenance Effectiveness Monitoring
(using PSA insides)

To apply level 1 PSA for target values development, several aspects should be considered:

- The reliability of the component groups should be estimated taking into account the system’s function.
- The Supporting systems should be eliminated from the considered systems’ fault trees.
- The human errors which cannot be prevented by maintenance should be eliminated from the fault trees.
- The failure on demands and failure to run events should be considered separate in the PSA model.

Maintenance Effectiveness Monitoring
(using PSA insides)

- reliability on demand
  - Assumes failure probability in PSA is correct
  - Estimate number of demands over next evaluation period
  - Calculate number of failures, using binomial distribution, such that, if PSA value is correct, there is approximately a 5% chance of seeing more than that number of failures

Criterion is at least a 5% chance of seeing more than that number of failures				
Slide 28				
Example	1	2/2	2/3	
Number of failures	1	2	3	
Demands	36	24	24	$f(x) = \binom{n}{x} p^x (1-p)^{n-x}$
Probability of failure	0.01	0.05	0.05	
Chance of seeing <= number of failures	0.95	0.88	0.97	
Chance of seeing > number of failures	5%	12%	3%	
Performance criteria at	1		2	or fewer failures over next evaluation period

Maintenance Effectiveness Monitoring

(using PSA insides)

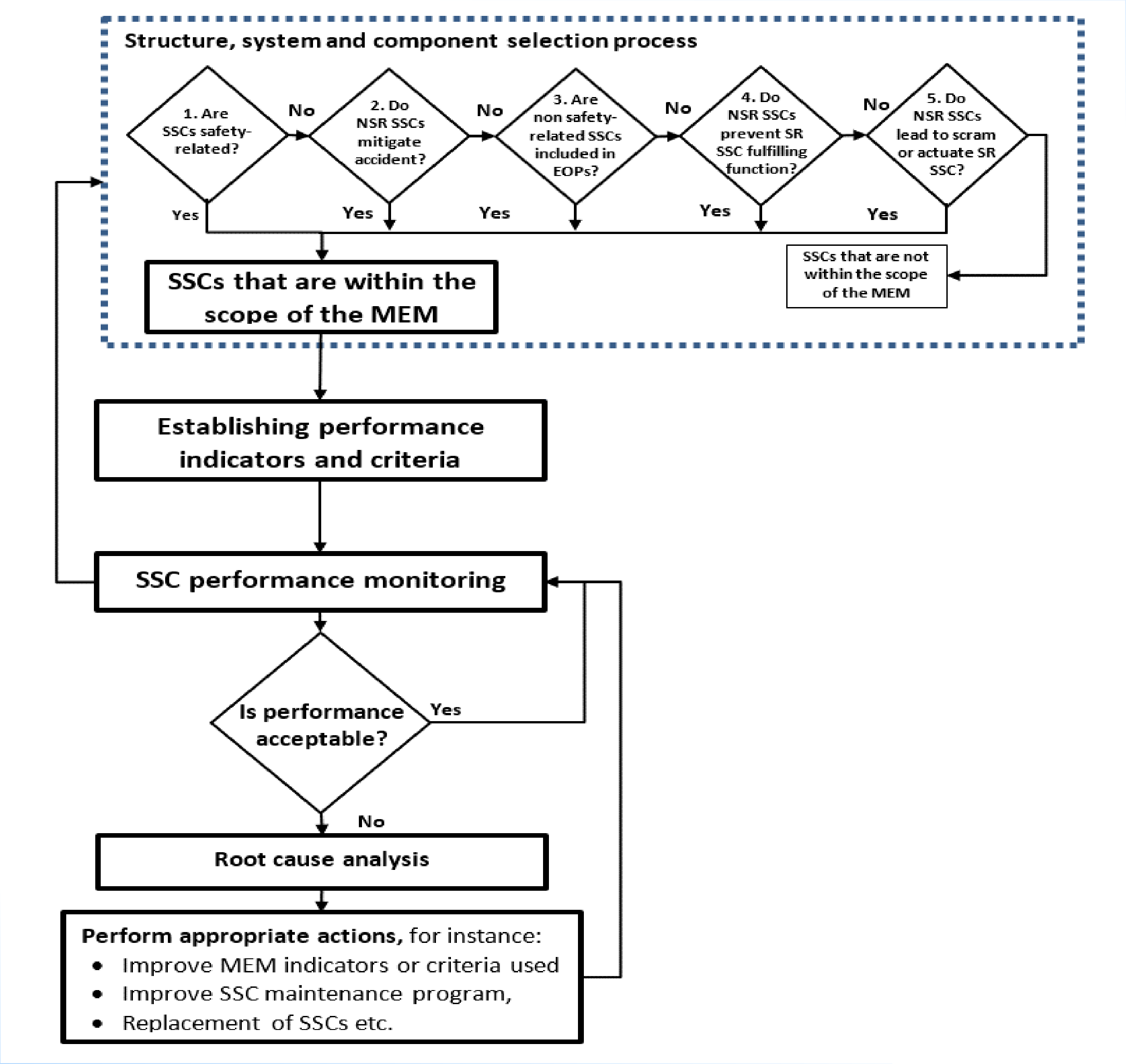
- Reliability of normally running SSCs
  - Assume failure rate in PSA is correct
  - Estimate total running time over next evaluation period
  - Calculate number of failures, using Poisson distribution, such that, if PSA value is correct, there is approximately a 5% chance of seeing more than that number of failures.

Criterion is at least a 5% chance of seeing more than that number of failures						
Slide 30						
Example	1/1	1/2				
Number of failures	1	2				
Failure rate	5.00E-05	5.00E-05				
Total running time	10000	10000				
Chance of seeing <= number of failures	0.91	0.99				
Chance of seeing > number of failures	9%	1%				
Performance criteria at	1		or fewer failures over next evaluation period			

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T},$$

Maintenance Effectiveness Monitoring

(using PSA insides)



Maintenance Effectiveness Monitoring

(using PSA insides)

- **Important: This approach do not replace traditional maintenance program, this approach compliment it.**
- Tests are performed with to ensure that the controlled parameters are in the acceptable range. These parameters of the components ensure that the system performs its intended function and reveal the system shortcomings which could lead to a loss of system's function. Such parameters are:
  - pressure on header,
  - pressure on suction,
  - vibration,
  - cooling air/medium temperature,
  - pump bearings temperature,
  - etc.

Conclusion

The examples of inspections, surveillance tests and MEM demonstrated the benefits of PSA applications

PSA applications provide an chance

- to understand hidden dependencies,
- to have a numerical estimate,
- to have additional justification for decision making.

Not Risked-based but risk-informed

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Thank you!

References

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- Guide NO. AERB/SG/O-8 (1999),
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