Integrated Common Cause Component Group Analysis of Diverse and Highly Redundant Release Systems of RBMK Control Rods

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The RBMK Nuclear Power Plant

- The RBMK is a Russian designed NPP with vertical pressure tubes, light water as coolant, and graphite as moderator
- The RBMK core is quite large (diameter 11.8 m, core volume 824 m^3 for Ignalina NPP)
- Characteristic:
  - Pressure tube design allows for refueling during operation
  - Moderator graphite leads to high positive void coefficient

RBMK Shutdown System

- RBMK was initially equipped with BSM shutdown system: MCR (manual control rods) dropping in water-cooled channels
- After Chernobyl, a fast shut-off system BAZ was backfitted with 24 FASR (Fast Acting Scram Rods) dropping in gas-filled channels cooled by water film
- Supporting the BAZ system 49 of the 187 MCR positions were equipped with diverse AZ/BSM cluster control rods and redesigned servo drives to form the AZ diverse shutdown system

RBMK Reactor Block

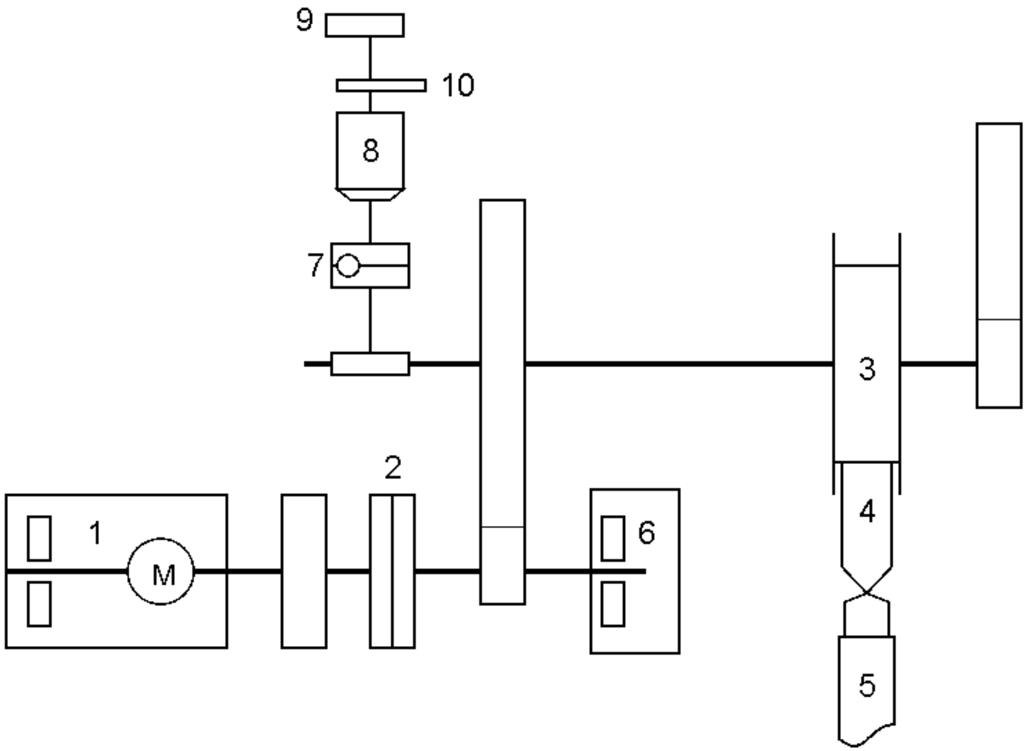
Failure Criteria for Shutdown Systems

- Shutdown assumed unsuccessful, if
  - > 5 out of 138 BSM MCRs fail to be inserted and
  - > 3 out of 24 BAZ CRs or > 4 out of 49 AZ/BSM CRs fail to be inserted
- Criteria are assumptions based on conservative reactivity balances
- More precise criteria would require detailed reactivity analyses, which were not made available for a detailed reliability assessment

AZ/BSM Servo Drives (New Servo Drives)

- New servo drives have complementary functions compared to older design:
  - Second and diverse protection clutch between motor and gearing
  - Additional hydraulic brake with selsyn driven actuation
  - Additional overload protection for selsyn blockages
- Other main components remain unchanged
  - Electromotor with electric brake
  - Selsyn for position indication
  - Drive‘s tape and tape drum

Kinematical Sketch of AZ/BSM Servo Drives



1 Electromotor with Brake
2 Protection Clutch
3 Tape Drum
4 Tape
5 Control Rod
6 Hydraulic Brake
7 Overload Protection
8 Selsyn
9 Position Indicator
10 Bowden Wire Actuation of Hydraulic Brake

Definition of Common Cause Component Groups

- BAZ servo drives are considered diverse to old BSM servo drives
- The new AZ/BSM servo drives are only partially diverse, since they have in common important parts with the old BSM design (electromotor and brake, selsyn, tape).
- For probabilistic assessment:
  - Detect components of new and old design with the same Common Cause Failure modes
  - Combine similar failure modes into Common Cause Component Groups (CCCG)

Common Cause Component Groups

CCCG	Description	Mean Failure Probability
BAZ	Failure of BAZ fast shut-off (long detection times)	1.0E-03
BSM_BRAKE	Failure of BSM brake and electromotor	5.0E-06
BSM_SEL	Failure of BSM selsyn	3.0E-06
BSM_TAPE	Failure of BSM tape or tape drum	1.0E-06
BSM_SP	Failures specific to BSM old servo drives	1.0E-05
NSD_BRAKE	Failure of new servo drive brake and electromotor	1.0E-04
NSD_SEL	Failure of new servo drive selsyn	1.0E-04
NSD_TAPE	Failure of new servo drive tape or tape drum	4.0E-05
NSD_CL	Failure of new mechanical clutch (few testing data)	1.0E-02
NSD_OVER	Failure of new overload protection (few testing data)	7.9E-02
NSD_SP	Failure specific to new servo drives (e.g. hydraulic brake)	7.7E-03

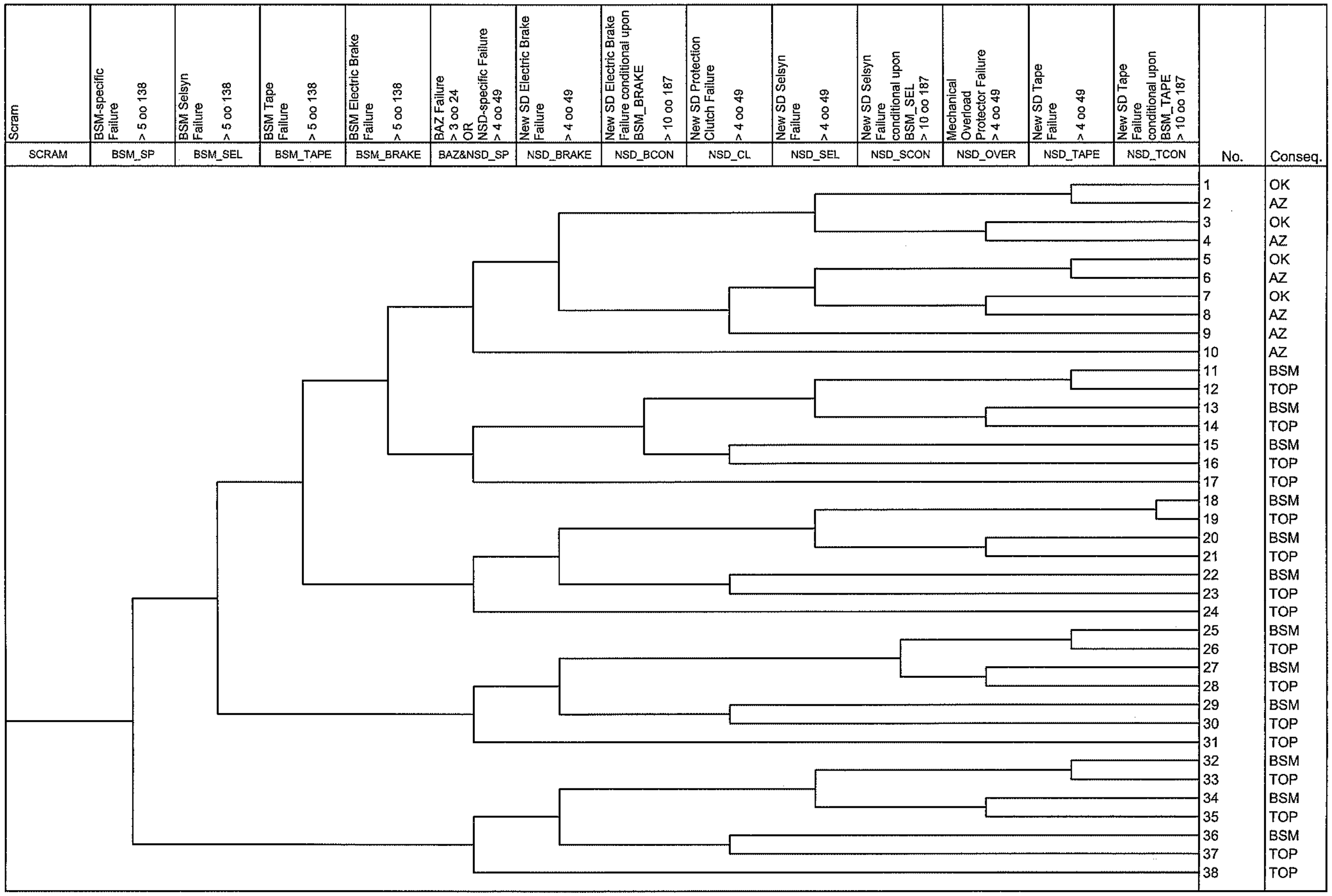
All failure probabilities describes by distribution functions (see paper)

Failure Probabilities of CCCGs

- Probabilities of CCCGs are estimated based on
  - Russian and Lithuanian data for component reliability
  - Testing data of the new servo drives
  - CCF failure rates derived by the Common Load Model
- For the CCCG failure modes for brake, selsyn and tape, the conditional transition probability from > 5 oo 138 to > 10 oo 187:

  NSD_BCON, NSD_SCON, NSD_TCON is 0.475 (mean) based Common Load Model

Event Tree for Servo Drives BSM, BAZ, and AZ/BSM



Failure Probabilities and Sensitivities

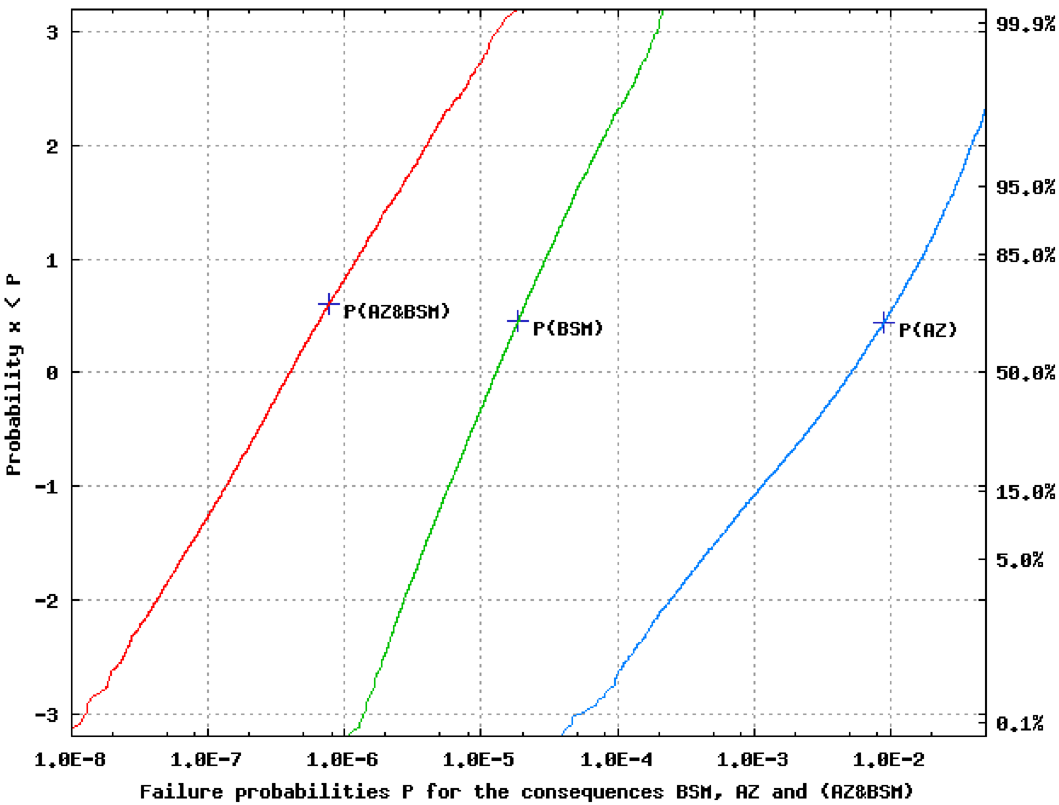
- Failure probabilities for functions BSM, AZ (BAZ or AZ/BSM failure), and BSM ∩ AZ (failure of shutdown)
- Failure for failure of BAZ or AZ/BSM conditional on BSM failure AZ | BSM. Probability defined by

$$\mathrm{P}\,(\mathrm{AZ}\,|\,\mathrm{BSM}) = \frac{\mathrm{P}\,(\mathrm{BSM} \cap \mathrm{AZ})}{\mathrm{P}(\mathrm{BSM})}$$

- Sensitivity study for all failure modes using fractional contribution. Sensitivity factor for AZ | BSM defined analogously as

$$S_i\,(\mathrm{AZ}\,|\,\mathrm{BSM}) = 1 - \frac{1 - I_i\,(\mathrm{BSM} \cap \mathrm{AZ})}{1 - I_i\,(\mathrm{BSM})}$$

Failure Probability Distributions for BSM, AZ and BSM ∩ AZ



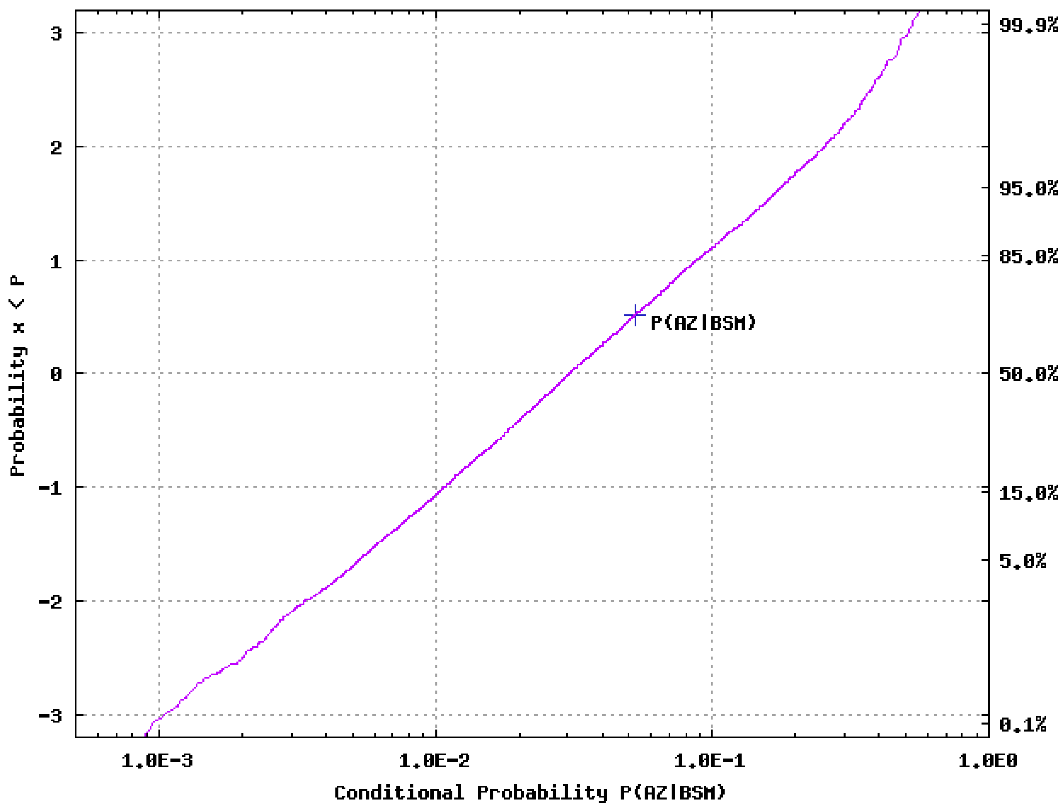
P(BSM) = 1.9E-05

P(AZ) = 8.8E-03

P(BSM ∩ AZ)
= 7.7E-07

Mean values based on calculations with RiskSpectrum and STREUSL

Conditional Failure Probability Distribution of AZ | BSM



P(AZ | BSM)
= 5.2E-02

compared to 8.8E-03
for AZ alone

Sensitivities of CCCGs

Fractional contribution						Sensitivity factor	
BSM		AZ		BSM ∩ AZ		AZ | BSM	
Basic event	percent	basic event	percent	basic event	Percent	basic event	Percent
BSM_SP	53.4 %	NSP_SP	87.8 %	BSM_TAPE	61.8 %	BSM_SP	-90.0 %
BSM_BRAKE	25.4 %	BAZ	11.8 %	NSD_TCON	60.7 %	BSM_BRAKE	-22.2 %
BSM_SEL	15.9 %			NSD_SP	19.2 %	BSM_SEL	2.3 %
BSM_TAPE	5.3 %			BSM_SEL	17.8 %	BSM_TAPE	59.7 %
				NSD_OVER	14.5 %	NSD_TCON	60.7 %
				NSD_SCON	14.4 %	NSD_SP	19.2 %
				BSM_SP	11.5 %	NSD_OVER	14.5 %
				BSM_BRAKE	8.8 %	NSD_SCON	14.4 %
				NSD_CL	3.1 %	NSD_CL	3.1 %
				NSD_BCON	3.1 %	NSD_BCON	3.1 %
				BAZ	2.4 %	BAZ	2.4 %

Summary

- A structured method was presented for propagating the reliability limits linked to Common Cause Component Groups of highly redundant system
- Gain in reliability demonstrated based on this structured analysis
- Conditional Probability P(AZ|BSM) and Sensitivity Factors show well-balanced design of new servo drives
- For a more precise analysis, detailed reactivity analyses are required
- Methodical and numerical approach should be reassessed on the basis of operational experience feedback