The Evaluation of Research Reactor TRIGA MARK II Safety

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Abstract
In the paper the Probabilistic Safety Analysis (PSA) of a research reactor is described. Five different initiating events were selected and analyzed with the use of event trees. Seven reactor systems were modeled with fault trees. Three groups of radiation releases were introduced - Success, Reactor-Hall, Environment - and their frequencies were estimated. The importance factors of initiating events, human errors and basic events were calculated regarding the consequence groups.

I. Introduction
For research reactor as a nuclear facility, a high reliable operation is required - from economical and environmental point of view. In the paper safety of the research reactor TRIGA MARK II in Podgorica was estimated by PSA - Probabilistic Safety Assessment-method where risk can be defined as a combination of initiating events frequencies, probabilities of safety systems failures and radiation release categories.

For the risk estimation it is necessary to find the consecutive events - accident sequences - which lead to an undesired event. The accident sequences are determined with event trees. Their construction is started with initiating events definition and continued with determination of safety systems response.

For safety systems which are included in the accident sequences due to their ability to prevent or mitigate the radiation releases, the probability of failure is calculated. This is done by logical models named fault trees. They are combination of basic events-basic faults requiring no further development. Mathematical background is based on Boolean algebra.

With computer treatment of event and fault trees it is possible to estimate the probability of an undesired event, the probability of safety systems failures, the probabilities of accident sequences with minimal number of events and the importance of single initiating events, safety systems and basic events. With these data it is possible to improve availability of an item.

II. Research Reactor Description
The TRIGA MARK II research reactor is used for operator training, research involving neutrons and isotope production. It has been operating since 1966 and modified to the pulse reactor in the year 1991. It has approximately 4000 operating hours per year. The thermal power of the reactor is 250 kW, maximal pulse power achieved during the benchmark experiment is 970 MW.
The reactor is open pool, light water reactor cooled by natural convection. The fuel is a homogenous mixture of uranium and zirconium hydride. It has a large prompt negative temperature coefficient, which leads to the inherent safety against reactivity accident.

III. Research Reactor Probability Model
As an undesired event the release of radioactivity to the reactor hall or in the environment was defined. Assumptions made during the initiating events analysis are:
- only internal events were included in the research,
- the collected data do not explicitly manifest the influence of component aging,
- analyzed events were caused by reactor operation.

The initiating events were selected regarding the consequences and frequency of occurrence.

The selected initiating events used in the analysis are:

- **Loss of Coolant Accidents:**
  - Primary Coolant Pipe Break/Rupture,
  - Reactor Vesssel Break;

- **Erroneous Handling or Failure of Equipment or Components:**
  - Fuel Element Cladding Failure,
  - Mechanical Damage of Fuel Element during the Transfer;

- **Experiments:**
  - Radiation caused by Experiments.

No initiating event which is caused by pulse operation of reactor was found. The reasons are the prompt negative temperature coefficient and reactor core limitations.

For each of initiating events an event tree was constructed. Safety systems which are needed to mitigate or prevent the consequences of the initiating event are:
- Reactor Protection System,
- Primary Coolant System,
- Secondary Coolant System,
- Emergency Water Supply System,
- Reactor Hall Ventilation System and
- Liquid Waste Processing System.

The support system for some of the safety systems operation is Electrical Power Supply System. All these systems were modeled with fault trees.

In the construction of event trees three groups of radiation releases were introduced:

- **Success:** No radiation release to the environment, possible release below allowable limits to the reactor hall.
• **Reactor Hall**: Possible release to the reactor hall, which is above allowable limits.

• **Environment**: Release in the environment under allowable limits.

### IV. Research Reactor Data Base

The input data for event tree and fault tree calculation are initiating events frequencies and basic event probabilities.

#### Initiating Events

For the initiating event Radiation Caused by Experiments the specific datum was used /1,2/. It was estimated with the use of operator log-books and with the conversation with the operators.

For the other initiating events generic data were used/3,4/. The estimated frequencies are as follows:

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Coolant Pipe Break/Rupture</td>
<td>... 3.3 x 10^{-2}/year,</td>
</tr>
<tr>
<td>Reactor Vessel Break</td>
<td>... 1.3 x 10^{-5}/year,</td>
</tr>
<tr>
<td>Fuel Element Cladding Failure</td>
<td>... 1.1 x 10^{-2}/year,</td>
</tr>
<tr>
<td>Mechanical Damage of Fuel Element during the Transfer</td>
<td>... 5.6 x 10^{-5}/year,</td>
</tr>
<tr>
<td>Radiation caused by Experiments</td>
<td>... 1/year.</td>
</tr>
</tbody>
</table>

#### Basic Events

Three types of different basic events were included in the fault trees: component unavailabilities, human errors and common cause failures.

Components were modeled with exponential and binomial distribution /5/, parameters for component models were obtained from literature /6,7/. Parameters were estimated by binomial, Poisson, lognormal and discrete distribution. For test intervals and repair times specific data were used for most of components /8,9/.

Human errors were estimated with ASEP (Accident Sequence Evaluation Programme) technique /10/. The demanded data for human error probability estimation are:

- the maximum allowable time to have correctly diagnosed an abnormal event and to have completed the necessary human actions,
- the time needed to get to a particular location plus the time needed to perform required actions once a diagnosis of an initiating event has been made,
- level of operator knowledge of the initiating event (training),
- operator stress level.

We got human operation data from conversation with operators, operator log-books and safety report /11/.

For common cause failures the beta factor model was used /5/. The parameter F128Mb is defined as the fraction of the total failure rate attributable to dependent failures /12/. The conservative assumption of this method is, that a common cause failure leads to a failure of all components in the common cause group. Components which were modeled with β factor are: control rods, filters, circuit breakers, fuses,
amplifier, thermocouple, ion chamber, limit parameter indicator, Geiger-Müller counter, water level meter, pump, transformer and manual valve. Data were obtained from literature /13,14,15,16,17/.

V. The Results of Research Reactor Probabilistic Safety Assessment
Two groups of consequences were analyzed: Reactor Hall and Environment. The releases to the environment were found to be under allowable limits. However, the computer analysis was done for this kind of releases because it may be needed for optimisation of safety of research reactor.

Three types of component importance factors were calculated:

- Fussell-Vesely importance (Im) of an item is the relative change in the risk for a relative change in the failure probability of the item,
- risk reduction worth (RRW) of an item is the ratio of the nominal risk to the risk that would result if the item was perfect,
- risk achievement worth (RAW) of an item is the ratio of the risk that results from the item failed to the nominal risk /12/.

Computer code Risk Spectrum does not calculate risk achievement worth (RAW) for events which are modeled with frequency as a parameter. This is the reason, why RAW was not calculated for initiating events.

Consequence Group Reactor Hall
The sequences with the biggest impact on consequence group frequency are (figure 1):

1 Reactor Vessel Break (Z2)
2 Radiation Caused by Experiments (Z5) and control rods fail to insert-common cause failure (KPALICE)
3 Radiation Caused by Experiments (Z5) and bistable for control rods power supply does not switch (RTSDC)
4 Mechanical Damage of Fuel Element during the Transfer (Z4)

The highest importance factors Im and RRW have initiating and basic events which have the biggest impact on consequence group frequency. A high RAW have basic events: "control rods fall to insert-common cause failure" and "bistable for control rods power supply does not switch". The importance factors are shown in the figure 2.
Consequence Group Environment

The following sequences contribute more than 99% to the frequency of consequence group Environment (figure 3):

1. Fuel Element Cladding Failure (Z3) and operator did not isolate reactor hall (VSHEPIS)

2. Primary Coolant Pipe Break/Rupture (Z1) and worker did not verify waste water activity (PSHEPSC)

3. Radiation caused by Experiments (Z5) and worker did not verify waste water activity (PSHEPCS) and bistable for control rods power supply does not switch (RTSDC)

4. Fuel Element Cladding Failure (Z3) and recirculation fan fail to start (VSQFSV3)

5. Primary Coolant Pipe Break/Rupture (Z1) and waste water activity meter fails-low output (PSACM)
Initiating and basic events which are in the first five sequences have the biggest Fussell-Vesely importance (Im) and risk reduction worth (RRW). High risk achievement worth (RAW) have some components of Reactor Hall Ventilation System and components of Electrical Power Supply System (figure 4):

ESCBAR01...bus R01 failure

![Diagram showing importance factors of consequence group Environment](image)

**Fig. 4 Importance factors of consequence group Environment**

ESKADR01...circuit breaker (400 A) failure to remain in position
ESKADL1... circuit breaker to inlet valve failure to remain in position
ESKADV3... circuit breaker to recirculation fan failure to change position
VSQFRV3... recirculation fan failure to run
VSVXOL4... recirculation valve failure to open
VSVXEL1... inlet valve failure to close

**Comparison of Some Results**

Figure 5 shows the comparison of frequencies of radiation release groups. The frequency of consequence group Environment is $4.29 \times 10^3$/year, the frequency of consequence group Reactor Hall is $3.81 \times 10^5$/year. The reason for significant difference between two frequencies are human errors and initiating events. Human errors have a great impact on the Radioactivity Release to the Environment and with their relative high probability increase frequency of the consequence group. The frequencies of initiating events which have a high impact on Reactor Hall frequency are small. Initiating event Radiation Caused by Experiments has higher
frequency, but it causes the radioactivity to the reactor hall only if the Reactor Protection System is unavailable. Initiating events which have a high impact on consequence group Environment have higher frequencies of occurrence.

In the figure 6 contributions of initiating events, components failures and human errors to the single consequence group frequency are shown. Big influence of initiating events to the frequency is evident. Their impact is of two type:
- initiating events selection and
- initiating events frequencies.

Initiating events were selected with operator log-books/8/ and specific documents/11/ analysis. Their frequencies were resumed by generic data for nuclear power stations and introduce into the analysis substantial uncertainty. However, they do not influence component unavailabilities, human error probabilities and their importance factors.

**VI. Conclusions**

The research of TRIGA MARK II reactor in Podgorica was done with the Probabilistic Safety Assessment (PSA) method. Five different initiating events were selected for analysis:
- Primary Coolant Pipe Break/Rupture,
- Reactor Vessel Break,
- Fuel Element Cladding Failure,
- Mechanical Damage of Fuel Element during the Transfer and
- Radiation caused by Experiments.

Two groups of consequences were analyzed:
- Reactor Hall and
- Environment.

The analysis shows a great impact of initiating events and human errors on consequence group frequencies. High importance of Reactor Hall Ventilation System components, Electrical Power Supply System component, control rods and waste water activity meter is also seen.

The presented PSA is the basis for improvements of research reactor safety, such like maintenance and testing optimisation, operation procedures modification and safety systems modifications.

VII. Literature


/8/ Operator log-books.


