Analysis of undesired event that leads to the initiation of early warning system of Kartini reactor

Syarip S1*, Muhtadan2
1Centre for Accelerator Science & Technology, JL. Babarsari, POB 6101 ykbb, Yogyakarta
2Polytechnic Institute Nuclear Technology, National Nuclear Energy Agency, Yogyakarta
*syarip@batan.go.id

Abstract. The identification analysis of physical parameters that might provide indication for the emergency condition of the Kartini nuclear research reactor operation, have been done. The aim of this research is to determine the key parameters that needed for early warning system (EWS) of Kartini reactor. The method used is a failure mode and effect analyses to identify the postulated initiating event which can lead to the release of radioactive substances, then event tree and fault tree analyses to determine the probability of radioactive release. The plume stack pattern of the Kartini reactor is then also analysed. The analysis result shows that the initiating event that can lead to a release of radioactive substance from Kartini reactor to the environment is a failure of spent nuclear fuel (SNF) handling system. The probability of radioactive release is in order of $10^{-6}$ event/year. The fission product isotopes which have a great probability to be released into the environment in the form of gas are among others: Kr, I and Xe isotopes. The effective distance of radiation monitoring for EWS is in the range: 200 m up to 1000 m.

1. Introduction
Safety, security, and health of workers and communities is a must in the utilization of nuclear reactor as the mandate of the Indonesian nuclear law No. 10 year 1997 Article 16 paragraph-1 [1]. Accidents in nuclear facilities can lead to the nuclear emergency, so it is necessary to activate the nuclear emergency preparedness. The Yogyakarta Nuclear Complex (YNC) is operated under National Nuclear Energy Agency (BATAN) which provide nuclear facilities mainly Kartini nuclear research reactor. Therefore, it has a potential accident causing nuclear emergency.

The strategy for emergency countermeasures should be done in an integrated manner and inseparable with the provincial and even national emergency countermeasures system as the disaster relief law No. 24 of 2007 and regulation of the Nuclear Regulatory Body (BAPETEN) [2,3]. Fast, precise, managed decision-making, a controlled and coordinated system requires a variety of information obtained from monitoring of environmental radiation levels, meteorology, and operation parameters of Kartini nuclear reactor. Therefore, it needs a support system decision for the preparedness of nuclear emergency in the YNC, and this is also a mandatory according to government regulations [4].

The aim of this study is to support the implementation of an early warning system of Kartini reactor operation. This study is a part of R&D of a prototype support system for the decision on the preparedness of nuclear emergency includes data acquisition systems, as well as analysis of decision-making based systems, and an early warning system (EWS). Several models related to the EWS for national nuclear
facilities have been developed [5,6]. The EWS is integrated and accessible by parties related to disaster (BPBD, police, fire Department, SAR, etc.), where the R&D activity is planned in three years with the final outcome is a conceptual design and prototype of integrated preparedness and nuclear emergency systems in the YNC [7].

According to Kartini reactor Safety Analysis Report (SAR), the worst accident that can cause the release of radioactive substances to the environment is the fall of fuel with maximum burn-up [8]. Nuclear fuel which has a very high hazard potential is spent nuclear fuel (SNF) or irradiated nuclear fuel which is a radioactive waste with high activity. It must be managed carefully, so that it is safe for humans and the environment and does not burden the future generations. The release of radioactive substances causes radiation exposure in the reactor building is monitored by gamma monitor area. The radiation exposure outside the reactor building is periodically monitored including: water, soil, plants, up to a 5 km radius from the reactor site.

2. Materials and method
The method used in this analysis is a failure mode effect and criticality analysis (FMECA) followed by fault tree (event tree) analysis. FMECA is the study of potential failures that might occur in any component of a system to determine the probable effect of each failure on all other components of the system and on probable operations success, and potential failure mode is ranked according to the combined influence of severity and probability of occurrence [9,10]. The basic thrust of the analysis tool is to prevent failures using a simple and cost-effective analysis that draws on the collective information of the team to find problems and resolve them before they occur. The FMECA is used for determining the probable effects on system operation of each failure mode and, in turn, on probable operational success, the results of which are ranked in order of seriousness.

Fault tree analysis (FTA) is a top-down process of defining the top-level problems and, through a deductive approach using parallel and series combinations of possible malfunctions, to find the root of the problem and correct it before the failure occurs [11,12,13]. The FTA technique provides a graphical aid for the analysis and it allows many failure modes including common-cause failures (CCFs), the frequency of failures is supported by the event tree analysis. The model of common cause failure mode will be used is Beta model.

The FTA is a system reliability analysis model where the major causes of dependence among a set of systems or components can be explicitly described. CCFs are considered the collection of all sources of dependencies, especially between components that are not known or are difficult to explicitly model in the system or component reliability analysis. CCFs have been shown by many reliability studies to contribute significantly to the overall unavailability or unreliability of complex systems.

Beta factor model is one of the single parameter models that use just one parameter in addition to the total component failure probability to calculate the CCF probabilities. The sole parameter of the model (β) can be associated with the fraction of the component failure rate that is due to common cause events shared by the other components in the system, the CCF can be written such as stated in Equation (1) [14,15].

\[
\beta = \frac{\lambda_C}{(\lambda_C + \lambda_I)} = \frac{\lambda_C}{\lambda_T}
\]  

(1)

where: \(\lambda_C\) = failure rate due to common cause failures, \(\lambda_I\) = failure rate due to independent failure, and \(\lambda_T = \lambda_C + \lambda_I\). Having the \(\beta\) value, we can use the expression of the multiple component failure frequency to calculate the required probabilities. After calculating the CCFs probabilities for redundant systems, they are added to fault trees logic to contribute to the overall probability. The component failure rate is described in Equation (2).

\[
\lambda = \frac{n}{mT}
\]  

(2)

where \(\lambda\) is failure rate, \(n\) is number of failures observed, \(m\) number of identical components, and \(T\) is total operation time of component/system.
The fault tree analysis with the “Top Event”: the radioactive/ radiation release from Kartini reactor stack, as master fault tree diagram, need a detail information on the fuel handling tool and reactor ventilation system. The fuel handling tool is shown in Figure 1 and it should be operated by 2 persons.

![Figure 1. The fuel handling tool (should be operated by 2 persons)](image)

The schematic diagram of ventilation system of Kartini reactor is shown in Figure 2, it consists of motor blowers, belt, blower, ducting, filters (pre-filter and absolute filter), stack, and reactor building, which have function as barriers (radiation protection), air circulation & negative pressure.

![Figure 2. Kartini reactor ventilation system](image)

The source term of radioactive substances of Kartini reactor core is calculated using ORIGEN-2 computer code. The calculation result will be used to estimate the ultimate goal of gaseous release to the environment. Then, the calculation of ground level concentration (the plume of gas release) is calculated using Pasquill-Gifford equation [16]

3. Result and discussion

The FMECA for Kartini reactor was done and the result is summarized as postulated initiating events (IEs). The list of IEs categories for research reactors is referred to the IAEA technical document [13,14]. There were identified eight postulated initiating events (PIEs) namely: loss of electric power, insertion of excess reactivity, loss of primary or secondary cooling flow, loss of coolant (LOCA), erroneous handling/function of equipment/ component, special internal events, external events, and human error. The most probable causing radioactive release i.e. erroneous handling or failure of equipment or components, which consists of three events as follows:

3.1 Fuel element cladding failure

The causes are corrosion process, original defect of fuel cladding (production defect). The event sequence, system response and related parameter are as follow: swelling the defect fuel element caused by high temperature and pressure in the cladding gap, leakage of fuel element, and release of fission products to reactor room/building. This will follow by the alarm sounds on area (gamma) monitor, and the reactor is manually scrammed. Reactor ventilation system is shut-off to isolate air in reactor room. The consequences are: radiation exposure in the reactor room increasing, and radioactive release to environment before ventilation system is shut off.
3.2 Failure of experimental apparatus or materials
The causes are container of experimental apparatus failure or defects, and operator error. While the event sequence, system response and related parameter are: expansion on material irradiated causing container damage, radioactivity released from the samples to the reactor room, alarm sound on gamma area monitor, reactor is manually scrammed, and reactor ventilation system is shut-off to isolate air in reactor room. The related safety system are high radiation alarm system, ventilation system, and scram system, and the consequence is the radiation exposure in the reactor room increasing.

3.3 Mechanical damage to reactor core/fuel
The fuel transfer cask dropped to the core is a most dominant event, followed by failure of fuel handling tool (see Figure 1) and fuel element dropped in to the core. The event sequence, system response and related parameter are as follows: in the loading – unloading fuel elements the transfer cask dropped into the reactor core, several fuel element damaged, release of fission product to reactor room, and alarm sound on area monitor, the reactor ventilation system is shut-off to isolate air in reactor room. The related safety systems are high radiation alarm system, and ventilation system. The consequences are radiation exposure in the reactor room increasing, and radioactive release to environment before ventilation system is shut off.

The quantification of fault tree analysis with the “Top Event”: the radioactive/ radiation release from Kartini reactor stack, as master fault tree diagram is described in Figure 3.

![Figure 3. Fault tree of radiation release from Kartini reactor stack](image)

![Figure 4. Fault tree for Kartini reactor ventilation system failure](image)
The fault tree in Figure 3 is developed based on configuration of components in ventilation system such as shown in Figure 2. Based on Figure 2, the logical picture or failure tree of ventilation system can be drawn such as shown in Figure 4. The basic events that need data failure rate are failures of air filters, damper, and air inlet plugged. Whiles, the blower sub-system failure (B) is developed further.

By using reactor components failure data base [10,13,14], and local components failure data calculated using Eq. (1) and Eq (2) [17,18], then the quantification of fault tree gives a probability of radioactive release from Kartini reactor stack is around 1.1x10^-6 per year. The result is in the range of values for similar research results which have been done for research reactors in general [19,20,21,22].

If the radioactive release from failure handling of an irradiated fuel rod is really happened, then it is necessary to know the amount of source term of the fuel. The source term is calculated for an irradiated fuel rod with highest burn-up of 10% or 3.8 g (for operation mode of 5 hours per day and 5 days per week of Kartini reactor). The calculation result by using ORIGEN-2 computer code is presented in Table 1, where the gas fission products of which dissoluble in water are: Kr, I, and Xe isotopes, generating radioactivity of 1.189 Ci, 25.48 Ci and 23.07 Ci respectively. Therefore, if the three isotopes fission product gases are added up, the amount of radioactivity caused by a failed fuel cladding and all resulting gases released into the reactor primary coolant is 49.74 Ci or at a distance of 30 meters from the reactor core is equivalent to 20.04 x 10^-2 Sv/h.

| Isotopes | Radioactivity (Ci) | Total radioactivity (Ci) | Total radioactivity (Ci): Kr, I and Xe | Total exposure rate (mR/h) |
|----------|-------------------|--------------------------|----------------------------------------|--------------------------|
| ^85mKr   | 0.6123            | 1,189                    | 49.74                                  | 20.04                    |
| ^88Kr    | 0.4159            |                          |                                        | (at 30 m from reactor core) |
| ^131I    | 3.450             | 2,548.10^1              |                                        |                          |
| ^132I    | 5.664             |                          |                                        |                          |
| ^133I    | 0.1046            |                          |                                        |                          |
| ^135I    | 5.911             |                          |                                        |                          |
| ^133mXe  | 8.211             | 2,307.10^1              |                                        |                          |
| ^135Xe   | 0.1363            |                          |                                        |                          |
| ^135mXe  | 0.9468            |                          |                                        |                          |

Figure 5. Total isotope FPs activity a reactor fuel during and after Kartini reactor operation
Conservatively, the calculation result of total fission products accumulated in the reactor fuel from the beginning of the reactor operation up to 5 hours operation time (time period of daily operation), and after reactor shut-down, is shown in Figure 5. It is shown that the total fission products (FPs) activity in an irradiated fuel is $5.238 \times 10^{6}$ Ci, it became $6.850 \times 10^{4}$ Ci after 24 hours decay. While, the research related to the pattern of Kartini reactor plum stack have been done [23,24,25] and in summary can be re-drawn such as described in Figure 6. It can be seen from Figure 6 that the effective distance for monitoring the radiation necessary for EWS is in the range of 200 m up to 1000 m from the reactor stack, i.e. at the average ground level radiation concentration around 2.9E-14 rad/m³.

4. Conclusion
The initiating event for the worst accident in Kartini reactor is a failure of fuel transfer-cask when it is being used in fuel loading and unloading processes (the fall of transfer-cask) and causing a rupture of a fuel. The probability of occurrence for this failure event is around $10^{-6}$/year. The radioactive release caused by the event can be used as triggering parameter for starting-up the Kartini reactor EWS. The effective distance for radiation monitoring system for EWS is proposed to be located in the range of 200 m up to 1000 m from the reactor stack site.

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