Using Risk Assessment Tool to Evaluate the Fire-Induced Core Damage Frequency

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***Abstract*—the frequency of fire-induced core melt can be calculated by averaging over the observed frequency of experienced events in the commercial nuclear power plants which was found to be 1E-5 per reactor-year. It means about 20% of the total core-melt probability estimated in the reactor safety study. Therefore, Fire PRA methods have been developed primarily during the last two decades to recommend some preparations for the nuclear plants to improve their fire safety. In this paper the core damage frequency of fire induced in Tehran Research Reactor has been examined. CFAST uses plant data such as identified compartments and their properties to calculate its outputs. The output from CFAST i.e. the target temperature and damage time are used to calculate the fire non-suppression probabilities following their special event trees by the aide of Risk Assessment Tool (RAT) which has been developed in the safety center of Shiraz University. Finally, the estimated probabilities are used as the initiating event frequencies for Core Damage State event trees to evaluate the core damage frequencies of the scenario. The results can be used to assess the fire risk of current situation, to conclude the appropriate preparations and finally to re-examine the suggested preparations to improve the fire safety systems.**

Index Terms CFAST, TRIGA, Non-Suppression Probability, Core Damage Frequency, Damage Time.

I. INTRODUCTION

CFAST is a two zone fire model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire.

The primary data file together with databases for objects, as the input data, contain information about the building geometry, connection between components fire properties and specifications for detectors, sprinklers and targets.

The outputs of CFAST (sensible variables needed for assessing the environment) are temperature, the ceiling, wall and the floor temperatures within each compartments, the visible smoke and gas species concentrations with each layer, the target temperatures and sprinkler activation time.

For the purpose of the FPRA, the plant is divided into a number of fire compartments. A fire compartment is a well-defined volume within the plan that is expected to substantially contain the adverse effects of fires within the compartment. The FPRA partitioning process is designed to minimize the level of effort spent on low fire risk areas of the plant and maximizes the level of detail used to analyze high-risk areas using expert judgments. Plan and elevation view of the different buildings, may be used by an expert analyst to perform this task. This process should be start with existing plant partitioning as documented in the fire hazard analysis or other equivalent compliance documentation. The analysis then considered the impact of fires in a given compartment.

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The equipment and cable list should be developed attending to the equipments that:

(1) if affected by a fire, will cause an initiating event such that the appropriate fire-induced initiator can be defined, or
(2) all equipment necessary to support those mitigating functions and operator actions that are credited in response to any initiator or
(3) That equipment which can be a source of undesirable responses adverse to the safety during a fire-induced accident sequence.

Every identified ignition source should be part of at least one fire scenario. The scenario follows two parallel and competing processes:

I. Fire growth, detection, suppression and eventual extinguishment on one hand
II. Equipment and cable exposure, compartment or system damage, and operator response on the other hand.

The non-suppression probability (P_{ns}) represents the likelihood that the fire is not suppressed before target damage occurs, which is a function of fire magnitude (SF) and its time duration. A general suppression event tree illustrated in Figure 1 is recommended to determine P_{ns}.

The fire-induced core damage frequency can be expressed as the product of three terms:

1. F_i : the frequency of the postulated fire or class of fires.
2. $P_{ed,j|i}$: The conditional probability that the postulated fire will cause damage to some set of plant equipment.
3. $P_{CD:k|i,j}$: The conditional probability that core damage will be resulted given the postulated equipment damage and operator's failure in recovering the plant.

This is expressed mathematically as:

$$\mathrm{CDF} = \sum_{l=1}^{m}\sum_{i=1}^{n} f_i \sum_{j} P_{ed,j|i} \sum_{k} P_{CD:k|i,j} \qquad \text{(I)}$$

$$\mathrm{CDF} = \sum_{l=1}^{m}\sum_{i=1}^{n} \lambda_g \cdot k \cdot W_g \cdot SF \cdot P_{ns} \cdot \sum_{j} P_{ed,j|i} \sum_{k} P_{CD:k|i,j} \qquad \text{(II)}$$

This equation gives the ignition fire frequency as the multiplication of the (1)generic frequency per ignition source ($\boldsymbol{\lambda}_g$), (2)the ignition source count (k), (3)the geometric weighting factor (W_g),(4) the severity factor (SF) and (5)the non-suppression probability (P_{ns}) for each ignition sources over the all fire areas. Ignition frequencies are assigned to fixed, transients and hotwork ignition sources.

SF is calculated for each unscreened ignition source, which is based on the HRR necessary to generate target damage. SF can be plotted for different materials versus the rational distance of the target from the ignition source. A number of special curves exist.

For the cases of targets in the hot gas layer, equation III is used to obtain HRR:

$$\dot{Q}_{dam} = \sqrt{\left(\frac{T_{dam} - T_{amb}}{6.85}\right)^3 A_0 \sqrt{H_0}\, h_k A_T} \qquad \text{(III)}$$

$\dot{Q}_{dam}$: HRR necessary for generating room damage (kW)
T_{dam} : target damage temperature
T_{amb} : Ambient temperature ~ (20℃)
A_0 : Operating area
H_0 : Height of opening
A_T : Internal surface area of the room (= 2l.w + 2w.h + 2 l.h -A_0 were l, w, and h are the room length, width and height respectively.)

$$h_k = \begin{cases} \sqrt{\dfrac{k \cdot d_m \cdot c_p}{t}} & t < t_p \\ \dfrac{k}{th} & t \geq t_p \end{cases} ,$$

$$t_p = \frac{th^2}{4\left(k/(d_m \cdot c_p)\right)} \qquad (IV)$$

k : Thermal conductivity of wall material
d_m : Density of wall material
c_p : Specific heat of wall material
th : Wall thickness
t : Fire duration

Then an appropriate plot should be used to obtain SF as a function of HRR for specific ignition sources.

Time to target damage can be obtained using the so-called curves.

It can be calculated using the equation V, considering the calculated incident heat flux for different locations of the target respect to the ignition source.

$$t_{dam} = \frac{\pi}{4} k\rho c \left(\frac{(T_{dam} - T_{amb})^2}{q''^2}\right) \text{ (sec)} \qquad (V)$$

Where
t_{dam} : The damage temperature of the targets
q'' : The incident heat flux as a function of time

II. MODELING

Inputs for CFAST like physical and thermal properties, ventilation systems characteristics and the geometry data has been obtained from the TRIGA's PSA documents.

The HRR values can be obtained from the NPP fire sources. The gamma distribution is used to obtain the HRR uncertainties.

To identify critical fire zones, the fire protection maps, the map of electrical cables in the plant, the possibility of existence of fixed and transient combustible ignition sources such as oil, filters and plastic and mitigating functions from level 1 PSA of evaluated for overall reactor site has been examined to have an appropriate zone portioning which should covered all the areas encompassed by the global plant analysis boundary and no two fire compartments should share same space. Critical zones have been identified after examining the mentioned maps, and accomplishing a screening process, which include equipment and cables associated with safety functions of TRIGA. The critical zones are as follows:

In the reactor containment:

1. Control Room
2. Reactor Hall
3. Ventilation Room #2

In the reactor laboratories:

4. Pump Room
5. Electrical Room
6. Diesel generator Room
7. Fan Room #1

It is also assumed that at any given time, only one fire ignition will occur. Secondary fires, similar to multiple fires have been not modeled in this analysis.

Associated ETs have been developed to calculate the non-suppression probabilities in each fire zone. Figure 2 represents an event tree modeled by RAT for fire detection in reactor hall.

Conservatively, the failure probabilities of smoke detection system and gas-detectors have been considered to be 0.05 and 0.15, respectively. The probability of failure in the alarm system has been assumed 0.01. The most important term is the failure probability of brigade fire fighter to make the fire under control. It can be obtained from appropriate charts which plots the non-suppression probabilities versus available time. The procedure is given below

Time to detection which can be obtained from the appropriate datasheets given for different equipments of detection and suppression, and time to target damage, obtained from CFAST, have to be compared. If time to detection is higher than the time to target damage, the non-suppression probability should be 1, it means the fire is not detected on time, also if time to suppression is higher than time to

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damage, the non-suppression probability is 1, it means target damages before fire suppression. If suppression activities start before target damage, due to the type of detection/suppression capabilities, a non-suppression probability can be obtained from the corresponding charts. Figure 3 represents a chart which plots P_{ns} versus ($T_{dam} - T_{det}$) for locations equipped with smoke detection and automatic sprinklers.

Once we obtained all the headings probabilities, P_{ns} can be estimated using the appropriate event tree, through summation of each branch of event tree which leads to Non-Suppression state (NS).

The calculated probabilities from suppression ETs are used as a fire initiating frequency to evaluate the CDF of each scenario resulted by fire induced ignition source. Figure 4 is an ET, modeled for fire initiating event in control room which accompanies with evacuation, by RAT. FT approach has been employed to calculate the frequencies of headings of ETs. Figure 5 represents an FT modeled for failure to scram in fire occurrence, by RAT interface.

Table I gives some of the top events failure probabilities, as an example.

Table II and III are presented here to show the results of examining a postulated fire in some compartments of the plant and the other quantities such as time to damage and non-suppression probabilities, as an example:

The negative non-suppression time indicates the damage occurs before the function of fire detection system and fire-fighting action to take the fire under-control.

The result indicates that the non-suppression probability is higher in the compartments without automatic detection systems, like electrical room and diesel generator room, than the compartments with such systems. Therefore the automatic detection systems must be installed to reduce P_{ns} and reduce the equipment damages.

CDSs are identified as follows:

CDS1: When the reactor shutdown takes place successfully but the natural circulation system fails (with no primary heat removal).

CDS2: When the reactor fails to shutdown and there is no primary heat removal.

CDS4: When the reactor does not shutdown in case of reactivity accident although the primary heat removal system works normally.

CDS5: When the reactor does not shutdown in case of reactivity accident and the primary heat removal system also fails.

The total frequency of each CDS is given in table IV. Core damage frequency is the summation of frequencies of all CDF given in table IV, except CDS1, since it does not lead to core damage.

The CDF resulted by internal fire in TRIGA has been calculated to be $1.697*10^{-3}$/yr. This value criticizes the current situation and performance of fire safety systems of TRIGA which should be developed.

Comparing the probability of CDS2 with fire occurrence and CDS2 for internal initiating events without fire, for TRIGA, it seems that this probability has increased by the order of 5. Fire-induced CDS2 is also the most contributors to the final core damage frequency. It can be concluded that increase in fire-induced CDS2 is the direct result of fire damage to drive system equipment of control rods. It can be identify using importance analysis (Risk Increment Worth concept).the RIR for the failure of all 4 rods in case of CDS2 is in the order of 5.it means that the probability of CDS2 will increase by the factor of 5 if all 4 rods fails to drop. Since this system fails completely as a result of fire, they should be protected from the fire by using more reliable, fire-resistant equipments. Installing Fire barriers can protect the system.

The other three CDS frequency (CDS1, CDS4, and CDS5) are in the same order for two situations.

The result indicates that the non-suppression probability is higher in the compartments without automatic detection systems, like electrical room and diesel generator room, than the compartments with such systems. Therefore the automatic detection systems must be installed to reduce P_{ns} and reduce the equipment damages.

The control room, pump room and emergency diesel generator compartments have the most contribution to the CDF from internal fire hazards.

It should be noted that the combination of individual component analyses and multi compartment analyses will reach the same final numerical estimates of the plant-wide fire risk, regardless of how the partitioning was performed. This will be accomplished since identification and analyses of multi-compartment fire scenarios will begin with all fire compartments that are screened qualitatively or quantitatively. Furthermore, the partitioning decisions impact the presentation and interpretation of the fire PRA results in terms of the single and multi-compartment fire scenarios contributions. Excessive partitioning may appear to artificially dilute the contribution of a given room to fire risk and should be avoided. When in doubt, retention of larger and more clearly delineated fire compartments is generally considered the more conservative approach.

It seems that the smoke propagation can impact the effectiveness of the operators and fire fighters. Current fire PRA methods remain weak in their treatment of smoke effects. Complication from such fires (for example the smoke propagation and operator error during plant shutdown) may lead to sequences otherwise consider as very unlikely.

For long duration fires, a delay in initiating the fire fighting activities and initial severity of the fire influence the duration of fires, and make the fire growth more complicated.

III. CONCLUSION:

In the present study, the CDF obtained by RAT has been 1,697*10-3 for TRIGA. To reduce of the current fire risk value, which is large, some preparations have to be applied in the maintenance procedures, equipment functions, safety systems and the operator action.CDS2 is the most contributors to the final CDF with the probability of 1.697*10-3 which is the result of failure in control rods drive system. The non-suppression probability of electrical room and diesel generator room are the most dominant contributor to fire CDF. Therefore they should be equipped with automatic detection and suppression systems. RAT can be used to estimate the fire-induced CDF with acceptable precision, using the outputs from CFAST. The uncertainties are due to limitation of fire modelling in CFAST or calculation procedure in RAT.

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IV. FIGURES AND TABLES

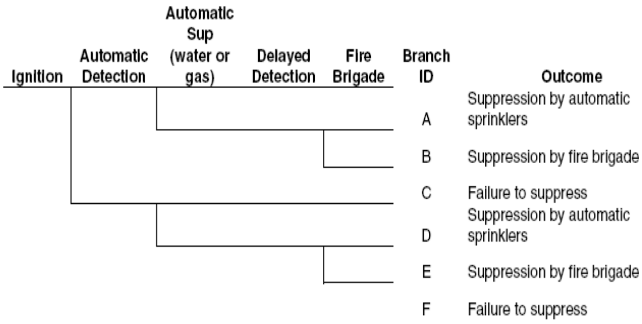

Fig 1.Fire Suppression Event Tree [5]

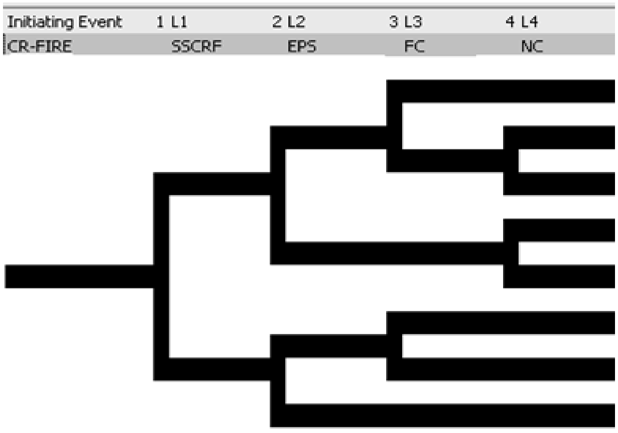

Fig 4.Fire in the Main Control Room

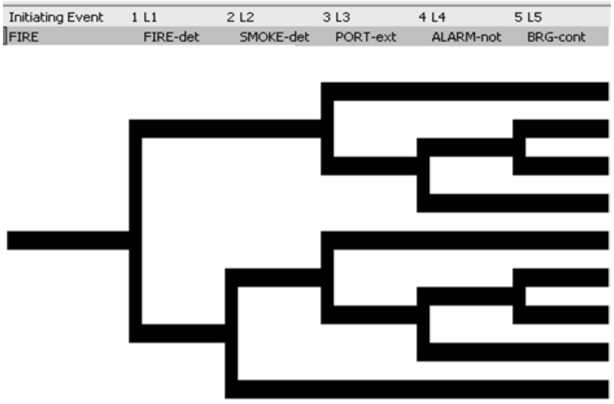

Fig 2.Suppression Event Tree for fire Reactor Hall

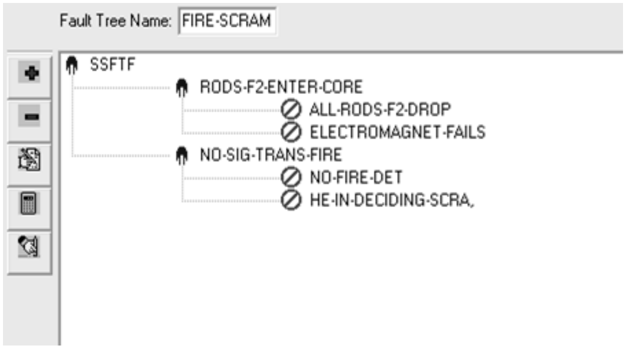

Fig 5.Failure to scram in Fire Occurrence

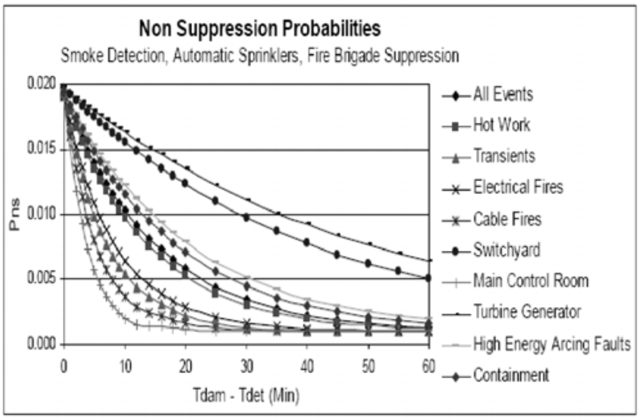

Fig 3.non-suppression probability chart [5]

Table I. Top Events Frequencies

Top event	Probability
CS	9.833×10^{-2}
SSPF	1.241×10^{-1}
EPS	1.852×10^{-4}
EV	2.658×10^{-2}
FC	9.963×10^{-3}
NC	7×10^{-5}
PPS-SYS-FAILS	2.784×10^{-3}
Rods fail to enter core	4.2×10^{-6}
SFS-SYS-FAILS	1.645×10^{-3}
Valve compressor fails	3.751×10^{-3}
SSCRF	5×10^{-1}
HPS-SYSTEM-CCF	3.386×10^{-6}
HRS-FAILS	1×10^{-1}
PS-FAILS	3.686×10^{-3}
SSPRF1	1.241×10^{-1}
SSPRF2	1.216×10^{-1}
SSFG50	1.881×10^{-1}
SSFG450	1.881×10^{-1}
EEPS-50kW	1.554×10^{-2}

Table II. Compartment Fire Characteristics

Compartment	$\lambda_{i,k}$	SF	T manual suppression
M.R # 2	3.7E-4	0.98	7.5 min
Reactor hall	4.4E-3	1	-10 min
Diesel Generator room	1.764×10^{-2}	0.98	64.166 min
Pump Room	5.246×10^{-3}	0.98	-150 min
Electrical Room	4.4×10^{-3}	1	-5 min

Table III. Compartments Fire Characteristics (cont.)

First ignition	Time To detect	Time to thermal damage	Target	fire brigade failure	P_{NS}
Oil	50 sec	800 sec	Cabinet	0.525	0.08397
Cable	300 sec	0	Cable itself	-	1
Diesel	900 sec	5050 sec	Cable	0.01	0.10059
Oil	100 sec	250 sec	Cable tray	1	0.15409
Cable	15 min	900 sec	Cabinet	1	0.23315

Table IV. Fire-induced core damage frequency

Core damage states	Frequency(1/yr)
CDS1	8.275×10^{-7}
CDS2	1.697×10^{-3}
CDS4	2.098×10^{-8}
CDS5	2.399×10^{-10}

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