CHAPTER 6

OPERATIONAL RISK ASSESSMENT IN INDUSTRIAL RADIOGRAPHY PRACTICE

CHAPTER OVERVIEW

This chapter describes in detail the research work carried out from an operational point of view for risk assessment in industrial radiography practice in India. The chapter outlines human actions involved in the operation of the radiography devices and also the concept of potential exposure in the area of radiation protection. The Probabilistic Safety Assessment (PSA) methodology has been utilized for the research work, which includes performing the fault tree and event tree analyses. Different practical scenarios have been considered for the risk assessment in industrial radiography practice. Data for human actions (or human errors) that occur generally during radiography operations was generated using an expert elicitation method; by conducting a Delphi Survey. This Chapter describes the event tree development to compute the probability of potential exposure to the operating personnel in the industrial radiography practice. The probabilities for each of the exposure categories have been calculated and the contributing factors for the potential exposures have been identified. The Chapter at its end proposes recommendations for risk management aimed to reduce the probability of potential exposure to the operating personnel.

6.1 OPERATIONAL RISK ASSESSMENT

Operational risk is the risk of failure, which results from failure or inadequacy of either the processes, the people or the systems. In the present scenario of risk assessment in industrial radiography practice, the loss is in terms of accidents leading to radiation injury, which in some cases may be fatal too. As is very clear from the preceding chapters of this thesis, the industrial radiography practice is carried out using the industrial gamma radiography exposure devices (IGREDs), which use a gamma-ray source of significantly high activity. Any unintended event due to an operational error or negligence by the operators may lead to potential doses to the operator and the other team members. Incidents reported in the past indicate that there is always a risk associated with the operation of radiography devices.

Industrial gamma radiography operations are carried out by an operator, who operates the radiography device manually. During an operation, the radioactive source comes out of the shielding and moves inside the flexible projection sheath. And after completion of the desired exposure, the source is retracted back into the exposure device. These forward and retractive movements of the radioactive source are done by rotating the handle provided in the control unit of the exposure device. Such operations are repeated several times in a day. Design and operation of the exposure device are simple, but any error in the operation may lead to accidents with severe consequences. This necessitates risk management in the practice. Like for any case, in this case too, the preliminary step for risk management is assessment of the associated risk in the industrial radiography practice.

Risk assessment in the operational aspects of industrial radiography practice has also been carried out by us in the present research work. The objectives of this operational risk assessment are the following:

a. Modeling the operational scenarios in industrial radiography practice.
b. Calculation of radiation monitoring equipment failure data.
c. Categorization of resultant doses to operating personnel, based on the individual errors/negligence during operational procedures.
d. Identification of the operational factors, which contribute to the potential exposures in the industrial radiography practice.
e. Calculation of relative contribution of each of the identified factors, which lead to potential exposure scenarios. This would help in

prioritizing the allocation of resources for risk management in the practice.

f. To verify the feasibility of PSA in this practice, since application of the PSA has not been tried for industrial radiography practice.

6.1.1 Concept of "Potential Exposure"

During an operation of a radiography exposure device, the operator in normal operating conditions too is expected to be exposed to some amount of radiation. However, in some instances, the amount of radiation exposure to the operator may be more than the normally expected one. This category of higher radiation exposure is termed as "potential exposure". Thus, potential exposure is an exposure, which is caused by some departure from normality. IAEA- INSAG-9 describes that most exposures of the worker are the result of normal operating conditions whose magnitude will vary with change in operating and environmental conditions [67]. However, sometimes the variation is not normal, and which is the case of potential exposure.

The Basic Safety Standard of IAEA describes potential exposure as 'prospective exposure that is not expected to be delivered with certainty, but which may result from an anticipated operational occurrence: accident at a source or owing to an event or sequence of events of a probabilistic nature, including equipment failures and operating errors [12].

Therefore, any radiation exposure which is more than that received from operations in planned exposure conditions, can be termed as 'potential exposure'. Thus, the events which may lead to potential exposure conditions are identified based on their association with the category of abnormal exposure.

6.2 RISK ASSESSMENT MODELING

We have carried out our present studies of risk assessment in industrial radiography practice in India, using the PSA modeling by generating the concerned event trees and fault trees. In the industrial radiography practice, the operation of radiography devices includes several actions by the operator, which directly affect the safety of the operator and the associated staff. Standard Operating Procedures (SOP) have been established, which outline the important steps to be followed by the team members and associated staff for safe operations. We have in our studies enlisted those steps of SOP, which affect the radiation safety of the operating personnel. It is understood that if any of the steps of the SOP is neglected by an operator, the resultant radiation dose may be different from the expected normal dose. The steps of SOP, and the deviation from which may result in potential exposure to the operating staff, have been shortlisted for both the operating scenarios. Those steps have been used for modeling the Event trees.

The Fault trees were designed to calculate the failure probabilities of the area monitoring instruments for their intended function, when their action is demanded. The failure rates obtained from the fault trees have been used in our studies one of the inputs of event tree.

6.2.1 Scenario Development for Risk Assessment

As is conveyed in the previous sections, we have studied risk assessment in industrial radiography practice in India in our present research work. Considering the practical situations where the operations are carried out, viz., in the open field and in enclosed areas, two different scenarios were considered for risk assessment: (i) Enclosed radiography operations, and (ii) Open field radiography operations. In our studies, in addition to calculating the probability for potential exposure to the occupational worker, our work aimed to compare the probabilities of potential exposure in both the scenarios of open field and enclosed radiography operations.

6.3 DATA GENERATION FOR RISK ASSESSMENT MODELING

The event tree type of assessment for operational risk assessment in industrial radiography requires data for human (operator) actions and instrument failures during operations as input data. Data for operator's actions during gamma radiography operations was a challenging task, since these data are not published anywhere. Data pertaining to operator's actions are neither reported by the radiography agencies nor are they recorded in the logbook of these agencies. Hence, collecting this data through observations during actual gamma radiography operations was considered as one of the options, but such data would be biased as the operator would be conscious of it all the time and the data would not pertain to that of normal working condition. Also, considering the large number of radiography institutions in India, the small sample size collected in such way would not be statistically acceptable.

Thus, due to unavailability of this data of operator's action during actual radiography operations, expert elicitation method, which is a well-established and accepted method for data collection, was found to be the most appropriate method for us. And the same has been utilized for this study. For this, a Delphi survey was conducted.

The Delphi technique is a method of eliciting and refining a group judgment. The Delphi technique, mainly developed by Dalkey and Helmer at the Rand Corporation in the 1950s, is a widely used and accepted method for achieving convergence of opinion concerning real-world knowledge solicited from experts within certain topic areas [68]. The Delphi survey requires multiple rounds until a consensus is formed among the respondents. The output of one round of survey is provided to the respondent of the second round, which allows them to reassess their opinion. Thus, Delphi is helpful for drawing a group consensus on a question of concern, especially in the cases where data is not available directly. Anonymous response, iteration and controlled feedback, and statistical group response are the important features of the Delphi technique [69]. Due to these advantages, the Delphi method has been utilized in various fields.

6.3.1 Delphi Survey

A Delphi survey was conducted for our present research work amongst experts having professional training and practical experience in the field of industrial radiography in India. The survey questionnaire was prepared based on the operator's actions required during normal radiography work, and these have been used as the event tree headings. We realized that some of the respondents may not provide correct responses due to fear of regulatory actions, and therefore anonymity of the respondents was maintained in our study by abstaining from seeking any personal information of the respondents, including their names and affiliations.

The questionnaires were prepared on the basis of the data required for event tree analysis, and mailed to the Radiological Safety Officers (RSOs) of the different industrial radiography institutions in India. All the questions in the first round of the survey were open ended type, i.e., the respondent was free to provide an answer of their choice. The RSOs were instructed to provide data based on their field experience and the current practices that they perform. Responses from 281 RSOs of industrial radiography agencies in India were received in all by us.

The results of a Delphi survey are presented in terms of some statistical distributions. The major statistics used in Delphi studies to present information concerning the collective judgments of the respondents are measures of central tendency (*means*, *median*, and *mode*) and level of dispersion (*standard deviation* and *interquartile range*) [70]. A common approach in such surveys observed in the published literature is to calculate central tendency (median) and Inter Quartile Range (IQR) for such type of studies. It is worth mentioning that Murphy et al. consider median and the IQR as more robust than the mean and standard deviation [71]. Also, Jacobs states “considering the anticipated consensus of opinion and the skewed expectation of responses as they were compiled, the median would inherently appear best suited to reflect the resultant convergence of opinion” [72]. Figure 6.1 below, shows a representation of median and interquartile range for a given range of data.

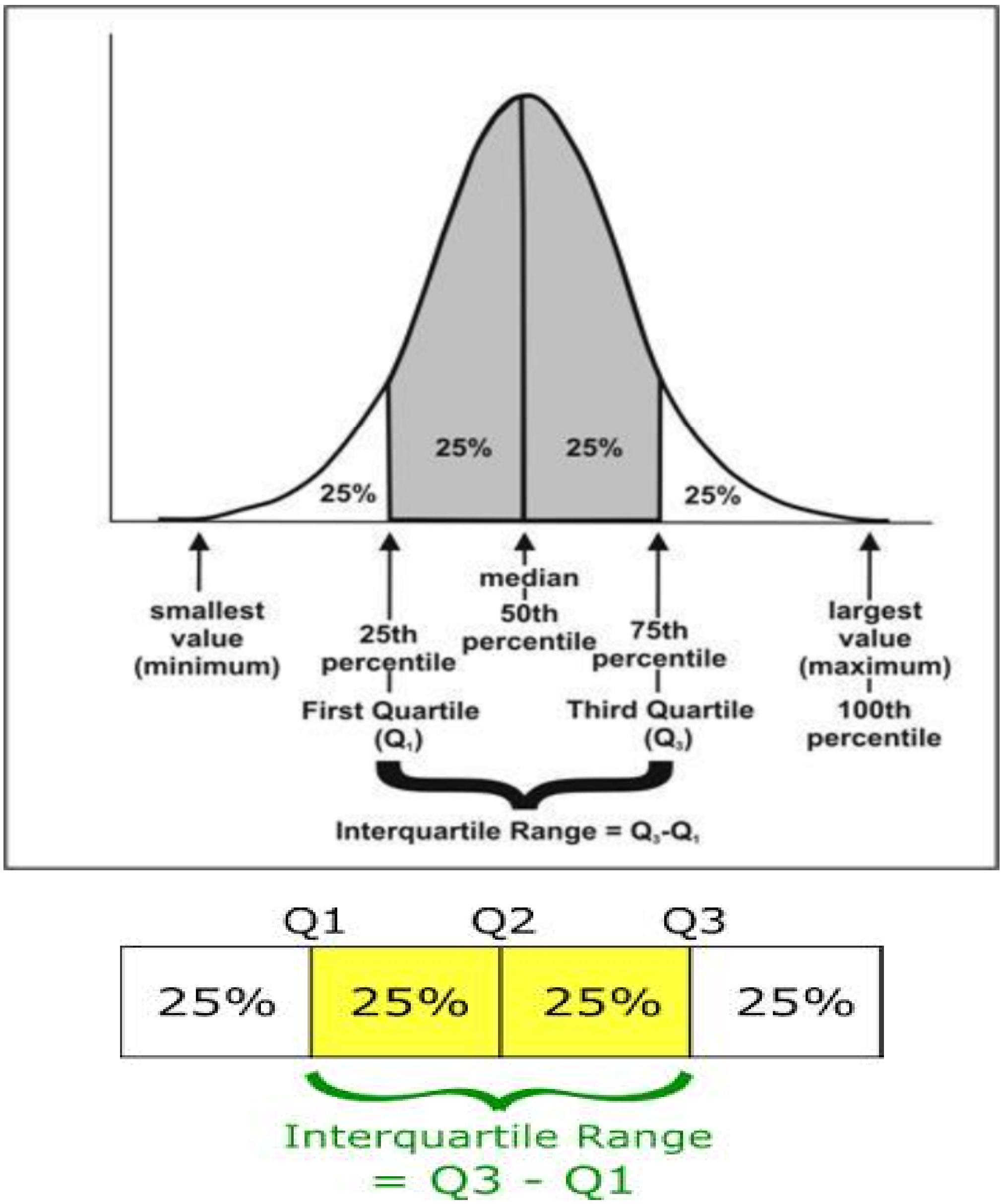


Figure 6.1 Representation of median and inter quartile range

It is clear from the above graphical representation that the lesser values of interquartile range represent smaller width between Q3 and Q1, which means high consensus on the given subject. The median and IQR values were calculated from the responses received for the survey for each of the headings of the event tree. Table 6.1 given below presents the calculated values of median and IQR from the data received from the first round of the survey. The IQR of the responses received in first round Delphi survey varied from 4.0 to 7.5.

Table 6.1 Median and IQR values from the first round of Delphi survey responses

Sr. No.	Actions	Median values of response	IQR of response
1	Radiation Survey Meter (RSM) obtained.	9.60E-1	5.0
2	Before taking out the device, a survey was carried out with the help of RSM around the device to verify the safe location of the source.	9.60E-1	4.0
3	After shifting the device (camera) to the radiography site, radiography work was postponed (due to various reasons e.g. No clearance for site, bad weather, job not ready etc.)	5.00E-1	7.5
4	The device is operated by the trained person (OR by the trainee radiographer in the presence of RSO/certified radiographer).	9.50E-1	4.5
5	Once gamma source is exposed, all team members moved to safe distance.	9.50E-1	6.625
6	When exposure time is over, enter the area with RSM.	9.80E-1	6.0
7	Guide tube and exposure device surveyed immediately with RSM to confirm the safe retrieval of the gamma source.	9.50E-1	6.5
8	Gamma source is retracted back in the camera in the first attempt.	9.80E-1	4.75
9	Search operation is performed inside enclosure.	9.80E-1	4.9

The consensus obtained from the first round of Delphi survey was reasonably good, but IQR of some of the responses was more than 5.0, which called for further narrowing down. Hence, a second round of the survey was also carried out. The same questionnaire was repeated in the second round of the survey. However, this time the respondents were allowed to provide their opinion within only the restricted data range of IQR of the first round. Also, the questionnaire was sent only to the respondents of the first round of the survey. In the latter rounds of a Delphi survey, it is expected that some of the respondents who earlier provided their responses outside the IQR may not agree with the responses that lay within the IQR. Therefore, responders who maintained their opinion outside the IQR were asked to provide a brief justification for their opinion. Only two respondents provided responses outside the IQR, along with their justifications. However, their opinion was not found reasonable, considering the practical scenarios involved, and were not contacted for further explanation.

The responses of the second round were also compiled and the data were processed. It was found that the responses of the second round were in good consensus, for all the questions, with the interquartile range variation lying between 0.1 and 2.0. The median values and the IQR obtained from the second round of Delphi survey for the operator's actions during radiography operations are shown in Table 6.2, given below. No further survey was not required in view of the consensus arrived among the responses of the second round. The data obtained from the second round of survey was utilized for modelling the event tree.

Table 6.2. Median and IQR values of the responses of the second round of Delphi survey.

Sr. No.	Actions	Median Value of response	IQR of response
1	Radiation Survey Meter (RSM) obtained	9.90E-1	0.1
2	Before taking out the device, the survey was carried out with the help of RSM around the device to verify the safe location of the source.	9.890E-1	0.2
3	After shifting the device (camera) to the radiography site, radiography work was postponed (due to various reasons e.g. No clearance for site, bad weather, job not ready etc.)	1.250E-2	2.0
4	The device is operated by the trained person (OR by the trainee radiographer in the presence of RSO/certified radiographer).	9.825E-1	0.25
5	Once gamma source is exposed, all team members moved to safe distance.	9.725E-1	1.75
6	When exposure time is over, enter the area with RSM.	9.880E-1	1.00
7	Guide tube and exposure device surveyed immediately with RSM to confirm the safe retrieval of the gamma source.	9.900E-1	0.10
8	Gamma source is retracted back in the camera in the first attempt.	9.9250E-1	0.25
9	Search operation is performed inside enclosure.	9.99E-1	0.100

6.4 PROBABILISTIC SAFETY ASSESSMENT IN INDUSTRIAL RADIOGRAPHY PRACTICE

The previous section describes in detail about generation of some of the data, which was required for our study of operational risk assessment in industrial radiography practice in India. The probabilities of potential exposure for the operating personnel in industrial gamma radiography practice play an important part in the risk assessment. These probabilities have been determined in our study using PSA methodology for the operational risk assessment.

6.4.1 Categorization of Resultant Radiation Exposure

Several potential exposure events in industrial radiography occur due to source getting stuck during transit in the guide tube of the IGRED. In the case of gamma ray source not retracting back in the device in the first attempt, the resultant exposure is not routine exposure and such exposure is classified as potential exposure.

There can be a large variation in the quantity of abnormal exposure (potential exposure) received during the practice depending on factors like, the cause of exposure, duration of exposure, source type & activity, and migratory actions. Since, all the abnormal exposures cannot be considered to be of the same level, the potential exposures arising from the operation of IGREDs have been categorized in our study into three classes. Basis of our classification is the description provided in INSAG-9 [67]. Therefore, for the purpose of this study resultant exposure has been categorized as presented below.

In the event tree analysis, each sequence in the event tree will lead to a specific range of exposure to the operating personnel depending on the progression of the operator's actions during radiography operations and on the availability of monitoring instruments. The different dose ranges, as obtained from the event tree analysis has been classified as, Occupational Exposure (OE), Potential

Exposure-I (PE-I), Potential Exposure-II (PE-II), Potential Exposure-III (PE-III) and No Significant Exposure (NSE). These are presented in Table 6.3.

Table 6.3 Categorization of resultant radiation exposure

Exposure Category	**Description**
Occupational Exposure (OE)	Whenever radiography devices are operated, the staff will certainly receive some amount of radiation dose. During normal operating conditions, the dose received by the operating staff is termed as "Occupational Exposure".
Potential Exposure-I (PE-I)	Exposure which is higher from that received during normal operating conditions but may not exceed the prescribed dose constraints for the occupational worker.
Potential Exposure-II (PE-II)	Exposure which exceeds the dose constraints but may not exceed the prescribed dose limits.
Potential Exposure-III (PE-III)	Exposure, which exceeds the prescribed dose limits and sometimes the exposure levels may be high enough to cause deterministic health effects due to localized dose to the operator.
No Significant Exposure (NSE)	Exposure which results when actions for exposure is initiated but the source is not projected out of the device due to various reasons such as no site clearance and job not offered for radiography after shifting the device to the radiography site. This dose is mainly due to leakage radiation levels from the gamma industrial radiography device and is not significant from the radiation safety view point.

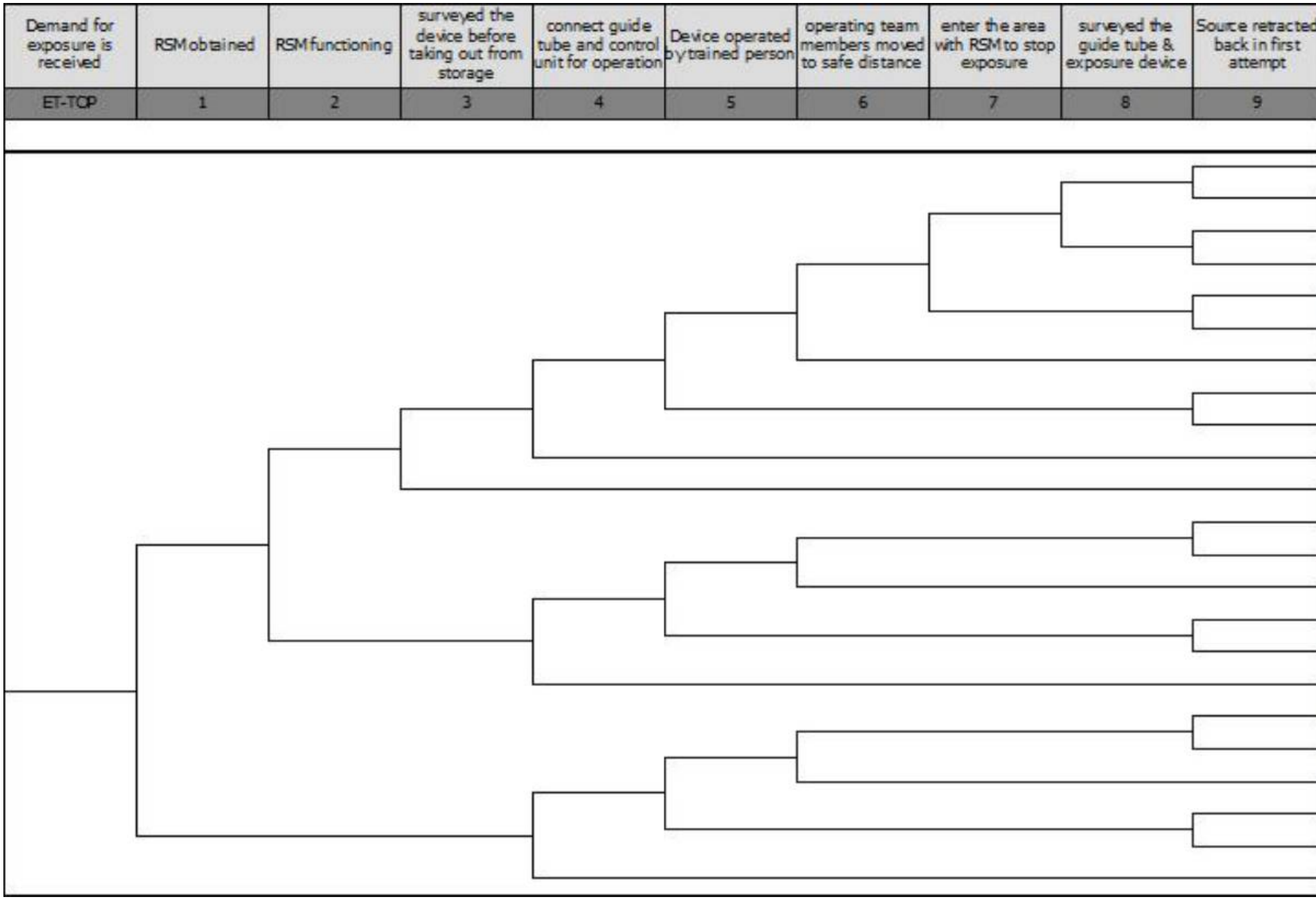
In the case of radiography operations performed inside an enclosure, both the instruments i.e., the area zone monitor and the portable radiation survey meter are used, and therefore an redundant monitoring instrument is available in case of failure of one the instruments. Therefore, for our probability calculations for the enclosed installation scenario, it is assumed that even if just any one area monitoring instrument (radiation survey meter or fixed zone monitor) is available in functional state and the gamma source is retracted back safely in the device in the first attempt, the resultant exposure would be considered to be the occupational exposure. Further, based on the field experience it is assumed for probability calculations in our study that untrained operator (or trainee) has insufficient knowledge to understand the significance of the radiation levels shown by the instruments.

6.4.2 Event Tree Assessment

As has been mentioned earlier in this thesis, the radiography devices are operated both, in the open field radiography and the enclosed radiography. We have performed risk assessment for both of these scenarios. The Event trees used for these assessments were created based on the recommended steps of SOPs for both, the open field and the enclosed installations. All the steps of SOPs that may affect the radiation safety and/or the potential dose to the operating staff were considered for modelling the event tree as shown in figures 5.5 and 5.6 of Chapter 5 of this thesis, for open field and enclosed radiography respectively.

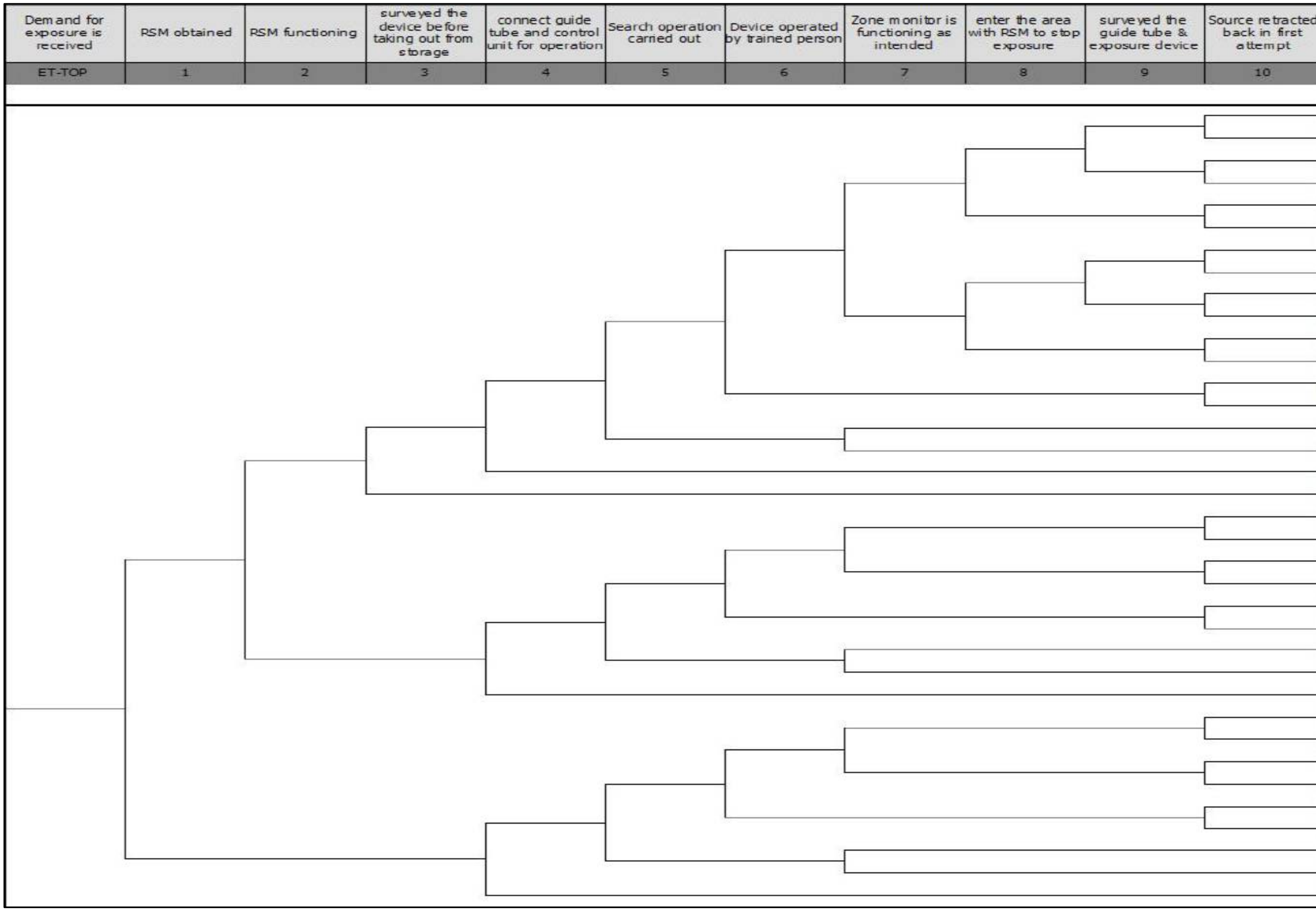
An Event tree analysis starts from an identified initiating event, which may lead to potentially hazardous situations. The "demand for gamma radiography exposure", as received by the operating team has been considered as the initiating event for event tree sequencing in the present research work. Beginning from the request received for radiography work, each step of SOP was considered as a separate heading of the event tree in the appropriate sequence. Figures 6.2 and 6.3 given below, show the event tree modeled for calculating the probabilities of occupational and potential exposures when gamma radiography work is carried out in the open field and enclosed installation respectively.

The median values obtained from the Delphi survey, as given in Table 6.2 and the data generated from the fault tree assessment for instruments failure, as described in chapter 5, were utilized for the probability calculations in the present event tree.



Seq#	Probability	Consequence
1	8.968E-001	OE
2	6.777E-003	PE-II
3	9.059E-003	PE-I
4	6.846E-005	PE-III
5	1.100E-002	PE-I
6	8.314E-005	PE-III
7	2.612E-002	PE-II
8	1.679E-002	PE-I
9	1.269E-004	PE-III
10	1.224E-002	NSE
11	1.089E-002	PE-II
12	1.044E-006	PE-I
13	7.888E-009	PE-III
14	2.974E-008	PE-II
15	1.912E-008	PE-I
16	1.445E-010	PE-III
17	1.393E-008	NSE
18	9.365E-003	PE-I
19	7.077E-005	PE-III
20	2.668E-004	PE-II
21	1.715E-004	PE-I
22	1.296E-006	PE-III
23	1.250E-004	NSE

Figure 6.2. Event tree for open field gamma radiography operations



Seq #	Probability	Consequence
1	9.203E-001	OE
2	6.954E-003	PE-II
3	9.296E-003	PE-I
4	7.024E-005	PE-II
5	1.129E-002	PE-I
6	8.532E-005	PE-II
7	9.227E-004	OE
8	6.973E-006	PE-II
9	9.321E-006	PE-I
10	7.043E-008	PE-III
11	1.132E-005	PE-I
12	8.555E-008	PE-III
13	1.677E-002	PE-I
14	1.268E-004	PE-III
15	9.658E-004	PE-II
16	9.684E-007	PE-III
17	1.224E-002	NSE
18	1.089E-002	PE-II
19	1.071E-006	OE
20	8.095E-009	PE-II
21	1.074E-009	PE-I
22	8.117E-012	PE-III
23	1.910E-008	PE-I
24	1.443E-010	PE-III
25	1.100E-009	PE-II
26	1.103E-012	PE-III
27	1.393E-008	NSE
28	9.610E-003	OE
29	7.262E-005	PE-II
30	9.636E-006	PE-I
31	7.282E-008	PE-III
32	1.713E-004	PE-I
33	1.295E-006	PE-III
34	9.865E-006	PE-II
35	9.892E-009	PE-III
36	1.250E-004	NSE

Figure 6.3 Event tree for enclosed gamma radiography operations

6.5 RESULT ANALYSIS AND DISCUSSION

We have used probabilistic safety assessment methodology to carry out risk assessment in the industrial radiography practice in India from operational viewpoint. This research work intended to calculate the probabilities of potential exposure to occupational workers involved with the industrial gamma radiography operations in India. As mentioned earlier, the risk assessment was performed for operating personnel of industrial gamma radiography practice in India for both, the open field and the enclosed industrial radiography operations. The results from that risk assessment exercise were obtained in terms of the probabilities of different exposure categories and are summarized in Table 6.4, given below.

Table 6.4 Assessment results for probabilities of radiation exposure to operating personnel

Exposure Category	Probability of Radiation Exposure	
	Open Field Radiography	**Enclosed Radiography**
Potential Exposure-III	3.506E-04	1.293E-04
Potential Exposure-II	4.405E-02	1.905E-02
Potential Exposure-I	4.639E-02	3.756E-02
Occupational Exposure (OE)	8.968E-01	9.309E-01
No Significant Exposure (NSE)	1.237E-02	1.236E-02

In this regard it is pertinent to note that the International Commission on Radiation Protection (ICRP) has suggested values, probability ranges, for the different categories of such exposures [40]. And, significantly, the probability values for potential exposure obtained from our assessment are within the range of limits suggested by the ICRP. The annual probabilities suggested by ICRP for a sequence of events which leads to normal exposure is 10^{-1} to 10^{-2}, and suggested probability values in the range of 10^{-2} to 10^{-6}, for doses above normal exposure, which may lead to stochastic and deterministic effects. Main contributors for PE-III category of exposures in open field and enclosed radiography have been presented as Pi Charts in Appendix C.

The following important observations were made by us from our results:

I. Analysis of our results show that the probability value of potential exposure in industrial radiography practice in India varies from 10^{-4} to 10^{-2}. The probability for the most severe exposure category (PE-III), which in few of the cases may also lead to deterministic biological effects, is about 10^{-4}, which reflects the fact that the probability of occurrence of very severe accidents in the existing industrial radiography practice is very low, although not negligible.

II. The probability values obtained in our study for non-potential exposures are 94.33E-02 and 90.92E-02 for enclosed and open field radiography operations respectively, which means that in most of the cases radiography devices are operated with due care for radiation safety and the recommended safety procedures are followed by the operating personnel. However, on few occasions the safety procedures look to be getting neglected due to either overconfidence or excessive workload.

III. The maximum value for probability of potential exposure obtained from our assessment is 4.639E-02, which is for the category PE-I for open field radiography scenarios. These exposures are understood to be due to minor deviations in operations from the recommended SOPs.

IV. Our results of this assessment, as given in Table 6.4, clearly indicate that the probability value of each category of potential exposure is smaller in the case of enclosed gamma radiography operations as compared to that of open field gamma radiography. Operations inside the radiography enclosures are considered inherently safe due to the availability of an additional area monitoring instrument and due to the presence of enclosure walls, which are permanent physical barriers for operators to protect themselves from radiation exposure.

V. The results from our study indicate that an industrial gamma radiography personnel in India receives normal occupational exposure in 89.68% and 93.1 % of the cases in the open field and the enclosed radiography practice respectively. The total probability of all types of potential exposures, which has been estimated by us to be 9.0 % and 5.6% for the open field and the enclosed radiography operations respectively. However, it may be noted that in our study the estimated probability of potential exposures in accidental scenarios, which may lead to (in few cases and not in all the cases) health hazards (biological effects) is less than 0.035 % and 0.012 % for the open field and the enclosed installation radiography respectively.

VI. We have used the Probabilistic Safety Assessment (PSA) methodology to perform risk assessment for the industrial gamma radiography practice in India. It is pertinent to note that application of PSA is still very limited for non-nuclear radiation applications. Thus, the feasibility of application of PSA for risk assessment in the industrial radiography practice has been established by this study.

Analysis of our results, in conjunction with the event tree headings, show that the main contributory events for potential exposure in the open field operations are i). The source getting stuck in the guide tube when the device is being operated by an untrained person, and ii) The operating team personnel not maintaining safe distances when the source is in exposed condition. Likewise, for the case of enclosed gamma radiography operations, the major contributory event is the same, i.e., the source getting stuck in the guide tube when the gamma radiography device is being operated by an untrained person. The important and significant results from our risk assessment study have been summarized in table 6.5, which presents the main contributing factors for each category of potential exposure.

Table 6.5. Main contributing factors for each category of potential exposure.

Exposure category	**Open field radiography (relative contribution)**	**Enclosed installation radiography (relative contribution)**
PE-III	Source stuck in the guide tube, when the device is being operated by an untrained person. (36%)	Source stuck in the guide tube, when the device is being operated by an untrained person. (98%)
PE-II	Operating team personnel not maintaining safe distances when gamma source is exposed. (60%)	Skipping the radiation survey of the IGRED before taking it out from the storage. (57%)
PE-I	Device is operated by an untrained person (36.2 %)	Radiography device operated by an untrained person, & not carrying the RSM while entering the enclosure to retract the source (75%)

6.6 RECOMMENDATIONS

The results of our risk assessment study have provided probability values for potential exposures under different operating scenarios to personnel involved in the operation of IGREDs in industrial radiography practice in India. These assessment results would be helpful in risk management, by identifying the areas that contribute significantly to the potential exposure probabilities. Indeed, the important contributory factors have been identified in the study with a view for risk management in the practice, by first identifying them and then working on them to reduce the probabilities of potential exposure. A discussion on some important operational steps that contribute to the potential exposure and the recommendations for corrective actions is presented below.

(i) In our study, the probability for the most severe exposure category (PE-III) in enclosed radiography operations has been calculated to be 1.293E-04. In this probability value, 98% of its contribution comes from the event of the gamma radiography source getting stuck in the guide tube, when the device is being independently operated by an untrained person or trainee. Such type of incidents have been reported in the past, which took place due to inadequate knowledge of the trainee, eventually leading to radiation injury to him. Ensuring that untrained person or trainees do not operate the radiography device by themselves, can reduce the probability of potential exposure, PE-III in enclosed operational scenario by 98%. Thus, Radiological Safety Officers should directly supervise the operation of radiography devices by an untrained person.

(ii) The above mentioned factor is also a significant contributor to the category of PE-III type of exposure in open field radiography scenario. However, this contribution in this case is about 36% of the total probability of PE-III type of exposure in open field radiography operations. Thus, implementation of recommendation made in point (i) above will also significantly reduce the probability of category PE-III of exposure in open field radiography.

(iii) The results from our study show that about 60% of contribution to the potential exposure of category, PE-II, in the case of open field radiography, comes from the event when the operating personnel do not maintain a safe distance from the source, when it is in exposed condition. Generally, permanent shielding for the protection of operator is not available in the case of open field radiography operations. In this class of radiography operations, if depending on the site location, some temporary shielding can be made available, then that would reduce the exposure to the operator. It is thus, recommended that for open field operations all the team members should move away from the source before the actual exposure starts.

In the case of working at heights, there may not be sufficient time for operators to move away from the source due to operational constraints such as small exposure duration of 2-5 minutes, which is not sufficient enough to go down and return to stop the exposure. Also there are not sufficient space so that operator could move to a safe distance. For such cases, the concept of mobile shields can be adopted, where the operator can stand or sit behind these shields to protect themselves. A mobile shield of a combination of lead and steel, of thickness of equivalent of 1.6 cm of lead would reduce the dose to the operator to one tenth of original dose. Also, mobile shielding would be economical as these can be fabricated once and, transported and utilized for various sites. Additional reduction in exposure can be achieved by using collimated exposure.

(iv) In the case of practice of enclosed radiography, lack of use of a portable radiation survey meter for surveying the device has been identified in our study as an important contributory factor, (57% of PE-II and 75% of PE-I type of potential exposures to operating personnel). Since fixed zone monitors are installed in the radiography enclosures due to which sometimes the portable survey meters are not used by the operators. However, the use of portable survey meter is essential in all the scenarios, especially for the radiation survey of the radiography devices. The fixed zone monitor are installed at a distance from the devices and may not be very effective for detection of low levels of abnormal radiations emanating from the IGRED. Hence, the use of portable survey meter should be insisted upon at all the times, whenever a survey is required.

(v) It has also been observed from our present study that although the radiation survey meters are carried by the operators most of the time, they are however not used on several occasions. As analysed in the previous chapter, the unavailability of the fixed zone monitor is much higher as compared to the portable radiation survey meter. In view of this the fixed zone monitor should be considered as a redundant system rather than the replacement of portable surveymeter.The operators should habitually use the radiation survey meter in the field under all the operating conditions.

It is very clear from our study that implementation of the above mentioned recommendations will be very effective in reducing the potential exposure to operating personnel in industrial radiography practice. We observe from our results that most of the contributory factors to potential exposure are due to the negligence of the operating personnel. Our study identifies some important operation related lapses in the practice of industrial radiography, and based on these results, it is recommended to develop a safety culture in the concerned institutions by the RSOs.

6.7 CHALLENGES FOR THE RESEARCH WORK

Risk assessment using the PSA methodology is popular in the nuclear industry, however that is only regarding the reactors and use of PSA for non-nuclear radiation facility is very limited. In general, the operation of any facility or system involves a lot of human actions. Industrial radiography practice also involves several human actions not only for the operation of the radiography devices, but also to ensure radiation safety. Operational risk assessment in the industrial radiography practice requires data for human errors during operations. However, unlike that for nuclear power plants, data for human errors in industrial radiography practice has not been published anywhere. And hence, due to this limitation, application of PSA has not been explored fully for operational risk assessment of industrial radiography practice, and so also for other similar practices that use radioactive sources. It was a challenging task to generate the data of human errors for the present research work.

To determine the final dose to an operator, it is required to consider all the tasks involved in the operation. Also, it is important to assign proper sequence of tasks for the operation, and any difference in the sequence of the event tree would yield a different result for the radiation dose to the operator. Therefore, the event tree sequencing in our study was done very carefully after a lot of brainstorming by the experts, and the concept of categorization of doses was adopted in the study for demarcation between different doses resulting due to different operating sequences.

6.8 CHAPTER SUMMARY

IGREDs are operated manually by the operators for the purpose of radiography exposures. Industrial radiography practice includes several human actions, not only for the operation of the devices, but also for ensuring radiation safety in the practice. Radiography operations are carried out inside radiography enclosures and also in the open field. The enclosed radiography practiced utilizes enclosed installations which are designed and constructed in such a way that the radiation levels outside the enclosures are within the prescribed radiation dose limits for the public. Therefore, these enclosures may be utilized round the clock for radiography operations. However, due to some practical difficulties, radiography work may not be feasible inside the enclosures on some occasions. In such cases, radiography is carried out in the open field by adhering to some safety precautions. Standard operating procedures have been established for the industrial radiography operations for both these scenarios.

The operation of the radiography devices certainly exposes the operators to some amount of radiation. Those exposures are within the stipulated permitted limits for the operators. However, during some operations the amount of radiation exposure to the operator may be more than those expected during normal operations. This category of exposure is termed as “potential exposure”. Thus, potential exposure is an ‘exposure’ which results due to departure from normality. Operational risk assessment has been carried out by us in this study to calculate the probabilities of potential exposure to the operating personnel in industrial radiography practice in India. Since all such ‘abnormal’ exposures are not at the same levels, the potential exposures arising from the operation of gamma radiography have been categorized by us into broadly three classes on the basis of the severity of the exposure, and they are presented in Table 6.3.

The probabilistic safety assessment methodology has been used by us in this study for risk assessment in the operational aspects of industrial radiography practice in India. For our study, event trees were designed for the open field and enclosed radiography scenarios based on the steps of SOP. The steps of SOP followed or disregarded by the operator affect the values of the resultant radiation exposure to the operating personnel. Generation of an event tree for analysis requires input data for human actions and so also the data of the failure of radiation monitoring equipment during the radiography practice. There is no published record for the data for human action in industrial radiography. And this data is not maintained by the operating agencies too. Therefore, the data of human action during radiography practice, had to be generated and it was generated by an expert elicitation method. Two rounds of Delphi survey were conducted for this purpose amongst the Radiological Safety Officers (RSO) of the industrial radiography institutions in India, and data was generated by consensus from those surveys.

The data thus generated was utilized for analysis using event trees. In the event tree analysis considered in our work, "demand of radiography exposure" was considered as an initiating event. Just as the literal meaning conveyed by the phrase, the initiating event is considered in this type of analysis to start a sequence of events which branch out into the different final outcomes. After the initiating event was chosen, the steps of SOP were sequenced properly to design the event tree. Thus, the different human actions performed during the radiography work, which form the different branches of the event tree, decide the eventual resultant dose to the operating personnel. The different resultant outcomes of the analysis were divided into the five different categories of exposures, viz, Potential Exposure-I (PE-I), Potential Exposure-II (PE-II), Potential Exposure–III (PE-III), Occupational Exposure (OE) and No Significant Exposure (NSE).

Our results for risk analysis in the present study found the probability values of the most severe category of potential exposure (i.e. PE-III), which in few of the cases may also lead to biological health effects, to be 3.506 E-04 and 1.293E-04 for the open field and the enclosed radiography operations respectively. Similarly probability of other categories of potential exposures also has been calculated. Our results tell that the probability values of all the categories of potential exposure are significantly smaller in the case of radiography work carried out in an enclosed installation as compared to those of open field radiography operations. These results provide a strong support for performing radiography work in enclosed installations.

Our present study also identifies the different contributing events/scenarios for the potential exposures along-with their relative contribution, and that is significantly useful for the purpose of risk management in the industrial radiography practice. The main contributory factors for potential exposure, as determined in our study, are the occurrences of independent (unsupervised) operation of radiography devices by an untrained person and the radiation survey meters not being used for the survey of the radiography devices. Based on the results of our study, we have made recommendations for risk management in the industrial radiography practice in India. We strongly believe that the implementations of these recommendations would significantly reduce the probability of potential exposure to the operating personnel. Quite significantly, we have established through the present study the feasibility of application of the probabilistic safety assessment method for risk assessment in industrial radiography practice.
