CHAPTER 5

OPERATIONAL ASPECTS & INSTRUMENTS RELIABILITY ASSESSMENT IN INDUSTRIAL RADIOGRAPHY PRACTICE

CHAPTER OVERVIEW

This chapter gives an overview of the operational and safety aspects of the industrial radiography practice. The importance of radiation monitoring instruments has been highlighted in this chapter. Reliability assessment of these instruments has been carried out using fault tree assessment. The different failure rates and the corresponding unavailability of radiation monitoring instruments have been determined in this chapter. The industrial gamma radiography exposure devices are operated manually by the operators several times in a day. Standard operating procedures (SOP) have been developed for them which have been outlined in this chapter. These procedures have been utilized for our risk assessment study. Dose limits prescribed by the national regulatory body for the radiation workers and the public is provided in the chapter. Various accidents which are reported in the industrial radiography practice are outlined, along with the necessity for conducting a risk assessment study.

5.1 OPERATIONAL ASPECTS OF INDUSTRIAL GAMMA RADIOGRAPHY EXPOSURE DEVICE

Accidents that occur in industrial radiography practice may happen due to either, the operational human error or due to equipment failure. Although the design of the industrial gamma radiography exposure devices (IGREDs) is simple, the probability of accidents in the practice of industrial radiography is much higher than that for other practices that use gamma sources for various applications. Several accidents have been reported in the industrial radiography practice which have happened due to ignorance and negligence about the safe operating procedures of the practice [1].

IGREDs are operated manually with the help of a rotatable handle provided in the control unit, to push the source out of the shielding. After the operation, the source is retracted back in the shielded container (source housing) by rotating the handle in the reverse direction. There are finite chances that during the operations, the source may get stuck in the transit location and may not reach the safe shielded condition, leading to accidental exposures. Although, safety features have been provided in the exposure devices which identify the source location, however, the source location can be accurately confirmed only by using appropriate radiation monitoring instruments.

There are finite chances that due to oversight or even overconfidence, an operator may not use a monitoring instrument after a radiography session to check if the source has returned safely back inside the device. Hence, in such cases, and when the source has actually not returned back to the safe shielded location, when the operator lifts the projection sheath containing the radioactive sources by his hands, he would be subjected to excessive radiation exposure. Depending on the source activity and the 'handling' time, this exposure dose may be high enough to cause radiation-induced skin injury or even require amputation of limbs. Other similar accidental scenarios are also possible due to such operational errors. Therefore, it is highly essential for the operating personnel to follow the set safety procedures while operating these devices.

The operation of IGREDs requires proper training, which includes sound familiarization with the radiography exposure devices and their operational and radiation safety aspects. Thus, the radiography devices, which use radioactive sources, should not be operated without proper training.

5.1.1 Dose Limits

Radiation safety of the operator and the other team members is one of the primary concerns during a radiography operation. The radiography exposures in an operation are planned in such a way that the total dose to the operator should not exceed the prescribed limits. In India, the regulatory body i.e. Atomic Energy Regulatory Board, has prescribed the annual dose limits for both, the radiation workers and the public. Table 5.1 summarizes the annual dose limits prescribed in India. The dose received by the operator during an operation is the deciding factor to describe and categorize the resultant operating condition, i.e.

a normal operating condition or an ‘accidental’ condition. The prescribed dose limits are also used for the design calculations of radiography enclosures, wherein it is assumed that operating the IGRED inside the enclosure keeps the radiation dose to the personnel and public present outside the enclosure to within the prescribed limits. And even for the open field radiography, the other scenario of operation, calculations are made based on the workload and area is cordoned-off such that radiation levels outside the cordoned area will remain within the prescribed limits.

Table 5.1 Prescribed annual dose limits for occupational worker and public in India

	Occupational	**Public**
Whole body (effective dose)	20 mSv per year, averaged over defined period of 5 years, with no more than 30 mSv in a single year	1 mSv in a year, averaged over 5 years
Parts of the body (Annual equivalent dose)		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	------

5.1.2 Radiation Monitoring Instruments

Unlike other hazardous materials, ionizing radiation cannot be sensed by our body or body parts/organs. Hence, we require radiation monitoring instruments to detect the presence of ionizing radiation. One of such instruments is the area monitoring instruments, which are used to detect radiation in the (working) environments. In the case of industrial radiography practice, two types of area monitoring instruments, namely the portable radiation survey meters and the fixed area monitors are used. Most of the monitoring instruments, for detection of ionizing radiations, for industrial radiography practice are based on the

Geiger-Muller (GM) counters. A GM counter has advantages of having a rugged design, required sensitivity for survey actions, small size and low cost. A variety of GM based monitoring instruments are available. Figure 5.1 shows some of the GM based instruments. The Portable radiation survey meters are handy and light weight, which should always be used by the operator during radiography operations. Fixed area monitors (or zone monitors) are used in the enclosed installations and these are fixed on the enclosure walls. These fixed area monitors give information about the radiation levels existing inside the enclosure, before the operator enters the enclosure.

Figure 5.1 Portable radiation survey meters and fixed zone monitors

5.2 PROBABILISTIC SAFETY ASSESSMENT

Prospective safety assessment of the practices involving hazardous materials, like the radioactive sources is essential for safety enhancement of the operators. As per the International Atomic Energy Agency (IAEA), the safety assessment of radiography practice should include the radiation risk from routine use, besides the probability of potential accidental exposures to radiography personnel [35]. For proper risk management, all the contributing factors that may lead to potential exposures need to be identified. Studies like our present one are very important for this, and the results of such studies are useful for the decision-making processes of engineered control measures, which are required for developing and updating standard operating procedures for the operators.

Various methodologies are used for risk assessment of the systems involved in the handling of hazardous materials, which include both the types; the deterministic as well as the probabilistic ones. The Probabilistic Safety Assessment (PSA) or Probabilistic Risk Assessment (PRA) method has been utilized for the present research study. The PSA is one of the important, effective and well-established techniques to quantify the risk measures. The PSA has several advantages over the other conventional deterministic techniques. The conventional techniques are based on single point estimates, that consider a particular single failure scenario and the result of the assessment is a single point value of exposure. On the other hand, in PSA all possible causes that result in a single failure are analyzed at a time (n: 1). Further, the PSA utilizes all possible failure scenarios for each failure modes. The PSA, thus, utilizes distributions of data from which multiple points are selected as inputs to the exposure equation over the course of multiple reproductions. As a result, the output of a probabilistic assessment is a distribution of potential exposure values. Results of PSA also provide relative contributions of each component/event failure, and therefore, one can prioritize the safety requirements and can decide the area where available resources can be applied more effectively. The PSA results also provide a common language to understand the level of risk involved in a practice, which is easier to communicate to the society.

Due to the aforementioned qualities, the PSA is being used for evaluating the existing (old) and the new nuclear power plants. However, very limited PSA studies have been carried out for risk assessment of non-reactor radiation facilities. The International Commission on Radiological Protection and International Atomic Energy Agency emphasizes the application of PSA for non-reactor radiation & nuclear facilities [39-41].

5.2.1 Fault Tree & Event Tree in PSA

The Probabilistic Safety Assessment (PSA) technique is able to answer as to how likely some events are going to lead to undesirable consequences, or as to what are their probabilities of occurring. Such questions are generally answered using the Boolean algebra and the logic gate methodology. A model can be developed using them and some probabilistic and/or statistical methods can be used to analyze and quantify the results. Generally, the Boolean logic methods used for such models include inductive methods such as the event tree analysis (ETA), and the deductive methods such as the fault tree analysis (FTA).

It is pertinent to note that in such assessments, if the probability of an event is known well from the previous experiences, and if the uncertainty of the data is low, then the statistical actuarial data can be used for them. However, if the failure data are very sparse, or if the uncertainty in the failure data is considerably high - which may be due to lack of system failure experiences too, then the probabilistic failure models should either be developed with deductive logic methods like the fault tree analysis, or with the inductive logic methods like the event tree analysis, or with the reliability block diagrams.

Fault Tree Analysis

The fault tree analysis (FTA) is a technique for risk and reliability assessment. It is one of the analytical logic techniques, which are used in the system reliability and operations research. The FTA was first used by Bell Telephone Laboratories in 1962, for its assignment for the United States Air Force. Later on, the FTA got popularity amongst other industries too, like those of aerospace, nuclear and chemical.

The FTA is basically a deductive method which is used to determine various combinations of system failures and human errors, which may lead to undesired outcomes, also referred to as top events of the system. The deductive method starts with a general conclusion and attempts to find the exact causes of the conclusion reached, by designing a diagram considering different failures and appropriately using logic gates. The diagram is referred to as a fault tree. And the approach is, what is known as, a top-down approach.

The main objective of the FTA is to recognize the potential causes of failures before the actual failure occurs. The FTA can also be utilized to estimate the probability of the uppermost event utilizing some statistical or analytical methods. The FTA calculation requires system reliability and maintainability data, such as the failure rate, the failure probability, and the repair rate. The FTA results can provide important inputs for areas of improvement of the system safety and reliability.

Event Tree Analysis

The Event Tree Analysis (ETA) is a PSA technique which is used to identify the consequences which can result from the occurrence of a potentially hazardous event(s). The ETA was first applied for risk assessments of nuclear power plants, and later on other hazardous industries like offshore oil production, transportation and chemical industries also adopted this technique.

The outcomes of an event tree analysis may be fatalities or some industry specific hazards. An Event tree allows the quantification of each of the outcome in terms of frequency or probability of occurrence. The triggering event for the potential hazard is termed as the "initiating event". The ETA is a forward logic or inductive technique, which observes all possible responses from the ‘safety systems’ or ‘safety barriers’, beginning with the ‘initiating event’, and proceeds from left to right in the diagram. Each ‘safety system’ in accordance to its response to the initiating event is branched in the event tree either as "failure" or "success". And the final outcome is likewise classified based on the response of all the safety systems/barriers. To perform this analysis, data are required to be fed to each of the headings of the event tree. It is worth mentioning that for some of the systems or subsystems, this mentioned data may be calculated from a fault tree analysis and its results can then be fed to the event tree.

The present research work has been carried out to evaluate the probabilities of potential exposure to the operating personnel of IGREDs in India. The risk assessment has been performed with the PSA methodology using the event tree and fault tree analyses. The failure of the monitoring instrument(s) and the exposure devices are also important factors to decide the resultant radiation exposure dose to the operator, and hence, have been considered for the present risk assessment study.

5.3 RELIABILITY ASSESSMENT FOR RADIATION MONITORING INSTRUMENTS

Radiation monitoring instruments are essential to determine accurately the exposure (radiation) levels in a specific area. Portable Radiation Survey Meters (RSM) and fixed area (zone) monitors are used for this purpose for the industrial radiography practice. These instruments have an important role in ensuring radiation safety during radiography operations. Failure of these instruments during radiography work may lead to potential exposures. For example, such potential exposure situations can occur when the radioactive source gets stuck in the guide tube of the exposure device. And hence, to detect such occurrences, radiation surveys should be performed for the equipment and the surrounding area to ensure the proper retraction of the source in the shielded housing. In spite of various safety features provided in the IGREDs, the exact source position, during operational procedures and otherwise, can be confirmed only with the help of the radiation monitoring instruments. Failure of radiation monitoring instruments may thus lead to severe accidental conditions. Since these radiation monitors are electronic instruments, there are finite possibilities for failure of these instruments during their use. Therefore, the reliability of these instruments is also an important factor in their risk assessment.

Failure data for these radiation monitoring instruments is, thus, also required as one of the important inputs for operational risk assessment. However, failure data of such instruments have not been published in the literature. Therefore, the required failure data for our study were generated using a fault tree analysis.

The Radiation monitoring instruments consist of various electronic components. Fault tree analysis of radiation monitoring instruments thus requires the failure data of each of these electronic components. For the purpose of this research work, it was not feasible to observe the behaviors of the population of each of the electronic component for a long time to arrive at their failure rates, and hence, data from secondary sources were utilized.

An extensive literature survey was carried out to collect the failure data of the different parts/components of the radiation monitoring instruments. This data was collected from different internationally published data sources, as shown in Table 5.2 which also shows their references. These data were used for fault tree assessments, for the calculation of failure rates of radiation monitoring instruments.

Table 5.2 Component failure data for radiation survey meter and gamma zone monitor

Sr. No	Failure Type	Failure Rate/ Probability	Data Source [Reference]
1	Electronic circuit failure	6.5E-10/hr.	MIL-HDBK-217F [61]
2	GM tube failure	1.0E-5/unit-hr.	INL/EXT-13-29336 [62]
3	Battery failure	1.5E-6/hr.	IAEA-TECDOC-508 [63]
4	Failed to reset	3.0 E-3/h	NUREG-CR-1278 [64]
5	Wrong alarm level set	3.0 E-3/hr.	NUREG-CR-1278 [64]
6	Electric supply failure	2.23E-4/hr.	IEEE-493-1997[65]
7	Very high radiation field present	1.0E-5/hr.	Assumption based on experience
8	Adverse weather conditions	1.0 E-6/hr.	

5.3.1 Fault Tree Analysis

Fault tree analysis (FTA) has been carried out to generate the failure data of the radiation monitoring instruments. Fault trees have been designed for the portable radiation monitors (or RSM) and the fixed zone monitors. Figures 5.2 and 5.3 given below show fault trees for calculation of failure rates for the radiation survey meters and the fixed zone monitors respectively, when their intended function (radiation level measurement) is demanded. As mentioned earlier, the FTA considers all the individual components of the monitoring instrument and their failures for the calculations.

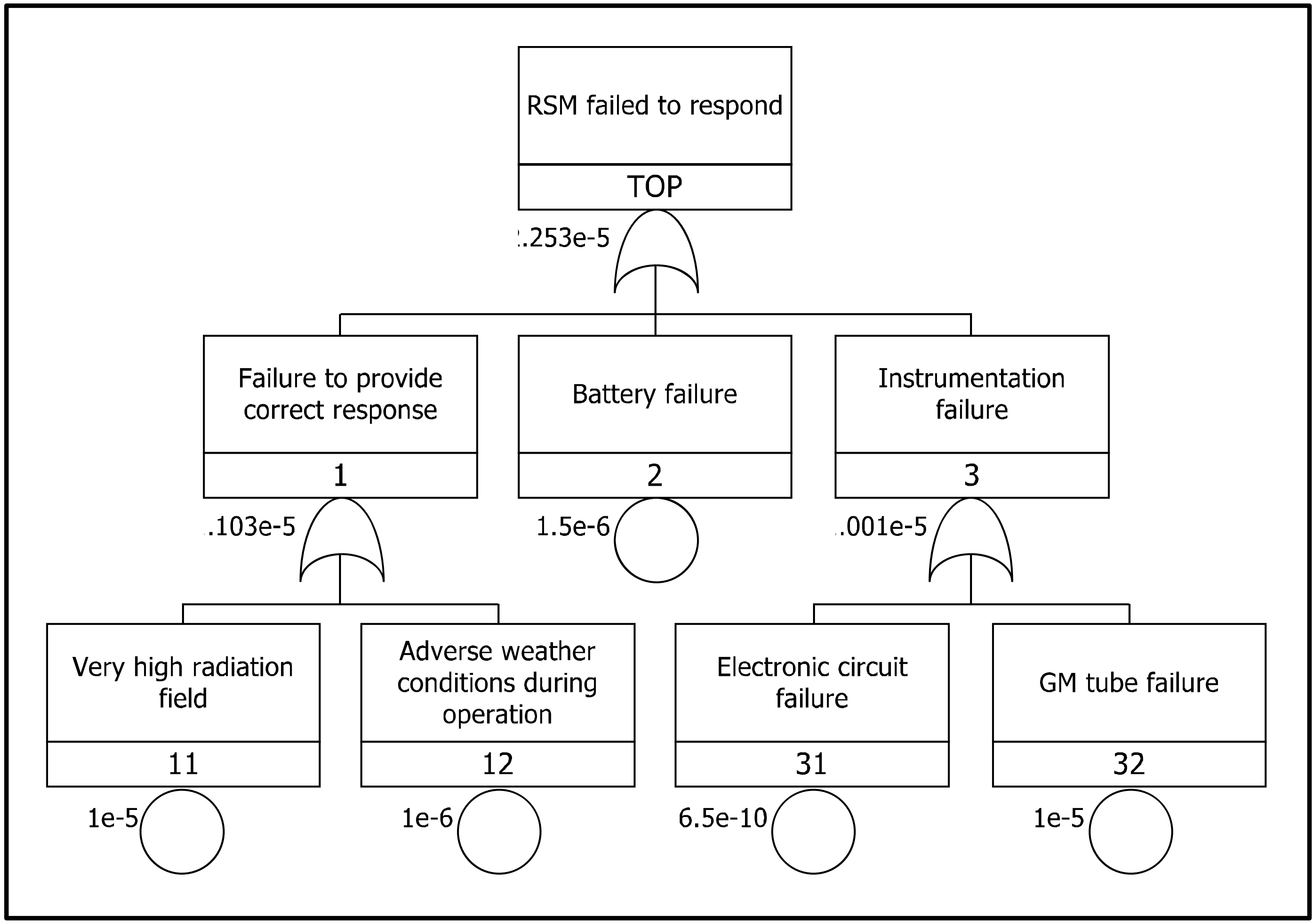

Figure 5.2. Fault tree analysis for failure of portable radiation survey meter

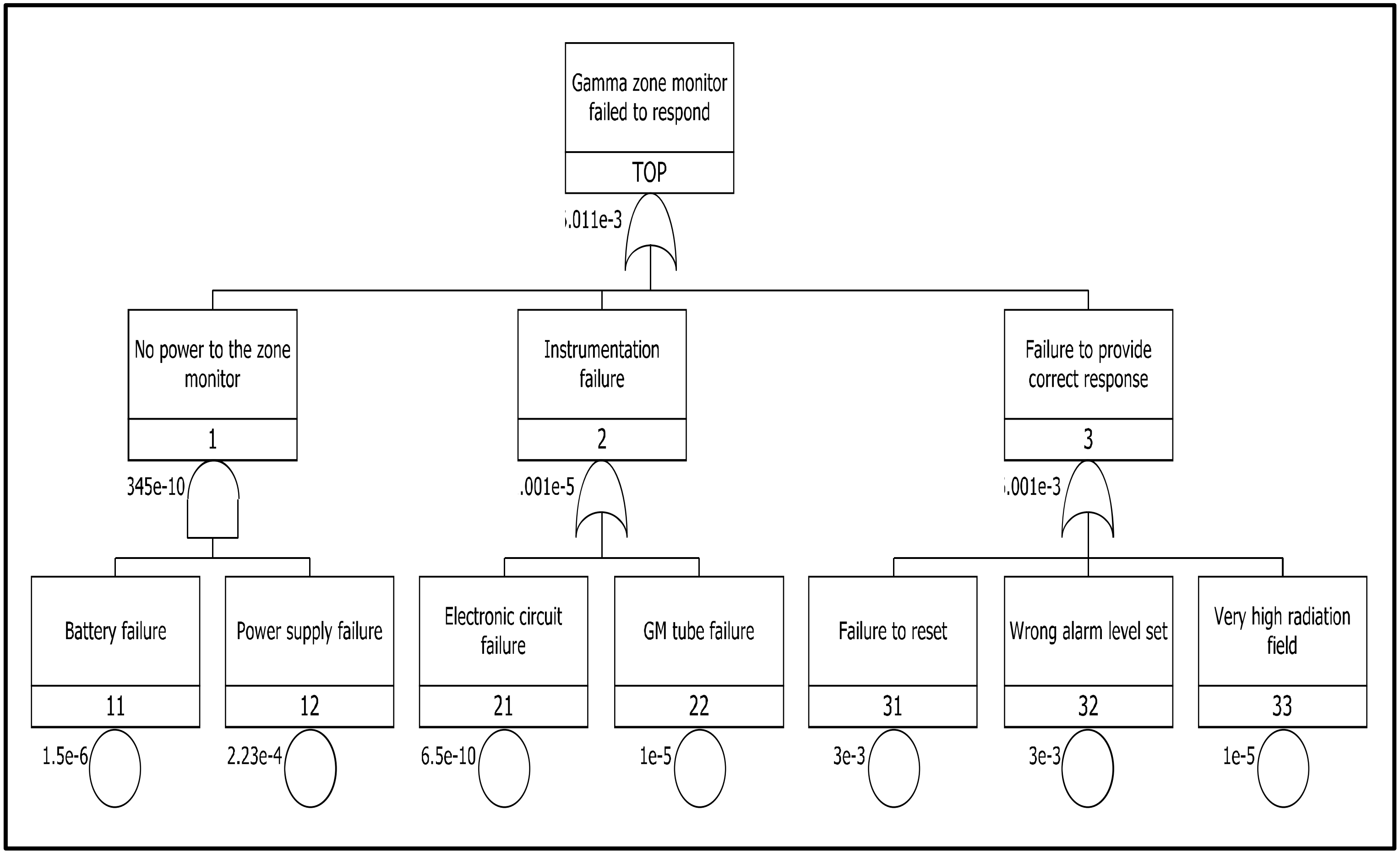

Figure 5.3. Fault tree analysis for failure of fixed gamma zone monitor

5.3.2 Reliability Assessment Results

The failure rates of the radiation monitoring instruments calculated from the FTA in our studies are as given below:

Instrument	Failure rate (λ_m) (per hour)
Radiation Survey Meter (Portable)	2.253E-5
Gamma Zone Monitor (Fixed)	6.011E-3

If the radiation monitoring instrument fails during a radiography operation, these instruments cannot be repaired or brought back to the functional state in the time interval of one exposure cycle which is few minutes. Therefore, for the unavailability calculation, RSM and gamma zone monitors have been considered as operating non-repairable component.

(Non-repairable items are components or systems such as a light bulb, transistor, rocket motor, etc. Their reliability is the survival probability over the items expected life or over a specific period of time during its life, when only one failure can occur).

Unavailability of operating but non-repairable components is calculated as ;

$$Q = 1 - \frac{1}{\lambda_m T}(1 - e^{-\lambda_m T}) \quad \text{Eq. (1)}$$

≈

$$Q = \frac{1}{2}\lambda_m T_m \qquad \text{Eq. (2)}$$

Where λ_m is operating failure rate, and T_m is the mission time (the time when the operation of equipment is demanded) [66]. T_m, the average time during an exposure cycle when the radiation monitoring instrument is required to be in operating condition, has been considered for the purpose of our calculations to be 6 minutes. The values for 'Unavailability' of radiation survey meter and gamma zone monitor have been calculated using equation 2 given above. The values of λ_m for the calculations have been obtained using fault trees, as described above. The corresponding values for 'Unavailability' for the two types of monitoring instruments were obtained in our calculations, and are given in the table presented below:

Instrument	**Unavailability (Q)**
Radiation Survey Meter (Portable)	1.126 E-6
Gamma Zone Monitor (Fixed)	1.001E-3

The results obtained by us indicate that the failure rates and the 'Unavailability' values for the fixed area monitors are more than those for the portable radiation monitors, which we consider is mainly due to the intervention required for the former instrument each time it is used; for resetting it and for setting a radiation level above which the instrument sends warning signals. The 'Unavailability' data generated by us for the monitoring instruments using the FTA was further utilized for operational risk assessment using event tree analysis, and is discussed in Chapter 6 of this thesis.

5.4 OPERATING SCENARIOS IN INDUSTRIAL RADIOGRAPHY PRACTICE

Industrial radiography operations are generally performed inside enclosed installations. These installations are designed and constructed in such a way that the radiation levels outside them are within the dose limits permissible for the general public. The enclosed installations allow round the clock radiography operations, without disturbing other activities in the vicinity, and without worrying about the occupancy around the enclosure. However, on some occasions, radiography work is not feasible inside an enclosure because of various reasons like large size of the specimen to be radiographed, a temporary job at an erection site where work will not continue in future etc. In such cases, the radiography operation is carried out in open field. During open field operations, appropriate safety measures have to be adopted for the workers as well as the public. The safety measures include cordoning off the concerned area, working in the night time when the human occupancy of the area is small, use of collimators etc. Figure 5.4 given below, shows a schematic diagram of the open field radiography operations. It may be observed that relatively more human interventions are involved in open field radiography practice, to ensure radiation safety, like estimating the cordon off area on each occasion depending on the workload, the source activity and surrounding occupancy.

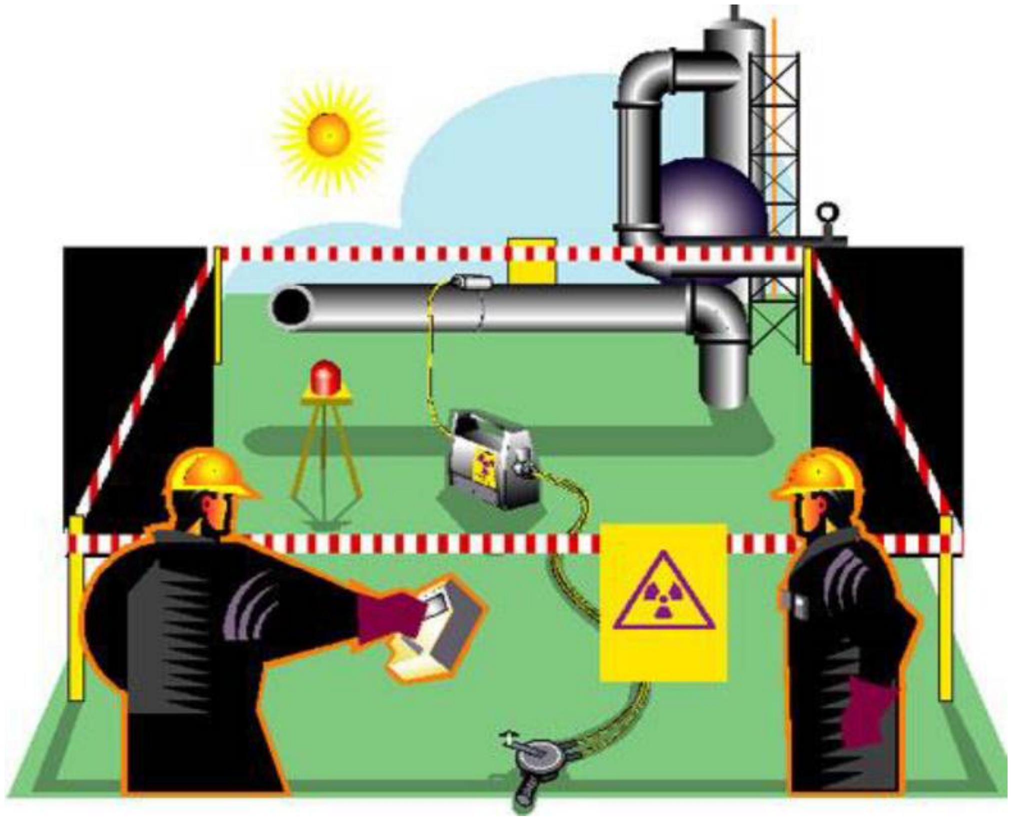

Figure 5.4. Schematic diagram of open field radiography

5.4.1 Standard Operating Procedure for Open Field Radiography Operations

Like for any other industrial practice, some Standard Operating Procedures (SOP) have been established for both, the enclosed and the open field radiography operations. It is expected that if all the steps of SOPs are followed diligently during radiography operations, unusual incidents due to human errors may be avoided. Several conscious human actions are involved, to ensure radiation safety during an open field radiography operation. The following are the sequential SOP steps for open field radiography.

1. The radiography operation should begin with first obtaining the Radiation Survey Meter (RSM), which should be in good working condition. The functionality of RSM should be ensured, including battery check.

2. After this, the operator and all other radiography team members must obtain their personal monitoring badges and pocket dosimeters.
3. The operator or the team member then must go to the source storage room where the radiography devices are stored. They should carefully monitor the radiation levels around the device with the help of RSM to confirm the safe position of the radioactive source inside the ‘shielding’.
4. Next important step is to safely transfer the device to the actual radiography site using suitable means of transport.
5. To cordon off the concerned area using ropes with warning flags. Warning lights with audio signal also to be used to caution the public, especially during night hours.
6. Careful inspection of the job to be radiographed must be done and preparation of radiography tasks like fixing of the films and mounting of the guide tube at desired location to be carefully done.
7. The next step includes connecting the guide-tube and the control unit to the exposure device to expose the source for operation.
8. The device to be operated by rotating the handle provided in the control unit. The device should be operated only by a trained person (Radiological Safety Officer (RSO)/certified radiographer).
9. When the source is completely exposed, the operator and all other team members are required to move to a safe distance, outside the cordoned area to avoid unnecessary radiation exposure.
10. The concerned responsible person (RSO/Radiographer) should verify the radiation levels outside the cordoned off area using a RSM, to check for the safety of the cordoned area.
11. Once the exposure time/operation is over, the operator should proceed towards the control unit to stop the exposure. This time the operator shall carry the RSM along to monitor the radiation levels.
12. The radiographer should rotate the control unit handle properly and adequately to retract the source fully into the device.
13. The operator must then immediately survey the guide tube and exposure device with RSM to confirm the safe retrieval of the source into the shielded position.

14. The above steps to be repeated for further operations/exposures, if required,
15. Else, disassemble the guide tube and the control unit properly, and transfer back the device to a safe and secured storage room.

5.4.2 Standard Operating Procedure for Enclosed Radiography Operations

Properly enclosed installations are designed and constructed considering the maximum estimated source activity and the workload, for enclosed radiography operations. The radiography operations inside the enclosure are considered safer than the open field radiography operations because of the concrete shielding provided for the protection of operators and the general public in the former. Also, these enclosures have permanently installed area monitoring instruments, which are used in addition to the portable radiation monitoring instruments. However, negligence during operation may cause accidents in enclosed radiography operations also. Following are the sequential SOP steps for industrial radiography work in enclosed installations.

1. To begin the radiography operation first obtain a Radiation Survey Meter (RSM), which should be in good working condition. The functionality of RSM should be ensured, including doing a battery check.
2. The Operator and all other team members must then obtain their personal monitoring badges and pocket dosimeters.
3. Thereafter the operator or a team member may go to the source storage room to obtain the required radiography device. The personnel should carefully monitor the radiation levels around the device with the help of the RSM to confirm the safe position of the source; inside the shielding.
4. Next (important step) is to safely transfer the device to the radiography enclosure using suitable means of transport.

5. A functional zone monitor (fixed) should be present in the enclosure to monitor the radiation levels inside the enclosure. Switch "ON" the zone monitor, before entering the enclosure with the radiography device.
6. The operator must inspect the job to be radiographed, and prepare the job for radiography, like fix the films and mount the guide tube at the desired location.
7. The operator should connect the guide-tube and the control unit to the exposure device to expose the source.
8. Before starting the exposure, the ‘search’ operation should be performed in the enclosure to ensure that all people have left the enclosure before actual exposure starts.
9. The operator should operate the device by rotating the handle provided in the control unit. The device should be operated only by a trained person (Radiological Safety Officer (RSO)/certified radiographer).
10. Once the exposure/operation is over, the operator should proceed towards the control unit to stop the exposure. This time the operator shall be carrying a RSM to monitor the radiation levels.
11. The operator should rotate the control unit handle properly to retract the source into the device.
12. The operator should immediately survey the guide tube and the exposure device with RSM to confirm the safe retrieval of the source into the shielded position.
13. The above steps to be repeated for further operations/exposures, if required,
14. Else, disassemble the guide tube and the control unit, and transfer the device to a safe and secured storage room.

5.4.3 SOP for Risk Assessment Study

As mentioned in the above, Industrial radiography is being carried out in two different scenarios i.e. open field radiography and enclosed radiography. The previous two sections describe in detail the standard operating procedures developed and practiced for each of these scenarios. During the present research work, risk assessment was carried out for the radiography operations performed in both of these scenarios. The steps of SOP, given above, followed by an operator and the team members were considered for accidental sequencing for the risk assessment study. A resultant category of exposure to the operator was assigned, based on this SOP sequencing, which is described in detail in chapter 6 of this thesis.

It is noteworthy, that some of the steps of SOP described in sections 5.4.1 and 5.4.2, whether followed or not, will not affect the level of radiation exposure received by the operating personnel, viz, the use of personal monitoring badges and fixing the films on the job to be radiographed. Therefore, considering these steps for calculation of exposure probabilities will give erroneous results. Hence, these steps are not considered for accidental sequencing in the present research work. The steps of SOP which have been utilized for the risk assessment in the open field and enclosed installation radiography are presented in figures 5.5 and 5.6 respectively.

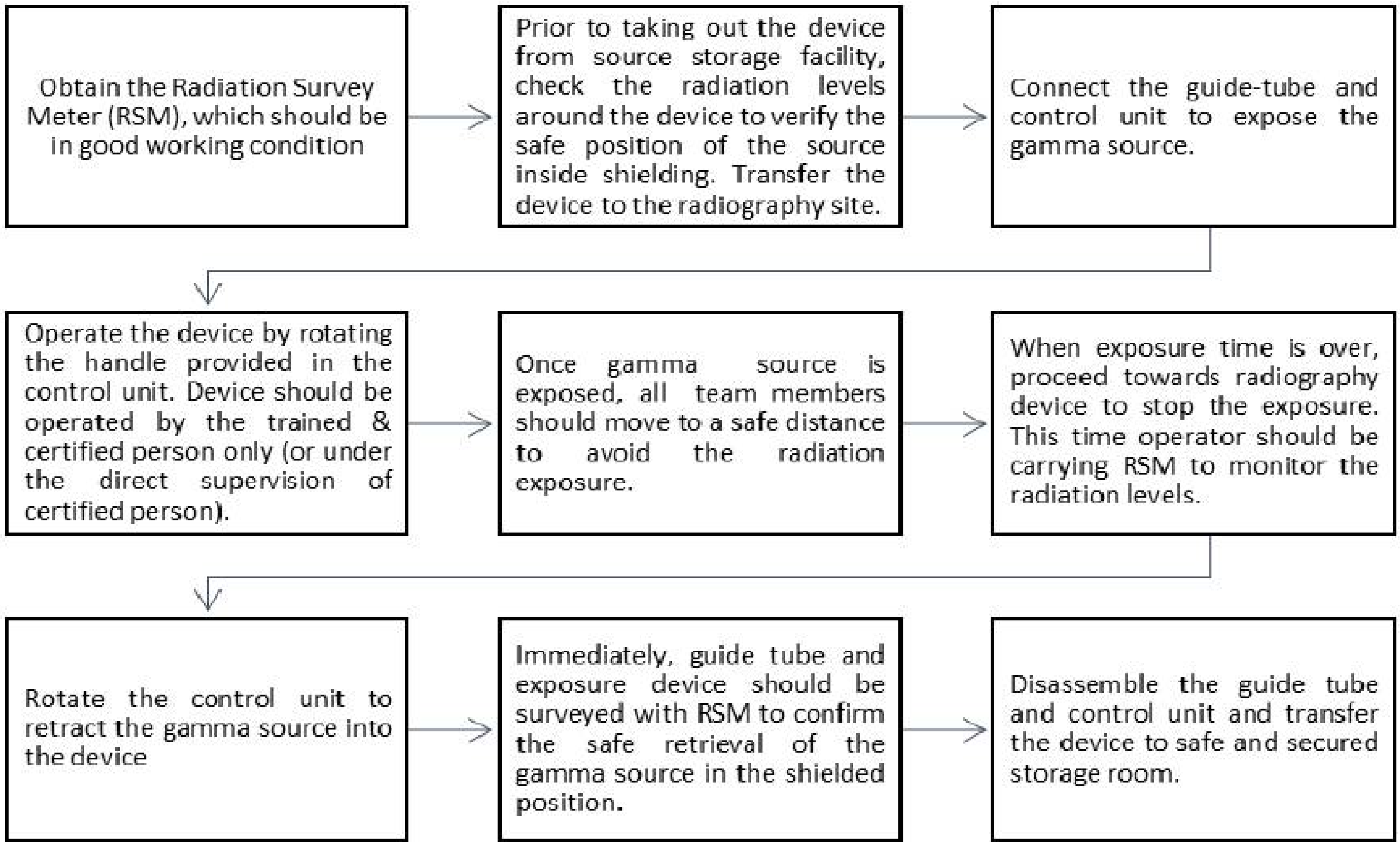

Figure 5.5 Standard operating procedures for industrial gamma radiography operations in open field

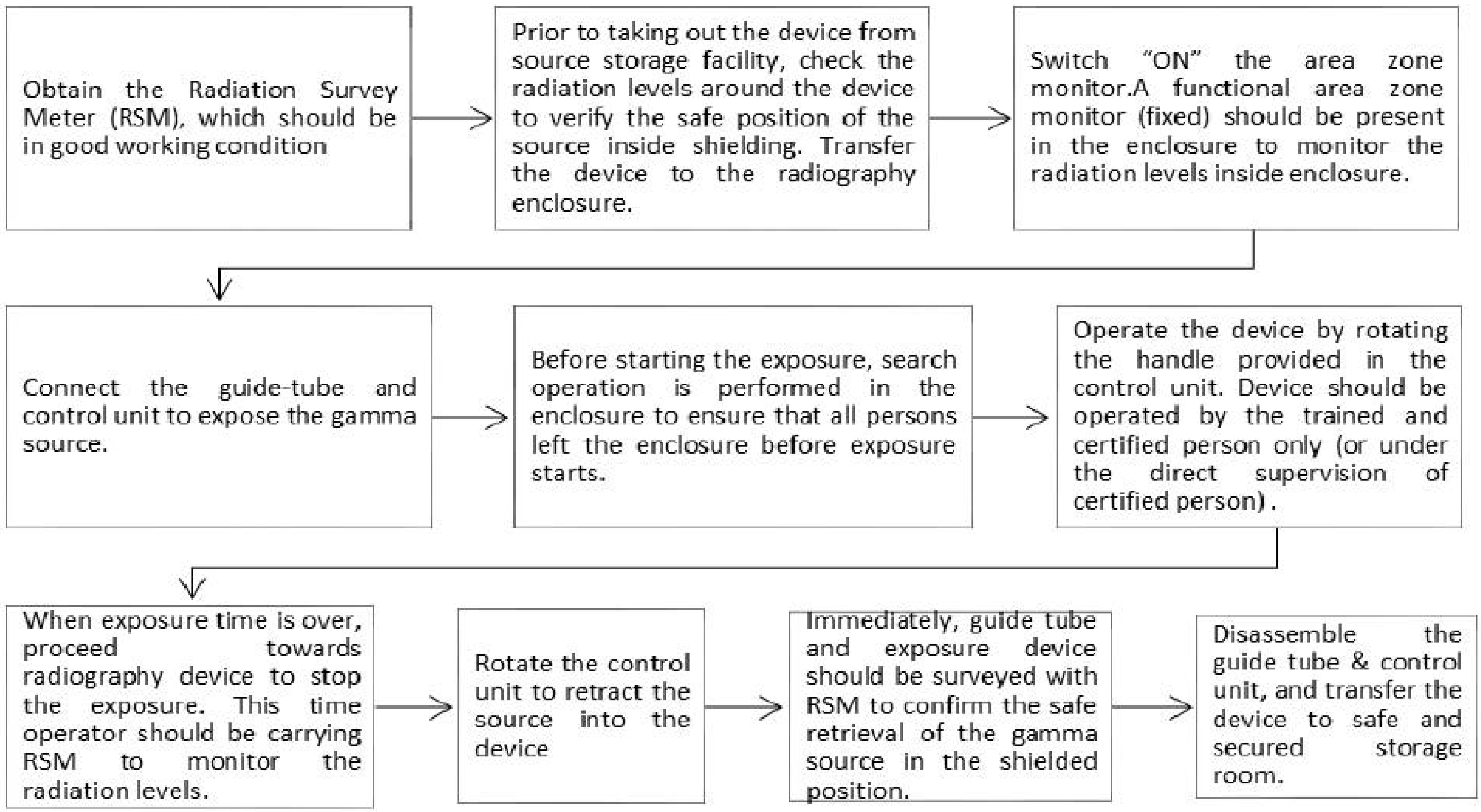

Figure 5.6: Standard operating procedures for industrial gamma radiography operations inside enclosed installation

5.5 COMMON REPORTED INCIDENTS IN INDUSTRIAL RADIOGRAPHY PRACTICE

Inspite of the precautions taken, several accidents have been reported in the past in industrial radiography practice in India, and internationally too. These accidents occurred due to equipment failures and operational errors. Some of the incidents/accidents scenarios reported in Industrial Radiography practice are presented below [1]:

i. Over exposure to the operating personnel due to negligence in operation.
ii. Source stuck in the guide tube during operation leading to excessive exposure to an operator.
iii. ‘Radiation’ syndrome/sickness to untrained person.
iv. Chest injury resulting from lack of training.
v. Death caused by the alleged mishandling of radiographic sources.
vi. Loss of radiography source leading to unintended exposure to a member of the public.

Hence, it is clear that risk management is required to be undertaken during handling and operation phases of industrial radiography to minimize such incidents. To prevent accidents, the first step is to carry out a risk assessment to identify the main contributory factors, along with their relative contributions to the accidents. This will help in prioritizing the actions for risk management.

5.6 CHAPTER SUMMARY

This chapter discusses about how accidents in the industrial radiography practice can occur due to operational errors. The functioning of the IGREDs, by design, requires manual operation through a remotely held control unit. In this, principally, the gamma source is brought out of the shielded position for exposure, and again retracted back into the shielded condition after operation, with the help of a handle provided in the control unit. These operations are repeated several times in a day. Negligence in operation or a human error can result in a radiation incident/accident. Dose limits for exposure to ionizing radiations have been prescribed by the regulatory agencies for both, the radiation workers and the public. Radiography operations are planned in such a way that the dose to the operator and the public remain much less than the prescribed dose limits.

In spite of the various safety features provided in the IGREDs, the exact location of the source during operational procedures can be confirmed only with the help of the radiation monitoring instruments. And, unlike other hazardous materials, radiation cannot be sensed by our body organs. The ambient radiation and the leakage radiation levels around the radiography devices are monitored by handheld radiation survey meters. Fixed area monitors are installed permanently inside the radiography enclosures, and are used to identify the radiation levels inside the enclosed areas. Failure of radiation monitoring instruments May thus, lead to severe accidental conditions. Therefore, the reliability of these instrument are an important factor in the risk assessment procedures for industrial radiography practice. Risk assessment for industrial radiography practice, undertaken in the present research work, has been carried out using the Fault Tree Analysis (FTA) technique for the reliability assessment of the instruments used in the practice The failure rates obtained from our studies using the FTA for the portable radiation survey meter and the fixed zone monitor were 2.253E-5 and 6.011E-3 per hour, respectively. The corresponding 'unavailability' values calculated from these failure rates were 1.126 E-6 and 1.001E-3, respectively for the portable survey meter and the fixed zone monitors.

Radiography operations are carried out both, inside the radiography enclosures, as well as in the open fields. The radiography enclosures are designed and constructed in such a way that the radiation levels outside the enclosures do not exceed the prescribed permissible dose limits for the public. This allows round the clock radiography operations inside the enclosure without worrying about the public occupancy outside. On the other hand, radiation safety in the open field radiography is ensured by adopting safety precautions, such as cordoning off the area and by the use of beam collimators. Standard operating procedures (SOP) have been developed and are followed for radiography operations performed inside the enclosures, as well as in the open field radiography. It is understood that if all the steps of SOP are followed, then the accidents due to operational errors will be negligible.

Several accidents in the industrial radiography practice have been reported worldwide, which include radiation injury and death in some cases. Risk management in the industrial radiography practice is required to prevent such accidents. Risk assessment is the first step for risk management. Risk assessment in the industrial radiography practice has been carried out in the present research study from an operation point of view too. For this, the different steps of SOP have been considered for accidental sequencing, which lead to different categories of doses to the operating personnel. Thus, all the important steps of SOP, which directly or indirectly affect the resultant exposure to the operating personnel have been shortlisted for risk assessment.
