# STUDY ON THE PERFORMANCE EVALUATION OF INDUSTRIAL RADIOGRAPHY FACILITIES VIS A VIS OPTIMISED SAFETY AND SECURITY

THESIS SUBMITTED
BY

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DOCTOR OF PHILOSOPHY (Engineering)

PRODUCTION ENGINEERING DEPARTMENT
FACULTY COUNCIL OF ENGINEERING & TECHNOLOGY
JADAVPUR UNIVERSITY
KOLKATA - 700 032, INDIA

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# STATEMENT OF ORIGINALITY

I, Manas Kumar Pathak, registered on September 1, 2016 do hereby declare that this thesis entitled “STUDY ON THE PERFORMANCE EVALUATION OF INDUSTRIAL RADIOGRAPHY FACILITIES VIS A VIS OPTIMISED SAFETY AND SECURITY” contains literature survey and original research work done by the undersigned as a part of doctorate studies.

All information in this thesis have been collected and presented in accordance with the existing academic rules and ethical conduct. I declare that as required by these rules and conducts I have fully cited and referred all materials and result that are not original to this work.

I also declare that I have checked this thesis as per the “Policy on Anti Plagiarism, Jadavpur University, 2019”, and the level of similarity as checked by iThenticate software is 4 %.

Date: 15/09/2023

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Manas Kumar Pathak

Certified by Supervisor(s): (Signature with date and seal)

Professor (Dr.) Soumya Sarkar,

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## CERTIFICATE FROM THE SUPERVISOR

*This is to certify that the thesis entitled* ***"STUDY ON THE PERFORMANCE EVALUATION OF INDUSTRIAL RADIOGRAPHY FACILITIES VIS A VIS OPTIMIZED SAFETY AND SECURITY",*** *submitted by Sri Manas Kumar Pathak, who got his name registered on September 1, 2016 for the award of Ph.D. (Engg.) Degree of Jadavpur University, is absolutely based upon his own work under the supervision of Prof. (Dr.) Soumya Sarkar and that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.*

15/09/23

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## PREFACE

Industrial Radiography (IR), one of the beneficial applications of ionising radiation, possess risks to the occupational workers if proper safety measures are not taken for handling of the device. Also, security is of paramount importance for facilities dealing with industrial gamma radiography exposure device (IGRED) as serious injury can occur to the members of the public due to theft or loss of the device containing radioactive source. Though many improvements on safety and security have been done for design, storage and operation of the device still unusual incidents like accidental exposure causing injury to radiographers, theft of device containing radioactive source occur some times. These incidents establish the fact that existing safety and security measures are not adequate to counteract the risks associated in handling the device particularly for portable IGRED. Accordingly, a detailed research has been carried out to identify the gap areas in the present safety & security systems of industrial radiography facility and to find out solutions to these problems through design and development of suitable device/system. The whole research work has been brought out in seven chapters in a well-designed manner including exhaustive review of literatures of the past.

Chapter-1 describes the working principle of x-ray based, source based and accelerator based radiography equipment, classification of radiography installation, hazards involved in handling different types of radiography equipment.

Chapter-2 identifies the gap areas in the existing safety and security system of IR facilities, past research carried out in these areas, research objective and scope of research.

A detailed safety performance assessment of different IR facilities operating in India has been carried out with respect to personnel dose received and global comparison, regulatory inspection findings, safety performance indicator values and unusual occurrences happened. Probability of occurrence of such unusual occurrences have also been calculated. All these have been discussed in chapter 3.

An IoT based radiation monitoring system for industrial radiography has been designed and developed for continuous and real-time measurement of radiation level during operation of the radiography equipment. The system has also provision for radiation data storage on cloud and analysis of the data. Details of the same has been presented in chapter 4.

At present, all the portable IGREDs are operated by manual cranking from a distance. Sometimes, due to unavailability of enough space for operation of the device from a distance like that of inside of a vessel or tank, operators get accidental radiation exposure. In order to solve this problem, automated cranking operation of a portable IGRED has been done using stepper motor and chain sprocket mechanism. ROLI-3 device has been selected for the same as it is one of the commonly used device in India. Details of the work with test results have been discussed in chapter -5.

Theft of portable IGRED particularly from an unmanned location like storage room has been identified as a potential hazard for facilities handling the device. Existing security system does not take care of early detection and notification of theft incidence. Hence, an advance theft detection system has been designed and developed using microcontroller and accelerometer for portable IGRED. All the details have been presented in chapter -6.

Finally, summary of observations & general conclusions of the whole research work have been drawn in chapter-7.

A detailed list of references used during the research work and thesis preparation has been listed in bibliography section.

**ACKNOWLEDGEMENT**

The author wants to express his sincere thanks to his thesis supervisor, Dr. Soumya Sarkar, Prof., Production Engineering, Jadavpur University (JU) for his valuable advice, guidance, constant help, support and encouragement at every stage of progress of this thesis work and also to other teachers of Production Engineering for their valuable guidance.

The author gratefully acknowledges the management of Atomic Energy Regulatory Board, Mumbai, India for giving permission to carry out this research work in Jadavpur University.

The author also expresses his gratitude to the radiography facilities named M/s, Royal Engineering Inspection, Medolab Scientific for their support and permission to carry out the experiments with the ROLI-3 IGRED device.

Special thanks are due to the Management of DGT Engineers, Kolkata who have helped in fabrication of different components for automated cranking operation of portable industrial gamma radiography exposure device.

The author is very much grateful to his father late N. R. Pathak who always motivated and encouraged to carry out research. The author also sincerely thanks his wife Mrs. Archana for her continuous support, encouragement, company and patience during the course of this work.

At last, the author wants to express his sincere thanks to all those, who were involved directly or indirectly in this research work and provided all supports to the author making this research work a success.

(Manas Kumar Pathak)

**BIOGRAPHY**

The author, Manas Kumar Pathak, Son of Lt. Nalini Ranjan Pathak & Lt. Sandhya Rani Pathak was born on January 7, 1972 in Village: Fulkusma, Bankura District, West Bengal. The author did his entire schooling in his mother tongue, Bengali from Govt. School. He Passed Madhyamik in the year 1987 under the West Bengal Board of Secondary Education and Higher Secondary in the year 1989 under the West Bengal Council of Higher Secondary Education.

The author obtained degree in Mechanical Engineering from Jalpaiguri Govt. Engineering College in 1994 with First Class. He completed his Master of Technology (M. Tech) in Computer Integrated Design & Manufacturing under Mechanical Engineering from RIT, Jamshedpur in 2002.

He worked as Assistant Engineer (Mechanical) in Durgapur Chemicals Ltd. (A Govt. of West Bengal Undertaking during the period of March, 1998 to April 2005. Prior to that he also worked as Management Trainee in the same organisation.

The author joined Atomic Energy Regulatory Board (AERB) on May, 2005 as Scientific Officer-E. Presently, he is working in the capacity of Scientific Officer-H and Officer-in-Charge, Eastern Regional Regulatory Centre (ERRC) of AERB. He is involved in safety review and regulatory inspection of Nuclear and Radiation Facilities. His area of interests is industrial radiography, accelerator, nuclear facilities, material handling equipment, Hazop study etc. The author has also some publications on different topics of safety.

*In the Memory of My Beloved Father*

*Lt. Nalini Ranjan Pathak*

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# CHAPTER -1

# INTRODUCTION

*Chapter 1 describes the Working principle of different types of radiography equipment namely x-ray, source, accelerator and neutron based, classification of radiography installations with safety provisions, hazards involved in handling different types of radiography equipment.*

**Working Principle of Industrial Radiography (IR)**

The use of ionising radiation is expanding globally, especially in industry and health. Both x-rays and gamma rays are used in industrial radiography to examine the integrity of structures and components. It is one of the oldest ionising radiation applications [1]. Almost all industries like oil and gas, nuclear, fabrication, chemical, forging & casting use radiographic testing (RT). A film or flat panel detector is positioned in line of the beam on the opposite side of the object being tested, which is then exposed to an x-ray or gamma ray beam. The detector measures the gamma or x-ray energy that enters the substance. The test material's variations in material density and thickness reduce penetrating radiation. When, x-ray or gamma ray travels through a material, the intensity of the beam is attenuated according to

$$I=I_0.e^{-\mu x} \text{ ---------------------------------- } (1.1)$$

Here, $I_0$ and I are the radiation intensities before and after attenuation respectively, μ is the linear attenuation coefficient and x is the material's linear thickness. Linear attenuation coefficient increases with the increase of atomic number and decreases with the energy. The mass attenuation coefficient is also taken into account for convenience based on density of a material.

From equation 1.1, it is evident that more x-rays or gamma rays can pass through thinner material whereas less for thinner material. As the material gets thinner, more rays flow through an imperfection, such as a crack or fault. Radiography of welding appears bright white because welding prevents almost all of the rays passing through, making it appear brighter than the other images. As the radiation completely pene trates the cracks, the same appear darker. An image of the cracks or flaws is created by the detector after receiving the rays passing through the cracks or flaws. The images thus formed, are referred as "Radiographs". Figure 1.1 shows the general working principle of IR [2].

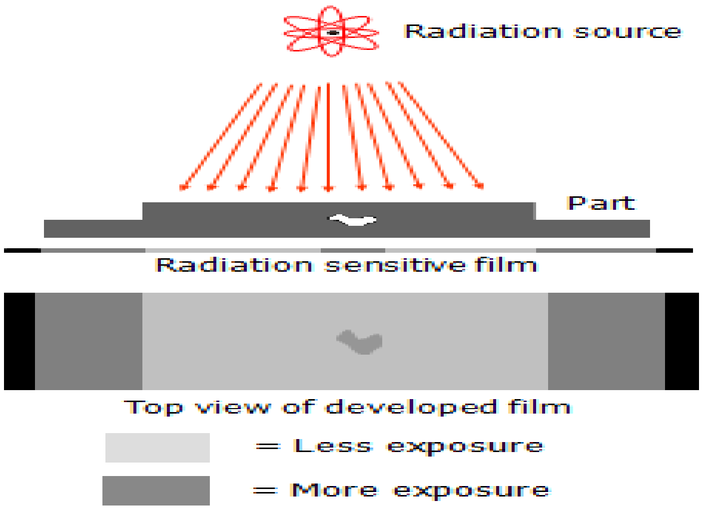



Fig. 1.1: General Working Principle of Radiography

There are number of advantages in radiography testing compared to other Non-Destructive Testing (NDT). These are as follows:

i) Both surface and internal defects can be found out. It is easy to determine the type of fault because radiography can visibly show the size and shape of flaws inside the material.

ii) Significant variation in composition can be detected.

iii) Minimum or no preparation of the components is required for examination.

iv) Permanent test record is obtained. Radiography film can be preserved long term and serve as the original record for future reference.

v) The possible negative effects of ionising radiation on live tissue are the more significant of two main drawbacks of IR. The second drawback is that radiography necessitates an expensive, complete infrastructure for film processing, viewing, and storage [3]. The amount of radiation exposure to the staffs working in radiography depends on the radiation type, object being radiographed, distance from source, amount of time spent, the film, and the developing technique [4].

X-ray based radiography

X-ray are produced when a stream of electrons strike at a target material such as tungsten, having high atomic number and are slowed down or stopped. X-ray based industrial radiography device are mostly fixed radiation generating equipment with peak tube voltages in the range of hundreds of kV, while tube currents in the range of 1-2 mA. In most cases, X-ray radiography is used in a fixed location. Only when the machine is turned ON, a radiation risk arises. X-ray tube, generator, control panel, and cooling system are the four main components of an X-ray machine. Figure 1.2 shows principle of X-ray production and figure 1.3 shows x-ray based industrial radiography exposure device.

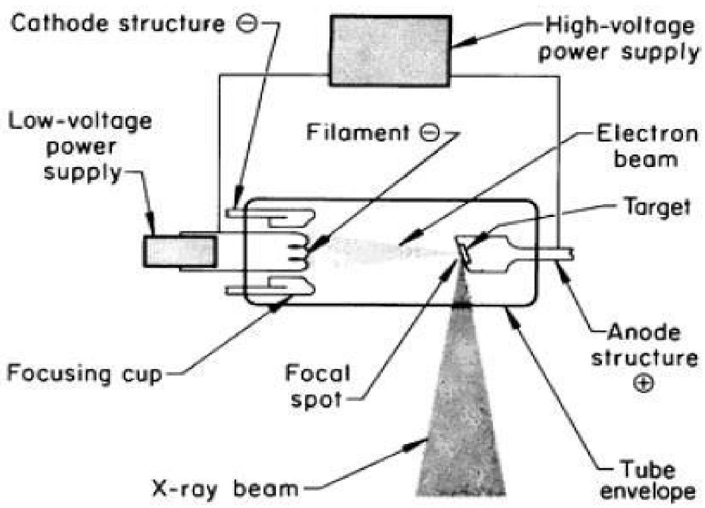



Fig. 1.2: Principle of X – ray Production

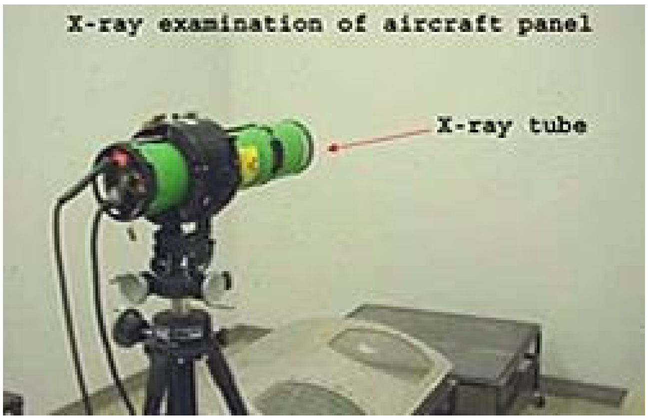



Fig. 1.3: X- ray Based Industrial Radiography Exposure Device

Source based radiography

Equipment containing radioisotopes like $Co^{60}$, $Ir^{192}$ and $Se^{75}$ with curies of activity are used for industrial radiography and are commonly called as Industrial Gamma Radiation Exposure Device (IGRED). At present, most commonly used radioisotope in IGRED is Ir-192.

Mostly used radionuclides in industrial radiography along with their properties are given in Table 1.1 [1].

| Radionuclide | Half life | Energies (MeV) | Optimum Steel thickness of object material (mm) |
|---|---|---|---|
| Co-60 | 5.3 years | High (1.17 and 1.33) | 50–150 |
| Cs-137 | 30 years | High (0.662) | 50–100 |
| Ir-192 | 74 days | Medium (0.2–1.4) | 10–70 |
| Se-75 | 120 days | Medium (0.12–0.97) | 4–28 |
| Yb-169 | 32 days | Low (0.008–0.31) | 2.5–15 |

Table 1.1: Radionuclides Mostly Used in Industrial Gamma Radiography

As, radiation is continuously emitted from the radiography device containing radioactive source, it is housed inside a container with adequate shielding.

Depleted uranium, lead, tungsten etc. are used as shielding material. When the device is not in use, the source is kept in locked condition inside device and cannot moved out to make an exposure. IGREDs are widely used by the industrial radiographers as it is easy to handle and can easily be moved from one site to other site. Also, the IGRED does not require any power for operation. The equipment is classified as portable, mobile or fixed depending on overall weight and mobility [1, 5]. Photograph of commonly used portable IGRED is shown in figure 1.4.

ROLI-2

DELTA-880

ROLI-3

Fig. 1.4: Commonly Used Portable IGRED

Gamma exposure devices are classified according to the operation of the source assembly into three categories namely Category-I, Category- II and Category-X [1, 5].

(a) Category–I: Source is not moved out from the device in this case. Opening the shutter, turning the sealed source inside the container, or using another method exposes the source. This type of device is shown in figure 1.5.

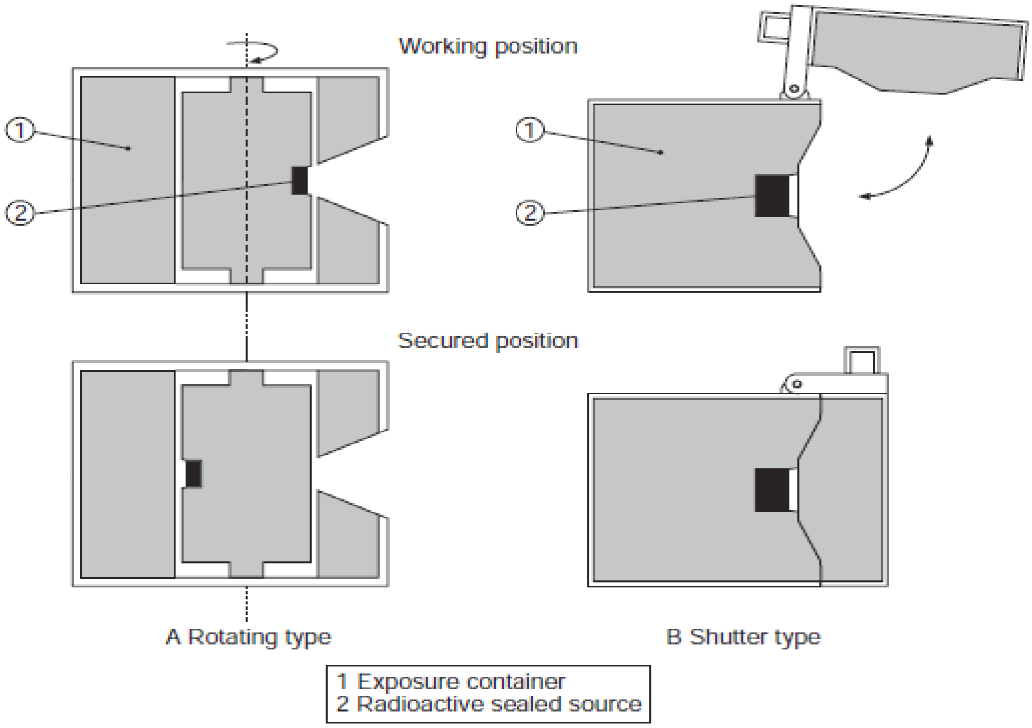



Fig. 1.5: Category-I Exposure Device

(b) Category-II: In this type of device, an operator projects the radiography source from the container to the exposure head for exposure through a guide tube, either operated mechanically, electrically, pneumatically, or by other means from a distance. Today, this device is mostly used. This type of device is shown in figure 1.6.

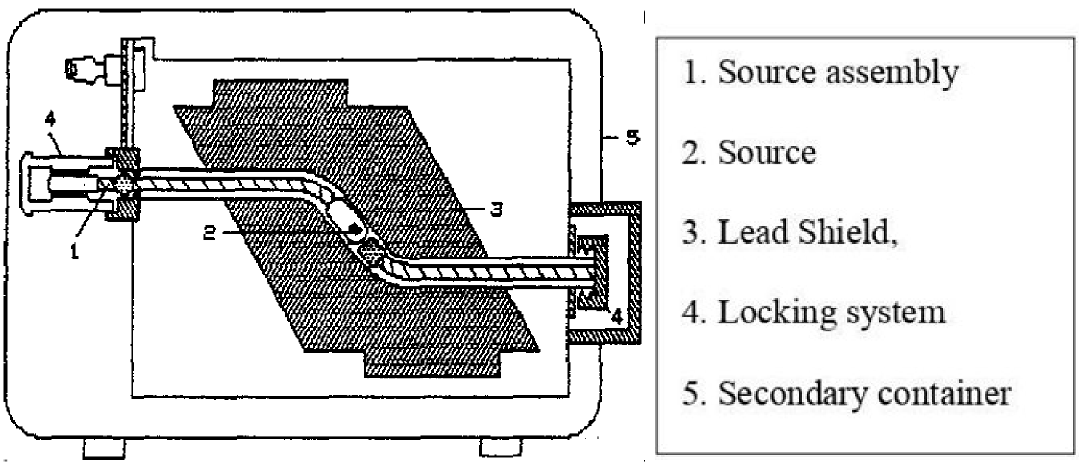



Fig. 1.6: Category-II Exposure Device

(c) Category X: Gamma exposure device designed for special purpose like pipe crawler equipment and underwater use.

Based on source path (conduit) designed inside the device, IGREDS are also classified as either “S conduit” or “Straight conduit” device.

In Category-II IGRED, exposure is given after moving the source assembly from the device by manually operating a cranking unit from a distance after connecting the drive side cable on back side and a guide tube on the front side of the IGRED. The source container, has depleted uranium / SS as shielding material. After the exposure, the source is retrieved back to the source container. The source assembly can be moved out only when both the drive side cable and guide tube are connected to the exposure device. With this setup, the pigtail containing the source, can be moved through guide tube in to the exposure head by manual cranking. Inside the gamma radiography exposure device, there are small radioactive sources in the form of pellets that gives radiation. The gamma radiation source assembly is called a pigtail [6]. Complete assembly of category-II IGRED is given in figure 1.7 and that of pigtail assembly in figure 1.8.

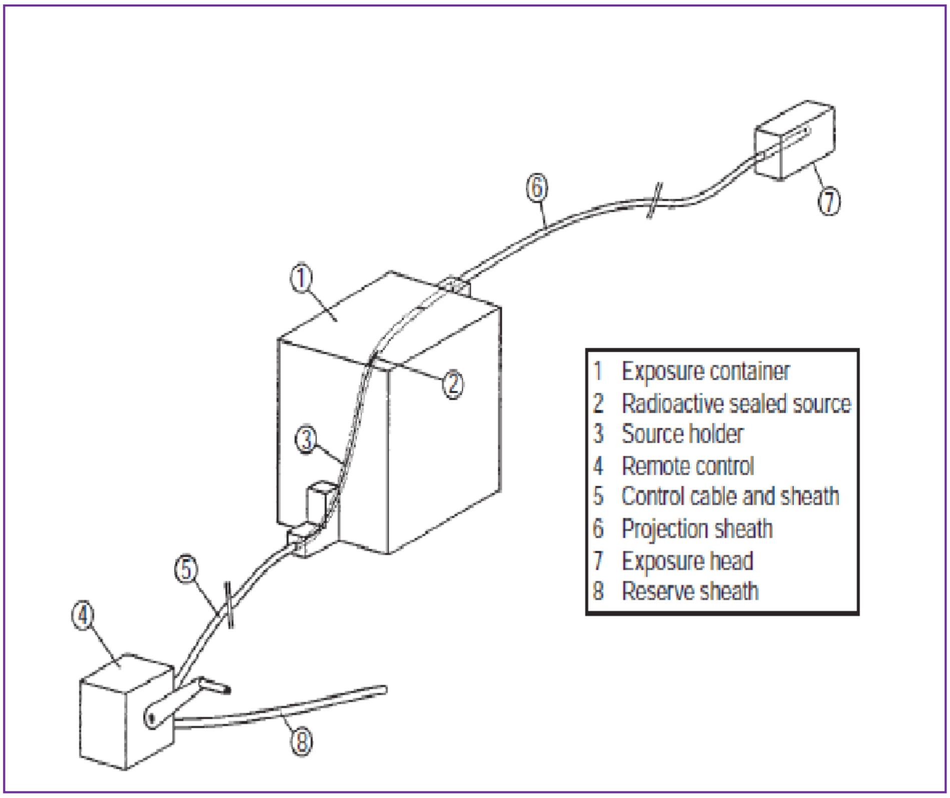



Fig. 1.7: Complete Assembly of Category-II IGRED

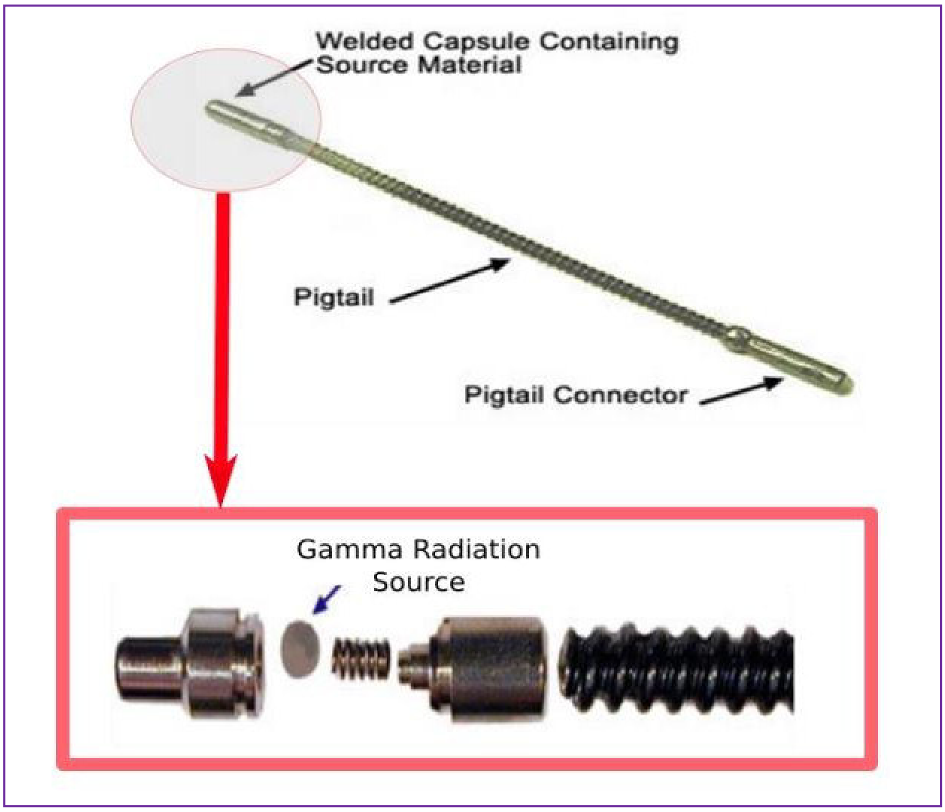



Fig. 1.8: Pigtail of IGRED

Accelerator based radiography

These are used mostly to generate high energy x-rays, typically in the range of 5-6 MeV, so as to carry out radiographic examinations requiring highly penetrating x-rays typically for large structures. Accelerator based radiography is generally carried out inside enclosure and exposure is given from control room. Large constructions like bridges can be inspected by radiography using smaller accelerators like cyclotrons. Radiographers can carry a portable accelerator into place after transporting it in a small vehicle. In a way, these are thus similar to industrial x-ray equipment. However, the hazard potential is higher considering the more penetrating x-rays. Accelerator based radiography equipment has been shown in figure 1.9.

Fig. 1.9: Accelerator Based Radiography Equipment

Neutron radiography

In few cases, radiography is done with neutrons and the same is called neutron radiography Applications include the utilisation of ‘sub-thermal’, ‘thermal’, ‘epithermal’, and ‘fast neutrons’ in steady state and pulsed beams at various energies. Though, neutrons can pass easily through different metals, hydrogenous materials of low density can absorb or scatter them. $^{241}$Am/Be & $^{252}$Cf are the two mostly used neutron sources.

**Classification of Industrial Radiography Installations**

Industrial radiography installations are generally of two types namely enclosure radiography and open field radiography [1, 5].

Enclosure radiography

In order to provide adequate radiation protection for those working outside of the enclosure and to prohibit unauthorised access into the enclosure during radiography operations, radiography activities are carried out in an enclosure. Enclosure radiography can be open top or roof top. An enclosure is used for work involving high dose rate. Material handling equipment like cranes, forklift etc. are used for loading and unloading of the object to be radiographed inside the enclosure. The device is operated from a control room situated outside the enclosure. Enclosure radiography with shielding and other arrangements in place ensures carrying out radiography work inside as well as other works outside safely and simultaneously. Radiation exposure to the operators can be kept '5 mSv or less' in an enclosure designed & constructed meeting different safety requirements [1] as compared to annual occupational dose limit of 20 mSv averaged for a five-year period [7]. Figure 1.10 shows an open top enclosure with provision of different safety systems in place and figure 1.11 shows a roof type enclosure.

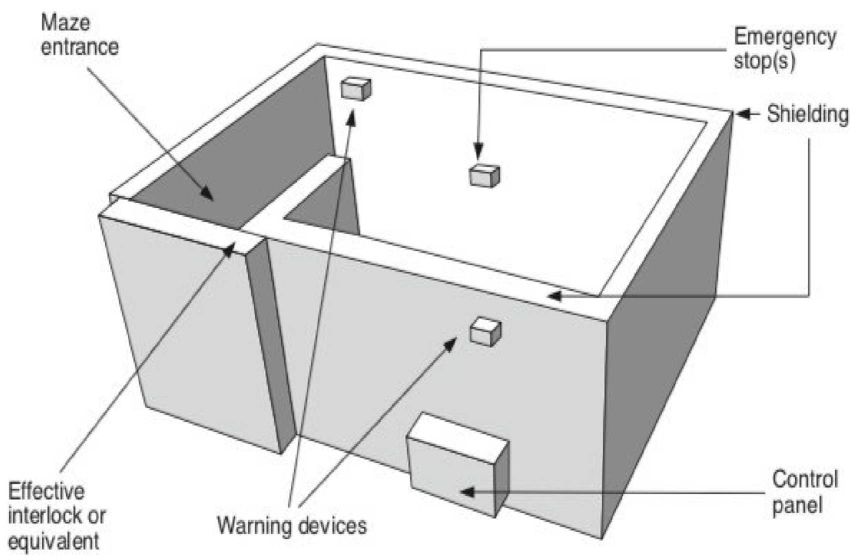



Fig. 1.10: Open Top Enclosure

Fig. 1.11: Roof Top Enclosure

Field radiography

Site/field radiography refers to radiography operations performed on shop floors, construction sites or other similar areas with provisions for adequate safety for radiographers and general people . Different safety systems of enclosure radiography are generally not available in site radiography. Hence, the hazards are higher for such installations. Site or field radiography planning needs to consider different aspects including nature of job, occupancy around the job location, timing of radiography and duration, location of job including conditions like work at height, confined place , under water. Job specific safety measures are required for site/field radiography. The control boundary is set based on a dose rate appropriate to the prevailing situation and specific exposure time. This is based on annual public dose limits of 1 mSv [7]. Site boundary is demarcated with proper warning symbols to minimize radiation hazards. In many cases like radiography inside vessel, confined space, it is not practicable to use physical barriers, and hence administrative controls are exercised to prevent unauthorized entry into the controlled areas. Radiological safety practices generally followed during open field or site radiography work is given in figure 1.12 [8].

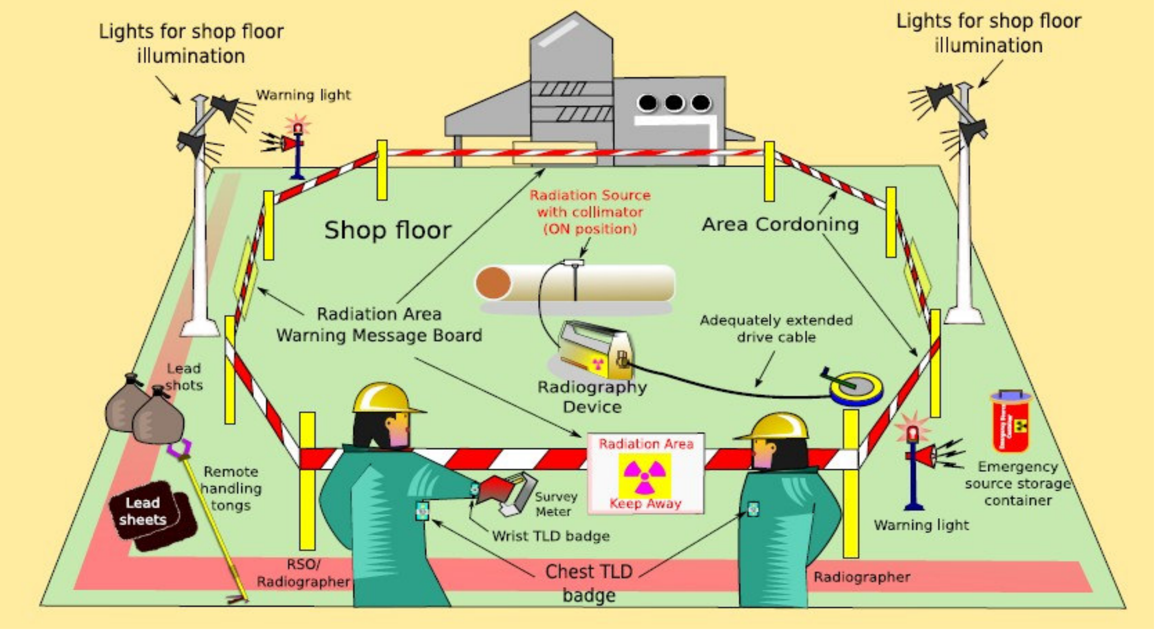



Fig. 1.12: Field Radiography

**Hazards of Industrial Radiography Facilities**

Industrial radiography like any other practice, poses negligible risks if performed in a safe manner. There have been incidents resulting in considerable radiation exposures and, in some cases, injuries to radiographers, despite strict regulatory supervision and regulations. There have been numbers of radiation accidents in this field and a few of them resulted in radiation injuries to the exposed individual [9]. As per a report published in 2012 [10], during a period of five years, the regulatory agencies received reports of 34 accidents with individual exposures more than the annual dose limit and 181 accidents with individual exposures less than the annual dose limit. In industrial radiography, X-rays and gamma rays are used to obtain images, and they can penetrate human tissue, which makes it potentially harmful. The level of hazard is influenced by factors such as the type of radiation, energy level, exposure time, and distance from the radiation source. High doses of ionizing radiation delivered in a short period can cause acute health effects, such as radiation burns, nausea, vomiting, diarrhoea and even death in extreme cases. Workers directly involved in radiography activities are at risk of receiving high doses if proper safety measures are not taken. On the other hand, chronic exposure to lower levels of radiation over an extended period may cause an incensement of risk in long run like that of developing cancer, genetic mutations, and other health conditions. Industrial radiography involves handling of radioactive materials or sources, which can also cause radiological contamination and pose risks to other workers and the public. The hazard potential of industrial radiography facility is determined considering the radiological risk to radiography staffs and common people taking account of amount of radiation generated and potential mode of exposure discounting the role of safety provisions. For the facilities handling gamma radiography device, categorization is based on A/D ratio where A is the activity and the D value represents a specific activity of radionuclide, which can have severe deterministic effect if uncontrolled including both internal exposure after the dispersal of the source material and external exposure from an unshielded source [11]. The hazard potential of radiation generating equipment like x-rays & accelerators is based on direct external dose rate at 1 m distance.

Hazards in handling IGRED

Industrial gamma radiography facilities handle category- 2 sources [11] which, if improperly handled or kept unsecured, may permanently harm a person who handles it or comes in contact with it even for short time. A typical IR facility involved in IGREDs may be considered to have the potential to cause deterministic health effects on-site but no or minor stochastic health effects off-site.

The pigtail of the IGRED contains a tiny but powerful gamma source. Due to its integrity with the device, the pigtail generally does not get detached from it. If the pigtail falls due to improper handling, the same can cause severe injury. Figure 1.13 shows severe burn injury to a person due to direct holding of the pigtail in accidental situation [6].

Fig. 1.13: Severe Burn Injury Due to Direct Holding of Pigtail

Major hazards involving radiological risk in handling IGRED include loss of control, source damage, and excessive exposure from the bare source. Hazards like high dose due to less space availability, stuck of source in the exposure path, loss of the device are many a times encountered by the user during operation of the device. Safe storage of the device is also an issue even when the same is not in operation. It has been seen that many incidences involving IGREDs have resulted in high dose or severe injuries to radiation workers. Excessive exposure to the radiography staffs can occur in the event of damage of the guide tube from inside resulting source stuck. The same has been identified as the most serious potential failure in the risk assessment study of industrial radiography [12]. Among the possible accidents, the loss of a radiography source can cause serious damage because the lost source can reach to general people who are ignorant of the hazards of radiation. The Regulatory authority of India, having responsibility of ensuring ionising radiation safety, has also expressed its deep concern regarding theft incidents of IGREDs through its circular [13]. Following incidents can occur during handling of IGRED and the same may cause emergency situation [14]:

i) Stuck of the source in the collimator, guide tube, or somewhere close to the exposure device's entrance.
ii) Shielding damage due to any event.
iii) The source gets separated from the drive cable and stays inside the guide tube.
iv) Source comes out from the tip of the guide tube.
v) Loss of source.
vi) Fire.
vii) Handling of the device by an untrained person causing injury.

Hazards in handling x-ray & accelerator based radiography device

In case of IR facilities involved in handling radiation generators (x-rays & accelerators), the hazard potential is estimated based on malfunctioning of equipment, leading to direct external dose rates of more than 10 mGy/hr (for x-ray equipment), or 1000 mGy/hr (for high energy accelerators) at 1 m distance [15]. Hazard potential of radiation generators is inherently lower as compared to IGREDs. Hence, the radiological impact is also lower when compared to hazards involving IGREDs. In addition, there will be no off-site consequences due to exposure arising from such equipment. Inadvertent exposure to high energy x-rays by working personnel could be either due to failure of automatic exposure timer, or accidental energisation of tube assembly due to interlock malfunction, or physical damage of shielding/filtration. The same can be minimized by formulation of appropriate maintenance and quality assurance program by the facility. Following incidents can occur during handling of x-ray based device and the same may cause emergency situation [14]:

i) Generation of radiation fails to terminate after the intended time period.

ii) Accidental energization of the device.

iii) A radiographer could not stop a manually operated x-ray device.

iv) A safety system or warning system does not work and the same is wilfully by-passed.

v) Physical damage is caused that affects the shielding or filtration.

# <u>CHAPTER-2</u>

## NEED OF RESEARCH, PREVIOUS RESEARCH WORKS, RESEARCH OBJECTIVE & SCOPE OF RESEARCH

*Chapter 2 identifies the gap areas in the existing safety and security system of Industrial Radiography (IR) facilities, previous research carried out, research objective and scope of research.*

**Need of Research on Safety & Security of IR Facilities**

An important non-destructive evaluation method is industrial radiography, which uses either X-ray or gamma ray for detection of defect of materials and various components. For source based radiography, different radioisotopes are employed, depending on the material thickness and necessary imaging parameters. However, Ir-192 is most popularly used radioisotope today and most of the radiography jobs can be done with the use of up to 50 Ci of the same radio isotope . [1]. A person unknowingly exposed to an radiography source may get a dose capable of causing harm within minutes due to the high dose rates in radiography. Also, damaged or corroded sources can cause contamination. Adverse work situations can lead to operational circumstances where the principle of radiation protection for keeping doses 'As Low As Reasonably Achievable (ALARA)' is difficult to implement [1]. In general, it has been found from the annual report of AERB that average radiation dose of exposed person involve in industrial radiography practices are comparatively more than other applications of ionizing radiation for medical, industrial and research in India. Most common shortcomings identified with IR facilities are [10]:

i) Radiation survey meters are not properly used;

ii) Warning system to prevent entry to the work site is not available;

iii) Emergency preparedness is not adequate;

iv) Improper use of alarm systems;

v) Dose rate is more than the permissible limit at the boundary of the work site.

Hence, a lots of research activities as well as stringent actions are initiated to minimize radiological risk of the workers and the members of the public. Dose monitoring for industrial radiography is done on monthly basis in India though the same is done on quarterly basis for other applications of radiation.

Among several industrial radiography devices, portable Industrial Gamma Radiography Exposure Devices (IGREDs) are widely used by the industrial radiographers but it is observed that some possibilities of accidents and on-site radiation exposure hazard are associated with these devices.

The radiography facilities handling portable IGRED are specifically facing the following three serious safety and security issues.

1) *Accidental Exposure of the Radiography Personnel in the Event of Failure to Use Radiation Survey Meter (RSM)*

In spite of stringent regulatory control and procedures there have been accidents with the Industrial Gamma Radiography Exposure Devices (IGREDs) resulting in significant radiation exposures and in some cases, injuries to radiographer. There have been numbers of radiation accidents in this field in India and a few of them resulted in radiation injuries to the exposed individuals [9]. In addition to the above, it was also reported that there were accidents and consequent radiation exposure/injury for not using the radiation survey meter particularly in the event of malfunctioning of IGREDs. The major cause of malfunctioning is the damage of inside damage of the guide tube which results in source jam inside the guide tube . This is identified as serious potential cause of accidental excessive exposure to radiographers [12]. Even in 2016, one such injury occurred to a radiographer when the source pigtail with the Ir-192 radioactive source of 30Ci became detached from the driving cable and remained in the guide tube during an IGRED operation. It was not known that the source was in exposed condition as no radiation survey meter was used and the operation was continued. Later, the pigtail was found in the guide tube and the operator tried to put it back inside the IGRED. Radiation injury on his right hand's fingers was noticed after eight to ten days of radiography work [16]. Pipeline inspection was carried out using 35 Ci of 192-Ir source. The source assembly was remained in an exposed condition even after exposure and the same was detected later as the darkroom technician complained of over exposure of the film. The source assembly remained inside the guide tube for about two hours and the radiographer's dosimeter recorded a dose of nine hundred thirty (930) mSv. Assistant of the radiographer touched the source for preparation of the job many a times. Bums on fingers were noticed about eleven days after the incident. Survey meter was not used during the work [17]. Similarly, failure to use survey meters during radiography works have been identified for many other accidents worldwide [17].

2) *Accidental Exposure of the Radiography Personnel due to Manual Cranking Operation of Portable GRED*

Portable IGRED is a shielded container that contains the radioactive source. The operator needs to rotate the cranking unit manually for radiography operations after connecting the drive cable and guide tube with the IGRED. After the end of the exposure, reverse cranking is done to get back the source inside shielded container. Length of the control cable and guide tube are kept long enough so that the manual cranking for projecting out of the source from the shielded position can be done from a considerable distance and as a result very less dose to the operator. However, for some jobs, like inside examination of vessel, pipelines etc. sufficient space is sometimes not available and radiographers are forced to work in close proximity of the source and get a significant amount of dose within a minute which otherwise could have be en received after one year of intense radiography works. Receiving of high amount of dose is a major safety issue for the IR facilities. Hence, ALARA principle of radiation protection is not met.

*3) Security Hazard due to Theft of Portable IGRED*

For IGRED, an accident can occur even when the device is not in use. Accidents have occurred in past due to the fact that source housing was stolen from the storage room. Among the possible accidents, loss of radiography source can cause serious consequences because the lost source can reach the hands of people totally ignorant of the radiation hazards. As per report published, stolen/missing radiography source/equipment accounts for nearly 50% (16 out of 33) of the total mishap [9]. In 1991, about 1 Ci of Ir-192 source assembly stored in a lead pot kept inside a pit, were theft. The Theft was not detected for some days. Theft source assembly was eventually found from a scrap dealer's shop after changing of hands many a times. Whole body dose of the scrap dealer and that of individual public were estimated as 200 mSv was 35 mSv respectively. Providing of adequate physical security was recommended for prevention of such theft resulting in public exposure [17]. Bijan S. et al., described about theft of two industrial gamma radiography projectors containing Ir-192 source of activities 24 and 30 Curies, one from an industrial area with security provision and the other one from home town without any security provision [18]. Atomic Energy Regulatory Board (AERB), the Indian Nation Regulator for ionising radiation in its website has informed about recovery of a theft IGRED from a scrap dealer around 10 Kms away from the accident site [19].

It is evident from the problems discussed above that stolen radiography sources/equipment have the chance of serious consequences. Hence, secured storage of the devices are of paramount importance. On the other hand, it is always a very challenging task to ensure secured storage of portable radiography devices that are particularly used in remote work place.

**Previous Research Works**

Some research works have been carried out to promote automation in IGRED. Lio T. W. et al., 1996 & 1998 developed an automation in radiography system for inspection of welding [20, 21]. Denis A Chamberlain D. A., et al., 1996 proposed handling of gamma radioactive sources by robot in site radiography of storage tanks made of steel [22]. Shinde R. et al., 2016 adopted automation in non-destructive examination for Thrust Chamber assembly of Vikas Engine [23]. But till date, no research work has been reported on automated cranking operation of the portable IGERD and in fact portable IGERED with automated cranking facility is not yet available in the market. Board of Radiation and Isotope Technology (BRIT) has developed ROLI-3 portable IGRED. The device is designed for operation from a distance using a cranking unit. Unauthorised handling and inadvertent exposure are prevented by the safety features built into the exposure device [24]. Most of the security related works of IR are focused on enhancing the security measures through improved security infrastructure and management as well as improving the safety regulation standard [25, 26]. Raghavendra P. et al., 2016 identified & implemented the security management system for preventing unauthorized access to the IGRED [25]. The methodology includes functions of detect, deter, delay, response, and security management of IGRED through five levels of security measures involving the technologies like CCTV, biometric access control, key control etc. at the institute perimeter, enclosure maize door, storage cage. So far no research work has been reported for developing an inbuilt security system for minimizing the incident of theft case and thus accidental radiation exposure.

*It is found that no research work has been carried out for prevention of excessive exposure due to non–use/failure of radiation survey meter & insufficient space for safe manual cranking and also for integrated security system for detection of theft of portable IGRED*.

**Research Objective**

*From the identified gap areas, it is seen that there are some safety and security related deficiencies for portable IGRED. Hence, primary aim of the research is to improve safety & security of portable industrial gamma radiography exposure device (IGRED).*

*Accordingly, based on the Gap areas observed pertaining to safety & security aspects of portable IGRED, following objectives have been set:*

*i) To minimise accidental exposure of the industrial radiographers occurred mainly due to failure to use survey meter;*

*iii) To eliminate accidental exposure of the industrial radiographers happened due to unavailability of sufficient space for manual cranking operation during radiography; and* *iv) To prevent theft incidences of Portable IGRED from unmanned location*

**Scope of Research**

*In order to achieve the above mentioned objectives, scope of the research activities are as follows;*

*(1) To assess safety performance of the IR facilities as excessive exposure to staffs, damage of IGRED, source stuck, theft of IGRED etc. are reported time to time. Assessment of safety performance will help in identification of the exact problems and measures to be taken. Accordingly, safety performance of around 1200 facilities operating in India will be studied and analysed considering parameters like personnel dose monitoring data, regulatory inspection findings, safety performance indicator values and unusual occurrences.*

*(2) To design and develop an IoT technology based continuous and real time radiation monitoring system for use in field radiography in order to overcome the limitation of the existing conventional radiation survey meters for prevention of accidental exposure causing injury of the radiography personnel either due to their non-usages or malfunctioning.*

*(3) To automate cranking operation of portable IGRED with the use of state of the art mechatronic control system keeping the existing provision of manual cranking also to add Defence in Depth (DID) in operation, that will particularly be beneficial for operation of portable IGRED where there is space constraint and sufficient distance cannot be maintained for safe manual cranking in radiography work like that in construction site. As increase in distance from radiation source reduces dose rate proportional*

*to square of distance, automated operation will help in reduction of dose to the radiography persons and thereby to meet ALARA.*

(4) *To develop an advance theft detection system that can be integrated with portable IGRED keeping provision for early detection of the theft incidence and notification to the authorised custodian of the device for prevention of such theft.*

# CHAPTER-3

## SAFETY PERFORMANCE ASSESSMENT OF INDUSTRIAL RADIOGRAPHY (IR) FACILITIES

*A detailed safety performance assessment of one thousand two hundred IR facilities operating in India has been carried out with respect to different parameters like personnel dose monitoring with global comparison, regulatory inspection findings, safety performance indicator and unusual occurrences happened. Probability of occurrence of different unusual occurrences have also been calculated using Fault Tree Analysis (FTA). All these have been discussed in chapter -3.*

**Framework for Safety Performance Assessment**

Good design, operational safety & human performance determine overall safety of a facility. Accordingly, all these aspects are evaluated for deciding safety performance. It is necessary to identify and assess performance indicators that have a relationship to the intended safety attributes for safe operation. A set of indicators has been identified to monitor performance in the areas that directly affect operational safety of the NPP (Nuclear Power Plant). Although actual values of indicators are not intended for direct measurement of safety performance, the same can be inferred from the outcomes as shown in figure 3.1 [27].

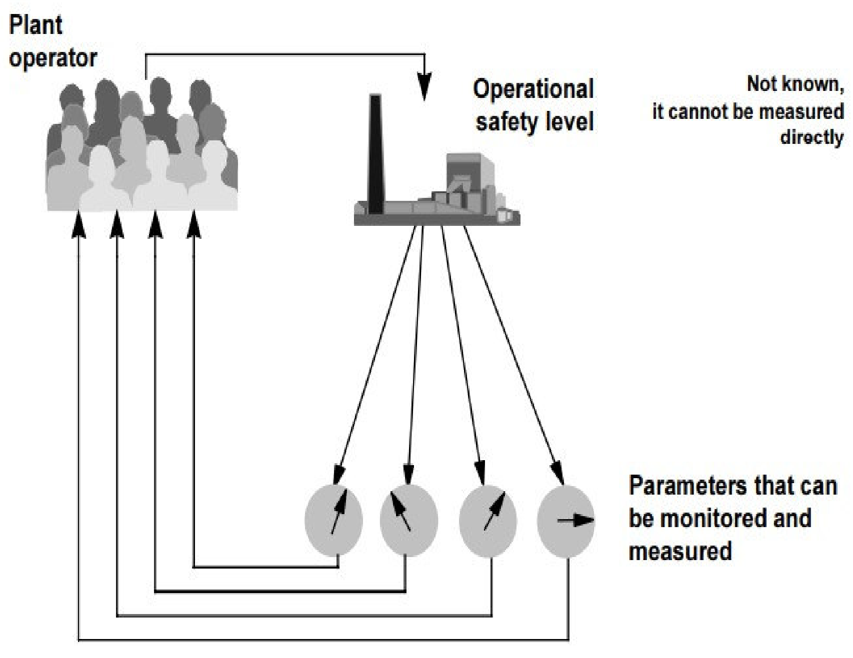



Fig. 3.1: Inferring Safety Performance Provided by the Indicators

As industrial radiography has radiation risks associated with it, hence operational safety performance is assessed [28]. Assessment of safety performance ensures compliance with relevant requirements for safety and radiation protection during normal operation s and accid ent conditio ns in Industrial radiograph y facilities.

Due to a growth in the number of facilities, NRPD- Iran, made a quantitative system of evaluating the safety performance of industrial radiography facilities and a complementing enforcement system. Each aspect was given a weighting factor based on its significance to safety in the system. The performance was evaluated quantitatively by adding up their scores. Following the implementation of this assessment system, safety related deficiencies of various facilities were significantly reduced [29]. International Atomic Energy Agency (IAEA) developed a Global Information System and Network to support the improvement of Occupational Radiation Protection in Industrial Radiography -ISEMIR (IR) [10]. ISEMIR-IR evaluated occupational exposures and radiation protection of staff in industrial radiography all over the world and identified both good practices and shortcomings and define d all types of actions required to be implemented by the facilities and regulatory bodies to avoid exposure & accidents, and to meet the ALARA principle [10].

**Industrial Radiography Facilities in India**

General functions of the regulatory authority with respect to industrial radiography facility include development of regulations and other documents like codes, guides, standards, safety review for issue of different consents like type approval of the device, procurement permission, license for operation carrying out periodic routine and special inspections to verify radiological safety status & stipulations made in different consents issued to the facilities and also enforcement, if required to ensure compliance [1]. Safety audit/inspection can be used as a tool for measurement of safety performances of any facility involving radiation risks [30]. Regulatory control for safe operation of industrial radiography is exercised by the Atomic Energy Regulatory Board (AERB) envisaged under the 'Atomic Energy Act- 1962' [31]. Foundation for safe use of radiation-generating equipment in India is provided by the 'Atomic Energy (Radiation Protection) Rules- 2004', which were issued under the 'Atomic Energy Act, 1962'. The regulations relevant to radiation safety of personnel using IGRED and X-ray based equipment for industrial radiography are outlined in AERB Safety Code No. AERB/IR/SC-1. AERB has introduced a state of the art e-Governance system named, e-LORA 'e-Licensing of Radiation Applications' for automation of different processes for radiation facilities including industrial radiography.

In India, there are around 1200 industrial radiography facilitates having 4744 equipment at present [32]. Distribution of the type of industrial radiography equipment have been shown in figure 3.2.

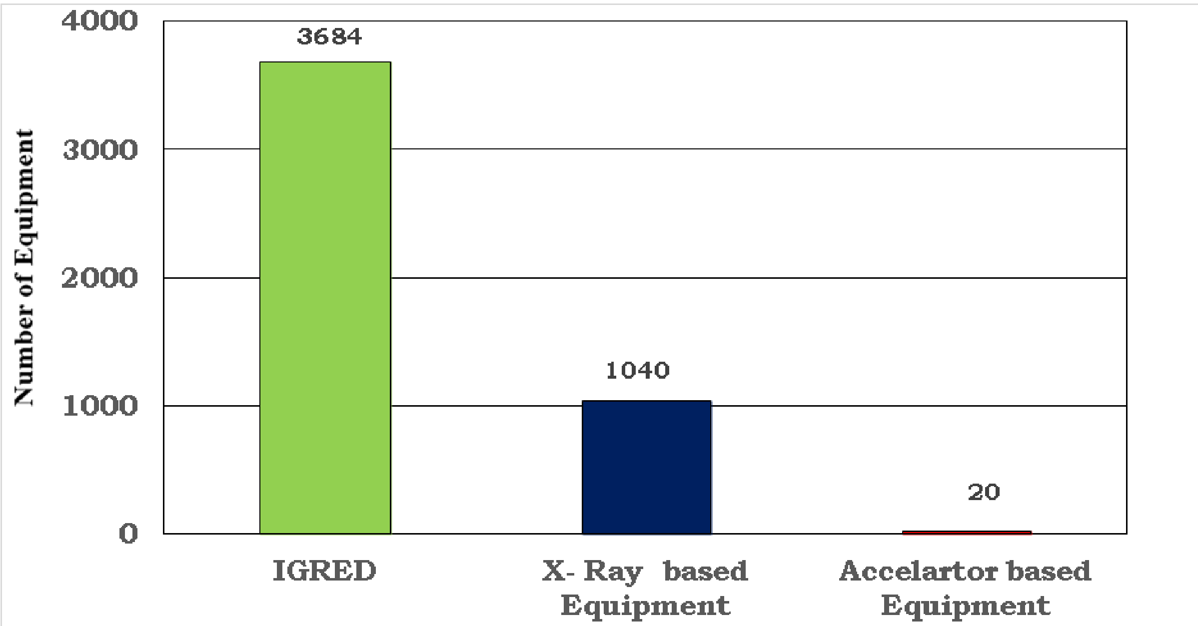



Fig. 3.2: Type of IR Equipment in India

It can be seen from Fig. 2.2 that majority of the equipment are IGRED (~ 77.6 %) followed by X-ray based device (22%) and few accelerator based equipment. Brief details of some commonly used IGRED with number of equipment, maximum source strength, shielding materials etc. is given in Table 3.1.

| Model | Max$^m$ Source Strength (TBq) | Shielding Material | No. of equipment | Weight of the IGRED (Kg) |
|---|---|---|---|---|
| DELTA 880 | 5.55 | Depleted Uranium | 1033 | 23.6 |
| RLI-2 | 2.74 | Lead and Heavy alloy | 566 | 38 |
| ROLI-3 | 0.74 | Lead and Heavy alloy | 329 | 25 |
| SPEC 150 | 3.7 | Depleted Uranium | 93 | 24 |
| EXERTUS CIRCA 80 | 2.96 | Tungsten encased in Stainless Steel housing | 56 | 8.8 |
| 1075 SCARPRO | 3 | Tungsten | 35 | 16.8 |
| IR-100 | 4.44 | Depleted Uranium | 28 | 24.1 |
| EXERTUS Dual 120 | 7.96 | Depleted uranium | 5 | 14 |
| EXERTUS CIRCA 120 | 4.44 | Tungsten encased in Stainless Steel housing | 1 | 9 |

Table 3.1: Brief Details of Commonly Used IGRED in India

X-ray equipment of models like Dang Dong XXQ 2505 (221 no), Dang Dong XXQ 2005 (67 no), Dang Dong XXQ 3005 (42 no), Dang Dong XXG 2505 (16 no) manufactured by Dan Dong Radiative Instrument Co. Ltd.; models X CUBE COMPACT (25 no), ISOVOLT 320 M2 (15 no), ISOVOLT TITAN (15no) manufactured by GE Sensing & Inspection Technology, 26 equipment manufactured by Baker Hughes etc. are commonly used in India. Also, 20 accelerator based radiography equipment like Linatron M9A (4 no), Linatron M6A (3 no) manufactured by Varex Imaging, Betatron 7.5 MeV (5 no) manufactured by GE Sensing and Inspection Technology etc. are used.

**Personnel Dose Monitoring**

Personnel dose monitoring or Personnel Monitoring Service (PMS) is an essential requirement for radiation protection in industrial radiography. In India, TLD badges are used for individual dose monitoring. Fresh TLD badge received from accredited laboratory are used by the radiation workers and at the end of monitoring period, returned back to the accredited laboratory for dose evaluation. Dose report on monthly basis is sent by the laboratory to the facilities which is reviewed by the facility and necessary measures are taken if required, based on the dose received. Occupational dose data of radiation workers, who have availed the personnel monitoring service are maintained, as a centralized dose records in National Occupational Dose Registry System (NODRS) [33]. NODRS provides online information on dose data, previous dose history, annual dose, lifetime dose of the individual radiation worker. Dose records are also maintained by the facility for future reference and also permanently in the National Occupational Dose Registry System (NODRS) for each individual against the assigned TLD number of individual and institute id of the facility. Frequency of dose monitoring is once in a month for industrial radiography whereas the same is once in three months for other types of radiation facilities and this is followed due to probability of more dose received in radiography work. In case of any exposure case exceeding dose constraint or limit, AERB carries out necessary investigation to find out the cause and necessary steps to be taken by the facility to prevent recurrence. AERB during inspection also verifies dose records of the radiation workers of the IR facility. A comparison of radiation dose received by the staffs [34] in IR facilities of India have been analysed for five years (2017-2021) in comparison to other types of radiation facilities i.e. Diagnostic Radiology (DR), Radiotherapy (RT), Nuclear Medicine (NM), and Radiation Processing Facilities (RPF). The same is presented in Table 3.2.

| Year | Practice wise Number of Persons Monitored , Average Dose Received in mSv, Average Dose Received among Dose Receiver in mSv | | | | | |
|---|---|---|---|---|---|---|
| | DR | RT | NM | IR | RPF | RESEARCH |
| 2021 | 141764, 0.23, 0.80 | 15473, 0.12, 0.52 | 2678, 0.45,1.02 | 8092, 0.33,1.52 | 148, 0.02, 0.14 | 3918, 0.08,0.34 |
| 2020 | 134873, 0.21, 0.76 | 15864, 0.10, 0.45 | 2546, 0.36,0.81 | 7452,0.35,1.33 | 140 ,0.04,0.33 | 4320, 0.1,0.51 |
| 2019 | 139075, 0.29, 0.86 | 16636, 0.17, 0.6 | 2788, 0.63, 1.01 | 7791, 0.48, 1.43 | 113, 0.11, 0.61 | 4539, 0.14, 0.52 |
| 2018 | 124375, 0.3,0.77 | 15782,0.17,0.48 | 2818, 0.53, 0.95 | 7545, 0.39,1.21 | 93, 0.06,0.43 | 4390, 0.12, 0.39 |
| 2017 | 107707, 0.30, 0.74 | 14665,0.18, 0.52 | 2698, 0.56, 0.92 | 7353,0.49, 1.17 | 71, 0.03, 0.19 | 4128, 0.14, 0.43 |

Table 3.2: Comparison of Dose Data of IR with Other Practice

From the above data, it is found that though average dose received by staffs of industrial radiography practice is second highest after NM but actually average dose received considering total number of dose receivers are highest and almost 1.27 to 1.64 times higher than that of NM for different years during 2017 to 21. Also, average dose received for IR is much higher compared to that of DR, RT, RPF & Research. Accordingly, it can be inferred that chances of receiving dose are generally higher in IR compared to other practice and the same signifies the hazardous nature of the facility.

Year wise dose data for five years (2017-2021) showing number of persons monitored, average dose received, actual number of dose receivers, average dose among the dose receivers and dose range with number of persons coming in the range have also been presented in Table 3.3.

| Year | No. of Monitored Persons | Average Dose for Monitored Persons (mSv) | No. of Persons Received Dose | Average Dose Among Dose Receiver (mSv) | No. of Persons Receiving Annual Individual Dose Excluding Zero Dose D (mSv) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | D≤20 | 20<D≤ 30 | 30<D ≤50 | D>50 |
| 2021 | 8092 | 0.33 | 1779 | 1.52 | 1774 | 3 | 2 | 0 |
| 2020 | 7452 | 0.35 | 1975 | 1.33 | 1971 | 3 | 0 | 1 |
| 2019 | 7578 | 0.40 | 2592 | 1.43 | 2583 | 6 | 1 | 2 |
| 2018 | 7545 | 0.36 | 2458 | 1.21 | 2455 | 2 | 1 | 0 |
| 2017 | 7353 | 0.49 | 2812 | 1.17 | 2810 | 1 | 0 | 1 |

Table 3.3: Year wise Dose Distribution of IR Facilities

From Table 3.3, it can be seen that average dose among dose receivers for IR facilities is on a rising trend except the year 2020 when average dose received was lower compared to 2021 & 2019. This may be attributed to Corona virus pandemic when industrial radiography facilities also suffered quite a lot like all other jobs. The rising trend of average dose received is a matter of concern and demand for more enhancement of safety in IR facilities. Though majority of the employees of industrial radiography have received annual dose very much within the limit, few cases have bee n reported where dose received by the staffs have exceeded annual dose limit [35]. In order to prevent recurrence of such excessive exposure case, necessary steps like improvement of preparation of job specific radiography procedure, engagement of multiple radiographers, job rotation policy, safety awareness training, and carrying out radiation survey during radiography works have been implemented.

Global dose received data for IR facilities [10] have been studied in order to compare the dose received by the staffs of industrial radiography facilities in

India. In this regard, global dose received data from 234 individual radiographers, data submitted by NDT Company for nearly 3500 radiographers and data submitted by regulatory body for over 16,000 radiographers have been shown in the figure 3.3. Average dose received was around 3 mSv the year 2009 and for some staffs dose received are on higher side i. e. more than 20 mSv. It can be inferred that average dose received by staffs of IR facilities in India is much lower compared to global data available.

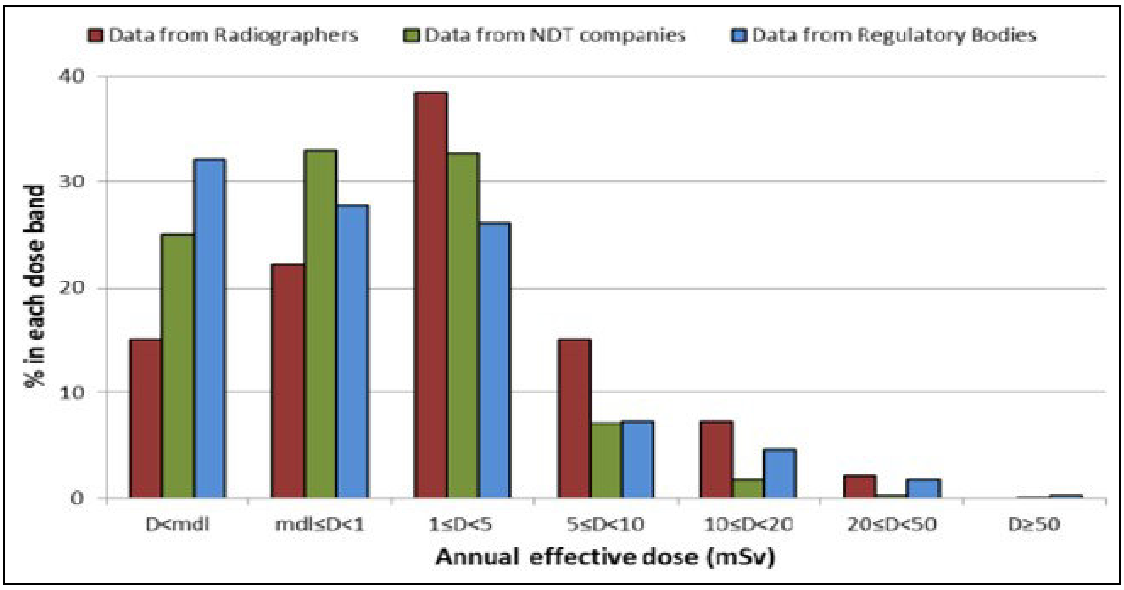



Fig.3.3: Global Dose Distribution of Radiographers

**Regulatory Inspection Findings**

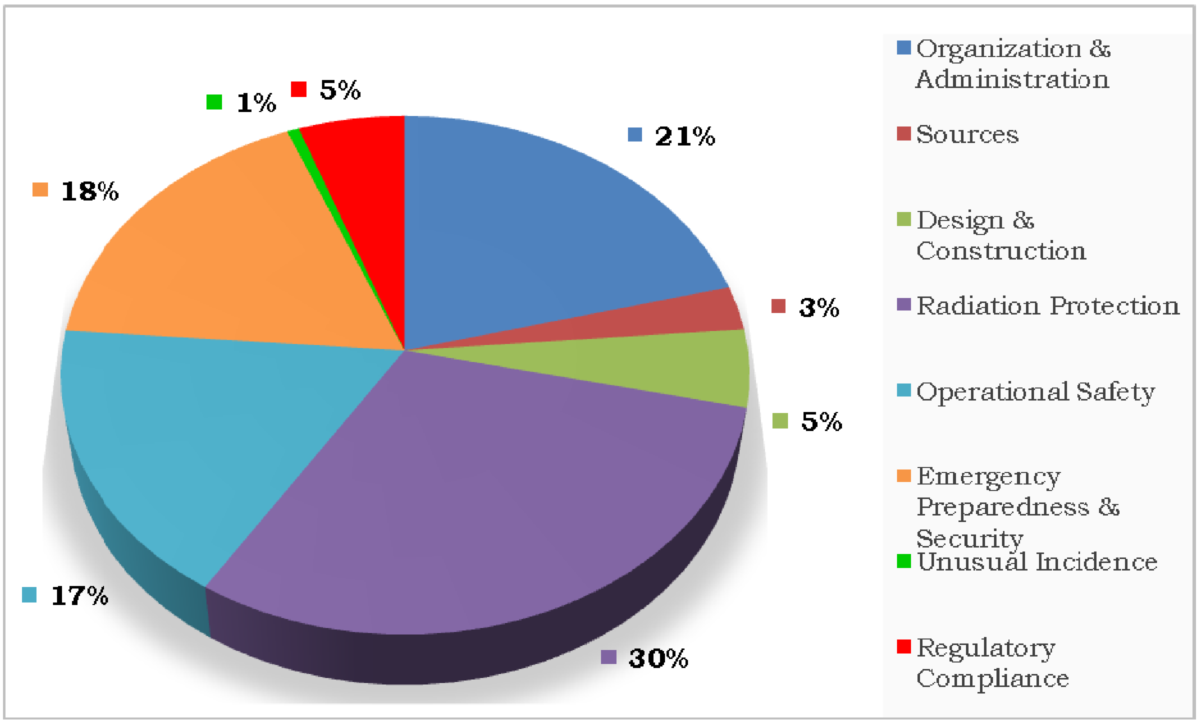
Radiation risks associated with the facility or activity need to be considered for inspections of facilities and activities following a graded approach and the findings of inspections are evaluated periodically [36]. Planned regulatory inspection of industrial radiography facilities once in three years are done apart from special inspections, if required by AERB [37]. The RI findings are categorized based on their safety significance into White, Grey. Orange & Red in increasing order of safety significance [38]. Analysis of inspection findings has been done to evaluate safety performance of IR facilities. Aspects like adequacy of shielding of equipment & enclosure, availability of qualified and trained personnel including radiographer and radiological safety officer (RSO), personnel monitoring service of radiation workers, radiation monitoring instruments including its functionality & calibration status, safe & secure source storage room, emergency preparedness plan & emergency handling tools, security plan and security arrangement, radiation protection survey, movement permission of device etc. are checked.

A total of 1285 RI findings were reported from 624 regulatory inspection of industrial radiography facilities during the period of January, 2020 to May 31, 2023 [32]. These RI findings have been analysed. Category wise safety significance based RI findings have been presented in Table 3.4.

| Type of RI Findings | Number of Findings |
|---|---|
| Red | 1 |
| Orange | 20 |
| Grey | 643 |
| White | 621 |

Table 3.4: Safety Significance Based RI Findings of IR Facilities

All of the above inspection findings have been divided into the functional areas of organisation & administration, sources & equipment, design & construction, radiation protection, operational safety, emergency preparedness, unusual incidence and regulatory compliance. Area wise distribution of regulatory inspection findings have been presented in figure 3.4.




Fig, 3.4: Distribution of Regulatory Inspection Findings in Different Functional Areas

RI findings in the area of organization and administration includes issues such as unavailability of license, movement permission for device, approval of radiography site & enclosure etc. Source and equipment related deficiency includes issues such as source mismatch and sources pending for disposal. Design & construction related issues include deficiencies regarding source storage room in open field radiography and enclosure in enclosed radiography. Issues related to PMS, radiation monitoring instruments, dose records etc. fall under radiation protection whereas operational safety issues are unavailability of RSO, trained radiographers, non-use of PMS during radiography work etc. Emergency preparedness and security issues consist of unavailability of emergency handling accessories, emergency & security plan, unavailability of security measures. Occurrence of excessive exposure fall under unusual occurrence whereas regulatory compliance issues pertain to non-submission of safety status reports and no response from the facilities either due to closure of the facility, death of employer or change of management. It is observed that majority of the RI findings (30 %) have been reported in area of radiation protection where unavailability of PMS for radiation workers is the main contributing factor in this area. Majority of the findings are non-availability of movement permission for IGREDs in the area of organization & administration which contributes 21% of the total inspection findings. All the inspection findings in the area of unusual occurrence are due to excessive exposures in some IR facilities. The single Red RI finding is due to theft of source, which was later on recovered. Issues like disused source pending for disposal, unavailability of RSO/ radiographer, PMS not available contribute to the Orange category inspection findings. Distribution of Orange category inspection findings is presented in Table 3.5.

| | |
|---|---|
| Disused Source Pending for Disposal | 2 |
| Unavailability of Radiographer / RSO | 9 |
| Unavailability of Emergency Accessories | 2 |
| PMS not available | 5 |
| Source Storage Room Deficiency | 2 |

Table 3.5: Distribution of Orange Category RI Findings

**Safety Performance Indicator**

AERB has introduced a system of assigning Safety Performance Indicator (SPI) value electronically (eSPI) to categorise the radiation facilities based on their compliances to safety and to optimise regulatory oversight [32]. The SPI value helps in safety review & assessment of licenced facilities and also prioritise regulatory inspection. Lower SPI value leads to non-issuance of approvals. Safety Performance Indicator (SPI) value refers to safety compliance of the facility based on factors such as no of existing Red, Orange & Grey Non-Compliance (NC) either auto system generated like that of expiry of calibration of radiation monitoring instrument or inspection related, submission of safety status reports, occurrence of excessive exposure and enforcement action against the Institute. The maximum value of SPI is 1, which refers no deviation, on the above parameters in last three years. Any reported deviation will lead to a reduction in SPI value of the facilities. IRFs having SPI in between 1 – 0.9 (Green) are said to have "satisfactory performance", between 0.9 and 0.8 (Yellow) as "Needs improvement" and less than 0.8 means "Unsatisfactory" (Red). Summary of safety performance of 1200 IR facilities based on SPI value has been presented in figure 3.5. It is observed that around 94 % of the facilities have shown "Satisfactory Performance" i.e. they have complied all regulatory requirements. However, it is observed that around 3 % of the facilities "Needs Improvement" which have some reported regulatory non compliances against them whereas 3 % of the facilities have shown "Unsatisfactory Performance".

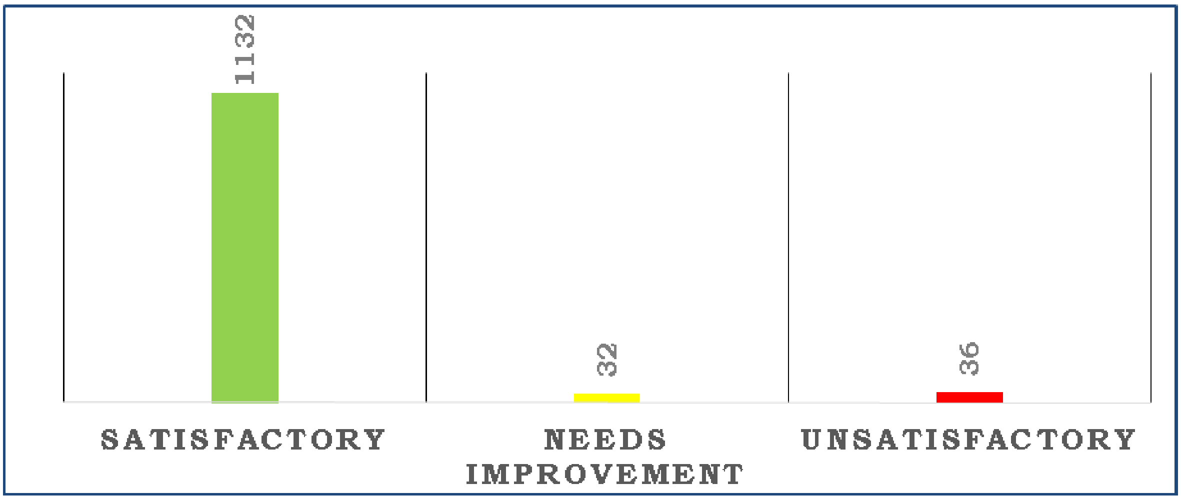



Fig. 3.5: Distribution of IR facilities Based on SPI

IR facilities falling under "Needs Improvement" and "Unsatisfactory" were further analysed to find out the root cause where no response from the facility, closing of the operation and excessive exposure case in the facility have been identified as the root causes. These are presented in figure 3.6.

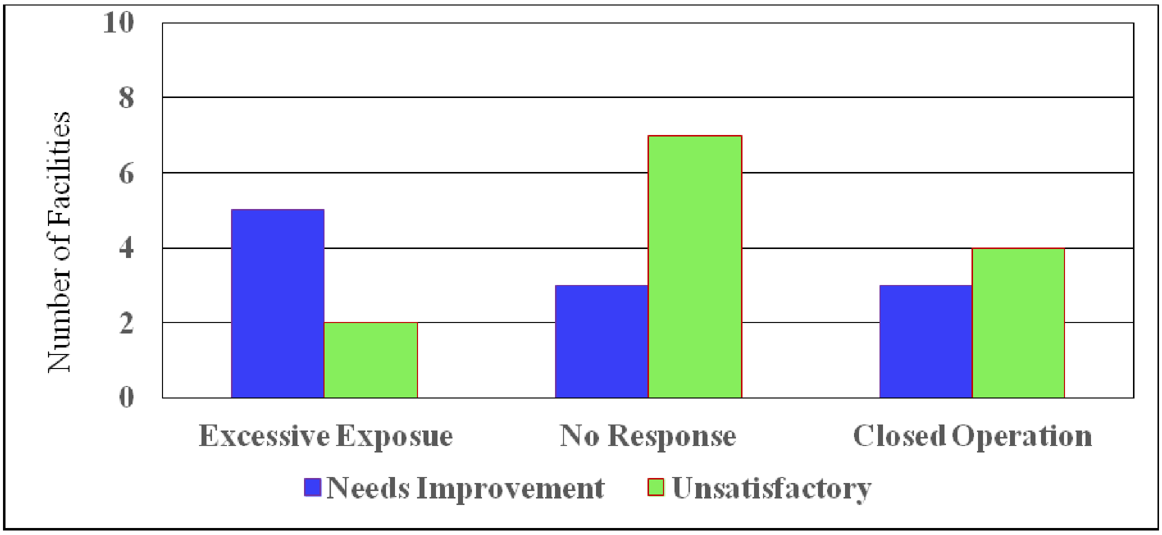



Fig.3.6: Root Cause for "Needs Improvement" & "Unsatisfactory" Performance

It is observed that majority of the Non-Compliances (NCs) are Grey category for facilities under "Needs Improvement". Non compliances (NCs) generated are of two types i.e. (i) inspection based and (ii) auto system generated for expiry of calibration of instrument, license for operation, unavailability or expiry of approval of RSO, non-submission of safety status report etc. Also, category of system generated NCs changes from lower safety significance to higher based on duration of compliance pending. For three such facilities, no response was received due to change of management whereas other three facilities have closed its operations and all equipment have been decommissioned or released to other after taking permissions. It is also observed that five facilities had excessive exposure cases. However, majority of the EEs are found non- genuine in nature.

For Facilities under "Unsatisfactory Performance", majority of the NCs are White category and mostly system generated with respect to expiry of calibration of radiation measuring instrument like radiation survey meter. Majority of Orange Category NCs under "Unsatisfactory Performance" are due to non-submission of periodic safety status report for a long time followed by NCs w.r.t unavailability of RSO. For seven such facilities, no response was received due to change of management whereas four facilities have closed its operations and all equipment have been decommissioned or released after taking permissions. Moreover, in two of such facilities, excessive exposure cases have been reported.

**Unusual Occurrences**

Accidents continue to happen mostly as a result of a lack of necessary protective measures, failure to follow procedures, and occasionally due to insufficient regulatory supervision, despite improvements in equipment design and enhanced safety systems. Some severe accidents have occurred due to inadequacy of human, procedural and equipment controls [27]. Unusual occurrences reported from facilities possessing IGREDs in India have been studied and analysed. It was observed that in the last five years, a total twenty-one unusual occurrences have been reported from radiography facilities handling IGRED. Type of the unusual occurrences that have been reported during handling of portable IGRED are given below:

a. Damage to IGRED due to improper handling – Seven incidents involving damage to IGREDs due to improper handling have been attributed due to reasons like crack on side of the coupling of male and female connection of source pigtail & damage to pigtail due to accidental fall of IGRED from height.

b. Damage to IGRED due to ageing – One incident happened due to breakage of pigtail with source and damage in female end of the pig tail.

c. Source stuck – Four incidents regarding source stuck are attributed to either damage to guide tube or damage to pigtail.

d. Damage to IGRED during transport – One event occurred due to accident of truck carrying the IGRED causing surface depression due to improper packaging.

e. Excessive exposures (EE): Out of the five excessive exposure cases, three were occurred as TLDs were mistakenly kept near the IGRED and concluded as non-genuine. One EE had occurred due to entry of personnel in radiation areas during exposure and proved to be genuine whereas another EE occurred as TLDs were used for a long time due to non-availability of fresh TLD and concluded as non-genuine.

f. Theft/ loss of IGRED – Three incidents involving theft/loss of IGREDs have been reported, out of which two happened during transport of the device and one from the source storage room.

Different unusual occurrences have been analysed using Fault Tree Analysis (FTA) which is a deductive system analysis. In FTA, basic fault chains that contribute to the unwanted event are systematically built up [40]. Probabilities for occurrence have also been calculated for different unusual occurrences. In the 1960s, the nuclear industry started to use fault trees to solve engineering problems. Boolean logics were used for fault trees to find the probability of final event [41].

Published data on probability of failure of different component or basic event have been considered for calculation of probability of unusual occurrences. The events for which data on probability of failure is not available, probability has been calculated based on the ratio of number of individual basic event (N) that has occurred to total operation hours (Z) of all licensed IGREDs in India considering a period of 5 years as all twenty-one unusual occurrences have occurred in a period of five years and 300 days of operation with daily average operation of one hour based on available data from logbook. So, total operation hours (Z) for all licensed portable IGRED comes around 2.37 E+06. It is found that unusual occurrence corresponding to "Damage of IGRED due to improper handling" contributes to 33.33 %, followed by 23.81 % to "Excessive Exposure", 19.05 % to "Source Stuck", 14.29 % to "Theft or Loss of IGRED" and 4.76 % each to "Damage of IGRED due to Ageing" and "Damage of IGRED during Transport". All three types of unusual occurrences related to "Damage to IGRED" either due to improper handling or ageing or during transport have been clubbed together and termed as "Damage to IGRED" and contributes a total 42.85 % of all unusual occurrence reported. Accordingly, four areas of unusual occurrences namely, "Damage to IGRED", "Source Stuck", "Excessive Exposure (EE)" and "Theft of IGRED" have been further analysed using FTA and probability of each such unusual occurrence has also been calculated.

Damage to IGRED

It is found from study that majority of the IGRED damage have occurred due to improper handling of the device by the radiographers. Some major events include falling of heavy objects onto the guide tube, falling of the equipment from height damaging the pigtail, explosion of hydrogen cylinder in the vicinity of the IGRED device leading to damage to the equipment, drowning of IGRED due to heavy rain leading to damage. One incident of crack on side of the coupling of male and female connection of source pigtail (female socket) due to ageing was also reported. One incident of surface depression on the equipment due to improper packaging during transport of the device to site was reported. Fault tree of the unusual occurrence "Damage to IGRED" has been presented in figure 3.7.

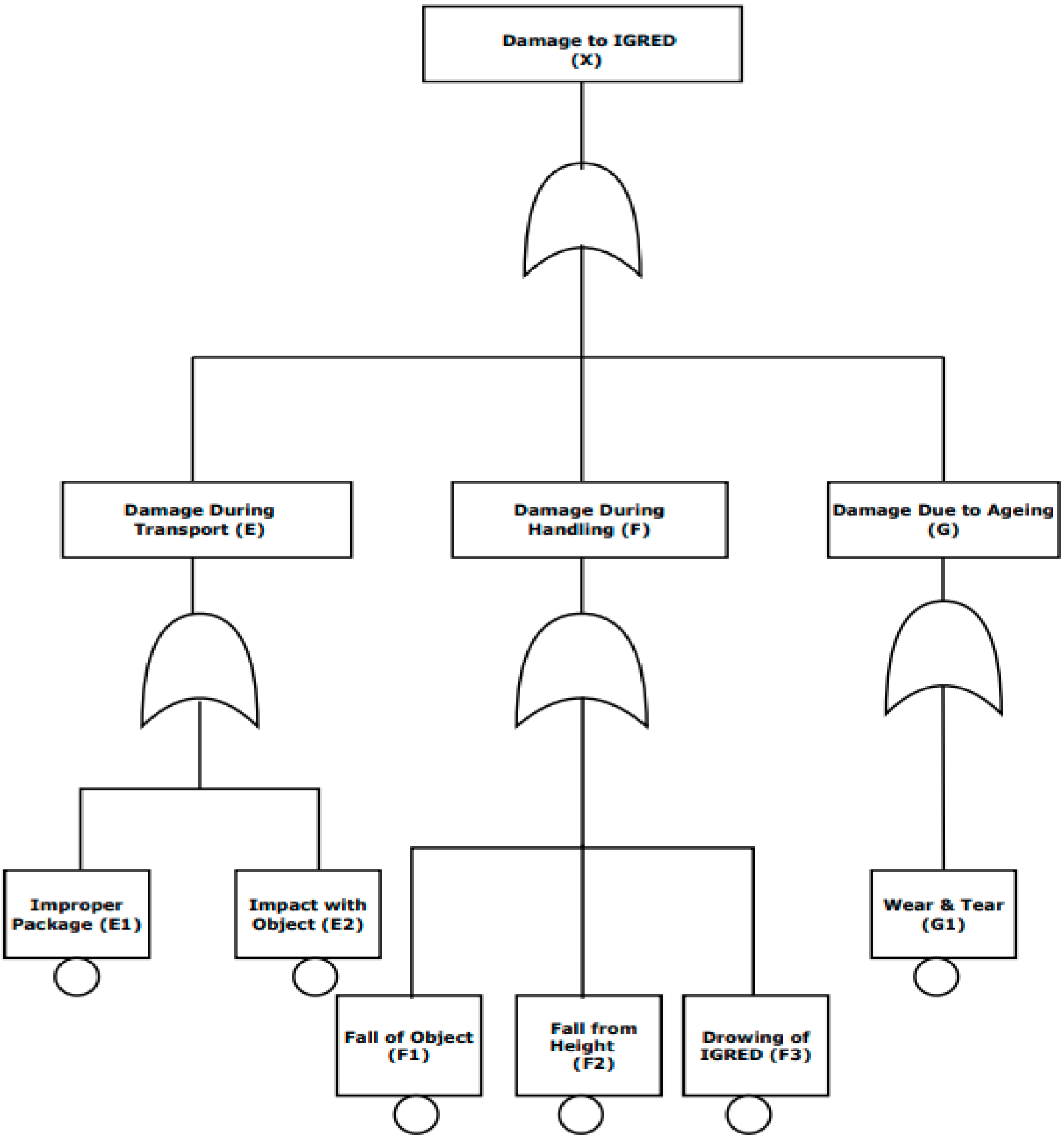



Fig. 3.7: Fault Tree of "Damage to IGRED"

All minimal cut set of the "Damage to IGRED" event is found as single component (E1, E2, F1, F2, F3 & G1) after applying the Boolean algebra where existence of each event will initiate the Damage to IGRED" event where top event X can be represented using Boolean functions of the primary input events as

$$X = E1 + E2 + F1 + F2 + F3 + G1 \text{ ------------------------ } (3.1)$$

Probability of X i.e.P(X) = P (E1) +P (E2) +P (F1) +P (F2) +P (F3) +P (G1) -- (3.2)

Probability of failure of different basic events as well total probability of unusual occurrence of “Damage to IGRED” i.e. P(X) is given in Table 3.6.

| Legend | Name of Basic Event | N/Z | Probability of Failure / hr. |
|---|---|---|---|
| E1 | Damage due to improper packaging | 1/2.37 E+06 | 4.219E-07 |
| E2 | Damage due to impact with objects | 1/2.37 E+06 | 4.219E-07 |
| F1 | Fall from Height | 2/2.37 E+06 | 8.439 E-07 |
| F2 | Object Falling on IGRED | 1/2.37 E+06 | 4.219E-07 |
| F3 | Drowning of IGRED | 1/2.37 E+06 | 4.219E-07 |
| G1 | Wear & Tear | 1/2.37 E+06 | 4.219 E-07 |
| P(X) = 1.27E-06 / hr. | | | |

Table 3.6: Probability of Occurrence of “Damage to IGRED”

Source stuck

Source Stuck has contributed to around 19 % of total unusual occurrences. This is one type of unusual occurrence which has serious consequences as the radiographer may be unaware about the situation and may also get excessive exposure unknowingly. Two cases have occurred due to damage to the guide tube of the equipment leading to inability to retrieve the source back, leading to high dose rate and excessive exposure to radiographer. In one case, damage of pigtail inside guide-tube leading to in-ability to retrieve back the source, has happened whereas in other case, breakage of pigtail from chain of control unit has occurred. Fault tree of the unusual occurrence “Source Stuck” has been presented in figure 3.8.

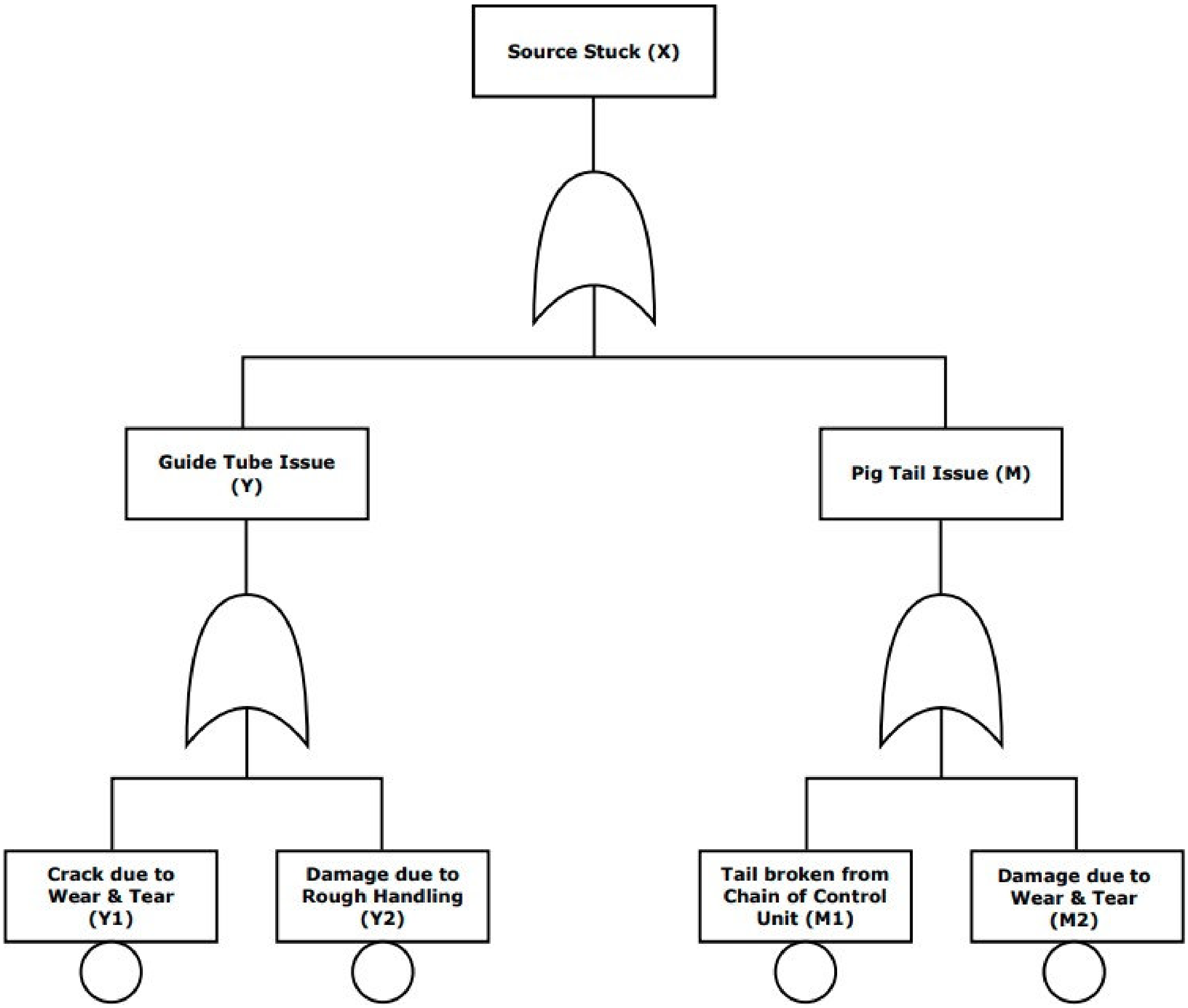



Fig. 3.8: Fault Tree of "Source Stuck"

All minimal cut set of the "Source Stuck" event is found as single component (Y1, Y2, M1 & M2) after applying the Boolean algebra where existence of each event will initiate the "Source Stuck" event. Top event X can be represented using Boolean functions of the primary input events as

$$X = Y1 + Y2 + M1 + M2 \text{ -------------------------------- } (3.3)$$

$$P(X) = P(Y1)+P(Y2)+P(M1)+P(M2) \text{ ------------------------}(3.4)$$

Probability of failure of different basic events as well total probability of unusual occurrence of "Source Stuck" i.e. P(X) is given in Table 3.7.

| Legend | Name of Basic Event | N/Z | Probability of Failure / hr. |
|---|---|---|---|
| Y1 | Crack in Guide tube due to wear & tear | 1/2.37 E+06 | 4.219 E-07 |
| Y2 | Damage to Guide tube due to rough handling | 1/2.37 E+06 | 4.219 E-07 |
| M1 | Damage to Pigtail due to wear & wear | 1/2.37 E+06 | 4.219 E-07 |
| M2 | Damage to Pigtail due breakage from chain of control unit | 1/2.37 E+06 | 4.219 E-07 |
| P(X) = 1.69 E-06 | | | |

Table 3.7: Probability of Occurrence of “Source Stuck”

Excessive exposure

Analysis of unusual occurrence related to excessive exposure (EE) have shown that three have happened due to mishandling of TLDs by radiographers as TLDs were left in radiation areas, one due to use of TLDs for long period while the other one is due to entry inside radiation area during exposure. Investigation carried by AERB has concluded four EE cases as non-genuine while one as genuine. “Lack of Safety Awareness” has been identified as root cause of these EE cases. FT of the unusual occurrence “EE” has been presented in figure 3.9.

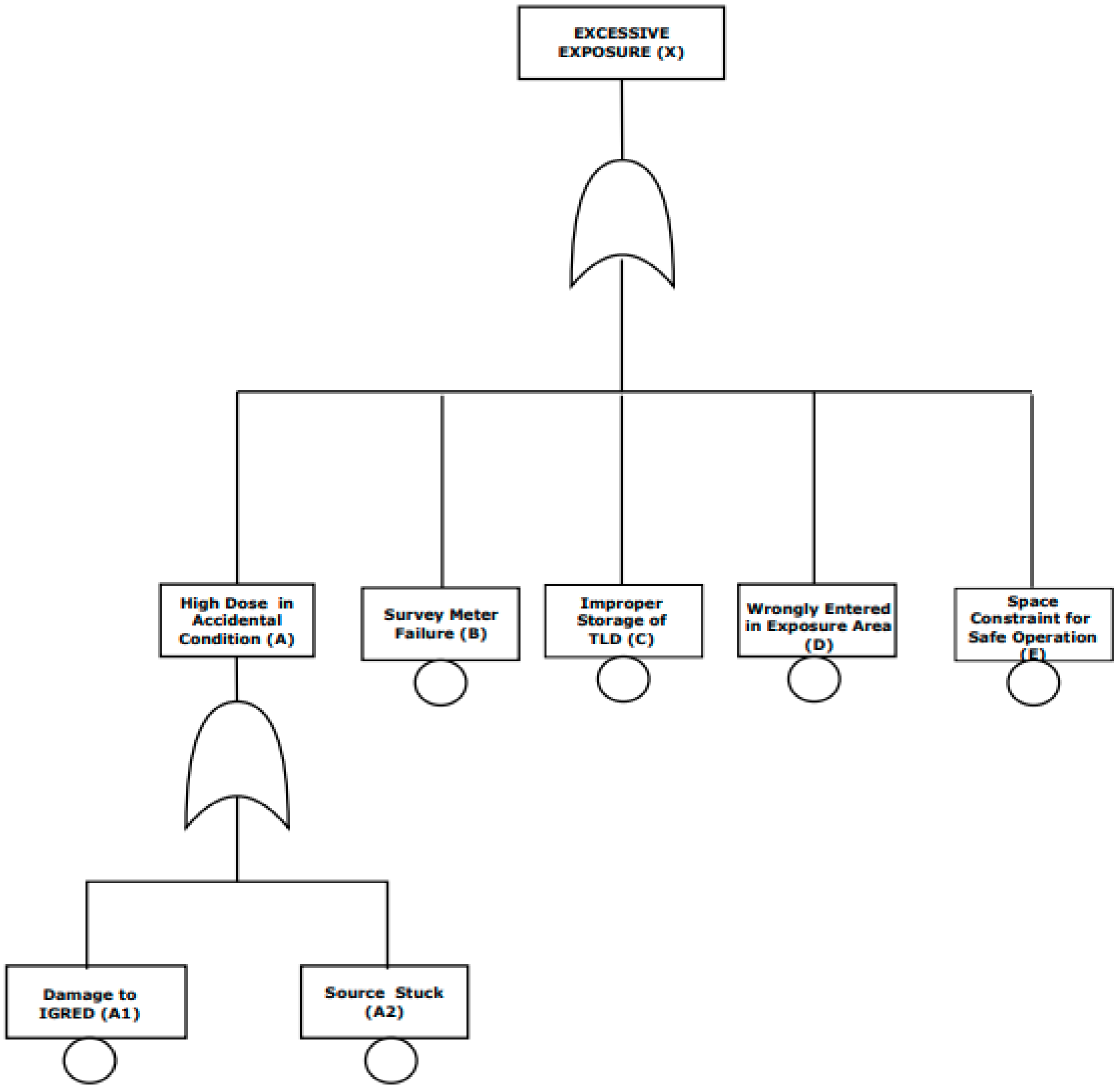



Fig. 3.9: Fault Tree of "Excessive Exposure"

All minimal cut set of the "EE" event is found as single component ( A1, A2, B, C, D & E) after applying the Boolean algebra where existence of each event will initiate the "EE" event where top event X can be represented using Boolean functions of the primary input events as

$$X = A1 + A2 + B + C + D + E \text{ ------------------------ } (3.5)$$

Probability of X i.e. P(X) = P (A1)+P (A2)+P (B)+P (C)+P (D)+P (E) -------------(3.6)

Probability of failure of different basic events as well total probability of unusual occurrence of "EE" i.e. P(X) is given in Table 3.8.

| Legend | Name of Basic Event | N/Z or Data Available | Probability of Failure / hr. |
|---|---|---|---|
| A1 | Damage to IGRED | From Earlier calculated probability of Table 3.6 | 1.27E-06 |
| A2 | Source Stuck | From Earlier calculated probability of Table 3.7 | 1.69 E-06 |
| B | Survey Meter failure | Reference [12] | 2.25 E-05 |
| C | Improper storage of TLDs | 3/2.37 E+06 | 1.26E-06 |
| D | Person wrongly entered radiation area | 1/2.37 E+06 | 4.22E-07 |
| E | Space constraint for Safe Operation | 1/2.37 E+06 | 4.22E-07 |
| P(X) = 2.65 E-05 / hr. | | | |

Table 3.8: Probability of Occurrence of “Excessive Exposure”

Theft of IGRED

Out of the three cases of theft of IGRED device, two have been reported during transport of IGRED and one has been reported during storage of IGRED. Both the incidents related to road accidents during which the equipment was theft by passerby and sold to scrap dealers. The event relatedtotheft of IGRED from storage has been attributed to unavailability of security provisions like security guard, CCTV and Lack of chain and locking mechanism. Fault tree of the unusual occurrence “Theft of IGRED” has been presented in figure 3.10.

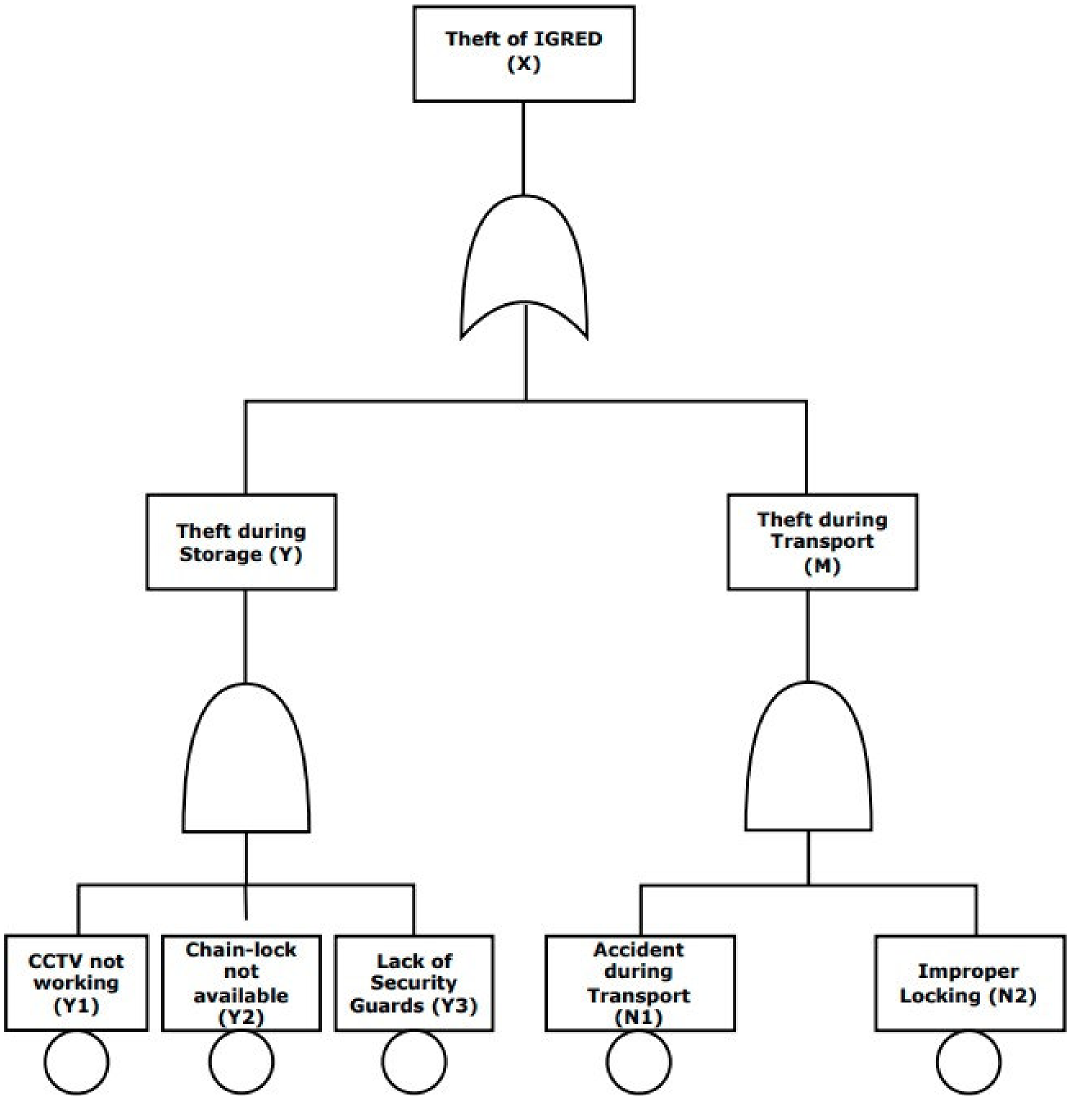



Fig. 3.10: Fault Tree of "Theft of IGRED"

Two minimal cut set of the "Theft of IGRED" event is found consisting of a triple component (Y1. Y2. Y3) and a double component (N1.N2) after applying the Boolean algebra where existence of each event will initiate the "Theft of IGRED" event where top event X can be represented using Boolean functions of the primary input events as

$$X = (Y1.Y2.Y3) + (N1.N2) \text{ ----------------------------- } (3.7)$$

As all the events Y1, Y2, Y3, N1 & N2 are independent,

$$P(X) = P(Y1).\ P(Y2).P(Y3)+P(N1).P(N2) \text{ ------------------ } (3.8)$$

Probability of failure of different basic events as well total probability of unusual occurrence of “Theft of IGRED” i.e P(X) is given in Table 3.9. In Case of “Theft of IGRED”, total hours (z) for the events to occur has been considered accounting all licensed portable IGRED for the past five years with 365 days and 24 hours in a day as theft can occur at any moment and the same comes around 6.92 E+07

| Legend | Name of Basic Event | N/Z | Probability of Failure / hr. | P(Y1).P(Y2).P(Y3) &P(N1).P(N2) |
|---|---|---|---|---|
| N1 | Accident during Transport | 2/6.92 E+07 | P(N1) =2.89 E-08 | P(N1).P(N2)= 8.352E-16/hr. |
| N2 | Improper Locking | 2/6.92 E+07 | P(N2) =2.89 E-08 | |
| Y1 | CCTV not working | 1/6.92 E+07 | P(E1) =1.45E-08 | P(Y1).P(Y2).P(Y3) =3.02E-24/hr |
| Y1 | Chain lack not available in storage | 1/6.92 E+07 | P(E2) =1.45E-08 | |
| M2 | Lack of Security guards | 1/6.92 E+07 | P(E3) =1.45E-08 | |
| P (X) = P (Y1).P (Y2).P (Y3)+P (N1).P (N2) = | | | | 8.35E-16/hr. |

Table 3.9: Probability of Occurrence of “Theft of IGRED”

Summary of probability of different types of unusual occurrence is presented in Table 3.10

| Unusual Occurrence | Probability of Occurrence |
|---|---|
| Damage to IGRED | 1.27 E-06 /hr. |
| Source Stuck | 1.69 E-06 /hr. |
| Excessive Exposure | 2.65 E-05 /hr. |
| Theft of IGRED | 8.35 E-16/hr. |

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Table 3.10: Probability of Occurrence of Different Events

# CHAPTER- 4

# DESIGN & DEVELOPMENT OF IoT BASED RADIATION MONITORING SYSTEM FOR INDUSTRIAL RADIOGRAPHY

*As conventional radiation survey meter is unable to prevent excessive exposure of radiographers either due to failure or non-use of the same, an IoT based radiation monitoring system for industrial radiography has been designed and developed for continuous and real-time measurement of radiation level during operation of the radiography equipment with a focus on field/site radiography. The system uses GM counter, Arduino microcontroller, ESP 8266 Wi-Fi module and Thingspeak IoT analytics platform. The system has provision for radiation data storage on cloud and analysis of the data. Details of developments and test results have been presented in Chapter -4.*

## Radiation Monitoring

Radiation monitoring in industrial radiography is crucial to ensure safety of the radiographers and the general people . The most crucial safety tool for radiographers is the Radiation Survey Metre (RSM), which is used to verify the return of source inside shielding of gamma exposure device after each exposure and that the shielding of the exposure device is intact before use or transport [42]. The radiation survey metres are used when approaching the IGRED and also it needs to be surveyed after each radiography exposure to prevent unintentional exposures.

## Types of Radiation Monitoring

Radiation monitoring instruments of industrial radiography facility includes Radiation Survey Meter (RSM), Area Radiation Monitor (ARM), Personnel Monitoring Device (PMD), Direct Reading Dosimeter (DRD) and Audible Alarm Rate Meter (AARM).

Radiation survey meter

Ion chambers and Geiger-Muller (GM) counters are the two types of radiation survey meter (RSM) used in IR. An electric field is applied across a volume of gas between two electrodes in an ion chamber or GM counter. The ion chamber can measure all ionising radiation types, but it is thought to be more accurate with X-rays. GM counter uses a gas-filled tube acting as cathode surrounding a central electrode which acts as an anode. The counter measures individual particles or ions, but if there are too many ions, it will become saturated. Although, Geiger counters are more sensitive than an ion chamber survey meter, the same is generally used to detect low to medium levels of radiation. GM counter loses accuracy measuring higher levels

[43]. Due to the same reason, ion chamber survey meter are used for X-ray based equipment by most industrial radiographers. It is required that all the survey meters be calibrated by a certified calibration agency periodically. RSMs used in IR are shown in figure 4.1


Fig. 4.1: Radiation Survey Meter

Area radiation monitor

Area radiation monitors are generally installed for enclosure radiography where detector is kept in the vicinity of the radioactive source inside the enclosure and display unit is kept in in operator’s location. Pre -set audio – visual alarm exist for alert & action in case of unwanted radiation exposure. Area Ration Monitors installed at the entrance of the enclosure is shown in figure 4.2.


Fig. 4.2: Area Radiation Monitor

Personnel monitoring device

At present, the most commonly used personnel monitoring device (PMD) is the thermo luminescent dosimeter (TLD) badge. TLD consists a thermo luminescent crystalline material which absorbs and traps some energy of the ionising- radiation when exposed to the same. The trapped energy is released as light when the material is heated later on and intensity of light emission depends on the intensity of the incident ionising radiation. One of the commonly used TLD badge is made up of three CaSO4: Dy discs positioned in a steel cage and encased in a multi-filter (Cu, Al and plastic) cassette. The beta, gamma, and x-ray doses can be tracked using the TLD badge. It is possible to discriminate between doses caused by various types of radiation because of various filters included in the badge. The TLD badge can measure doses in the range of 0.1 mSv to 10 Sv. Apart from TLD badges, film badge and optically stimulated luminescence dosimeters (OSLDs) are also used in different countries. A TLD has several advantages over other PMDs, including a linear response to dose, a relatively low energy requirement, and sensitivity to low dose. Another advantage is its reusability over film badge. Major disadvantage associated with use of TLD badge is that it cannot provide instantaneous report of dose received during radiation work. Details of TLD badge used in India for dose monitoring is shown in figure 4.3.

Fig. 4.3: TLD Badge Used in India

Direct reading dosimeter

Direct reading dosimeter (DRD) is a dose monitoring device which provides an instantaneous reading of the dose received by a person. These dosimeters could be electronic like pen dosimeters, pocket dosimeters, or they could be air ionisation chambers [1]. DRD can record a dose in the range of 1mSv to 100 Sv. DRD performs a similar function like that of TLD badge except the later records the dosage over a longer period of time (monthly for industrial radiography in India). While handling the radiography equipment, the radiography personnel use DRD in addition to TLD. Radiographers can monitor the dose received during radiography work and protect them from excessive exposure. Conventional DRDS are analog in nature as shown in figure 4.4. However, digital dosimeters with provision to set alarm, are available in market nowadays.

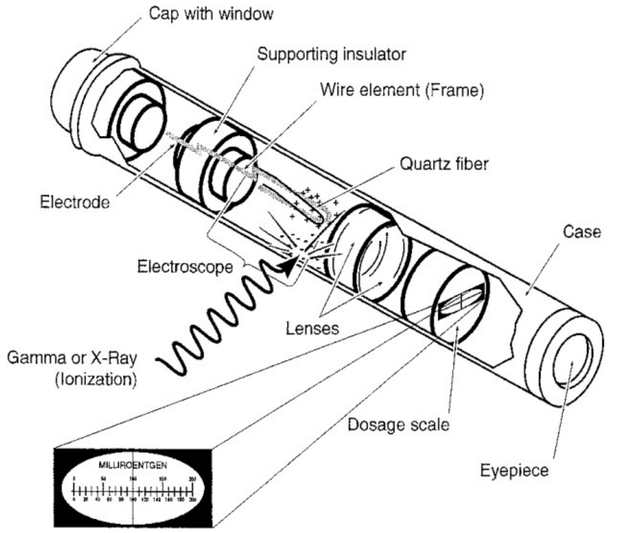



Fig. 4.4: Conventional Pocket Dosimeter

Audible alarm rate meter

Audible alarm rate meter is a portable radiation monitoring instrument that generates a beep sound when exposed to a pre-fixed amount of radiation. The instrument contains a GM counter and output of the counter is collected and when pre-fixed amount of exposure is exceeded, the collected charge is discharged through a speaker emitting an audible sound. Rate of beep sound is directly related to the intensity of radiation. These instruments can minimise the possibility of unintentional exposures to the industrial radiographers, when properly used. Typical alarm rate metres operate between 0.45 and 0.5 mSv/hr of radiation level [44].


Fig. 4.5: Audible Alarm Rate Meter

**IOT Based Radiation Monitoring**

Conventional radiation monitoring systems involve manual collection of data, which may lead to delays in detecting radiation anomalies or potential safety breaches. Also operator might forget to do radiation survey and as a result, excessive exposure can occur. From accidents happened in industrial radiography, it has been observed that in majority of the time, affected radiography personnel either did not use or improperly used a RSM. In the majority of situations, the affected person did not follow the proper steps, namely failing to conduct a sufficient survey [17] or the RSM was not functioning properly and also not calibrated [45]. Traditional radiation monitoring is performed manually to detect presence of radioactive materials or source, on the other hand online radiation monitoring will allow continuous, real-time measurement and monitoring of radiation levels during IR operation. This ensures immediate detection of any abnormal radiation level enabling prompt action to mitigate risks and to ensure safety of the workers. The online radiation monitoring is done using an IoT based approach. Greengard, 2015 mentioned that the Internet of Things (IoT) was conceived as a means of information exchange in 1999 and was proposed by Kevin Ashton [46]. IoT refers to a group of connected, data-exchanging gadgets that link to one another and the cloud. Mechanical, digital, and consumer products can all be used as IoT devices because they are often embedded with technology like sensors and software [47]. In the last two decades, IoT has developed to contain a variety of operational modes, including access points, Bluetooth, Wi-Fi, infrared and sensor based waste bin. It also monitors the environment and uses IoT for irrigation, traffic and healthcare systems [48]. IoT based radiation monitoring system will help greatly to take preventive measures and alleviate the risk of excessive exposure to radiography persons.

**Literature Review**

Though not for industrial radiography work, some research have already been carried out on IoT based radiation monitoring for other applications of radiation like that for measurement of radon concentration, background radiation detection, nuclear emergency preparedness, dose received from natural and artificial radioisotopes.

Mbarndouka T. J. et al., 2022 manufactured a smart electronic device for radiation protection and nuclear security [49]. A temperature and relative humidity (RH) sensor, an arduino microcontroller board, and XBee-based wireless communication modules made up the device. The reference device monitors the relative humidity, temperature, and radon content in enclosed spaces.

Holovatyy A. et al., 2020 developed a micro controller based system radiation measurement system for background radiation [50]. The radiation level is measured by the microcontroller system, which also evaluates the data it receives and sends it to the PC. When the radiation level exceeds a certain point, an alert signal is sent. The Arduino Uno board, which is based on the ATmega328P microprocessor, was used to build the system. Hardware and software are both included in the designed system. The created system consists of 'data processing module, components for environmental data collecting and control, and elements for displayed processed data'. A gas-discharge Geiger-Mueller "SBM-20" tube wasused to obtain the radiation level data.

Muhtadan et al., 2020 developed a radiation monitor area device working based on IoT technology and consisted of micro-controller and GM detector to support preparedness for radiological emergency in the "Yogyakarta Nuclear Area (YNA)" [51]. The IoT based radiation monitor was designed for analysing the nuclear emergency potential in the nuclear emergency preparedness and response system.

An Internet of Things-based radiation monitoring system was developed by Mahatab T. A. et al., 2018 [52] using microcontroller, geiger counter and humidity, light & temperature sensors. The acquired data were stored and monitored in real time through the online interface. The findings indicated that a relation between light intensity and radiation exists, but there is no relation between humidity or temperature and radiation in the area under consideration.

In order to get real-time data on the radiation dose that people receive when exposed to natural or artificial radioactive sources, Navarro R. B. et al., 2020 developed an IoT-based environmental dosimetry instrument [53].

Saifullah M. et al., 2022 created an IoT enabled intelligent system for radiation measurement and notification by identifying nature of radiations and related effects on newborns [48]. Data collected by the system are stored in data base for further use. Different sensors like electromagnetic, gamma radiation, infrared, ultraviolet are linked to the microcontroller. The system uses a mobile application based on android technology to notify the user when the radiation intensity reaches an alarming level.

An IOT based radiation monitoring system has been developed for industrial radiography facility. The system detects immediately any abnormal radiation level, enabling prompt action to mitigate risks of workers, the members of the public and the environment. The subsequent section describes architecture of the system and test result.

**System Design & Development**

Block diagram of the IoT based radiation monitoring system design for IR operation has been shown in figure 4.6.

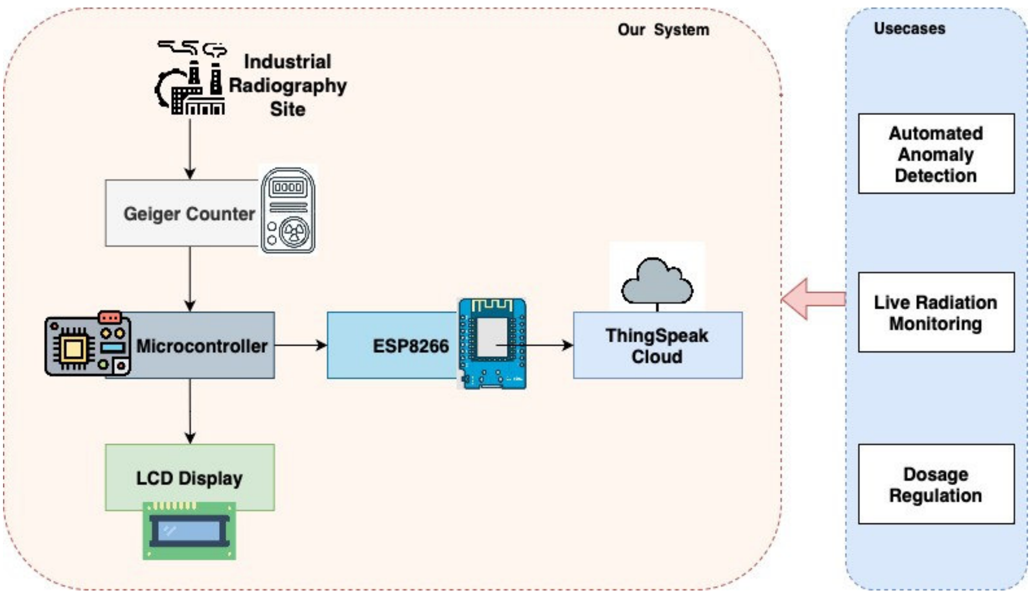



Fig. 4.6: Block Diagram of the IOT Based Radiation Monitoring System

Different components used for making the IoT base d radiation monitoring system are described below:

i) Geiger Muller (GM) Counter

Ionising radiation like beta particles and gamma rays are detected and measured most commonly using a GM counter. Ionising radiation like gamma rays and beta particles are detected and measured using a GM counter. Inert gas like helium, argon are filled inside the tube which turns electrically conductive when a high-energy particle strikes it [54]. For radiation measurement in IR operation, an assembled GM tube has been used. The GM tube is capable of detecting gamma rays within the range of 20 mR/hr to 120 mR/hr. Additionally, it can detect soft beta rays within the range of 100 to 1800 counts per minute (cpm) per square centimeter. It requires 5V power supply. The maximum count rate of the tube is 25 times/min and life is greater than 1 x $10^9$ pulse. The module is compatible with arduino. Photograph of the 'Geekcreit Assembled Geiger Counter' has been shown in figure 4.7.


Fig. 4.7: Assembled Geiger Counter

ii) Microcontroller

An integrated circuit that houses a tiny computer is called a microcontroller. In terms of modern terminology, it is comparable to but less complicated than a system on a chip (SoC). A SoC can have a microcontroller as one of its components. The memory, programmable input/output peripherals, and one or more CPUs are all included in a microcontroller. As compared to a microprocessor, a microcontroller has the various components such as memory, I/O module, clock module all built into a single chip. This reduced dependence on external chips enable them work at a very low power consumption [55]. For the IoT System, 'Arduino UNO Rev 3' microcontroller development board has been used. It is based on the 'ATMega328P – Atmel's 8 Bit AVR microcontroller with 32KB of programmable flash memory' [56]. The large programmable flash memory allows for a larger and more complicated application logic to be deployed as required in the case of the IoT based radiation monitoring system. It contains '6 analogue inputs, a 16 MHz ceramic resonator, a USB port, a power jack, an ICSP header, and a reset button'. All components required to support the functions of the microcontroller is included and it requires only a power source like battery, USB connection, AC to DC adapter for use. Photograph of the Arduino development board is shown in figure 4.8.

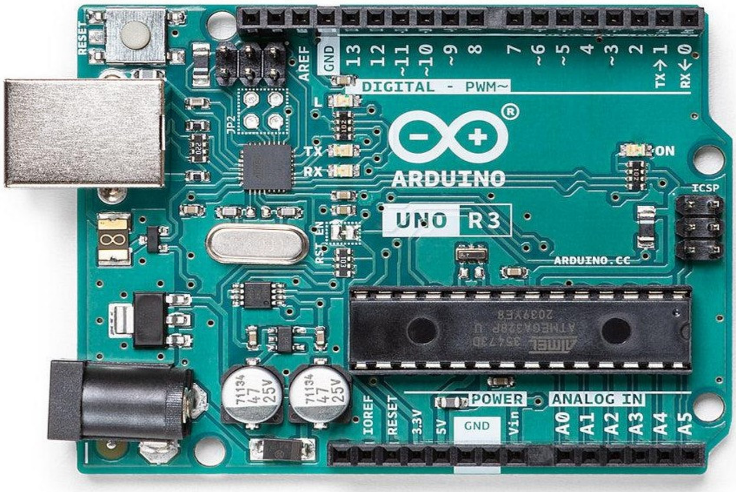



Fig. 4.8: Arduino Uno R3 Development Board

iii) Wi-Fi Module

'ESP8266 Wi-Fi' module has been used which receives data from microcontroller and uploads to IOT platform. 'ESP8266' is a system on chip (SoC) module that supports Wi-Fi and is mostly used for creating embedded Internet of Things applications. A set of AT instructions are used by the microcontroller in order to communicate with the 'ESP8266' module [57]. Photograph of ESP8266 is shown in the figure 4.9.

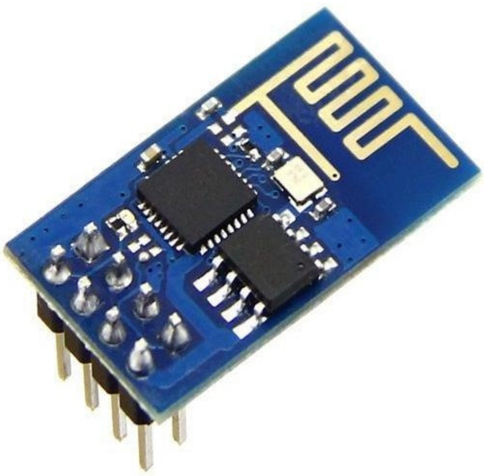


Fig. 4.9: ESP 8266 Wi-Fi Module

iv) IoT Analytics Platform

The Wi-Fi module uploads the live radiation measurements to ‘Thingspeak’, an IoT analytics platform service allowing users to analyse the recorded data from anywhere around the globe. ‘Thingspeak’, open source platform for Internet of Things devices, enables users to upload and log data, analyse, retrieve, and store findings by graphical representation with Matlab support [58].

The square wave pulses sent by the GM tube are received in the microcontroller as counts. The number of counts recorded is then used for calculating the counts per minute (CPM). As per characteristic of the tube, 151CPM equals to 1μSv/hr and accordingly, CPM is changed to μSv/hr. with the index [54]. Microcontroller communicate with the ESP8266 module using set of AT commands. The Wi-Fi module uploads the live radiation measurements to ThingSpeak, a platform for IoT analytics to enable cloud-based aggregation, visualisation, and analysis of real-time data streams. ThingSpeak provides immediate visualizations of data sent by ESP 8266 module. This cloud based data storage would enable facility to keep a track of radiation exposures during industrial radiography and take necessary steps as deemed to be fit. Diagram of the developed Radiation Survey Meter is shown in figure 4.10.

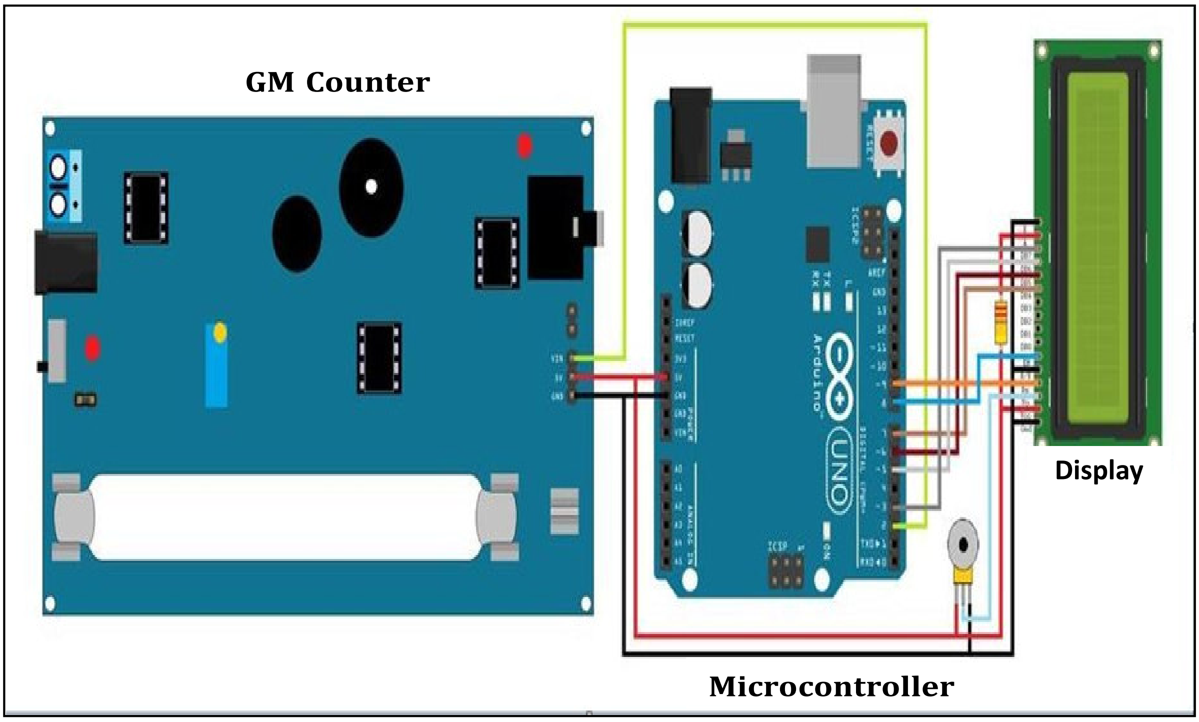



Fig. 4.10: Circuit Diagram of Developed Radiation Survey Meter

**Testing of the Developed Radiation Survey Meter**

Initially, the radiation detection system was tested in-house to check its functionality as shown in figure 4.11.

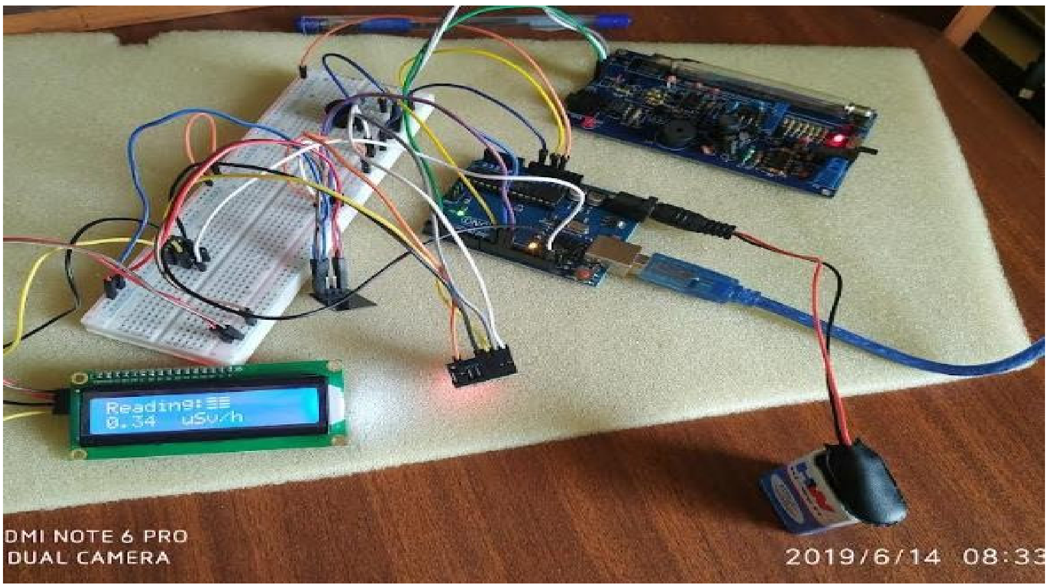



Fig. 4.11: In-house Testing of RSM

Subsequently, the system was tested on field using a ROLI-3 portable IGRED containing an Ir-192 radioactive source of activity 9.7 Ci. Radiation levels were measured at different distances ranging from 0.05 m to 4.5 m from the ROLI-3 device during "NO Exposure" condition (i.e. the source is inside shielded enclosure of the device) and at 20 m, 25 m and 30 m distances during "Exposure" condition. Two standard RSMs; one Thermo Scientific RadEye PRD and another Pulsecho Minirad were also used simultaneously side by side to record the radiation levels at the same location for comparison of the effectiveness of the developed system. Figure 4.12 (i) & (ii) given below present comparative results of radiation level measured during "No Exposure" (source is in shielded position) and "Exposure" condition respectively using three different RSMs.

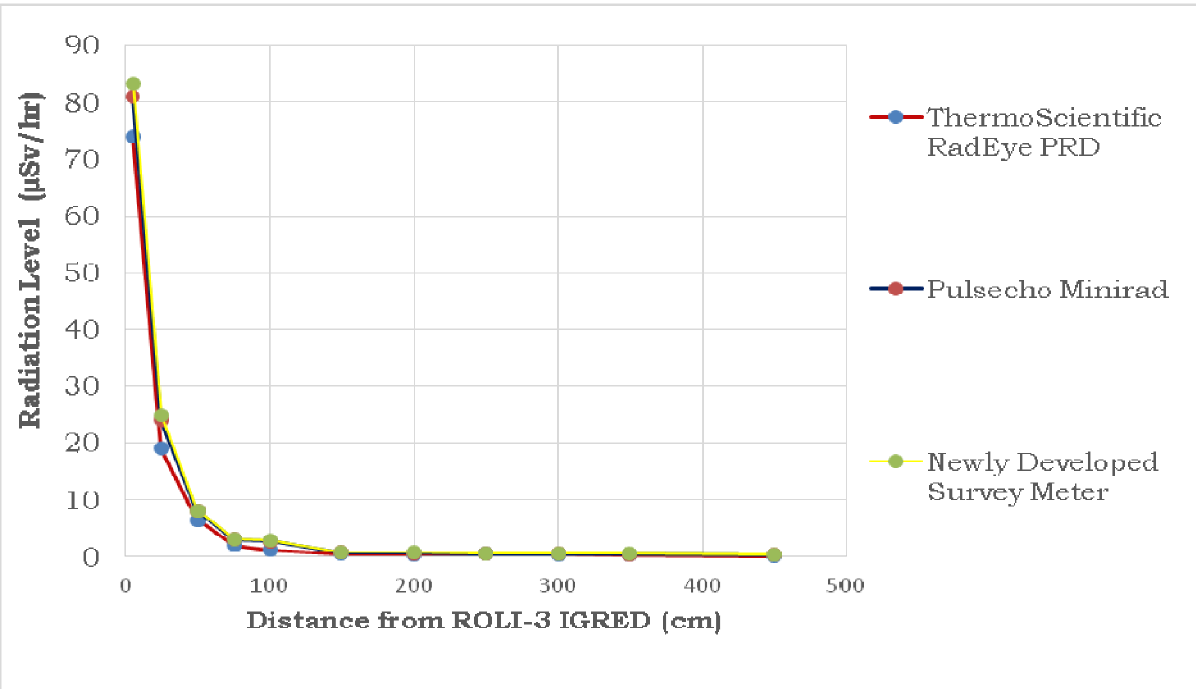



Fig. 4.12 (i)

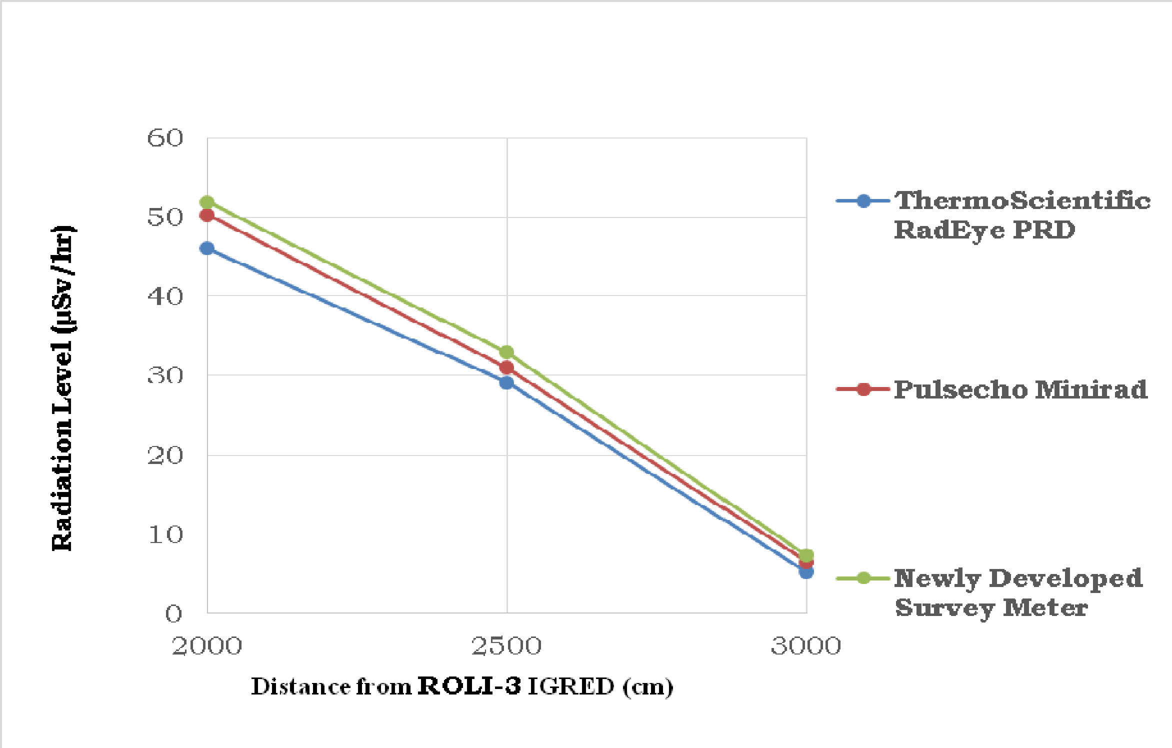



Fig. 4.12 (ii)

Fig. 4.12 (i) and (ii): Radiation Levels Measured during "No Exposure" and "Exposure" Condition Using Three RSMs

### Accuracy of the System Developed

Mean Absolute Error (MAE) between the radiation levels measured by the system developed and other two survey meters used for reference are calculated in order to check accuracy of the system developed. For calculating MAE, the following formula is used.

$$MAE = \frac{\sum_{i=0}^{n} |x_i - \hat{x}_i|}{n} \quad \text{.......................................................(4.1)}$$

Here $x_i$ refers to the radiation measurement obtained at a certain distance from the system developed, $\hat{x}_i$ refers to the radiation measurement obtained at the same location from the reference device and n is number of observations. It is found that difference of reading is higher comparatively at high radiation level. It is seen that the developed radiation survey meter had a MAE of 0.58 μSv/hr and 2.31 μSv/hr with respect to the Pulsecho Minirad and the Thermo Scientific RadEye PRD respectively with comparatively higher differences are observed during exposure situation. This indicates that the prototype device developed is working accurately in radiography operation.

**Radiation Data Uploading & Monitoring**

The ThingSpeak channel where the outputs recorded by the developed system are transmitted and analyzed is shown in figure 4.13. Apart from displaying the current radiation measurement, historical readings are also available. This thus enables facility to constantly monitor the radiography operation and detect any abnormal radiation level.

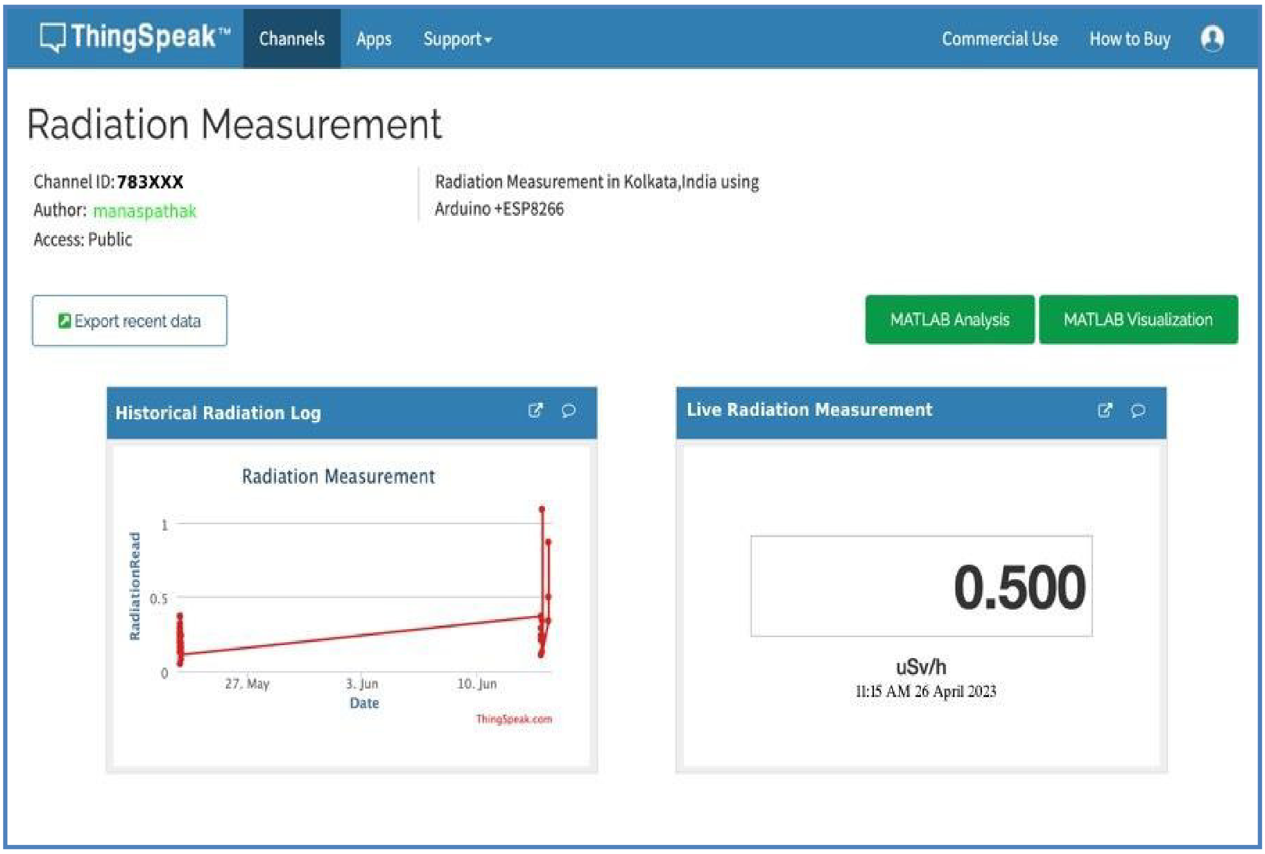



Fig 4.13: Portal for Visualising & Analyzing Radiation Data

**Pseudo Code for IoT Based Radiation Monitoring System**

**Algorithm 1** Initial Setup

```
global variables
    Counts, Number of interrupts received
    Last ReadTime, Time when last measurement was read
    ReadInterval, Interval after which we take a new reading
end global variables
procedure setup
    counts ← 0                                  ➢ Initialise the counts
    LastReadTime ← 0
    ReadInterval ← 15                           ➢ In seconds
    Initialise the i2c LCD Display
    Initialise the WiFi Module
    Set TUBE_IMPULSE as the interrupt handler for Geiger counter
    while True do                               ➢ Run infinitely
        call SENSOR_READ
    end while
end procedure
```

**Algorithm 2** Interrupt Handler

```
global variables
    Counts
end global variables
procedure tube_impulse
    counts ← counts + 1              ➢ Increment the number of interrupts received
end procedure
```

**Algorithm 3** Radiation Measurement

```
global variables
    Counts
    LastReadTime
end global variables
procedure Sensor_Read
    CurrentTime ← Current Time in Second
    if CurrentTime − LastReadTime ≥ ReadInterval then
        LastReadTime ← CurrentTime
        cpm ← Counts ∗ 4             ➢ How many times we read in a minute
        Reading ← cpm/151            ➢ Convert to μSv/h
        Display Reading on LCD
        Upload Reading to cloud via WiFi Module
    end if
end procedure
```

# CHAPTER - 5

# AUTOMATED CRANKING OPERATION OF PORTABLE INDUSTRIAL GAMMA RADIOGRAPHY EXPOSURE DEVICE (IGRED)

*At present, all the portable IGREDs are operated by manual cranking from a distance. Sometimes, due to unavailability of enough space for operation of the device from a distance like that of inside of a vessel or tank, operators get accidental radiation exposure. In order to solve this problem, automated cranking operation of a portable IGRED has been done. ROLI-3 device has been selected for the same as it is one of the commonly used device in India. The electrical & control system uses a NEMA 127 hybrid stepper motor, RMCS-1102 driver, arduino microcontroller, IR sensor and mechanical system like chain & sprocket arrangement and overload protection system including ball detent mechanism, compression spring and locking ring. Details of the works carried out with test results have been discussed in chapter -5.*

**Need of Automated Cranking**

At present, industrial radiography exposure device is designed as per ISO 3999:2004. As per the design, radioactive source is required to be kept in shielded condition inside a housing called as exposure device. For radiography operations, cranking unit is required to be rotated manually. The source assembly is required to be connected with the cranking unit by a cable to drive it out from the shielded position inside the guide tube. After completion of radiography work, source is brought back inside the shielded container, using reverse rotating of the cranking unit. Existing process for operation of IGRED in enclosure radiography is given in figure 5.1 where shielding is provided by means of structural wall and the drive cable is operated manually cranking through a small hole generally made in "S" shape on the wall to prevent radiation streaming [59] and the source is taken back inside the exposure device after completion of the radiography.

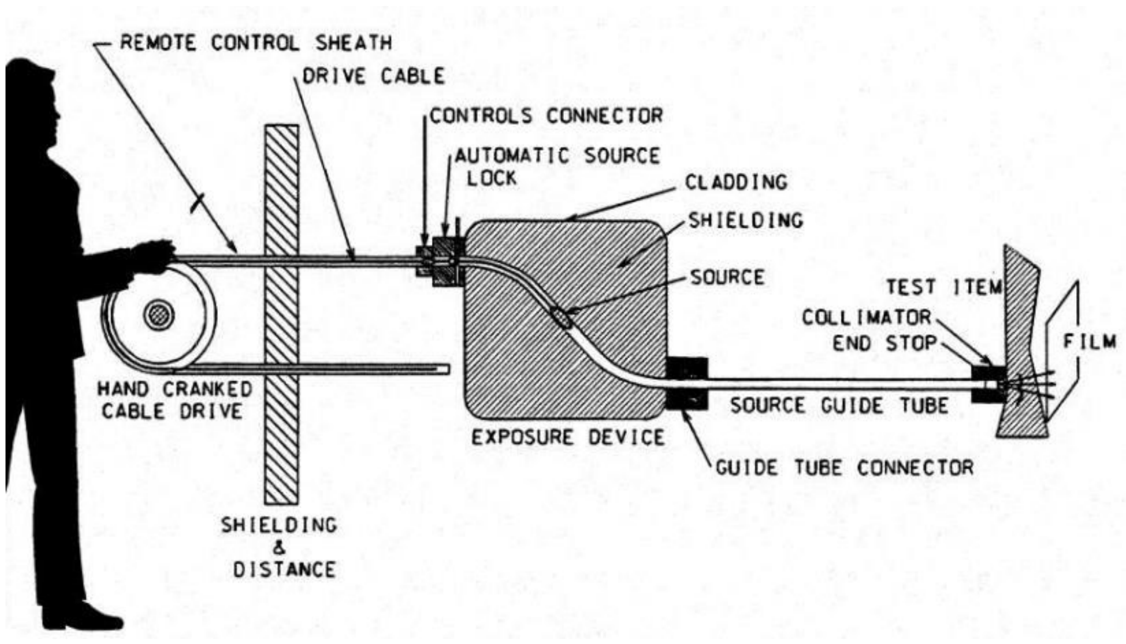



Fig. 5.1: Operation of IGRED in Enclosure Radiography

However, during field radiography, there is no such shielding arrangement and only option is manual cranking of the drive system from distance. Also, for some jobs, safe distance in order to reduce the dose to the extent possible could not be made and radiographers are forced to work in close proximity of the source and get a significant amount of dose. Accordingly, there are possibility of radiation exposure hazard in field radiography. Instead of manual cranking system for giving exposure and for retracting the source after exposure, use of motor driven automated system for movement of radioactive source will allow workers to remain at far distance from the radioactive source. Since, radiation intensity follows inverse square law, change of distance between the source of radiation and the position of operator will cause significant changes in exposure. In order to reduce the unwanted radiation exposure of the radiographers and to meet the ALARA principle, automated cranking operation of a portable IGRED has been designed and developed, keeping intact the manual provision.

**Literature Review**

Though no significant work has been done for automated cranking operation of portable IGRED, some works related to automation of other systems were consulted in design and development of automated cranking operation of portable IGRED.

In order to automate the coal feeding rate of thermal power plant, Das S. et al., 2013 used a microcontroller and a stepper motor with safety interlocks in the motors [60]. In the system design, PIC 16F72 microcontroller, unipolar stepper motor with 1.8 degree step angle and ULN2308 stepper motor driver were used to modify the feed rate while taking into account energy demand during peak and off-peak hours by adjusting the speed of the conveyor belt's motor. This system's interlocks trigger the motors in the event of any anomaly, protecting the system from damage.

To enable medical professionals and other supporting staffs to focus on their primary responsibilities rather than engaging in window opening and closing, Nnamdi S. O. et al., 2017 devised an automatic window opening and closure system during and after a rain fall respectively [61]. When a moisture detection sensor gives a signal to the system's microcontroller, it becomes activated. Stepwise window control is made possible by the microcontroller's activation of the stepper motor through an integrated circuit (IC) chip. As a result, the window closes itself when it detects rain but remains open when it doesn't. Susilo et. al., 2018 built microCT from digital radiography and moved the object with a stepper motor under the control of a microcontroller [62]. Stepper motor, CMOS detector, microprocessor and digital radiography unit made up the system. Using a computer, 2D image slices taken by rotating the object from 0 degree to 360 degree were combined to create a 3D image.

**Selection of IGRED**

ROLI-3 portable IGRED, manufactured by Board of Radiation and Isotope Technology (BRIT), India has been selected for automated cranking operation due to its ease of availability and rugged construction. Photograph of ROLI-3 IGRED has been shown in figure 5.2.


Fig. 5.2: ROLI-3 Portable IGRED

Features of ROLI-3 Portable IGRED is given below in Table 5.1 [32].

| Sl. No. | Items | Specifications |
|---|---|---|
| 1. | Exposure Device | |
| i) | Name & Model | ROLI-3, cranking operated, Type (A) |
| ii) | Category of the IGRED | Portable |
| iii) | Gross weight | 25 Kg |
| iv) | Overall outside Measurement | 390 m.m. (Length), 181 m.m. (Width) and 300 m.m. (Height) |
| v) | Maximum source capacity | 0.74 TBq (20 Ci) of Ir-192 |
| vi) | Exposure mechanism | Manual operated Teleflex cable drive from distance |
| 2. | Source Housing | |
| i) | Material of shielding & its weight | Lead and heavy alloy |
| ii) | Maximum thickness and minimum | Heavy alloy (Tungsten): Max. : 35 mm and Min. :9 mm, Lead: Max. : 67 mm and Min. : 16 mm |
| iii) | Source location from external reference points | 140 mm approx. from lock position |
| iv) | Leakage radiation at maximum source activity | |
| a) | At 5 cm from the IGRED | 0.42 mSv/hr |
| b) | At 100 cm from the IGRED | 0.009 mSv/hr |
| 3. | Safety Provisions | |

| | | |
|---|---|---|
| i) | Locking mechanism | ▪ Godrej cam lock provided on the back cover to keep the camera in locked condition.<br>▪ Safety interlocks which holds the source holder in safe position and allows the source holder to move forward only after connecting the drive system with interlock, then unlock the key operated lock provided in the interlock and press the source holder release knob.<br>▪ Front arrestor mechanism stops the source coming out of the camera accidently. |
| ii) | Is it possible to remove the source component from the apparatus without using the drive mechanism? | No |
| iii) | Collimation | Yes, Tungsten collimator is used |
| 4. | Radioactive Source Assembly | |
| i) | External dimensions | Outer capsule 6.5 mm OD x 25 mm long |
| ii) | Gross weight | Pigtail assembly 20g |
| iii) | Materials of construction | |
| | a) Source capsule | SS-316 (L) |
| | b) Source holder | Consist of Teleflex cable and ball & socket arrangement. |
| iv) | Classification number and produce certificate issued along with the source | RC-2-RT-Ir |
| v) | Type of coupling provided between the source assembly and driving mechanism | Ball and socket |
| 5. | Source Drive System | |
| i) | Type | Manually operated from distance |
| ii) | Gross weight | 12 Kg |
| iii) | Overall external dimensions | 530 mm (L) x 370 mm (H) x 181 mm (W) |
| iv) | Source guide tube assembly | |
| | a) Material | Flexible steel (SS-304) braided hose having PVC sheathing |
| | b) Diameter | 13.6 mm OD & 8.1 mm ID |
| | c) Length | 3 M – 1 no. & 1 M – 1 no. |
| v) | Source drive cable | |
| | a) Material | Spring steel grade – 1 as per IS – 4454 (Teleflex cable) |
| | b) Diameter | 4.65 mm |

| | | |
|---|---|---|
| | c) Length | 11.7 m |
| vi) | End fittings | |
| | a) Material | SS-304 |
| | b) Diameter | Conduit holder, ID - 13.6 mm & OD – 15.4 mm |
| | c) Length | 60 mm & 75 mm |
| vii) | Maximum separation distance between the cranking unit and IGRED | 8.0 metre |
| viii) | Maximum separation distance between the IGRED and the position of source in exposure condition | 3.0 metre |
| ix) | Operational mechanism of the cranking unit | i) Interlock operates only after connecting the drive system properly<br>ii) when the source is in inside the shielding of the exposure device, source releasing knob pops up.<br>iii) Counter reads the source travel distance. |
| x) | a) Type of the guide tube | Flexible |
| | b) Material of Construction and dimension of the Guide tube | Flexible steel (SS-304) braided hose having PVC sheathing and 13.6 mm OD & 8.1 mm ID |
| xi) | Type of mounting provided for cranking unit | Spool type |

Table 5.1: Features of ROLI-3 IGRED

Setup with Drive System & Guide Tube of ROLI-3 IGRED is shown in figure (i) [63] and manual cranking unit of ROLI-3 IGRED in figure 5.3 (ii).

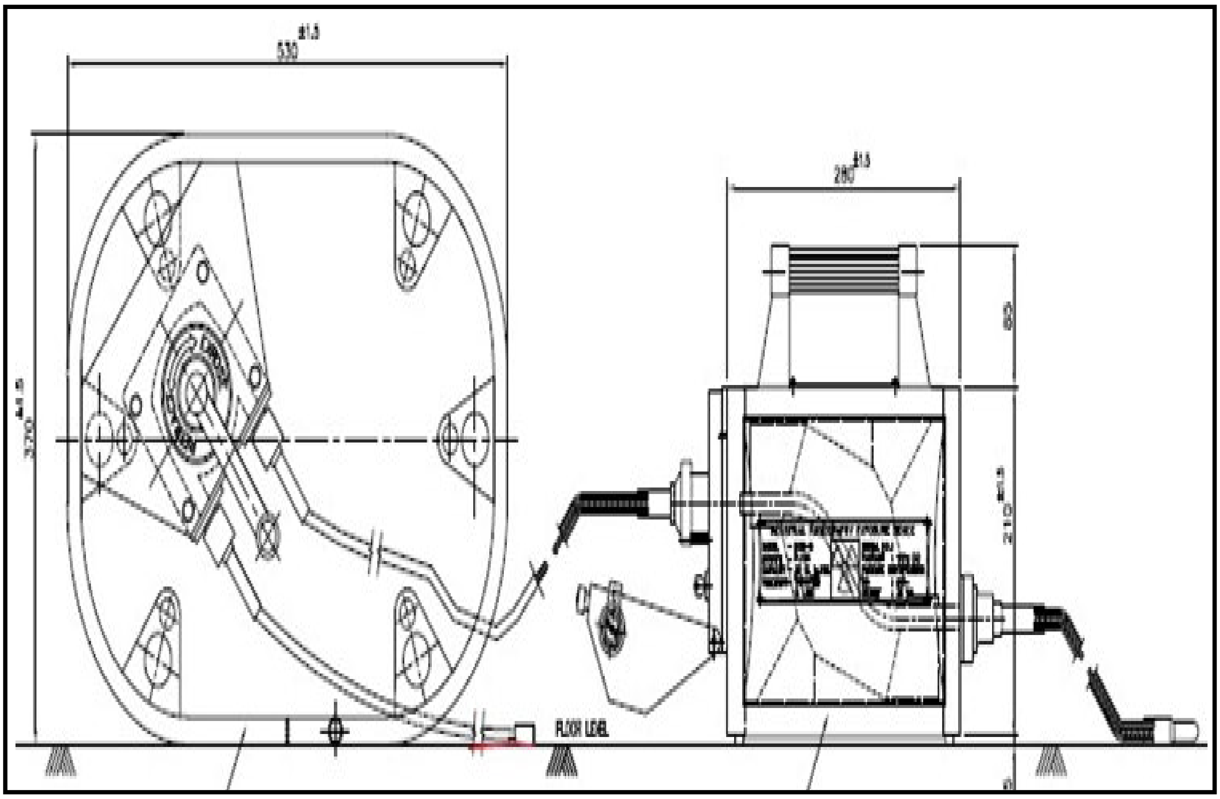



Fig. 5.3 (i): Setup with Drive System & Guide Tube of ROLI-3 IGRED

Fig. 5.3 (ii): Manual Cranking Unit of ROLI-3 IGRED

## Automated Cranking System Design

Automated cranking operation of ROLI-3 portable IGRED has been designed keeping provision for existing manual cranking system. Accordingly, components have been selected considering basic dimension of the shaft used for manual cranking and torque required to move the cranking shaft.

Automated cranking operation consists of Electrical & control system like stepper motor, driver, power supply, microcontroller, IR sensor. Mechanical system consists of chain, sprockets & other components required for overload protection.

While development of automated cranking operation of ROLI-3 portable IGRED, manual cranking operation of ROLI-3 has been consulted. From design of the manual cranking system, it is known that 12 rotations of the cranking system are required for reaching the source from shielded position to the exposure head using a guide tube length of 3 metres and time required is one minute. The same was verified also in field and feedback of radiographers were taken. As, the manual cranking is done with ease by an adult normal human being, a torque of 40 Kgf-cm has been estimated. Accordingly, components like stepper motor, sprocket & chain assembly, overload protector have been selected. Different components used for development of automated cranking system have been discussed subsequently.

### Electrical & control system

Brief details of different components used for electrical and control system are given below:

I. Stepper Motor

DC electrical pulses are converted to discrete mechanical motions by a stepper motor, an electromechanical type of device. Rotor is moved and hold in position with a fixed step angle by sending a single pulse in the desired phase. The stepper motor functions similarly to a Brush Less DC (BLDC) motor, but the magnetic fields in a stepper are aligned to provide a very high holding torque. A stepper motor is made of a rotor with well-defined outward-facing teeth and a stator with a set of center-facing electromagnets. 'Permanent Magnet (PM)', 'Variable Reluctance (VR)' and 'Hybrid' are the three types of steeper motors that are at present available . The rotation speed and distance of rotation are directly related to the frequency and number of the input pulses. Stepper motors are used in applications like printers, plotters, laser cutters, engraving machines, pick-place devices [64]. A NEMA17 planetary geared hybrid stepper motor has been used for driving the cranking unit. Specifications of the hybrid stepper motor is given in the Table 5.2 and photograph is given in figure 5.4 [65].

| Sr. | Parameter | Value |
|---|---|---|
| 1. | Configuration | 4 Wire stepper motor |
| 2. | Permissible Torque | 60 Kg-cm |
| 3. | Holding Torque | 58 kg-cm |
| 4. | Step Angle | 1.8 Degree |
| 5. | Rated Speed | 15 RPM |
| 6. | Rated Voltage | 2.8 V DC |
| 7. | Rated Current | 1.68 Amps |
| 8. | Shaft Length | 20 mm |
| 9. | Shaft Dia. | 8 mm |
| 10. | Gear Ratio | 1: 19 |
| 11. | Efficiency | 0.71% |
| 12. | Weight | 564 grams |

Table 5.2: Specifications of Planetary Geared Hybrid Stepper Motor


Fig 5.4: NEMA17 Planetary Geared Hybrid Stepper Motor

II. Stepper Motor Driver

RMCS -1102 stepper motor driver has been used for motion control of the selected stepper motor. RMCS-1102 is a micro-stepping drive for 1.8 deg bipolar stepper motors. It is made to operate quietly and smoothly without sacrificing control or torque at higher speeds. Khan A. et. al., 2018 made a three axis CNC milling machine using stepper motor and RMCS-1102 driver along with other components like belt and pulley for machining of wood, plastic and other tin materials [66].

Features of RMCS-1102 stepper motor driver which has been used is givn below [67].

i) Input supply voltage from 15 V DC to 50 V DC
ii) Selectable peak coil current from 0.5A to 5A
iii) It has provision for selection up to 20000 micro-steps per rotation
iv) Use of advanced PID loop control algorithm generates higher motor torque and higher speeds
v) Provision of PULSE and DIRECTION alteration along with motor free and locked position

vi) Provision of short-circuit protection in case of over-voltage and under-voltage

Photograph of the RMCS-1102 stepper motor driver is given below in figure 5.5 [66].

Fig. 5.5: Stepper Motor Driver RMCS-1102

I. Microcontroller

Arduino Uno R3 microcontroller has been used for automation work. Details of the same has already been mentioned in 4.5(ii).

II. 24 V Power Supply

To overcome the initial inertia, motors draw a large current during start-up. Similarly, when under heavy load, for example, when the pigtail is stuck, a large current is drawn from the power supply. To ensure that these peak loads can be handled without any failure, a 24V 1.1A industrial power supply has been used. Input voltage of the power supply is 230 V AC. Photograph of the same has been shown in figure 5.6.

Fig. 5.6: Industrial Power Supply

III. IR Receiver & Remote Control

To increase the distance between the operator and the radiography exposure device, an IR receiver and remote were used to control the automated cranking operation. An IR receiver essentially consists of a photo diode that is sensitive to electromagnetic radiation in the infrared spectrum. When a light beam of wavelength in the infrared region falls on the receiver, a pulse is generated on the signal pin. This is connected to the microcontroller ( arduino) digital pin to decode the incoming signal. The IR receiver receives the commands from the remote control and send the same to microcontroller for execution. The remote control issues commands such as Forward, Reverse, Stop, Speed Increase and Speed Decrease. The choice of the IR Sensor was done based on cost, small form factor and sturdy design. Win K. et al., 2020 used a TSOP1838 IR sensor in order to control different home appliances like TV, fan, motor, light etc. after receiving a signal from a remote control unit and selectively sending the same signal by Arduino microcontroller through different relays for making the appliance on/off [68]. A TSP 1838 IR sensor has been used for the automated cranking operation. Photograph of the IR sensor is shown in figure 5.7.


Fig. 5.7: TSOP1838 IR Sensor

For the remote, a 38 KHz universal infrared IR Remote Control has been used. This uses the NEC protocol for transmission of commands. It has 21 keys, allowing for a large number of commands to be issued to control the stepper motor operation and remote control distance is more than eight meters. Vijayalakshmi K., et al., 2020 used a remote control unit, capable of generating 38 KHz IR signal for controlling different home appliances from a distance of ten metres [69]. Photograph of the remote control unit used for automated cranking operation of portable ROLI-3 IGRED is shown in figure 5.8. Following five keys of remote control unit have been used to support various modes of operation as mentioned in Table 5.3.


Fig. 5.8: Remote Control

| Key on the Remote | Operation |
|---|---|
| CH+ | Forward Motion |
| CH- | Reverse Motion |
| CH | STOP |
| VOL- | Reduce Speed |
| VOL+ | Increase Speed |

Table 5.3: Motion Control Keys of Remote

IV. Overall Assembly

Block Diagram of drive system for automated cranking operation of ROLI-3 IGRED has been shown in figure 5.9 and box containing different components of control systems has been shown in figure 5.10. Arduino UNO R3 acts as the central microcontroller, responsible for decoding the incoming pulses from the

IR Sensor and generating the corresponding control signals for the stepper motor.

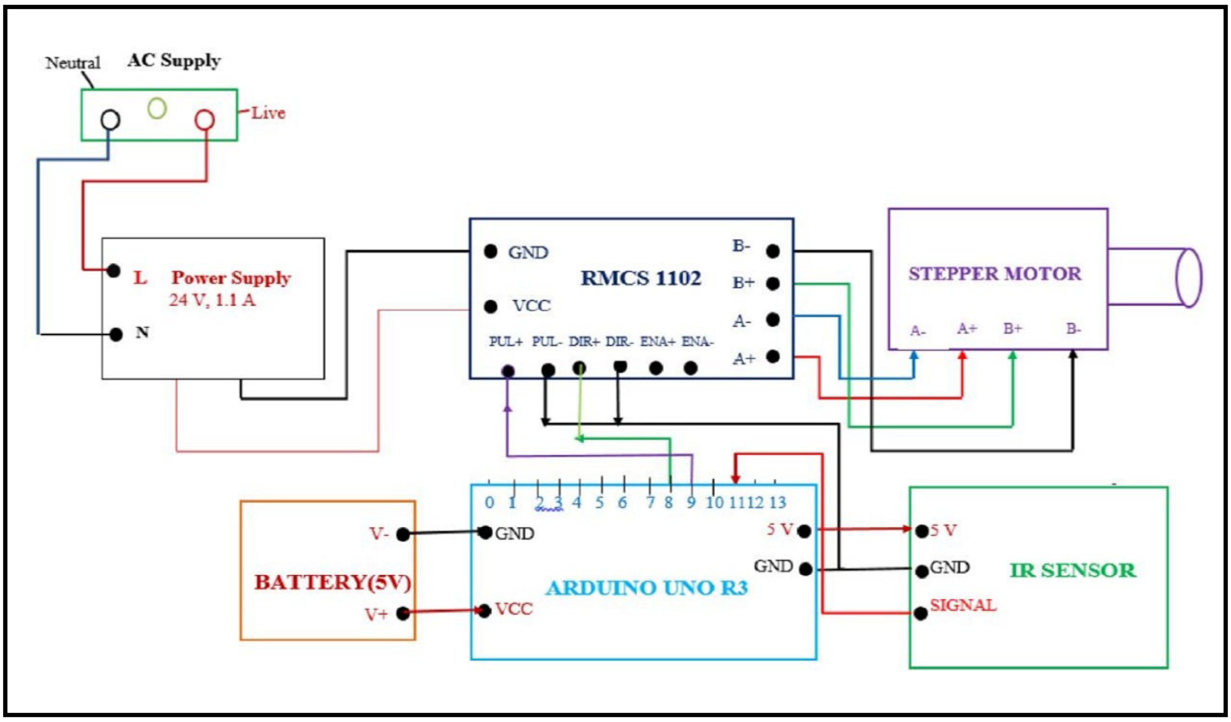



Fig. 5.9: Block Diagram of Drive System for Automated Cranking Operation

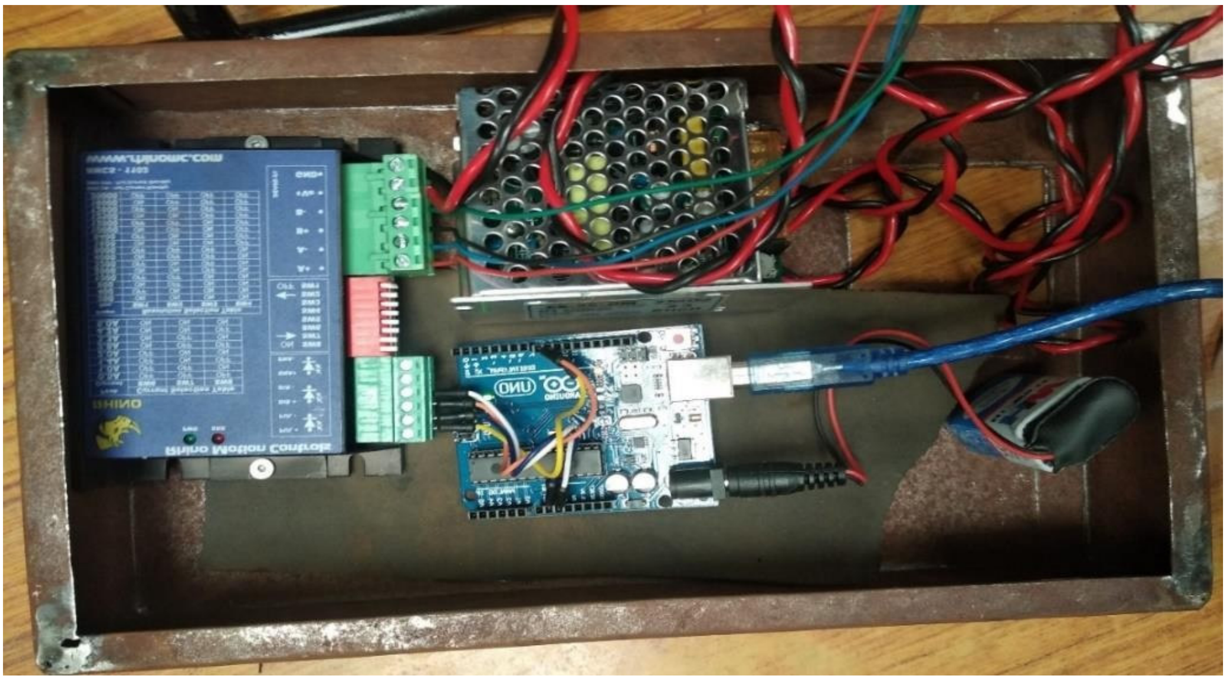


Fig. 5.10: Different Components of the Control System

## Mechanical system

Mechanical system for automated cranking operation is basically a chain sprocket with overload tripping arrangement. Different components used for development of the system are as follows:

i) Driver & Driven Sprocket
ii) Chain
iii) Bush
iv) Washer
v) Ball Retaining Guard
vi) Compression spring
vii) Locking Ring
viii) Manual handle

Chain and sprockets have been used for power transmission from stepper motor to cranking shaft as it prevents slip during operation. Driver sprocket has been selected with twenty one numbers of teeth considering following specifications of stepper motor;

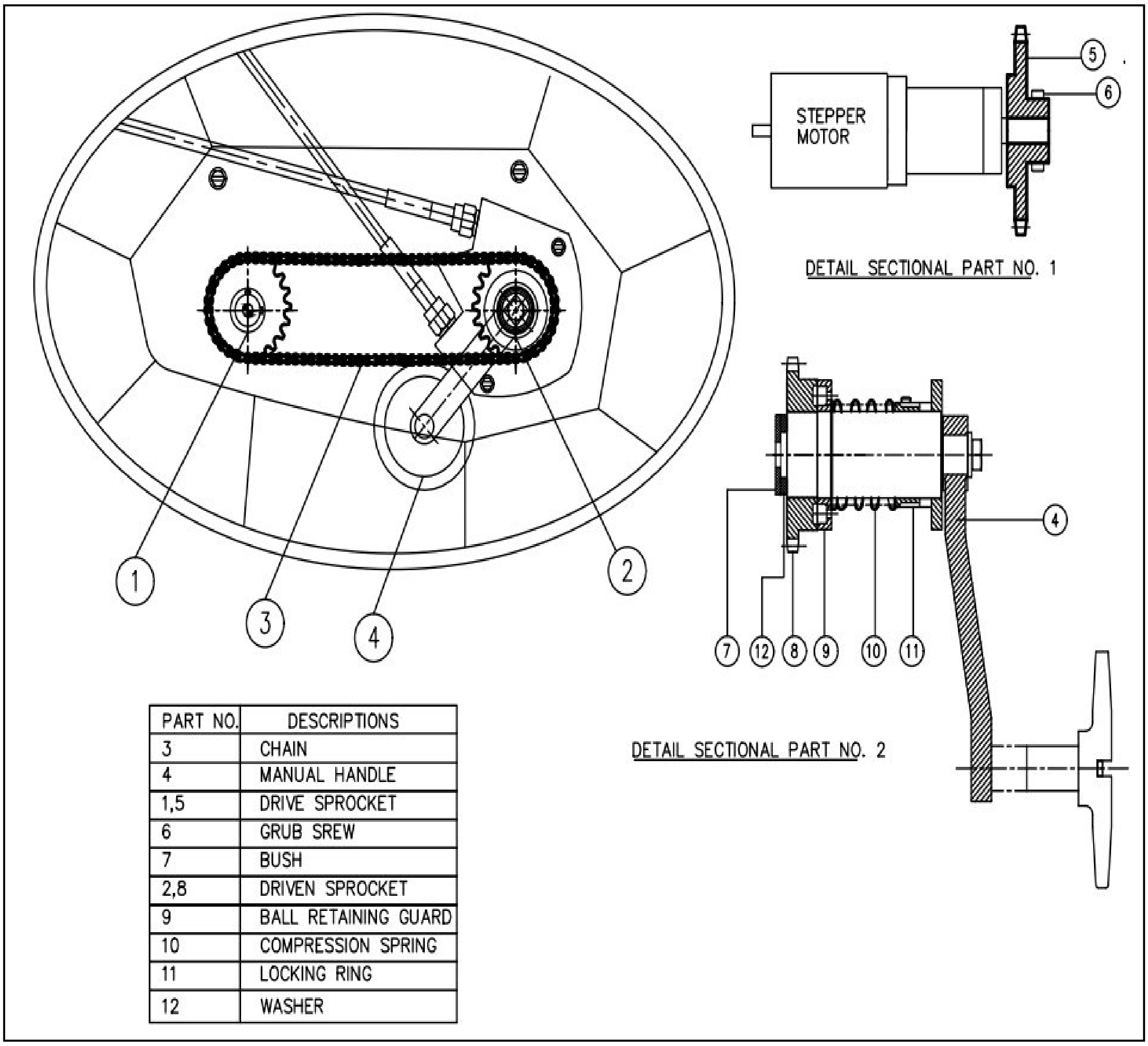
i) shaft diameter: 8 mm
ii) torque: 6o kgf-cm
iii) rpm :15.

Driver sprocket is directly mounted on the stepper motor's shaft with two numbers of grub screw. From design of the manual cranking system as well as based on operator's feedback, it is known that twelve rotations of the cranking system is required for exposing the source from shielded position to exposure head with a guide tube of three metre length and cranking time is one minute. Hence, rpm of the cranking shaft is considered as twelve. So, r pm of both the driving stepper motor and cranking system are almost same and driven sprocket is selected identical to the driving sprocket as no speed reduction or increase is required. Also, to accommodate the sprockets with minimum space in the assembly, Type-B sprockets with minimum numbers of teeth have been chosen. Material of construction for both the sprockets are SS-304 and have been directly procured from market. A roller chain of 9.52 mm pitch, 55 numbers of links with total length of 524 mm has been used in matching with the sprockets. The chain and sprocket drive were simulated before actual fixing.

It is measured that shaft for manual cranking is projected with 23.8 mm length out of which 13.2 mm is of circular shape and remaining portion of square shape for inserting cranking handle. In order to accommodate different components for power transmission and overload protection, a bush has been fitted on the cranking shaft with press fit. Bush is locked with the shaft through a dowel pin of 5 mm dia. Bush acts as the holder for different components used for automated cranking operation. A nylon washer has been used before the sprocket and after the collar of the bush to keep the sprocket is position. Ball detent mechanism with provisions of four numbers of steel ball of 7 mm dia with a ball retaining guard to keep the balls in position are used in combination with a helical compression spring and locking ring for overload protection like that happened during jamming condition of the Teleflex cable inside guide tube.

Helical spring has three active turns and made of spring steel grade -2 conforming to IS 4454 Part I, Grade-2 ASTM A 227 with spring constant of 5 N/mm. A locking ring has been used to keep the spring in compression and ball detent mechanism with dowel pin sets inside the groove of the locking ring during normal operation. Whenever, an overload happens, the balls are pushed from it's position and subsequently release the spring compression which in turn moves the locking ring from locked position to free position and thus the driven sprocket slips preventing damage to the assembly. Bush, ball retaining guard and locking ring have been made up of mild steel.

A cover has been fitted over the assembly. Drawings of whole assembly and individual parts have been shown in figure 5.11 to 5.20. All dimensions shown are in mm.




| PART NO. | DESCRIPTIONS |
|---|---|
| 3 | CHAIN |
| 4 | MANUAL HANDLE |
| 1,5 | DRIVE SPROCKET |
| 6 | GRUB SREW |
| 7 | BUSH |
| 2,8 | DRIVEN SPROCKET |
| 9 | BALL RETAINING GUARD |
| 10 | COMPRESSION SPRING |
| 11 | LOCKING RING |
| 12 | WASHER |

Fig 5.11: Chain Sprocket & Associated Assembly for Automated Cranking Operation

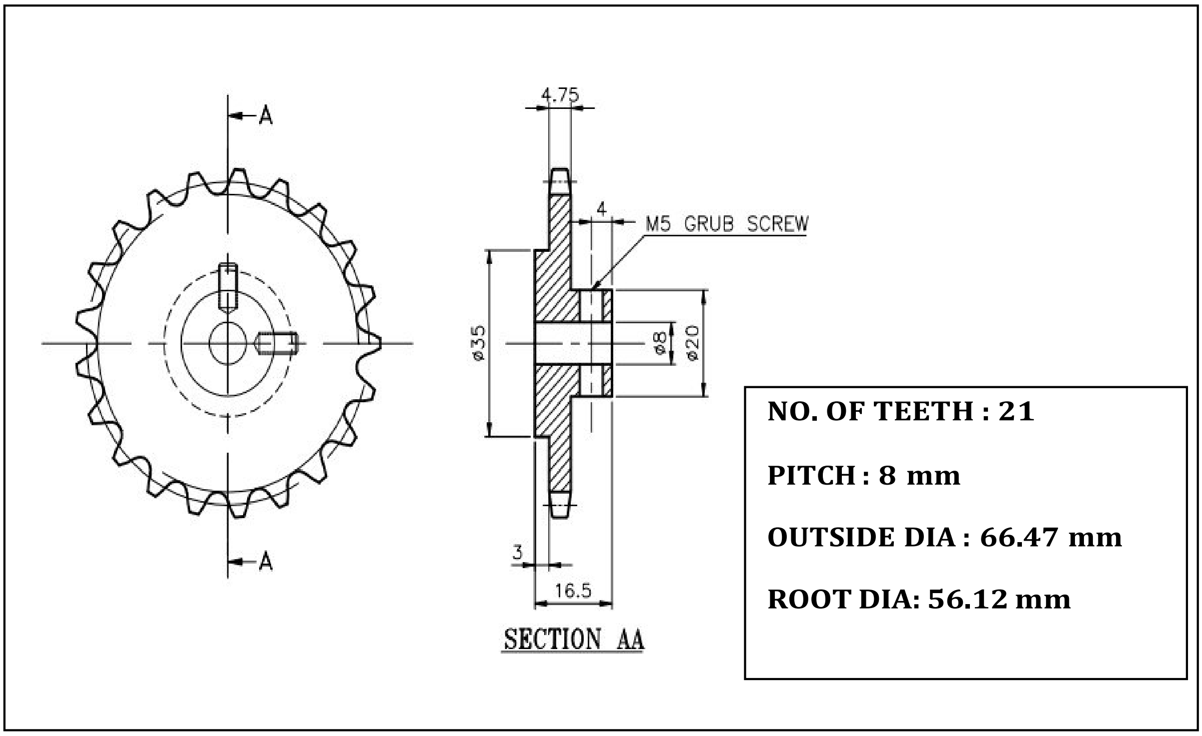



Fig. 5.12: Drive Side Sprocket

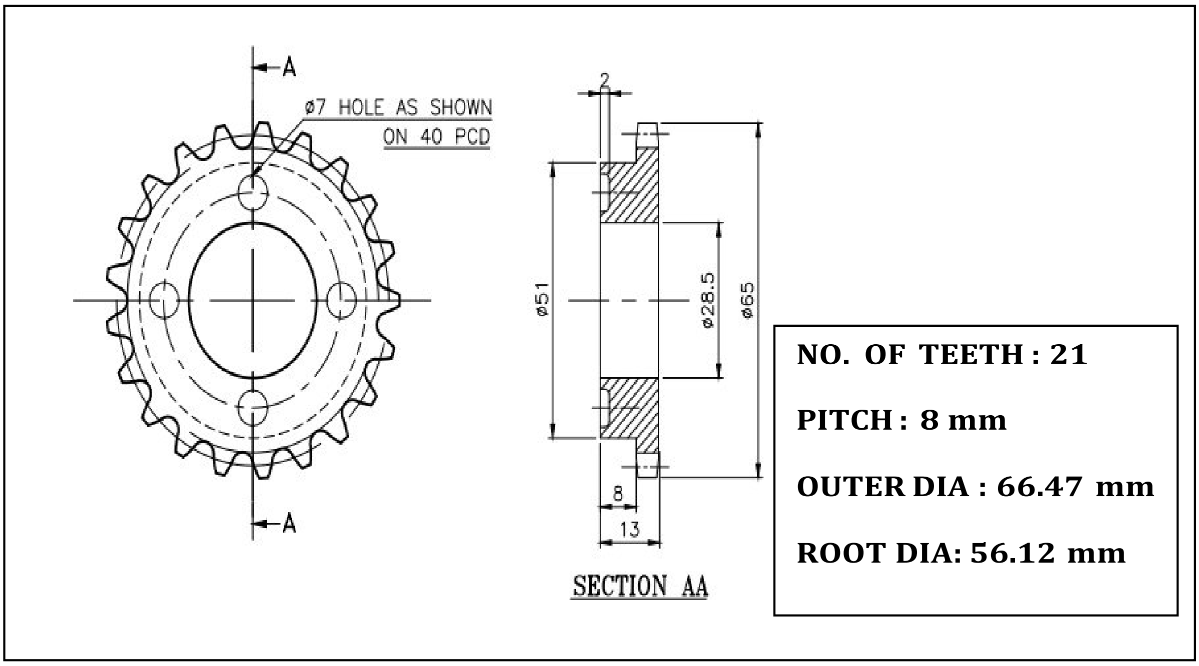



Fig. 5.13: Driven Side Sprocket

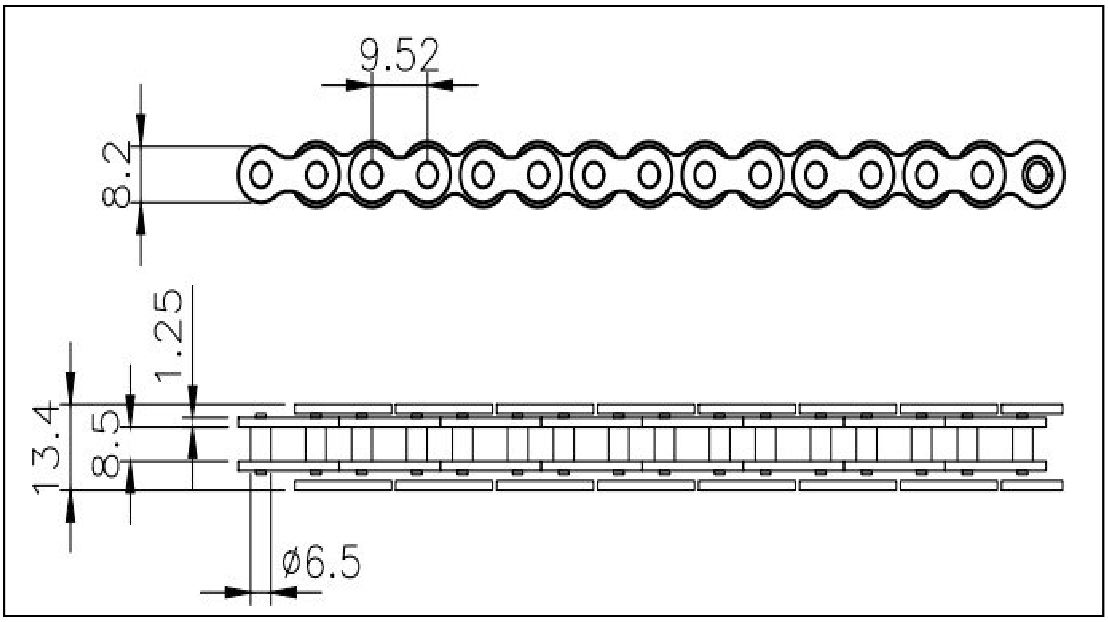



Fig. 5.14: Roller Chain

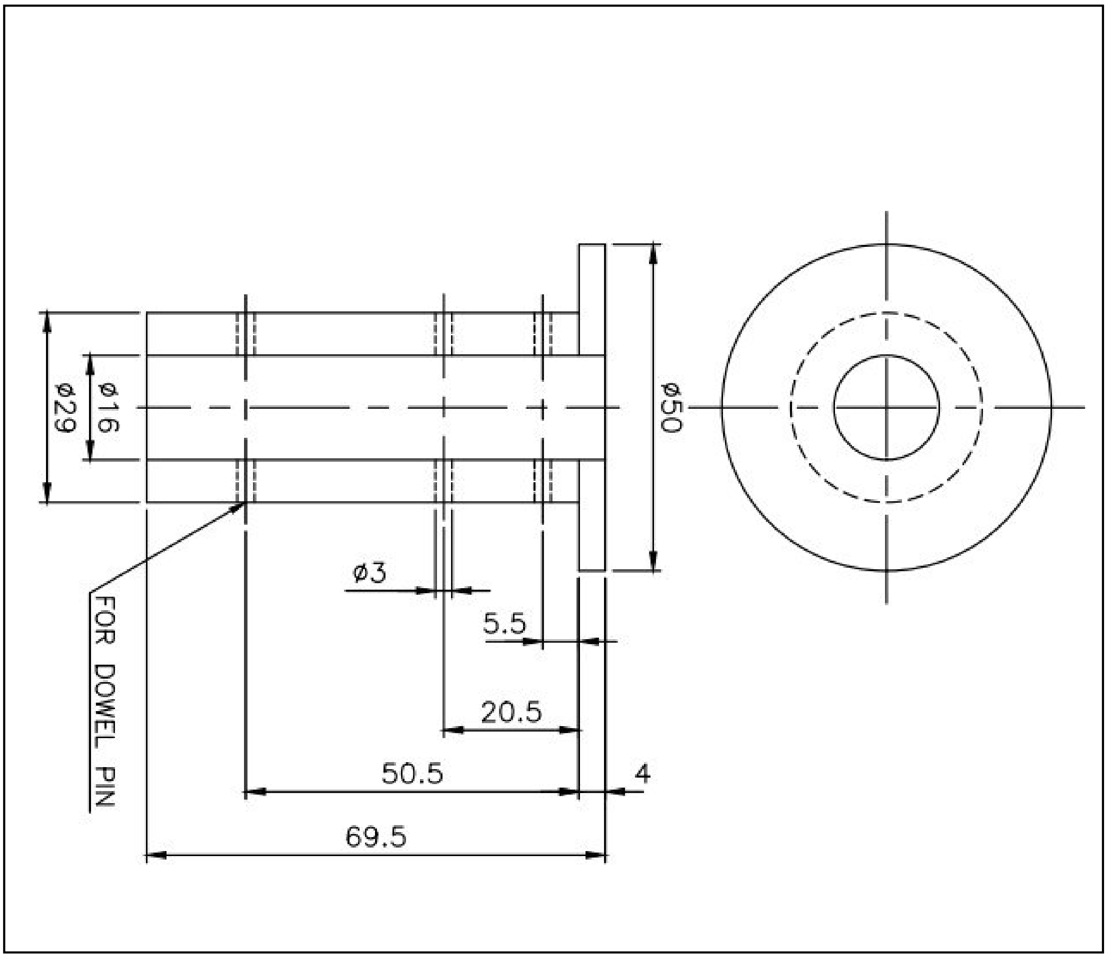



Fig. 5.15: Bush

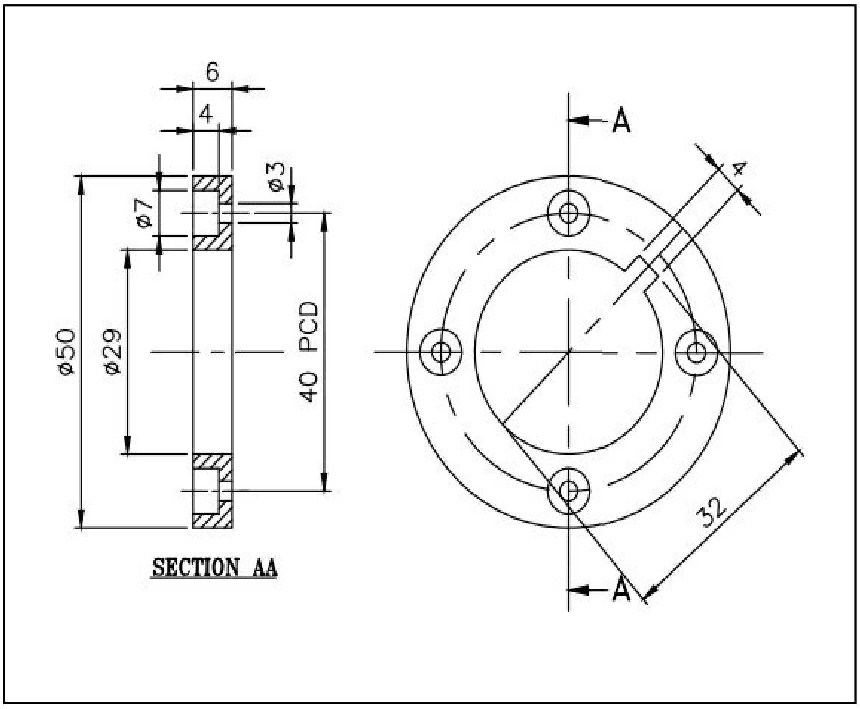



Fig. 5.16: Ball Retaining Guard

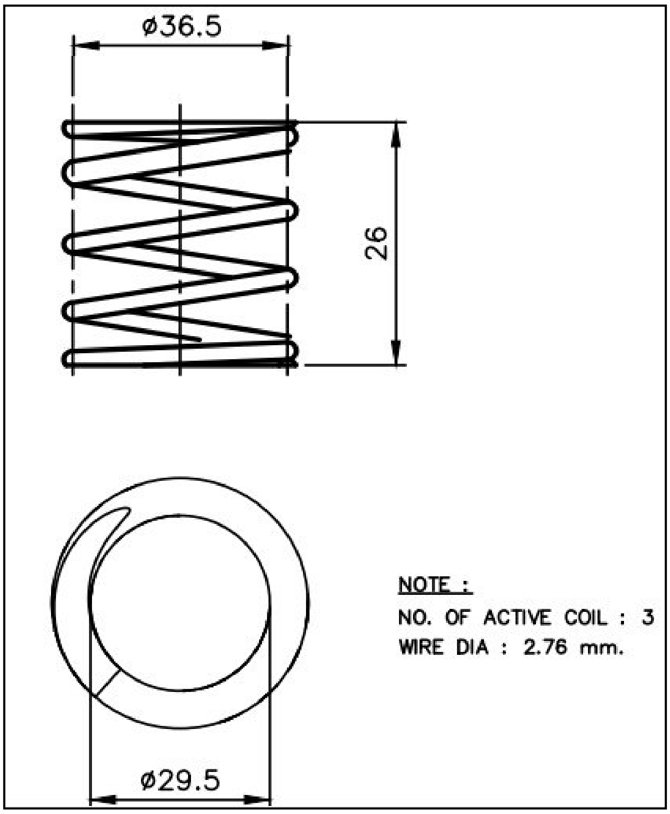



Fig. 5.17: Compression Spring

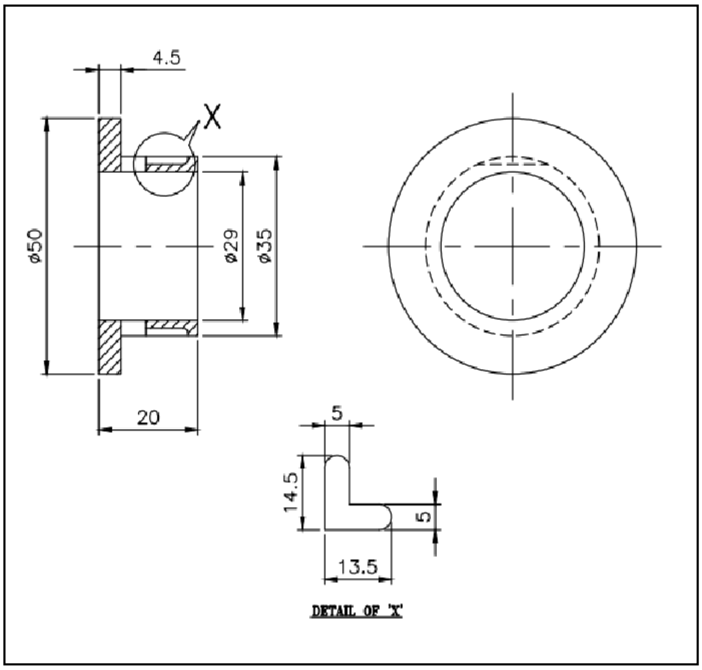



Fig.5.18: Locking Ring

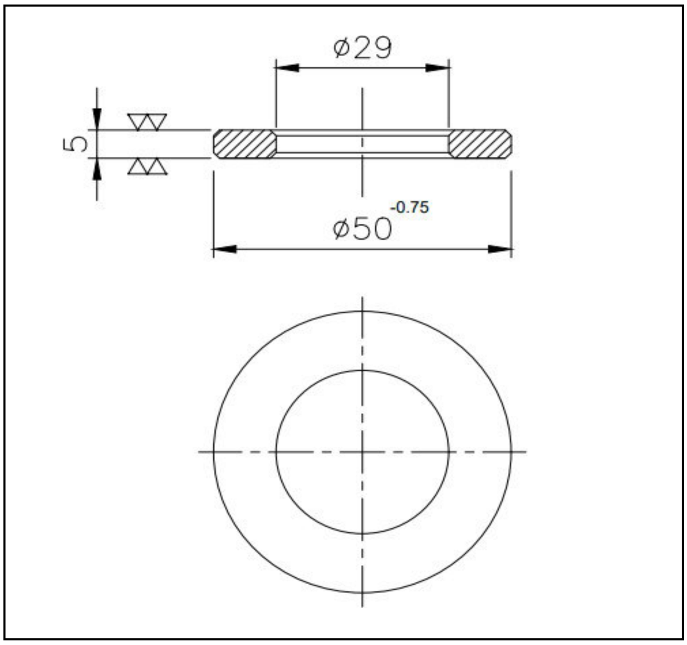



Fig. 5.19: Washer

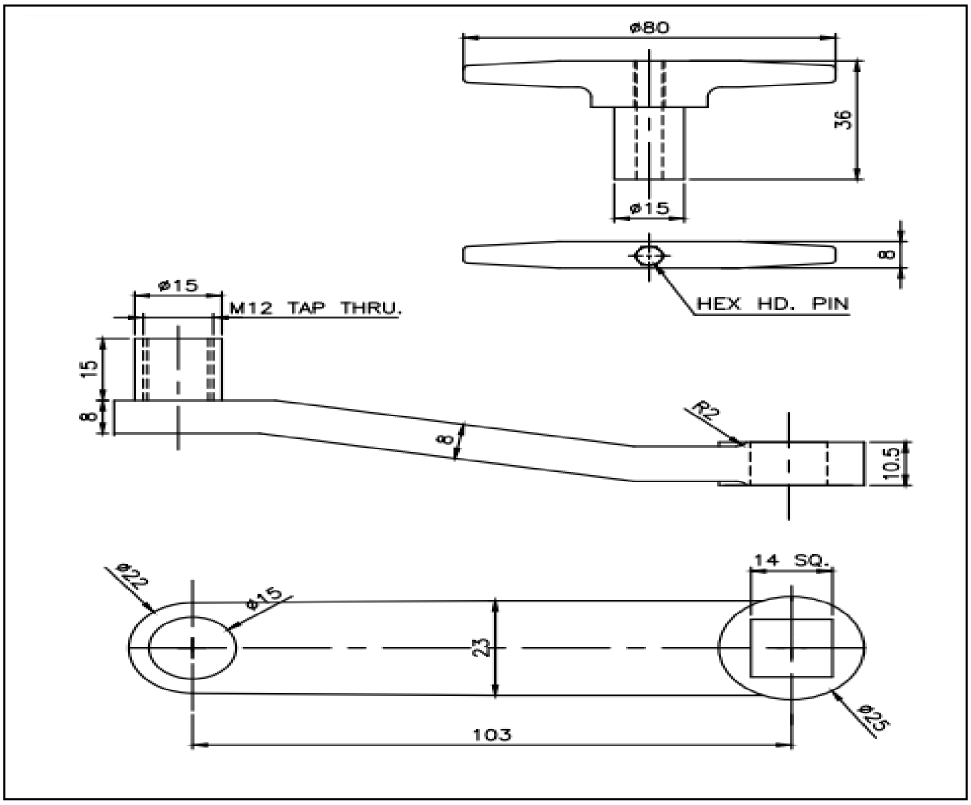



Fig. 5.20: Manual Handle

### Testing of the Automated Cranking System

Initially, the automated cranking system was tested without any load i.e. without connecting the drive assembly with IGRED. It was observed that the system was running smoothly. Photograph of the developed assembly without connecting to IGRED is shown in figure 5.21 & 5.22. Later on, the system was tested with a device housing a dummy source and it was observed that the automated cranking system was working satisfactorily.

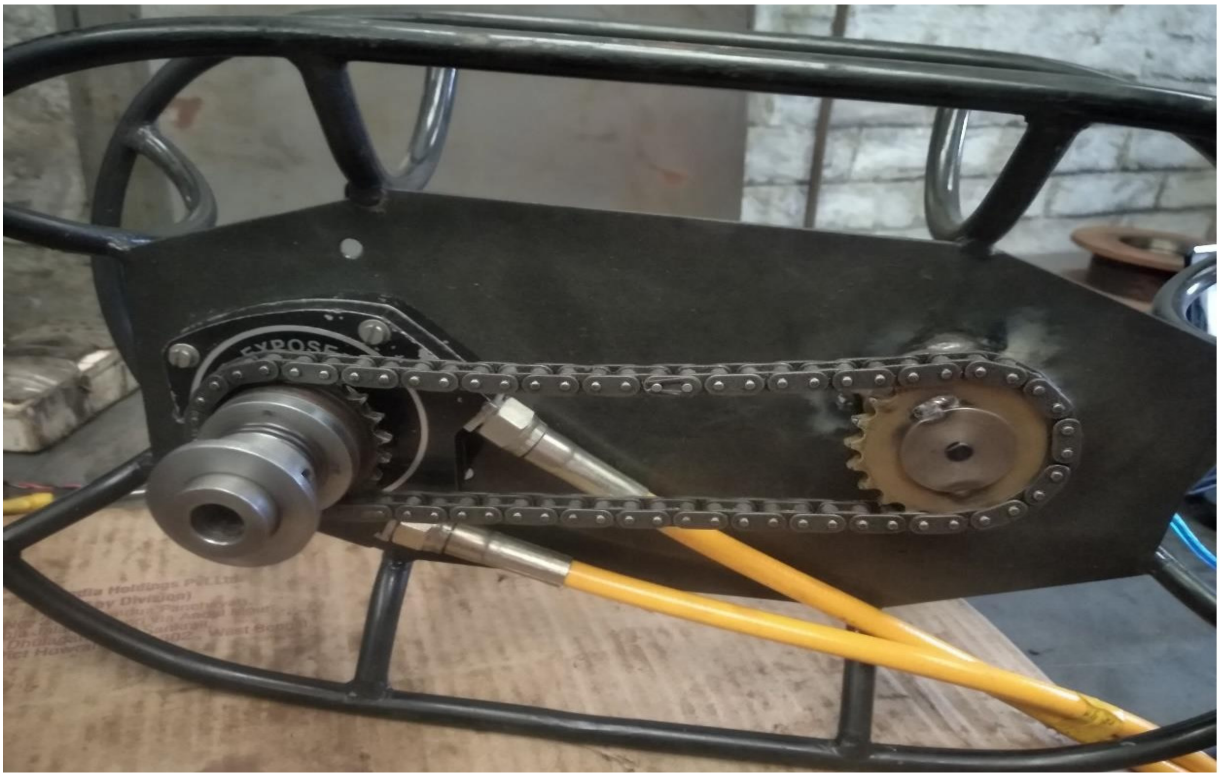


Fig. 5.21: Chain & Sprocket Assembly with Associated Components

Fig. 5.22: Chain & Sprocket Assembly with Cover Fitted

The system after successful testing at “No Load” Condition was tested on field for testing of welding joint of a tank after connecting the cranking assembly with ROLI-3 IGRED. Subsequently, exposure was given through remote control from a distance of eight metres from the cranking unit of ROLI-3 IGRED containing 9.7 Ci Ir-192 activity with forward movement of the source assembly from the shielded container to exposure head slowly and steadily. Then after desired exposure of around three minutes the source assembly was retraced back to the device by reverse movement of the cranking assembly. It was noted that developed automated cranking operation was working smoothly. Control of speed and movement was done using the IR receiver and remote control. Photographs regarding field testing of system done at night time is given in figure 5.23 and 5.24.

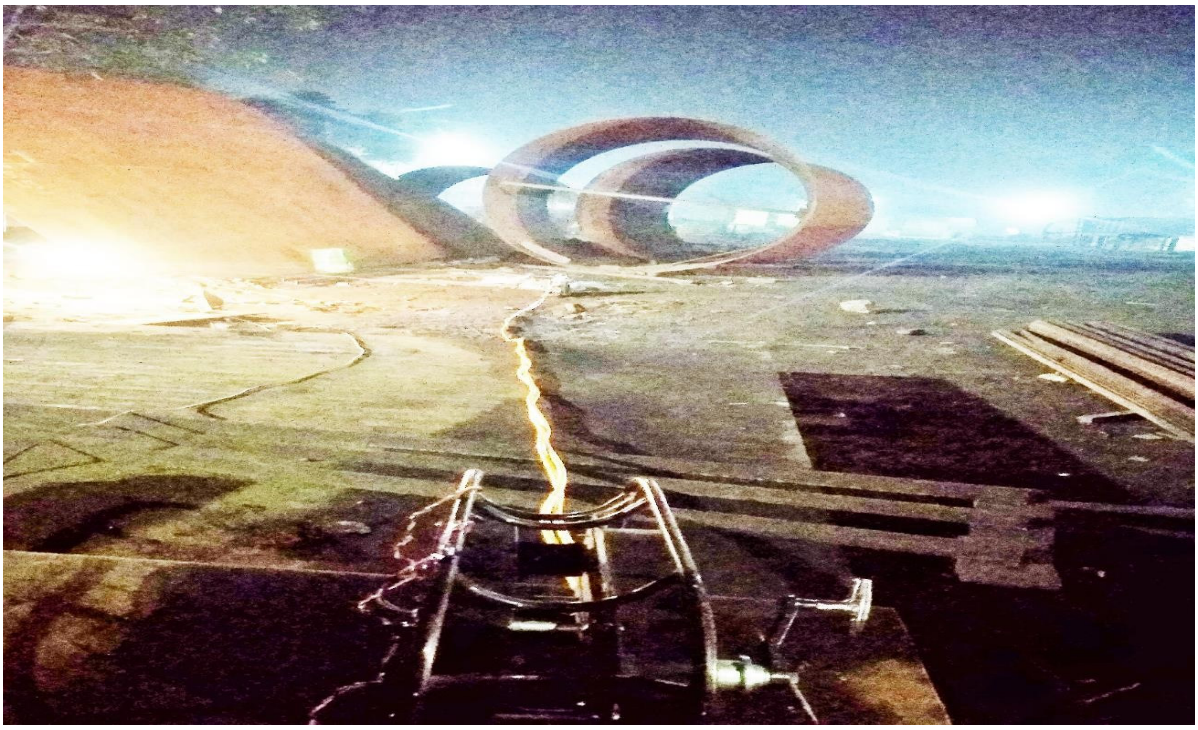


Fig. 5.23: Field Testing of Automated Cranking Operation (Night Time)

Fig. 5.24: Field Testing of Automated Cranking Operation (Night Time)

**Result**

Field testing of the developed system used for automated cranking operation of ROLI-3 IGRED demonstrates that source assembly movement from the shielded container to the exposure head and vice versa can be controlled as per choice with increase or decrease of speed. Also, it was observed that the remote can be operated in range up to at least eight metres away from the cranking unit. Accordingly, it can be concluded the remote operation can be done in a range based on available space and location of the job to be radiographed. Also, manual cranking system was checked keeping the automated system in off condition. It was found that the manual system works similar tray originally designed for cranking.

Radiation level near the cranking unit and eight metre distance from the cranking unit were measured using a calibrated Pulsecho Minirad radiation survey meter. Radiation level at 5 cm from the surface of the device was noted around 315 μSv/hr whereas in the distance of remote operation, the same was observed around 88 μSv/hr which comes around 70 % less. This result is clearly in line with the inverse square law of radiation.

Thus it can be concluded that adopting the automated cranking operation of portable IGRED, there will be a significant reduction of dose to the operators and chance of excessive exposure will greatly diminish which proves efficiency and effectiveness of the automation. Also, as manual cranking provision originally adopted for cranking operation has been kept intact, there is Defence In Depth (DID) in the operation of the cranking system i.e., in event of any failure of the automation, manual will take care.

**Pseudo Code**

Pseudo Code for development of automated cranking operation is given in figure 5.25.

**Algorithm 1** Initial Setup

```
global variables
    Power, whether system is on or off
    Speed, Increase speed of motor
end global variables
procedure setup
    Start the IR Receiver
    Power ← OFF                          ➢ Initially Powered off
    Speed ← 10                           ➢ Initial Speed of the motor
    Direction ← FORWARD
end procedure
```

**Algorithm 2** Decode the IR Readings

**global variables**<br>
    **Power**, Whether system is on or off<br>
    **Speed**, Speed at which motor runs<br>
    **Direction**, Direction of rotation<br>
**end global variables**<br>
**procedure** Decode IR<br>
    $READING \leftarrow$ Key pressed on remote<br>
    **if** $READING$ is $CH$ **then**<br>
        Invert $Power$ variable<br>
    **else if** $READING$ is $CH+$ **then**<br>
        $Direction \leftarrow FORWARD$<br>
    **else if** $READING$ is $CH-$ **then**<br>
        $Direction \leftarrow BACKWARD$<br>
    **else if** $READING$ is $VOL+$ **then**<br>
        $SPEED \leftarrow SPEED + 2$<br>
    **else if** $READING$ is $VOL-$ **then**<br>
        $SPEED \leftarrow SPEED - 2$<br>
    **end if**<br>
**end procedure**

**Algorithm 3** Automated Cranking System

**global variables**<br>
    **Power**, Whether system is on or off<br>
    **Speed**, speed at which motor runs<br>
    **Direction**, direction of rotation<br>
**end global variables**<br>
**procedure** setup<br>
    **while** $TRUE$ **do**<br>
        DECODE_IR ( )<br>
        **if Power** is $ON$ **then**<br>
            Rotate motor in **Direction** with **Speed**<br>
        **end if**<br>
    **end while**<br>
**end procedure**

# CHAPTER -6

# DEVELOPMENT OF ADVANCE THEFT DETECTION SYTEM FOR PORTABLE INDUSTRIAL GAMMA RADIOGRAPHY EXPOSURE DEVICE (IGRED)

*Theft of portable IGRED particularly from an unmanned location like storage room has been identified as a potential hazard for facilities handling the device. Existing security system does not take care of early detection and notification of theft incidence. Hence, an advance theft detection system has been designed and developed using Arduino microcontroller, MPU 6050 accelerometer and Shim 9001 GSM Module. An algorithm has been developed considering best test and continuous test that are to be successfully passed in order to recognise a theft incidence. Provision has been made for sending message and call to the authorised custodian of the device and also to generate local alarms for theft notification. All the details have been discussed in Chapter - 6.*

## Requirement of Advance Theft Detection System

Out of all the industrial radiography equipment, portable IGRED is most vulnerable from security point of view as it is always on move from one site to another considering different nature of jobs performed with the same. There were number of cases reported from facilities involving theft incidence of the IGRED as mentioned in section 2.1.3. Also, as far as portable IGRED is concerned, theft of the source can occur even when the device is not in use and kept in storage room. The theft of a radiography source can cause severe hazard as the source can reach to the public who are ignorant of the radiation hazards. At present, there is no inbuilt security system in the IGRED to detect theft instantaneously, particularly from an unmanned location in odd hours, thus preventing possibility of accidental radiation exposure. It is found that majority of the works carried out for security measures in the field of industrial radiography are focused on improvement of security infrastructure and management as well as improving the safety regulation standard [25].

## Literature Review

Though research work has not been carried out directly to build integrated security system for theft detection and notification of portable IGRED, research works carried out in other field related to the same have been consulted. Some of these are mentioned below:

Iyapo K. O. et al., 2017 built an intrusion detection with an alarm system for prevention of frequent and rampant cases of burglary [70]. The system makes use of an embedded PICI8F2423 microcontroller, which can detect movement of an intruder in a restricted area and then sounds an alarm. Pyro electric infrared motion sensor use body heat to detect movements of people.

Chowdhury I. et al., 2021 developed a microcontroller-based solar-powered anti-theft security system to detect possible intrusion incidents in the home or other area [71]. Based on the information from the motion sensor, fire sensor, and glass break sensor, the system can generate three different sorts of alarms, including buzzer, bi-color LED, and SMS with a security breach warning. A light-dependent resistor (LDR) and a potentiometer (POT) were employed as motion sensors, a temperature detector (LM35) served as a fire sensor, and a sensitive metal strip served as a glass-break sensor. SIM 900 (GSM) was used for generation of SMS.

Mudgiil et al., 2014 created a burglar detection and locking system for homes and other buildings [72] employing an IR sensor, shock sensor, MCU AT89S52 microcontroller, and lock mechanism to automatically lock the intruder. A GSM module sent SMS after detection of intruder in the room and an LCD to display regarding detection of the intruder. Buzzer of the developed system used to sound whenever intruder enters into the room.

Atharva K. et al., 2020 used microcontroller and accelerometer for smart home systems to detect any home intrusion [73]. To detect any angular or linear acceleration, the system used a gyroscope sensor MPU-6050 of GY-521 architecture. ESP8266 is connected with the MPU-6050 sensor. The sensor alerts the ESP8266 with a signal when the door is moved or broken. The ESP8266 module, which has Wi-Fi capabilities, transmits notifications to the owner directly via Internet of Things applications and also activates a burglar alarm that alerts the neighborhood. In case, gas cutters are employed by the thieves, the GY-521 board uses an ambient temperature sensor to look for temperature abnormalities.

Mariska L. et al., 2022 designed a prototype of movement monitoring objects to detect falling objects, falling motorcycles and others using MPU 6050 for motion detection and SIM 900A for sending notification [74]. The system uses the MPU6050 sensor to detect motion, and the SIM900A to provide the results of acceleration for the x, y, and z axes.

Pachica A. O. et al., 2017 developed a motorbike theft prevention and recovery system using microcontroller, GSM, GPS and camera. The user will be notified via an alert message if the motorbike is transported far away or stolen [75]. Movement and vibrations of the motorbike are picked up by a shake sensor. The system's image-capturing technology is provided by the camera. When the alarm system is activated, the engine is immobilised or the vehicle's engine is disabled by the use of the kill switch, preventing thieves from stealing or riding off in it.

Al-Dahan T. Z. et al., 2016 designed a fall detection system for elderly or epilepsy patient to prevent injury [76]. To identify falls and fall-detection, the system combines the threshold method and acceleration measurement. ‘Arduino-UNO’ as microcontroller and ‘MPU6050’ for measurement of velocity and acceleration have been used. An algorithm has been used for calibration of several fall parameters and possible falls. Total sum acceleration vector distinguishes between falling and activities of daily living.

Saranu P. N. et al., 2018 developed an advanced surveillance system using RP and PIR sensors for theft detection [77]. PIR sensor detects the motion of the intruder entering the the house. To monitor and manage the fire occurrence, if happens inside the house, a temperature sensor and a camera are used. Chloroform is sprayed through a motor with solenoid valve arrangement to make the stranger unconscious. The camera is switched on automatically if there is any movement inside the room. System has provision so that the owner of the house can see the events live. An email and telephone phone call are sent to alert the owner about the stranger's action.

**Development of Advance Theft Detection System**

Following major components have been used in development of advance theft detection system (ATHEDES):

I. Motion Sensor

Motion sensor is an important component of any security system. Various means, including infrared, sound, and vibration, can be used to detect motion. The main purpose of motion detectors is to identify moving objects and collect information about their position, acceleration, and velocity. The sensor provides data about motion to alert the user regarding motion in the area or perform certain tasks [78]. MPU6050 is a six-axis motion tracking device with provision of 3-Axis acceleration measurement and 3-Axis angular velocity measurement, embedded on a single chip [79]. In our system, only the acceleration measurements have been used for detecting theft.

II. Microcontroller

Microcontroller is a compact integrated circuit consisting of a processor, memory and other peripherals embedded in a single chip. Microcontrollers are widely used for various applications like security systems, home automation, industrial control, and consumer electronics. Arduino is one of the commonly used microcontrollers for security systems due to its simplicity, ease of use and large community support. 'Arduino UNO R3' microcontroller development board based on the 'ATmega328P' has been used [56]. It is programmed with the theft detection algorithm, receives power supply and distributes it to all the peripherals.

III. GSM Module

Global System for Mobile Communication (GSM) technology is used in security systems to enhance its functionality and to do remote monitoring with control capabilities. For GPRS/GSM communication, smallest and the most affordable GSM module is the SIM900A. GPRS/GSM technology is provided by the module for mobile SIM-based communication. 900 and 1800 MHz frequency bands are used for mobile and SMS transmission and reception by users [80]. SIM 900 A has been used in the theft detection system to send notifications in the forms of messages & call to the licensee's in case of theft detected and also for receiving passcode from the licensee to stop the alarm. Block diagram and circuit diagram of the system have been presented in figure 6.1 (i) and (ii) respectively.

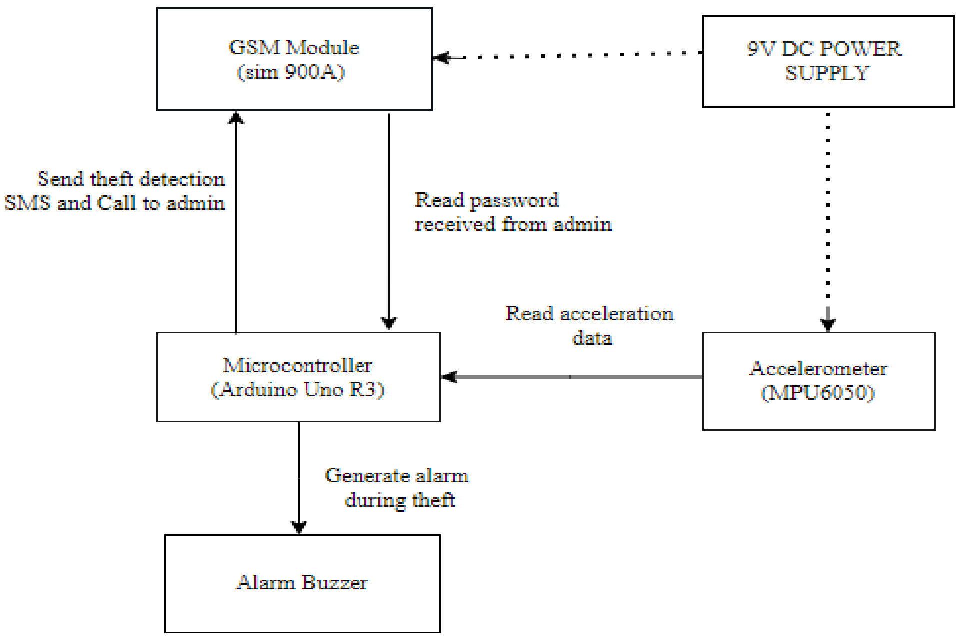



Fig. 6.1 (i): Block Diagram of the Advance Theft Detection System

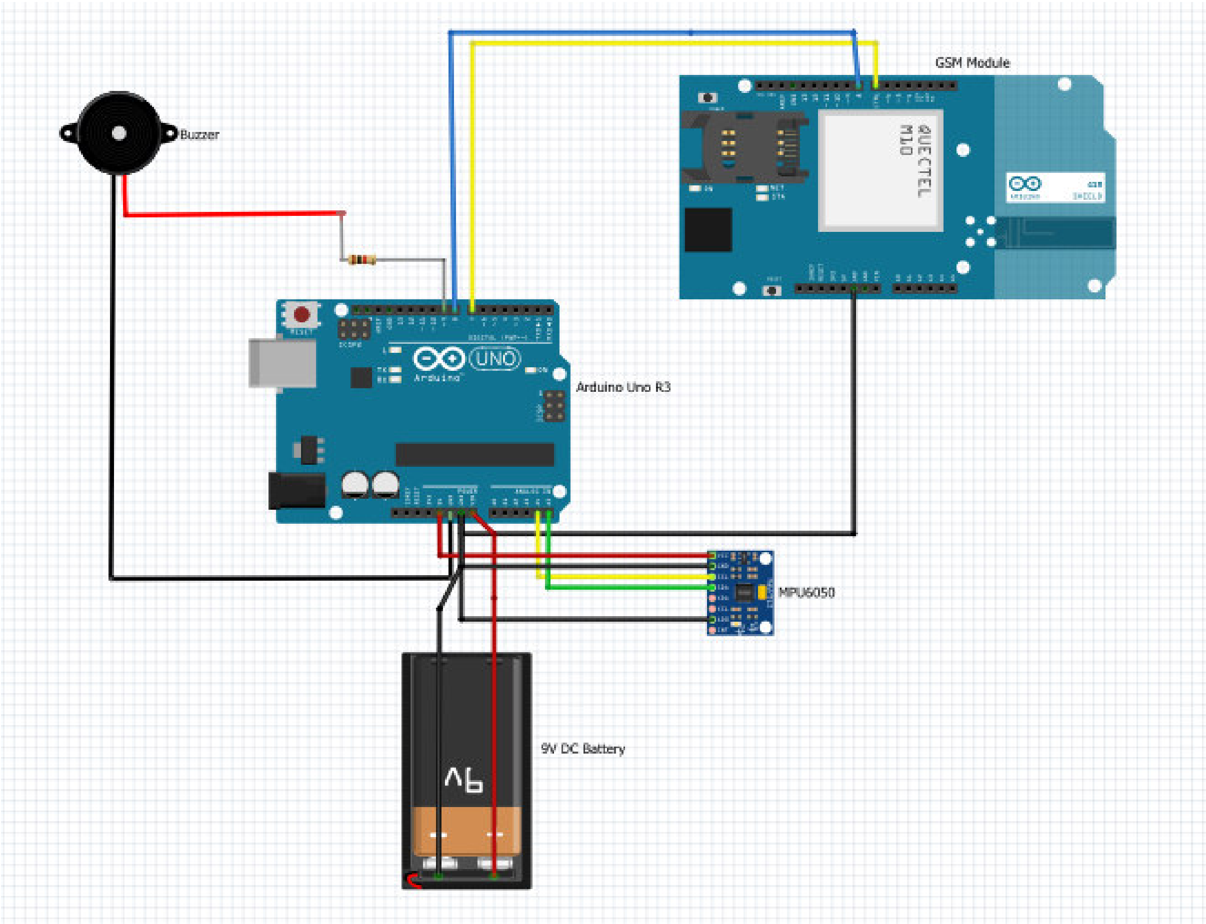



Fig. 6.1 (ii): Circuit Diagram of the Advance Theft Detection System

The advance theft detection system has been tested using a portable IGRED of model ROLI-3 because it is one of the most widely utilised IGREDs. The system after detection of possible theft is going to generate a local alarm. It is also going to simultaneously transmit a notification message three times to the mobile number of Licensee of the ROLI-3 IGRED which is pre-programmed into the device and also a call. The licensee can switch the alarm off by using a predefined passcode.

**Theft Detection Algorithm**

Algorithm for theft detection of the IGRED has been designed considering two stages through which theft can occur; (i) an initial motion where the thief tries to pick up the equipment and is expected to occur over a brief span of time, and (ii) a subsequent motion where the thief attempts to carry the equipment and typically going to occur over an extended period of time. Considering these two stages, the theft detection algorithm runs in cycles, with each cycle consisting of two tests namely: (i) Base Test that detects the presence of initial motion during the theft, running once in each cycle, and (ii) Continuous Test which detects the presence of the subsequent motion in the theft. The Continuous Test runs over an extended period of time provided the Base Test passes. If the Continuous Test passes, then theft detection occurs and alarm is raised. System paramete rs with abbreviation and definition used for the advance theft detection algorithm is given in Table 6.1. Flowchart for advance theft detection system has been presented in figure 6.2.

| System Parameter | Abbreviation | Definition |
| --- | --- | --- |
| Base Test Score | BTS | Threshold value for Base Test |
| Continuous Test Score | CTS | Threshold value for an individual Continuous Test |
| Maximum Time Limit | MTL | Time period over which Continuous Test runs |
| Base Probability | PROB_BASE | Minimum Probability for passing of Continuous Test |
| Acceleration components | $A_x$, $A_y$ and $A_z$ | Acceleration values received from the accelerometer |
| Magnitude of Acceleration | A | $\sqrt{A_x^2 + A_y^2 + A_z^2}$ |

Table 6.1: System Parameters of Theft Detection Algorithm

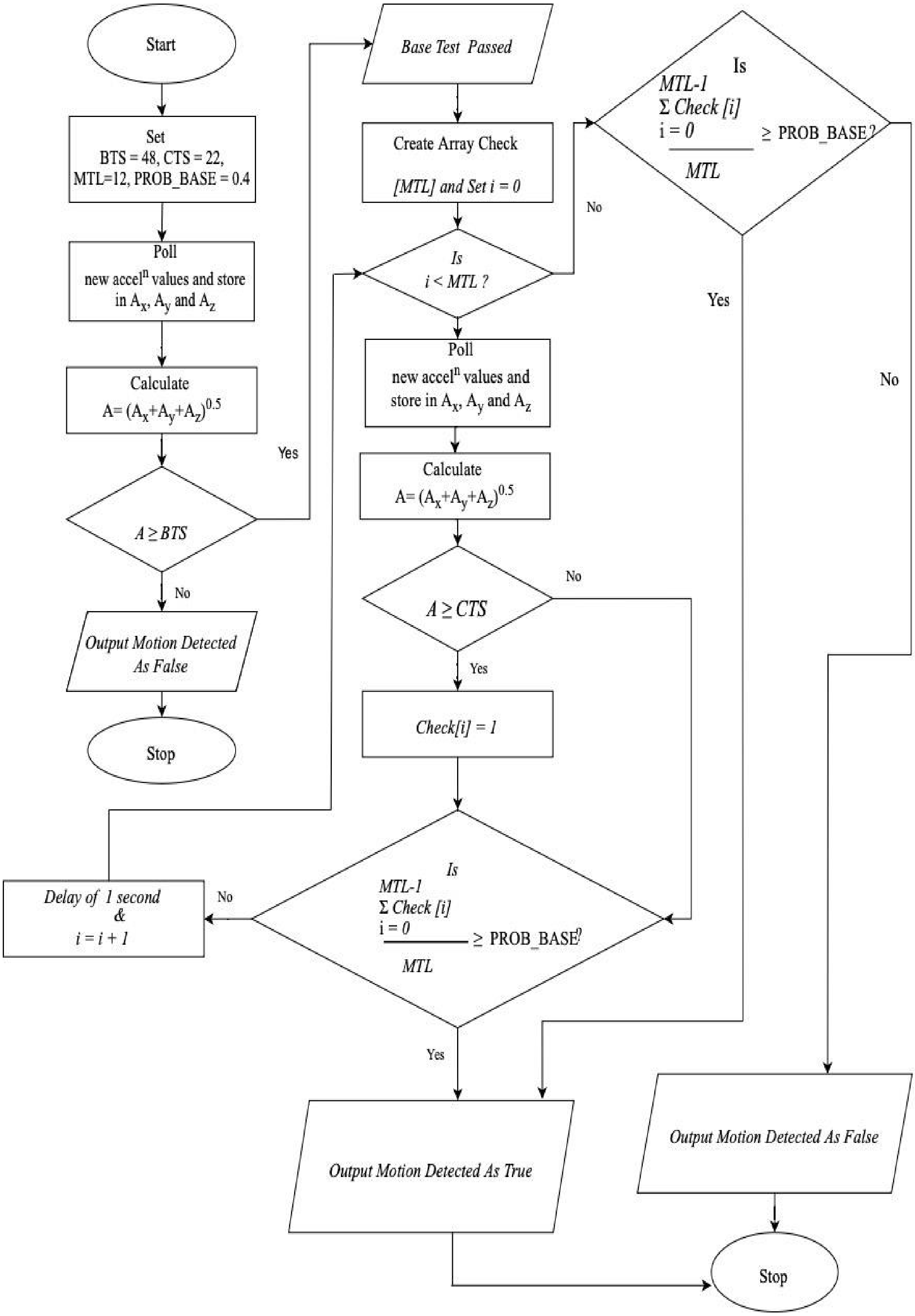



Fig. 6.2: Flowchart for Advance Theft Detection System

**Data Collection**

Following three types of events have been simulated for finding the values of the various parameters namely BTS, CTS, MTL and PROB_BASE.

i) The IGRED is at rest, henceforth referred to as the at Rest event.

ii) The thief picks up the IGRED and then takes slow steps henceforth referred to as the Pickup and Slow Steps event.

iii) The thief picks up the IGRED and then tries to run henceforth referred to as the Pickup and Run event.

30 instances of each event have been considered and the acceleration values of each instance for a period of 20 s have been recorded. The acceleration values were measured by the accelerometer and then logged into a micro SD card connected to the microcontroller. The acceleration values have been polled from the accelerometer every 0.1 s and thus each instance has 200 accelerometer readings. Figure 6.3 (i), (ii) and (iii) shows variation of accelerations during one sampled instance of each event.

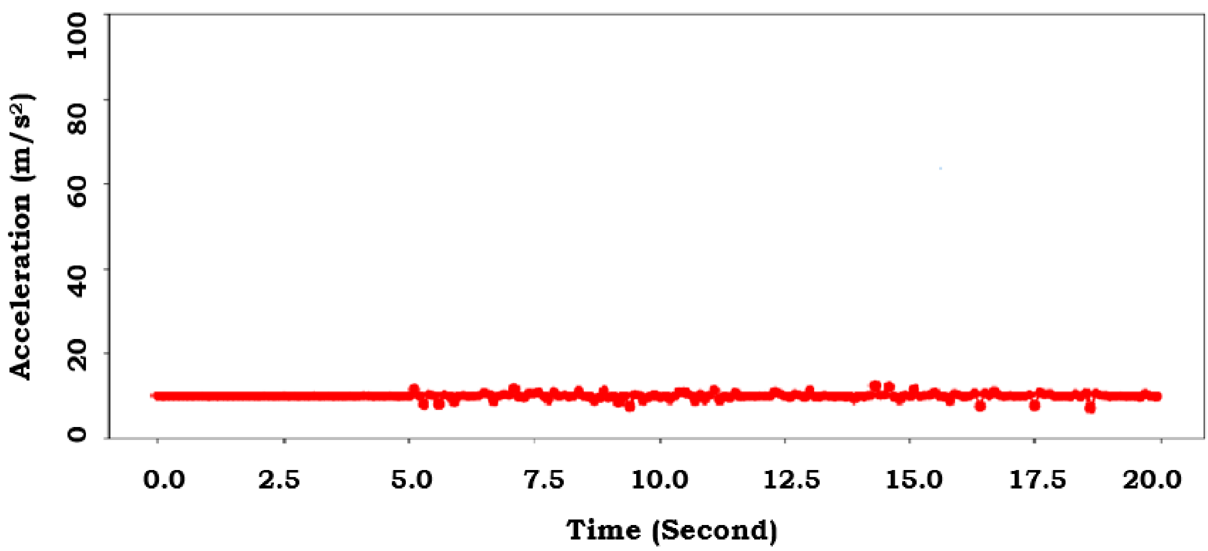



Fig. 6.3 (i): Acceleration during one Simulated at Rest Event

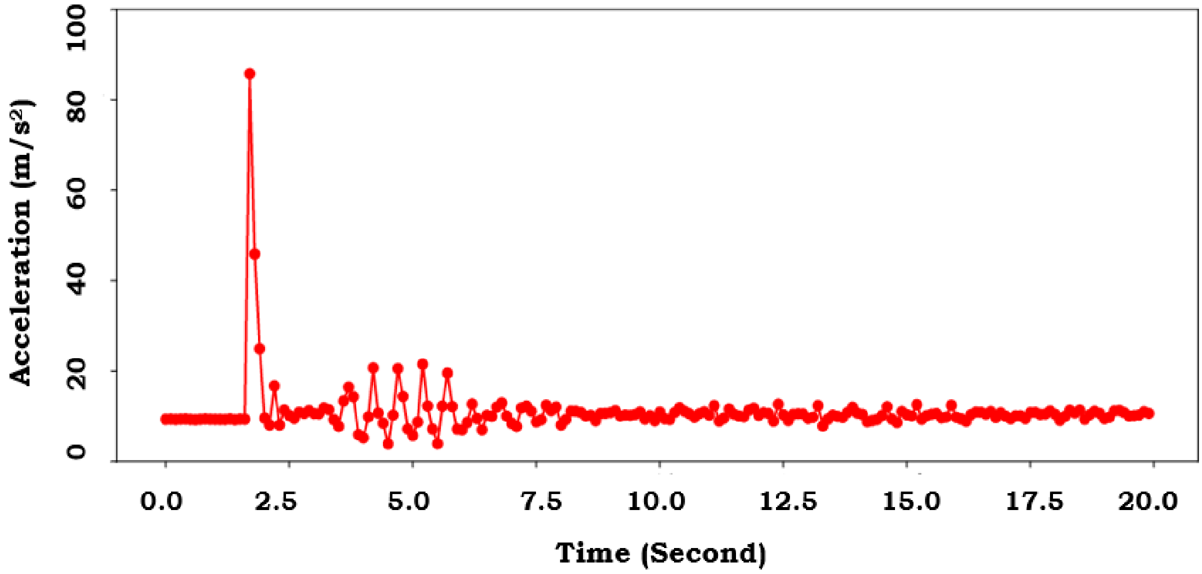



Fig. 6.3 (ii): Acceleration during One Simulated at Pickup and Slow Step event

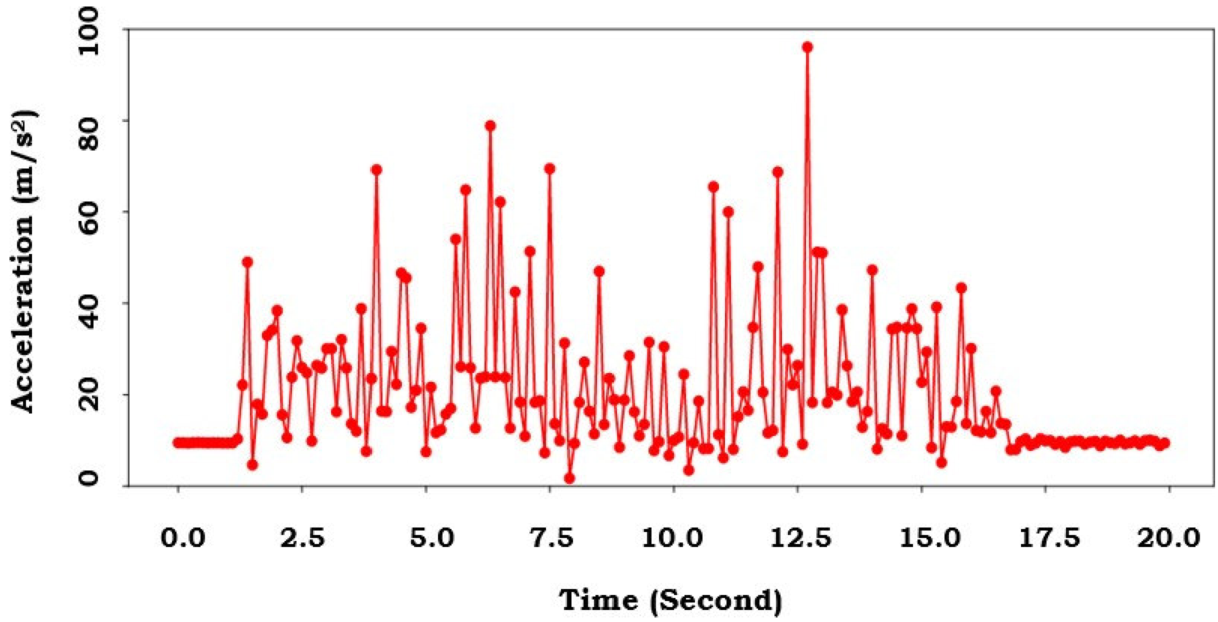



Fig. 6.3 (iii) : Acceleration during one Simulated Pickup and Run Event

**Parameter Optimisation**

For system parameter optimisation, magnitudes of acceleration have been considered rather individual X, Y and Z component as the magnitude is nondirectional and thus more robust to changes in the orientation of the IGRED. The data collected has been split into two sets A and B containing 20 and 10 instances of each event respectively, i.e. A contains a total of 60 instances and B contains a total of 30 instances. The following observations have been considered for deciding bounds for the parameters:

i) From the At Rest event in set A, lower bound for BTS and CTS are obtained. Magnitude of acceleration is nearly constant during rest and to prevent false detections our BTS and CTS values must be greater than this. This has been done by averaging the maximum acceleration magnitude obtained in each of the set A's At Rest event, i.e.

$$\mathbf{BTS, CTS} > \frac{\sum_{i=1}^{i=20} \max_{1\le j\le 200} \mathbf{A_{i,j}}}{\mathbf{20}} \quad \text{----------------------------- (6.1)}$$

Where $A_{i,j} = \sqrt{a^2_{x_{i,j}} + a^2_{y_{i,j}} + a^2_{z_{i,j}}}$ and $a_{x_{i,j}}, a_{y_{i,j}}, a_{z_{i,j}}$ are respectively the x, y and z accelerations observed in the $j^{th}$ data point of $i^{th}$ instance in set A's At Rest data.

ii) From the Pickup and Slow Steps event in set A, an upper bound for CTS is calculated by averaging the second maximum acceleration values obtained in each of the set A's Pickup and Slow Steps instance, i.e.

$$\mathbf{CTS} \le \frac{\sum_{i=1}^{i=20} \mathbf{second\_max}(\mathbf{A_{i,1}, A_{i,2}, \ldots A_{i,200}})}{\mathbf{20}} \quad \text{-----------------------------(6.2)}$$

Where second_max $(x_1, x_2, x_3 \ldots x_n)$ returns the $(n-1)^{th}$ order statistics of the sample $x_1, x_2, x_3 \ldots x_n$, and $A_{i,j}$ and $a_{x_{i,j}}, a_{y_{i,j}}, a_{z_{i,j}}$ are similarly defined as above for instances in setA's Pickup and Slow Steps data. During this event the major acceleration takes place at the pickup stage, where the base test is passed.

Hence for the continuous tests to be passed, the CTS has to less than the second maximum value recorded.

iii) Upper bound for BTS is calculated by averaging over the maximum values of acceleration in both the theft scenarios i.e. the combined set of instances in Pickup and Slow Steps and Pick up and Run , i.e.

$$\mathbf{BTS} \leq \frac{\sum_{i=1}^{i=40} \mathbf{max}(\mathbf{A}_{i,1}, \mathbf{A}_{i,2}, \ldots \mathbf{A}_{i,200})}{\mathbf{40}} \qquad \text{---------------------(6.3)}$$

Where $A_{i,j}$ and $a_{x_{i,j}}$, $a_{y_{i,j}}$, $a_{z_{i,j}}$ are similarly defined as in for instances in set A's combined Pickup and Slow Steps and Pick up and Run data.

iv) Since each simulation is taking place for 20 s,

$$\mathbf{1 \leq MTL \leq 20} \qquad \text{.....................................(6.4)}$$

v) The PROB_BASE parameter takes values in the range [0,1] in steps of 0.1.

Best choice of the values of the parameters have been decided after establishing the ranges in which the parameters lie. For this, the set B of instances have been used. All possibilities of the tuple (MTL, BTS, CTS, PROB_BASE) were looped over and the tuple which gave the best accuracy i.e. when theft detection algorithm runs with these values on the instances in set B has been chosen. Using the above methodology, the following values for system parameters are obtained: System parameters obtained by using the above methods are given in Table 6.2.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| BTS | 48 | MTL | 12 |
| CTS | 22 | PROB_BASE | 0.4 |

Table 6.2: System Parameters Values

**Theft Notification**

Once the theft is detected, ATHEDES sends notification in the form of call, message and also generates alarms. Figure 6.4 presents the flow chart for theft notification.

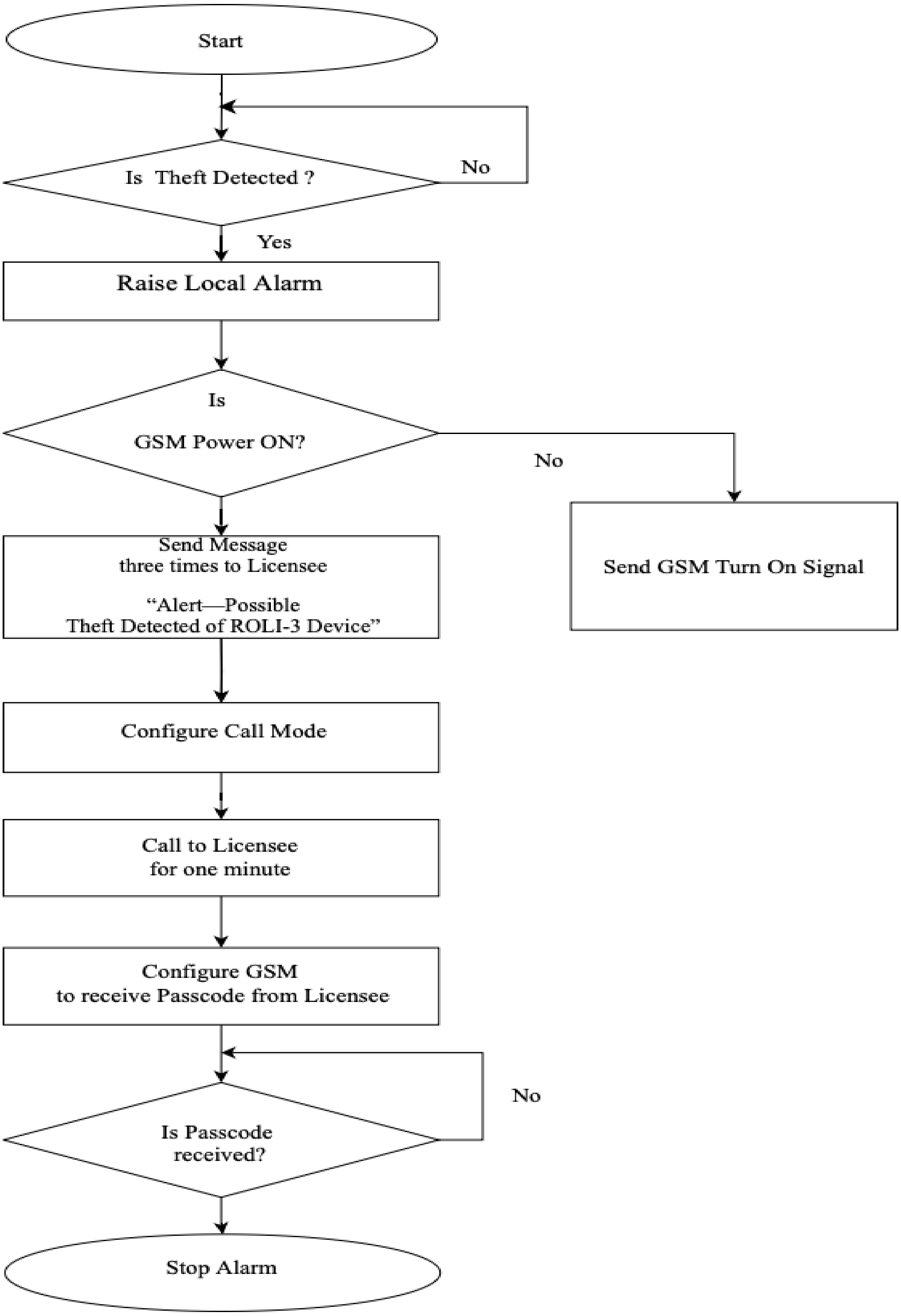



Fig. 6.4: Flowchart for Theft Notification

**Testing of the System**

The advance theft detection system developed for portable IGRED was initially tested in-house as shown in figure 6.5. During the field test, the system was attached to a ROLI-3 portable IGRED device. A 4G-enabled SIM card was used to establish communication with the Licensee's mobile number. The purpose of this test was to assess the system's performance in detecting theft incidents. During the test, a theft incidence was simulated when an individual attempted to escape with the ROLI-3 device from the radiography site as shown in figure 6.6.

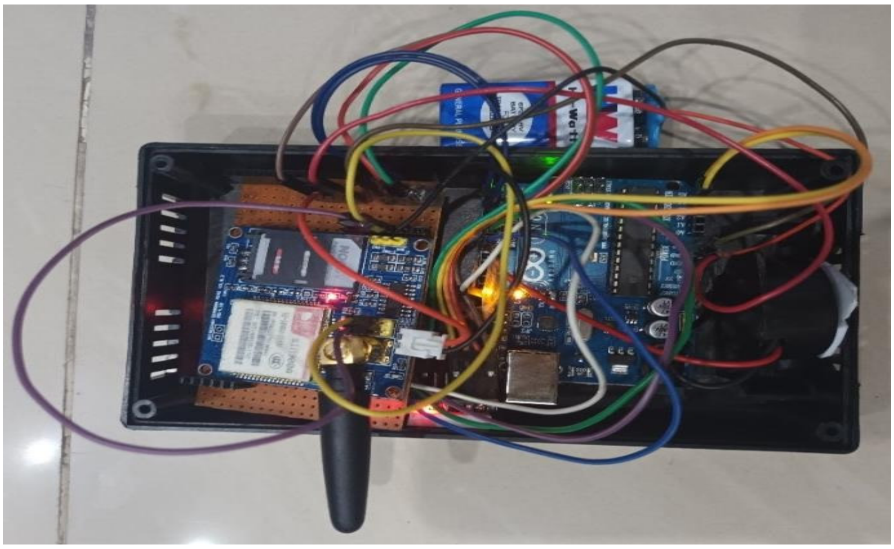


Fig. 6.5: In-house Testing of the Advance Theft Detection System

Fig. 6.6: Field Testing of the Advance Theft Detection System with ROLI-3 IGRED

The system successfully detected the theft and promptly sent three alert messages to the Licensee's mobile number. Additionally, a phone call of one minute duration was made to the Licensee's mobile number as part of the notification process. Moreover, a local alarm was activated, which was heard in the vicinity. Upon receiving the alert messages and phone call, the Licensee verified the situations in two different instances. In the first instance, after receiving the theft detection message and call, the Licensee responded by sending a pre -set eight-digit pass code to the device. As a result, the local alarm was deactivated and stopped. Messages received and pass code sent during field checking of the advance theft detection system, is shown in figure 6.7.

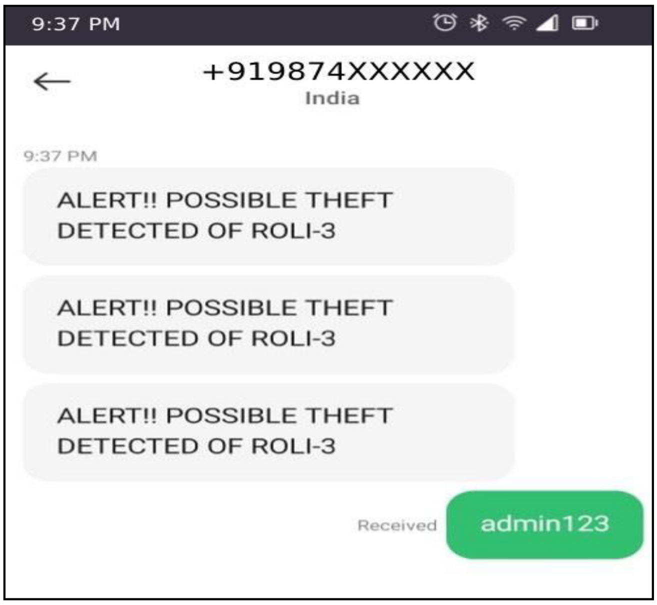



Fig. 6.7: Message Received and Pass Code Sent during Field Testing

In the second instance, when another theft incidence was represented, the Licensee did not send the pass code after receiving the message and call. In this case, the device continued to generate the local alarm until it was manually stopped locally. Overall, the field test demonstrated that the advance theft detection system could effectively detect the theft incidence and promptly notify the Licensee through multiple channels, including alert messages, a phone call, and a local alarm. The system's ability to be disarmed remotely by the Licensee using the pass code was also successfully validated.

# CHAPTER -7

## SUMMARY & GENERAL CONCLUSIONS

Industrial Radiography (IR) is an important NDT technique for investigation of integrity of materials and components but it possesses serious health hazards associated with ionising radiation. From previous reports of accidents and incidents, it is found that portable industrial gamma radiography exposure device (IGRED) is most hazardous in nature due to its frequent movement and unsecured storage particularly in construction site. From the study and assessment of safety performance of around 1200 IR facilities of India, with respect to personnel dose monitoring, regulatory inspection findings, safety performance indicator and unusual occurrences, following observations are made:

i) It has been seen that dose received by radiographers are highest among all applications of radiation in India. Though average dose received by the industrial radiography personnel are very much within the prescribed dose limit, excessive exposure of radiographers happens not only in in India but globally.

ii) Though majority of regulatory inspection findings are either Grey or White in nature with very low safety significance or no safety significance, one highest safety significance (Red) based RI finding was observed due to loss of industrial radiography source from one facility suggesting security of device is of paramount importance and existing security measures are unable to address security related issue such as early detection of theft.

iii) It is found that majority of industrial radiography facilities (94%) have shown "Satisfactory" safety performance and only 3 % of the facilities fall under "Needs Improvement" & 3 % of the facilities are under "Unsatisfactory" safety performance . One of the main reasons of the facilities falling under "Needs Improvement" and "Unsatisfactory" are found as excessive exposure case happened there.

iv) It is found from the study of unusual occurrences that "Theft of IGRED" has occurred from the IGRED storage room itself due to lack of security arrangements.

v) From calculation of probability of different unusual occurrences, it is found that probability of occurrence of "Excessive Exposure" is the highest one.

In order to overcome the above shortcomings and to improve safety & security of portable Industrial Gamma Radiography Exposure Device (IGRED) for minimisation of accidental exposure of the radiographers and prevention of theft incidence; IoT based radiation monitoring, automated cranking operation and advance theft detection system for portable IGRED have been designed and developed. Based upon the present research and development studies, the following observations & conclusions can be made;

I. The designed and developed IoT based radiation monitoring system for industrial radiography operation using GM tube, micro controlle r, ESP 8266 Wi-Fi module and ThingSpeak IoT analytics platform is accurate enough for radiation monitoring in IR operation and can also successfully record and store radiation measurement data in cloud during radiography. Also, cost involved to make the IOT based radiation monitoring system comes much lower compared to the minimum cost of RSM used by the IR facilities which has only manual provision of radiation level measurement. Accordingly, low cost and easy availability of the components make it practical and affordable.

*Hence, it can be concluded that the developed IOT based radiation monitoring system will certainly benefit IR facilities to enhance safety, improve real-time awareness on radiation levels & thus to prevent radiation exposure and ensure compliance with regulations.*

II. The fabricated automated cranking system for ROLI-3 Portable IGRED using stepper motor, RMCS 1102 driver, microcontroller, IR receiver, remote control, power supply and mechanical system consisting of chain, sprocket, bush, spring etc. found to perform quite satisfactorily in field testing. The developed system demonstrated that source assembly movement from the shielded container of ROLI-3 to the exposure head and vice versa can be controlled in accordance with the desired manner with increase or decrease of speed, forward and backward movement. Remote operation of the automated cranking system was checked and it was observed that the remote can be operated from a distance of at least eight meters away from the cranking unit. Considerable reduction of radiation level at operator's location with automated cranking operation was observed during field testing of automated cranking system. Also, as manual cranking provision originally designed for cranking operation has been kept intact to add Defense in Depth (DID) for the operation of the cranking system, manual cranking can be done in case the automated system fails due to any reason. Also, automated cranking operation for other models of portable IGREDs can be developed in the same way with very little modification.

*Accordingly, it can be concluded that remote operation can be done in a range based on available space and location of the job to be radiographed and automated cranking operation of portable IGRED will reduce dose to the operators significantly and chance of excessive exposure cases will greatly diminish which proves efficiency and effectiveness of the automation. It can also be concluded that methods applied for design and development of the automated cranking system of portable IGRED are unique in nature and can be adopted for all other models of portable IGREDs.*

III. The advance theft detection system (ATHEDES) using microcontroller, MPU 6050 accelerometer, SIM 900A GSM integrated with the ROLI-3 IGRED was totally successful. The field demonstration of the advanced theft detection system has proven its effectiveness in generating timely alarms and notifying the licensee of the ROLI-3 IGRED through message and call about possible theft incident. The message and call can be sent to any other person based on the choice and programmed. The system is practical, reliable, and cost effective. With minor adjustments to the box configuration, it can also be adapted for use with other models of IGRED.

*Thus, it can be concluded that the ATHEDES holds great potential as a tool to eliminate theft incidents involving portable IGRED, thereby mitigating the risk of unwanted radiation exposure and related injuries.*

Finally, it may be stated that all these research works successfully address the potential solutions for recurring problems like excessive exposure/injury of the radiography personnel and theft incidence of the IGRED faced by the industrial radiography facilities as well as by regulators. The prope r use of these developed technology will help in promoting safer and more reliable radiography than ever before.

Future research work could address on the design of the housing for the developed systems considering presence of continuous radiation environment.

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