Principles of Forensic Engineering Applied to INDUSTRIAL ACCIDENTS

Luca Fiorentini and Luca Marmo

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To my wonderful family: to my beloved wife Sonia and to my incredible children Riccardo, Lodovico and Ettore.
To all those who, thanks to this book, will take their first steps in the world of forensic engineering or increase their interest in this fascinating discipline.

Luca Fiorentini

To Baba, Beat, Bibi, Chicco.
To all those guys that believe in science, evidences and knowledge.

Luca Marmo

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Foreword by Giomi

Fires and explosions, by their very nature, tend to delete any evidence of their causes, destroying it or making it unrecognizable. Establishing the origins and causes of fire, as well as the related responsibilities, therefore requires significantly complex investigations.

Simple considerations illustrate these difficulties. In the case of arson retarding devices may be used to delay the phenomenon, or accelerating substances, such as petroleum derivatives, alcohols and solvents, by pouring them on combustible materials present on site. The use of flammable and/or combustible liquids determines a higher propagation velocity, the possible presence of several outbreaks of diffuse type – which do not occur in accidental fires that usually start from single points, in addition temperatures are higher than those that would result from just solid fuels, such as paper, wood or textiles.

Generally, in accidental fires, burning develops slowly with a rate that varies according to the type and quantity of combustible materials present, as well as to the ventilation conditions of involved buildings. In addition, temperatures are, on the average, lower than those reached in malicious acts.

Obviously, these considerations must be applied to the context: the discovery of a container of flammable liquid is not in itself a proof of arson, on the other hand, the absence of traces of ignition at the place of the fire is not evidence that the fire is of an accidental nature!

Forensic Engineering, science and technology at the same time, interprets critically the results of an experiment in order to explain the phenomena involved, borrowing from science the method of investigation, replacing the experimental results with the evidence collected in the investigation, to understand how a given phenomenon took place and what were its causes, and also any related responsibility.

The reconstruction takes place through reverse engineering to establish the possible causes of the event.

The same scientific and engineering methodologies are used for the analysis of failures of particular elements (failure analysis) as well as the procedures for the review of what happened, researching the primary causes (root causes analysis).

The accident is seen as the unwanted final event of a path that starts from organizational and contextual conditions with shortcomings, due to inefficiencies and errors of design and actual conditions in which individuals find themselves working, and continues by examining the unsafe actions, human errors and violations that lead to the occurrence of the accident itself.

The assessment of the scientific skills and abilities of the forensic engineer should not be limited, as often happens, to just ascertaining the existence of the specialization, but should also include the verification of an actual qualified competence, deducting it from previous experiences of a professional, didactic, judicial, etc. nature.

In this context, the book "Principi di ingegneria forense applicati ad incidenti industriali" (Principles of forensic engineering applied to industrial accidents) by Prof. Luca Fiorentini and Prof. Luca Marmo constitutes an essential text for researchers and professionals in forensic engineering, as well as for all those, including technical consultants, who are preparing to systematically approach the discipline of the so-called "industrial forensic engineering".

The authors, industrial process safety experts and recognised "investigators" on fires and explosions, starting from the analysis of accidents or quasi-accidents that actually occurred in the industrial field, offer, among other things, an overview of the methodologies to be adopted for collecting evidence and storing it by means of an appropriate measurement chain, illustrate some analysis methodologies for the identification of causes and dynamics of accidents and provide guidance for the identification of the responsibilities in an industrial accident.

The illustration of some highly complex cases requiring the use of specialist knowledge ensures that this text can also be a useful reference for the Investigative Police, that, as is well known, in order to validate the sources of evidence must be able to understand the progress of the events.

Gioacchino Giomi
Head, National Fire Brigade, Italy

Foreword by Chiaia

The number and the magnitude of industrial accidents worldwide has risen since the 70s and continues to grow in both frequency and impact on human wellbeing and economic costs. Several major accidents (see, e.g. the Seveso disaster in 1976, the Bhopal gas tragedy in 1984, the Chernobyl accident in 1986, and Deepwater Horizon oil spill in 2010) and the increased number of hazardous substances and materials have been under the lens of the United Nations Office for Disaster Risk Reduction (UNISDR), which puts great effort in developing safety guidelines within the Sendai Framework for Disaster Risk Reduction 2015–2030.

On the other hand, man-made and technological accidents still represent a major concern in both the advanced countries and in under-developed ones. In the first case, risk is related not only to possible human losses but also to the domino effects, in terms of fires, explosions and possible biological effects in highly populated areas. Indeed, as pointed out by a great number of forensic engineering cases, the safety regulations for industries in developed countries are usually very strict and demanding. On the contrary, in underdeveloped countries, there is clear evidence that industrial regulations are less strict and that a general lack of the "culture of safety" which generally results in a looser application of the rules, thus providing higher frequency of industrial accidents.

Quite often, the default of a plant component or a human error are individuated as the principal causes of an accident. However, in most cases the picture is not so simple. For instance, the *intrinsic probability* of experiencing a human error within a certain industrial process is a crucial factor that should be kept in mind when designing the process *ex-ante* and, inversely, during a forensic investigation *ex-post,* to highlight correctly responsibilities and mistakes. Another source of complexity is represented by the so-called *black swans*, i.e. the negative events which were not considered before their occurrence (i.e. neither during the plant design, nor during functioning of the plant) simply because no one had never encountered such events (black swans are also called the *unknown unknowns*).

In this complex framework, Forensic Engineering, as applied in the realm of industrial accidents, plays the critical and fundamental role of knowledge booster. As pointed out by Fiorentini and Marmo in this excellent and comprehensive book, application of the structured methods of *reverse engineering* coupled with the specific intuition of the smart, experienced consultant, permits the reader to reconstruct the fault event tree, to individuate the causes of defaults and even to identify, *a posteriori*, possible black swan events. In this way, a well-conducted Forensic Engineering activity not only aims at solving the specific investigation problem but, in many cases, provides significant advancements for science, technology, and industrial engineering.

Bernardino Chiaia
Vice Rector, Politecnico di Torino, Italy

Foreword by Tee

It is my pleasure and privilege to write the foreword for this book, titled *Principles of Forensic Engineering Applied to Industrial Accidents*. I was invited to do so by one author of this book, Luca Fiorentini, who is the editorial board member of the International Journal of Forensic Engineering published by Inderscience Publishers.

Forensic engineering is defined as the application of engineering methods in determination and interpretation of causes of damage to, or failure of, equipment, machines or structures. Despite prevention and mitigation efforts, disasters still occur everywhere around the world. Nothing is so certain as the unexpected. Engineering failures and disasters are quite common and occur because of flaws in design, human error and certain uncontrollable situations, for instance, collapse of the I-35 West bridge in Minneapolis, crash of Air France Flight 447, catastrophic pipe failure in Weston, Fukushima nuclear disaster, just to name a few. Forensic engineering has played increasingly important roles in discovering the root cause of failure, determining whether the failure was accidental or intentional, lending engineering rationale to dispute resolution and legal processes, reducing future risk and improving next generation technology.

Nevertheless, forensic engineering investigations are not widely published, partly because most of the investigations are confidential. It then denies others the opportunity to learn from failure so as to reduce the risk of repeated failure. As forensic engineering is continuing to develop as a mature professional field, the launch of this book is timely. The topics of this book are well balanced and provide a good example of the focus and coverage in forensic engineering. The scope of this book includes all aspects of industrial accidents and related fields. Its content includes, but is not limited to, investigation methods, real case studies and lessons learned. This book was motivated by the author's experience as an expert witness and forensic engineer. It is appropriate for use to raise awareness of current forensic engineering practices both to the forensic community itself and to a wider audience. I believe this book has great value to students, academician and practitioners from world-wide as well as all others who are interested in forensic engineering.

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Preface

If you read this book, you are forensic engineers, or you would like to become one. Or you are simply curious. We hope this reading will stimulate your curiosity. A forensic engineer must be curious. He/she must look for answers to facts, give them scientific proof and above all he/she must not stop at the first explanation of the facts, even when it may seem the most obvious and solid.

A forensic engineer collects fragments, and, with these, he/she builds a mosaic where each tessera has one and only one natural location. Why do we do it? The reasons may be different. You could work on behalf of justice, or for the defence of an accused, or for an insurance company called to compensate an accident, just to name a few. Whatever your principle, you have a responsibility that goes beyond the professional one. A scientific responsibility. By reconstructing the mosaic of the facts that led to the disaster you are investigating or will investigate, you will give your explanation of the facts and the causes that determined them. If our explanation is based irrefutably on scientific arguments and the evidence, free from considerations related to the standards and desires of our principle, we will have made a contribution, sometimes small, sometimes significant, to progress. How much did the fire of the Deepwater Horizon, the release of Methyl Isocyanate of Bhopal or the fire of the ThyssenKrupp of Turin or the explosion of Chernobyl cost to the human community? Sometimes we find it difficult to estimate exactly the tribute of human lives; it is even more challenging to estimate material, image and environmental damage. If in the profession of the forensic engineer there is a mission, it is to contribute so that these facts are not repeated, so that the community learns from its mistakes, so that our well-being is increasingly based on sustainable activities, respectful of the rights of those who are more vulnerable or more exposed.

Galileo Galilei said: “Philosophy is written in this great book that is constantly open in front of our eyes (I say the universe), but we cannot understand it if we do not learn to understand the language first and know the characters in which it is written. It is written in mathematical language, and the characters are triangles, circles, and other geometric figures, without which it is impossible to understand them on a human scale; without these, it is a vain wandering through an obscure labyrinth.” In our opinion, it also applies to the Forensic Engineer. The facts and their causes are written in the universe of the scene of the disaster, but we must understand the language and the characters of the writing. In reconstructing the dynamics and causes of an accident we must apply science to the facts, we must reconcile the reconstruction based on objective evidence with its explanation based on scientific evidence. In this way, in our opinion, one can ultimately achieve a precious result, that is expanding knowledge, drawing lessons from adverse facts so that they do not repeat themselves. We believe this is the highest mission that a forensic engineer can pursue in his/her professional life. Professor Trevor Kletz showed us how important it is to learn from accidents. This belief is the basis of the large space given in this book to the case studies. Obviously, we need a systematic and orderly method of work, which is what we have tried to describe in the text. And then we need a team. The forensic engineer cannot, in our opinion, have such a large baggage to deal with a complex case like the Thyssen Krupp case described in Chapter 7. We need specialists with very different characteristics to retrieve the data of a control system and interpret them, to simulate a jet fire and to determine the chemical-physical properties of the substances involved. We believe that a forensic engineer should never be afraid to seek the help of a specialist, but rather should fear to possess not the technical and scientific skills to dialogue with the many specialists who will contribute in his/her investigations. We hope that reading this text can help you build some of these bases.

Luca Fiorentini
Luca Marmo

Acknowledgement

Writing a book on the principles of forensic engineering represented a double challenge. First of all, the writing activity, whatever is written, requires moments of reflection to be devoted solely to the composition and in today's life this may mean taking a few hours from sleep. But such a large work, although limited to the principles of this discipline, could not be achieved without the precious contribution of those people who helped us to gather the necessary information for some topics of this text, as well as for the various case studies mentioned in Chapter 7.

In particular, we would like to thank MFCforensic for the valuable help provided in the preparation of this book. Clarifying that the objective of this book is not to publicise an investigative tool, but to provide a wide knowledge about the main methodologies used, a special thank you, however, goes to those who have allowed us to enrich the volume with a broad examination of the main instruments at the service of the forensic investigator. We therefore thank CGE Risk Management Solution for providing important support with its images on the main investigative tools, such as BSCAT™, Tripod Beta and BFA, which have undoubtedly embellished this text. Special thanks also to Fadi E. Rahal for providing the necessary material for the knowledge of Apollo RCA™; Mark Paradies and Barbara Carr for TapRoot®; and Jason Elliot Jones for Reason© RCA.

One of the most important contributions comes from those who have shared with us the information necessary for drafting the case studies reported in Chapter 7, often offering themselves for writing them. Proceeding in the order in which the case studies are presented in the book, we wish to thank Norberto Piccinini, former professor of Industrial Safety at the Turin Polytechnic, for his invaluable collaboration on the ThyssenKruup case; ARCOS Engineering s.r.l., in the person of Rosario Sicari, Alessandro Cantelli Forti, CNIT researcher at the Radar and Surveillance Systems National Laboratory of Pisa, and Simone Bigi by Tecsa s.r.l. for their help in drafting the case on the Norman Atlantic; Giovanni Pinetti and Pasquale Fanelli by Tecsa s.r.l. for having shared the material concerning a LOPC of flammable substance; Salvatore Tafaro, commander of the provincial command of Vibo Valentia of Italian National Fire Brigade, for valuable information on the case study of a refinery pipeway fire; Vincenzo Puccia, director of the provincial command of the Padua National Fire Brigade, and Serena Padovani for their contribution about the flash fire at silo and the explosion of a rotisserie van case studies; a special thanks to Vincenzo also for his example about the value of the digital evidence, shown in Paragraph 4.4.3.1; Numerics GmbH, in the person of Ernst Rottenkolber and Stefan Greulich, for the valuable collaboration on the case study of the fragment projection; Iplom S.p.A., in the person of Gianfranco

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The authors give a special thanks to Rosario Sicari who oversaw the drafting of the work with care, precision and dedication, qualities that distinguish his activity as a forensic engineer and that we have been able to appreciate on several occasions of shared professional activity, from which have made Rosario not only an esteemed colleague to entrust the management of this complex and important work, but also an excellent friend with whom to share in the future, with great confidence, a growing number of assignments in the forensic field.

List of Acronyms

AHJ	Authorities Having Jurisdiction
AI	Accident Investigation
AIT	Auto Ignition Temperature
AIChE	American Institute of Chemical Engineers
ALARP	As Low As Reasonably Practicable
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ATG	Automatic Tank Gauging
BBS	Behavior Based Safety
BFA	Barrier Failure Analysis
BFD	Block Flow Diagram
BLEVE	Boiling Liquid Expanding Vaprs Explosion
BOP	Blow Out Preventer
BPCS	Basic Process Control System
BRF	Basic Risk Factor
BSCAT	Barrier-based Systematic Cause Analysis Technique
CAC	Critical Administrative Control
CAS	Chemical Abstracts Service (number)
CCDM	Cause-Consequence Diagram Method
CCPS	Centre for Chemical Process Safety
CEO	Chief Executive Officer
CFD	Computational Fluid Dynamics
COMAH	Control Of Major Accident Hazards
CSB	US Chemical Safety Board
CPU	Central Processing Unit
DCS	Distributed Control System
E/E/PE	Electrical/Electronic/Programmable Electronic
EFV	Excessive Flow Valve
EIV	Emergency Isolation Valve
EPA	U.S. Environmental Protection Agency
EPG	Equipment Performance Gaps
ERT	Emergency Response Team
ESReDA	European Safety Reliability and Data Association
ETA	Event Tree Analysis

FLPPG	Front-Line Personnel Performance Gaps
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FDS	Fire Dynamics Simulator
FPT	Flash Point Temperature
FRC	Flow Recorder Controller
FTA	Fault Tree Analysis
GIGO	Garbage In Garbage Out
HAZID	HAZard IDentification
HAZOP	HAZard and OPerability Analysis
HD	Hard Disk
HDA	HydroDeAlkylation
HEMP	Hazard and Effects Management Process
HIRA	Hazard Identification and Risk Analysis
HPEP	Human Performance Evaluation Process
HR	Human Resources
HRR	Heat Release Rate
HSE	Health, Safety and Environmental
HSSE	Health, Safety, Security and Environmental
ICT	Information Computer Technology
IE	Initiating Event
IEC	International Electrotechnical Commission
IHLS	Independent High-Level Switch
IPL	Individual Protection Layer
ISO	International Organization for Standardization
IT	Information Technology
JA	Job Ability
JD	Job Demand
LEL	Lower Explosive Limit
LFE	Learning From Experience
LFL	Lower Flammability Limit
LI	Level Indicator
LLA	Low-Level Alarm
LOC	Limiting Oxygen Concentration
LOPA	Layer Of Protection Analysis
LOPC	Loss Of Primary Containment
LPG	Liquefied Petroleum Gases
LTA	Less Than Adequate
MARS	Major Accident Reporting System
MIC	Methyl-IsoCyanate
MIE	Minimum Ignition Energy
MOC	Management Of Change
MOC	Minimum Oxygen Concentration
MOOC	Management Of Organizational Change
MORT	Management Oversight Risk Tree
MSDS	Material Safety Data Sheet
MTO	Man, Technology and Organization

NFPA	National Fire Protection Association
NIST	U.S. National Institute for Standards and Technology
OCM	Organizational Change Management
OE	Operational Excellence
OSHA	Occupational Safety and Health Administration
PAH	Polycyclic Aromatic Hydrocarbons
P&A	Pickling and Annealing
P&ID	Piping and Instrumentation Diagram
PFD	Probability of Failure on Demand
PFS	Process Flow Sheet
PFH	Probability of Failure per Hour
PHA	Process Hazard Analysis / Preliminary Hazard Analysis
PLC	Programmable Logic Controller
PM	Project Manager
PPE	Personal Protective Equipment
PRP	Primary Responsible Party
PSI	Process Safety Information
PSM	Process Safety Management
PSV	Pressure Safety Valve
PV	PhotoVoltaic
QIQO	Quality In Quality Out
QRA	Quantitative Risk Assessment
RA	Risk Assessment
RCA	Root Cause Analysis
RCV	Remote Controller isolation Valve
R&D	Research & Development
RMP	Risk Management Program
ROI	Return On Investment
RPN	Risk Priority Number
RV	Relief Valve
SCE	Safety Critical Equipment
SIF	Safety Instrumented Functions
SIL	Safety Integrity Level
SIS	Safety Instrumented System
SLC	Safety Life Cycle
SMS	Safety Management System
SPAC	Standard, Policies and Administrative Control
SRK	Skill-Rule-Knowledge
STEP	Sequentially Timed Events Plotting
SWOT	Strengths, Weaknesses, Opportunities and Threats analysis
TCDD	TetraChloroDibenzoDioxin
TCP	TriChloroPhenol
TIC	Temperature Indicator Controller
TRV	Thermal Relief Valve
UEL	Upper Explosive Limit

UFL	Upper Flammability Limit
UVCE	Unconfined Vapor Cloud Explosion
VCE	Vapor Cloud Explosion
VDR	Voyage Data Recorder
VGS	Vent Gas Scrubber

1

Introduction

1.1 Who Should Read This Book?

"Principles of forensic engineering applied to industrial accidents" is intended to be an introductory volume on the investigation of industrial accidents. Forensic engineering should be seen as a rigorous approach to the discovery of root causes that lead to an accident or a near-miss. The approach should be suitable to identify both the immediate causes as well as the underlying factors that affected, amplified or modified the events (regarding consequences, evolution, dynamics), and the contribute by an eventual "human error".

A number of books have already been published on similar topics. The idea behind this book is not to replace those important volumes but to obtain a single concise and introductory volume (also for students and authorities) to the forensic engineering discipline that helps understand the link among those critical but very functional aspects of the same problem in the global strategy of learning from accidents (or near-misses). The reader, in this sense, will benefit from a single point of access to this vast technical literature that can be only accessed with proficiency having the right terms, definitions, and links in mind. On the contrary, the reader could get lost in all the quoted literature that day by day increases due to the speed of the research in this complex field.

The intent of the book is:

- Presenting simple real cases as well as give an overview of more complex ones, each of them investigated with the same framework;
- giving the readers the bibliography to access more in-depth specific aspects;
- giving them an overview of the most and commonly used methodologies and techniques to investigate accidents;
- giving them a summary of the evidence, which should be collected to define the cause, dynamics, and responsibilities of an industrial accident;
- giving them an overview of the most appropriate methods to collect and to preserve evidence through an appropriate chain of custody; and
- giving an overview of the main mistakes that can lead to misjudgment or loss of proof.

The book is an introductory volume for readers in academia as well as professionals who want to know more about the forensic engineering methodologies to be applied to discover more about the causes of industrial accidents in order to derive lessons. Among those professionals, we can identify process and safety managers, risk managers,

Principles of Forensic Engineering Applied to Industrial Accidents, First Edition.
Luca Fiorentini and Luca Marmo.

industrial risks consultants, attorneys, authorities having jurisdiction, judges and prosecutors, and so on.

It is particularly addressed to those who would like to approach the fundamentals of forensic engineering discipline without directly going to specialised already available volumes and handbooks that need a sound background to be read. Nonetheless, reading this book may help professionals (e.g. loss adjusters, risk engineers, safety professionals, safety management systems consultants.) and students who want to have a concise book as prompt reference towards the main important recognised resources available (e.g. CCPS©-AIChE© books also edited by Wiley, NFPA© 921 Standard, etc.) or as a bridge between risk assessment and accidents investigation (as a tool to learn from real accidents or near-misses in order to improve safety).

1.2 Going Beyond the Widget!

When investigating an industrial accident or a near miss, it should be well kept in mind that the primary goal to be reached is not to find a concise fault of a well-defined widget, confined to a distinct domain. A rigorous approach to the forensic discipline requires going much deeper in the investigation, not stopping at the main relevant evidence, even if properly gathered and analysed. It often happens that accident reports are one-dimensional [1]: in simple words, they identify only a single cause, usually corresponding to the outer layer of the complexity that surrounds the reconstruction of the incidental dynamics. Even when multiple causes are discovered, the investigator seldom looks beyond them.

In the industrial context, a complex system of relations, information, and people is present, with its peculiarity and hierarchy, creating a structured entity that needs to be considered when investigating an accident or a near miss. Thus, it becomes necessary to consider as an element of investigation the management systems as well, as some causes of the accident may be related to management failure, so to take the corrective actions and to prevent a further similar failure. A good investigator does not find culprits, does not blame. A good investigator collects evidence, analyses it and finds the root causes and the relations among them that lead to the accident, whilst also considering the managerial duties and, as usually happens, then provides suggestions about corrective actions to avoid the reoccurrence of the undesired event.

Focusing on the system, rather than the individual, represents the right way to face an investigation, at least for two reasons [2]. Firstly, if equipment and systems provided to persons reveal to be not effective, thus it is not the individual responsibility that has to be pointed out as the fault cause. Secondly, it is much easier to change a managerial choice rather than a person or his/her behavior, which is susceptible to vary daily. Third, human errors may often be the consequence of insufficient training, motivation or attention to safety, all being aspects that the management should promote and monitor. It is a matter of controllability and reliability, as they are the two most essential ingredients to ensure that the lesson learnt will guarantee an increasing, or a restoration at least, of the safety level accepted in the industry at the corporate, field and line levels. Metaphorically speaking, an accident investigation is like peeling an onion: this concept, cited in [3], gives us a live image of what we are called to solve (see Figure 1.1). Technical problems and mechanical failures are the outer layers of the onion: they are the immediate causes.