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API RP 581 Risk-Based Inspection Methodology

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PART 1 CONTENTS

Risk-Based Inspection Methodology
Part 1—Introduction to Risk-Based Inspection Methodology

1 Foreword

This recommended practice, API 581, *Risk-Based Inspection Methodology*, provides semi-quantitative analysis procedures to establish an inspection program using risk-based methods for pressurized fixed equipment including pressure vessel, piping, tankage, pressure-relief devices (PRDs), and heat exchanger tube bundles. API 580, *Risk-Based Inspection* provides guidance for developing risk-based inspection (RBI) programs on fixed equipment in refining, petrochemical, chemical process plants, and oil and gas production facilities. The intent is for API 580 to introduce the principles and present minimum general guidelines for RBI, while this recommended practice provides examples of semi-quantitative calculation methods to determine risk and associated inspection plan.

2 Scope

The calculation of risk outlined in API 581 involves the determination of a probability of failure (POF) combined with the consequence of failure (COF). Failure is defined as a loss of containment from the pressure boundary resulting in leakage to the atmosphere or rupture of a pressurized component. Risk increases as damage accumulates during in-service operation as the risk tolerance or risk target is approached and an inspection is recommended of sufficient effectiveness to better quantify the damage state of the component. The inspection action itself does not reduce the risk; however, it does reduce uncertainty and therefore allows more accurate quantification of the damage present in the component.

2.1 Risk Management

In most situations, once risks have been identified, alternate opportunities are available to reduce them. However, nearly all major commercial losses are the result of a failure to understand or manage risk. In the past, the focus of a risk assessment has been on-site safety-related issues. Presently, there is an increased awareness of the need to assess risk resulting from:

a) on-site risk to employees,

b) off-site risk to the community,

c) business interruption risks, and

d) risk of damage to the environment.

Any combination of these types of risks may be factored into decisions concerning when, where, and how to inspect equipment.

The overall risk of a plant may be managed by focusing inspection efforts on the process equipment with higher risk. API 581 provides a basis for managing risk by making an informed decision on inspection frequency, level of detail, and types of nondestructive examination (NDE). It is a consensus document containing methodology that owner~~–user~~operators may apply to their RBI programs. In most plants, a large percent of the total unit risk will be concentrated in a relatively small percent of the equipment items. These potential higher risk components may require greater attention, perhaps through a revised inspection plan. The cost of the increased inspection effort can sometimes be offset by reducing excessive inspection efforts in the areas identified as having lower risk. Inspection will continue to be conducted as defined in existing working documents, but priorities, scope, and frequencies can be guided by the methodology contained in API 581.

This approach can be made cost-effective by integration with industry initiatives and government regulations, such as Process Safety Management of Highly Hazardous Chemicals (OSHA 29 CFR 1910.119), or the EPA risk management programs for chemical accident release prevention (Section 112(r) of the Clean Air Act Amendments), or Oil and Gas and Sulphur Operations in the Outer Continental Shelf (30 CFR Part 250).

2.2 Organization and Use

The API 581 methodology is presented in a five-part volume:

a) Part 1—Introduction to Risk Based Inspection ~~Planning~~ Methodology,

b) Part 2—Probability of Failure Methodology,

c) Part 3—Consequence of Failure Methodology,

d) Part 4—Inspection Planning Methodology,

e) Part 5—Special Equipment.

Part 1 serves as an introduction and establishes the basic premise for using this standard.~~51 provides methods used to develop an inspection plan for fixed equipment, including pressure vessels, piping, atmospheric storage tanks (ASTs), PRDs, and heat exchanger tube bundles. The pressure boundaries of rotating equipment may also be evaluated using the methods in Part 1.~~ The methods for calculating the POF for fixed equipment are covered in ~~Part 1 and~~ Part 2. The POF is based on the component type and damage mechanisms present based on the process fluid characteristics, design conditions, materials of construction, and the original construction code. The pressure boundaries of rotating equipment may also be evaluated using the methods in Part 2. Part 3 provides methods for computing the COF. Two methods are provided: Level 1 is based on equations with a finite set of well-known variables generated for common fluids or fluid groups found in refinery and petrochemical processing units, while Level 2 is a more rigorous method that can be used for any fluid stream composition. Part 4 provides methods used to develop an inspection plan for fixed equipment, including pressure vessels and piping. Part 5 provides RBI methods for equipment which are not represented well using the Part 2 methodology directly. This includes atmospheric storage tanks (ASTs), PRDs, heat exchanger tube bundles, and steam systems.

An overview of the POF and COF methodology calculations, with reference to the associated sections within this document, is provided in Table 4.1.

Commented [RS1]: A lot of what was said here was outdated. I tried to organize the statements in flow of the document instead of starting with Part 5. Please feel free to use better verbiage.

3 Normative References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any addenda) applies.

API Recommended Practice 580*, Risk-Based Inspection*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 3—Consequence of Failure Methodology*

4 Terms, Definitions, Acronyms, and Abbreviations

4.1 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.
4.1.1

aerosol
Liquid droplets small enough to be entrained in a vapor stream.

~~3.1.1~~ 4.1.2
atmospheric dispersion
The low momentum mixing of a gas or vapor with air. The mixing is the result of turbulent energy exchange, which is a function of wind (mechanical eddy formation) and atmospheric temperature profile (thermal eddy formation).

~~3.1.2~~ 4.1.3
autoignition temperature
AIT
The lowest temperature at which a fluid mixture can ignite without a source of ignition.

~~3.1.3~~ 4.1.4
boiling liquid expanding vapor explosion
BLEVE
An event that occurs from the sudden release of a large mass of pressurized liquid (above the boiling point) to the atmosphere. A primary cause is an external flame impinging on the shell of a vessel above the liquid level, weakening the shell and resulting in sudden rupture.

~~3.1.4~~ 4.1.5
business interruption costs
financial consequence
Includes the costs that are associated with any failure of equipment in a process plant. These include, but are not limited to, the cost of equipment repair and replacement, downtime associated with equipment repair and replacement, costs due to potential injuries associated with a failure, and environmental cleanup costs.

~~3.1.5~~ 4.1.6
component
Any part that is designed and fabricated to a recognized code or standard. For example, a pressure boundary may consist of components (cylindrical shell sections, formed heads, nozzles, AST shell courses, AST bottom plate, etc.).

~~3.1.6~~ 4.1.7

component type
Category of any part of a covered equipment (see component) and is used to assign gff, calculate t_{min}, and develop inspection plans.

~~3.1.7~~ 4.1.8
consequence
The outcome of an event or situation expressed qualitatively or quantitatively, being a loss, injury, disadvantage, or gain.

~~3.1.8~~ 4.1.9
consequence analysis
The analysis of the expected effects of incident outcome cases independent of frequency or probability.

~~3.1.9~~ 4.1.10
consequence area
The area impacted as a result of an equipment failure using calculations defined in API 581.

~~3.1.10~~ 4.1.11
consequence of failure
COF
The outcome of a failure event used in relative ranking of equipment. COF can be determined for safety, environmental, or financial events.

~~3.1.11~~ 4.1.12
consequence methodology
The consequence modeling approach that is defined in API 581.

~~3.1.12~~ 4.1.13
consequence modeling
Prediction of failure consequences based on a set of empirical equations, using release rate (for continuous releases) or mass (for instantaneous releases).

~~3.1.13~~ 4.1.14
continuous release
A release that occurs over a longer period of time. In consequence modeling, a continuous release is modeled as steady state plume.

~~3.1.14~~ 4.1.15
corrosion allowance
The excess thickness available above the minimum required thickness (e.g. based initially on furnished thickness or measured thickness and is not necessarily the initial or nameplate corrosion allowance).

~~3.1.15~~ 4.1.16
critical point
The thermodynamic state in which liquid and gas phases of a substance coexist in equilibrium at the highest possible temperature. At higher temperatures than the critical, no liquid phase can exist.

~~3.1.16~~ 4.1.17

damage factor
DF
An adjustment factor applied to the generic failure frequency (GFF) of a component to account for damage mechanisms that are active in a component.

~~3.1.17~~ 4.1.18

damage mechanism
A process that induces deleterious micro and/or macro material changes over time that is harmful to the material condition or mechanical properties. Damage mechanisms are usually incremental, cumulative, and in some instances unrecoverable. Common damage mechanisms include corrosion, chemical attack, creep, erosion, fatigue, fracture, and thermal aging.

~~3.1.18~~ 4.1.19

deflagration
A release of energy caused by the propagation of a chemical reaction in which the reaction front advances into the unreacted substance at less than sonic velocity in the unreacted material. Where a blast wave is produced with the potential to cause damage, the term **explosive deflagration** may be used.

~~3.1.19~~ 4.1.20

dense gas
A gas with density exceeding that of air at ambient temperature.

~~3.1.20~~ 4.1.21

detonation
A release of energy caused by the extremely rapid chemical reaction of a substance in which the reaction front advances into the unreacted substance at greater than sonic velocity.

~~3.1.21~~ 4.1.22

dispersion
When a vapor or volatile liquid is released to the environment, a vapor cloud is formed. The vapor cloud can be dispersed or scattered through the mixing of air, thermal action, gravity spreading, or other mixing methods until the concentration reaches a safe level or is ignited.

~~3.1.22~~ 4.1.23
entrainment
The suspension of liquid as an aerosol in the atmospheric dispersion of a two-phase release or the aspiration of air into a jet discharge.

~~3.1.23~~ 4.1.24
equipment
An individual item that is part of a system; equipment is comprised of an assemblage of components. Examples include pressure vessels, PRDs, piping, boilers, and heaters.

~~3.1.24~~ 4.1.25
event
An incident or situation that occurs in a particular place during a particular interval of time.

~~3.1.25~~ 4.1.26
event tree
Model used to show how various individual event probabilities should be combined to calculate the probability for the chain of events that may lead to undesirable outcomes.

~~3.1.26~~ 4.1.27
failure
The loss of function of a system, structure, asset, or component to perform its required or intended function(s). The main function of the systems, assets, and components included in the scope of this document is considered

to be containment of fluid. Therefore, for pressure boundary components, failure is associated with a loss of containment due to operating conditions, discontinuities, damage, loss of material properties, or a combination of these parameters.

~~3.1.27~~ 4.1.28
fireball
The atmospheric burning of a fuel-air cloud in which the energy is mostly emitted in the form of radiant heat. The inner core of the fuel release consists of almost pure fuel, whereas the outer layer in which ignition first occurs is a flammable fuel-air mixture. As buoyancy forces of the hot gases begin to dominate, the burning cloud rises and becomes more spherical in shape.

~~3.1.28~~ 4.1.29
Fitness-For-Service
FFS
A methodology whereby damage or flaws/imperfections contained within a component or equipment item are assessed in order to determine acceptability for continued service.

~~3.1.29~~ 4.1.30
flammability range
Difference between upper and lower flammability limits.

~~3.1.30~~ 4.1.31
flammable consequence
Result of the release of a flammable fluid in the environment.

~~3.1.31~~ 4.1.32
flash fire
The combustion of a flammable vapor and air mixture in which flame passes through that mixture at less the sonic velocity, such that negligible damaging overpressure is generated.

~~3.1.32~~ 4.1.33
flashpoint temperature
Temperature above which a material can vaporize to form a flammable mixture.

~~3.1.33~~ 4.1.34
generic failure frequency
GFF
A POF developed for specific component types based on a large population of component data that does not include the effects of specific damage mechanisms. The population of component data may include data from all plants within a company or from various plants within an industry, from literature sources, past reports, and commercial databases.

~~3.1.34~~ 4.1.35
hazard and operability study
HAZOP
A structured brainstorming exercise that utilizes a list of guidewords to stimulate team discussions. The guidewords focus on process parameters such as flow, level, temperature, and pressure and then branch out to include other concerns, such as human factors and operating outside normal parameters.

~~3.1.35~~ 4.1.36
hydraulic conductivity
Also referred to as the coefficient of permeability. This value is based on soil properties and indicates the ease with which water can move through the material. It has the same units as velocity.

~~3.1.36~~ 4.1.37
inspection

A series of activities performed to evaluate the condition of the equipment or component.

~~3.1.37~~ 4.1.38
inspection effectiveness
The ability of the inspection activity to reduce the uncertainty in the damage state of the equipment or component. Inspection effectiveness categories are used to reduce uncertainty in the models for calculating the POF (see Annex 2.C).

~~3.1.38~~ 4.1.39
inspection plan
A documented set of actions detailing the scope, extent, methods, and timing of the inspection activities for equipment to determine the current condition.

~~3.1.39~~ 4.1.40
inspection program
A program that develops, maintains, monitors, and manages a set of inspection, testing, and preventative maintenance (PM) activities to maintain the mechanical integrity of equipment.

~~3.1.40~~ 4.1.41
instantaneous release
A release that occurs so rapidly that the fluid disperses as a single large cloud or pool.

~~3.1.41~~ 4.1.42
intrusive
Requires entry into the equipment.

~~3.1.42~~ 4.1.43
inventory group
Inventory of attached equipment that can realistically contribute fluid mass to a leaking equipment item.

~~3.1.43~~ 4.1.44
iso-risk
A line of constant risk and method of graphically showing POF and COF values in a log-log, two-dimensional plot where risk increases toward the upper right-hand corner. Components near an iso-risk line (or iso-line for risk) represent an equivalent level of risk while the contribution of POF and COF may vary significantly.

~~3.1.44~~ 4.1.45
jet fire
Results when a high-momentum gas, liquid, or two-phase release is ignited.

~~3.1.45~~ 4.1.46
loss of containment
Occurs when the pressure boundary is breached.

~~3.1.46~~ 4.1.47
management systems factor
An adjustment factor that accounts for the portions of the facility's management system that most directly impact the POF of a component. Adjusts the GFFs for differences in PSM systems. The factor is derived from the results of an evaluation of a facility or operating unit's management systems that affect plant risk.

~~3.1.47~~ 4.1.48
minimum required thickness
t_{min}
The minimum thickness without corrosion allowance for an element or component of a pressure vessel or piping system based on the appropriate design code calculations and code allowable stress that considers

pressure, mechanical, and structural loadings. Alternatively, minimum required thickness can be reassessed using a Fitness-for-Service (FFS) analysis in accordance with API 579-1/ASME FFS-1.

~~3.1.48~~ 4.1.49
mitigation systems
System designed to detect, isolate, and reduce the effects of a release of hazardous materials.

~~3.1.49~~ 4.1.50
neutrally buoyant gas
A gas with density approximately equal to that of air at ambient temperature.

~~3.1.50~~ 4.1.51
nonintrusive
Can be performed externally.

~~3.1.51~~ 4.1.51
owner–~~user~~operator
The party who owns the facility where the asset is operated. The owner is typically also the ~~user~~operator.

~~3.1.52~~ 4.1.52
physical explosion
The catastrophic rupture of a pressurized gas-filled vessel.

~~3.1.53~~ 4.1.53
plan date
Date set by the owner–~~user~~operator that defines the end of plan period.

~~3.1.54~~ 4.1.54
plan period
Time period set by the owner–~~user~~operator that the equipment or component risk is calculated, criteria evaluated, and the recommended inspection plan is valid.

~~3.1.55~~ 4.1.55
pool fire
Caused when liquid pools of flammable materials ignite.

~~3.1.56~~ 4.1.56
probability
Extent to which an event is likely to occur within the time frame under consideration. The mathematical definition of probability is a real number in the scale 0 to 1 attached to a random event. Probability can be related to a long-run relative frequency of occurrence or to a degree of belief that an event will occur. For a high degree of belief, the probability is near 1. Frequency rather than probability may be used in describing risk. Degrees of belief about probability can be chosen as classes or ranks, such as

— rare, unlikely, moderate, likely, almost certain, or

— incredible, improbable, remote, occasional, probable, frequent.

~~3.1.57~~ 4.1.57
probability of failure
POF
Likelihood of an equipment or component failure due to a single damage mechanism or multiple damage mechanisms occurring under specific operating conditions.

~~3.1.58~~ 4.1.58
probit
The random variable with a mean of 5 and a variance of 1, which is used in various effect models.

~~3.1.59~~ 4.1.59
process safety management
PSM
A management system that is focused on prevention of, preparedness for, mitigation of, response to, and restoration from catastrophic releases of chemicals or energy from a process associated with a facility.

~~3.1.60~~ 4.1.60
process unit
A group of systems arranged in a specific fashion to produce a product or service. Examples of processes include power generation, acid production, fuel oil production, and ethylene production.

~~3.1.61~~ 4.1.61
RBI date
Date set by the owner–~~user~~operator that defines the start of a plan period.

~~3.1.62~~ 4.1.62
risk
The combination of the probability of an event and its consequence. In some situations, risk is a deviation from the expected. Risk is defined as the product of probability and consequence when probability and consequence are expressed numerically.

~~3.1.63~~ 4.1.63
risk analysis
Systematic use of information to identify sources and to estimate the risk. Risk analysis provides a basis for risk evaluation, risk mitigation, and risk acceptance. Information can include historical data, theoretical analysis, informed opinions, and concerns of stakeholders.

~~3.1.64~~ 4.1.64
risk-based inspection
RBI
A risk assessment and management process that is focused on loss of containment of pressurized equipment in processing facilities, due to damage mechanisms. These risks are managed primarily through equipment inspection.

~~3.1.65~~ 4.1.65
risk driver
An item affecting either the probability, consequence, or both such that it constitutes a significant portion of the risk.

~~3.1.66~~ 4.1.66
risk management
Coordinated activities to direct and control an organization with regard to risk. Risk management typically includes risk assessment, risk mitigation, risk acceptance, and risk communication.

~~3.1.67~~ 4.1.67
risk mitigation
Process of selection and implementation of measures to modify risk. The term risk mitigation is sometimes used for measures themselves.

~~3.1.68~~ 4.1.68
risk target
A level of acceptable risk that triggers the inspection planning process. The risk target may be expressed in safety (ft^2/year), financial ($/year), or injury (serious injuries/year) terms, based on the owner-~~user~~operator preference.

~~3.1.69~~ 4.1.69
safe dispersion
Occurs when a nontoxic, flammable fluid is released and then disperses without ignition.

~~3.1.70~~ 4.1.70
side-on pressure
The pressure that would be recorded on the side of a structure parallel to the blast.

~~3.1.71~~ 4.1.71
SLAB
A model for denser-than-air gaseous plume releases that utilizes the one-dimensional equations of momentum, conservation of mass and energy, and the equation of state. SLAB handles point source ground-level releases, elevated jet releases, releases from volume sources, and releases from the evaporation of volatile liquid spill pools.

~~3.1.72~~ 4.1.72
soil porosity
The percentage of an entire volume of soil that is either vapor or liquid phase (i.e. air, water, etc.). Clays typically have higher values due to their ability to hold water and air in its structure.

~~3.1.73~~ 4.1.73
source model or term
A model used to determine the rate of discharge, the total quantity released (or total time) of a discharge of material from a process, and the physical state of the discharged material.

~~3.1.74~~ 4.1.74
system
A collection of equipment assembled for a specific function within a process unit. Examples of systems include service water system, distillation systems, and separation systems.

~~3.1.75~~ 4.1.75
target date
Date where the risk target is expected to be reached and is the date at or before the recommended inspection should be performed.

~~3.1.76~~ 4.1.76
TNO multi-energy model
A blast model based on the theory that the energy of explosion is highly dependent on the level of congestion and less dependent on the fuel in the cloud.

~~3.1.77~~ 4.1.77
TNT equivalency model
An explosion model based on the explosion of a thermodynamically equivalent mass of trinitrotoluene (TNT).

~~3.1.78~~ 4.1.78
transmissivity
The fraction of radiant energy that is transmitted from the radiating object through the atmosphere to a target; the transmissivity is reduced due to the absorption and scattering of energy by the atmosphere itself.

~~3.1.79~~ 4.1.79
toxic chemical
Any chemical that presents a physical or health hazard or an environmental hazard according to the appropriate material safety data sheet (MSDS). These chemicals (when ingested, inhaled, or absorbed through the skin) can cause damage to living tissue, impairment of the central nervous system, severe illness, or in extreme cases, death. These chemicals may also result in adverse effects to the environment (measured as ecotoxicity and related to persistence and bioaccumulation potential).

~~3.1.80~~ 4.1.80

vapor cloud explosion

VCE

When a flammable vapor is released, its mixture with air will form a flammable vapor cloud. If ignited, the flame speed may accelerate to high velocities and produce significant blast overpressure.

5 ACRONYMS AND ABBREVIATIONS

For the purposes of this document, the following ~~terms and definitions~~acronyms and abbreviations apply.

ACFM	alternating current field measurement
ACSCC	alkaline carbonate stress corrosion cracking
AE	acoustic emission
AEGL	acute exposure guideline level
AHF	anhydrous hydrofluoric acid
AIHA	American Industrial Hygiene Association
AIT	autoignition temperature
ASME	American Society of Mechanical Engineers
AST	atmospheric storage tank
ASTM	American Society for Testing and Materials
AU	additional uncertainty
AWWA	American Water Works Association
BFW	boiler feed water
BLEVE	boiling liquid expanding vapor explosion
BOD	biological oxygen demand
CA	corrosion allowance
CCPS	Center for Chemical Process Safety
CFR	*Code of Federal Regulations*
CLSCC	chloride stress corrosion cracking
CML	condition monitoring location
COD	chemical oxygen demand
COF	consequence of failure
CP	cathodic protection
CUI	corrosion under insulation
CUI CLSCC	external chloride stress corrosion cracking under insulation
DCVG	direct current voltage gradient
DEA	diethanolamine
DEGADIS	dense gas dispersion
DF	damage factor
DGA	diglycolamine

DIPA	diisopropanolamine
DIPPR	Design Institute of Physical Properties
DO	dissolved oxygen
DPO	device partially open
DRRF	demand rate reduction factor
DSO	device stuck open
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guidelines
EVA	extreme value analysis
external CLSCC	external chloride stress corrosion cracking
FC	financial consequence
FCC	fluid catalytic cracking
FCCU	fluid catalytic cracking unit
FFS	Fitness-For-Service
FRP	fiberglass reinforced plastic
FSM	field signature method
FTO	fail to open
GOR	gas–oil ratio
GFF	generic failure frequency
HAZ	heat-affected zone
HCl	hydrochloric acid
HF	hydrofluoric acid
HGO	heavy gas oil
HIC	hydrogen-induced cracking
HP	high pressure
HSAS	heat stable amine salts
HSC	hydrogen stress cracking
HTHA	high temperature hydrogen attack
ID	inside diameter
IDLH	immediately dangerous to life or health
KO	knock-out
LBC	lower bound confidence

LFL	lower flammability limit
LoIE	level of inspection effectiveness
LOPA	layer of protection analysis
LP	low pressure linear polarization
LPD	leakage past device
LPG	liquefied petroleum gas
LSI	Langelier Saturation Index
LV	liquid volume
MAT	minimum allowable temperature
MAWP	maximum allowable working pressure
MDEA	methyldiethanolamine
MDMT	minimum design metal temperature
MEA	monoethanolamine
MEM	multi-energy method
MFL	magnetic flux leakage
MIC	microbiologically induced corrosion
MSDS	material safety data sheet
MT	magnetic testing
MTR	material test report
MTTF	mean time to failure
MW	molecular weight
NACE	National Association of Corrosion Engineers
NBP	normal boiling point
NDE	nondestructive examination
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
OASP	opens above set pressure
OD	outside diameter
OSHA	Occupational Safety and Health Administration
P/A	pumparound
PASCC	polythionic acid stress corrosion cracking
PE	polyethelene

PHA	process hazard analysis
PHAST	process hazard analysis software tools
P&ID	piping and instrumentation diagram
PM	preventative maintenance
POF	probability of failure
POFOD	probability of failure on demand
POL	probability of leak
PP	polypropelene
PRD	pressure-relief device
PRV	pressure-relief valve
PSM	process safety management
PT	penetrant testing
PTA	polythionic acid
P/V	pressure/vacuum vent
PVC	polyvinyl chloride
PWHT	postweld heat treatment
RBI	risk-based inspection
REM	rare earth mineral
RH	relative humidity
RMP	risk management plan
RPB	release prevention barrier
RSI	Ryznar Stability Index
RT	radiographic testing
SCC	stress corrosion cracking
SCE	step cooling embrittlement
SFPE	Society of Fire Protection Engineers
SOHIC	stress-oriented hydrogen induced cracking
SOP	standard operating procedure
SPO	spurious or premature opening
SRB	sulfate-reducing bacteria
SS	stainless steel
SSC	sulfide stress cracking

TAN	total acid number
TDS	total dissolved solids
TEEL	temporary emergency exposure limits
TEMA	Tubular Exchanger Manufacturers Association
TKS	total key species
TNO	The Netherlands Organization for Applied Scientific Research
TNT	trinitrotoluene
TOFD	time of flight diffraction
UFL	upper flammability limit
UNS	unified numbering system
UT	ultrasonic testing
VCE	vapor cloud explosion
VT	visual testing
WFMT	wet fluorescent magnetic (particle) testing

6 Basic Concepts

6.1 Probability of Failure (POF)

Overview

Two methods of calculating POF are used within the text: the GFF method and a two-parameter Weibull distribution method. The GFF method is used to predict loss of containment POF from pressure boundary equipment. The Weibull distribution method is used to predict POF for PRDs and heat exchanger bundles.

GFF Method

6.1.1.1 General

The POF using the GFF method is calculated from Equation (1.1).

$$P_f(t) = gff \cdot F_{MS} \cdot D_f(t) \tag{1.1}$$

The POF as a function of time, $P_f(t)$, is determined as the product of a generic failure frequency, gff, a damage factor, $D_f(t)$, and a management systems factor, F_{MS}.

6.1.1.2 GFF

The GFF for different component types is set at a value representative of the refining and petrochemical industry's failure data (see Part 2, Section 3.3).

6.1.1.3 Management Systems Factor

The management systems factor, F_{MS}, is an adjustment factor that accounts for the influence of the facility's management system on the mechanical integrity of the plant equipment. This factor is derived from the results of an evaluation of facility or operating unit management systems that affect plant risk. The management systems evaluation is provided in Part 2, Annex 2.A of this document. Owner-~~User~~operators may elect to use a MSF of 1.0, and forego the evaluation if their site Management Systems are believed to be industry average or better. ~~The management systems evaluation is provided in Part 2, Annex 2.A of this document.~~ Owner-operators may elect to use an MSF of 1.0 and forego the evaluation if their site Management Systems are believed to be industry average or better.

6.1.1.4 Damage Factors (DFs)

The DF is determined based on the applicable damage mechanisms relevant to the materials of construction and the process service, the physical condition of the component, and the inspection techniques used to quantify damage. The DF modifies the industry GFF and makes it specific to the component under evaluation.

DFs do not provide a definitive FFS assessment of the component. FFS analyses for pressurized component are covered by API 579-1/ASME FFS-1 [1]. The basic function of the DF is to statistically evaluate the amount of damage that may be present as a function of time in service and the effectiveness of the inspection activity to quantify that damage.

Methods for determining DFs are provided in Part 2 for the following damage mechanisms:

a) thinning (both general and local);

b) component lining damage;

c) external damage (thinning and cracking);

d) stress corrosion cracking (SCC);

e) high temperature hydrogen attack (HTHA);

f) mechanical fatigue (piping only);

g) brittle fracture, including low-temperature brittle fracture, low alloy embrittlement, 885 °F embrittlement, and sigma phase embrittlement.

When more than one damage mechanism is active, the DF for each mechanism is calculated and then combined, to determine a total DF for the component, as defined in Part 2, Section 3.4.2.

Two-parameter Weibull Distribution Method

6.1.1.5 General

The POF is using the Weibull method is calculated from Equation (1.2):

$$P_f\left(t\right) = 1 - exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{1.2}$$

Where the Weibull Shape Parameter, β, is unit-less, the Weibull characteristic life parameter, η, in years, and t is the independent variable time in years.

6.1.1.6 Weibull Shape Factor

The β parameter shows how the failure rate develops over time. Failure modes related with infant mortality, random, or wear-out have significantly different β values. The β parameter determines which member of the Weibull family of distributions is most appropriate. Different members have different shapes. The Weibull distribution fits a broad range of life data compared to other distributions.

6.1.1.7 Weibull Characteristic Life

The η parameter is defined as the time at which 63.2 % of the units have failed. For β = 1, the mean time to failure (MTTF) and η are equal. Adjustments are made to the characteristic life parameter to increase or decrease the POF as a result of environmental factors, asset types, or as a result of actual inspection data. These adjustments may be viewed as an adjustment to the MTTF.

6.2 Consequence of Failure (COF)

Overview

Loss of containment of hazardous fluids from pressurized processing equipment may result in damage to surrounding equipment, serious injury to personnel, production losses, and undesirable environmental impacts. The consequence of a loss of containment is determined using well-established consequence analysis techniques [2], [3], [4], [5], [6] and is expressed as an affected impact area or in financial terms. Impact areas from event outcomes such as pool fires, flash fires, fireballs, jet fires, and vapor cloud explosions (VCEs) are quantified based on the effects of thermal radiation and overpressure on surrounding equipment and personnel. Additionally, cloud dispersion analysis methods are used to quantify the magnitude of flammable releases and to determine the extent and duration of personnel exposure to toxic releases. Event trees are used to assess the probability of each of the various event outcomes and to provide a mechanism for probability weighting the loss of containment consequences.

An overview of the COF methodology is provided in Part 3, Figure 4.1.

Methodologies for two levels of consequence analysis are provided in Part 3. A Level 1 consequence analysis provides a method to estimate the consequence area based on lookup tables for a limited number of generic or reference hazardous fluids. A Level 2 consequence analysis is more rigorous because it incorporates a detailed calculation procedure that can be applied to a wider range of hazardous fluids.

Level 1 COF

The Level 1 consequence analysis evaluates the consequence of hazardous releases for a limited number of reference fluids (reference fluids are shown in Part 3, Table 4.1). The reference fluid that closely matches the normal boiling point (NBP) and molecular weight (MW) of the fluid contained within the process equipment should be used. The flammable consequence area is then determined from a simple polynomial expression that is a function of the release magnitude.

For each discrete hole size, release rates are calculated based on the phase of the fluid, as described in Part 3, Section 4.3. These releases are then used in closed form equations to determine the flammable consequence.

For the Level 1 analysis, a series of consequence analyses were performed to generate consequence areas as a function of the reference fluid and release magnitude. In these analyses, the major consequences were associated with pool fires for liquid releases and VCEs for vapor releases. Probabilities of ignition, probabilities of delayed ignition, and other probabilities in the Level 1 event tree were selected based on expert opinion for each of the reference fluids and release types (i.e. continuous or instantaneous). These probabilities were constant and independent of release rate or mass. The closed form flammable consequence area equation is shown in Equation (1.3) based on the analysis developed to calculate consequence areas.

$$CA_f = a \cdot x^b \tag{1.3}$$

Values for variables a and b in Equation (1.3) are provided for the reference fluids in Part 3, Table 4.8 and Table 4.9. If the fluid release is steady state and continuous (such as the case for small hole sizes), the release rate is used for X in Equation (1.3). However, if the release is considered instantaneous (e.g. as a result of a vessel or pipe rupture), the release mass is used for X in Equation (1.3). The transition between a continuous release and an instantaneous release is defined as a release where more than 10,000 lb (4,536 kg) of fluid mass escapes in less than 3 minutes; see Part 3, Section 4.5.

The final flammable consequence areas are determined as a probability weighted average of the individual consequence areas calculated for each release hole size. Four hole sizes are used; the lowest hole size represents a small leak and the largest hole size represents a rupture or complete release of contents. This is performed for both the equipment damage and the personnel injury consequence areas. The probability weighting uses the hole size distribution and the GFFs of the release hole sizes selected. The equation for probability weighting of the flammable consequence areas is given by Equation (1.4).

$$C_f^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{f,n}^{flam}}{gff_{total}} \right) \tag{1.4}$$

The total GFF, gff_{total}, in the above equation is determined using Equation (1.5).

$$gff_{total} = \sum_{n=1}^{4} gff_n \tag{1.5}$$

The Level 1 consequence analysis is a method for approximating the consequence area of a hazardous release. The inputs required are basic fluid properties (such as MW, density, and ideal gas specific heat ratio, k) and operating conditions. A calculation of the release rate or the available mass in the inventory group (i.e. the inventory of attached equipment that contributes fluid mass to a leaking equipment item) is also required. Once these terms are known, the flammable consequence area is determined from Equation (1.3) and Equation (1.4).

A similar procedure is used for determining the consequence associated with release of toxic chemicals such as H_2S, ammonia, or chlorine. Toxic impact areas are based on probit equations and can be assessed whether the stream is pure or a percentage of a process stream.

Level 2 COF

A detailed procedure is provided for determining the consequence of loss of containment of hazardous fluids from pressurized equipment. The Level 2 consequence analysis was developed as a tool to use where the assumptions of Level 1 consequence analysis were not valid. Examples of where Level 2 calculations may be desired or necessary are cited below.

a) The specific fluid is not represented adequately within the list of reference fluids provided in Part 3, Table 4.1, including cases where the fluid is a wide-range boiling mixture or where the fluids toxic consequence is not represented adequately by any of the reference fluids.

b) The stored fluid is close to its critical point, in which case, the ideal gas assumptions for the vapor release equations are invalid.

c) The effects of two-phase releases, including liquid jet entrainment as well as rainout, need to be included in the methodology.

d) The effects of boiling liquid expanding vapor explosion (BLEVE) are to be included in the methodology.

e) The effects of pressurized nonflammable explosions, such as are possible when nonflammable pressurized gases (e.g. air or nitrogen) are released during a vessel rupture, are to be included in the methodology.

f) The meteorological assumptions used in the dispersion calculations that form the basis for the Level 1 COF table lookups do not represent the site data.

The Level 2 consequence procedures presented in Part 3, Section 5 provide equations and background information necessary to calculate consequence areas for several flammable and toxic event outcomes. A summary of these events is provided in Part 3, Table 3.1.

To perform Level 2 calculations, the actual composition of the fluid stored in the equipment is modeled. Fluid property solvers are available that allow the analyst to calculate fluid physical properties more accurately. The fluid solver also provides the ability to perform flash calculations to better determine the release phase of the fluid and to account for two-phase releases. In many of the consequence calculations, physical properties of the released fluid are required at storage conditions as well as conditions after release to the atmosphere.

A cloud dispersion analysis must also be performed as part of a Level 2 consequence analysis to assess the quantity of flammable material or toxic concentration throughout vapor clouds that are generated after a release of volatile material. Modeling a release depends on the source term conditions, the atmospheric conditions, the release surroundings, and the hazard being evaluated. Employment of many commercially available models, including SLAB or dense gas dispersion (DEGADIS) [7], account for these important factors and will produce the desired data for the Level 2 analysis.

The event trees used in the Level 2 consequence analysis are shown in Part 3, Figure 5.3 and Figure 5.4. Improvement in the calculations of the probabilities on the event trees have been made in the Level 2 procedure. Unlike the Level 1 procedure, the probabilities of ignition on the event tree are not constant with release magnitude. Consistent with the work of Cox, Lees, and Ang [8], the Level 2 event tree ignition probabilities are directly proportional to the release rate. The probabilities of ignition are also a function of the flash point temperature of the fluid. The probability that an ignition will be a delayed ignition is also a function of the release magnitude and how close the operating temperature is to the autoignition temperature (AIT) of the fluid. These improvements to the event tree will result in consequence impact areas that are more dependent on the size of release and the flammability and reactivity properties of the fluid being released.

6.3 Risk Analysis

Determination of Risk

In general, the calculation of risk is determined in accordance with Equation (1.6), as a function of time. The equation combines the POF and the COF described in Section 6.1 and Section 6.2, respectively.

$$R(t) = P_f(t) \cdot C_f \tag{1.6}$$

The POF, $P_f(t)$, is a function of time since the DF shown in Equation (1.1) increases as the damage in the component accumulates with time.

Process operational changes over time can result in changes to the POF and COF. Process operational changes, such as in temperature, pressure, or corrosive composition of the process stream, can result in an increased POF due to increased damage rates or initiation of additional damage mechanisms. These types of changes are identified by the plant management of change procedure and/or integrity operating windows program.

The COF is assumed to be invariant as a function of time. However, significant process changes can result in COF changes. Process change examples may include changes in the flammable, toxic, and nonflammable/nontoxic components of the process stream, changes in the process stream from the production source, variations in production over the lifetime of an asset or unit, and repurposing or revamping of an asset or unit that impacts the operation and/or service of gas/liquid processing plant equipment. In addition, modifications to detection, isolation, and mitigation systems will affect the COF. Factors that may impact the financial COF may include but are not limited to personnel population density, fluid values, and the cost of lost production. As defined in API 580, a reassessment is required when the original risk basis for the POF and/or COF changes significantly.

Equation (1.6) is rewritten in terms of area, financial, and safety-based risk, as shown in Equation (1.7) through Equation (1.9).

$$R(t) = P_f(t) \cdot C_f^{area} \quad \text{for safety-based risk} \tag{1.7}$$

$$R(t) = P_f(t) \cdot C_f^{fin} \quad \text{for financial-based risk} \tag{1.8}$$

$$R(t) = P_f(t) \cdot C_f^{inj} \quad \text{for injury-based risk} \tag{1.9}$$

In these equations:

C_f^{area} is the consequence of failure impact area expressed in units of area;

C_f^{fin} is the financial consequence of failure expressed in economic terms; and

C_f^{inj} is the safety consequence of failure expressed in term of injuries.

Note that risk in Equation (1.7), Equation (1.8) and Equation (1.9) varies as a function of time because POF varies as a function of time. Figure 4.1 illustrates that the risk associated with individual damage mechanisms can be added together by superposition to provide the overall risk as a function of time.

Risk Plotting

6.3.1.1 General

Plotting POF and COF values on a risk matrix is an effective method of representing risk graphically. POF is plotted along one axis, increasing in magnitude from the origin, while COF is plotted along the other axis. It is the responsibility of the owner–~~user~~operator to define and document the basis for POF and COF category ranges and risk targets used. This section provides risk matrix examples only.

6.3.1.2 Risk Matrix Examples

Presenting the risk results in a matrix is an effective way of showing the distribution of risks for components in a process unit without using numerical values. In the risk matrix, POF and COF categories are arranged so that the highest risk components are towards the upper right-hand corner.

Two risk matrix examples are shown in Figure 4.2 and Figure 4.3. In both figures, POF is expressed in terms of the number of failures over time, $P_f(t)$, or DF. COF is expressed in area, financial, or safety terms. Example numerical values associated with POF and COF (as safety, financial, or injury) categories are shown in Table 4.2 and Table 4.3. The matrices do not need to be square (i.e. 4x5 risk matrix, 7x5 risk matrix, etc.).

a) Unbalanced Risk Matrix (Figure 4.2)—POF and COF value ranges are assigned numerical and lettered categories, respectively, increasing in order of magnitude. Risk categories (i.e. Low, Medium, Medium High, and High) are assigned to the boxes with the risk category shading asymmetrical. For example, using Table 4.2 values, a POF of 5.00E-04 is assigned a Category 3 and a COF of 800 ft^2 corresponds to a Category B. The 3B box is Low risk category when plotted on Figure 4.2.

b) Balanced Risk Matrix (Figure 4.3)—Similar to Figure 4.2, POF and COF value ranges are assigned numerical and lettered categories, respectively, increasing in order of magnitude. In this example, risk categories (i.e. Low, Medium, Medium High, and High) are assigned symmetrically to the boxes. When values from Table 4.2 are used, a POF of 5.00E-04 failures/year is assigned a Category 3 and a COF of 800 ft^2 corresponds to a Category B. However, the 3B box in the Figure 4.3 example corresponds to a Medium risk category.

Note that all ranges and risk category shading provided in Table 4.2 and Table 4.3 as well as Figure 4.2 and Figure 4.3 are examples of dividing the plot into risk categories and are not recommended risk targets and/or thresholds. It is the owner–~~user~~operators' responsibility to establish the ranges and target values for their risk-based programs.

4.3.2.3 Iso-Risk Plot Example

Another effective method of presenting risk results is an iso-risk plot. An iso-risk plot graphically shows POF and COF values in a log-log, two-dimensional graph where risk increases toward the upper right-hand corner. Examples of iso-risk plots for safety, financial and injury COF are shown in Figure 4.4, Figure 4.5 and Figure 4.6, respectively. Components near an iso-risk line represent an equivalent level of risk. Components are ranked based on risk for inspection, and inspection plans are developed for components based on the defined risk acceptance criteria that has been set.

As in a risk matrix, POF is expressed in failures over time, $P_f(t)$, or DF while COF is expressed in area, financial, or safety terms. Risk categories (i.e. Low, Medium, Medium High, and High) are assigned to the areas between the iso-risk lines and dependent upon the level of risk assigned as a threshold between risk categories, as shown in Figure 4.4. For example, a POF of 5.00E-04 and a COF of $125,000 are assigned a Medium risk category.

4.3.3 General Comments Concerning Risk Plotting

Note the following when using the examples in Figure 4.2 through Figure 4.5:

a) as the POF values increase, the risk becomes more POF driven;

b) as the COF values increase, the risk becomes more COF driven.

In risk mitigation planning, equipment items residing towards the upper right-hand corner of the risk matrix will most likely take priority for inspection planning because these items have the highest risk. Similarly, items residing toward the lower left-hand corner of the risk matrix tend to take lower priority because these items have the lowest risk. A risk matrix is used as a screening tool during the prioritization process.

Using the examples in Figure 4.2 though Figure 4.5 in consideration to risk mitigation planning:

a) if POF drives the risk (the data drift toward the POF axis), the risk mitigation strategy may be weighted more towards inspection-based methods;

b) if COF drives the risk (the data drift toward the COF axis), the risk mitigation strategy may be weighted more towards engineering/management methods;

c) if both POF and COF drive risk, the risk mitigation strategy may require both inspection-based methods coupled with engineering and management methods.

It is the responsibility of the owner–~~user~~operator to:

1) determine the type of plot to be used for reporting and prioritization,

2) determine the risk acceptance criteria (POF and COF category ranges),

3) document the risk plotting process,

4) provide for risk mitigation strategies based upon the plot chosen.

6.4 Inspection Planning Based on Risk Analysis

Overview

Inspection planning based on risk assumes that at some point in time, the risk as defined by Equation (1.7), Equation (1.8) and Equation (1.9) will reach or exceed a user-defined area, financial, or safety risk target. When or before the user-defined risk target is reached, an inspection of the equipment is recommended based on the component damage mechanisms with the highest DFs. The user may set additional targets to initiate an inspection, such as POF, DF, COF, or thickness. In addition, inspection may be conducted solely to gather information to reduce uncertainty in the component condition or based on an engineering evaluation of the fitness for continued service rather than the RBI results.

Although inspection of a component does not reduce the inherent risk, inspection provides improved knowledge of the current state of the component and therefore reduces uncertainty. The probability that loss of containment will occur is directly related to the known condition of the component based on information from inspection and the ability to accurately quantify damage.

Reduction in uncertainty in the damage state of a component is a function of the effectiveness of the inspection to identify the type and quantify the extent of damage. Inspection plans are designed to detect and quantify the specific types of damage expected such as local or general thinning, cracking, and other types of damage. An inspection technique that is appropriate for general thinning will not be effective in detecting and quantifying damage due to local thinning or cracking. Therefore, the inspection effectiveness is a function of the inspection method and extent of coverage used for detecting the type of damage expected.

Risk is a function of time, as shown in Equation (1.7), Equation (1.8) and Equation (1.9), as well as a function of the knowledge of the current state of the component determined from past inspections. When inspection effectiveness is introduced into risk Equation (1.7), Equation (1.8) and Equation (1.9), the equations can be rewritten as Equation (1.10), Equation (1.11) and Equation (1.12):

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{area} \text{ for area-based risk} \quad (1.10)$$

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{fin} \text{ for financial-based risk} \quad (1.11)$$

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{inj} \text{ for safety-based risk} \quad (1.12)$$

Targets

A target is defined as the maximum value acceptable for continued operation without requiring a mitigating action. Once the target has been met or exceeded, an activity such as inspection is triggered. Several targets can be defined in an RBI program to initiate and define risk mitigation activities, as follows.

a) Risk Target—A level of acceptable risk that triggers the inspection planning process. The risk target may be expressed in area (ft^2/year), financial ($/year) or safety (injuries/year) terms, based on the owner–~~user~~operator preference.

b) POF Target—A frequency of failure or leak (#/year) that is considered unacceptable and triggers the inspection planning process.

c) DF Target—A damage state that reflects an unacceptable failure frequency factor greater than the generic and triggers the inspection planning process.

d) COF Target—A level of unacceptable consequence in terms of area consequence (C_f^{area}), financial consequence (C_f^{fin}), or safety consequence (C_f^{inj}) based on owner–~~user~~operator preference. Because risk driven by COF is not reduced by inspection activities, risk mitigation activities to reduce release inventory or ignition are required.

e) Thickness Target—A specific thickness, often the minimum required thickness, t_{min}, considered unacceptable, triggering the inspection planning process.

f) Maximum Inspection Interval Target—A specific inspection frequency considered unacceptable, triggering the inspection planning process. A maximum inspection interval may be set by the owner–~~user~~operator's corporate standards or may be set based on a jurisdictional requirement

It is important to note that defining targets is the responsibility of the owner–~~user~~operator and that specific target criteria is not provided within this document. The above targets should be developed based on owner–~~user~~operator internal guidelines and overall risk tolerance. Owner–~~user~~operators often have corporate risk criteria defining acceptable and prudent levels of safety, environmental, and financial risks. These owner–~~user~~operator criteria should be used when making RBI decisions since acceptable risk levels and risk management decision-making will vary among companies.

Inspection Effectiveness—The Value of Inspection

An estimate of the POF for a component depends on how well the independent variables of the limit state are known and understood. Using examples and guidance for inspection effectiveness provided in Part 2, Annex 2.C, an inspection plan is developed, as risk results require. The inspection strategy is implemented to obtain the necessary information to decrease uncertainty about the actual damage state of the equipment by confirming the presence of damage, obtaining a more accurate estimate of the damage rate, and evaluating the extent of damage.

An inspection plan is the combination of NDE methods (i.e. visual, ultrasonic, radiographic, etc.), frequency of inspection, and the location and coverage of an inspection to find a specific type of damage. Inspection plans vary in their overall effectiveness for locating and sizing specific damage and understanding the extent of the damage.

Inspection effectiveness is introduced into the POF calculation using Bayesian Analysis, which updates the POF when additional data are gathered through inspection. The extent of reduction in the POF depends on the effectiveness of the inspection to detect and quantify a specific damage type of damage mechanism. Therefore, higher inspection effectiveness levels will reduce the uncertainty of the damage state of the component and reduce the POF. The POF and associated risk may be calculated at a current and/or future time period using Equation (1.10), Equation (1.11) and Equation (1.12).

Examples of the levels of inspection effectiveness categories for various damage mechanisms and the associated generic inspection plan (i.e. NDE techniques and coverage) for each damage mechanism are provided in Part 2, Annex 2.C. These tables provide examples of the levels of generic inspection plans for a specific damage mechanism. The tables are provided as a matter of example only, and it is the responsibility of the owner–~~user~~operator to create, adopt, and document their own specific levels of inspection effectiveness tables.

Inspection Planning

The methodology for developing inspection plans for a defined plan period is provided in Part 4. ~~An inspection plan date covers a defined plan period and includes one or more future maintenance turnarounds. Within this plan period, three cases are possible based on predicted risk and the risk target.~~

~~a) Case 1—Risk Target Is Exceeded During the Plan Period—As shown in Figure 4.7, the inspection plan will be based on the inspection effectiveness required to reduce the risk and maintain it below the risk target through the plan period.~~

~~b) Case 2—Risk Exceeds the Risk Target at the Time the RBI Date—As shown in Figure 4.8, the risk at the start time of the RBI analysis, or RBI date, exceeds the risk target. An inspection is recommended to reduce the risk so that the risk after inspection remains below the risk target by the plan date.~~

~~c) Case 3—Risk at the Plan Date Does Not Exceed the Risk Target—As shown in Figure 4.9, the risk at the plan date does not exceed the risk target and therefore no inspection is required during the plan period. In this case, the inspection due date for inspection scheduling purposes may be set to the plan date so that reanalysis of risk will be performed by the end of the plan period.~~

~~The concept of how the different inspection techniques with different effectiveness levels can reduce risk is shown in Figure 4.7. In the example shown, a minimum of a *B Level* inspection was recommended at the target date. This inspection level was sufficient since the risk predicted after the inspection was performed was determined to be below the risk target at the plan date. In Figure 4.7, a *C Level* inspection at the target date would not have been sufficient to satisfy the risk target criteria.~~

6.5 Nomenclature

C_f is the COF, ft^2 (m^2), $ or injuries

C_f^{area}	is the flammable consequence of failure impact area, ft^2 (m^2)
C_f^{fin}	is the financial consequence of failure, $
C_f^{inj}	is the safety consequence of failure, injuries
$D_{f\text{-}total}$	is total DF for POF calculation
$P_f(t)$	is the POF as a function of time, failures/year
$P_f(t,I_E)$	is the POF as a function of time and inspection effectiveness, failures/year
$R(t)$	is the risk as a function of time, ft^2/year (m^2/year), $/year or injuries/year
$R(t,I_E)$	is the risk as a function of time and inspection effectiveness, ft^2/year (m^2/year) or $/year

6.6 Tables

Table 4.1—POF, COF, Risk, and Inspection Planning Calculations [1]

Equipment Type	POF Calculation	COF Calculation		Risk Calculation	Inspection Planning
		Safety	Financial		
Pressure vessels	Part 2	Part 3, Section 4 or 5	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
Heat exchangers [2]	Part 2	Part 3, Section 4 or 5	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
Air fin heat exchanger header boxes	Part 2	Part 3, Section 4 or 5	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
Pipes & tubes	Part 2	Part 3, Section 4 or 5	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
AST—shell courses	Part 2	Part 3, Section 4 or 5	Part 5,Section 3.4	Part 1, Section 4.3	Part 4
AST—tank bottom	Part 5, Section 3.2	NA	Part 5, Section 3.17	Part 1, Section 4.3	Part 4
Compressors [3]	Part 2	Part 3, Section 4 or 5	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
Pumps [3]	Part 2	Part 3, Section 4 or 6	Part 3, Section 4 or 5	Part 1, Section 4.3	Part 4
PRDs [4]	Part 5, Sections 5.2 and 5.3	NA	Part 5, Sections 5.4 and 5.5	Part 5, Section 5.6	Part 5, Section 5.7
Heat exchanger tube bundles	Part 5, Section 4.5	NA	Part 5, Section 4.6	Part 5, Section 4.78.5	Part 5, Section 4.9

NOTE 1 All referenced sections and parts refer to API 581.

NOTE 2 Shellside and tubeside pressure boundary components.

NOTE 3 Pressure boundary only.

NOTE 4 Including protected equipment.

Table 4.2—Numerical Values Associated with POF and Area-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	DF Range	Category	Range (ft^2)
1	$P_f(t,I_E) \le$ 3.06E-05	$D_{f\text{-}total} \le 1$	A	$C_f^{area} \le 100$
2	3.06E-05 $< P_f(t,I_E) \le$ 3.06E-04	$1 < D_{f\text{-}total} \le 10$	B	$100 < C_f^{area} \le 1{,}000$
3	3.06E-04 $< P_f(t,I_E) \le$ 3.06E-03	$10 < D_{f\text{-}total} \le 100$	C	$1{,}000 < C_f^{area} \le 10{,}000$
4	3.06E-03 $< P_f(t,I_E) \le$ 3.06E-02	$100 < D_{f\text{-}total} \le 1{,}000$	D	$10{,}000 < C_f^{area} \le 100{,}000$
5	$P_f(t,I_E) >$ 3.06E-02	$D_{f\text{-}total} > 1{,}000$	E	$C_f^{area} > 100{,}000$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values in Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms, and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.11.4.

Table 4.2M—Numerical Values Associated with POF and Area-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** (m^2)
1	$P_f(t,I_E) \le$ 3.06E-05	$D_{f\text{-}total} \le 1$	A	$C_f^{area} \le 9.29$
2	3.06E-05 < $P_f(t,I_E) \le$ 3.06E-04	$1 < D_{f\text{-}total} \le 10$	B	$9.29 < C_f^{area} \le 92.9$
3	3.06E-04 < $P_f(t,I_E) \le$ 3.06E-03	$10 < D_{f\text{-}total} \le 100$	C	$92.9 < C_f^{area} \le 929$
4	3.06E-03 < $P_f(t,I_E) \le$ 3.06E-02	$100 < D_{f\text{-}total} \le 1000$	D	$929 < C_f^{area} \le 9290$
5	$P_f(t,I_E)$ > 3.06E-02	$D_{f\text{-}total} > 1000$	E	$C_f^{area} > 9290$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms, and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.11.4.

Table 4.3—Numerical Values Associated with POF and Financial-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** ($)
1	$P_f(t,I_E) \le$ 3.06E-05	$D_{f\text{-}total} \le 1$	A	$C_f^{fin} \le 10{,}000$
2	3.06E-05 < $P_f(t,I_E) \le$ 3.06E-04	$1 < D_{f\text{-}total} \le 10$	B	$10{,}000 < C_f^{fin} \le 100{,}000$
3	3.06E-04 < $P_f(t,I_E) \le$ 3.06E-03	$10 < D_{f\text{-}total} \le 100$	C	$100{,}000 < C_f^{fin} \le 1{,}000{,}000$
4	3.06E-03 < $P_f(t,I_E) \le$ 3.06E-02	$100 < D_{f\text{-}total} \le 1000$	D	$1{,}000{,}000 < C_f^{fin} \le 10{,}000{,}000$
5	$P_f(t,I_E)$ > 3.06E-02	$D_{f\text{-}total} > 1000$	E	$C_f^{fin} > 10{,}000{,}000$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.12.1.

Table 4.4—Numerical Values Associated with POF and Safety-Based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** (injuries)
1	$P_f\,(t,I_E) \leq$ 3.06E-05	$D_{f\text{-}total} \leq 1$	A	$C_f^{inj} \leq$ 3.27E-04
2	3.06E-05 < $P_f\,(t,I_E) \leq$ 3.06E-04	$1 < D_{f\text{-}total} \leq 10$	B	3.27E-04< $C_f^{inj} \leq$ 3.27E-03
3	3.06E-04 < $P_f\,(t,I_E) \leq$ 3.06E-03	$10 < D_{f\text{-}total} \leq 100$	C	3.27E-03< $C_f^{inj} \leq$ 3.27E-02
4	3.06E-03 < $P_f\,(t,I_E) \leq$ 3.06E-02	$100 < D_{f\text{-}total} \leq 1000$	D	3.27E-02< $C_f^{inj} \leq$ 3.27E-01
5	$P_f\,(t,I_E) >$ 3.06E-02	$D_{f\text{-}total} > 1000$	E	$C_f^{inj} >$ 3.27E-01

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.13.1.

6.7 Figures

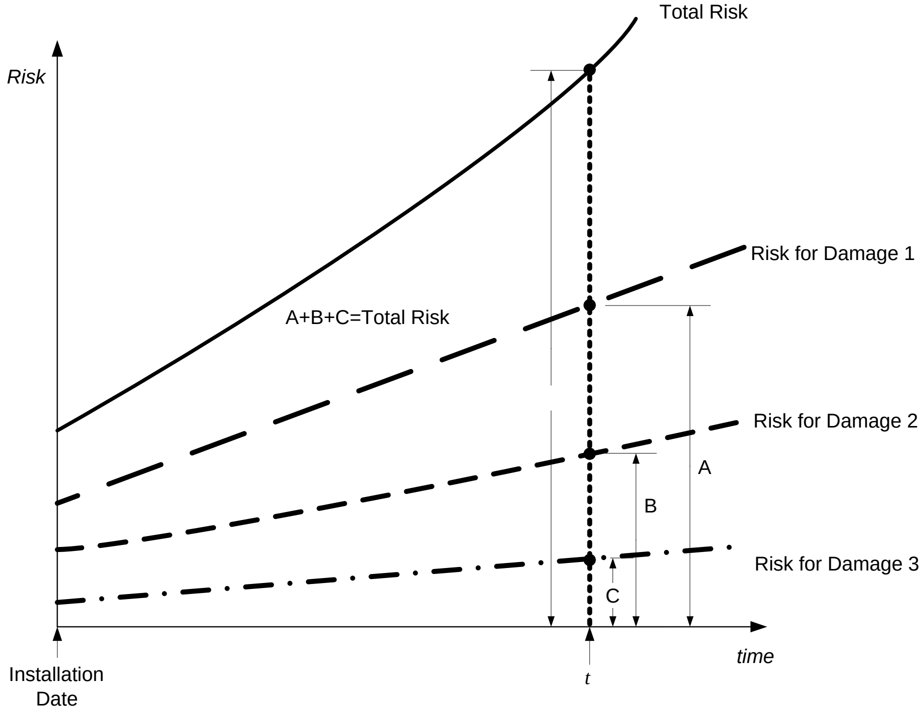
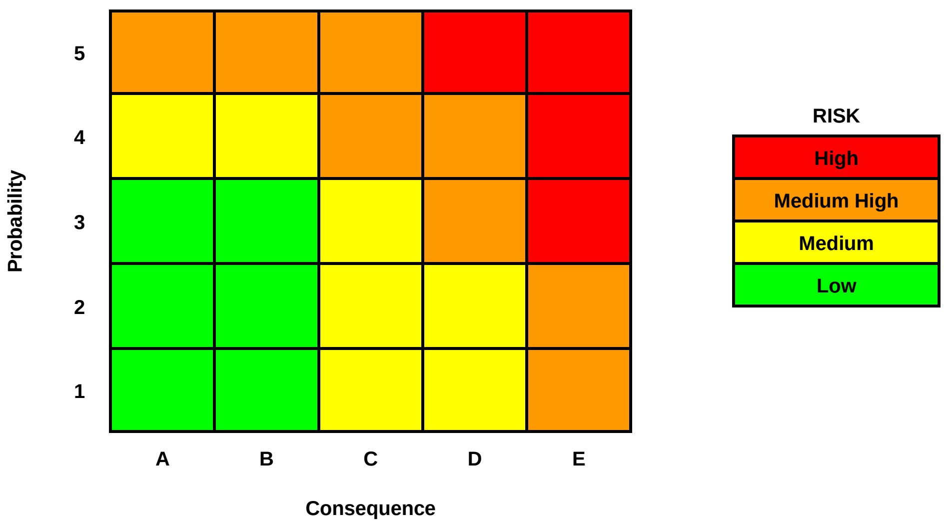
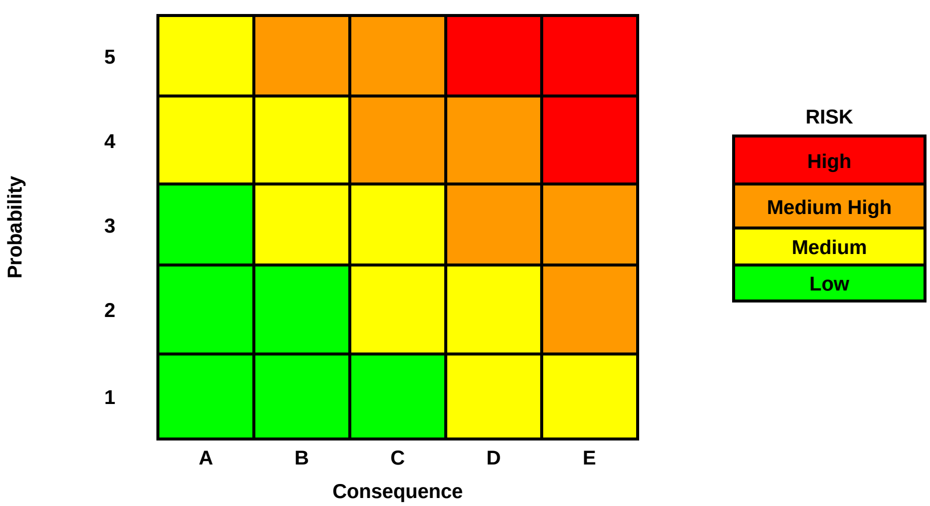


Figure 4.1—Superposition Principle for the Calculation of Risk



NOTE See Table 4.2 and Table 4.3 for ranges in probability and consequence categories.

Figure 4.2—Unbalanced Risk Matrix Example



NOTE See Table 4.2 and Table 4.3 for ranges in probability and consequence categories.

Figure 4.3—Balanced Risk Matrix Example

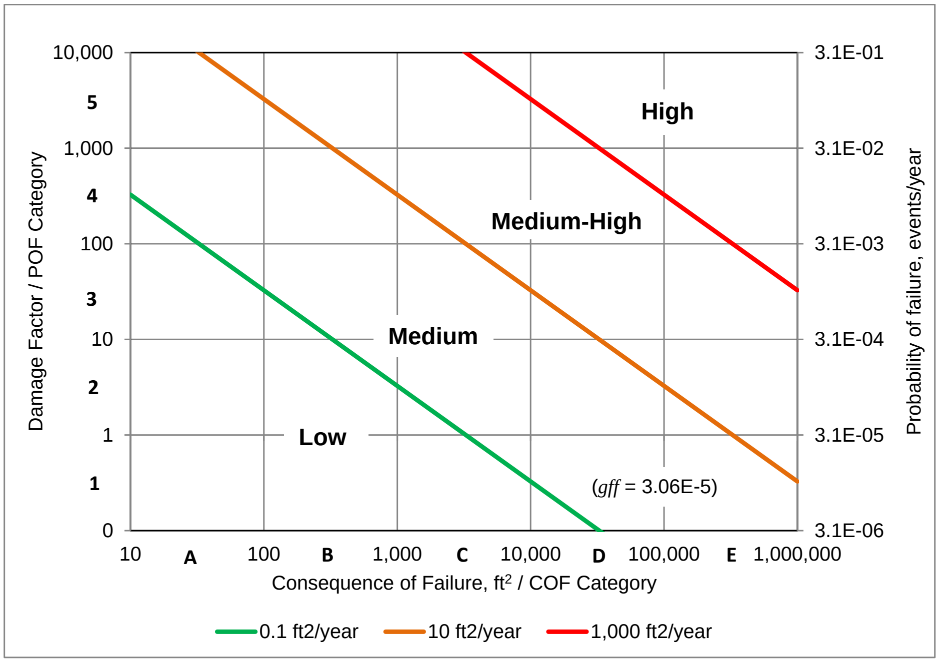


Figure 4.4—Example Iso-risk Plot for Consequence Area

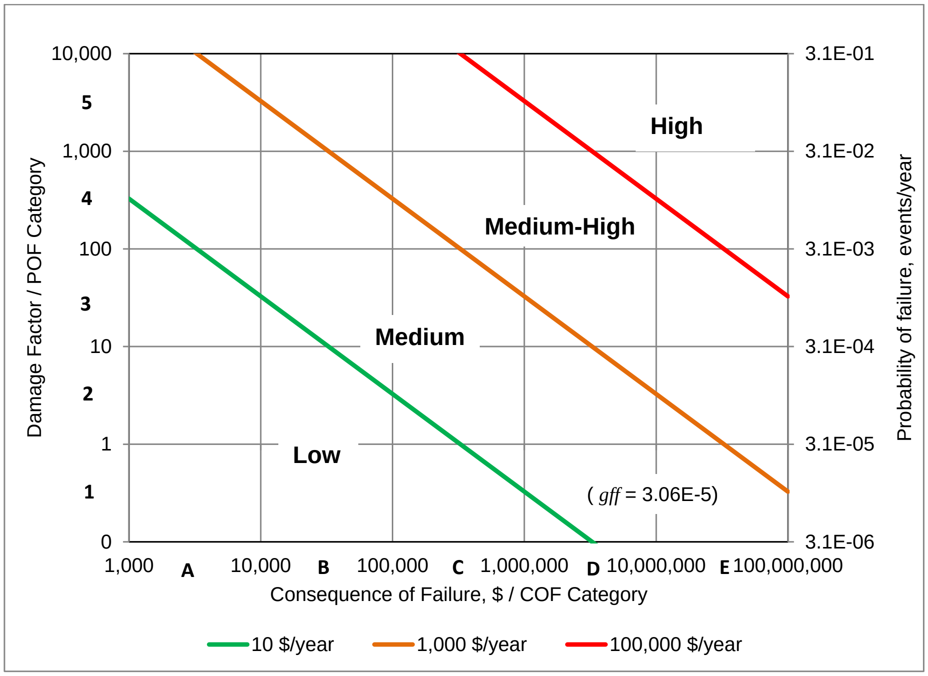


Figure 4.5—Example Iso-risk Plot for Financial Consequence

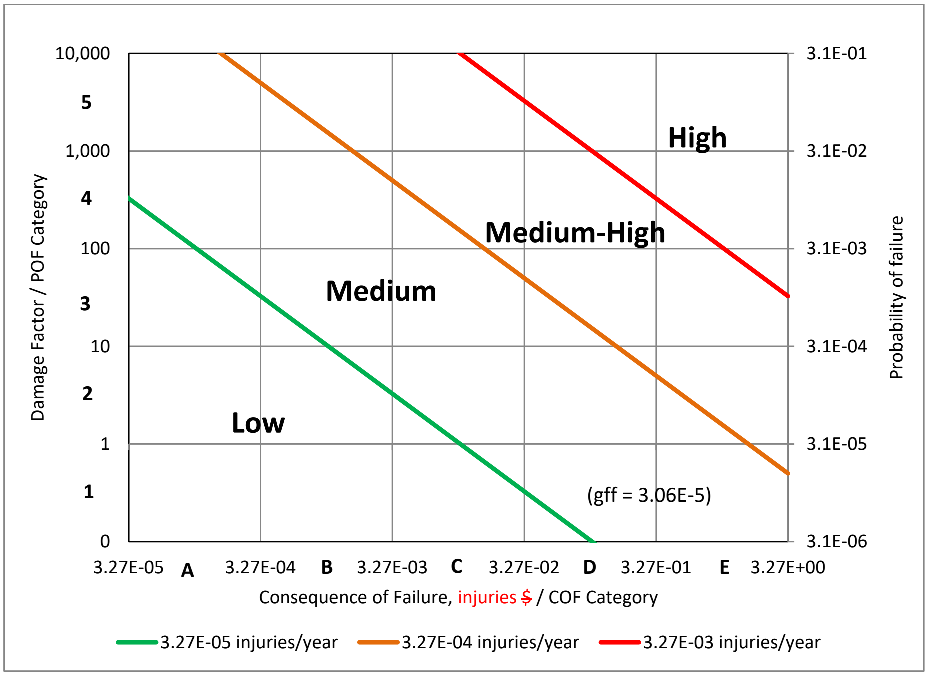
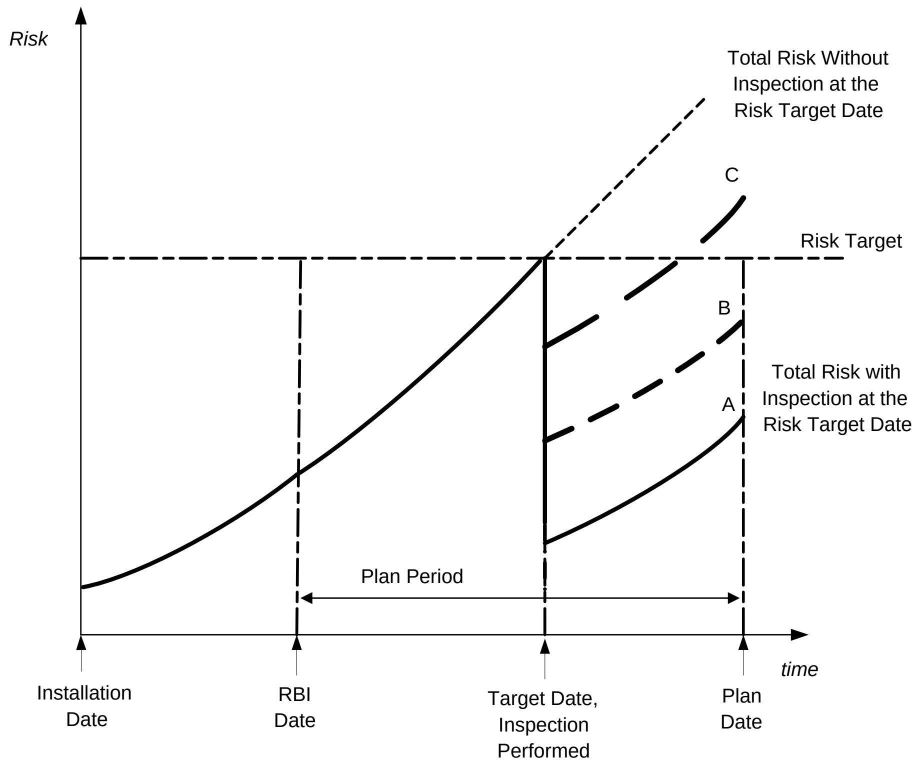
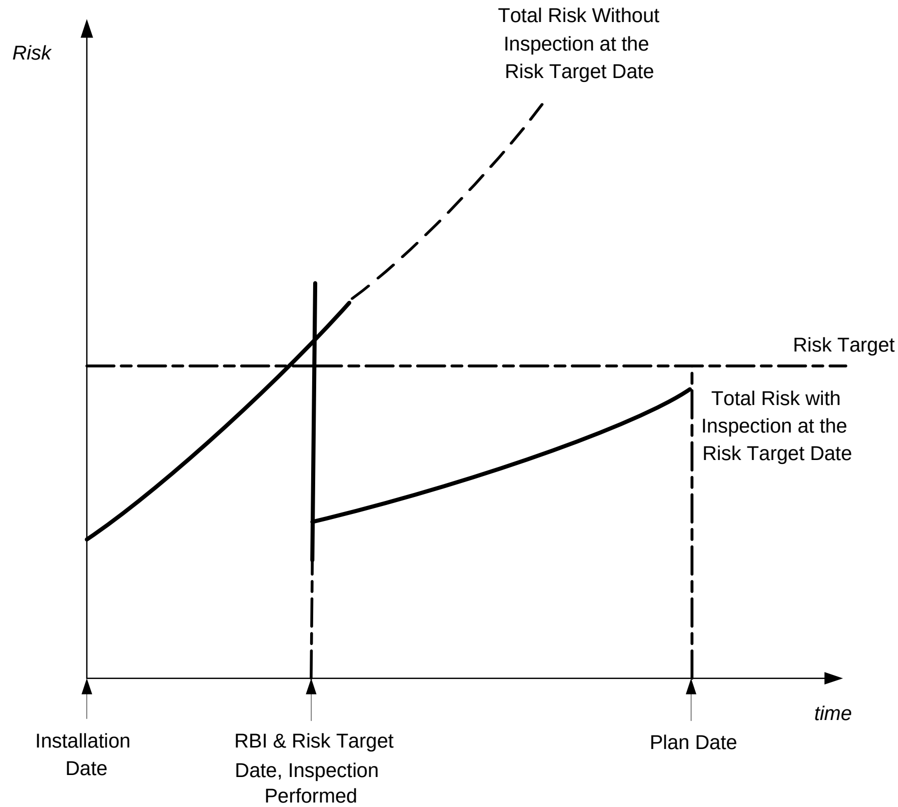


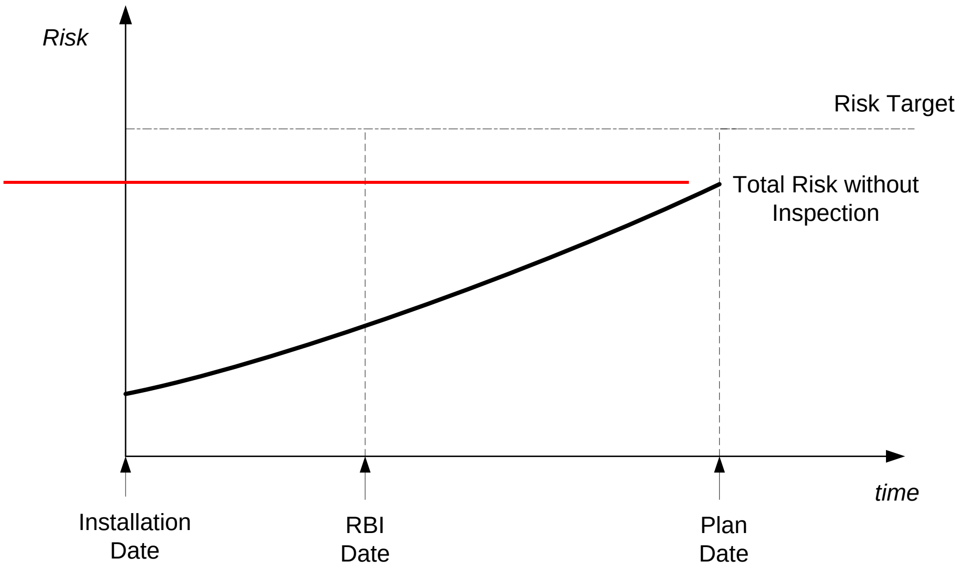
Figure 4.6—Example Iso-risk Plot for Safety Consequence



~~**Figure 4.7—Case 1: Inspection Planning when the Risk Target Is Exceeded During the Plan Period**~~



~~**Figure 4.8—Case 2: Inspection Planning when the Risk Target Has Been Exceeded at or Prior to the RBI Date**~~



~~**Figure 4.9—Case 3: Inspection Planning when Risk Target Is Not Exceeded During the Plan Period**~~