Creation of CPQRA Data Base

2009_2nd semester

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Introduction

- Present an overview of the data in CPQRA
- Basic information necessary for a CPQRA of new or existing facility
  - Material information
  - Process chemistry
  - Material toxicity
  - Process flow diagram and P&ID
  - Control strategy
  - Operation and maintenance philosophy
  - Emergency response considerations
  - Material interactions
  - Equipment specification
  - Operating procedure
  - Maintenance practice

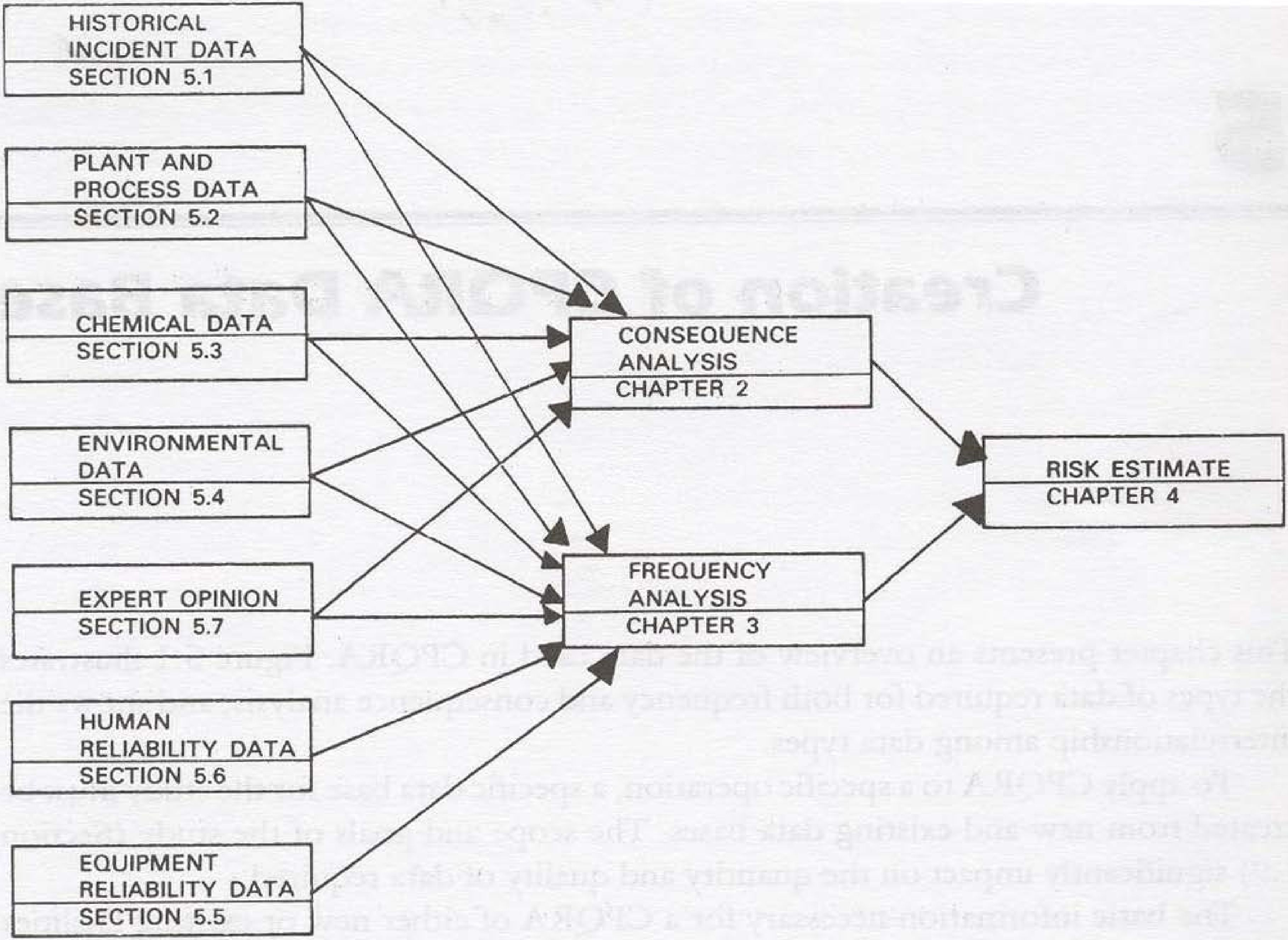


FIGURE 5.1. Flow chart for data inputs to risk estimates.

- Various type of data that should be considered
  - Equipment failure rate
  - Toxicity
  - Human error
  - Materials of construction
  - Ignition source
  - Location-specific data for nearby population
  - Meteorology
  - External events
  - Nearby waterway, road, railroad and airports

Historical Incident data

- May be used directly to estimate top event frequencies
- Most of these data sources address major events or failure such as
  - Leak of toxic materials
  - Major fires or explosion
  - Pipeline leaks and rupture
  - Transportation accidents
  - Accidents causing fatalities or serious injuries
- Data source can be grouped into three categories
  - Failure mechanisms and cause
  - Consequence effects
  - Frequencies of certain types of incidents

TABLE 5.1. Some Historical Incident Data Sources

Source	Description/title
M & M Protection Consultants 1221 Avenue of the Americas New York, New York 10020	"One Hundred Largest Losses" Annual review of large losses in the hydrocarbon-chemical industries. Updated yearly. Free
Lees (1980)	"Loss Prevention in the Process Industries" Appendix 3 contains some case studies of major chemical incidents and a chronological listing of many more
V. C. Marshall (1987)	"Major Chemical Hazards" Contains 40 case studies of major incidents
Loss Prevention Bulletin, I.Chem.E., UK.	Annual survey of chemical industry accidents (worldwide), covering a wide range of accidents and with accident descriptions
J. H. Sorensen (1986)	"Evacuations due to Chemical Accidents: Experience from 1980 to 1984"
Office of Radiation Programs, U.S. Environmental Protection Agency	"The Consequences and Frequency of Selected Man-Originated Accident Events" NTIS PB80-211303
B. J. Robinson (1987)	"A Three Year Survey of Accidents and World Dangerous Occurrences in the UK Chemical Industry" Covers 1982 to 1984/5
J. A. Davenport (1983)	"A Study of Vapor Cloud Incidents—An Update" Lists UVCE incidents, cross-referenced to Gugan (see below)
K. Gugan (1979)	"Unconfined Vapor Cloud Explosions" Lists UVCEs; includes some BLEVEs and partially confined explosions
P. Field (1982)	Dust Explosions Lists major incidents of this type
N. C. Harris (1978)	"Analysis of Chlorine Accident Reports" Chlorine Institute, Washington, DC
U.S. Department of Transportation, Research and Special Programs Administration, Office of Pipeline Safety, Washington, DC	Pipeline Leak Reports for Onshore Gas Transmission and Gathering Lines, and Liquid Lines (see also 3.1)
CONCAWE The Oil Companies' European Organization for Environmental and Health Protection, The Hague, The Netherlands	Annual reports of leaks from cross country pipelines in Europe

Process and Plant Data

- Plant layout and system description
  - Process chemistry
    - Including side reactions under normal and abnormal conditions)
  - Physical and chemical properties of all process materials
  - Chemical and material of construction interactions
  - Process flow diagram
    - Including process description and specific operating parameters such as flow rates, pressures, temperature and stream compositions)
  - Process design basis
    - Including external events)
  - Process utilities
    - Cooling, steam, electricity, instrument air and utility back-up systems
  - Water treatment system

- Plant layout and system description(cont.)
  - Equipment specification
    - Including material of construction
  - Equipment detail drawings
  - P&ID
    - Including utilities and relief systems
  - Plant layout drawings
    - Plant and immediate surroundings including elevations
  - Firewater and drainage drawings
  - Material properties
    - Including in-process intermediates
  - Control logic
    - Instrument loopsheets, relay logic diagram

- Plant layout and system description(cont.)
  - Operating instrument
  - Operating philosophy
    - Storage inventory levels, operating schedule, staffing, start-up and shutdown, operator training, safety policy
  - Safety equipment
    - Fire protection, emergency relief interlock and alarm systems
  - Historical incident and maintenance records
  - Maintenance philosophy and program

Ignition sources and data

- The risk for flammable material is dependent on
  - The chance that the material ignites
  - The ignition energy
  - The level of confinement of the released cloud
- Typical source of ignition
  - Flares, Boiler, Fired heaters
  - Static electricity
  - Electrical motors, vehicle traffic
  - Hot work : welding and cutting
  - Lightning
  - Overhead high voltage lines
  - Mechanical : sparks, friction, impact, vibration
  - Chemical reaction

TABLE 5.2. Ignition Data for Some Gases[a]

Material	Minimum ignition energy (mJ)	Autoignition temperature (°C)
Carbon disulfide	0.015	100
Hydrogen	0.017	520
Acetylene	0.017	305
Ethylene	0.007	490
Methane	0.30	630
Propane	0.26	450
Acetone	1.15	465

[a]Kuchta (1985) and Zabetakis (1965) Data in air at 25°C.

TABLE 5.3. Ignition Data for Some Dusts[a]

Material	Minimum cloud ignition energy (mJ)	Cloud ignition temperature (°C)	Layer ignition temperature (°C)
Coal, Pittsburgh	30	610	170
Polyethylene	30	450	380
Aluminum (flake)	10	610	326
Sulfur	15	190	220
Adipic acid	60	550	—

[a]McKinnon (1981).

Caution: Dust ignition energies and temperature are a function of the physical characteristics of the dust (i.e., size, porosity, shape, etc.)

Ignition probability

- Typically modeled as a function of two components
  - The first is the probability the ignition source will be present to ignite the mixture
    - Presence Factor
  - The second is the probability that, given the ignite source is present, it is actually ignites the cloud in a given time interval
    - Strength Factor
- Each potential ignition source will have its own unique combination of presence and strength factor

- Typical ranges for on site-strength factors for hydrocarbons

Furnaces, boilers, heaters	0.9-1.0
Substations	0.001-0.3
Office building	0.1-0.2
Truck loading/Unloading area	0.1-0.5
Cars	0.2-0.4
Construction fabrication shop	0.1-0.5

TABLE 5-4. Canvey Report Ignition Probabilities

Sources of ignition	Ignition probability
None	0.1
Very Few	0.2
Few	0.5
Many	0.9

Examples of these include:

None: "None readily identifiable" e.g., limited release of liquid hydrocarbon into a bund after overfilling a tank.

Very Few: Large release of gas liquified under pressure after a catastrophic failure of a tank in a tank farm.

Few: Release of flammable material near noncontinuous operations, e.g., LPG release from a tank near to road/rail facilities.

Many: Release of flammable material near a plant or a release resulting from a nearby fire or explosion.

Chemical Data

- Types of data
  - Thermodynamic data
    - Including vapor pressure, boiling point, freezing point, critical temperature and pressure, enthalpies, entropies, specific and latent heats, heat of combustion
    - Flammability
      - Flash point and fire point
      - LFL, UFL
      - Autoignition temperature
      - Maximum allowable oxygen content
      - Minimum ignition energy
      - Deflagration index for gasses
      - Burning velocity
    - Dust explosion data
      - Maximum rate of pressure rise
      - Maximum rate in a closed chamber
      - Layer ignition temperature

- Types of data(cont.)
  - Industrial hygiene and toxicity data
    - Short-term exposure data such as LD50, LC50, ERPG's
    - Protective equipment needed
  - Miscellaneous
  - Chemical interaction and reactivity data
    - Shock sensitivity
    - Thermal analysis data
    - Accelerating rate calorimetry(ARC) data
    - Vent sizing package(VSP) data
    - Reaction kinetics and thermodynamic models

- Source
  - Flammability data
    - NFPA 325M(1984), Bulletin 627(Zabetakis, 1965), Fire Protection Handbook(cote, 1986)
  - Dust explosion data
    - NFPA 68(1994)
  - Industrial hygiene and toxicity data sources
    - Threshold Limit Values for Chemical Substances and Physical Agent(1996)
    - Emergency Response Planning Guidelines(1994)
    - Pocket Guide to Chemical Hazards(1994)
  - Chemical reactivity hazards data
    - Guidelines for Chemical Reactivity Evaluation and Application to Process Design(1995)

Environmental Data

- Population data
  - Necessary to know the population distribution on and around the site to estimate risk
  - Generally defined as population density
  - Source of population data for an area
    - Census reports
    - Detailed map
    - Aerial photographs and site inspection
  - Typical population density estimates for different categories of occupancy
    - Urban : 19,000-40,000 people/square mile
    - Suburban : 5,000-19,000 people/square mile
    - Scattered housing : 250-5,000 people/square mile

Meteorological Data

- Weather condition
  - Major effect on the way a release spreads
  - Generally use typical 16 point wind rose
  - Generally many risk analysis employ at least two weather condition
    - Stable (2m/s, Stability F)
    - Average condition (5m/s, Stability D)
  - Meteorological data source
    - Weather data can be obtained from the National Oceanic and Atmospheric Administration(NOAA)

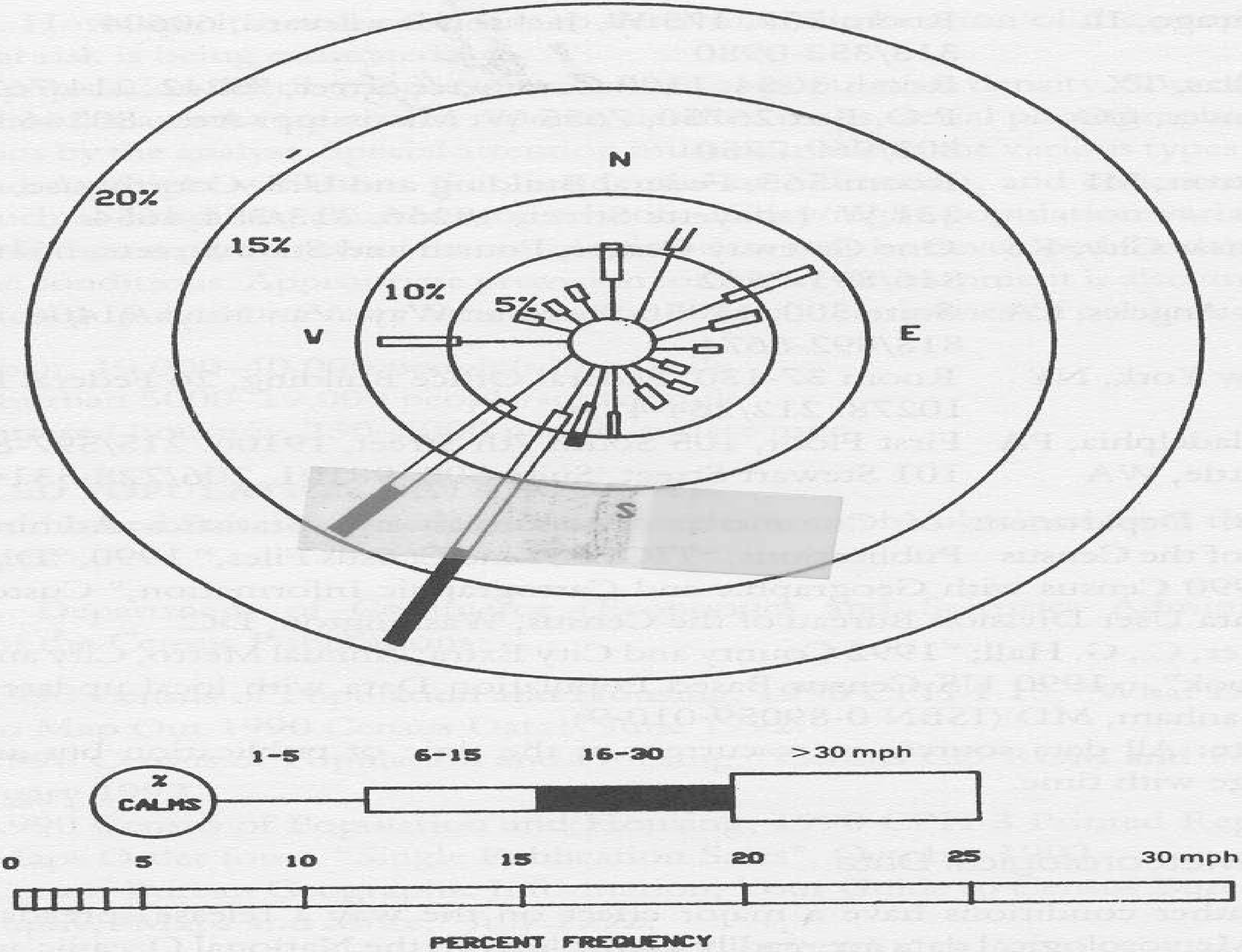


FIGURE 5.2. Typical wind rose data.

Geographic Data

- Include local and site maps on a scale adequate to met the CPQRA objective
  - Aerial photographs, on-site tours and local building characteristics also provide useful information

Topographic Data

- Local topography is important in modeling the dispersion of a gas
- Consider large obstacles ranging from trees to mountains and valley
- Four types of models which can be used to analyze such release scenarios
  - Standard EPA Gaussian models that are corrected for plume lifting as the plume approaches the hill
  - Drainage flow model(for dense gas flow down slopes)
  - Three dimensional models
  - Puff trajectory models for nonhomogeneous wind field

External Event Data

- External events are either man-made(aircraft crashes) or natural(earthquake, Floods)
  - Design data should be obtained on individual critical items(e.g., vessels, pipes, control building, blast wall) to determine their performance under incident conditions

Equipment Reliability Data

- Equipment reliability
  - Defined as the probability that process equipment will perform its intended function adequately for a specified exposure period
  - Three important point about equipment reliability
    - A probability
    - A function of the exposure period
    - A function of the definition of equipment failure

$$R(t) = 1 - F(t)$$

- R(t) is reliability as a function of t
- F(t) is a cumulative failure distribution as a function of t
- t is time

- Probability(Failure) density function, f(t)

$$f(t) = \frac{dF(t)}{dt} \qquad F(t) = \int_0^t f(t)dt$$

- Substituting (5.5.3) into (5.5.1)

$$R(t) = 1 - \int_0^t f(t)dt$$

- Since the total area under the probability density function, f(t), must be unity, so

$$R(t) = \int_t^\infty f(t)dt$$

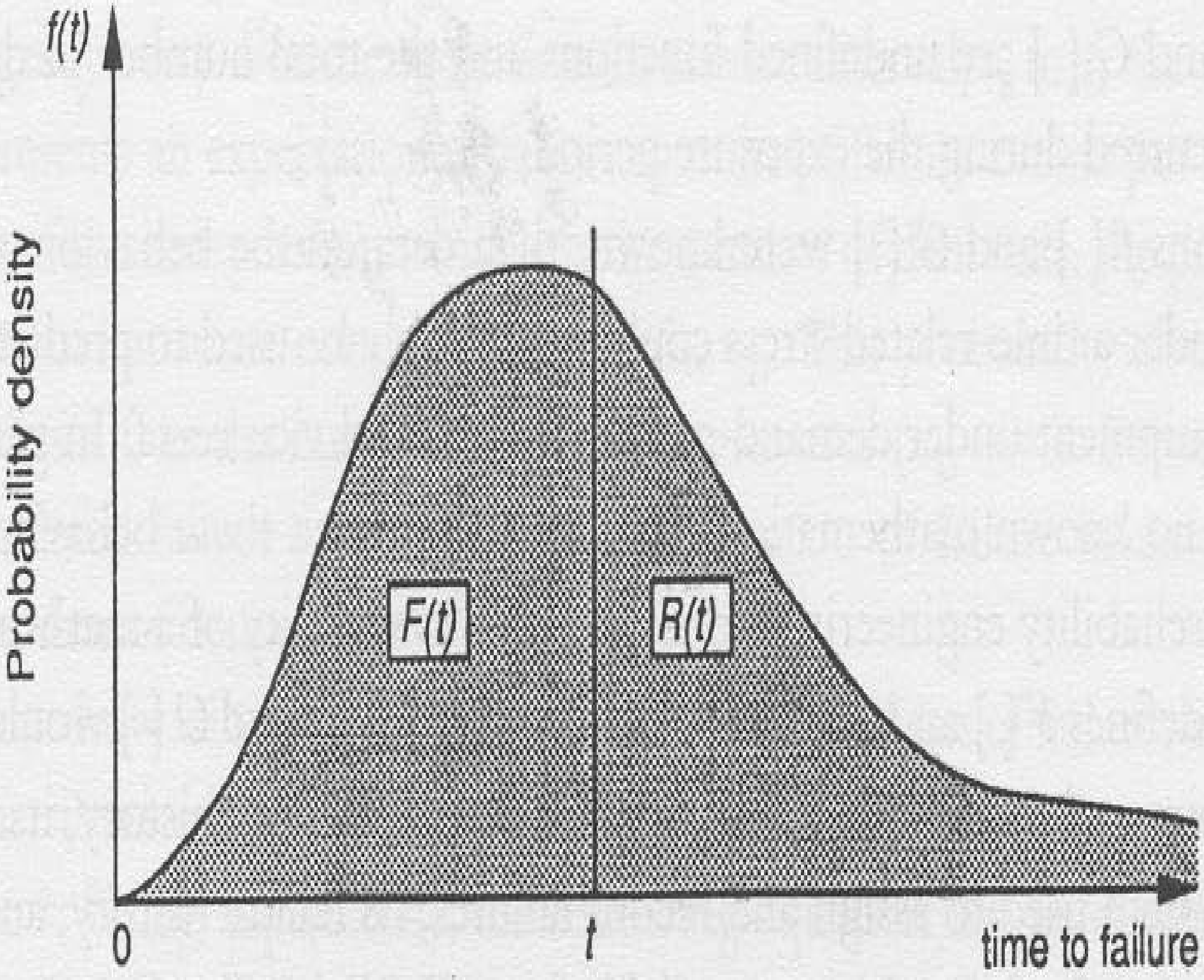


FIGURE 5.3. Hypothetical probability density function, f(t), as a function of time, t. F(t), the cumulative failure distribution, is the fractional probability of failure up to t_1 while R(t) is the probability of surviving beyond time t. (From Billinton and Allan, 1983.).

Equipment failure rates

- Defined for time-dependent and demand dependent exposure periods
- Time-dependent equipment failure rate

$$\lambda(t) = \frac{\text{number of equipment failures per unit time}}{\text{number of pieces of equipment exposed to failure}}$$

- Demand-dependent equipment failure rate

$$\lambda(n_D) = \frac{\text{number of equipment failures per demand}}{\text{number of pieces of equipment exposed to failure}}$$

  - n_D represent the number of demand

- Time-related failure rates
  - Often represent as the number of failures per 10^6 hr
  - For equipment which is normally functioning
    - Running pump, temperature or pressure transmitter
- Demand-related failure rates
  - Typically given as the number of failure per 103 demands
  - For equipment that is normally static but is called upon at random interval
    - A switch, a standby generator

- Failure rate versus frequency
  - Time-related equipment failure frequency can be defined as the number of failure events that occur, divided by the total elapsed calendar time during which these event occur
  - Time-related equipment failure rate can be defined as the number of failure events that occur, divided by the total elapsed operating time during which these events occur

- Probability of failure rate
  - Represented by a probability distribution function
  - Probability distribution function
    - If the independent variable is time, the probability of time-related failure at some time-in-service, t, is the probability that the equipment will between t_0 and t
    - This probability approaches 1.0 as the equipment ages ($t \rightarrow$ infinite)

- Using eq.(5.5.6) convert failure rates to probabilities of failure

$$\lambda(t) = \frac{F(t)}{R(T)}$$

  - λ(t) is instantaneous failure rate
  - f(t) is probability density function of t
  - R(t)is reliability as a function of t
  - T is time
- From eqs.(5.5.1) (5.5.2) and (5.5.3)

$$\lambda(t) = \frac{dR(t)}{R(t)dt}$$

- Eq.(5.5.10) can be integrated and solved for R(t)

$$R(t) = \exp\left[-\int_0^t \lambda(t)dt\right]$$

- Functional form

$$R(t) = \Phi[\lambda(t), t]$$

$\Phi[\lambda(t), t]$ is probaility distribution function of $\lambda(t)$ and t

Constant failure rate model

- Appropriately used to define the reliability of components which are subject only to failures occurring at random interval
- Generally based on the exponential distribution
- Reliability of a component in the time interval(0,t)

$$R(t) = e^{-\lambda t}$$

  - e is the base of the natural logarithm(2.71828)
  - λ is the time constant failure rate(1/mean time between failure)
  - T is operating time for which we want to know the reliability R of the component

- Complement of the reliability(failure probability)

$$P_f(t) = 1 - e^{-\lambda t}$$

  - P_f is the probability of failure of the component in the time interval(0,t)

Nonconstant failure rate model

- The most commonly model is Weibull-distribution-based models
- Used to identify the infant mortality, useful life(constant failure rate) and wear-out modes of failure
- Two parameters in Weibull model
  - Beta parameter(shape parameter)
    - Determined the shape of the Weibull curve
    - When the value of shape parameter is greater than 1, the rate of failure increases with time
  - Alpha parameter(the scale or characteristic life parameter)
    - Amount the curve is spread out along the abscissa depend on alpha parameter
    - Expressed in unit of time, typically hours

- Reliability formula associated with the Weibull density function

$$R(t) = e^{-(t/\alpha)^{*}\beta}$$

- Formula for estimating failure rate associated with the Weibull density function

$$Fr(t) = (\beta / \alpha^{\beta})(t)^{\beta-1}$$

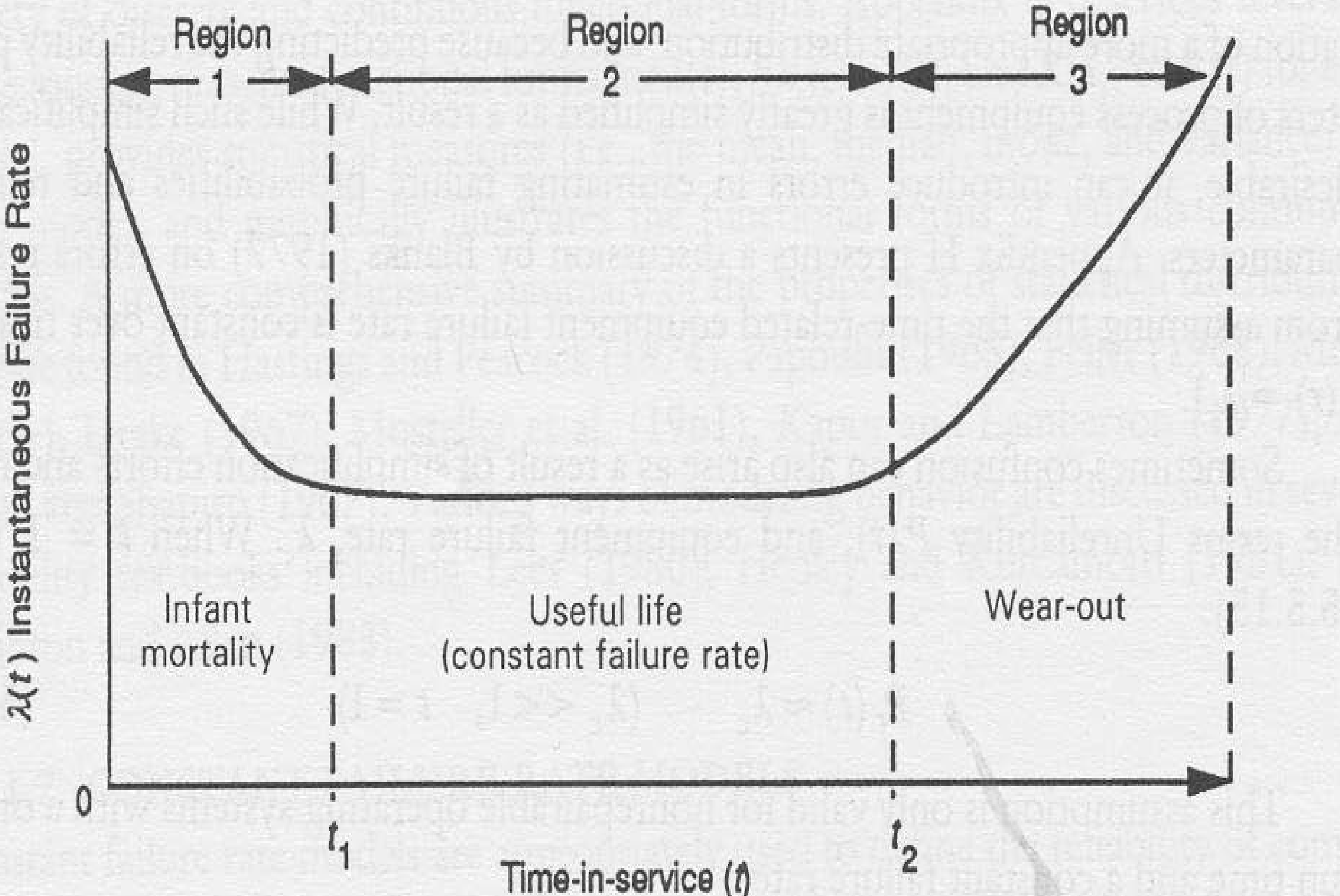


FIGURE 5.4. Equipment failure rate in service, t (or equipment age)—the "bathtub curve."

Types and Source of Failure Rate data

- Plant specific data
  - Contain failure rates specific to equipment
    - Valve or pump in use at a facility by manufacturer, make, model and serial number
- Generic data
  - Less specific and detailed than the data derived from specific equipment failure history
  - The PERD Guidelines offer an generic data base of equipment failure rate data for use in CPQRA

TABLE 5.5. Selected Equipment Reliability Data Resources from the **PERD Guidelines**[a]

Source	*PERD Guidelines* resource number	Availability	Basis	Comments
Rasmussen (1975) [WASH-1400] *Reacator Safety Study*	4.8–9	Published	Nuclear power plant records and other relevant data	One of the early, historical sources much quoted and referenced. Supported by Licensee Event Report Analysis
IEEE Std. 500 (1984)	4.6–12	Published	A large collection of component reliability data	Mainly nuclear sources
IPRDS In-Plant Reliability Data System [see drago et al. (1982), Borkowski et al. (1983), and Kahl et al. (1987)]	4.6–11	Published and computerized	Reviews of nuclear plant maintenance records	Large detailed data base on nuclear plants, updated continuously
NPRDS Nuclear Plant Reliability Data System managed by INPO (Institute of Nuclear Power Operations) 1100 Circle 75 Pkwy., Ste 1500, Atlanta, GA 30339	4.6–2	On-line access and data retrieval; floppy disks; summary reports	Nuclear plant data in a consistent and comprehensive format	Failure data on 44,000 events available; but may well be the most significant nuclear data base in the near future
Lees (1980)	4.4-3, 4.4-4	Published	Data on wide range of process equipment	Numerous tables and an index
Offshore Reliability Data Handbook (OREDA Participants, 1984), 1st Edition	4.6–14	Published	Reliability data from offshore drilling and production platforms	Concentration on the Norwegian Sector of the North Sea
OREDA-92, OREDA-97	N/A	Published	New and updated reliability data from offshore drilling and production platforms	Concentrates on the Norwegian Sector of the North Sea. All three editions contain some unique data
Systems Reliability Service (SYREL) Data Base, UK Atomic Energy Authority, Culcheth, Warrington, Wigshaw Lane WA3 4NE, England	4.6–9	Proprietary data base	Reliability data from nuclear, power generation, and other industries	Concentrates on UK and European data
Rinjmond Public Authority (1982)	4.5–2	Published	Process industry reliability data	Early compilation directed specifically to the CPI

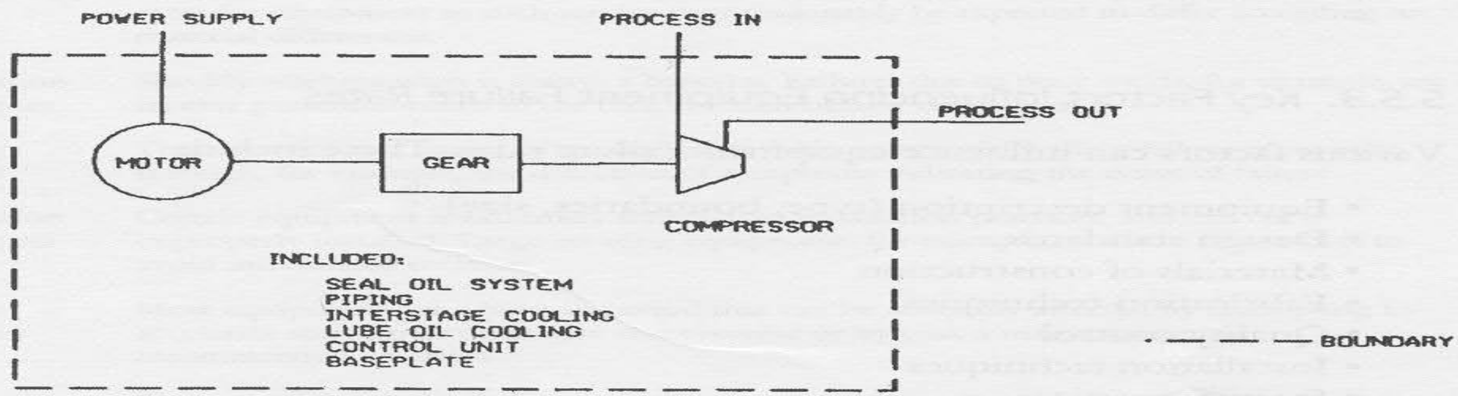
[a] AIChE/CCPS (1989).

DATA ON SELECTED PROCESS SYSTEMS AND EQUIPMENT	
Taxonomy No. 3.3.2.1	Equipment Description ROTATING EQUIPMENT-COMPRESSORS-ELECTRIC MOTOR DRIVEN
Operating Mode	Process Severity UNKNOWN

Population	Samples	Aggregated time in service (10^6 h)		No. of Demands
		Calendar time	Operating time	

Failure mode	Failures (per 10^6 h)			Failures (per 10^3 demands)		
	Lower	Mean	Upper	Lower	Mean	Upper
CATASTROPHIC	27.9	2470.0	9690.0			
a. Fails While Running						
b. Rupture						
c. Spurious Start/Command Fault						
d. Fails to Start on Demand						
e. Fails to Stop on Demand						
DEGRADED						
a. External Leakage						

Equipment Boundary



Data Reference No. (Table 5.1): 8.4

FIGURE 5.6. Sample generic failure rate data sheet from **PERD Guidelines** (AIChE/CCPS, 1989).

Key Factors Influencing Equipment Failure Data

- Various factors influencing equipment failure rate
  - Equipment description(type, boundaries, size)
  - Design standards
  - Materials of construction
  - Fabrication technique
  - Quality control
  - Installation techniques
  - Startup practice
  - Operating strategy
  - Process medium
  - Internal environment
  - External environment
  - Maintenance strategy
  - Failure mode
  - Equipment age

TABLE 5.6. Discussion of Factors Influencing Equipment Failure Rates

Factor	Discussion
Equipment type	Different equipment fails at different rates. Rotating equipment is expected to fail differently than process vessels and piping, Failure rates are also different within classes of equipment, Consequently, failure rates need to be distinguished by equipment type, For example, there are gear, centrifugal and positive displacement pump types
Equipment boundaries	Boundaries need to be clearly defined. Failure rates for a compressor including the drive unit, gearbox, and compression unit obviously differ from those for the compression unit only
Equipment size	This is meant to be a general term covering flow rates, pressures, horsepower, physical dimensions, speed, etc. Small items may suffer from problems not inherent in larger machines or vice versa. For example, fine tolerances may be required on small items, while high mechanical stresses may be problems on high-pressure or high-speed systems
Design standards	Design standards present equipment requirements so as to prevent recurrence of historical failures. Equipment designed accordingly is not expected to fail in the same mode or as often as equipment otherwise designed
Materials of construction	While it is assumed that materials of construction are selected to be compatible with the process media, a variety of materials may be acceptable for a given service. Failure rates for equipment in such service may reasonably be expected to differ according to material differences.
Fabrication techniques	Shoddy workmanship is always a concern. Failures due to poor welds, for example, are an ever present concern in the filed erection of new equipment
Quality control	The existence and nature of quality control can substantially affect failure experience, through, for example, the detection of symptoms indicating the onset of failure
Installation techniques	Certain equipment is extremely sensitive to installation practices, and can fail if improperly installed. Large rotating equipment, for example, needs to be set level to avoid imbalanced rotation
Startup practices	Most equipment has a burn-in period that can be adversely affected by attempting to accelerate start-up or otherwise compromise or by-pass a manufacturer's recommended practices
Duty	Equipment lightly loaded can be expected to fail less often than if heavily loaded. Running close to design limits usually increases equipment failure rates
Operating strategy	Continuous operation under uniform conditions is often less arduous than repeated stops and starts. Temperature or pressure cycling, start-up loading, and even standby duty may increase equipment failure rates. Batch operations often include a combination of factors. A pump used on batches of different materials may operate with a different process media, strategy, and duty from one batch to another. The operating strategy should also account for the level of training and performance of operating personnel

- Key factors to characterize equipment failure rate(PERD guidelines(AIChE/CCPS)
  - Equipment description
  - Process medium
  - Failure mode
  - Causes
  - severity

Failure modes, causes and severity

- Failure rate can be characterized according to the mode, cause and severity of failure
- Failure mode
  - Defines the manner in which a piece of equipment fails to perform its intended function
- Failure cause
  - Describes the condition that cause the faulty performance
- Failure severity
  - Express the extent to which equipment performance is impaired for a given failure mode and cause

<table>
<tr><th colspan="3"></th><th colspan="3">Failure Severity</th></tr>
<tr><th colspan="3"></th><th>Catastrophic</th><th>Degraded</th><th>Incipient</th></tr>
<tr><td rowspan="3">Change in item or equipment condition</td><td colspan="2">Change in operation</td><td>1. Failure to operate (run)
2. No output</td><td>1. Low output
2. High output
3. Erratic output
4. Locked in one mode of operation
5. Output above or below specified requirements</td><td>Discovered through:
1. Local inspection (overheating, leaks, contamination, noise, severe vibration, odor, cracks, etc)
2. Testing: (output above or below specified limits while in stand-by mode of operation)
3. Monitoring (trend towards failure)</td></tr>
<tr><td rowspan="2">Change of state</td><td>Change without demand</td><td>A spurious:
1. Start/Stop
2. Insertion
3. Withdrawal
4. Actuation
5. Response
6. Opening
7. Closing</td><td>1. Premature or delayed actuation (an actua tion that occurs out of timing sequence)
2. Won't stay open or closed</td><td rowspan="2">Discovered through:
1. Testing: Failure or diminished ability to transmit or retain energy during the stand-by mode of operation
2. Local inspection</td></tr>
<tr><td>No change on demand</td><td>Failure to:
1. Start
2. Stop
3. Insert
4. Withdraw
5. Actuate
6. Respond to command
7. Open
8. Close</td><td>Improper Response:
1. Partially open, close, etc.
2. Oscillation (failure to assume a fixed position)</td></tr>
</table>

FIGURE 5.7. Active equipment failure classification matrix. (Reprinted from ANSI/IEEE Std. 500-1984, ©1984 by the IEEE, with permission of the IEEE Standards Department.)

Failure Severity				
	Catastrophic	**Degraded**		**Incipient**
Change in item or equipment condition	Failure to retain or transmit energy	Diminished ability to retain or transmit energy	Change in operation	
	1.0 Breach of pressure or static fluid boundary	1.0 Degradation of pressure or static fluid boundary		(1) Testing: Failure of diminished ability to transmit or retain energy during the energized mode of operation
	1.1 Major leaks	1.1 Minor leaks		(2) Local inspection (leaks, vibration, odor, cracks, etc.)
	1.1.1 External leaks	1.1.1 External leaks		(3) Monitoring: Monitoring trend towards failure, during the energized mode of operation
	1.1.2 Internal leaks	1.1.2 Internal leaks		
	1.2 Explosions	2.0 Interference with energy transport or exchange capability		
	1.3 Implosions	2.1 Restricted flow		
	2.0 Loss of energy transport or exchange capability	2.2 Reduced heat transfer capability		
	2.1 Blocked or stopped flow	2.3 Minor heat loss		
	2.2 Loss of heat transfer capability (scale buildup	3.0 Structural integrity compromised		
	2.3 Major heat loss (loss of insulation	3.1 Reduced support capability	Change of state	(1) Testing: Failure or diminished ability to transmit or retain energy during the stand-by mode of operation
	3.0 Loss of structural integrity	3.1.1 Fracture of part of the structural members		(2) Local inspection
	3.1 Failure to support or brace	3.1.2 Minor physical distortion		
	3.1.1 Fracture (of all members)	3.2 Partial failure to fasten or join		
	3.1.2 Physical distortion (permanent set)			
	3.1.3 Distortion under load (without perm. set)			
	3.2 Failure to fasten or join			
	3.2.1 Removable fastener failure			
	3.2.2 Failure of permanent joint			
	3.2.2.1 Weld failure			
	3.2.2.2 Imbed failure			

FIGURE 5.8. Passive equipment failure classification matrix. (Reprinted from ANSI/IEEE Std. 500-1984, ©1984 by the IEEE, with permission of the IEEE Standards Department.)

- Equipment age
  - The variation of equipment failure rate with time-in-service can be divided into three regions
    - Burn-in
      - Often called "infant mortality". The equipment failure rate is high. Such failure is usually due to factors such as defective manufacturer or incorrect installation
    - Normal operation
      - The equipment failure rate declines during normal operation until a constant rate is reached
    - Wear-out
      - The equipment failure rate rises again as deterioration sets in, often described as wear-out failure

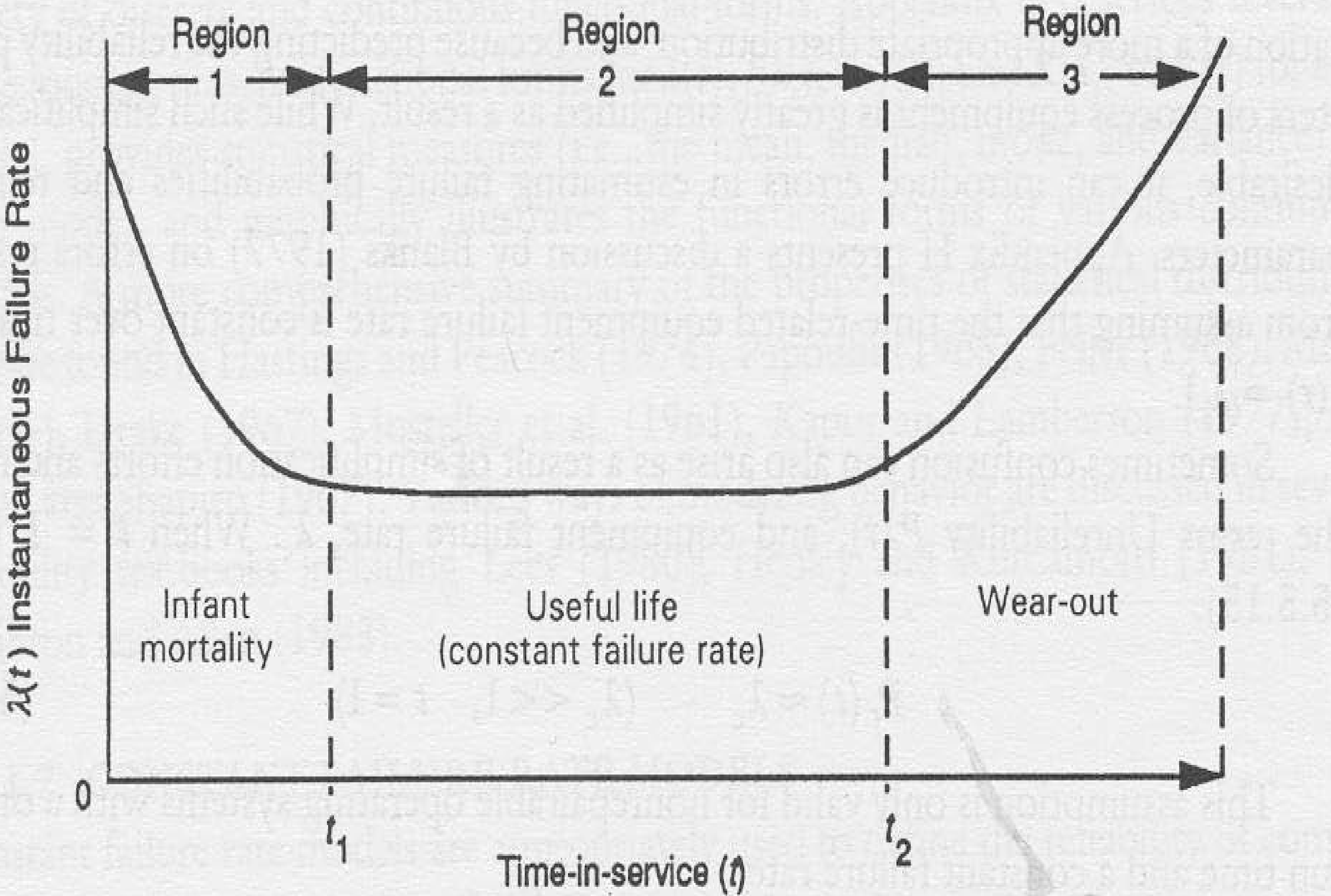


FIGURE 5.4. Equipment failure rate in service, t (or equipment age)—the "bathtub curve."

Failure rate adjustment factors

$$\lambda_A = \lambda_g \prod_{i=1}^{n} f_i$$

- λ is adjusted equipment failure rate
- λ_g is generic equipment failure rate
- f_i is adjustment factor i (i=1 to n)
- n is number of adjustment factors that apply

TABLE 5.7. Generic Failure Rate Data Adjustment Factors [a] (Numbers supplied for illustration purposes only)

Equipment failure rate influences	Adjustment factors [f_i in Equation (5.5.19)]	
	Instruments	Valves
Process medium factors		
Corrosion	1.07	1.14
Erosion	1.14	1.28
Fouling, plugging	1.07	1.14
Pulsating flow	1.14	1.07
Temperature extremes	1.07	1.07
External environmental factors		
Vibration	1.42	1.21
Corrosive atmosphere	1.21	1.21
Dirty atmosphere	1.07	1.07
High temperature and/or humidity	1.07	1.07
Location factors		
Exposed mechanical damage	1.07	1.07
Inaccessible for inspection	1.07	1.07

[a] du Pont (1987).

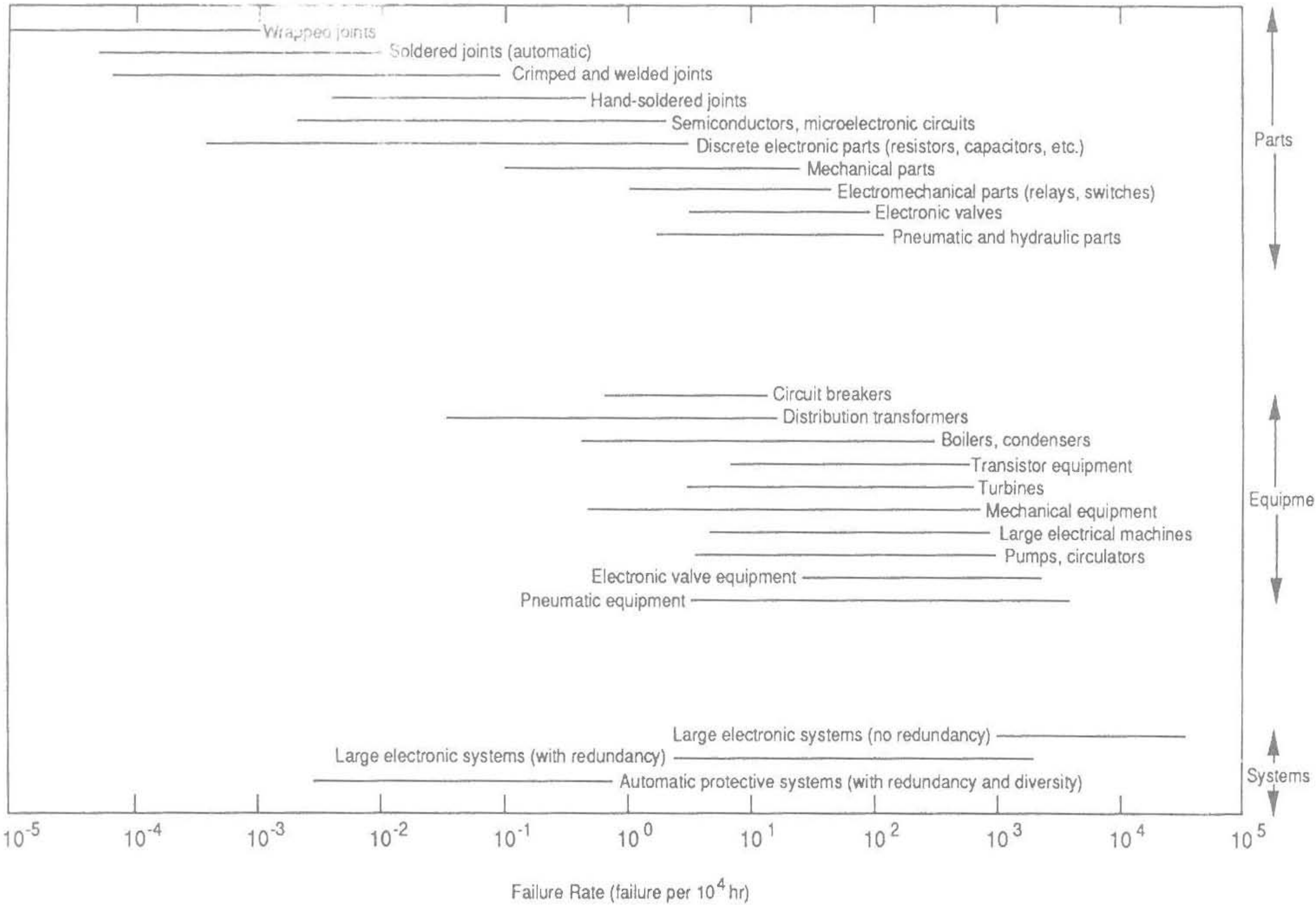


FIGURE 5.11. Typical ranges of failure rates for parts, equipment, and systems.

- Collection and processing of raw plant data
  - Raw failure data collection and processing procedure
    - Collect and review raw plant data
    - Classify and sort raw data into taxonomy data cells
    - Divide and count demand-related and time-related failures
    - Estimate exposure periods
    - Screen for zero failures
    - Screen for trends by failure mode
    - Calculate failure rates
    - Determine confidence limits
    - Reduce the failure rate data set

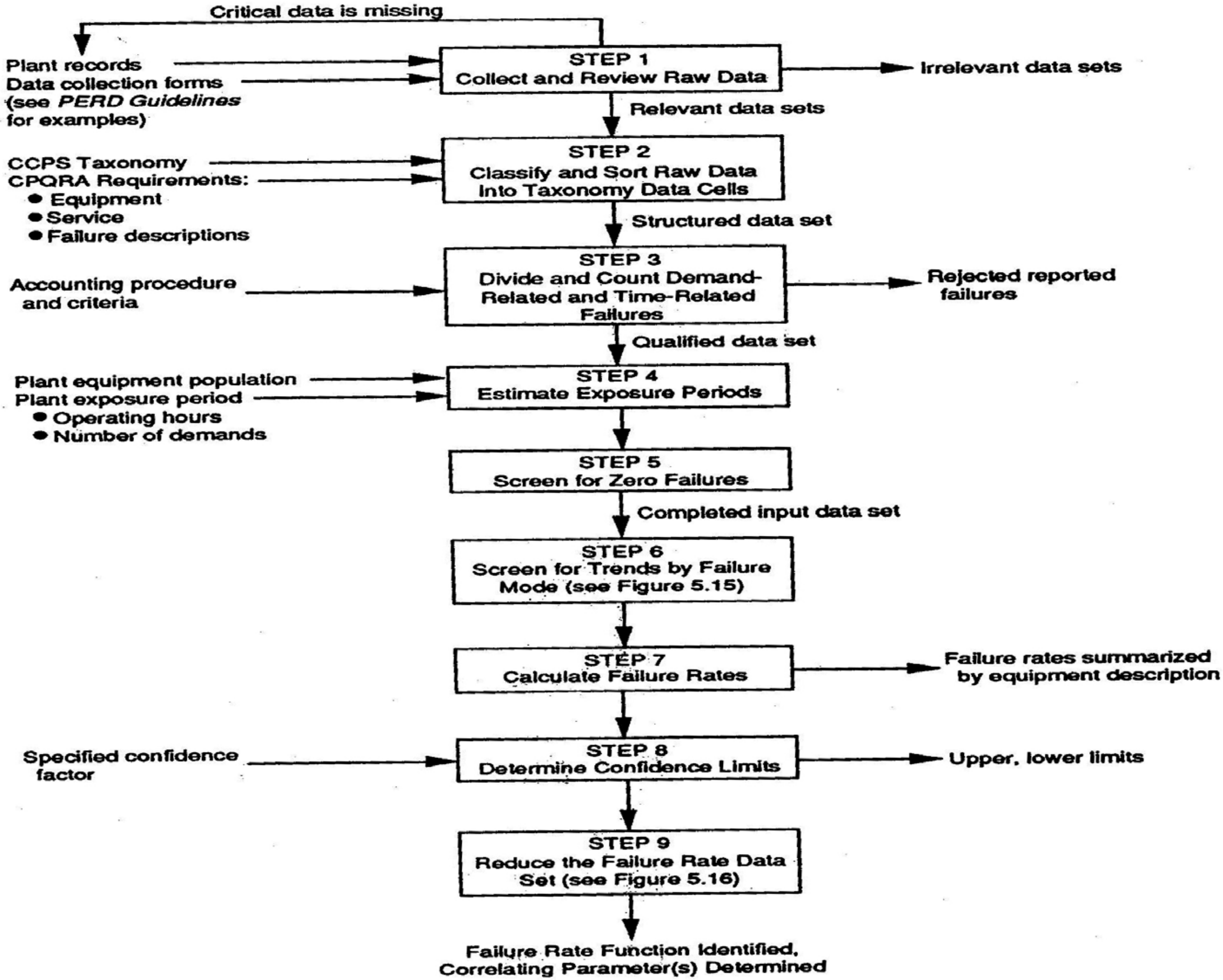


FIGURE 5.14. Raw failure data collection and processing procedure.

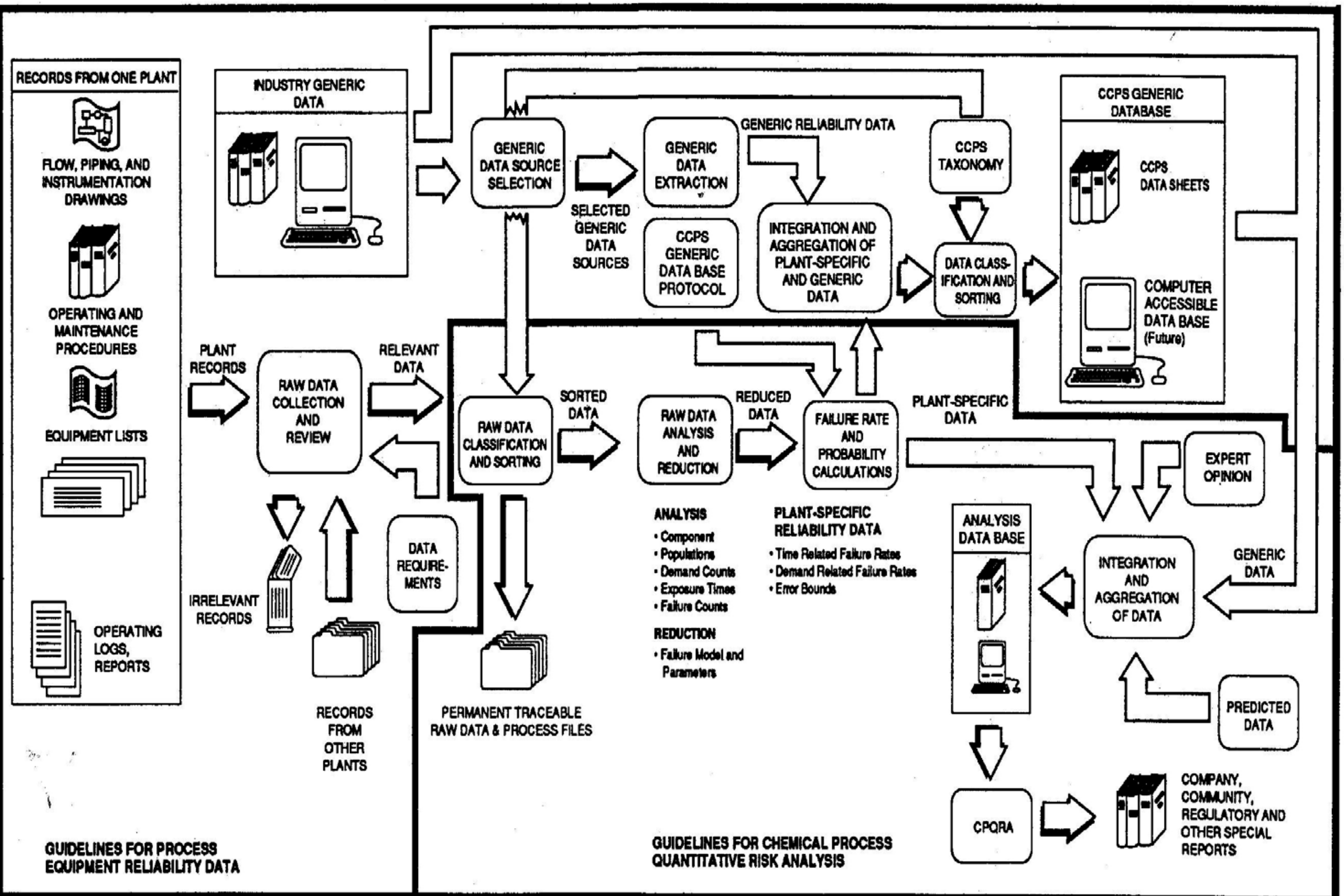


FIGURE 5.13. Process equipment reliability data (with guideline references): data development and use flow diagram. (PERD Guidelines = CCPS Guidelines for Process Equipment Reliability Data; CPQRA Guidelines = CCPS Guidelines for Chemical Process Quantitative Risk Analysis).

- Preparation of the CPQRA equipment failure rate data set
  - Procedure for creating the equipment failure rate data segment of a CPQRA analysis data base
    - Define equipment in CPQRA
    - Define taxonomy data cells
    - Determine data accuracy requirements
    - Identify failure rate models
    - Collect available data
    - Construct initial data set
    - Screen initial data set
    - Aggregate and smooth available data
    - Determine sensitivity and uncertainty in the finalized data set

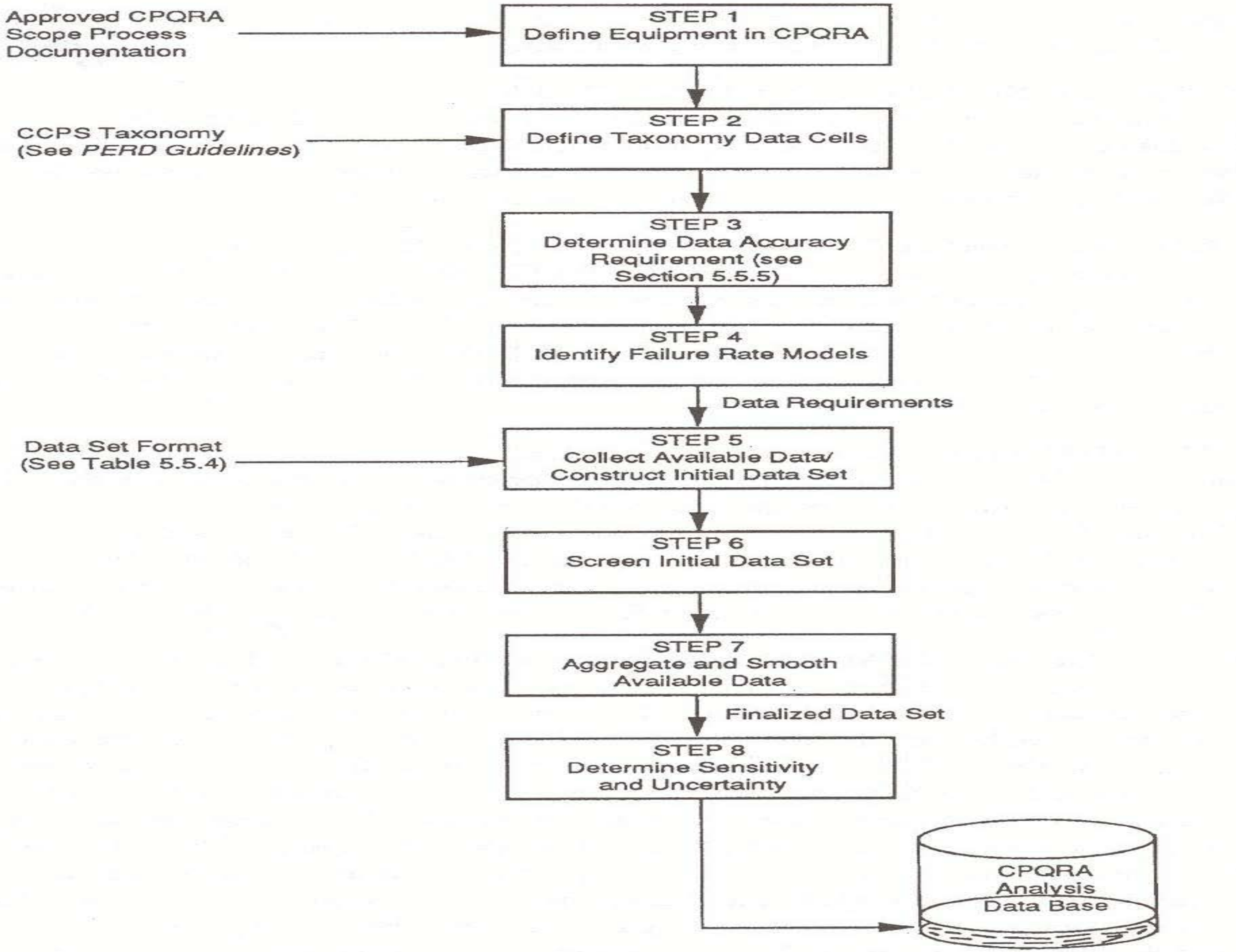


FIGURE 5.17. Procedure for creating the equipment failure rate data segment of a CPQRA analysis data base.

Human reliability data

- Factors can affect the reliability
  - Types of task
  - Environmental conditions
  - System element and characteristics
  - Types of system
  - Quality of human engineering of control and displays
  - Motivation
  - Level or perceived psychological stress
  - Skill and training
  - Presence and quality of written instructions and methods used
  - Coupling of human actions
  - Personal redundancy