Performance and Reliability of Fire Protection Systems

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References

- Hall, U.S. Experience With Sprinklers, NFPA, 2011
- Milke, Campanella, Childers, and Wright, “Performance of Smoke Detectors and Sprinklers in Residential and Health-Care Occupancies,” for NEMA, UMD, 2010.
- Nowlen, Kazarians and Wyant, NUREG/CR 6738, 2001
- Rosenbaum, Eric, MS Thesis, UMD/FPE, 1996.
- SFPE Handbook of Fire Protection Engineering, 2008
  - Chapter 5-3
  - Chapter 5-4

Reliability Analysis

- Definition – reliability
  - The ability of an item (product, system …) to operate under designated operating conditions for a designated period of time or number of cycles.

Performance and Reliability Data

- System
  - Holistic analysis
- Component
  - Field studies of component failures
  - System reliability assessed via engineering analysis

Reliability of FP Systems

- **Sources of reliability assessments**
  - **Delphi panel**
  - **NFIRS data**
    - Rosenbaum thesis (1996)
    - UMD research
  - **Insurance surveys**
  - **Academic surveys**
  - **DOE**
  - **NUREG**

Warrington Study

Fire protection strategy	Residential Occupancies	Commercial Occupancies	Institutional Occupancies
Sprinklers	96	95	96
Smoke detectors	75	75	85
Fire resistance rated construction	70	70	70

Delphi panel

Principal Structural Defects Influencing Fire Spread in Fires with Property Damage of $250K+

	Factor	Incidents	Percent
Vertical Spread	Stairway or other open shafts	47	7.5
	Non-fire-stopped walls	31	5.0
Horizontal Spread	Non-fire-stopped areas including floors & concealed spaces above/below floors & ceilings.	240	38.4
	Interior wall openings, unprotected	31	5.0
	Exterior Finish	29	4.7
Combustible Framing/ Finish	Structure or framing	224	36.0
	Ceiling, walls, floors	21	3.4

NFPA, Fire Protection Handbook, 1976

Reliability Data for Fire Doors

- **FMGlobal:**
  - **1600 listed fire doors tested (previously listed by FM, UL or other NRTL)**
  - **Door types:**
    - rolling steel
    - horizontal sliding on inclined tracks, counterweight closures or spring closures
    - vertical sliding
    - swinging
  - **Average: 82%**
    - Rolling steel had lowest, 80%
    - Vertical sliding had greatest, 93%

Reliability Data for Fire Doors

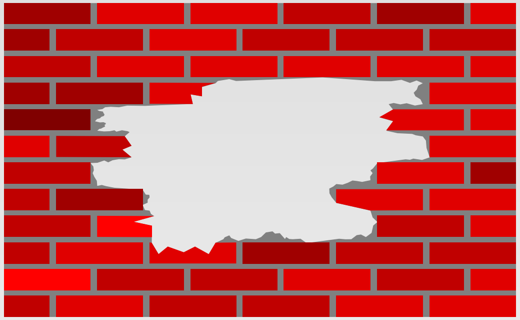
- **CIGNA Property and Casualty:**
  - **Loss control staff evaluated in-place performance of 805 doors**
  - **"41.1% of all doors had some type of physical or mechanical problem which would prevent them from operating properly during a fire event" [Rosenbaum, 1996]**
  - **Reliability = 58.9%**

Reliability Data for Fire Doors

- Dusing, Buchanan and Elms (1979)
- Survey of 91,909 in-place fire doors in various occupancies
- 12,349 were propped open → 86.6% reliability
  - 95% reliability in assembly
  - 61% reliability in institutional

Other Fire Resistance Issues

- **Spruce, 1994**
  - **Estimate of inadequately protected openings in fire rated construction in buildings ≥ 5 years old: 95%**



From Rosenbaum, 1996

WTC 5 Stair Enclosure

Fire Dampers – WTC 5

Reliability of Fire Barriers in PRA

- **Source: NUREG/CR 6738 (Nowlen, Kazarians and Wyant, 2001)**
  - **6 incidents reviewed as case studies**
  - **Suggest reliability of 0.99 per demand**

Case studies

Waterford 3	fire propagated along a vertical cable riser past fire stop in vertical section of the cable tray (no spread to other room)
Zaporizhzhya	inference of fire overwhelming existing and intact fire barriers; propagated to adjacent areas
South Ukraine	hot gases/flames damaged seals in the ceiling of initial fire compartment, opened path for hot gases to expose and ignite cables in upper compartment (no flame propagation)
Armenia	open hatchways, open doors and unsealed cable penetrations allowed fire to propagate from a cable gallery into a cable shaft
Browns Ferry	fire propagated through gap in incomplete cable penetration seal (seal was still under construction) into adjacent reactor building
Belvarsk	fire propagated into adjacent control building via open cable penetrations and leaking or open doors and hatches

Fire Pumps / NFPA 25

- **Reliability analysis with 2 test frequencies**

Fire pump	Test Frequency	Failure rate (per yr)	Reliability (% per demand)
Electric driven	Monthly	0.64	97.3
	Weekly		99.4
Diesel driven	Monthly	1.02	96.0
	Weekly		99.1

8.3 Testing (Proposed NFPA 25, 2014)

8.3.1 Frequency.

8.3.1.1* Diesel engine driven fire pump

> ***8.3.1.1.1 Except as permitted in 8.3.1.1.2, weekly test frequency required.***
>
> ***8.3.1.1.2* Test frequency may be established by approved risk analysis.***

Ital = proposed changes, NFPA 25 ROC 92

8.3 Testing (Proposed NFPA 25, 2014)

8.3.1.2* Electric motor drive fire pumps

8.3.1.2.1 Except as permitted in 8.3.1.2.2 and 8.3.1.2.3, weekly test frequency required for:

(1). Fire pumps that serve fire protection systems in high rise buildings that are beyond the pumping capacity of the fire department.

(2). Fire pumps with limited service controllers.

(3). Vertical turbine fire pumps.

(4). *Fire pumps taking suction from ground level tanks or a water source that does not provide sufficient pressure to be of material value without pump*

8.3.1.2.2 monthly test frequency permitted for electric fire pumps not identified in 8.3.1.2.1.

8.3.1.2.3* monthly test frequency permitted for electric fire pump systems having a redundant fire pump.

8.3.1.2.4* The test frequency may be established by an approved risk analysis.

Ital = proposed changes, NFPA 25 ROC 92

DOE Experience

- **Maybee (1988)**
  - **184 fires during 1958-1987**
  - **Only 1 sprinkler failure → reliability = 99.5%**

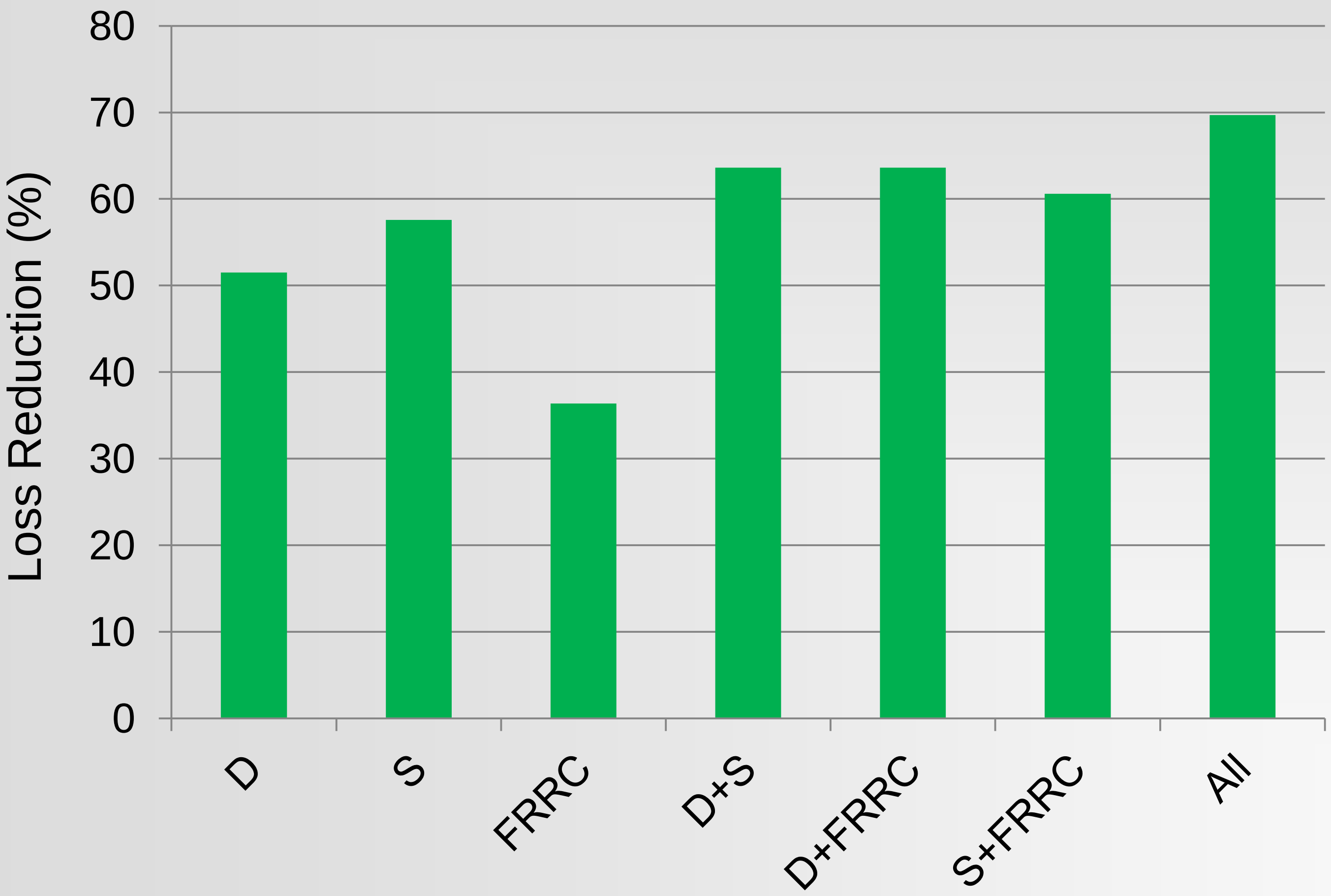
NFIRS Data (1989-1994)

	Extent of Damage			
Protection	Room	Floor	Structure	Expected Loss ($1000)
None	59	4	37	33
D	85	4	11	16
S	89	3	8	14
FRRC	77	4	19	21
D+S	92	2	6	12
D+FRRC	92	3	5	12
S+FRRC	91	3	7	13
All	95	2	3	10
Avg Loss ($1000)	7.3	57	70	

- ***D=Detection***
- ***S=Sprinkler***
- ***FRRC=Fire resistance rated construction***

Commercial occupancies (Rosenbaum, 1996)

NFIRS Data (1989-1994)



- ***D=Detection***
- ***S=Sprinkler***
- ***FRRC=Fire resistance rated construction***

Commercial occupancies (Rosenbaum, 1996)

NFIRS Fire Incidents

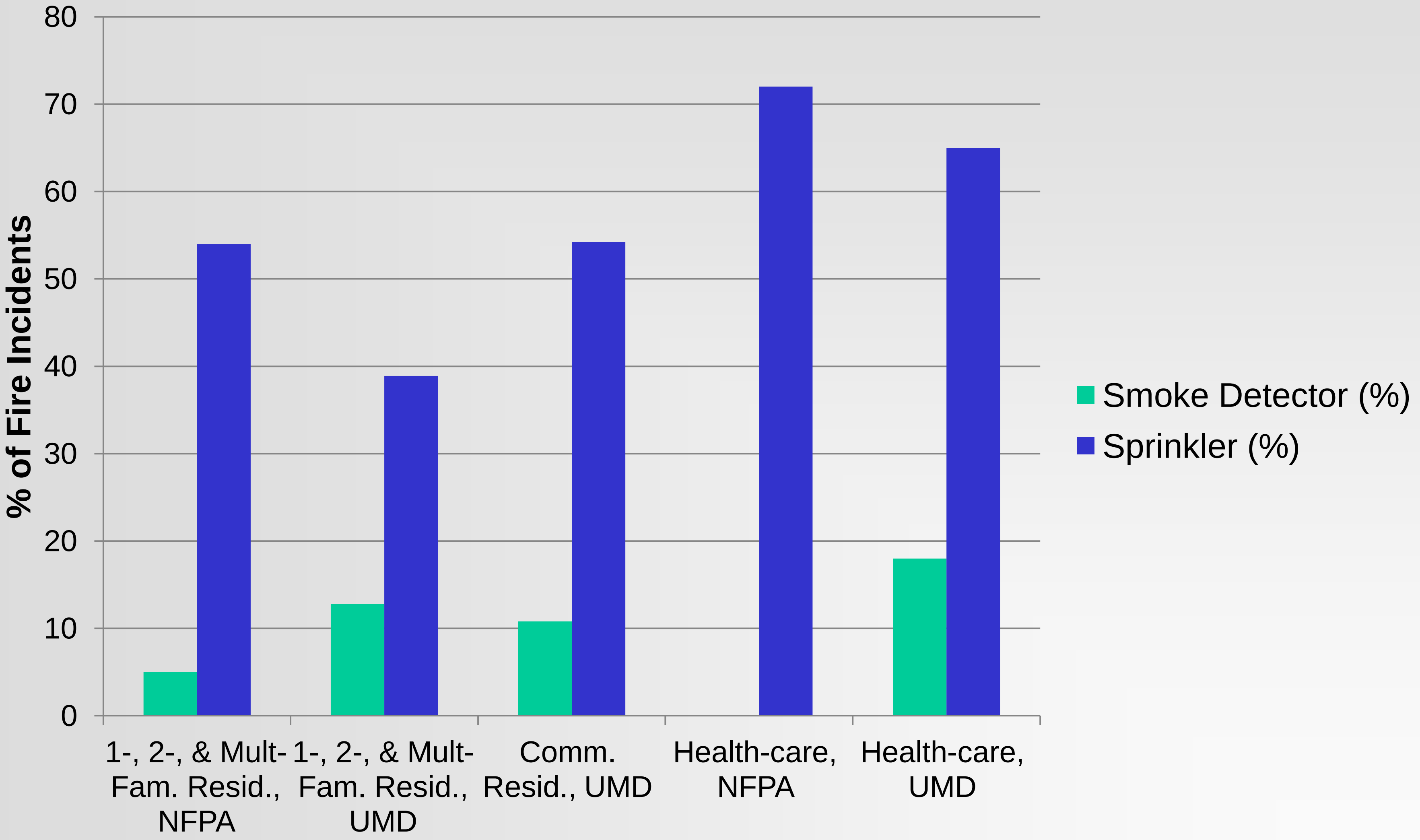
- **UMD Analysis of NFIRS Data, 2003-2007**

Occupancy	Unsprinklered	Sprinklered	Total
1- & 2-Family and, Multi-Family Residential	188,143	4,416	192,559
Commercial Residential	1,473	883	2,356
Health-care	735	1,132	1,867

Casualty Rates, Operation of Devices

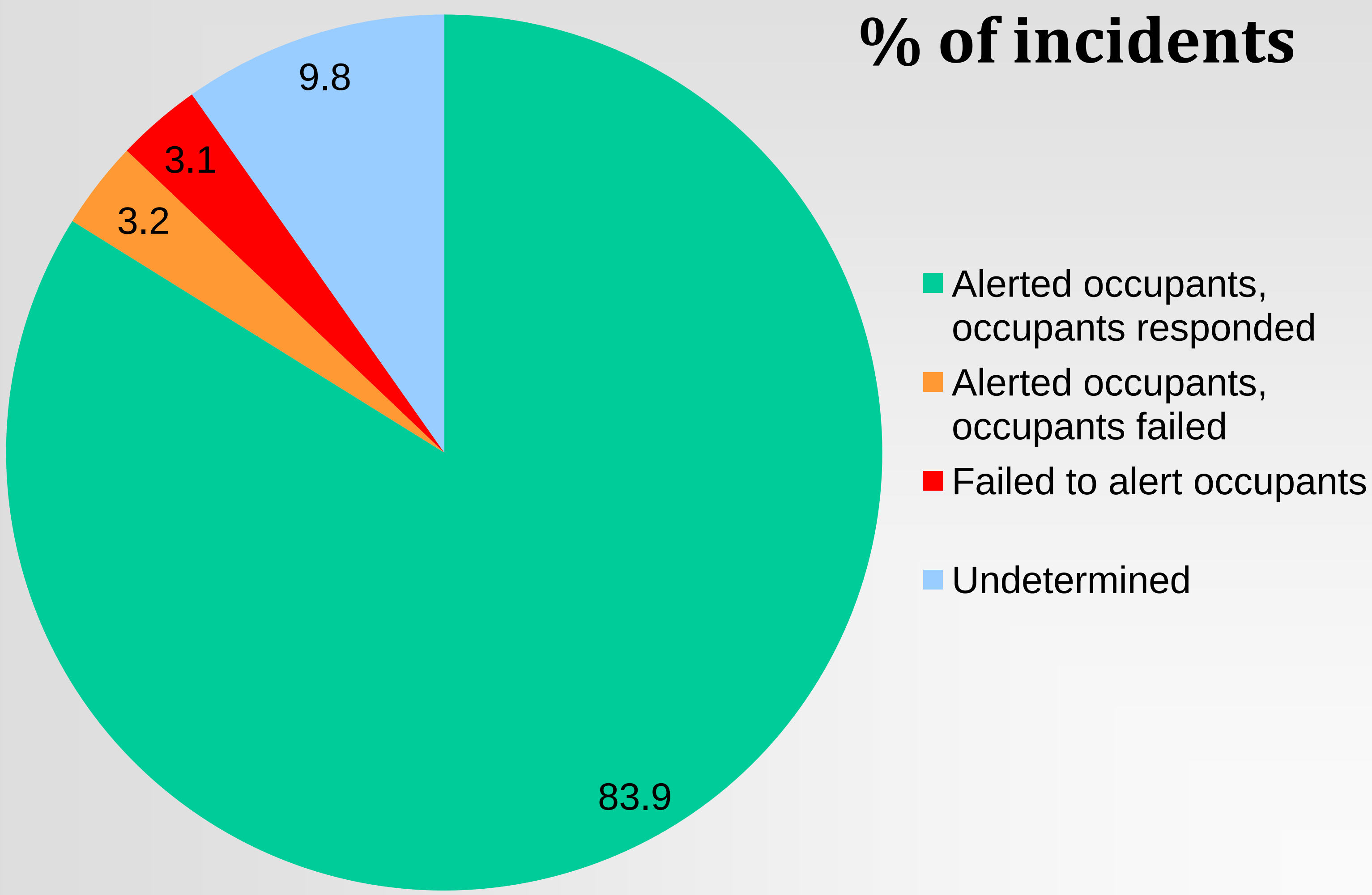
	Casualty Rate (casualties /100 fires)		
Occupancy	Operating Smoke Detector	Operating Sprinkler	Ratio: Sprinkler/ Smoke Detector
1- & 2-Family and, Multi-Family Residential	3.17	2.06	0.65
Commercial Residential	2.38	0.91	0.38
Health-care	3.08	1.14	0.37

Too Small to Activate



sprinklered buildings

Response to Smoke Alarms
Unsprinklered Residences



NFIRS Analysis by UMD

Commercial	Industrial
Restaurant or cafeteria	Electric-generating plant
Bar/tavern or nightclub	Manufacturing plant
Elementary school, kindergarten	Warehouse
High school, junior high	
College, adult education	
Clinic, clinic-type infirmary	
Doctor/dentist office	
Prison or jail, not juvenile	
Food and beverage sales	
Household goods, sales, repairs	
Business office	
Laboratory/science laboratory	

Casualties – Commercial Occupancies

Casualty Symptom	None	Smoke Detectors Only	Sprinklers Only
A	18	26	1
B	9	12	0
C	31	9	1
D	8	11	0
E	1	0	0
F	1	0	0
Legend for casualty symptoms: Intimate with the fire (in the room of origin), with symptom: A. burns B. smoke inhalation C. combination of burns and smoke inhalation Not intimate with the fire (not in the room of origin), with symptom: D. burns E. smoke inhalation F. combination of burns and smoke inhalation			

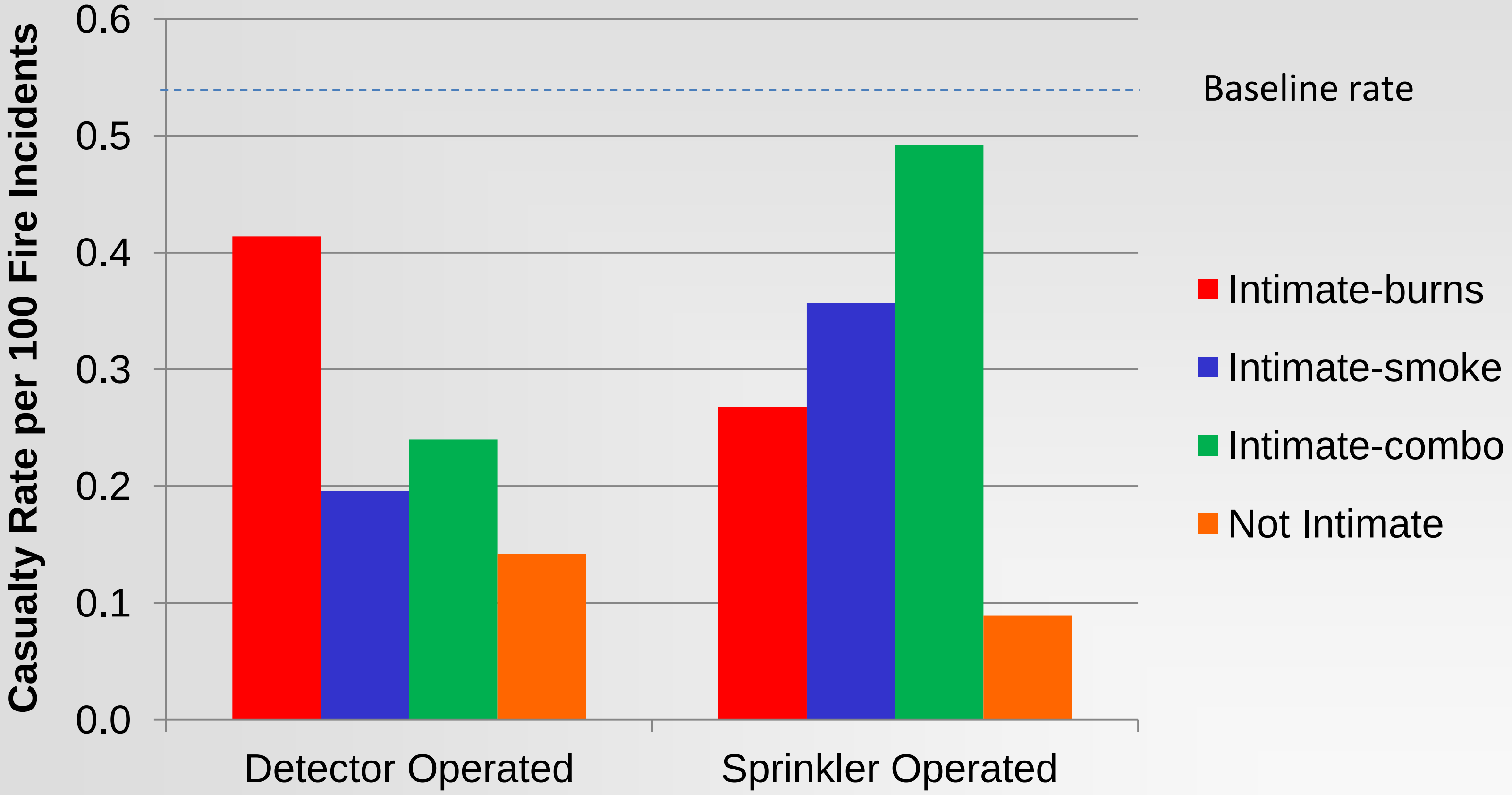
Smoke Detectors Only Provided

Commercial Occupancies

Sprinklers Only Provided

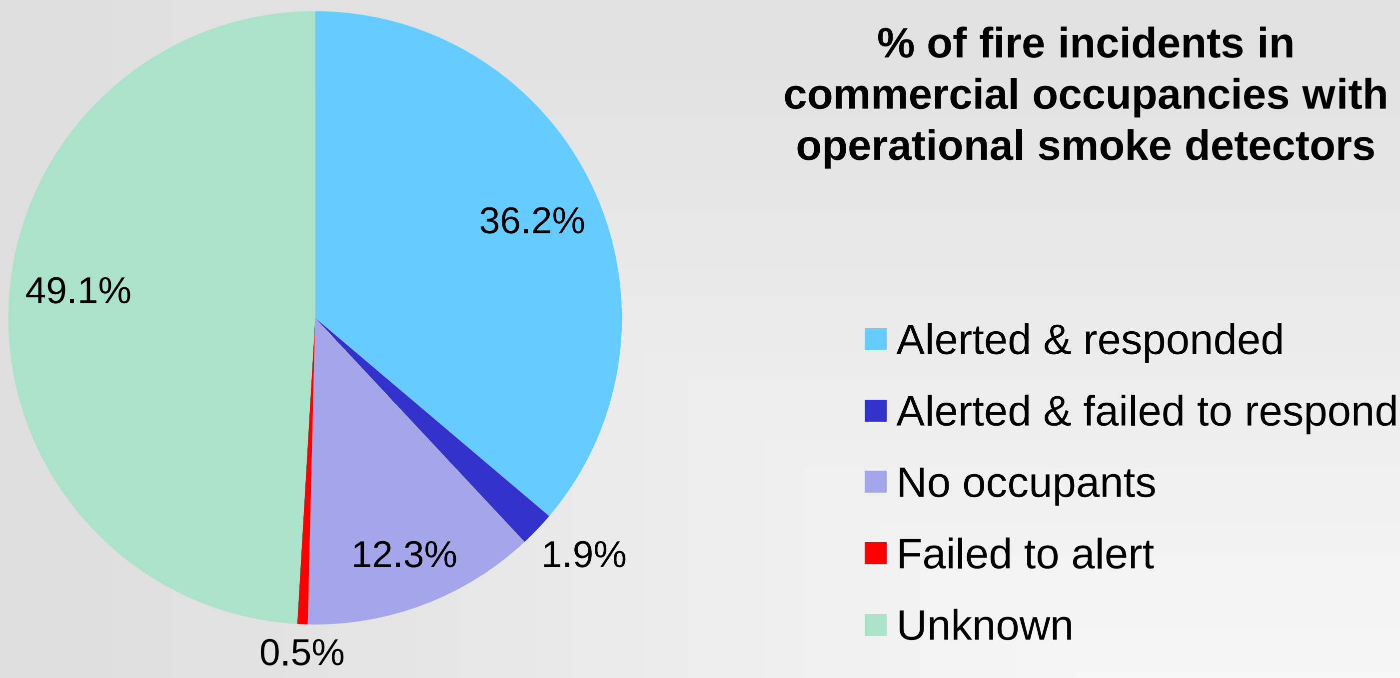
Commercial Occupancies

Smoke Detectors & Sprinklers Provided



Commercial Occupancies

Response by Occupants
Commercial Occupancies



Note: in residential incidents, ‘alerted & responded occupants’ occurred in 86.5% of the incidents

Casualty Rates[1]: Fires Too Small

Occupancy	Too Small for Smoke Detector	Too Small for Sprinkler	Ratio: Sprinkler/ Smoke Detector
Commercial	0.66	0.80	1.2
Industrial	0.18	1.42	7.9
1- & 2-Family and Multi-Family Residential	0.36	1.47	4.1
Commercial Residential	0.11	1.70	15.5
Health-care	1.06	3.08	2.9

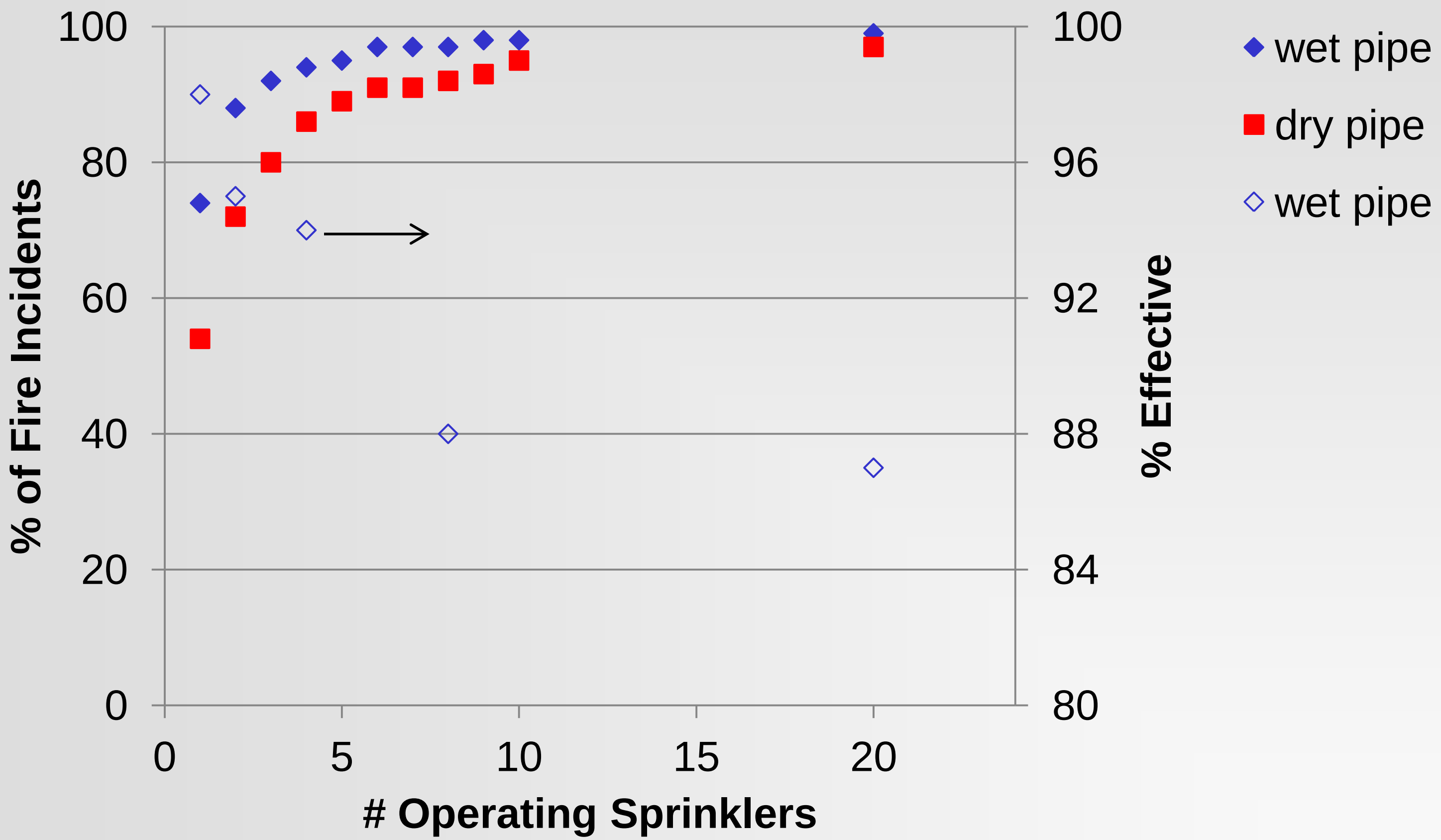
[1] Casualty rates: # of casualties per 100 fire incidents

Analysis of Sprinkler Performance

Type system	% operation in fire incidents	% effective when operated
Wet pipe	92	97
Dry pipe	80	92
Total	91	96

Structure Fires, 2005-2009
Hall, U.S. Experience With Sprinklers, NFPA, 2011

Sprinklers Operating



Structure Fires, 2005-2009
Hall, U.S. Experience With Sprinklers, NFPA, 2011

Sprinklers: reduction in civilian deaths

2005-2009 structure fires

Occupancy	Fire death rate[1] without auto extinguishing	Fire death rate[1] with wet pipe sprinkler	% reduction
All public assembly	0.4	0.0	100
Residential	7.4	1.2	84
Store/Office	1.2	0.2	81
Manufacturing	1.8	0.3	84
Warehouse	1.2	2.0	-67
Total	6.2	0.9	85

[1] **Fire death rate: civilian deaths/1000 fires**

Structure Fires, 2005-2009
Hall, U.S. Experience With Sprinklers, NFPA, 2011

Percent of fires confined to room of origin

Property Use	No Auto. Extinguishing equipment	With sprinkler of any type	Difference
Public Assembly	75	93	18
Educational	89	97	8
Health Care	92	97	5
Residential	75	97	22
Store or Office	69	92	23
Manufacturing	67	86	19
Storage	30	80	50
All	73	95	22

Structure Fires, 2005-2009
Hall, U.S. Experience With Sprinklers, NFPA, 2011

Reasons for Failure to Operate

Reason for Failure	All	Wet Pipe	Dry Pipe
System Shut off	65	61	74
Manual intervention defeated system	16	19	8
Lack of maintenance	7	8	4
System component damaged	7	6	10
Inappropriate system for type of fire	5	6	3
Total fire per year	738	564	130

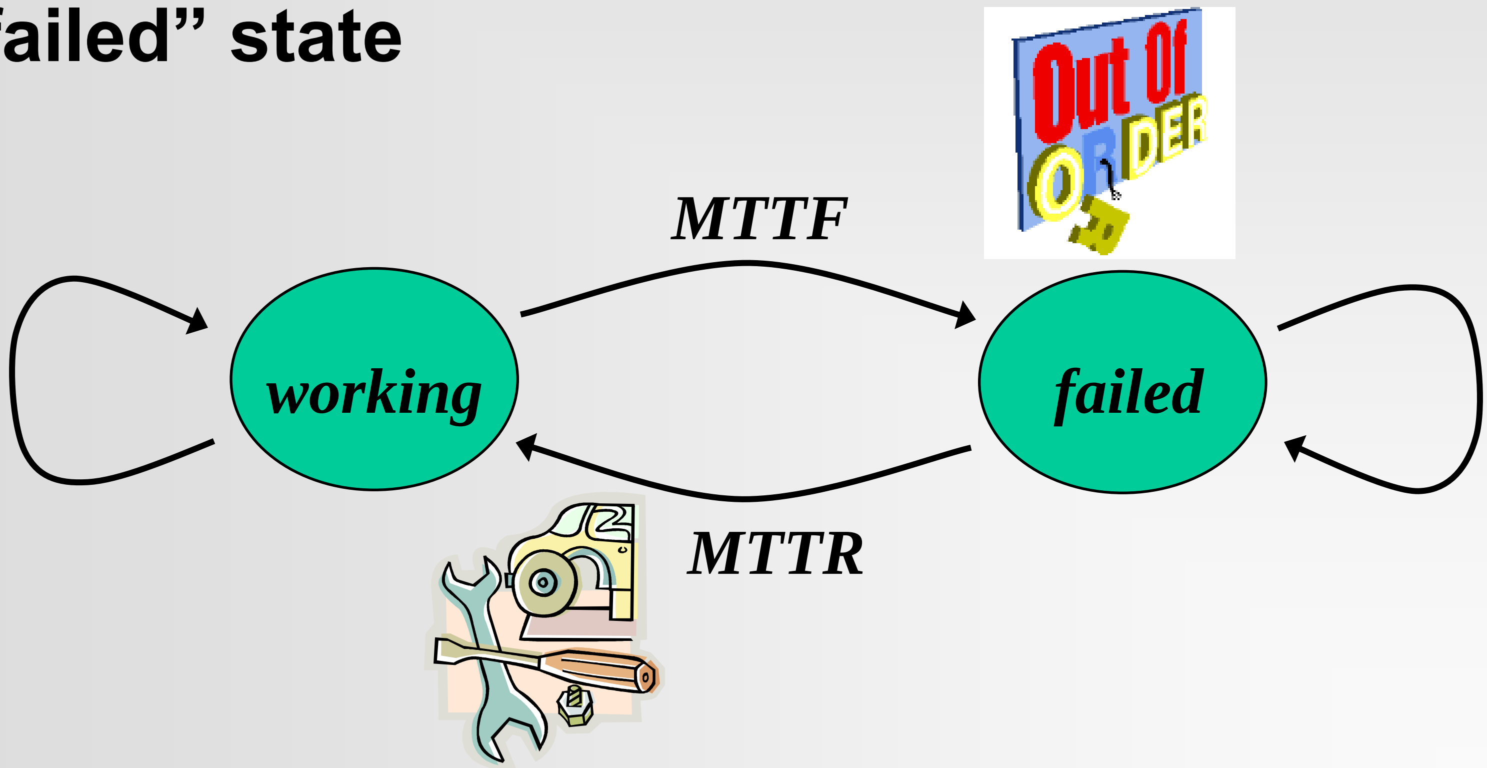
Structure Fires, 2005-2009
Hall, U.S. Experience With Sprinklers, NFPA, 2011

Component Failures

- **Use principles of reliability engineering**
  - **Requires determination of failure and repair rates of components**
  - **Relationship of components in a system**
    - Series (any one component failure causes system failure)
    - Parallel (more than one component failure needed for system failure)

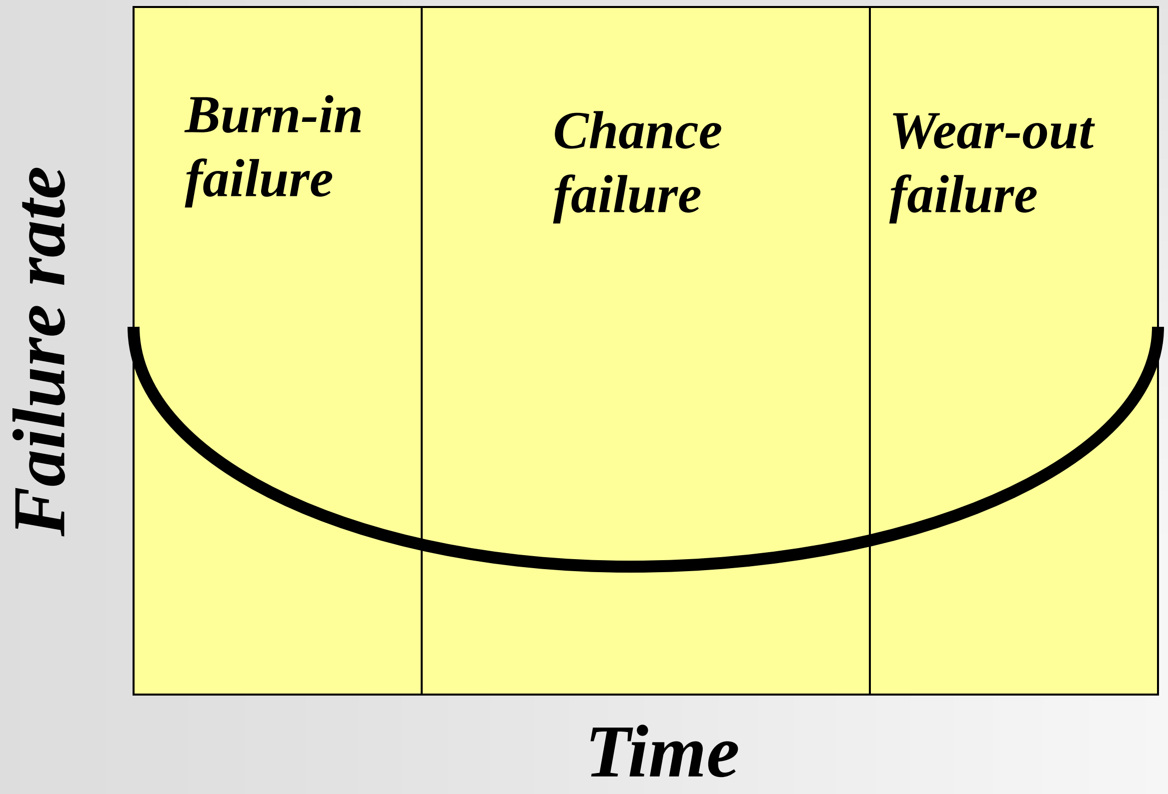
Transition Diagrams

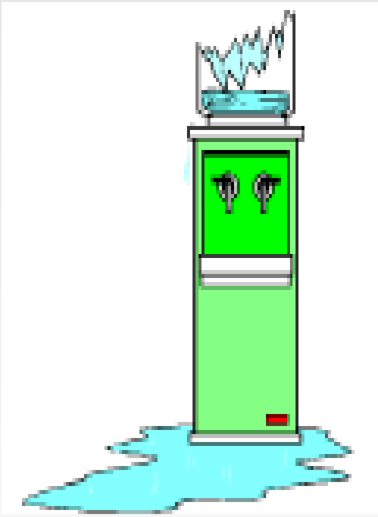
- Consider system to be in a "working" state. If it "fails", the system transitions to a "failed" state



Bathtub curve

- Common shape of component failure rates





Exponential distribution

- **Example**
  - **Component has a failure rate λ = 1/(1000 hr)**
  - **What is probability it works at least 1200 hr?**
- **Fails prior to 1200 hr?**

$$\Pr(T \le t) = \exp\left(-\lambda t\right) = 1 - \exp(-1200/1000) = 0.70$$

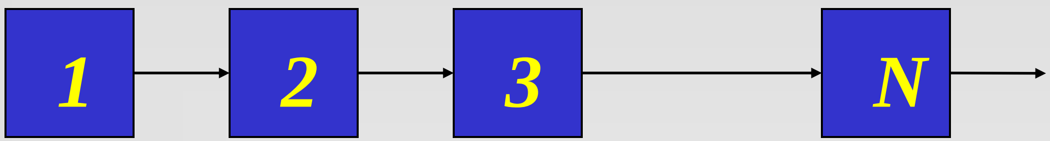
- **Is still working at 1200 hr?**

$$\Pr(t > 1200) = 1 - \Pr(t \le 1200) = 0.30$$

Analysis of System Reliability

- **Use reliability engineering to address effect of component reliability**
  - **Arrangement of components in the system**
    - Series
    - Parallel
    - Standby
    - Shared load
    - Complex systems
  - **Logic tree methods**
    - FTA / FMEA

Series systems



- All components must function successfully for the intended system mission time
- Reliability of system requires that all N units succeed during mission time, t

$$R_s = R_1 \cdot R_2 \cdot \ldots R_N$$

Series systems

- **Example:**
  - **System is composed of 5 components**
  - **Each component has reliability of 0.95**

system reliability = 0.95 x 0.95 x 0.95 x 0.95 x 0.95 = 0.77

Series systems

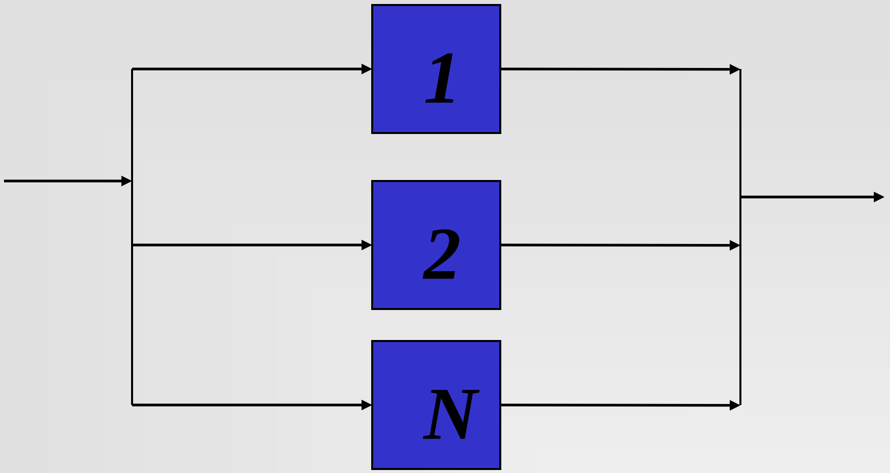
❖ **MTTF of a series system**

$$MTTF_s = \frac{1}{\frac{1}{MTTF_1} + \frac{1}{MTTF_2} + \cdots + \frac{1}{MTTF_n}}$$

❖ **Example: System is composed of 3 components (MTTF's in years):**

	System A	System B
Component 1	2	5
Component 2	10	10
Component 3	20	20
System	1.5	2.9

Parallel systems



- Success of only one unit is sufficient for success
- Failure of all units results in system failure
- System failure given as:

$$F_s(t) = F_1 \cdot F_2 \cdot \ldots \cdot F_N$$

Parallel systems

- Parallel system reliability defined as

$$R_s(t) = 1 - F_s(t)$$

- For special case of identical parallel units with same failure rate:

$$R_s = 1 - [1 - R]^N$$

Parallel systems

- For special case of identical parallel units with constant failure rate:

$$MTTF_S = MTTF_C\left(1 + \frac{1}{2} + \ldots + \frac{1}{N}\right)$$

- Redundant units increase system MTTF, but each additional unit has diminishing effect
  - 2 components: $MTTF_S = 1.5 \times MTTF_C$
  - 3 components: $MTTF_S = 1.8 \times MTTF_C$

Summary

- All components and systems are subject to failure
- System failure rates are dependent on
  - Component performance
  - # of components
  - Arrangement of components
  - Age of components
  - Repair frequency
- Balanced fire protection is important to provide adequate fire safety