Fire Safety Engineering Design Calculations – When and How Should They Be Used?

Kathy A. Notarianni Ph.D., PE

1st International Fire Safety Engineering Congress

May 17, 2019

San Giorgio Island, Venice (IT)

2019 Venice FSE
Fire Safety Engineering

Today’s Example

Time to Activation of a Sprinkler ?

Lecture – Four Main Points

1. **Every Decision Related to Fire Safety is a Fire Risk Decision, whether it is treated as such or not.**

2. **Fire Risk Assessment is the Most Important Factor/Framework for Reducing Risk**

3. **Uncertainty Abounds in Fire Safety Engineering Calculations**

4. **A Simple Example of Calculation of the Time to Activation With Treatment of Uncertainty**

Lecture – Point Number One

1. **Every Decision Related to Fire Safety is a <u>Fire Risk Decision</u>, whether it is treated as such or not.**

    1. What is Risk?
    2. Fire Hazard vs. Fire Risk ?
    3. How is Risk a part of a prescriptive-based Fire Code?
    4. The Fire Risk Analysis Context
    5. Acceptable Level of Risk in Prescriptive, Performance, and Hybrid Building and Fire Codes

What is Risk?

- The potential for realization of unwanted, adverse consequences to human life, health, property, or the environment

Why is this not a Risk ?

Chance vs. Risk

- When someone ventures out onto a frozen lake, that person is taking a risk because there is uncertainty as to if/when the ice might break and there is a potential for a negative consequence
- In contrast, for a lake where no one is trying to cross it we would talk of the "chance" of the ice breaking.
- We would only use the term "risk" IF the breaking ice had an impact on someone or something.
- The take-home point: If there is no uncertainty, or there are no consequences to speak of, there is no risk.

Definition of Risk

– Risk can be succinctly defined as a "measure of the probability and consequence of uncertain future events"

Risk= Probability X Consequence

(Here, the uncertain event is represented mathematically using probability theory)

Fire Hazard vs. Fire Risk

Fire Hazard

- A fire safety hazard is something that could give rise to a fire or smoke.
- For example, this could be rack storage of cardboard boxes or badly managed combustible or flammable materials.

Fire Risk

- Estimation of the level of risk posed by a fire hazard is the assessment of the likelihood of harm, firstly to people, but also to property and business continuity.
- During a fire risk assessment questions are posed on various areas of hazard
  - "Are flammable liquids stored appropriately?" If not this constitutes a fire hazard.
- Similarly we query fire safety procedures: -
  - "Are the fire doors checked regularly for correct operation?" If they are not, this constitutes a hazard because smoke or flame could potentially spread unchecked through the building and escape routes.

Fire Risk Analysis Seeks to Answer:

- What could happen?
- How likely is it?
- How bad would it be if it did happen?

Early Fire Sprinkler Systems

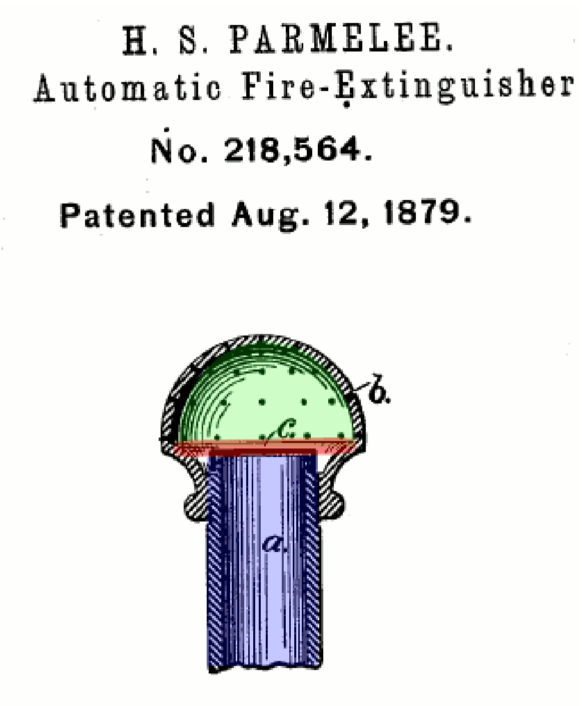
- What could happen?
  - Ignition and rapid flame spread
- How likely is it?
  - Very likely - the candles, gas lights, & torches used in theatres in the 1800's, posed a significant fire risk
- How bad would it be if it did happen?
  - Hundreds of deaths and even more injuries, complete destruction of the theatre - precedent showed this

1812 – Sir William Congreve's manually operated fire sprinkler system was installed in a theatre in London's Drury Lane. Totally reliant upon someone outside the theatre opening a valve, the device comprised a water-tight reservoir, distribution pipework and series of smaller, perforated pipes.

Sprinklers - Technology Development

- The Industrial Revolution fueled unprecedented growth of American cities during the 19th century and the risk of fire increased.
- Henry S. Parmelee, owner of a Piano Works company, spent years designing a workable fire-suppression system that he used throughout his factory.
- On August 11, 1874, he received a patent.
- Not the first to rely on a network of water pipes attached to a ceiling, however, he invented the first automatic sprinkler head — a spring-loaded mechanism that would release water upon detecting high levels of smoke or heat.
- Incredible success - over 200,000 Parmelee-style sprinkler systems were installed in factories across New England in the first eight years after his patent was secured, and today, automatic fire suppression systems are mandatory in new commercial construction.
- One man’s quest saved a lot of lives, drastically reduced property loss, and ensured business continuity.

Spurred Development of Fire Codes

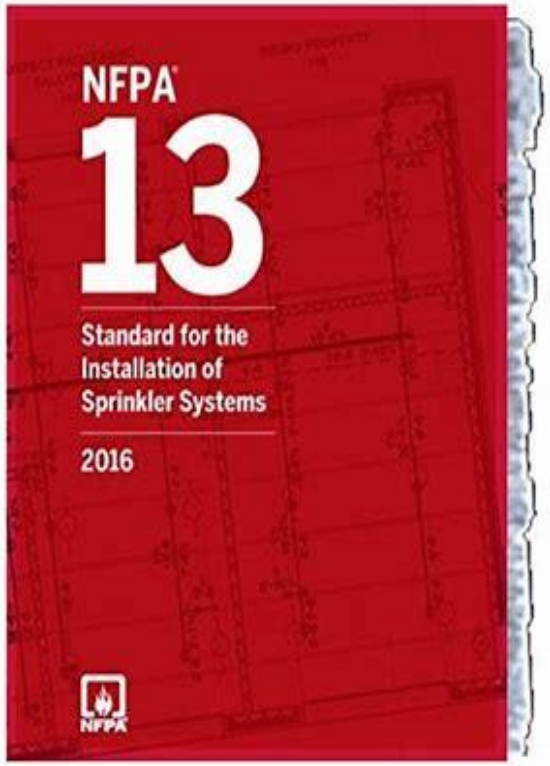


Modern fire safety codes and standards, and in particular those developed by the NFPA, trace their origins to the nineteenth-century development of automatic sprinklers.

Fire Underwriters realized that plumbing issues had to be resolved or the rate of sprinkler system failure might prove unacceptable.

A committee meet and the release of sprinkler installation rules entitled: "Report of Committee on Automatic Sprinkler Protection".

Risk and Prescriptive Based Fire Codes



The U.S. National Fire Protection Association (NFPA) was established and the first fire code was written in 1896.

The Report of Committee eventually became "NFPA 13, Standard for the Installation of Sprinkler Systems‟

NFPA 13 has a performance objective – “Maintain control of the fire and keep it from spreading beyond the general area of origin”

Acceptable Risk

- **Acceptable risk** is a level of risk exposure that is deemed acceptable to an individual, organization, community or nation.
- Acceptable risks are defined in terms of the probability and impact of a particular risk.
- They serve to set practical targets for risk management and are often more helpful than the ideal that no risk is acceptable.
- In practice, risk often can't be reduced to zero due to factors such as cost and secondary risk
- "Acceptable" varies between "voluntary vs. involuntary", age of person at risk, and # of people put at risk

Risk and a Prescriptive Code

- Risk is not stated quantitatively, however, every requirement of a prescriptive fire code is put there to reduce risk
- Prescriptive codes are updated to address new technologies, and information gained from large loss fires
- The prescriptive fire codes are basically composed of certain requirements which attempt to specify all the different components and devices of the system to provide fire safety for a building or an industrial activity.
- Nevertheless, the contribution of each requirement to the level of safety provided by the system is not known and the interactions between the components are not generally known or taken into account.
- In addition, when the safety targets have to be satisfied in pre-existing buildings or in activities that are going to be modified into more complex ones, there are more constraints to cope with and it could be difficult to achieve an acceptable level of fire risk using prescriptive-based fire codes and regulations.
- These inherent deficiencies lead to a lack of flexibility, conservative outcomes and unnecessary cost burdens.

Risk and Performance-Based Codes

- The idea behind PBD is that the designers can use any solution they like, as long as it meets the goal stated in the performance based code.
- The goals of a performance based code are usually in very broad terms.
- The IFC, following the fire safety engineering principles, sees the process of fire safety design considering the system as a whole by focusing on the safety targets whether they are life safety, property loss, business interruption, environmental damage or heritage preservation.
- The IFC gives a new approach to fire safety design. Supported by a quantitative fire risk assessment, the new design methodology can guide the practitioner during the fire design process in choosing the best fire provision to reduce and mitigate the assessed fire risk to an acceptable level. T
- Nowadays, actual studies and experiments for understanding fire-related phenomena increase the capability of the fire engineering community to assess and predict the performance of structures and protection systems when exposed to a fire event.
- The use of analytical tools such as empirical models, finite element analysis, and computational fluid dynamics, in conjunction with bench top and full-scale testing has improved the ability of fire prevention operator to develop performance-based solutions to challenging fire safety design.

Fire Protection Engineering Design

Fire Protection Engineering as defined by the Society of Fire Protection Engineers (SFPE) is:

The application of science and engineering principles to protect people and their environment from the destructive fire and includes:

- analysis of fire hazards;
- mitigation of fire damage by proper design, construction, arrangement, and use of buildings, materials, structures, industrial processes, and transportation systems;
- the design, installation and maintenance of fire detection and suppression and communication systems; and
- post-fire investigation and analysis.

Italian Fire Code (IFC)

- A hybrid code with a more performance-based approach to Fire Safety Design

- States that “Fire Risk Assessment is the most important factor of the IFC method”

IFC is a Hybrid Code

- The IFC design method is very “Flexible”: for each fire-safety project it gives design solutions that are semi-performance based (the so called “deemed-to-satisfy solutions”).
- These compliant solutions contain prescriptive examples of materials, products, design factors, construction and installation methods, which - if adopted - comply with the performance requirements of the IFC.
- If the deemed-to-satisfy solution cannot be put in place, the IFC offers performance-based solutions called “alternative solutions”. The alternative solution is any solution that can meet the IFC performance requirements, other than a deemed-to-satisfy solution, using the following allowed methods:
  - Fire Safety Engineering;
  - Innovative technologies, products and systems
  - Alternative, authoritative fire codes or regulations, national or international. The alternative solution implies that the requested level of performance is in any case achieved.

The Fire Risk Analysis Context

- As we discussed, every decision related to fire safety is a fire risk decision.
- Although our scientific understanding and our suite of quantitative engineering tools have rapidly expanded, we have discovered that *in order to make more scientific and quantitative-based decisions, we must first place our new engineering tools into an appropriate fire risk analysis context.*
- Basing decisions on fire risk requires:
  - Technical steps of fire risk estimation AND
  - The identification of an acceptable level of risk (more philosophical than technical)

Lecture – Four Main Points

1. **Every Decision Related to Fire Safety is a Fire Risk Decision, whether it is treated as such or not.**

2. **Fire Risk Assessment is the Most Important Factor/Framework for Reducing Risk**

   ***FSE Calculations range from hand calcs to field models – and they share the same benefits and shortcomings*. IFC**

3. **Uncertainty Abounds, in parameters relating to a) Fire, b) FSE calculations, c) data - What is the nature of these parameters ? Why should they be an official part of FSE analysis and design?**

4. **There are Various Methods for the Treatment of Uncertainty in Fire Safety Engineering Design Calculations**

   These range from simple to highly mathematical. I will show an example calculation for a fire sprinkler activation and discuss how it informs risk mitigation.

What Industries Conduct Risk Assessments?

- In all types of engineering of complex systems sophisticated risk assessments are often made when it concerns threats to life, environment or machine functioning.
- The **nuclear**, **aerospace**, **oil**, **rail** and **military** industries have a long history of dealing with risk assessment.
- Also, **medical**, **hospital**, and **food industries** control risks and perform risk assessments on a continual basis.

Fire Risk Assessment

We want to know:

What is the fire risk with no action taken?

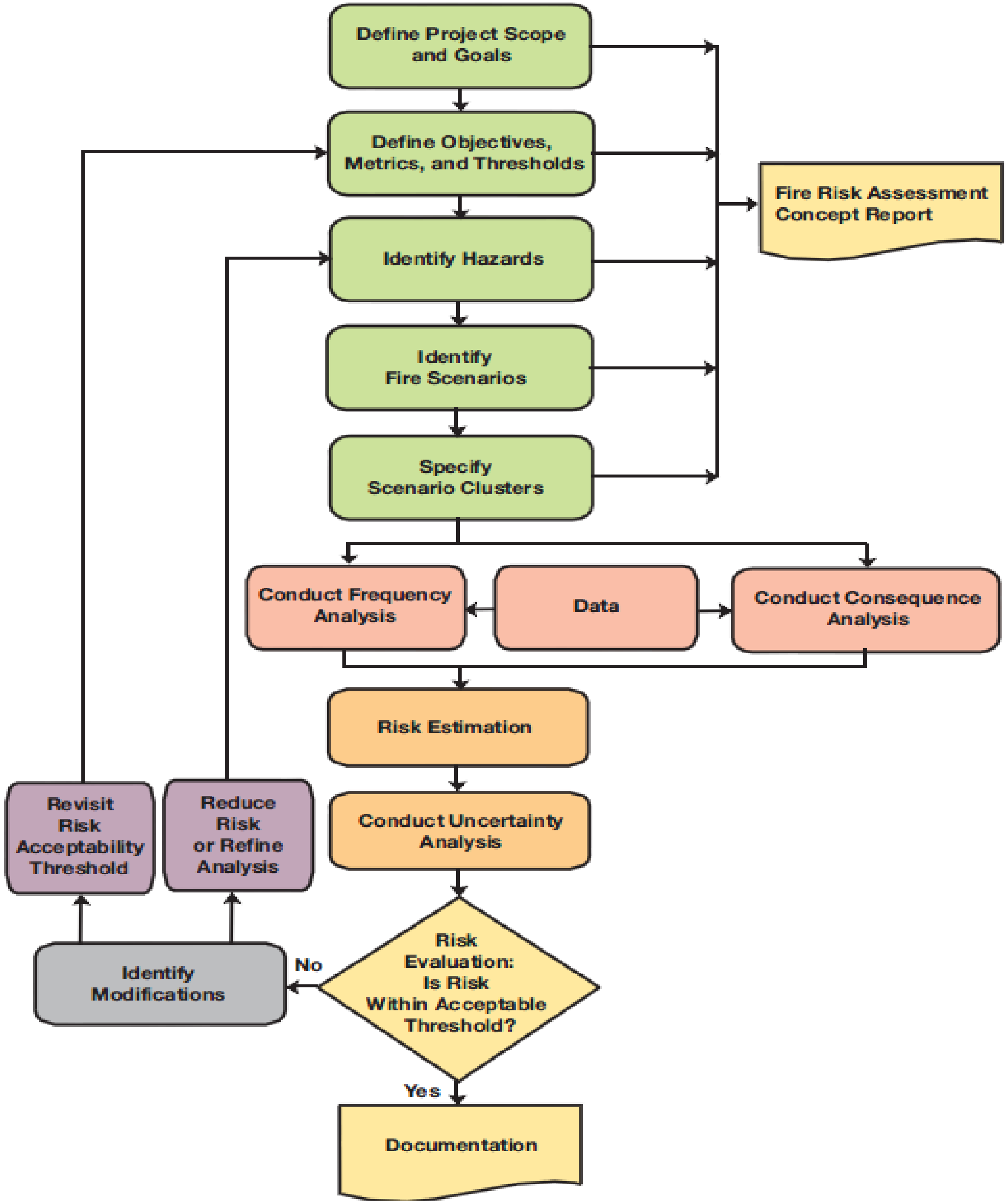
- **Which risks are high priority?**
- **Baseline scenario**

What is the residual risk if we take Action A, B, A&B, etc..

- **If we take Action A, is the residual risk acceptable?**
- **If we do A, is it worth also doing B?**

How do we measure fire risk?

SFPE Fire Risk Assessment Process

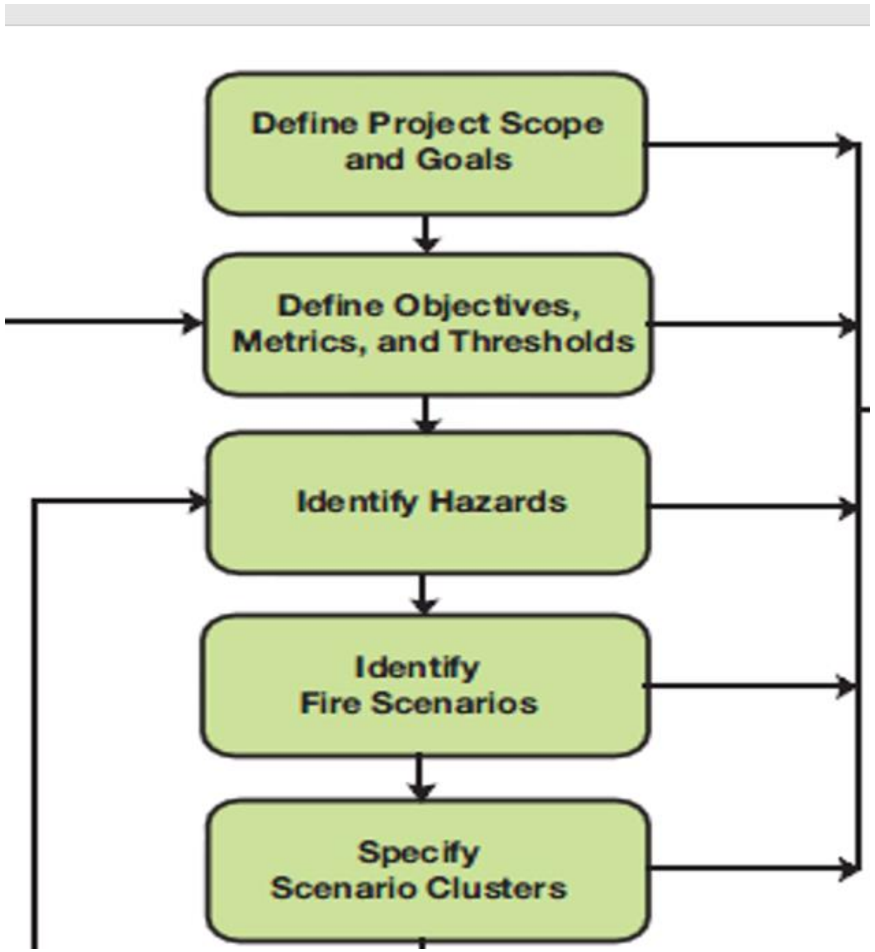


Time to Activation of an Automatic Fire Sprinkler

Ex. Fire Risk Assessment

- You are charged with specifying an automatic fire sprinkler (temperature and RTI) for use in a bedroom at the top of a 3 - story apartment building in Worcester, MA.
- The floor area of the room measures 4m x 4.5m, and the ceiling is 2.44m high.
- There is no air-conditioning.
- **The RSET is 50s or more**
- The ASET is dependent upon timely activation of the automatic fire sprinkler.

Assessment Procedure: Pre-calculation Steps



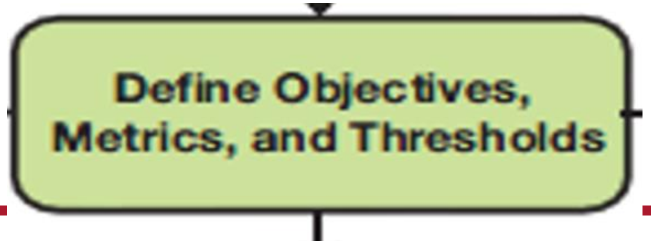
- Define scope and goals
- Develop a probabilistic statement of performance (objectives, metrics, thresholds)
- Identify hazards
- Develop a distribution of statistically significant fire scenarios

Scope and Goals

- Ex. Of a clearly stated goal:

"The sprinkler shall provide an environment for occupants that is reasonably safe from fire by protection of occupants not intimate with the initial fire development and shall improve the survivability of occupants intimate with the initial fire development"

Define Criteria for Acceptability



- Probabilistic Statement of Performance:

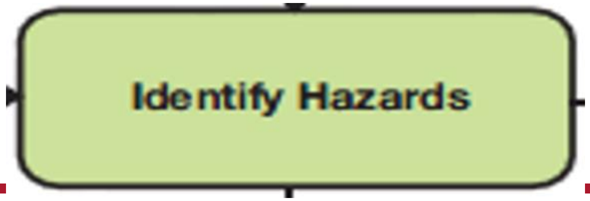
  a) contains the criteria by which to judge acceptability of a design

  b) has a minimum of four elements: Probability, time, performance criteria, and threshold value

- Issues- which criterion should one evaluate?
  - One could select in addition to or instead of temperature - levels of CO, heat flux, or obscuration
- Disagreement in literature as to what values cause negative consequences
  - Must be defined: threshold that best represents incapacitation or lethality?

In order to meet the design criteria and be considered acceptable, the sprinkler must have a 0.99 probability of activating in 40 seconds or less of being exposed to a range of statistically likely bedroom fires, corresponding to a maximum temperature in the room of 65 ^{0}C.

Fire Hazards



- A FIRE hazard is defined as the primary hazard whose potential for harm arises from unwanted fire.

From fire statistics:

- The most common “first item ignited” in a bedroom is typically either the mattress or a trashcan

Use of Fire Barriers To Construct Fire Scenarios

- In FRA, fire protection measures are referred to as barriers against five major fire events – each related to a major phase of fire development and hazard
  - Fire ignition
  - Fire growth
  - Smoke spread
  - Failure of occupants to evacuate
  - Failure of the fire department to respond
- Barriers 1,2, and 3 are those that try to control the development and spread of a fire, whereas barriers 4 and 5 are those that try to expedite the evacuation and rescue of the occupants.

- Each major barrier represents a group of individual barriers, each of which can provide the same fire protection.
- Ex. A barrier to fire growth can consist of sprinklers, fire resistant compartmentation, and door self-closures
- So, two factors effect the residual level of risk:
  - The number of individual barriers
  - The reliability of each barrier

Fire Barriers and Scenario Development

– A man falls asleep on his couch in the living room. Ignition occurs. That means that Barrier 1. (preventing ignition) is not working 100%.

– Secondly, most houses don't have sprinklers or enclosed living rooms, (doors) to contain the fire. Barrier 2 is not there and the fire will grow.

– Most houses also don't have smoke control systems to prevent the smoke from spreading to the whole house, including any egress paths such as stairs. Barrier 3 is not there and smoke will spread with certainty.

– Thus, the only defense in a house fire is Barrier four and five– and only if they are timely.

– Barriers 4 and 5 are only effective if they work and work early against fast growing fires. (occupant egress takes a set amount of time after a detector sounds and the fire department arrival time is critical)

– This is why house fires are deadly because they can grow very fast and there are usually not enough barriers to protect the occupants.

Simplified Example of Event Tree

- The number of fire scenarios depends on the number of permutations that can be constructed based on all of the fire protection measures in place and all the fire events anticipated

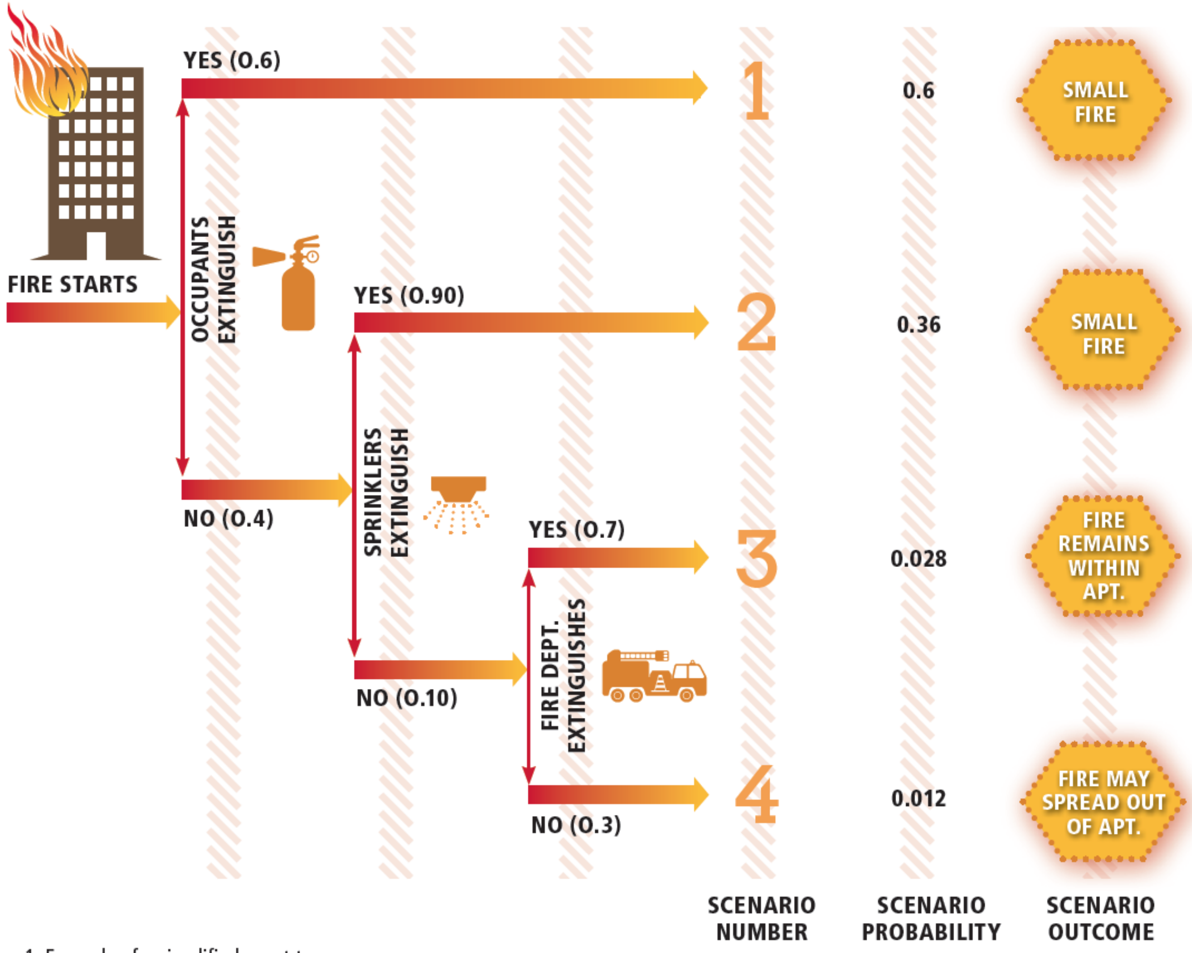


Figure 1. Example of a simplified event tree.

Ceiling Jet – Alpert's Correlations

Temperature:

– r /H> 0.18

$$T - T_\infty = \frac{5.38\left(\dot{Q}/r\right)^{2/3}}{H}$$

– r /H<= 0.18

$$T - T_\infty = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}}$$

Velocity:

-r /H> 0.15

$$v = \frac{0.195\dot{Q}^{1/3}H^{1/2}}{r^{5/6}}$$

-r /H<= 0.15

$$v = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3}$$

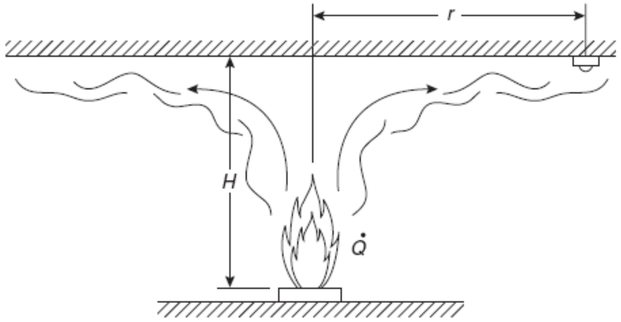


Figure 2-2.1. *Ceiling jet flow beneath an unconfined ceiling.*

Tg – Temp (K)
v – velocity (m/s)
T_∞ – Ambient Temp (K)
$\dot{Q}$ – HRR (kW)
r – radius (m)
H – Height (m)

Source: SFPE Handbook of Fire Protection Engineering, 3rd ed.

Fire Safety Engineering Calculation

- $$tr = \frac{RTI}{U\,1/2} \ln\left(\frac{T_g - Ta}{T_g - Td}\right)$$

t_r = time to response of sprinkler (s)
RTI = Response Time Index ($m^{1/2}\ s^{1/2}$)
T_a = ambient temperature (^{0}C)
T_d = set response temperature of the sprinkler (^{0}C)

T_g = Temperature of the hot gas (^{0}C)
U = Velocity of the hot gas (m/s)

Candidate Designs – both allowed by NFPA 13

- Sprinkler 1: (Quick Response)
  Pendant
  Activation Temperature = 68 C
  Response Time Index = 40

- Sprinkler 2: (Standard Response)
  Pendant
  Activation Temperature = 79 C
  Response Time Index = 55

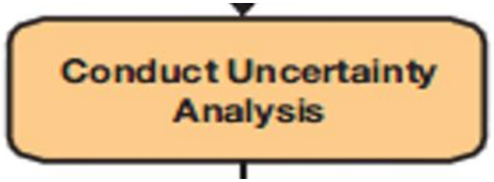
Using best estimate values,

T_{r1} = 18 s

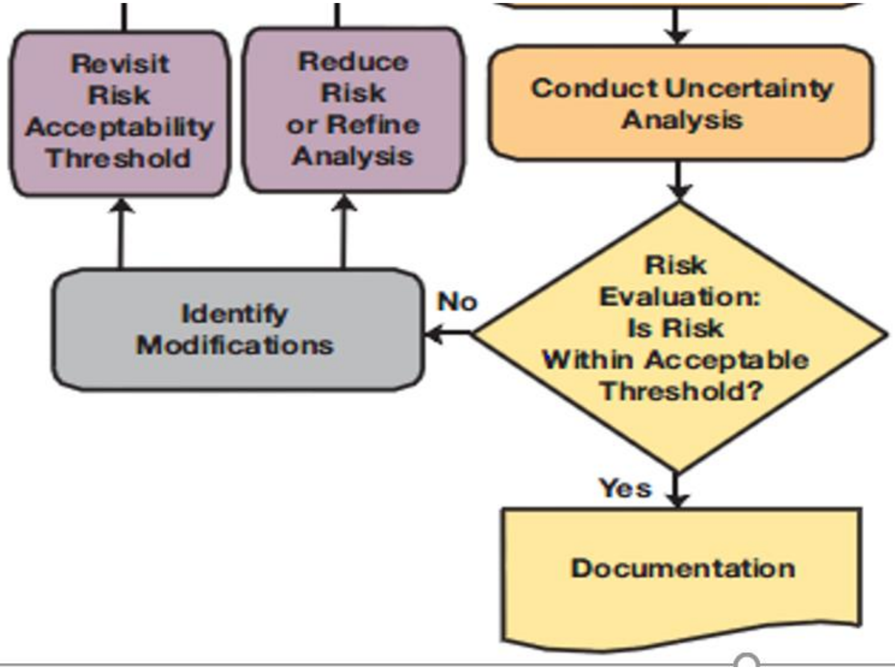
T_{r2} = 30 s

The Engineer has been asked to quantify the uncertainty in these predictions to ensure ASET is met.

Next Step



The next step – Uncertainty Analysis



Lecture – Four Main Points

1. **Every Decision Related to Fire Safety is a Fire Risk Decision, whether it is treated as such or not.**

2. **Fire Risk Assessment is the Most Important Factor/Framework for Reducing Risk**

3. **Uncertainty Abounds in Fire Safety Engineering Calculations**

4. **A Simple Example of Calculation of the Time to Activation With Treatment of Uncertainty**

Understanding and Assessing Uncertainty in Fire Protection Engineering

Not to be absolutely certain is, I think, one of the essential things in rationality.

Bertrand Russell

Introduction

- An understanding and characterization of
- the impact of uncertainties on
- the results of fire safety engineering calculations is essential to
- ensuring that
- the decisions made using those results are meaningful and defendable.

Introduction

- True for all fire safety engineering calculations whether conducted to:
  - Meet a Performance Based Code
  - Aid in the establishment of prescriptive requirement
  - Assess equivalency of a PBD to its prescriptive counterpart
  - Part of risk analysis

Judging Safety

- Criteria for safe design
  - ASET > RSET
- Sure, but how much greater?
- How certain are we of either number?
- ASET is a function of:
  - Location of fire initiation, fire growth and spread rate, heat release rate
  - Presence of and performance of fire alarms; time to alert occupants
  - Size and geometry of room of origin, openings to adjacent spaces, amount of ventilation
  - Chemical composition of materials burning/toxicity
  - Smoke management system design and performance, presence of and performance of suppression systems
  - Fire department arrival and intervention
- RSET is a function of:
  - Time from alarm notification to egress to a safe area
    - How well do we know walking speeds, stairway concerns, pre-movement activities, etc…. ?
    - Cultural differences, gender differences, group psychology
  - Physical characteristics of the occupants
    - age, weight, health, pre-existing conditions
    - Mobility/wheel chair bound folks
    - Movement and actions of the fire department (ex. WTC stairs)

Understanding the Nature and Sources of Uncertainty

Broad and general term used to describe a variety of concepts such as:

- Lack of knowledge
- Variability
- Randomness
- Indeterminacy
- Judgment
- Approximation
- Linguistic Imprecision

Lack of Complete Knowledge

- Disagreement between information sources
  - Example: Rates of generation of products of combustion per gram of fuel burned
  - Vary from study to study and even from test to test in the same study using the same instruments
- Inability to test each and every possible scenario
  - What is the heat release rate or radiative fraction of a mixed-fuel package?
  - We have not measured and cannot reliable predict the value of these quantities for all potential fuel packages
  - Furthermore…. HRR and radiative fraction vary with parameters such as geometry, source and strength of ignition, and ventilation
-

Variability and Randomness

- Variability – Time & Space
  - Ambient temperature, housing/occupant density
  - These quantities vary in time by season, day, time of day
  - They also vary in space by region of the country, community size
- Randomness
  - Where and When the Fire will Start

Indeterminacy and Judgement

Indeterminacy

- Defined as the inability to know what will happen in the future
  - Building occupancy and furnishings may differ 10 or 20 years later
  - Natural events may effect fire protection

Judgment

- Commodity classification
- Area-density curves

Problem Definition and Analysis

- Unpredictability of Human Behavior
  - Actions of each individual upon alarm is unknown
- Difficulties defining the problem
  - "Equivalency" vs. "Risk" vs. "Safety"
- Linguistic imprecision
  - Use of subjective terms to define a goal
    - "worst-case," "majority"
    - Ex. Goals: "flame spread should be limited";

      "provide adequate time for egress"; fire retardant; etc…

Uncertainties in the design process and the problem of switchover

Occurs when outcome criteria change enough to cause a change in design decision

Critical!

Know if different inputs, scenarios, or parameters used in Fire Safety Engineering Calculations could lead to different acceptable designs

Uncertainties in the Design Process

- Often go ignored or unrecognized
- Many of these uncertainties are inherent in the design process itself
- SFPE Engineering Guide
  - "provides guidance that can be used by both design engineers and approving authorities as means to determine and document achievement of agreed upon levels of fire safety for a particular project"

Society of Fire Protection Engineers, *SFPE Engineering Guide to Performance-Based Fire Protection,* 2nd ed., Society of Fire Protection Engineers and National Fire Protection Association, Quincy, MA (2007).

- Direct measurements of the fire safety performance of a building/system is not usually possible
- We rely on the "technical predictability" of scientific tools
  - Fire Models
  - Simulations
  - Existing database

Seven Barriers

1. Performance criteria are not established or no agreement exists
   – Stakeholders select the criteria to be used

- Problems:
  - Is selected criteria sufficient?
  - Different criteria for different subpopulations?
  - What happens if the original use of building changes?
  - *Variations in criteria can cause the same design to pass or fail*

- Since there is no global "standard," decisions or assumptions made differ from location to location
- *Same building could be deemed acceptable and unacceptable under two different jurisdictions*

"Worst-Case" Scenario

- May be defined in terms of many different variables based on values of the stakeholder
  - Most likely to cause death
  - Potential for large property loss
- Complications:
  - Not always intuitive
  - Fast-flaming fire may not pose greatest danger if it activates the sprinkler more quickly. Slower fire may be able to overcome the sprinkler system in some cases, and may be enclosed/protected from sprinkler.

Seven Barriers (cont.)

3. Assumptions are made about human behaviors during a fire
   – Existing egress models need to be evaluated in order to recognize uncertainties

ASSUMPTIONS	REALITY
100% of occupants are readily mobile upon alarm	Disabled people; children; elderly; sleeping; etc.
Occupants begin leaving immediately	Gather belongings; find person/pet; panic; "hero"
Equal number of people egress through each available exit	One will follow path he/she normally uses to exit
Many more to simplify the calculations- "educated guesses"	Cannot predict the actions of each person in time of alarm

Seven Barriers (cont.)

5. Outputs of Fire Models are point values that do not directly incorporate uncertainty
   - Without knowing the uncertainty of a prediction, it is *impossible* to be secure in a design's acceptability

- Problems:
  - Outputs do not reflect inherent input uncertainties
    - Fire growth rates; initial conditions; etc.
  - Predictions and assumptions are used that could cause discrepancies

Lecture – Four Main Points

1. **Every Decision Related to Fire Safety is a Fire Risk Decision, whether it is treated as such or not.**

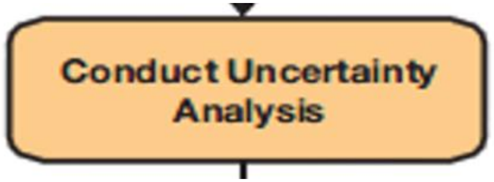
2. **Fire Risk Assessment is the Most Important Factor/Framework for Reducing Risk**

3. **Uncertainty Abounds in Fire Safety Engineering Calculations**

4. **A Simple Example of Calculation of the Time to Activation With Treatment of Uncertainty**

Time to Activation of an Automatic Fire Sprinkler

Uncertain Parameters



The next step – Uncertainty Analysis/Switchover

What parameters are uncertain?

$t_r = \frac{RTI}{U^{1/2}} \ln\left(\frac{T_g - Ta}{T_g - Td}\right)$ and T_g and $U^{1/2}$ may be calculated using parameters that are uncertain,

- From Alpert's correlations:
  - T_∞ – Ambient Temp (K)
  - $\dot{Q}$ – HRR (kW)
  - r – radius (m)
  - H – Height (m)

__Crucial variables__- parameters whose uncertainty is great enough to change decisions in final design

Sprinkler Assessment - Fire Scenario $\dot{Q}$

- Research typical bedroom fires and determine a reasonable range for an idealized steady state HRR.

- From literature, a mattress ignited at the center produces a HRR of approximately 700 kW, while a mattress ignited at the corner demonstrated a steady-state HRR of approximately 1000 kW.
- If the bedding was included in addition to the mattress itself, the idealized steady-state HRR was approximately 2000 kW.
- While a waste basket fire produced a steady state HRR of approximately 15 kW – 350 kW (trash bag)

Selecting a Fire Scenario – fire Origin (r)

- Based upon the requirements for sprinkler spacing and the room dimensions, determine a range of values for the possible location of a fire in the room (in radial distance from the fire).
- Based on a room size of 4 m by 4.5 m, one sprinkler placed at the center of the bedroom with a maximum area of coverage of 225 ft2 (15x 15ft) for light hazard residential occupancies would be acceptable. Therefore, the placement of the sprinkler would be at the center of the room at 2 m by 2.25 m.
- Using the Pythagorean theorem, the maximum distance the fire could be from the sprinkler is 3 ft – accounting for the diagonal distance from the corner of the room to the sprinkler. Therefore, the range would be between 0 m (directly under the sprinkler) to a radial distance of 3 m.

Selecting a Fire Scenario – fire Origin (H)

- Based on engineering judgement and knowledge of typical "first item ignited" in a bedroom, determine a range of values for the potential height (the distance from the base of the fire to the sprinkler head/ceiling). Justify your choices.
- It can be assumed that the trashcan would be on the floor, so the distance between the base of the fire and the floor would be 2.44 m (the distance between the floor and ceiling).
- If the fire started on the mattress, the distance between the top surface of the mattress and the floor is approximately 28 inches (0.7112 m) based on a measurement of the mattress height in my bedroom. This would make the distance between the base of the fire on the mattress to the ceiling a distance of 1.73 m.

Variability in Ambient Temperature

- Research potentially reasonable ambient temperatures (no fire) for such a room and determine a reasonable range for ambient temperature. Justify your choices.
- Temperature data month of October for this year in Worcester, MA. The high temps ranged between 58 and 80F, giving an average “high” temperature of 69.8 F with a standard deviation of 6.4.
- Low temperatures ranged between 40 and 68 F, giving an average low temperature of 54.1 F with a standard deviation of 7.2. This produced a range of reasonable low ambient temperature between 47 F and 61 F.
- The range of ambient temperatures is 68 F (20 C) to 86 F (30 C).
  – Accounts for a slightly higher temp inside than outside

Define Distributions & Model Correlations

- The uncertainty and variability surrounding each variable must be captured in mathematical description of that variable
- All available knowledge should be incorporated into the input scenario generator includin*g:*
  - Empirically measured values
  - Known Variations
  - Statistically compiled data
- NFPA publishes statistical data that can be incorporated (room of origin, 1st item ignited, ….)

Define Distributions & Model Correlations

- When two or more variables are correlated, knowledge of the value of one variable tells us something about the value of the other variable(s)
- Correlation modeled so generator will not produce *unrealistic scenarios*
- Ex: design incorporates weather module
  - Value sampled from temperature distribution from random month to be correlated with:
    - external pressure, relative humidity, likelihood of windows being open/closed, etc.
    - Information prevents software from generating scenario of fire on below freezing day in August, in California, with all windows open

Selecting Sampling Method

- Number of independent fire scenarios can be generated by:
  - Sampling single value from each distribution
  - Combining those numbers w/ input values that are being treated as certain
- Large number of scenarios increases statistical significance of results – to a point
  - Depends on sampling method ; not linear
  - 2000 runs may not provide any more insight than 500

Calculate Set of Values for Each Outcome Criterion

- A single value will be determined for each outcome criterion calculated for each design fire scenario run
- Information obtained by:
  - Observation of range of values for criteria of interest
  - Cumulative distribution functions generated from the set of all values
- If criteria are time-series values, each scenario will predict a different curve
- Ex. If upper layer temperature is the criteria of interest, four design fire scenarios would produce four curves of upper-layer temperature vs. time.

Calculating Time to Activation – 50x

- Showing a distribution of values for the outcome parameter, here, time to activation of a fire sprinkler.

Calculation #	Q	r	H	Ta
1	350	1.05	2.44	26
2	1000	2.61	1.73	30
3	700	.09	1.73	28
4	2000	1.34	1.73	21
5	700	.07	2.44	25
6	700	2.02	1.73	26
7	350	1.55	2.44	20
8	1000	.04	2.44	28
9	350	1.10	2.44	27

Time to Activation
40
9.1
30
3.2
31
30
12
6.0
42

Creating a Cumulative Distribution Function

- Re-order these from quickest time to activation to longest time

Frequency		Time to Activation
1/# calculated values		
1/50	.02	3
2/50	.04	3.4
3/50	.06	3.9
…	…	…
…	…	…
…	…	…
…	…	…
50/50	1.0	110

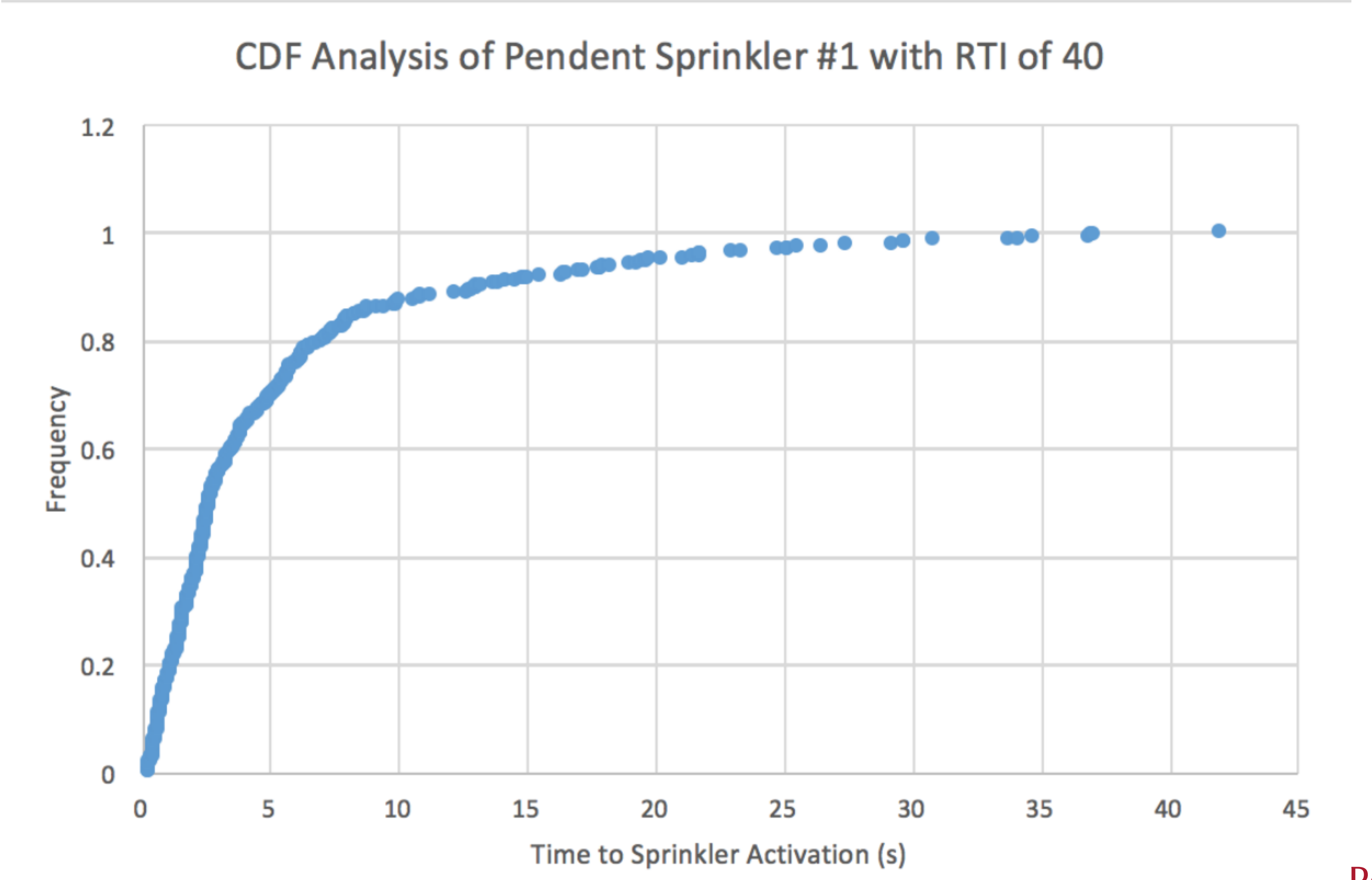
Ex. If you ran the calculation 50 times

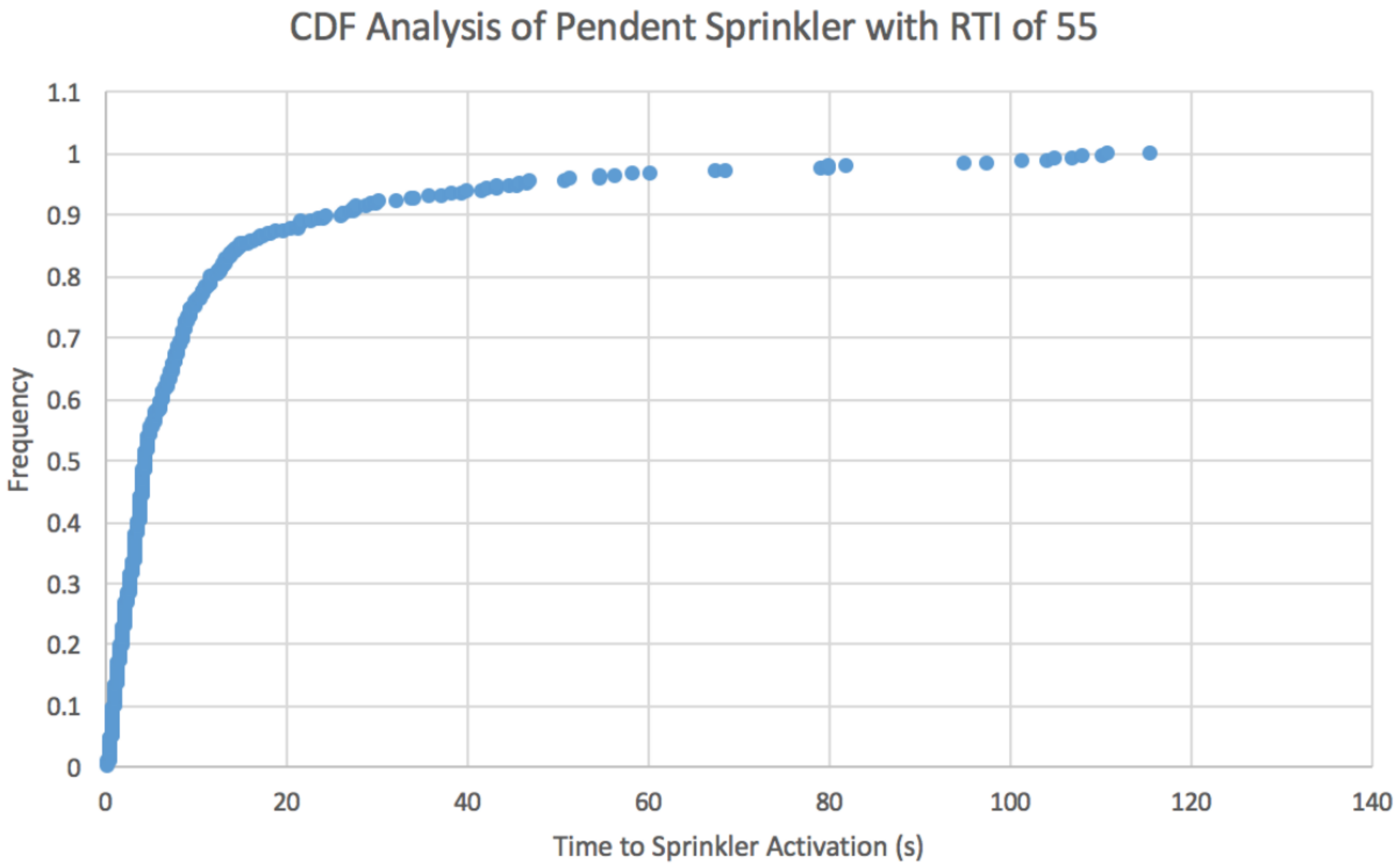
First entry under frequency is 1/50 or 0.02

Up to 50/50
Probability of 1

Actual Spreedsheet Calculations

Run #	T(amb) ©	HRR (kW)	r (m)	Height (m)	RTI spk 1	Det. Temp of Spk 1 (C)	T(gas) ©	u (m/s)	Time to Activation (s)	Copied T(act)	Frequency
1	26	350	0.06	2.44	40	68	189.7939467	4.972975786	2.308002928	0.203263556	0.002
2	30	1000	1.11	1.73	40	68	320.31695	2.413922497	1.56855863	0.208834229	0.004
3	28	700	1.89	1.73	40	68	188.404572	1.374373396	4.250443135	0.214086088	0.006
4	21	700	1.42	1.73	40	68	215.2808238	1.746309562	3.640879187	0.21710698	0.008
5	25	700	2.54	1.73	40	68	156.8382008	1.075561867	6.612387318	0.224574791	0.01
6	26	700	2.05	1.73	40	68	177.7938986	1.282778598	4.968261949	0.229811653	0.012
7	27	1000	1.91	1.73	40	68	228.8932798	1.532975312	3.184920994	0.236845911	0.014
8	28	1000	0.03	1.73	40	68	677.8649824	7.913614752	0.392297373	0.238131858	0.016
9	20	350	1.98	2.44	40	68	89.33372123	1.243457547	18.36161533	0.25592145	0.018
10	28	1000	1.77	1.73	40	68	240.2679421	1.632068352	2.839239721	0.258842232	0.02
11	21	350	0.09	2.44	40	68	189.7939467	4.972975786	2.542243659	0.288203132	0.022
12	22	700	2.09	1.73	40	68	172.0463373	1.264344896	5.656144778	0.293161763	0.024
13	26	700	2.09	1.73	40	68	175.8071583	1.261826137	5.087996122	0.295374558	0.026
14	26	2000	0.57	1.73	40	68	741.6458667	5.272183807	0.457580199	0.340215508	0.028
15	25	2000	1.17	1.73	40	68	469.3242633	2.905647126	1.037304214	0.37326325	0.03
16	26	700	1.83	1.73	40	68	189.9003741	1.411915619	4.328245011	0.382787645	0.032
17	20	350	2.40	2.44	40	68	81.10115165	1.061725065	25.96038965	0.382787645	0.034
18	28	2000	1.20	1.73	40	68	465.7410847	2.851934001	0.985733516	0.382787645	0.036
19	21	700	1.96	1.73	40	68	177.6610182	1.334396803	5.364055005	0.392297373	0.038
20	20	2000	2.68	1.73	40	68	276.0549519	1.458929506	2.985611153	0.411273006	0.04
21	26	350	1.25	2.44	40	68	120.6047639	1.833756148	7.529020346	0.411273006	0.042
22	20	2000	0.27	1.73	40	68	1076.043586	9.900359641	0.256826788	0.430190509	0.044
23	28	2000	2.91	1.73	40	68	269.9160333	1.358934892	2.693371626	0.435723773	0.046
24	28	350	2.55	2.44	40	68	86.67033058	1.009191291	19.79987602	0.439627573	0.048
25	28	2000	0.61	1.73	40	68	716.3584935	5.022109504	0.464067777	0.439627573	0.05
26	21	2000	1.62	1.73	40	68	378.3946672	2.213364391	1.646360215	0.439627573	0.052
27	30	2000	2.05	1.73	40	68	335.4143947	1.818568698	1.711616565	0.440196293	0.054
28	25	2000	2.04	1.73	40	68	332.3029999	1.832636506	1.934323266	0.449050237	0.056
29	25	700	1.04	1.73	40	68	264.1371329	2.264084252	2.288507073	0.460683534	0.058
30	25	700	1.65	1.73	40	68	200.8527755	1.541772679	3.923022318	0.463798891	0.06
31	26	700	0.87	1.73	40	68	294.8040853	2.620466684	1.823218436	0.468000127	0.062
32	20	1000	1.07	1.73	40	68	316.3774241	2.477075423	1.950170382	0.492145108	0.064
33	27	2000	0.45	1.73	40	68	872.0742247	6.489876065	0.339132728	0.515454139	0.066
34	30	350	1.38	2.44	40	68	118.3038045	1.682381925	7.536346139	0.526277985	0.068
35	22	2000	1.91	1.73	40	68	342.6611722	1.932750541	1.934900376	0.536312588	0.07
36	22	2000	0.56	1.73	40	68	747.2095579	5.360400423	0.491690886	0.53923187	0.072
37	21	2000	2.94	1.73	40	68	261.7696045	1.350889755	3.245902281	0.53923187	0.074
38	21	1000	2.20	1.73	40	68	204.8824751	1.363980801	4.390545179	0.5521602	0.076
39	30	350	1.68	2.44	40	68	107.5896889	1.431216512	9.770574812	0.556691591	0.078
40	20	2000	2.35	1.73	40	68	299.066869	1.624625193	2.572417852	0.565063077	0.08
41	30	2000	2.61	1.73	40	68	290.2276451	1.488708346	2.247483522	0.565063077	0.082
42	21	700	0.85	1.73	40	68	293.2262279	2.662234262	2.01787726	0.567606981	0.084
43	21	350	1.91	2.44	40	68	92.14810325	1.284264516	16.56399441	0.576585489	0.086
44	23	2000	0.19	1.73	40	68	1076.043586	9.970529806	0.240270446	0.582951726	0.088
45	24	2000	0.90	1.73	40	68	551.919185	3.604351522	0.796299109	0.587805925	0.09


CDF Analysis of Pendent Sprinkler #1 with RTI of 40
Frequency
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
Time to Sprinkler Activation (s)


CDF Analysis of Pendent Sprinkler with RTI of 55
Frequency
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time to Sprinkler Activation (s)

Determine Sensitivity

- Determine Sensitivity of Outcome Criteria to Elements of Probabilistic Statement of Performance
- Must be known before good policy and good design practice can be established
  - Probabilistic elements *are not agreed upon* by fire safety professionals or the public
  - Major conclusions checked in order to demonstrate sensitivity to uncertainty in each element
- Same design may be judged on *two different performance criteria* or by *two different critical values* of the same performance criteria

Sensitivity Analysis

- This type of evaluation is a good way to focus discussion among stakeholders on deciding:
  - Tenability criteria to be included
  - Effect of threshold values
  - Probability level that is acceptable to the stakeholders
  - How to select final design
- At the end of this step, final performance criteria must be selected to *judge acceptability* of designs and *choose a final design*

Evaluate the Base Case

- Compare candidate design to base-case design that may be a design that:
  - Meets the prescriptive code
  - Includes the fire protection options currently in the building
  - Has no active fire suppression system
- Used to *benchmark the effects* of fire on the building and on the building conditions *against each of the designs*

Evaluate Uncertainty Importance

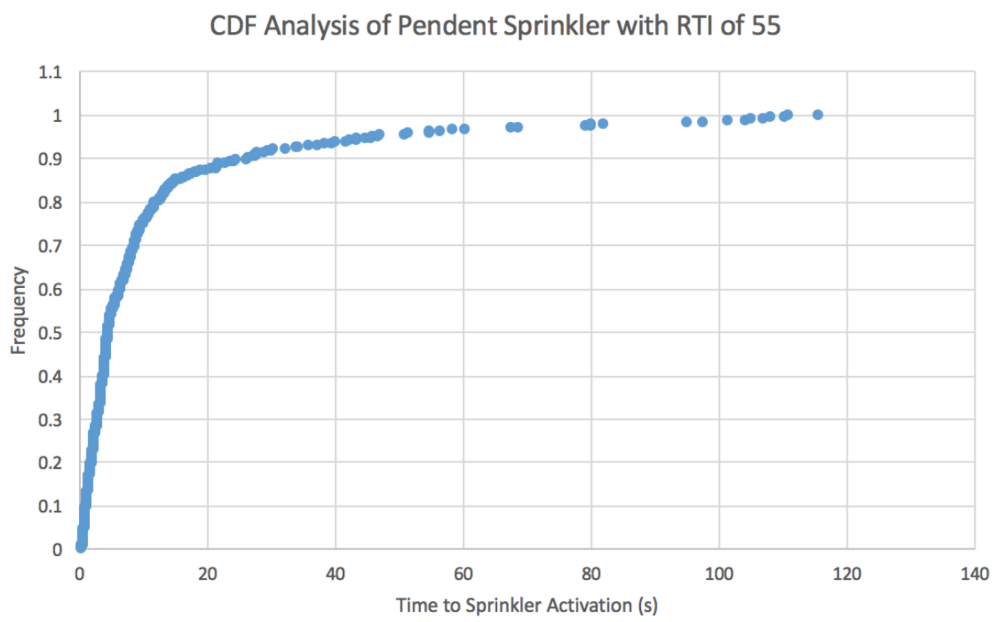
- Importance analysis is a particular type of sensitivity analysis
- Determines which uncertain input *contributes most* to outcome uncertainty
- Simplifies a future PBD by *identifying most important inputs*
- Variable's importance scaled from 0 to 1
  - 0 indicates the variable's uncertainty has *no effect* on the uncertainty of the output
  - Inputs can be correlated to composite or derived outcomes
  - Input variables may also be combined for correlation

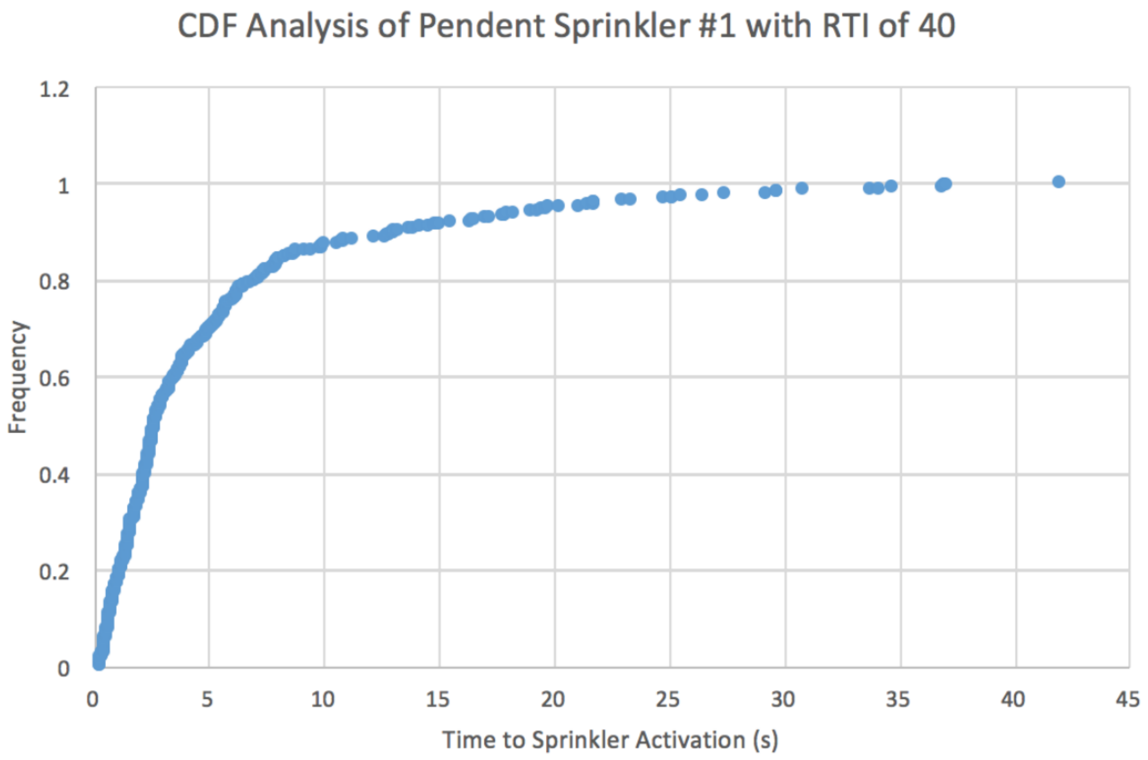
Evaluate Uncertainty Importance

- Simplifies future uncertainty analysis by determining most crucial input uncertainty
- Demonstrates where additional research would be most effective in reducing uncertainty
  - Ensures safer, more predictable building
- Correlation does not equal causation
  - Any strong correlation that is counterintuitive should be investigated with good engineering judgment

Judge Design's Acceptability

- Against probabilistic statement of performance
- In order to meet the design criteria and be considered acceptable, the sprinkler must have a 0.99 probability of activating in 40 seconds or less of being exposed to a range of statistically likely bedroom fires, corresponding to a maximum temperature in the room of 65 ^{0}C.





Select Final Design

- If more than one design meets all 4 *elements of probabilistic statement of performance*:
  - Other factors considered- cost, preference
- If considering multiple designs, or designs with very different features
  - Multi-criteria decision analysis model may be developed

Prepare Documentation

- So all parties involved understand what is necessary for *design implementation, maintenance, and continuity of fire protection design*
- *SFPE GUIDE* suggests 4 parts
  1. Fire Protection Engineering design brief
  2. Performance design report
  3. Detail specifications and drawings
  4. Building operations and maintenance manual

- Performance design report should include:
  – Expected hazards, risks, and performance over entire building life
  – Project scope, goal, and objectives
  – Probabilistic design statements
  – Discussion of design fires and design fire scenarios
  – Any critical design assumptions

Stakeholders

Stakeholder	Interest
Engineers and Architects	Safety; flexibility
Code Officials	Assurance for approval
Researchers	Where the most bang for the buck in new research is (greatest uncertainty importance)
Policy Makers	Risk Reduction vs. Cost for a New Code Requirement
Insurance Companies	Likelihood and Magnitude of Loss
Building Owners	Design to Their Acceptable Level of Risk
Product Manufacturers	Future Needs….