Beyond 2oo3: Multi-sensor Architecture in SIF Design

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Introduction

- Reasons for using multiple sensors
- Recognizing different multi-sensor architectures
- Taking common cause failures into account
- PFD_{AVG} and Fault Tolerance calculations for multi-sensor architectures

Why have multiple devices?

- Redundancy
- Separate hazards
- Interdependent
- Process profiles
- Localized problems

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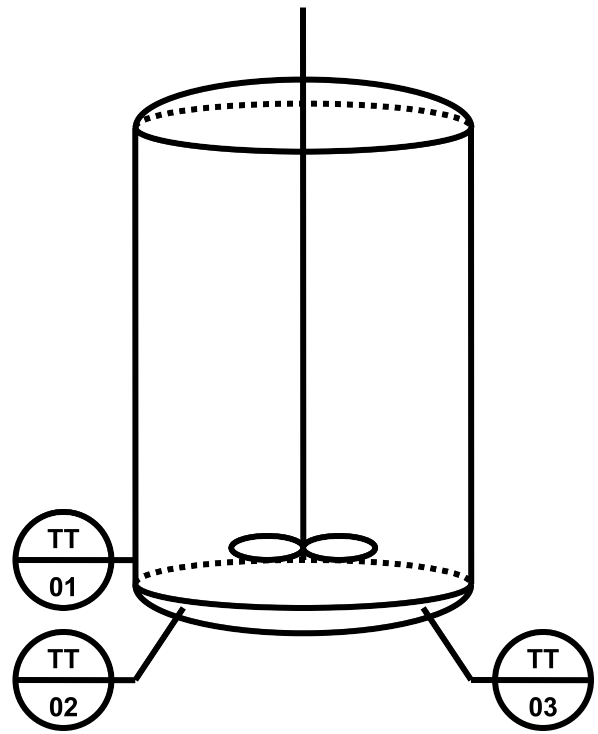
What is redundancy?

- Serving exactly the same purpose at the same point in the process
- Possible architectures:
  - 1oo3
  - 2oo3
  - 3oo3



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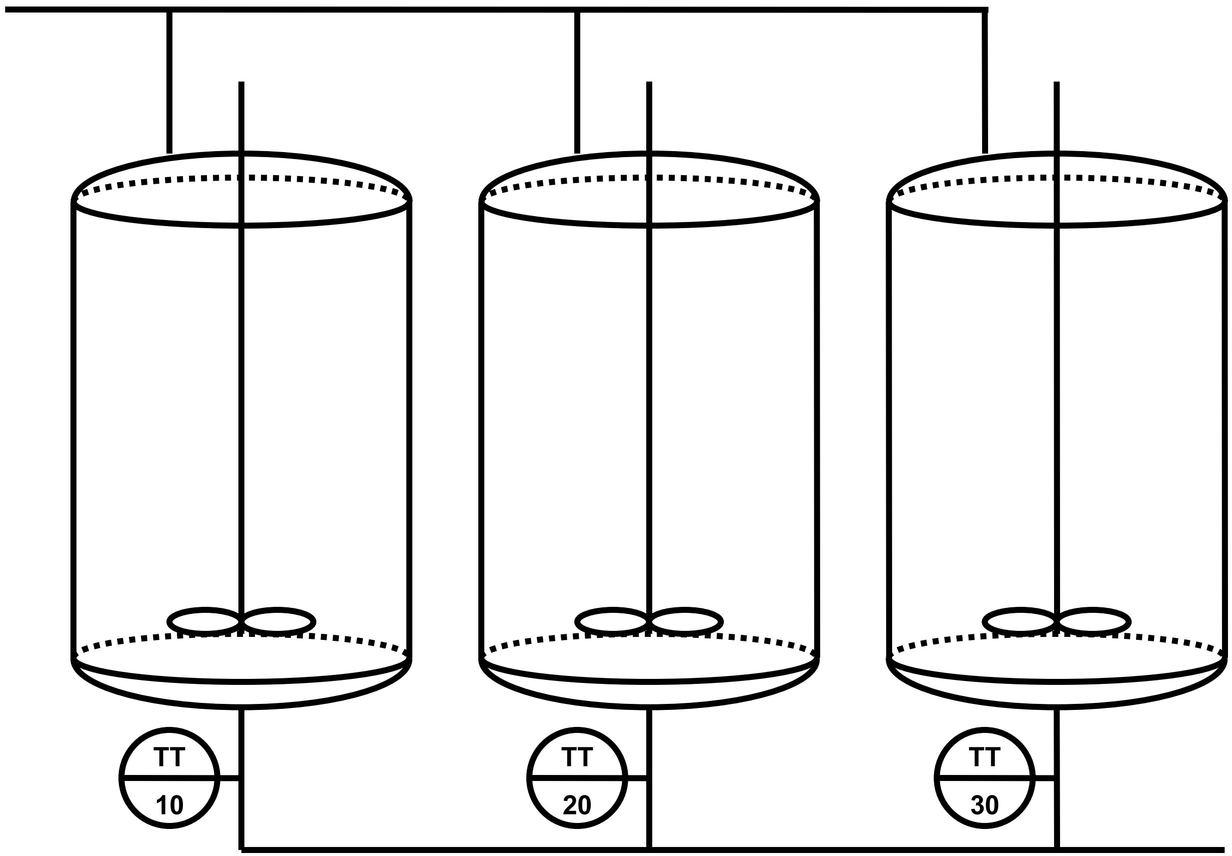
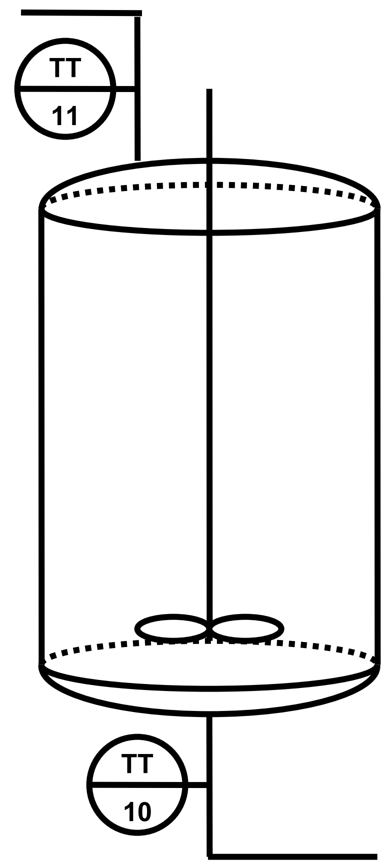
Separate hazards?

- Serving purposes that are unrelated or at independent points in the process



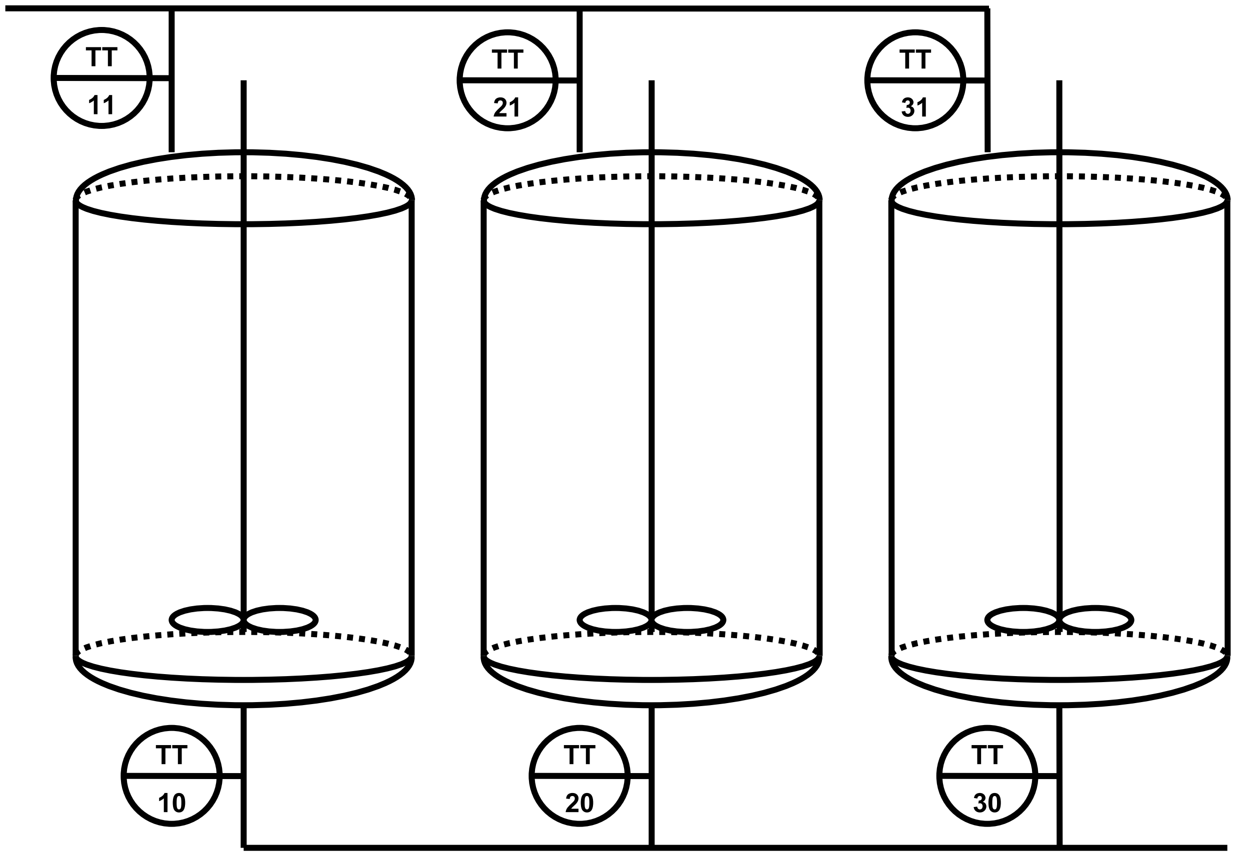
Interdependent?

- Requiring more than one device to achieve the purpose
- Possible architectures
  - 1oo2
  - 2oo2
  - two device 1oo1



Interdependent and redundant?

- Simple MooN descriptions of the sensor architecture may be inadequate.



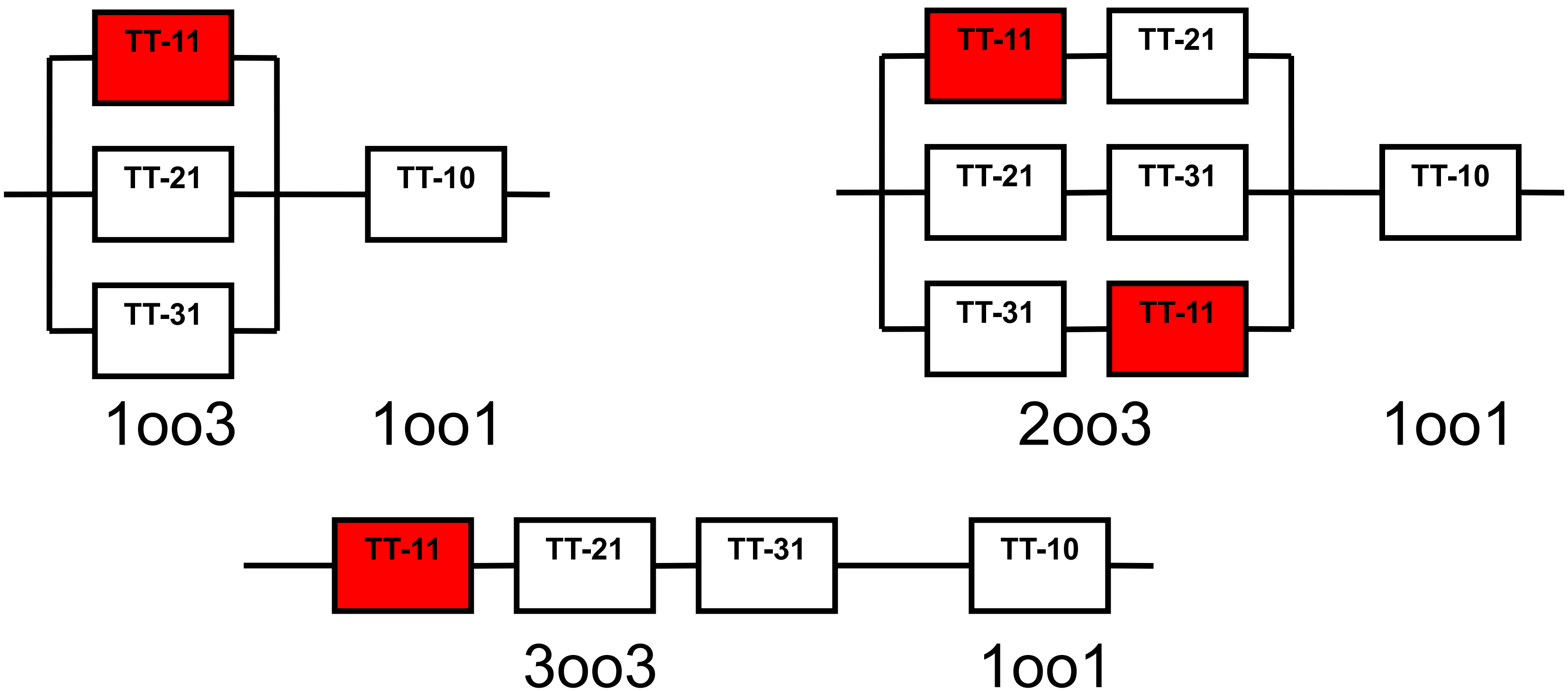
Mixed architecture

Consider Reactor 1

- Inlet temperatures: TT-11, TT-21, TT-31
  - Architecture may be 1oo3, 2oo3, or 3oo3 for PFD calcs
- Outlet temperature: TT-10
  - Architecture may be 1oo1 for PFD calcs
- Voting block: [TT-10] – [TT-11]
  [TT-10] – [TT-21]
  [TT-10] – [TT-31]
  - Architecture may be 1oo3, 2oo3, or 3oo3 for voting
  - TT-10 is a common source of failure

PFD_{AVG} of sensors

- A block reliability diagram shows how calculating the PFD_{AVG} should be approached.



Common cause failure?

$\lambda = \lambda_N + \lambda_C$

- λ_N – Failure rate from causes that do not result in common causes (independent failures)
- λ_C – Failure rate from causes that result in common failures (common cause failures)
- $\lambda_C = \beta\lambda$
- $\lambda_N = (1-\beta)\lambda$

What value for β?

- Literature values: 0.2% to 10%
- IEC 61508-6, Annex D:

Table D.4 – Calculation of β or β_D

Score (S or S_D)	Corresponding value of β or β_D for the:	
	Logic subsystem	Sensors or final elements
120 or above	0,5 %	1 %
70 to 120	1 %	2 %
45 to 70	2 %	5 %
Less than 45	5 %	10 %

NOTE 1 The maximum levels of β_D shown in this table are lower than would normally be used, reflecting the use of the techniques specified elsewhere in this standard for the reduction in the probability of systematic failures as a whole, and of common cause failures as a result of this.

NOTE 2 Values of β_D lower than 0,5 % for the logic subsystem and 1 % for the sensors would be difficult to justify.

Impact of common cause?

Consider a typical SIF:

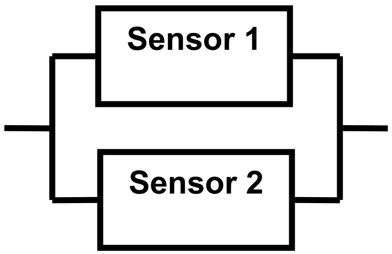
- $\lambda = 0.03$ failures/yr
- $\beta = 3\%$
- $T = 1$ year

So

- $\lambda_C = \beta\lambda = 0.03 \times 0.03 = 0.0009$ failures/yr
- $\lambda_N = (1-\beta)\lambda = (1 - 0.03) \times 0.03 = 0.0291$ failures/yr
- For service with a single device
- $PFD_{AVG} = \lambda T/2 = 0.03 \times 1 / 2 = 0.015$

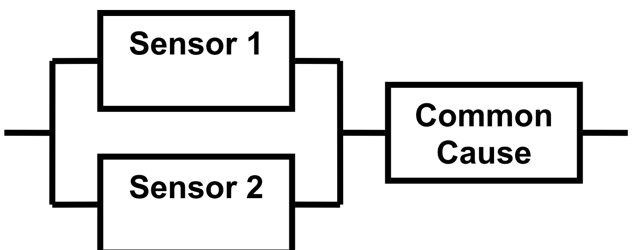
Double redundant

- Duplex, but without considering common cause



$PFD_{AVG} = (\lambda T)^2/3 = (0.03)^2/3 = 0.0003$

- Duplex, considering common cause



$PFD_{AVG} = (\lambda_N T)^2/3 + \lambda_C T = (0.0291)^2/3 + 0.0009 = 0.00118$

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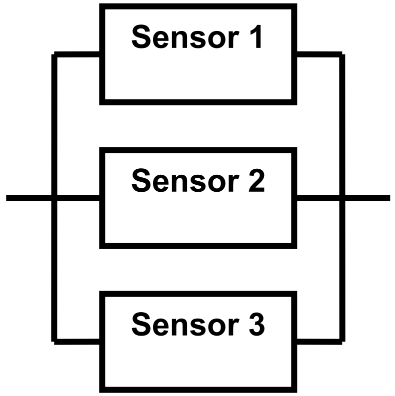
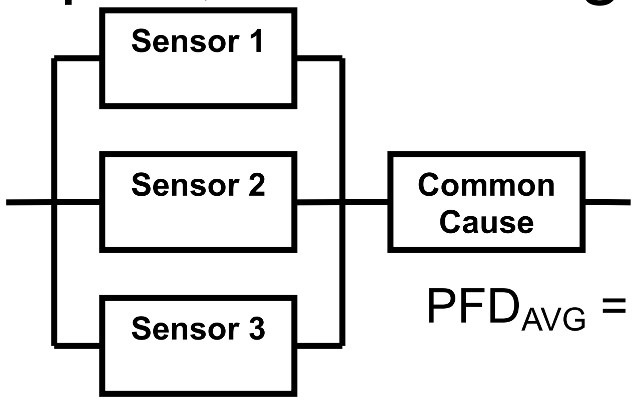
Triple redundant

- Triplex, but without considering common cause



$PFD_{AVG} = (\lambda T)^3/4 = (0.03)^3/4 = 0.00000675$

- Triplex, considering common cause



$PFD_{AVG} = (\lambda_N T)^3/4 + \lambda_C T = (0.0291)^3/4 + 0.0009 = 0.000906$

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Why use more than three sensors?

- Process profiles
  - Temperature profile in distillation column
  - Temperature profile in packed or fluidized bed reactor
- Localized problem within process unit
  - Hot spots
  - Leaks

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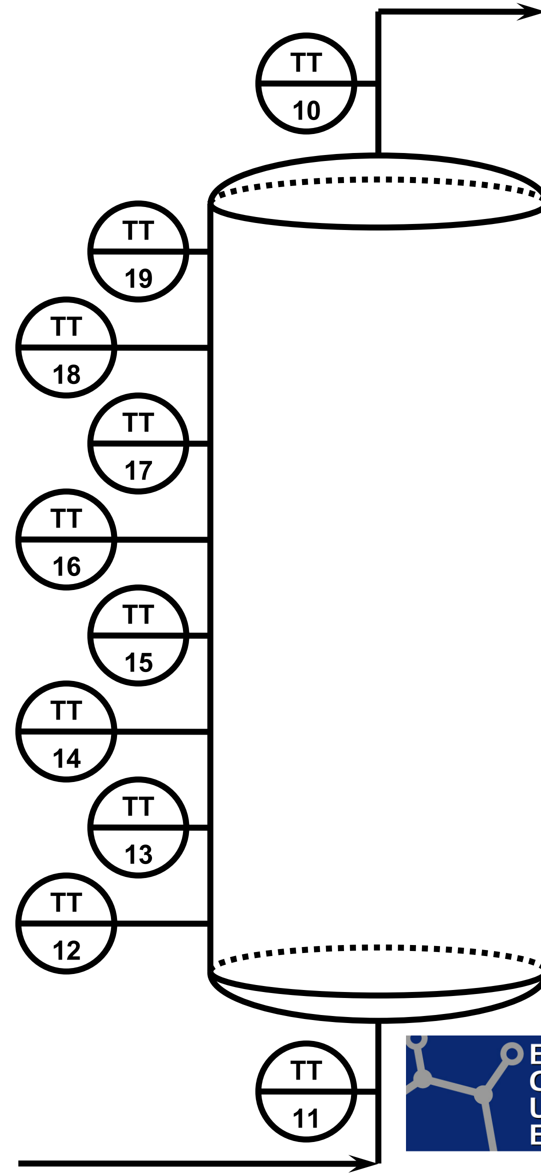
Process profiles

Temperature profile in packed bed reactor

- Trips on abnormal profile, calc block determines when profile is abnormal
- No redundant devices—each of N devices measures different point in the process
- Minimum number of devices, M, to establish profile
- PFD_{AVG} based on MooN
- Voting based on single profile, so 1oo1



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Typical PFD_{AVG} for process profiles

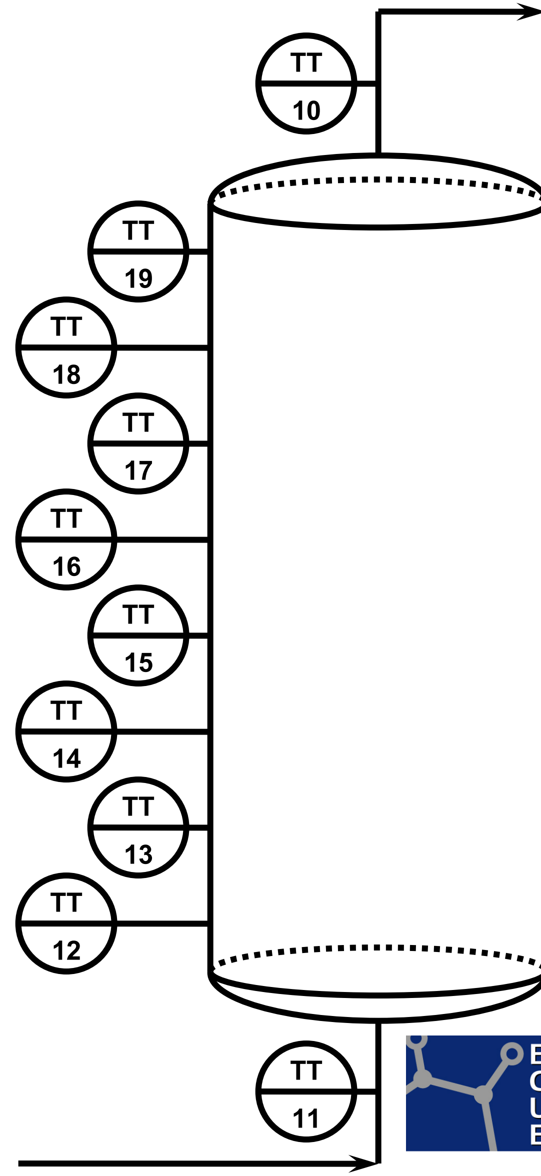
The number of sensors allowed to fault typically is less than 25%.

- 4oo5 $PFD_{AVG} = 10(\lambda T)^2/3$
- 5oo5 $PFD_{AVG} = 5\lambda T/2$
- 5oo6 $PFD_{AVG} = 5(\lambda T)^2$
- 6oo6 $PFD_{AVG} = 3\lambda T$
- 6oo7 $PFD_{AVG} = 7(\lambda T)^2$
- 7oo7 $PFD_{AVG} = 7\lambda T/2$
- 7oo8 $PFD_{AVG} = 28(\lambda T)^2/3$
- 7oo9 $PFD_{AVG} = 21(\lambda T)^3$
- 8oo8 $PFD_{AVG} = 4\lambda T$
- 8oo9 $PFD_{AVG} = 12(\lambda T)^2$
- 8oo10 $PFD_{AVG} = 30(\lambda T)^3$
- MooN $PFD_{AVG} = (N!/(M-1)!/(N-M+1)!)(\lambda T)^{N-M+1}/(N-M+2)$
- NooN $PFD_{AVG} = N\lambda T/2$

Considering common cause

Temperature profile in packed bed reactor

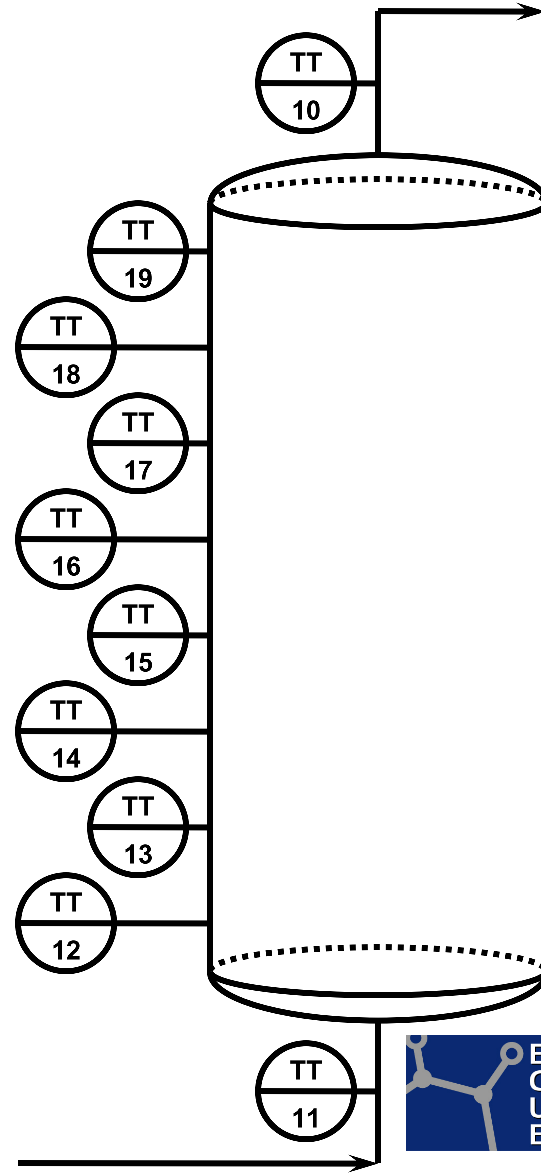
- All required: 10oo10
  $PFD_{AVG} = 10\lambda T/2$
- Nine required: 9oo10
  $PFD_{AVG} = 45(\lambda_N T)^2 + \lambda_C T/2$
- Eight required: 8oo10
  $PFD_{AVG} = 30(\lambda_N T)^3 + \lambda_C T/2$



Localized problems

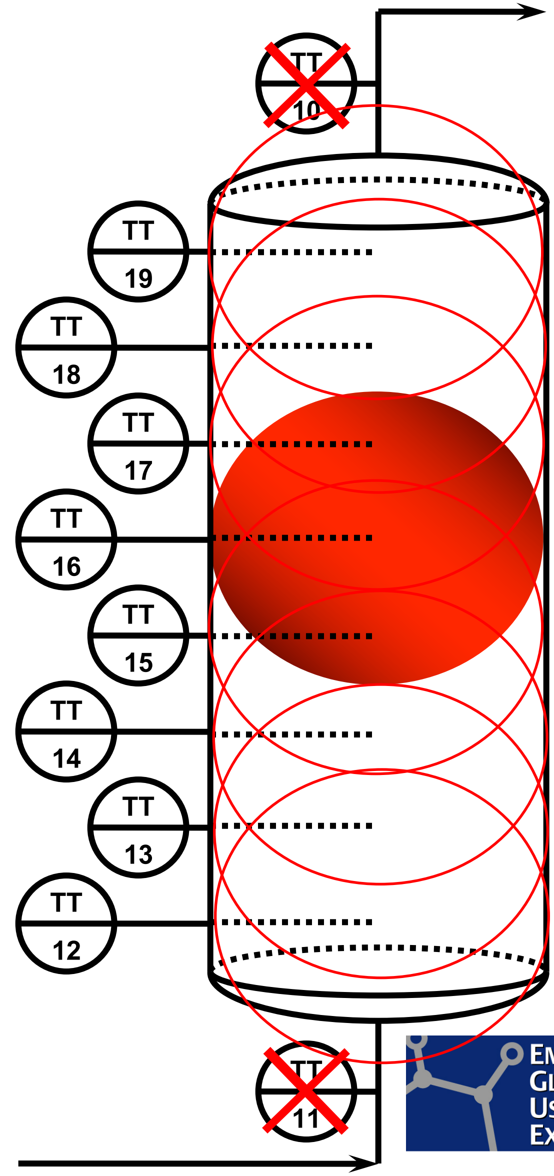
Hot spots in packed bed reactor

- Trips on any point being too hot
- Each hot spot treated as independent
- PFD_{AVG} calcs begin with 1oo1 architecture



Geometry

- Arrangement driven by ability to detect hot spot
- There is usually symmetry and overlap
- While tripped on a single device exceeding set point, frequently not tripped based on single fault – implied redundancy



Inherent redundancy

- Adjacent sensors also act to detect the problem
- Uses all adjacent sensors
- Often with more conservative set point

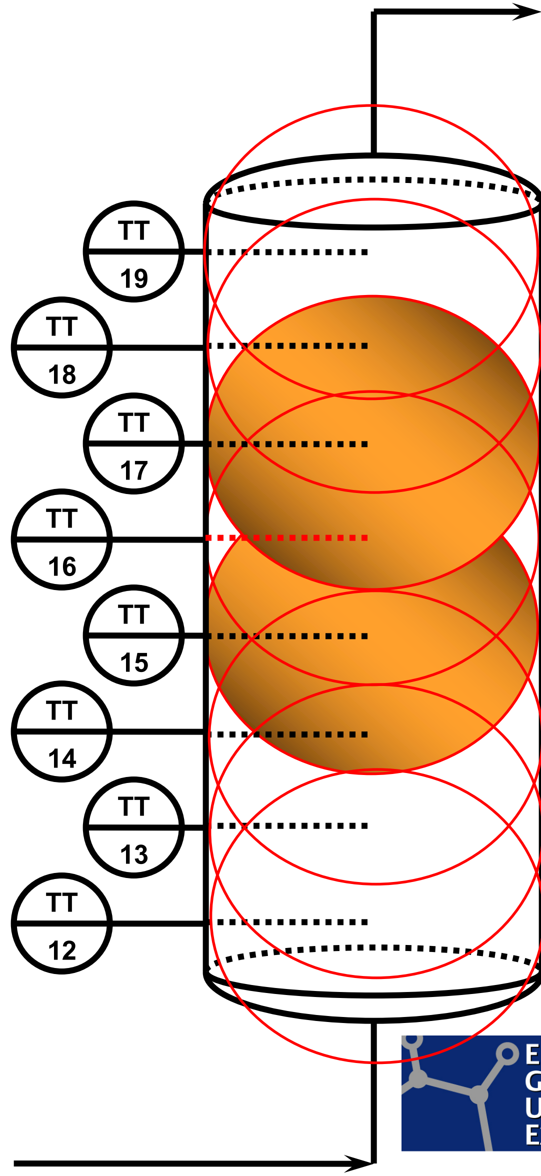
For example

Primary: TT-16 – SP = 200 C

Secondary: TT-15 – SP = 190 C

Secondary: TT-17 – SP = 190 C

- Voting on sensors is 1oo3, 1oo2 at the top and bottom



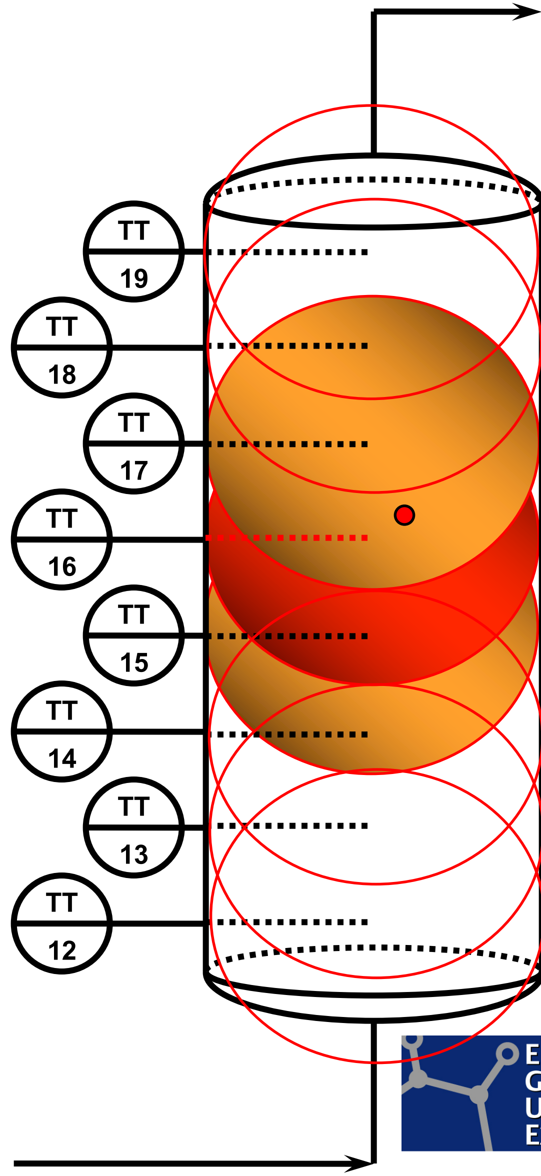
How to calculate PFD_{AVG}

- Only the primary sensor and the nearest adjacent sensor are relied on to detect a problem at a particular point

For example, this hot spot detected by

  - TT-16 > 200 C, or
  - TT-17 > 190 C

- PFD_{AVG} and fault tolerance based on 1oo2
- No credit taken for other secondary sensors



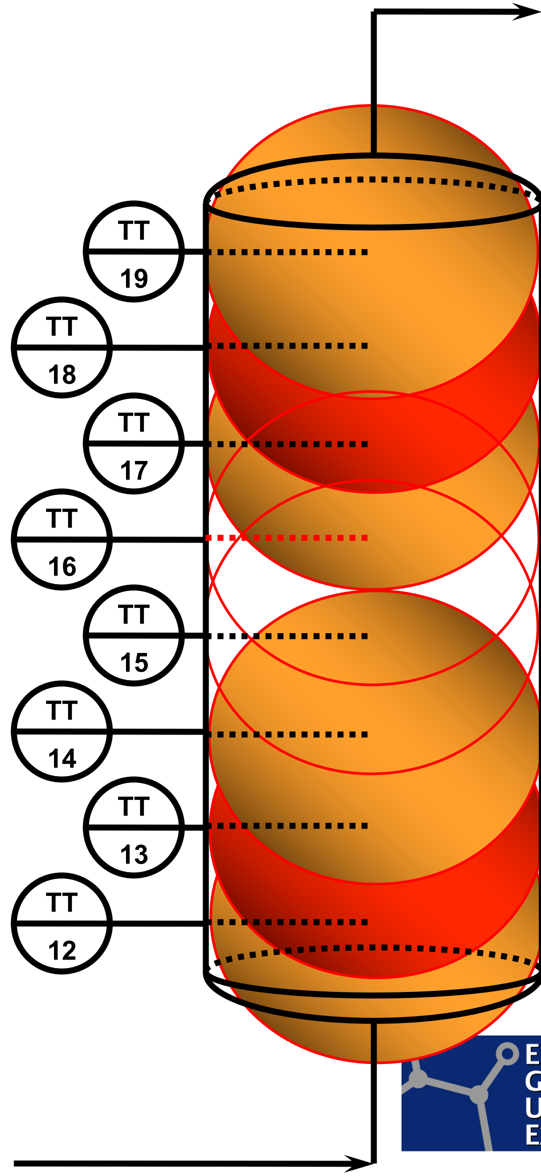
Impact on set points

	TT-12	TT-13	TT-14	TT-15	TT-16	TT-17	TT-18	TT-19
SIF TT-12	200	190						
SIF TT-13	190	200	190					
SIF TT-14		190	200	190				
SIF TT-15			190	200	190			
SIF TT-16				190	200	190		
SIF TT-17					190	200	190	
SIF TT-18						190	200	190
SIF TT-19							190	200

- Even though the primary set point is higher in each SIF, the secondary set point becomes the effective set point

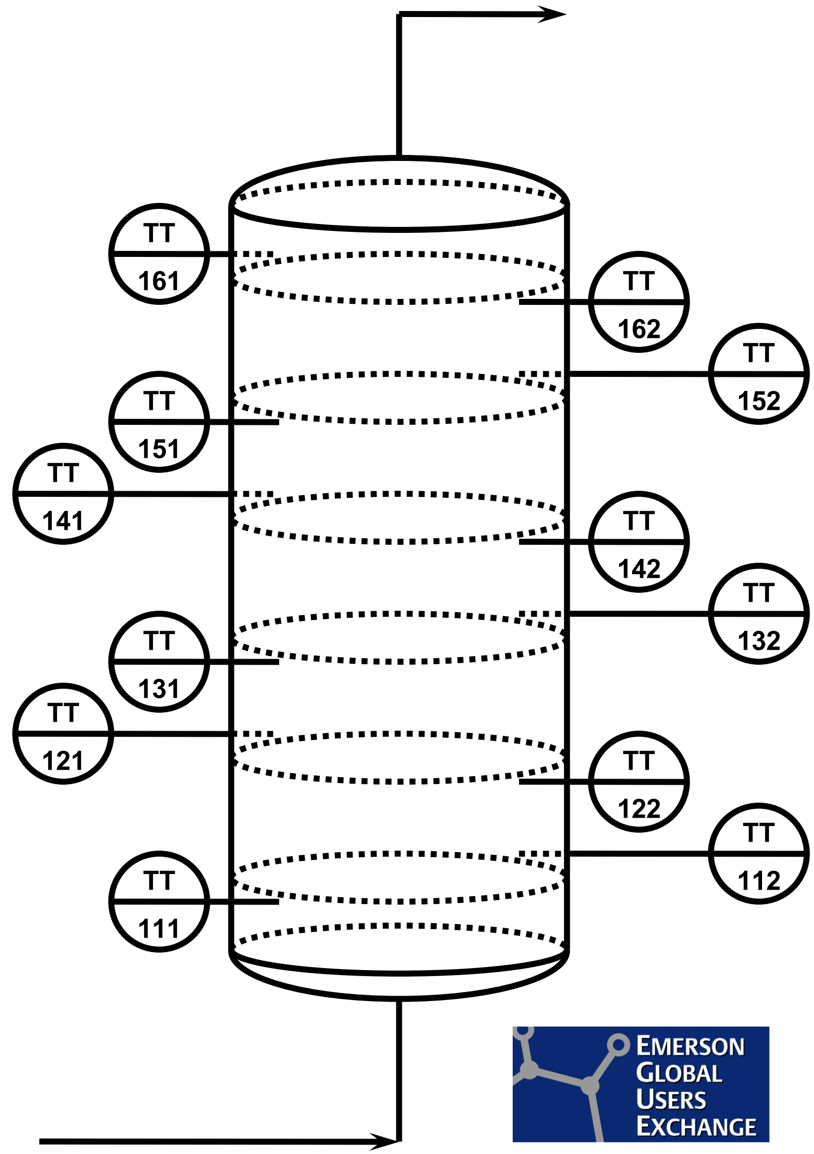
Localized, but independent

- A sensor fault impacts all hot-spot SIFs that share the sensor.
- If the SIS uses degraded architecture on a fault, all SIFs that share the sensor will need to have their architecture degraded.
- SIFs that do not use the faulted sensor are independent, hence still completely functional.
- Most SIS's do not allow multiple faults without a trip



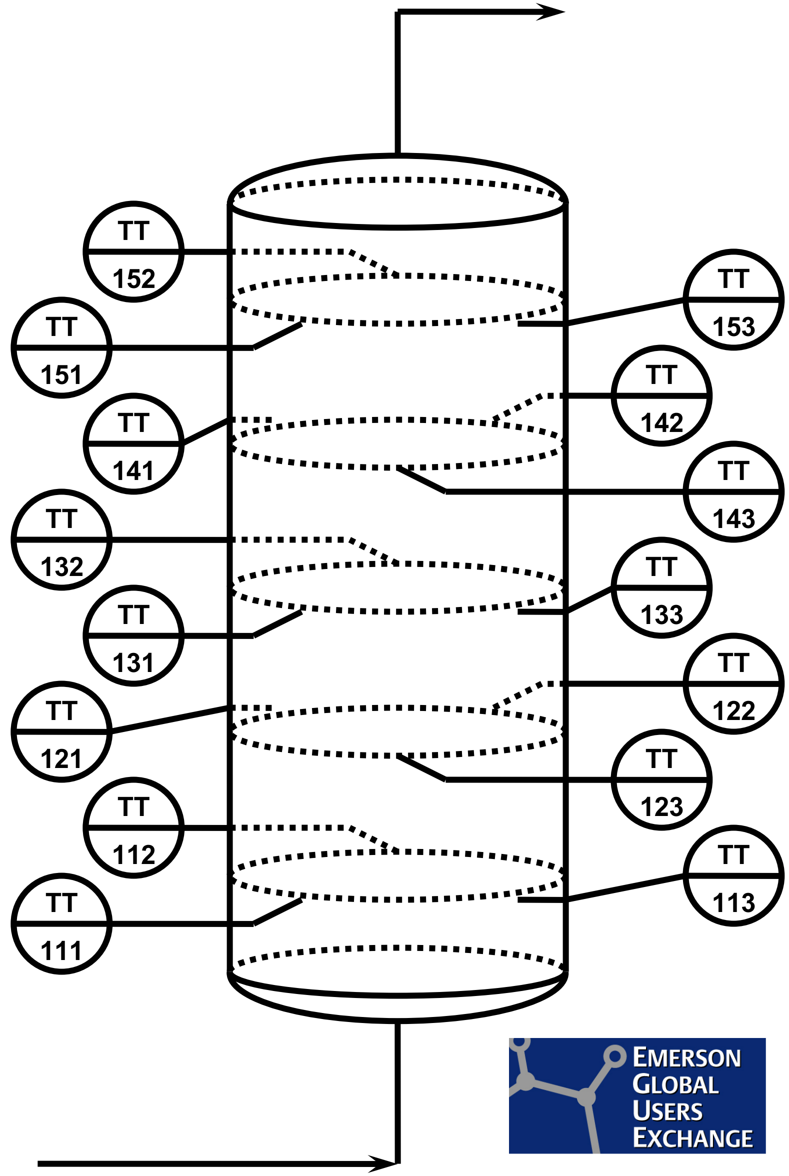
What about other geometries?

- Two sensors per elevation, staggered
  - Fewer elevations
  - More sensors altogether



Or other geometries?

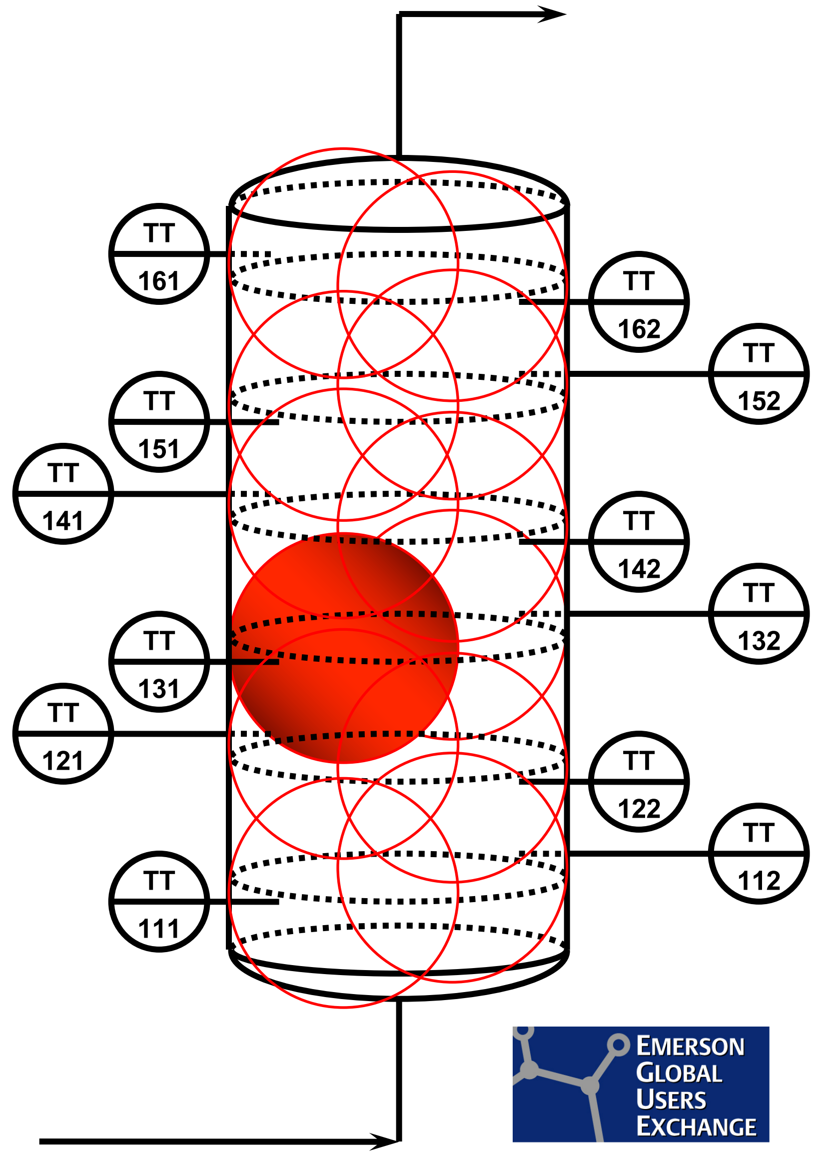
- Three sensors per elevation, staggered
  - Even fewer elevations
  - Still more sensors altogether



There are more adjacent sensors...

Two sensors per elevation, staggered

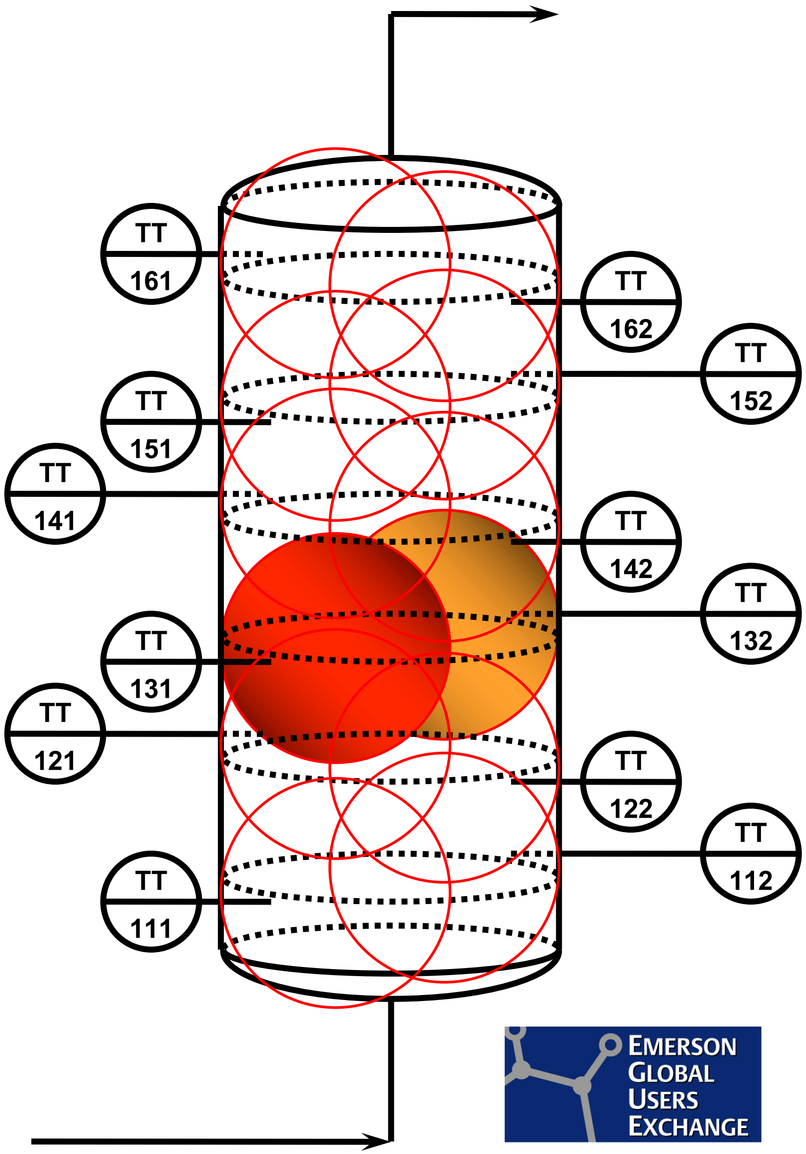
- Primary sensor



There are more adjacent sensors...

Two sensors per elevation, staggered

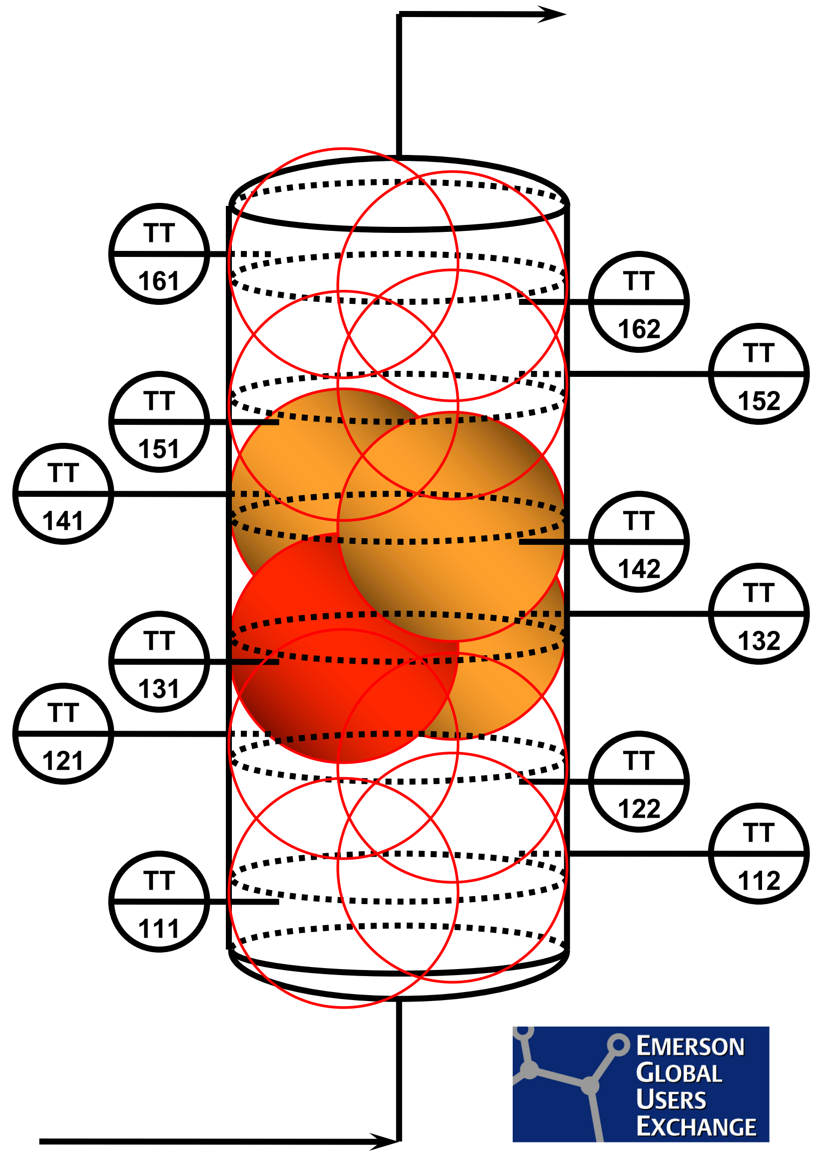
- Primary sensor
- Backed up by
  - One secondary sensor at the same elevation



There are more adjacent sensors...

Two sensors per elevation, staggered

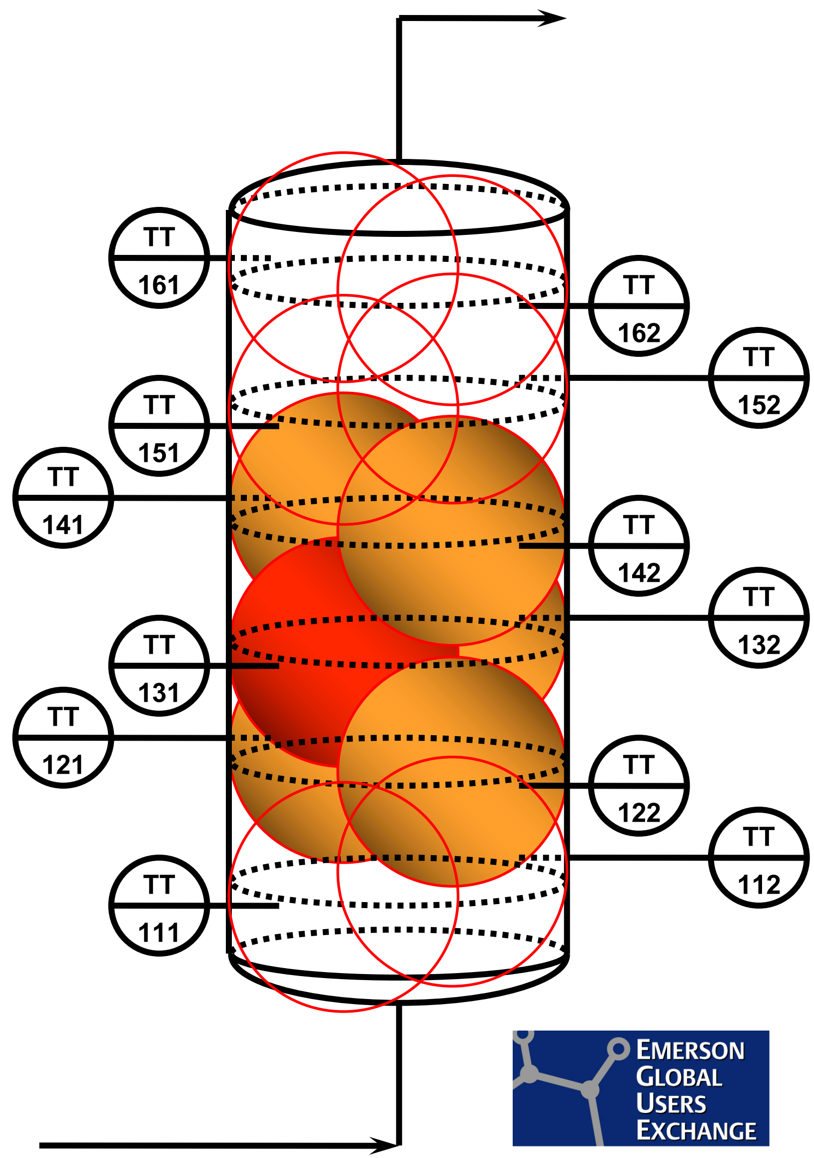
- Primary sensor
- Backed up by
  - One secondary sensor at the same elevation
  - Two secondary sensors at the elevation above



There are more adjacent sensors...

Two sensors per elevation, staggered

- Primary sensor
- Backed up by
  - One secondary sensor at the same elevation
  - Two secondary sensors at the elevation above
  - Two secondary sensors at the elevations below



...but PFD_{AVG} doesn't change

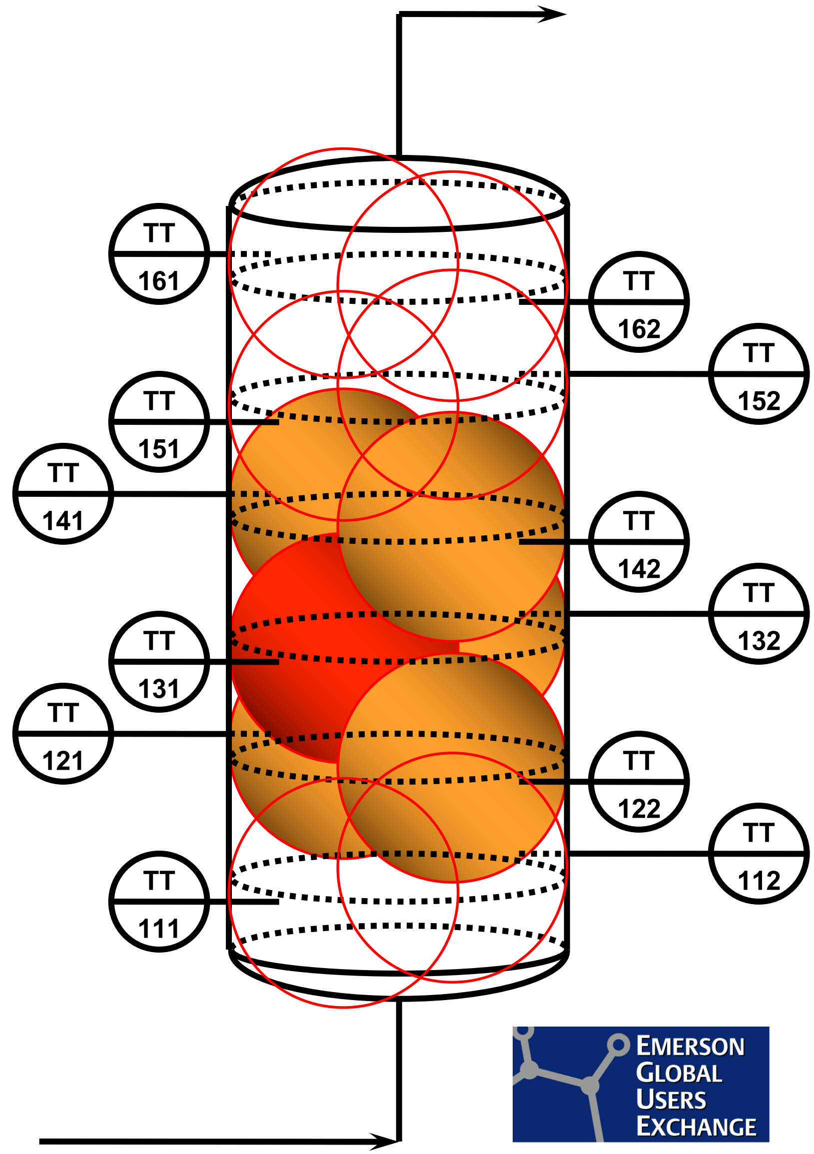
Two sensors per elevation, staggered

So,

- Voting is based on 1oo6 architecture

But,

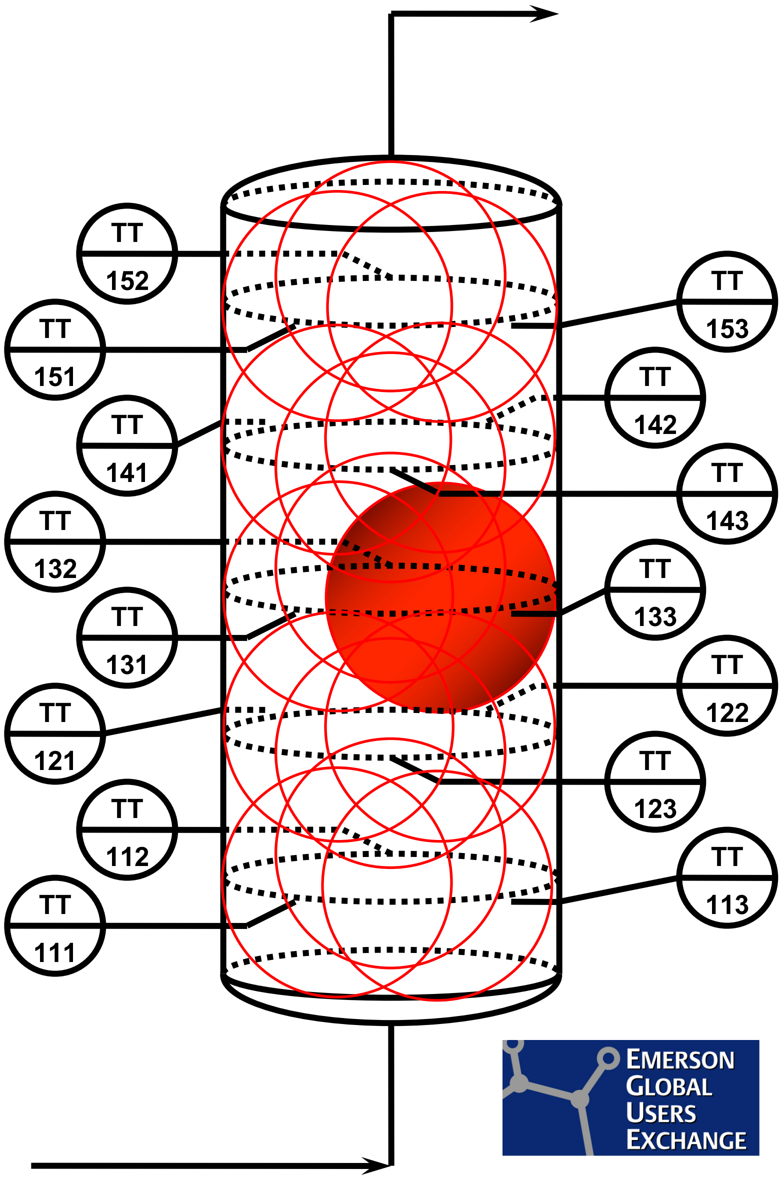
- PFD_{AVG} calculation is based on 1oo2 architecture
- Fault tolerance is also based on 1oo2 architecture—one



With even more adjacent sensors...

Three sensors per elevation, staggered

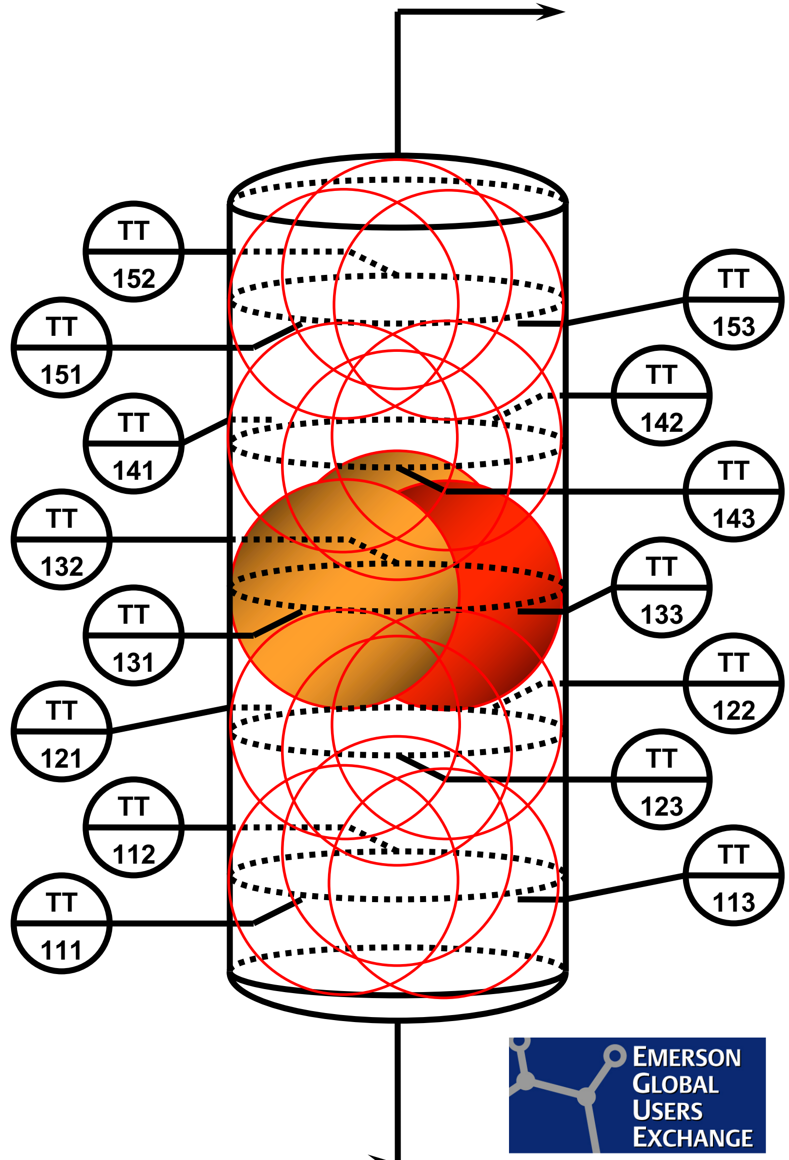
- Primary sensor



With even more adjacent sensors...

Three sensors per elevation, staggered

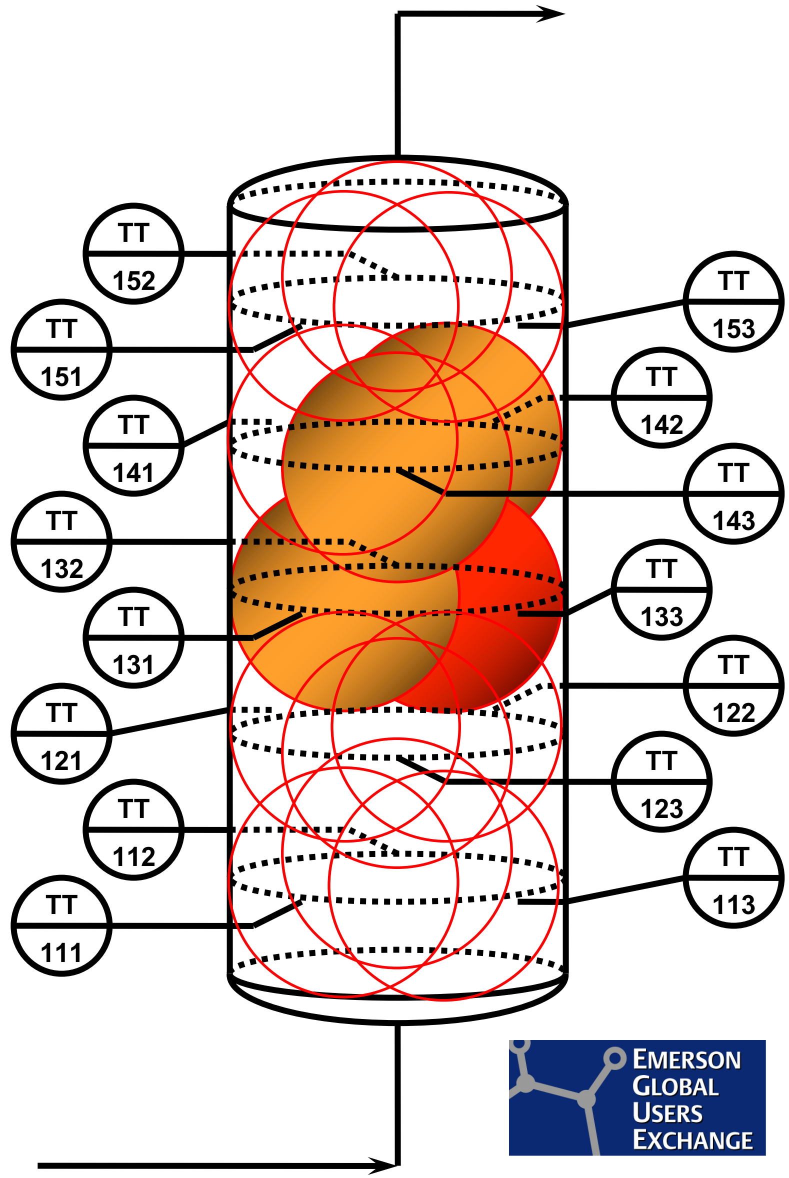
- Primary sensor
- Backed up by
  - Two secondary sensors at the same elevation



With even more adjacent sensors...

Three sensors per elevation, staggered

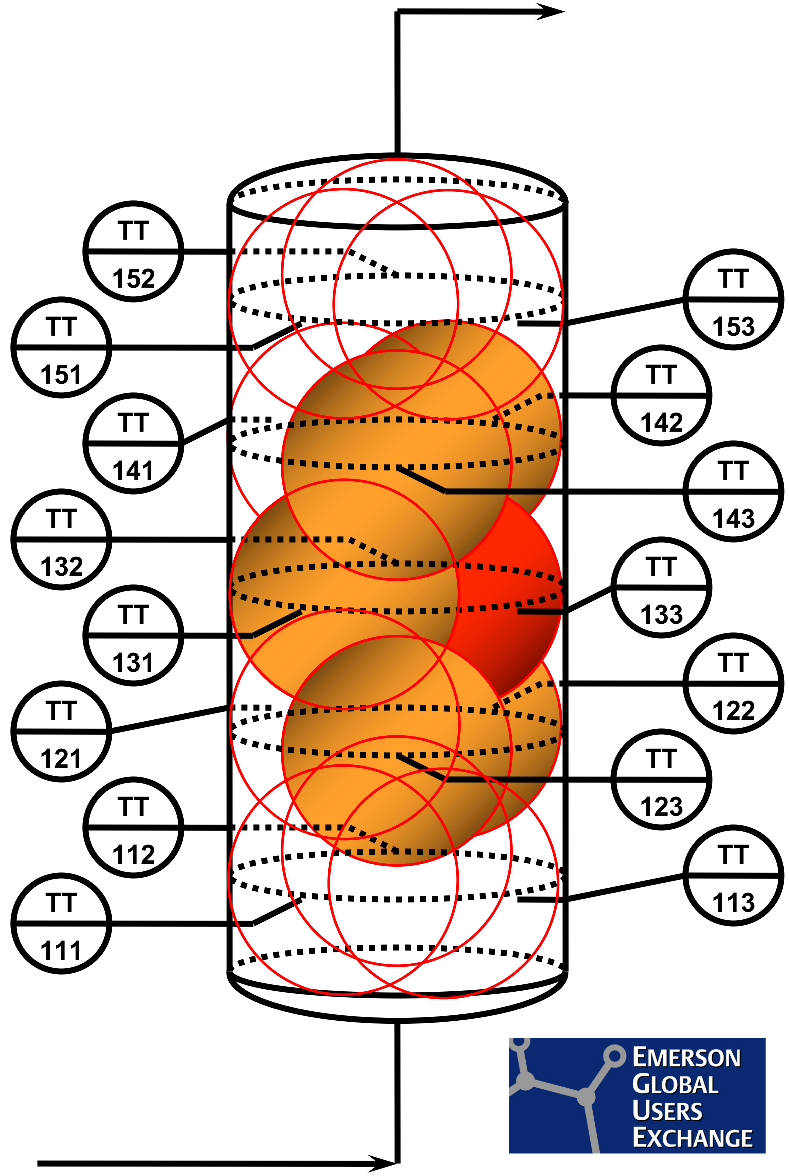
- Primary sensor
- Backed up by
  - Two secondary sensors at the same elevation
  - Two secondary sensors at the elevation above



With even more adjacent sensors...

Three sensors per elevation, staggered

- Primary sensor
- Backed up by
  - Two secondary sensors at the same elevation
  - Two secondary sensors at the elevation above
  - Two secondary sensors at the elevations below



...the PFD_{AVG} still doesn't change

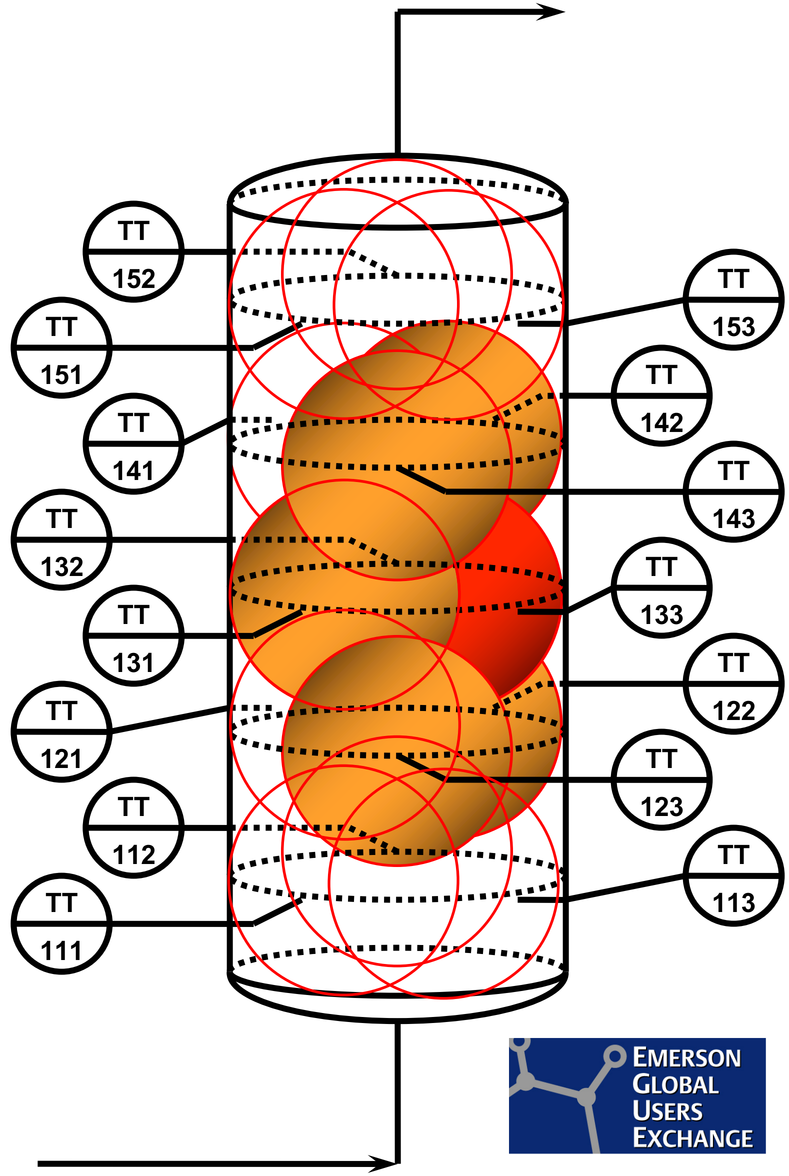
Three sensors per elevation, staggered

So,

- Voting is based on 1oo7 architecture

But still,

- PFD_{AVG} calculation is based on 1oo2 architecture
- Fault tolerance is also based on 1oo2 architecture—one



Fault tolerance for hot spots

- Basic design has sensors spaced as widely as possible
  - There are no secondary sensors
  - There is no fault tolerance
  - Voting is 1oo1 and PFD_{AVG} is based on 1oo1
- Fault tolerant design requires overlap
  - Only overlapping sensors serve as secondary sensors
  - Fault tolerance is one, regardless of number of secondary sensors
  - With X secondary sensors, voting is 1oo(X+1), while PFD_{AVG} is based on 1oo2
- True, regardless of overall size of array

Some notes on spacing

Two sensor, staggered design:

When

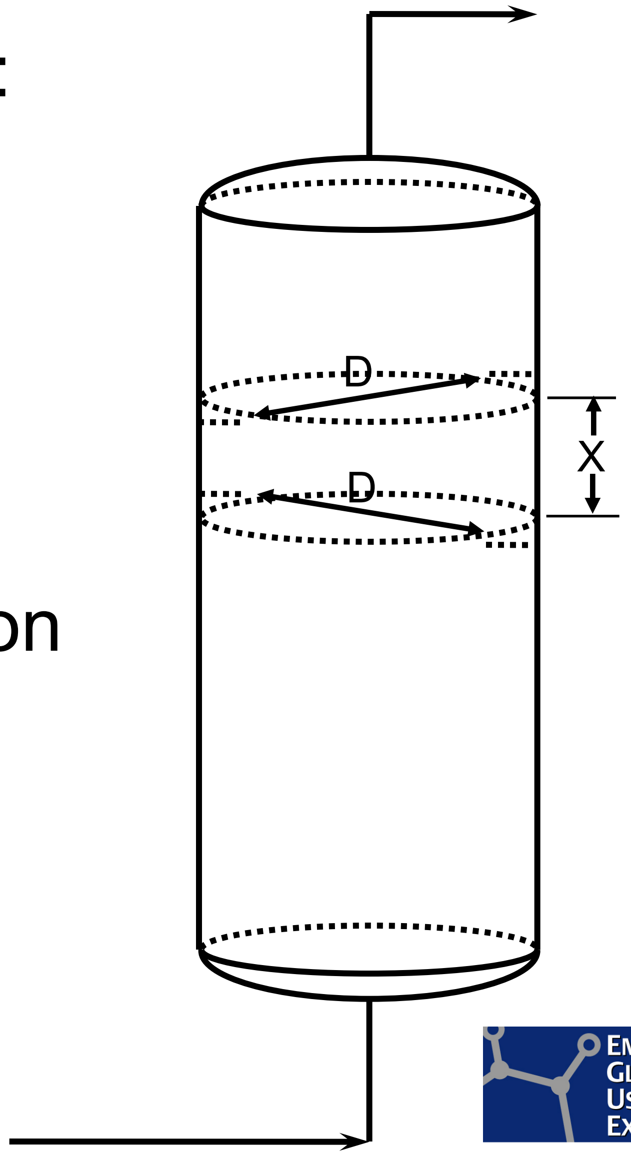
- X, is the distance between elevations

  and

- D, is the distance between sensors at the same elevation (not diameter of unit)

Ideally,

X ~ 0.7D



Some notes on spacing

Three sensor, staggered design:

When

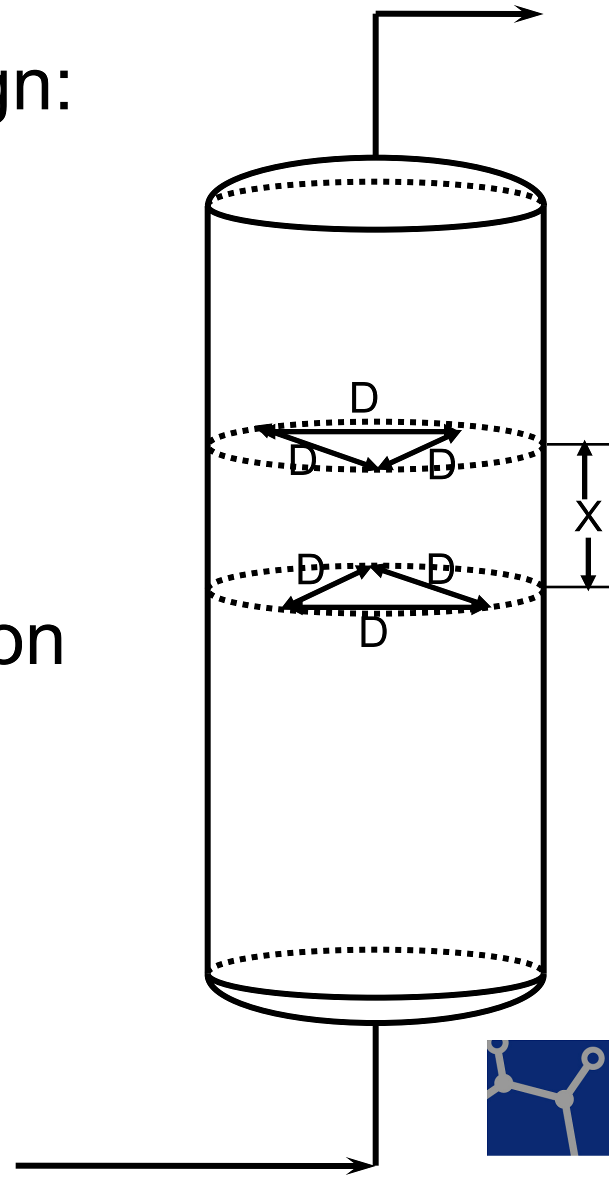
- X, is the distance between elevations

  and

- D, is the distance between sensors at the same elevation (not diameter of unit)

Ideally,

X ~ 0.8D



Business Results Achieved

- The number of sensors required for a SIF can be optimized to achieve the necessary coverage and the required redundancy. They are not the same.
- Designs calling for more than Moo3 architectures should be carefully evaluated to see any meaningful improvement is being achieved for the additional capital and operating expense.
- The necessary calculations have been identified to allow alternative designs to be compared.

Summary

- There are reasons to use more than three sensors in a SIF.
- Because of common cause failures, redundancy is not one of them.
- Voting architecture can differ from the architecture used for PFD_{AVG} calcs
- Advances in configuration allow multi-sensor architectures to generate profiles used to trip SIFs
- Multi-sensor arrays to detect localized problems are designed for coverage, not redundancy

Questions???

Where To Get More Information

Emerson Process Management, SIS Consulting

- Refining and Chemical Industry Center
  St. Louis, Missouri
  (314) 872-9058
  Overland Park, Kansas
  (913) 529-4201
  Houston, Texas
  (281) 207-2800

- Hydrocarbon and Energy Industry Center
  Calgary, Alberta
  (403) 258-6200

Subsystems with identical components

1oo1 $PFD_{AVG} = \lambda T/2$

1oo2 $PFD_{AVG} = (\lambda T)^2/3$

2oo2 $PFD_{AVG} = \lambda T$

1oo3 $PFD_{AVG} = (\lambda T)^3/4$

2oo3 $PFD_{AVG} = (\lambda T)2$

3oo3 $PFD_{AVG} = 3\lambda T/2$

1oo4 $PFD_{AVG} = (\lambda T)^4/5$

2oo4 $PFD_{AVG} = (\lambda T)^3$

3oo4 $PFD_{AVG} = 2(\lambda T)^2$

4oo4 $PFD_{AVG} = 2\lambda T$

1ooN $PFD_{AVG} = (\lambda T)^N/(N+1)$

2ooN $PFD_{AVG} = (\lambda T)^{N-1}$

3ooN $PFD_{AVG} = N(\lambda T)^{N-2}/2$

MooN $PFD_{AVG} = (N!/(M-1)!/(N-M+1)!)(\lambda T)^{N-M+1}/(N-M+2)$

NooN $PFD_{AVG} = N\lambda T/2$

- Note that PFD_{AVG} can be summed, but not multiplied.

Subsystems with diverse components

1oo1 $PFD_{AVG} = \lambda T/2$

1oo2 $PFD_{AVG} = \lambda_1\lambda_2 T^2/3$

2oo2 $PFD_{AVG} = (\lambda_1 + \lambda_2)T/2$

1oo3 $PFD_{AVG} = \lambda_1\lambda_2\lambda_3 T^3/4$

2oo3 $PFD_{AVG} = (\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_1\lambda_3)T^2/3$

3oo3 $PFD_{AVG} = (\lambda_1 + \lambda_2 + \lambda_3)T/2$

1oo4 $PFD_{AVG} = \lambda_1\lambda_2\lambda_3\lambda_4 T^4/5$

2oo4 $PFD_{AVG} = (\lambda_1\lambda_2\lambda_3 + \lambda_1\lambda_2\lambda_4 + \lambda_1\lambda_3\lambda_4 + \lambda_2\lambda_3\lambda_4)T^3/4$

3oo4 $PFD_{AVG} = (\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_1\lambda_4 + \lambda_2\lambda_3 + \lambda_2\lambda_4 + \lambda_3\lambda_4)T^2/3$

4oo4 $PFD_{AVG} = (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)T/2$

1ooN $PFD_{AVG} = \lambda_1\lambda_2\lambda_3 ... \lambda_N T^N/(N+1)$

NooN $PFD_{AVG} = (\lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_N)T/2$

- Note that PFD_{AVG} can be summed, but not multiplied.