



# ***Beyond 2003: Multi-sensor Architecture in SIF Design***

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- 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

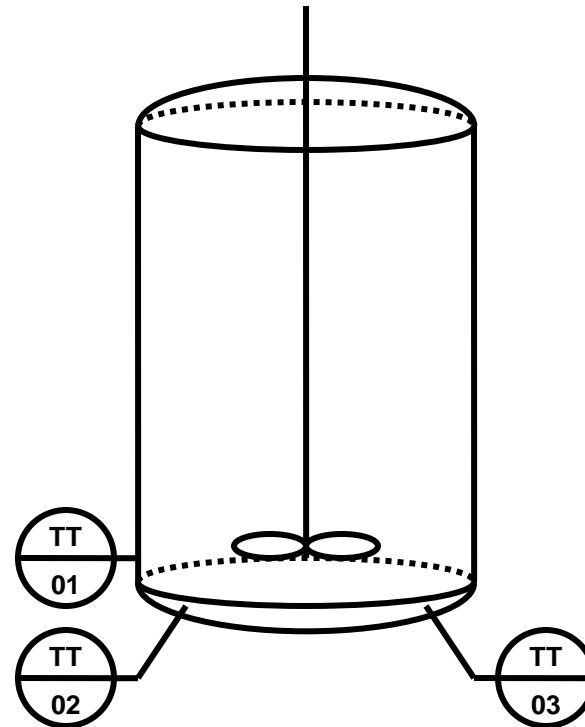
# *Why have multiple devices?*

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

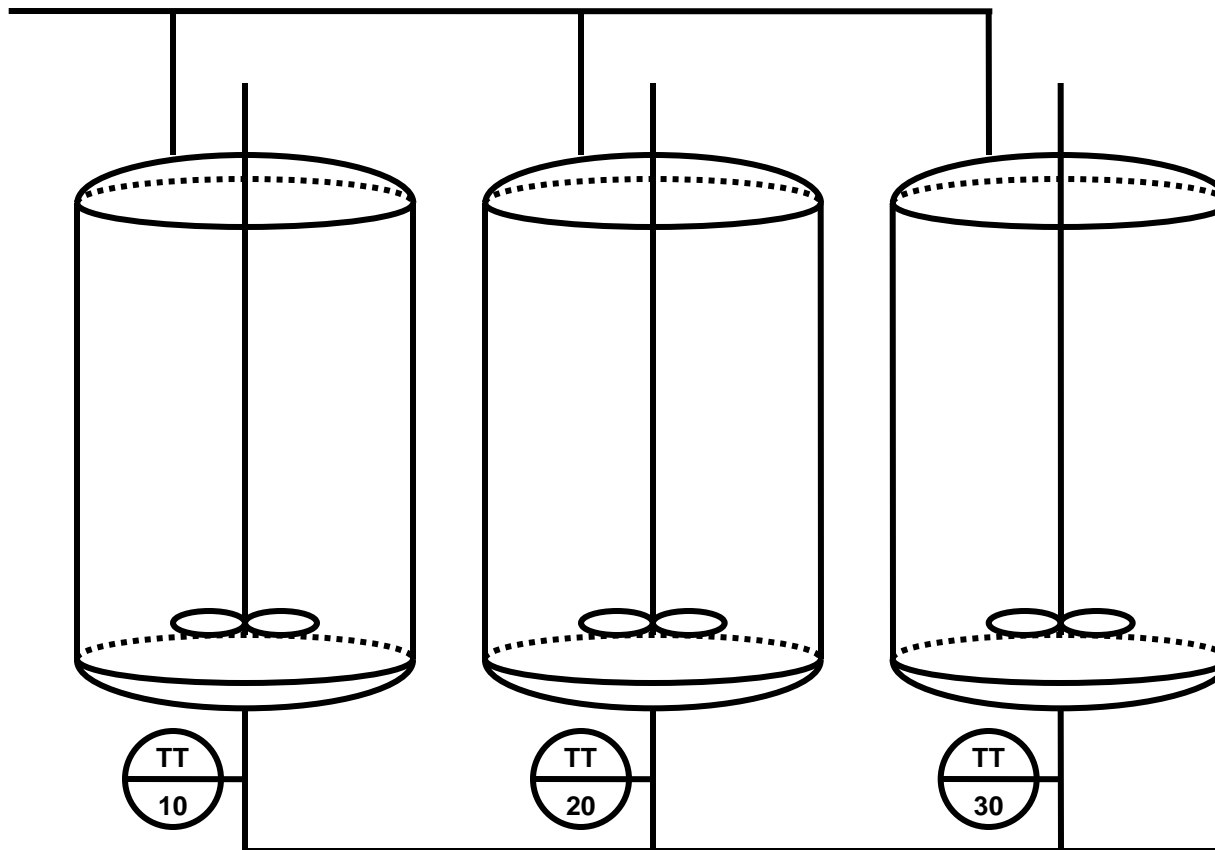
# *What is redundancy?*

- Serving exactly the same purpose at the same point in the process
- Possible architectures:
  - 1003
  - 2003
  - 3003

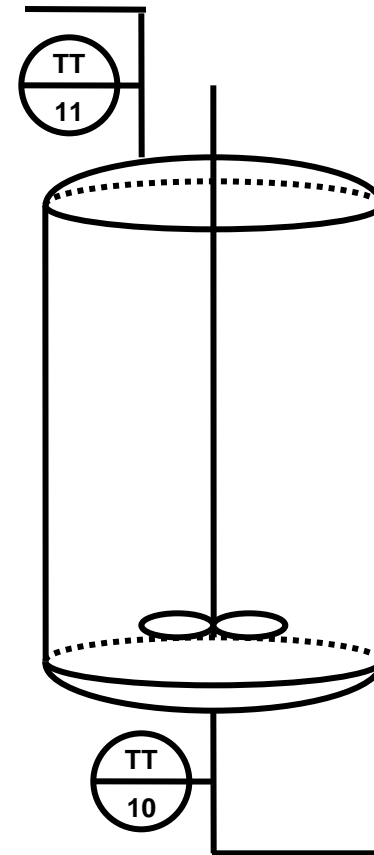


# Separate hazards?

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

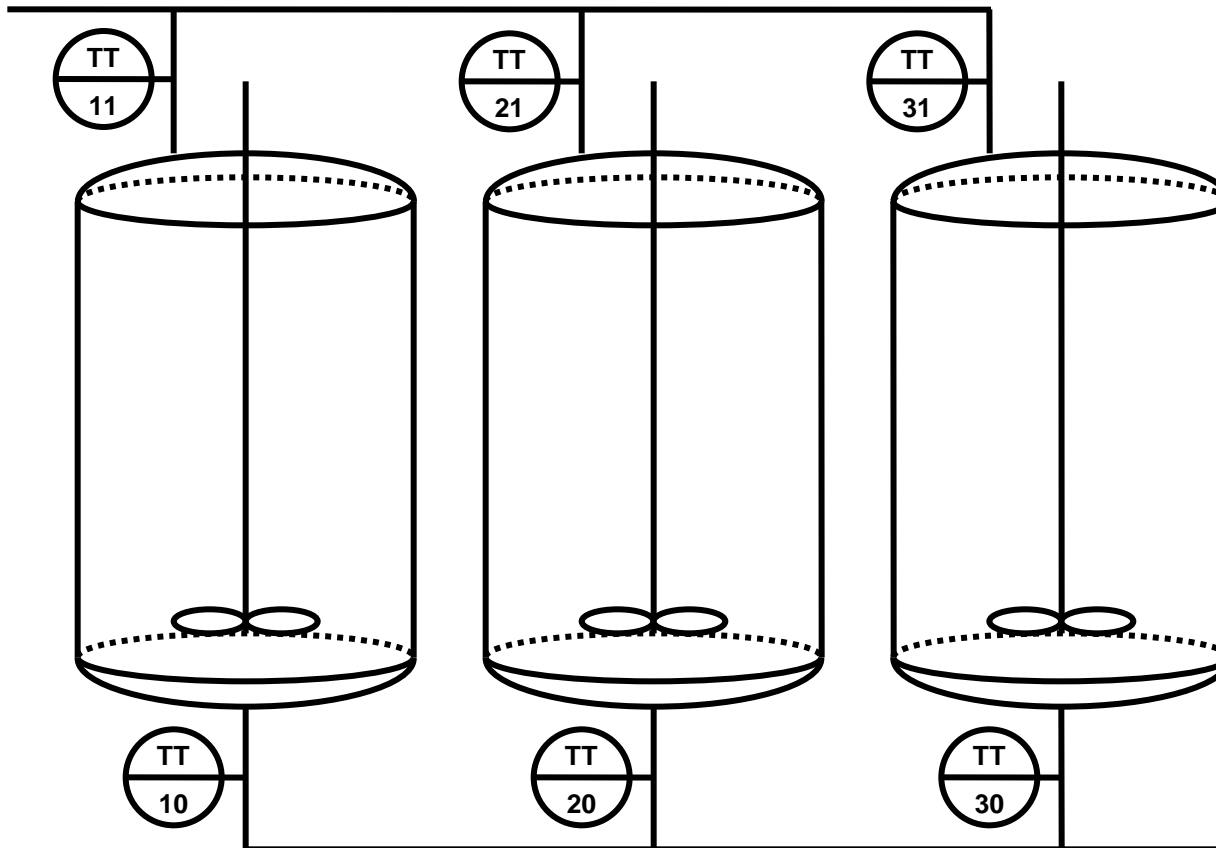


- Requiring more than one device to achieve the purpose
- Possible architectures
  - 1~~00~~2
  - 2~~00~~2
  - two device 1001



# *Interdependent and redundant?*

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

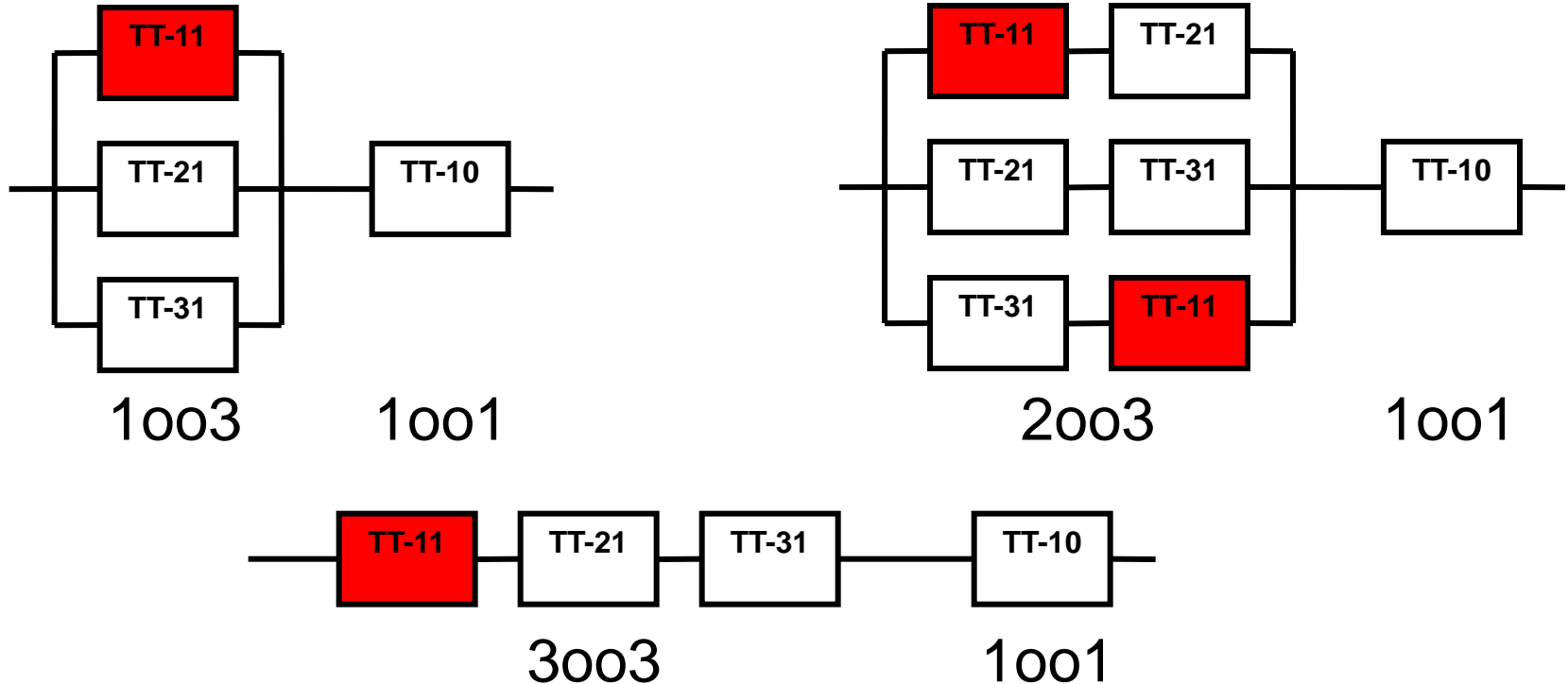




## Consider Reactor 1

- 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:
  - $$\begin{array}{l} [TT-10] - [TT-11] \\ [TT-10] - [TT-21] \\ [TT-10] - [TT-31] \end{array}$$
  - Architecture may be 1oo3, 2oo3, or 3oo3 for voting
  - TT-10 is a common source of failure

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



## *Common cause failure?*

$$\lambda = \lambda_N + \lambda_C$$

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

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

Table D.4 – Calculation of  $\beta$  or  $\beta_D$

Score ( $S$ or $S_D$ )	Corresponding value of $\beta$ or $\beta_D$ 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  $\beta_D$  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  $\beta_D$  lower than 0,5 % for the logic subsystem and 1 % for the sensors would be difficult to justify.

## *Impact of common cause?*

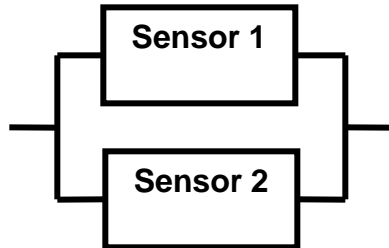
Consider a typical SIF:

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

So

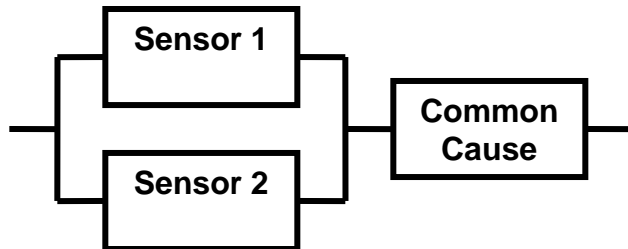
- $\lambda_C = \beta\lambda = 0.03 \times 0.03 = 0.0009$  failures/yr
- $\lambda_N = (1-\beta)\lambda = (1 - 0.03) \times 0.03 = 0.0291$  failures/yr
- For service with a single device
- $PFD_{AVG} = \lambda T / 2 = 0.03 \times 1 / 2 = 0.015$

- Duplex, but without considering common cause



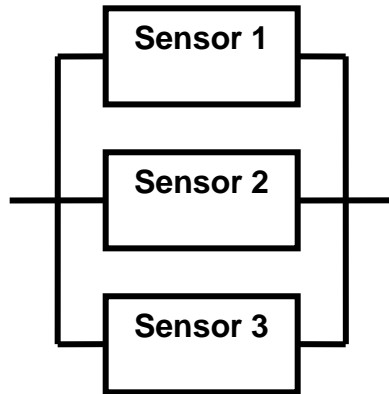
$$PFD_{AVG} = (\lambda T)^2/3 = (0.03)^2/3 = 0.0003$$

- Duplex, considering common cause



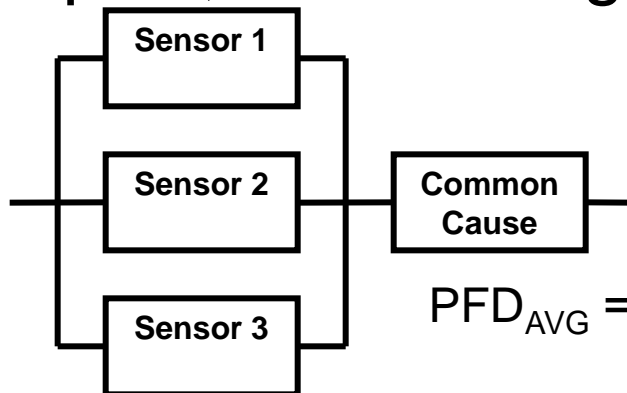
$$PFD_{AVG} = (\lambda_N T)^2/3 + \lambda_C T = (0.0291)^2/3 + 0.0009 = 0.00118$$

- Triplex, but without considering common cause



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

- Triplex, considering common cause



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

# *Why use more than three sensors?*

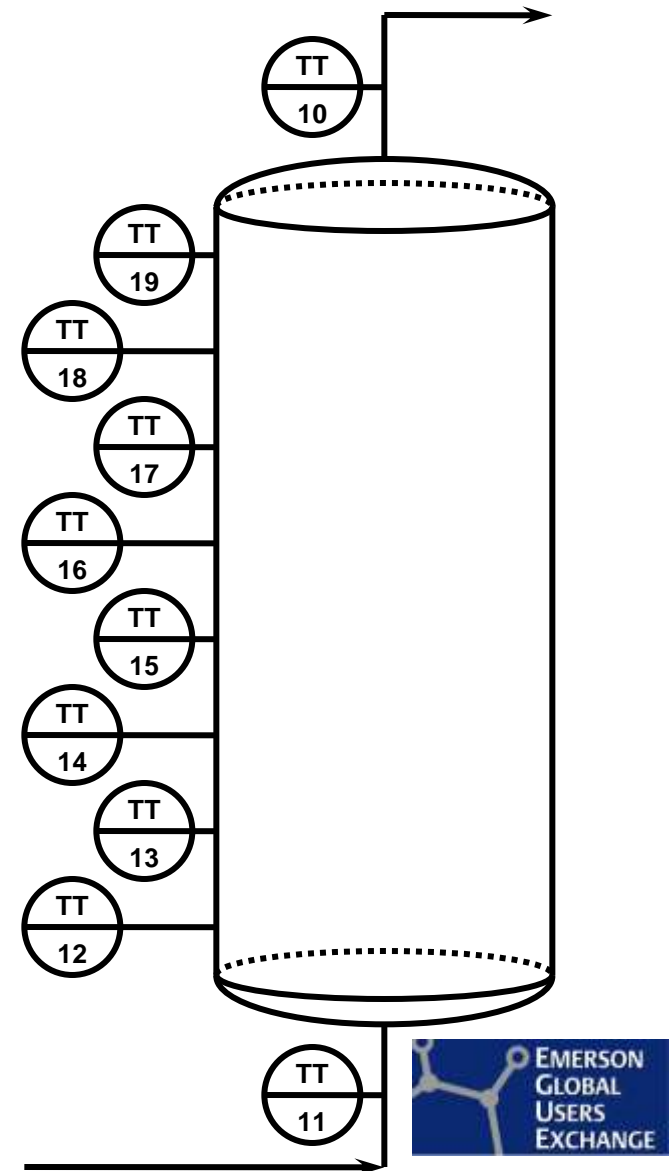
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- Process profiles
  - Temperature profile in distillation column
  - Temperature profile in packed or fluidized bed reactor
- Localized problem within process unit
  - Hot spots
  - Leaks



## 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  $M \text{ on } N$
- Voting based on single profile, so 1001



# Typical $PFD_{AVG}$ for process profiles

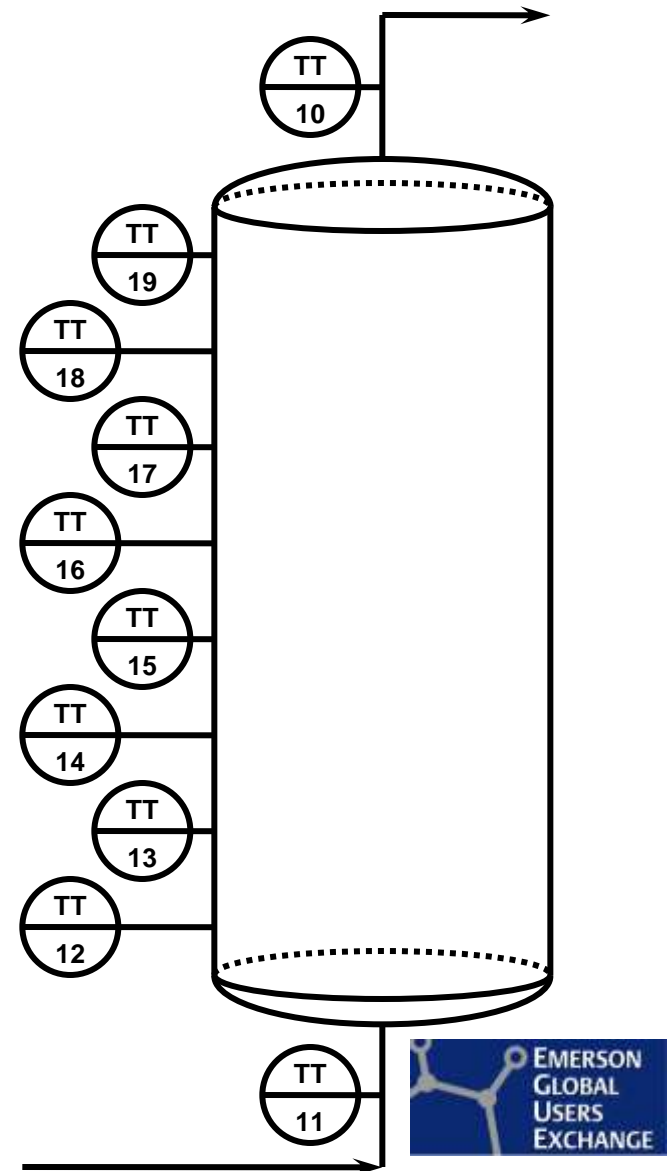
The number of sensors allowed to fault typically is less than 25%.

- 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

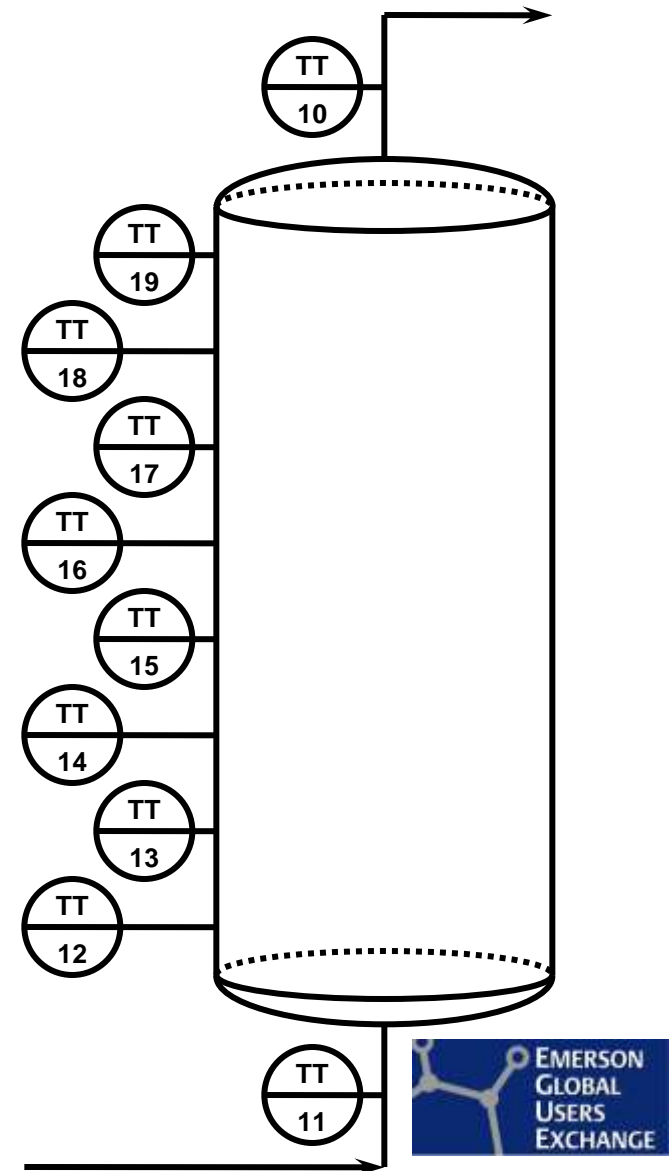
## Temperature profile in packed bed reactor

- 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  
 $PFD_{AVG} = 30(\lambda_N T)^3 + \lambda_C T/2$

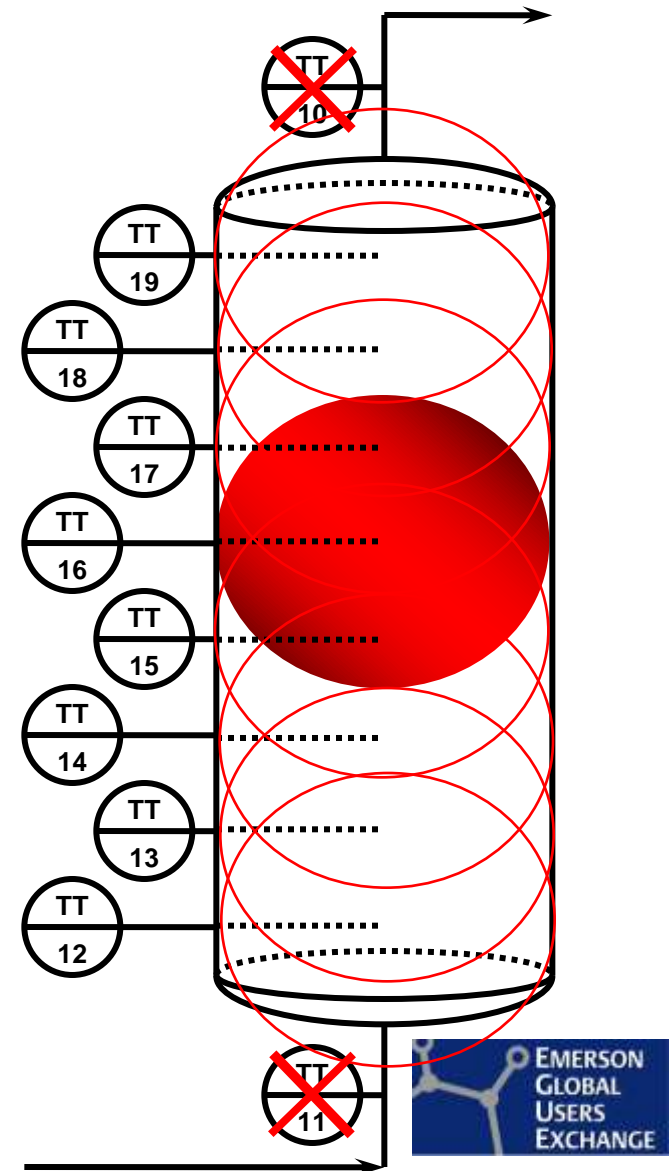


## Hot spots in packed bed reactor

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



- 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



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

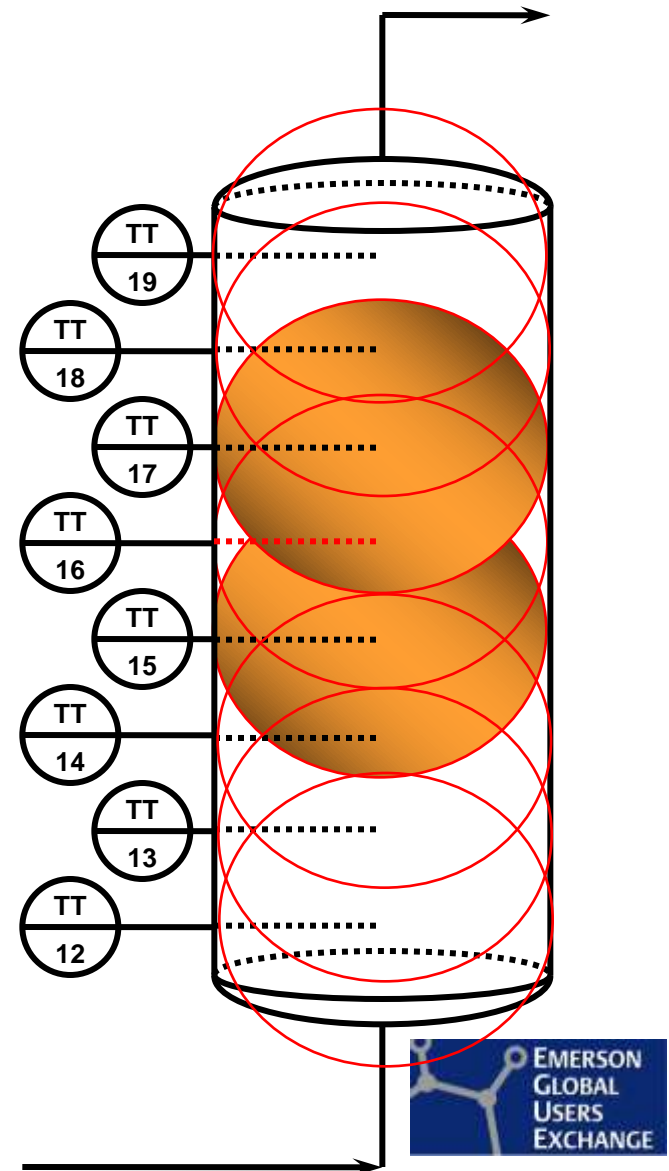
For example

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

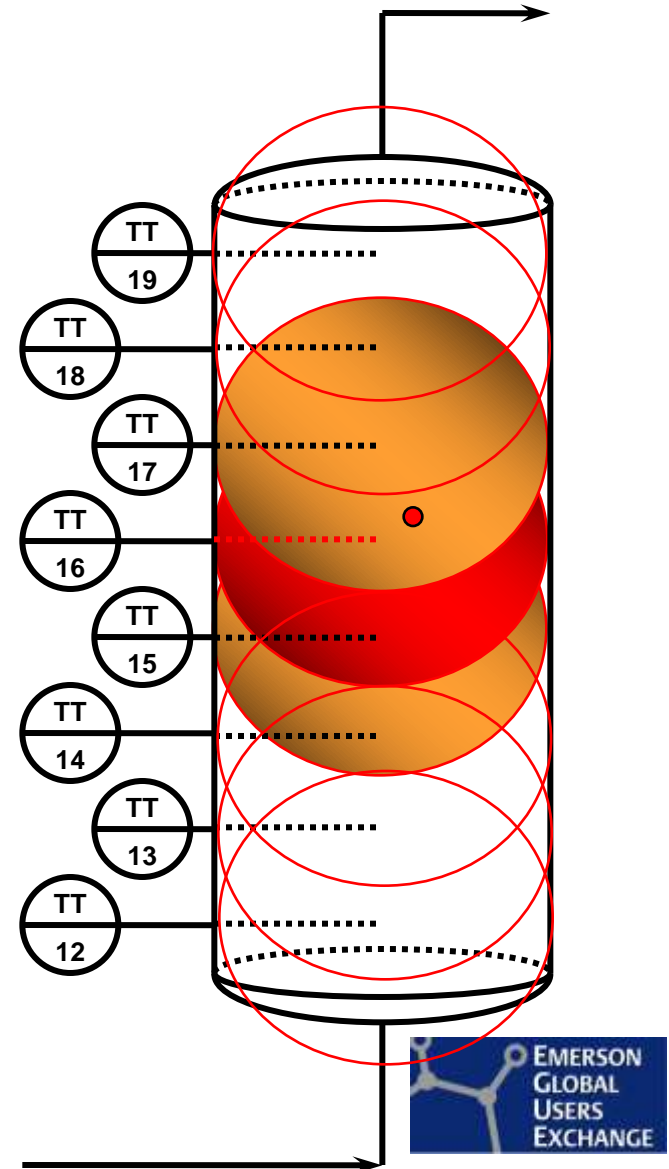


# How to calculate $PFD_{AVG}$

- 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*

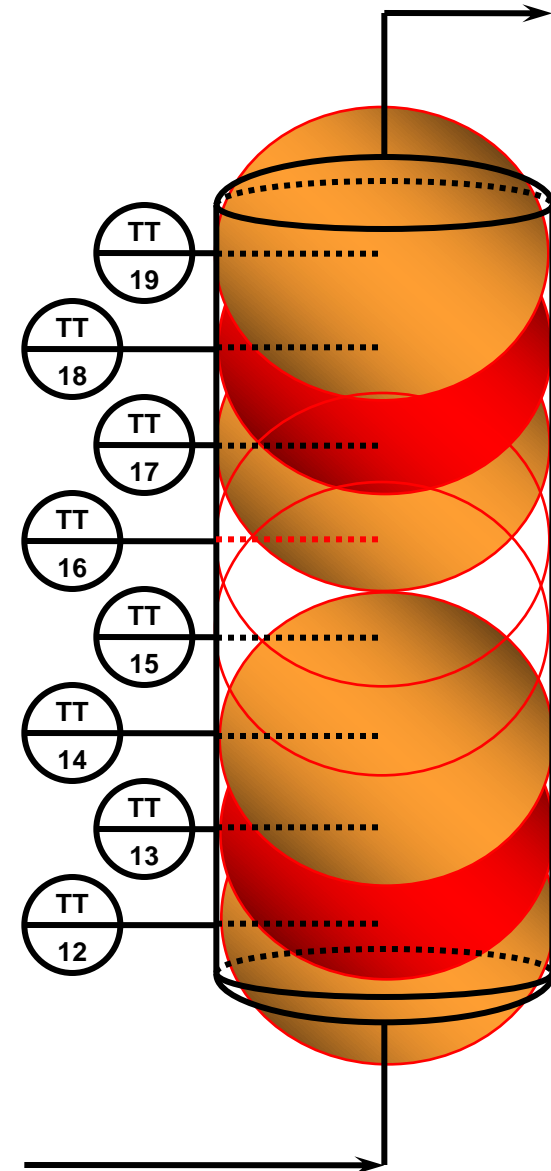
	<u>TT-12</u>	<u>TT-13</u>	<u>TT-14</u>	<u>TT-15</u>	<u>TT-16</u>	<u>TT-17</u>	<u>TT-18</u>	<u>TT-19</u>
SIF TT-12	200	190						
SIF TT-13	190	200	190					
SIF TT-14		190	200	190				
SIF TT-15			190	200	190			
SIF TT-16				190	200	190		
SIF TT-17					190	200	190	
SIF TT-18						190	200	190
SIF TT-19							190	200

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



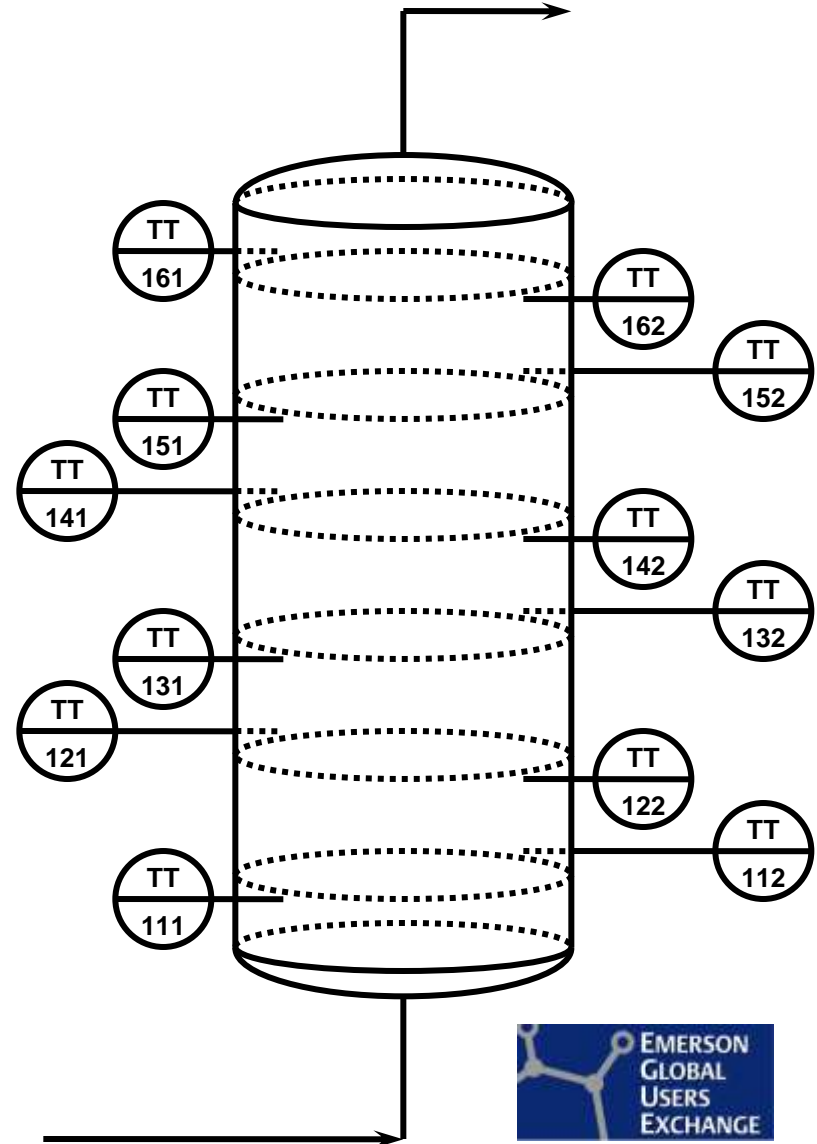
## *Localized, but independent*

- 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



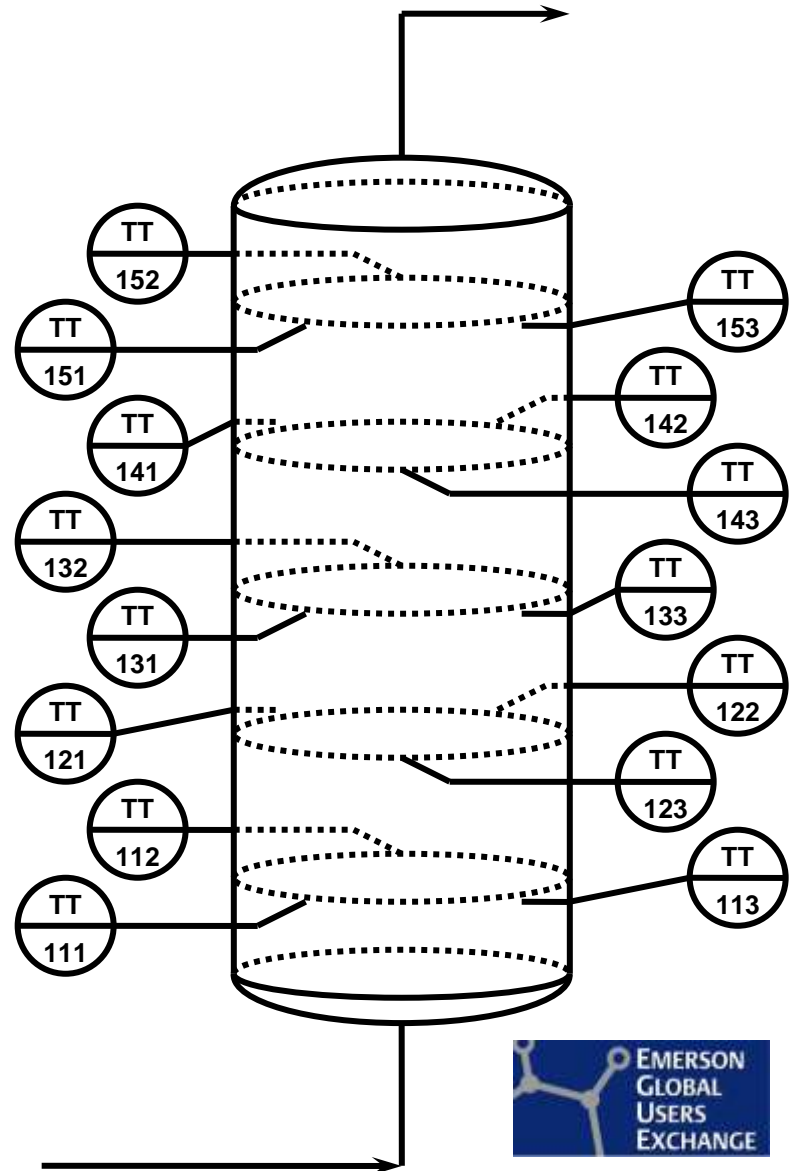
# What about other geometries?

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



## Or other geometries?

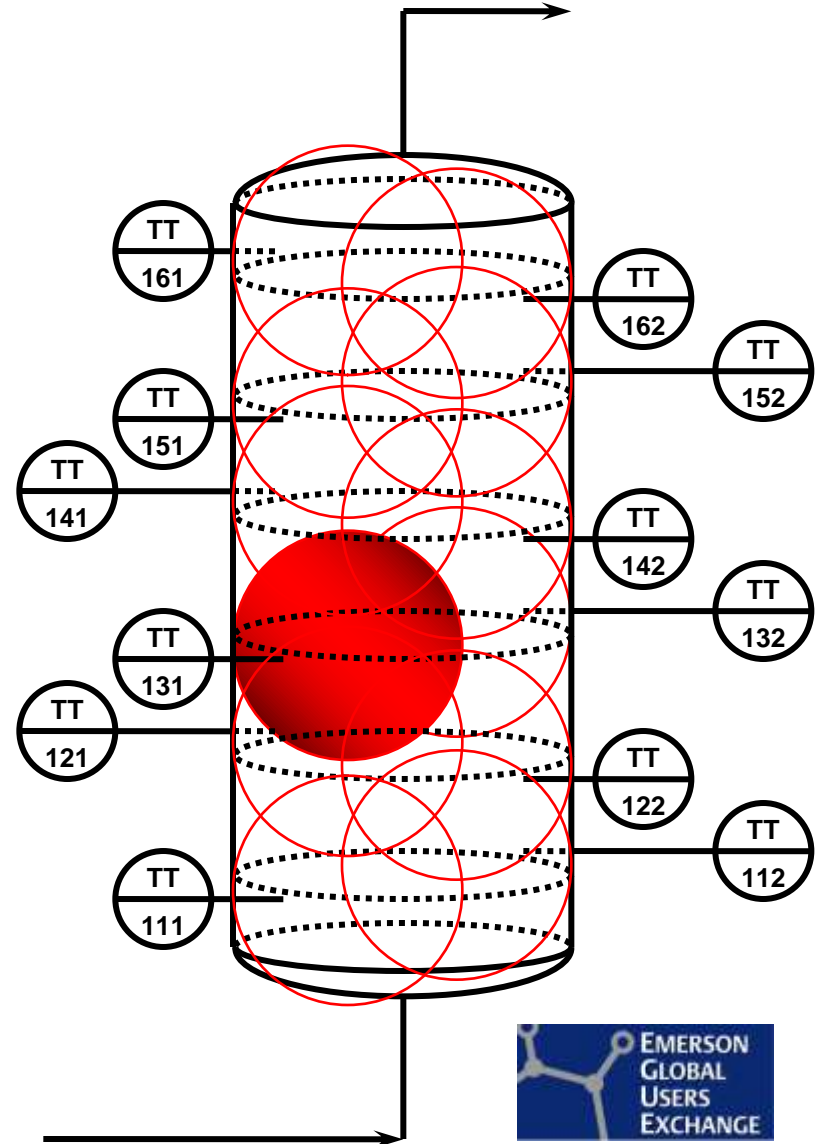
- Three sensors per elevation, staggered
  - Even fewer elevations
  - Still more sensors altogether



# *There are more adjacent sensors...*

Two sensors per elevation,  
staggered

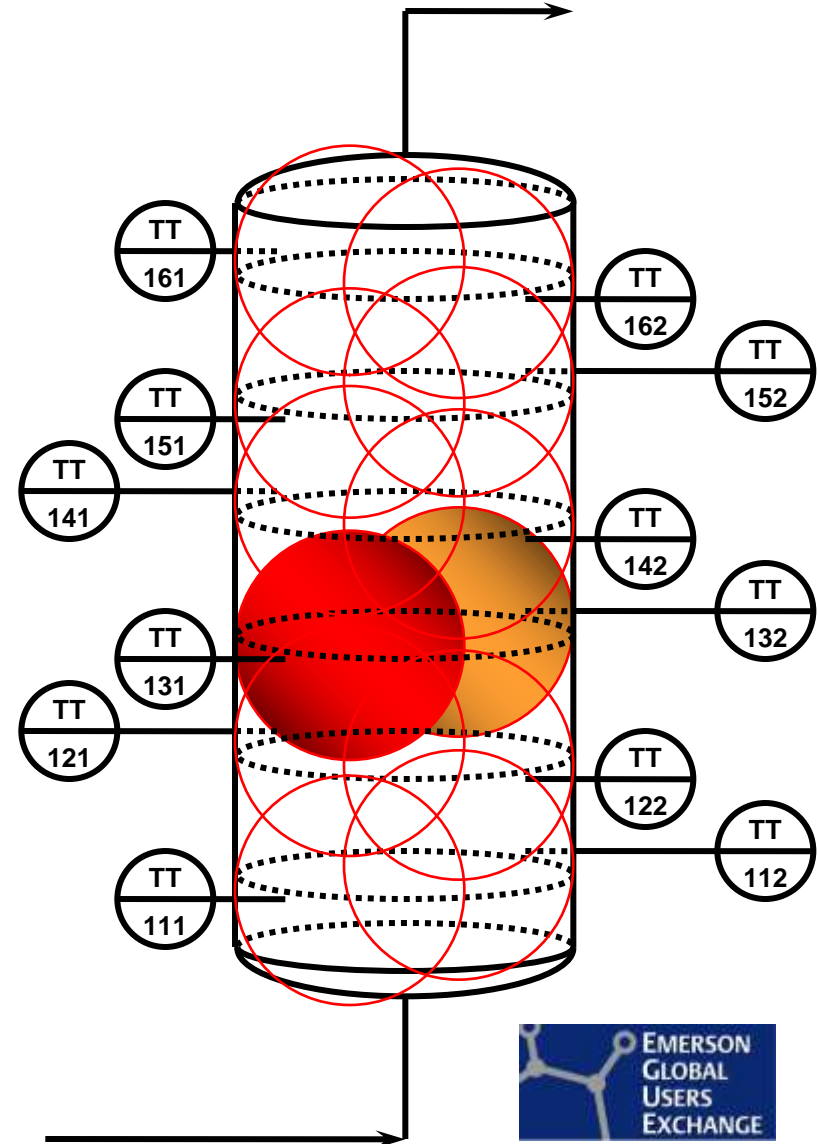
- Primary sensor



# *There are more adjacent sensors...*

Two sensors per elevation,  
staggered

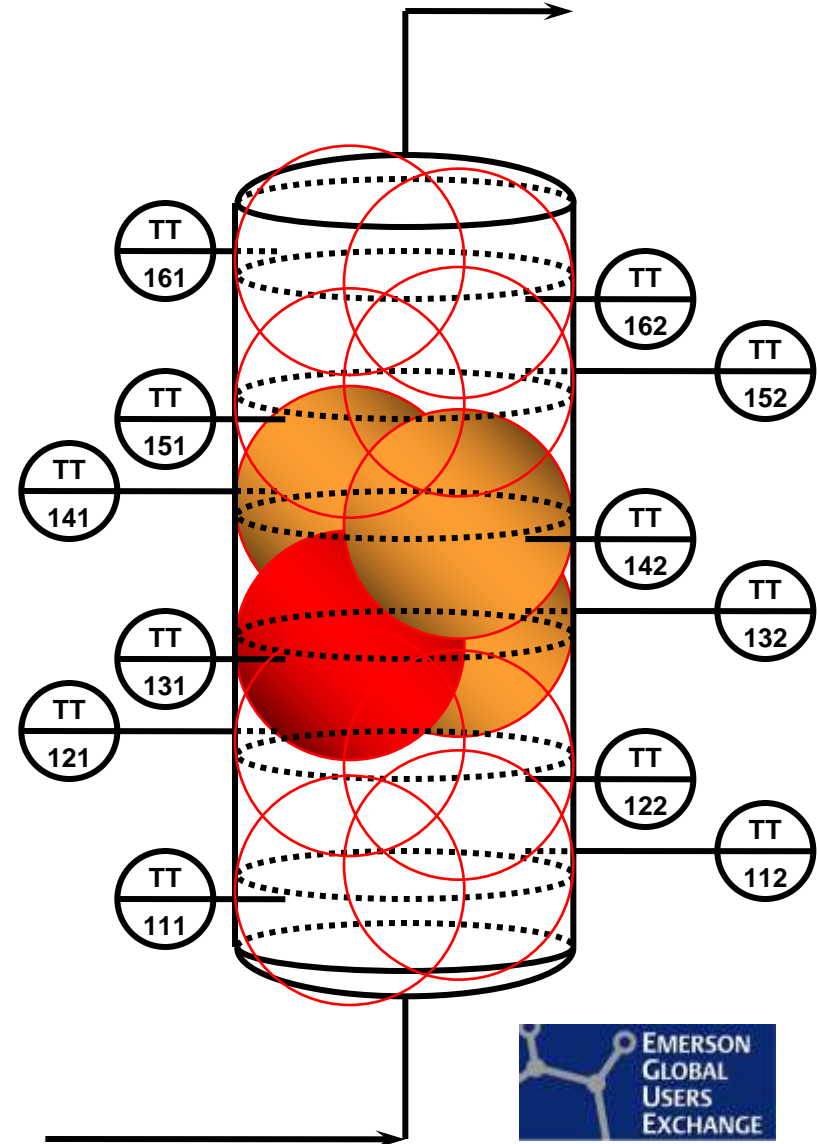
- Primary sensor
- Backed up by
  - One secondary sensor at the same elevation



# *There are more adjacent sensors...*

Two sensors per elevation,  
staggered

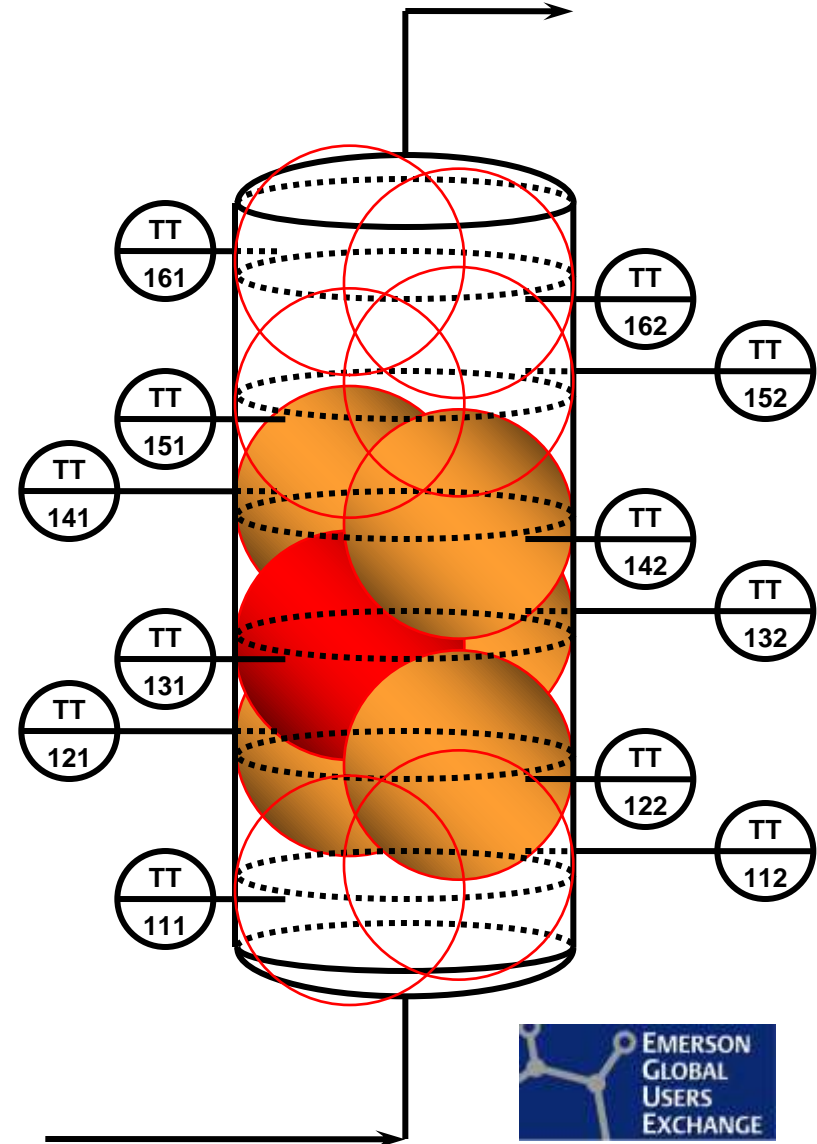
- Primary sensor
- Backed up by
  - One secondary sensor at the same elevation
  - Two secondary sensors at the elevation above



# *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

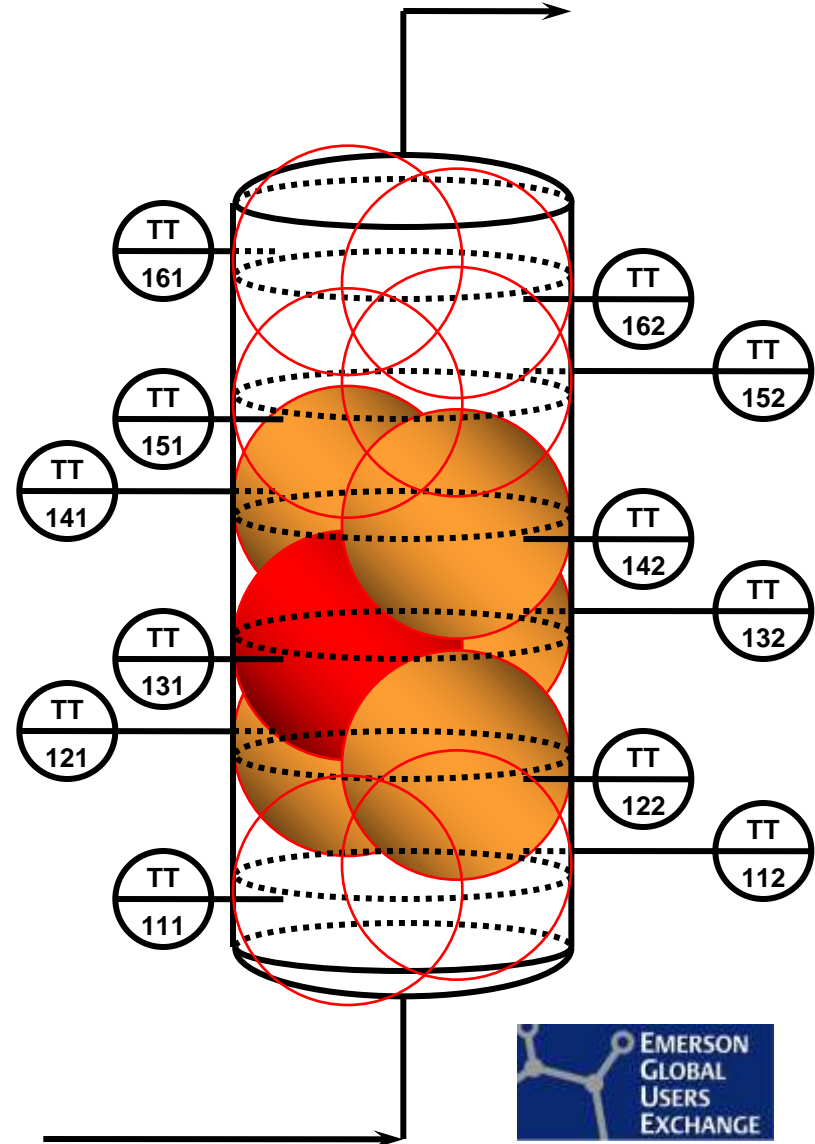
Two sensors per elevation,  
staggered

So,

- Voting is based on 1006 architecture

But,

- $PFD_{AVG}$  calculation is based on 1002 architecture
- Fault tolerance is also based on 1002 architecture—one

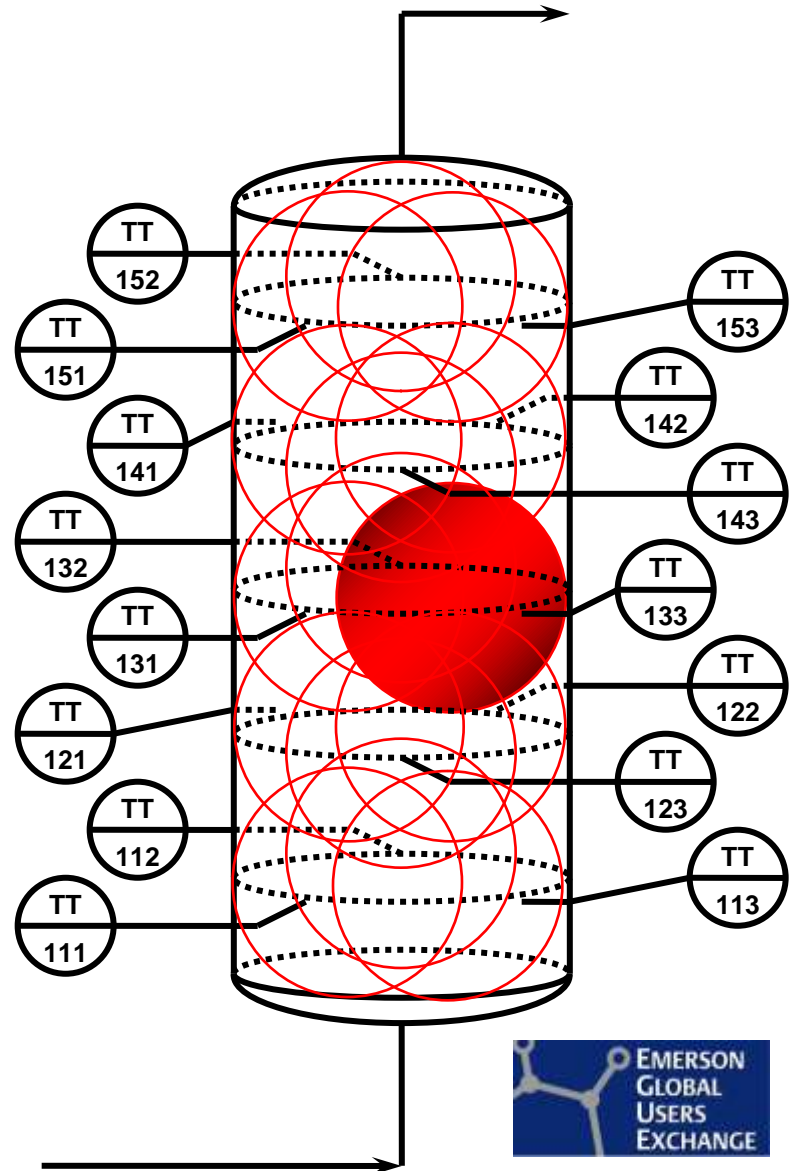




# *With even more adjacent sensors...*

Three sensors per elevation,  
staggered

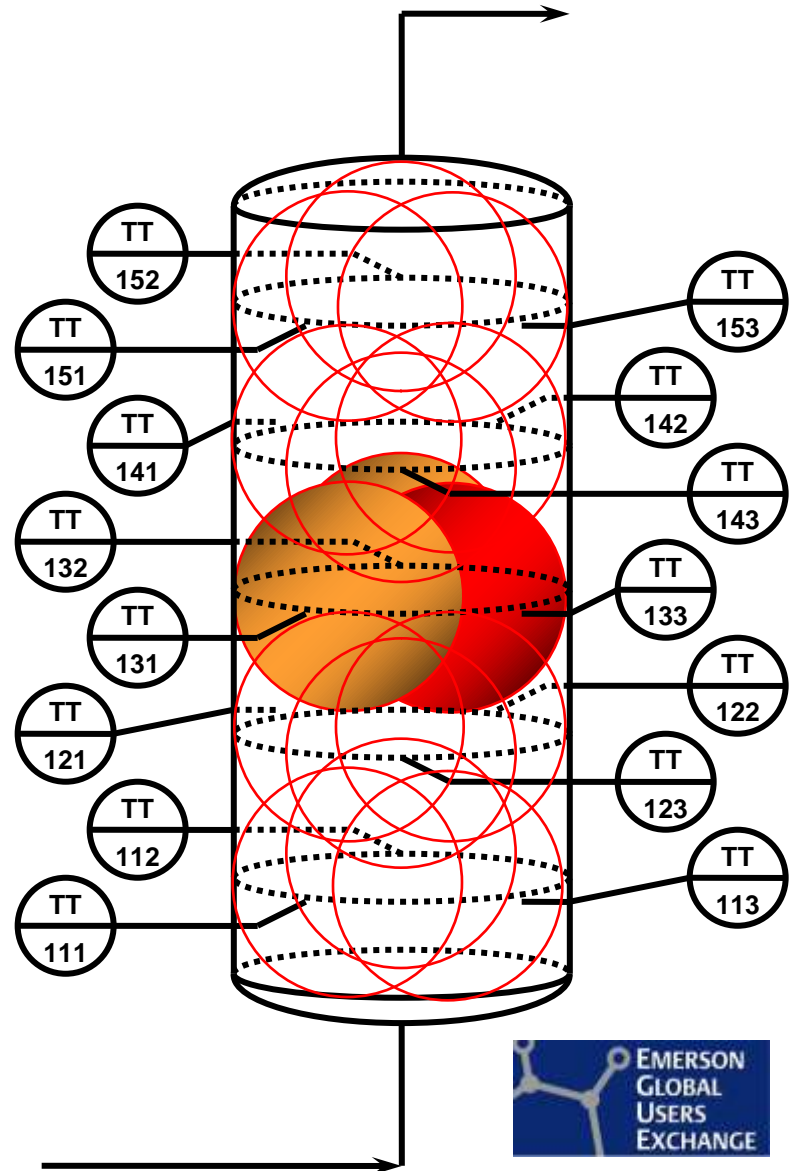
- Primary sensor



## *With even more adjacent sensors...*

Three sensors per elevation,  
staggered

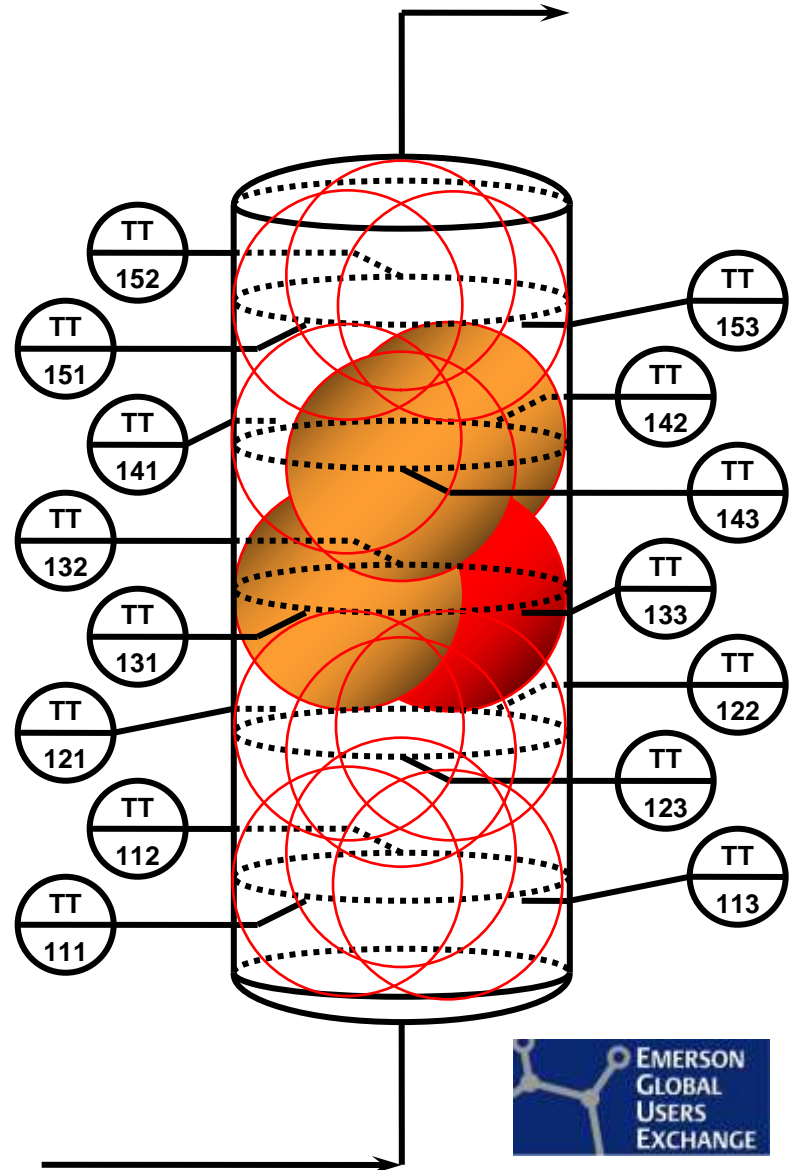
- Primary sensor
- Backed up by
  - Two secondary sensors at the same elevation



## *With even more adjacent sensors...*

Three sensors per elevation,  
staggered

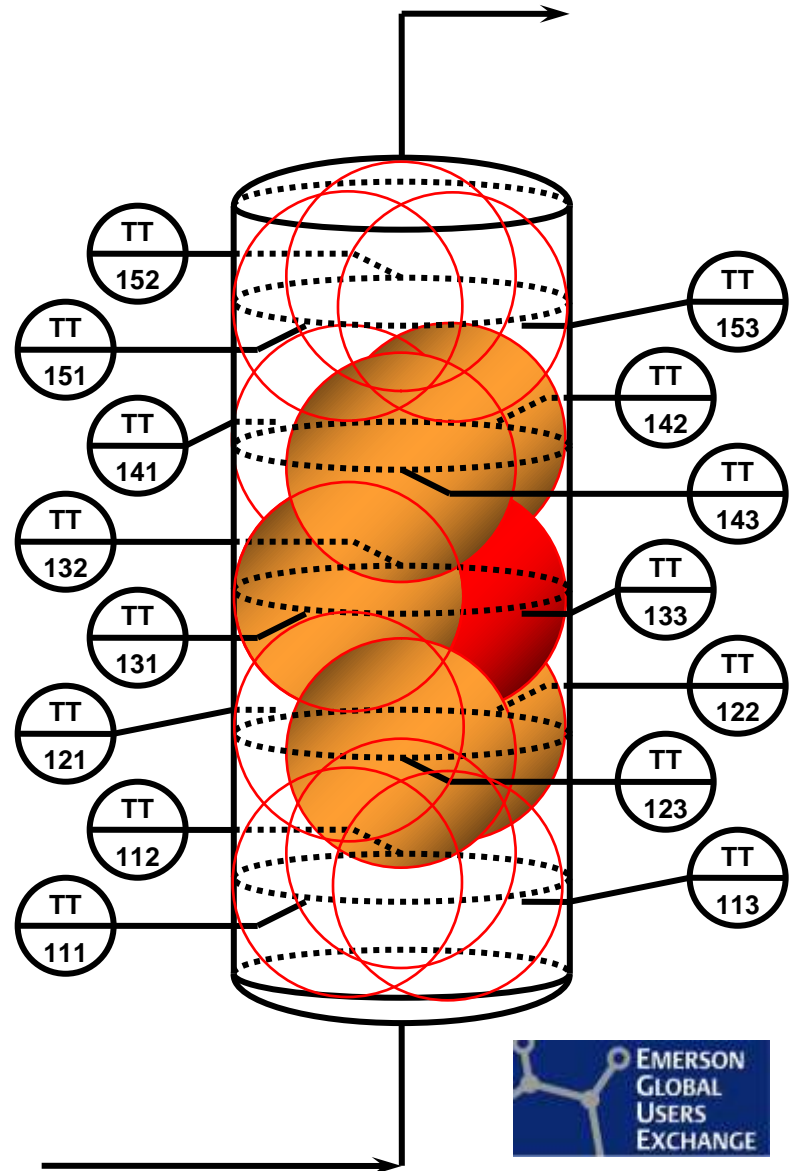
- Primary sensor
- Backed up by
  - Two secondary sensors at the same elevation
  - Two secondary sensors at the elevation above



## *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

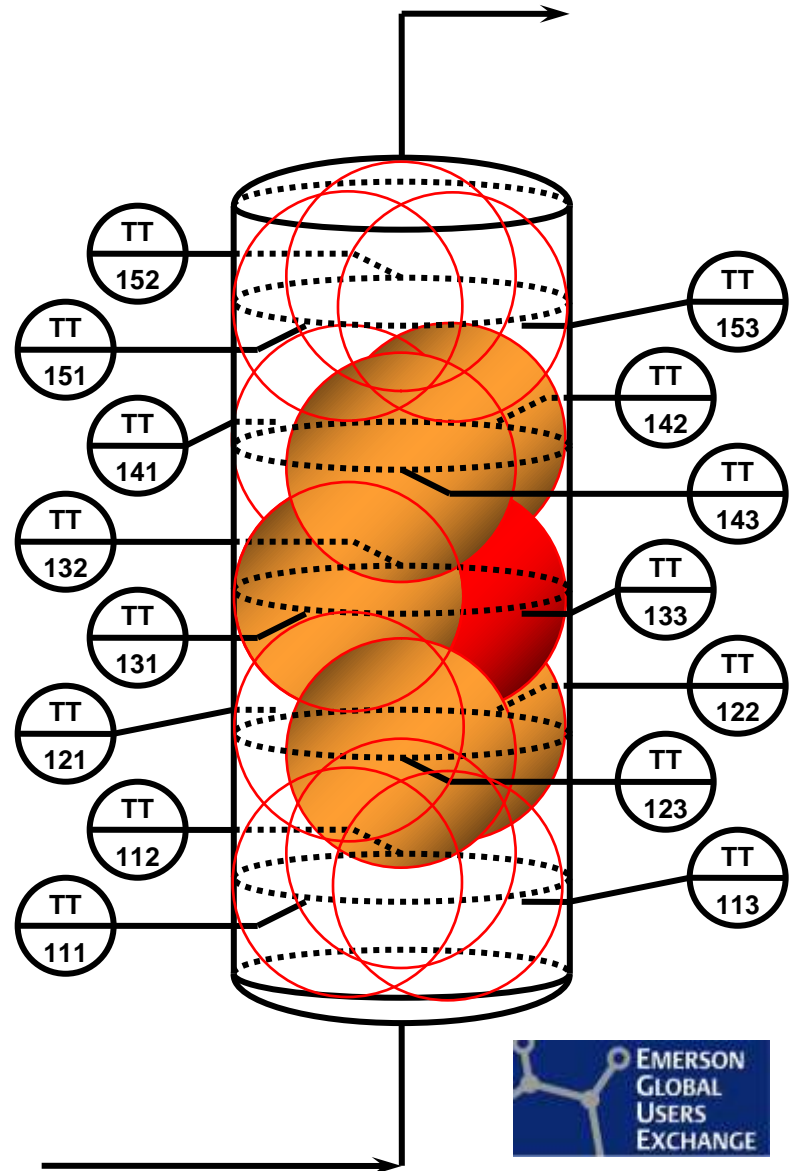
Three sensors per elevation,  
staggered

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***

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- Basic design has sensors spaced as widely as possible
  - There are no secondary sensors
  - There is no fault tolerance
  - Voting is 1001 and  $PFD_{AVG}$  is based on 1001
- 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 100( $X+1$ ), while  $PFD_{AVG}$  is based on 1002
- True, regardless of overall size of array

# Some notes on spacing

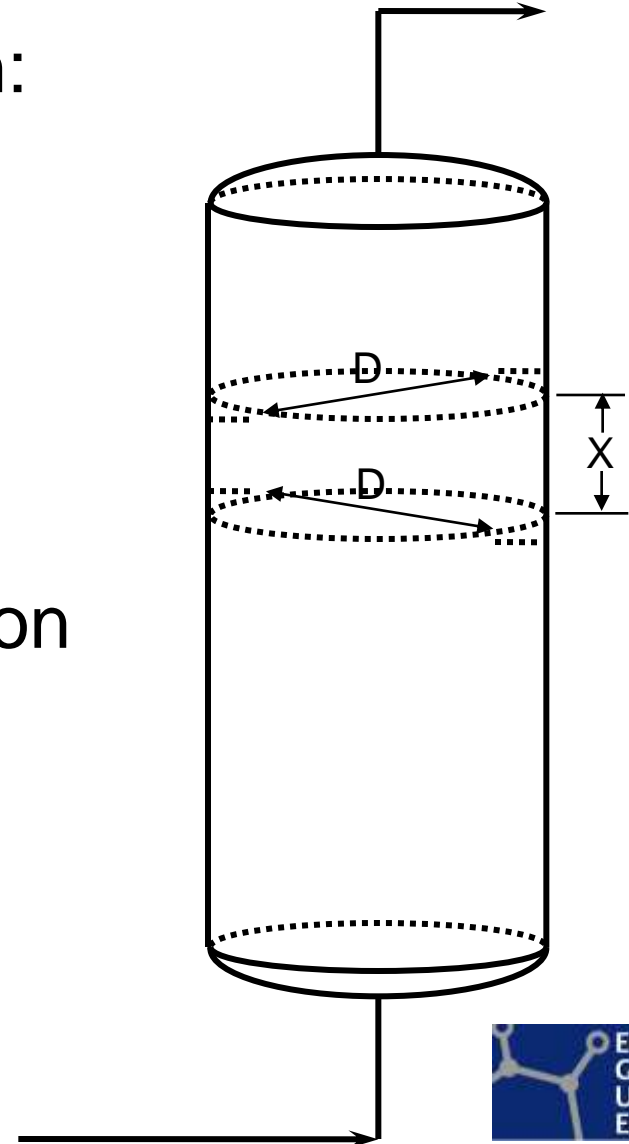
Two sensor, staggered design:

When

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

Ideally,

$$X \sim 0.7D$$



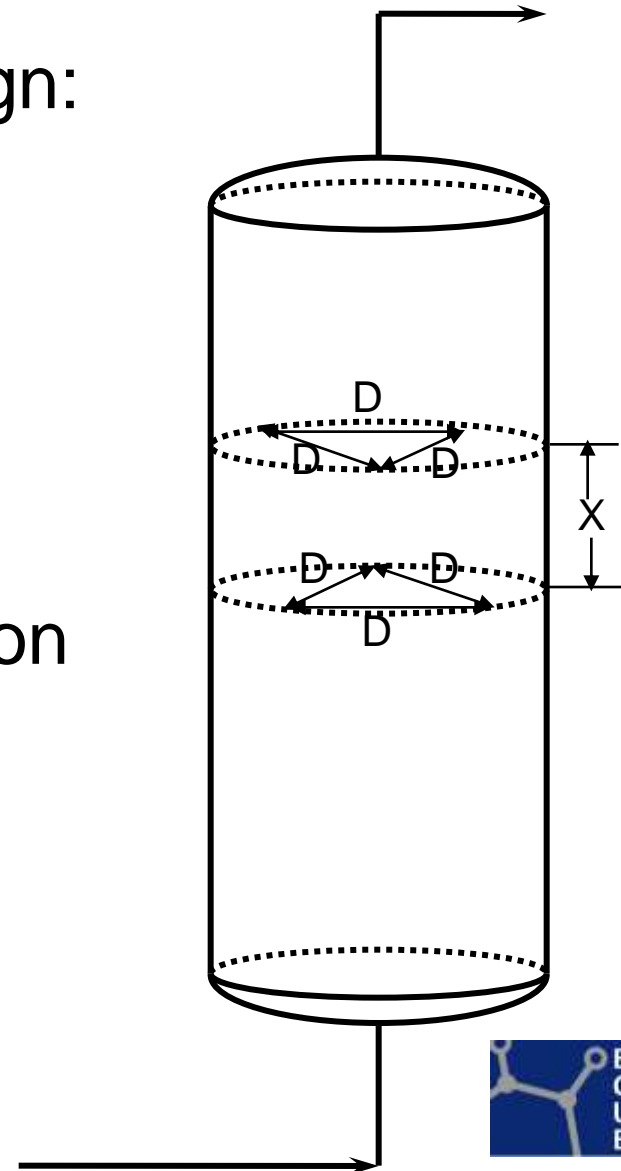
Three sensor, staggered design:

When

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

Ideally,

$$X \sim 0.8D$$





## ***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.

- 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*

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### 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*

- 1001  $PFD_{AVG} = \lambda T/2$
- 1002  $PFD_{AVG} = (\lambda T)^2/3$
- 2002  $PFD_{AVG} = \lambda T$
- 1003  $PFD_{AVG} = (\lambda T)^3/4$
- 2003  $PFD_{AVG} = (\lambda T)^2$
- 3003  $PFD_{AVG} = 3\lambda T/2$
- 1004  $PFD_{AVG} = (\lambda T)^4/5$
- 2004  $PFD_{AVG} = (\lambda T)^3$
- 3004  $PFD_{AVG} = 2(\lambda T)^2$
- 4004  $PFD_{AVG} = 2\lambda T$
- 100N  $PFD_{AVG} = (\lambda T)^N/(N+1)$
- 200N  $PFD_{AVG} = (\lambda T)^{N-1}$
- 300N  $PFD_{AVG} = N(\lambda T)^{N-2}/2$
- M00N  $PFD_{AVG} = (N!/(M-1)!/(N-M+1)!)(\lambda T)^{N-M+1}/(N-M+2)$
- N00N  $PFD_{AVG} = N\lambda T/2$
- Note that  $PFD_{AVG}$  can be summed, but not multiplied.

## Subsystems with diverse components

$$1001 \quad \text{PFD}_{\text{AVG}} = \lambda T/2$$

$$1002 \quad \text{PFD}_{\text{AVG}} = \lambda_1 \lambda_2 T^2/3$$

$$2002 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 + \lambda_2) T/2$$

$$1003 \quad \text{PFD}_{\text{AVG}} = \lambda_1 \lambda_2 \lambda_3 T^3/4$$

$$2003 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_1 \lambda_3) T^2/3$$

$$3003 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 + \lambda_2 + \lambda_3) T/2$$

$$1004 \quad \text{PFD}_{\text{AVG}} = \lambda_1 \lambda_2 \lambda_3 \lambda_4 T^4/5$$

$$2004 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 \lambda_2 \lambda_3 + \lambda_1 \lambda_2 \lambda_4 + \lambda_1 \lambda_3 \lambda_4 + \lambda_2 \lambda_3 \lambda_4) T^3/4$$

$$3004 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_1 \lambda_4 + \lambda_2 \lambda_3 + \lambda_2 \lambda_4 + \lambda_3 \lambda_4) T^2/3$$

$$4004 \quad \text{PFD}_{\text{AVG}} = (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) T/2$$

$$100N \quad \text{PFD}_{\text{AVG}} = \lambda_1 \lambda_2 \lambda_3 \dots \lambda_N T^N / (N+1)$$

$$N00N \quad \text{PFD}_{\text{AVG}} = (\lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_N) T/2$$

- Note that  $\text{PFD}_{\text{AVG}}$  can be summed, but not multiplied.