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# Tunnel Fire Dynamics and Evacuation Simulations

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DGS-SEE Seminar on Fire Protection for Physics Research Facilities

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# Introduction (Background)

- Presentation data based on Hughes Associations Inc. (HAI) report and presentation of May 2010, in support of a International Linear Collider (ILC) conceptual design addressing a single tunnel 100m (328ft.) and 30m (100ft.) below the surface
- Main LINAC & Damping Ring Tunnel diameter sizes included 4.5m (14.75ft), 5.0m (16.4ft) 5.5m (18ft), and 6.5m (21.3ft)
- Total ILC Tunnel length 29.6km (18 miles)
- Pumps, oil filled transformers, mineral oil, office furniture, office related equipment (significant combustible loads) will be located above ground

# Goals

- Understand the spread of fire and smoke in the Main LINAC and Damping Ring tunnels
  - Understand fire and smoke behavior for a range of tunnel diameters
- Determine the fire size required to create untenable conditions in the tunnel before occupants can evacuate
- Analyze the fuel loads in the Main LINAC and damping ring tunnels and base caverns and assess fire scenarios
- Develop guidelines for tunnels and base caverns that will allow occupants in the tunnel to evacuate safely in the event of a fire

# Approach

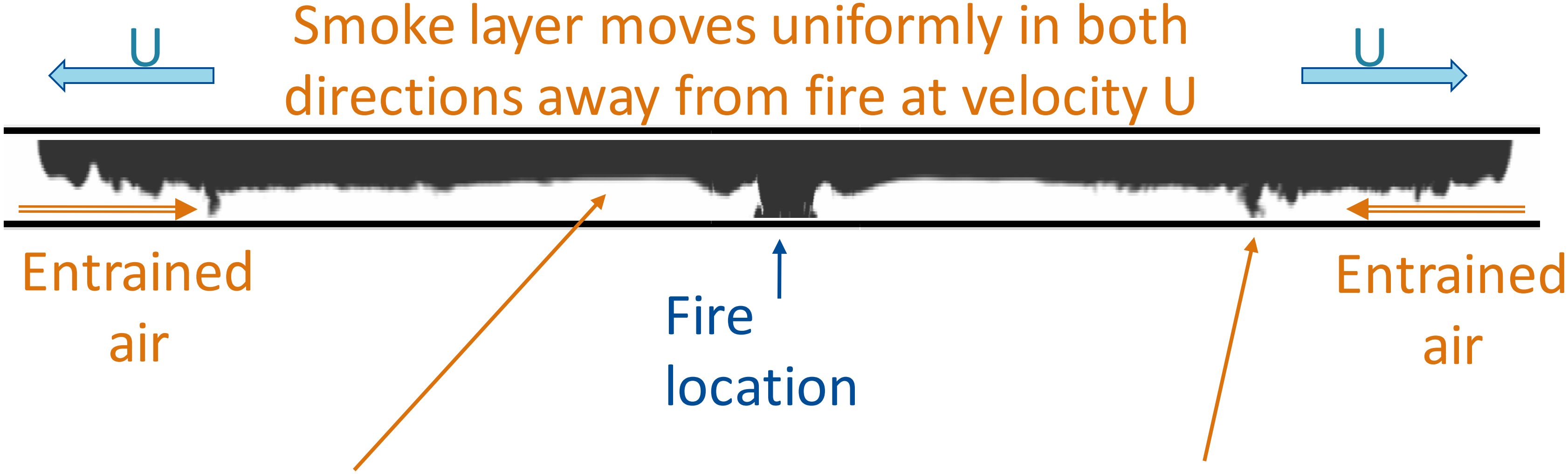
- Research tunnel fire dynamics
- Model representative tunnel fire scenarios using FDS to analyze the effects of:
  - Smoke movement
  - Fire size
  - Fire location (tunnel or base cavern)
- Determine the time required for occupants to evacuate
- Determine the maximum fire size that will allow occupants to evacuate safely

# References (Partial)

- Beard A. and Carvel R., “The Handbook of Tunnel Fire Safety,” Thomas Telford Publishing, London 2005
- Hu, L., H., Huo, R., Chow, W.K., Wang, H.B., & Yang R.X, “Decay of Buoyant Smoke Layer Temperature along the Longitudinal Direction in Tunnel Fires,” Journal of Applied Fire Science, 2005
- Babrauska V., “Heat Release Rates,” Chapter 3, Society of Fire Protection Engineering Handbook of Fire Protection Engineering 4th Edition, National Fire Protection Association (NFPA) Quincy, MA 2008
- Bryan, J. “Behavioral Response to Fire and Smoke,” Chapter 12, Society of Fire Protection Engineering Handbook of Fire Protection Engineering 4th Edition, National Fire Protection Association (NFPA) Quincy, MA 2008

# Tunnel Fire Dynamics

- Smoke movement in level, naturally ventilated tunnels



U

Smoke layer moves uniformly in both directions away from fire at velocity U

U

Entrained air

Fire location

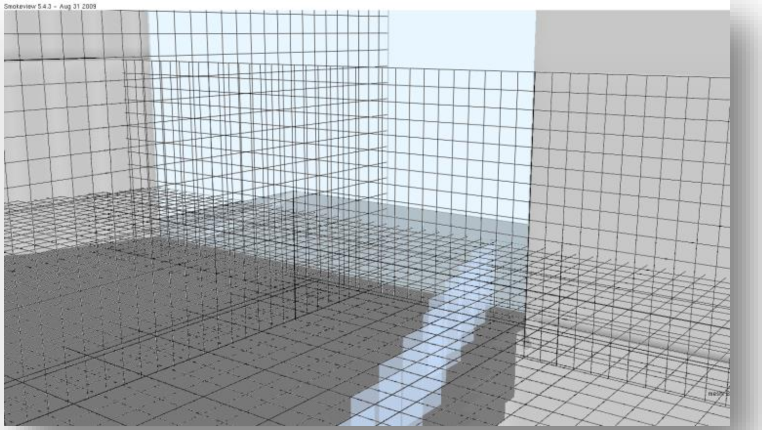
Entrained air

Near the fire, the smoke layer is hot (strong buoyancy) and remains close to the ceiling with little mixing.

As the smoke moves away from the fire, cooling occurs causing smoke to loose buoyancy. Descending smoke mixes with the entrained air and is drawn back towards the fire. This is referred to as “back-layering”

# Fire Dynamics Simulator (FDS) (How)

- Developed by the National Institute of Standards and Technology (NIST)
  - Computational fluid dynamics (CFD) software
  - Specifically formulated to calculate heat and smoke transport from fires
  - Extensively validated against experimental data
- Model comprised of one or more numerical domains (meshes)
  - Each domain divided into rectilinear numerical grid

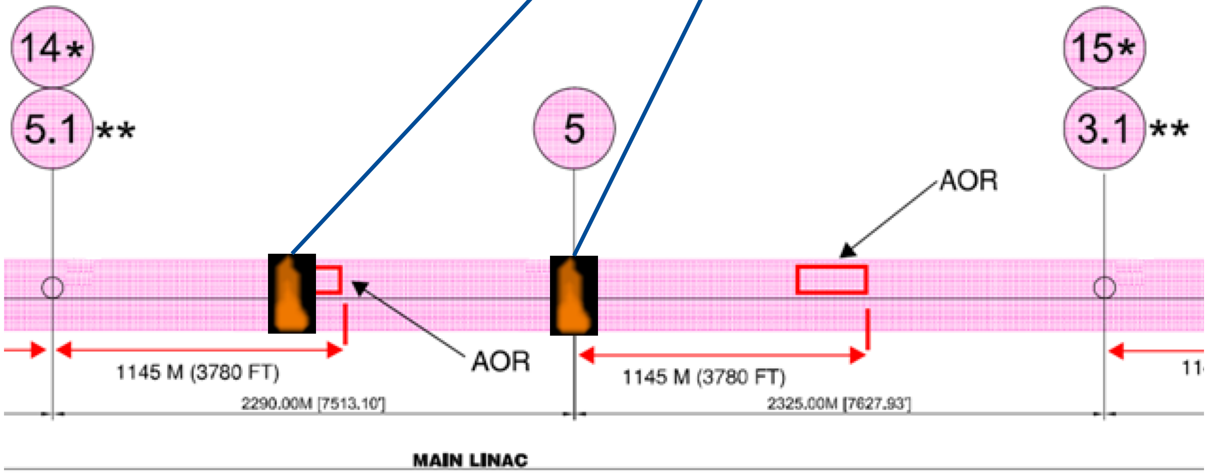


# Main LINAC Fire Scenarios

- Representative fire scenarios
  - Model using the Fire Dynamics Simulator (FDS)

**Scenario 1:** Fire located between vertical exits representing the maximum travel distance to vertical exits

**Scenario 2:** Fire in base cavern represents the maximum travel distances for occupants to area of refuge (AOR)

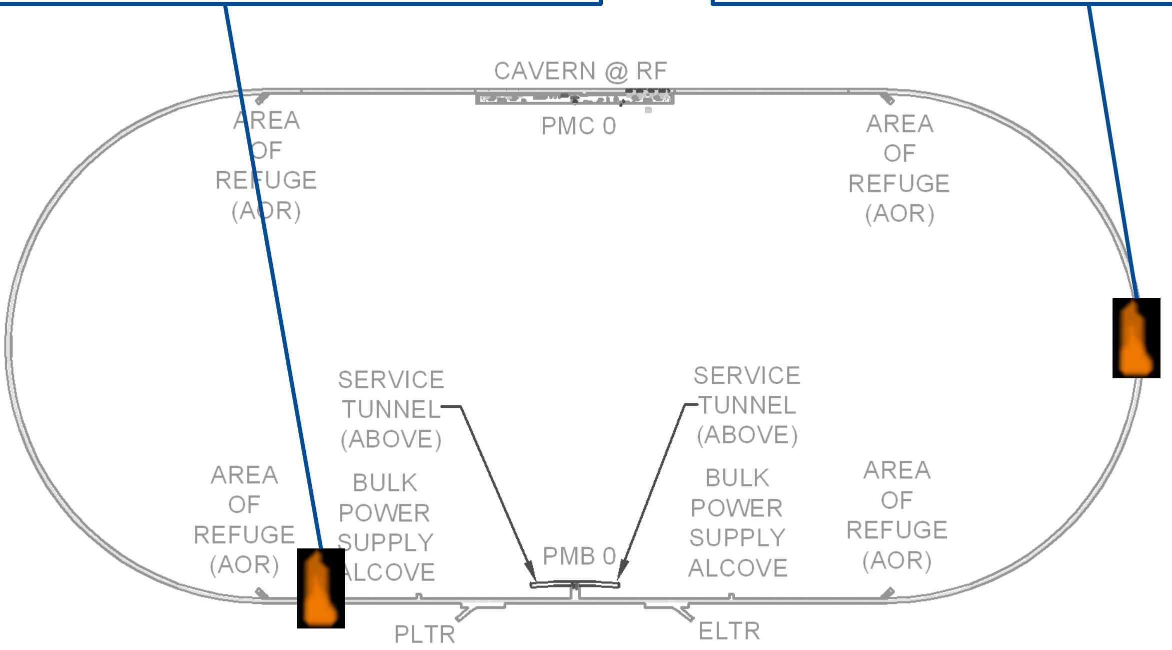


# Damping Ring Fire Scenarios

- Representative fire scenarios
  - Fire scenarios not modeled in damping ring base cavern and straight section housing wigglers since it is isolated from open tunnel areas by isolation barriers

**Scenario 1:** Fire located in straight portion of damping ring

**Scenario 2:** Fire located in curved portion of damping ring



# Fire Model: Potential Fire Scenarios

- Cable Tray Fires
  - Low cable loadings
  - Cables embedded under concrete floors or encased in rigid conduit
- Miscellaneous Combustibles
  - Trash
  - Other combustibles

- Pool / spill fires
  - Rapid growth
  - Primary fuel present is transformer oil (mineral oil)
  - Multiple components in ILC tunnel and base cavern contain oil
  - One 76 meter section of tunnel may contain up to 470 gallons of oil
  - Largest quantity of oil in single component is a 100 gallon tank housed in a step down transformer
- **Pool / spill fires represent the most demanding fire scenarios**

# Pool/Spill Fires

- Pool fires are defined as the burning of liquids in a contained area (i.e. dike) → burning area is constant
- Spill fires refer to the burning of an unconfined area of liquid fuel
  - Continuous spill → burning is fed by a flow of spilling fuel
  - Unconfined spill → fixed volume of fuel is spilled on a surface and burns until fuel is consumed
- Pool/spill fires grow to peak size at rapid rate
  - Model fires as instant growth, steady burning
- Incremental fire sizes simulated for each scenario in FDS model
  - **Determine maximum fire size which allows for safe egress of tunnel occupants**
  - **Determine maximum pool fire area**
  - **Determine maximum spill rate**

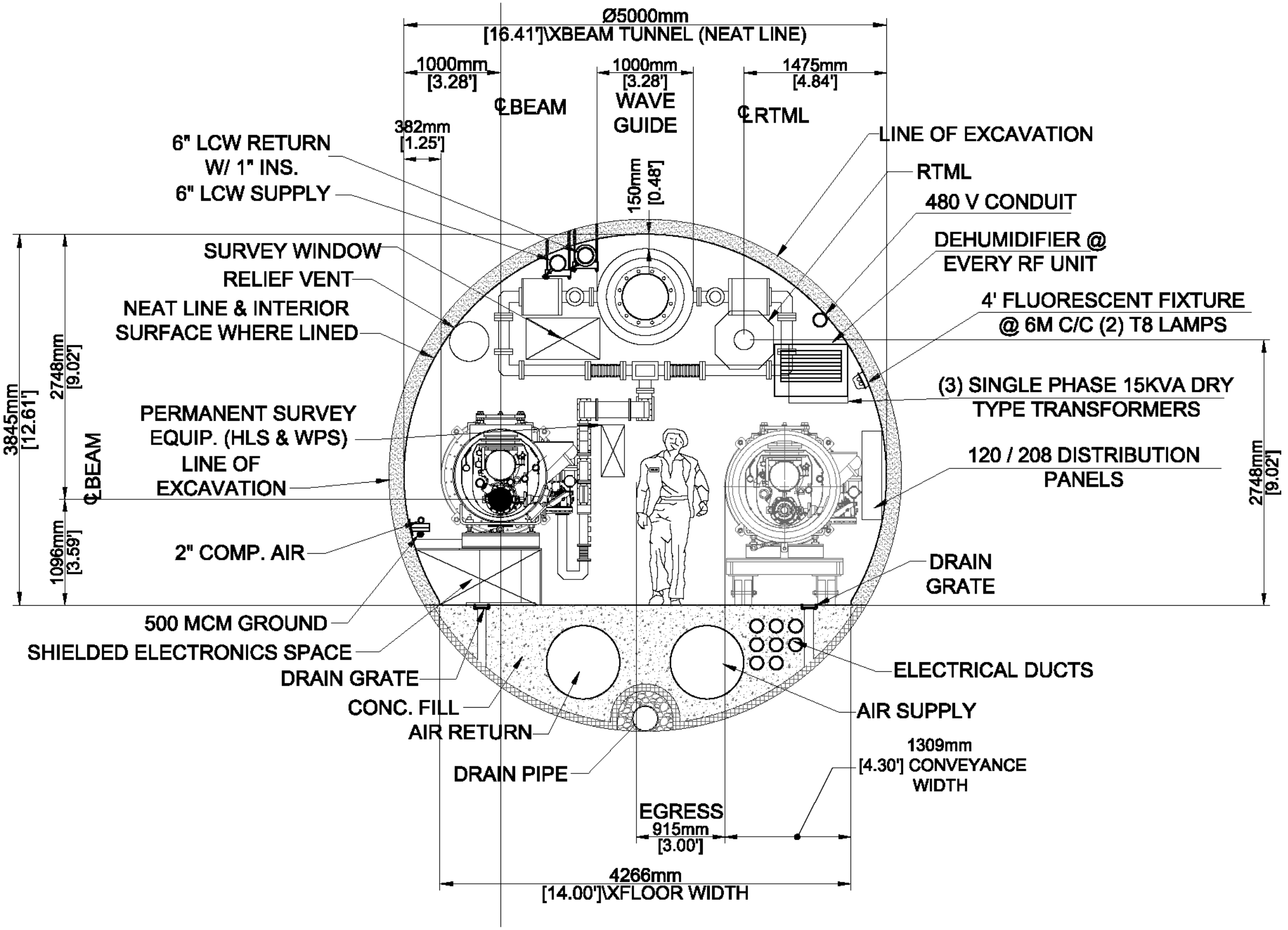
# Fire Modeling Approach

- Create tunnel geometry in FDS
  - Tunnel geometry remote from fire incorporating 12.7cm (5 inches) x 12.7cm (5 inches) x 30cm (12 inch) cells
- Model Main LINAC, base caverns, and Damping Ring for a range of tunnel diameters
  - 4.5m (14.75ft), 5.0m (16.4ft) 5.5m (18ft), and 6.5m (21.3ft) tunnel diameters
- Model tunnel length of 500m (1,600ft.) to determine maximum smoke filling rates.
- Determine expected occupant travel speeds and use FDS models to determine maximum fire size that can be tolerated such that the smoke travel rate is less than the occupant travel speed.

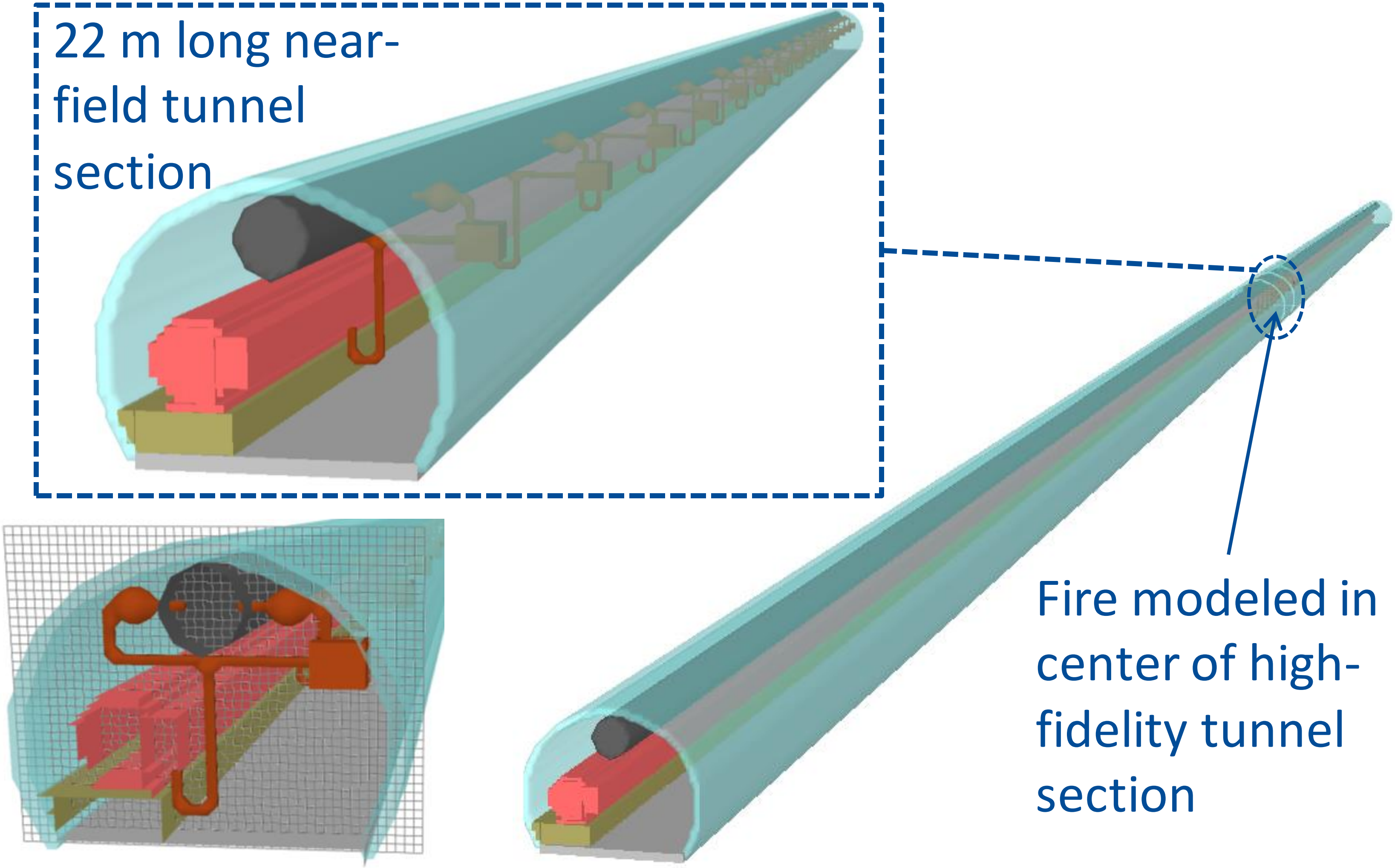
# Assumptions and Limitations

- Hughes recommends sprinkler protection throughout; however, 5m diameter tunnel was also modeled without sprinklers
- Excludes any construction scenario
- Tunnel Ventilation
  - Airflow velocities were assumed to be less than 1 m/s
  - Smoke exhaust is not modeled, nor assumed to be provided
  - Airflow effects in tunnel caused by temperature-driven flow in vertical shafts and/or wind effects above ground were not considered – vertical shafts were considered sealed
  - No considered for smoke may vent from the base cavern fire into vertical access shafts – again access shafts were considered sealed

# Main LINAC Section Drawing



# Main LINAC Tunnel FDS Geometry



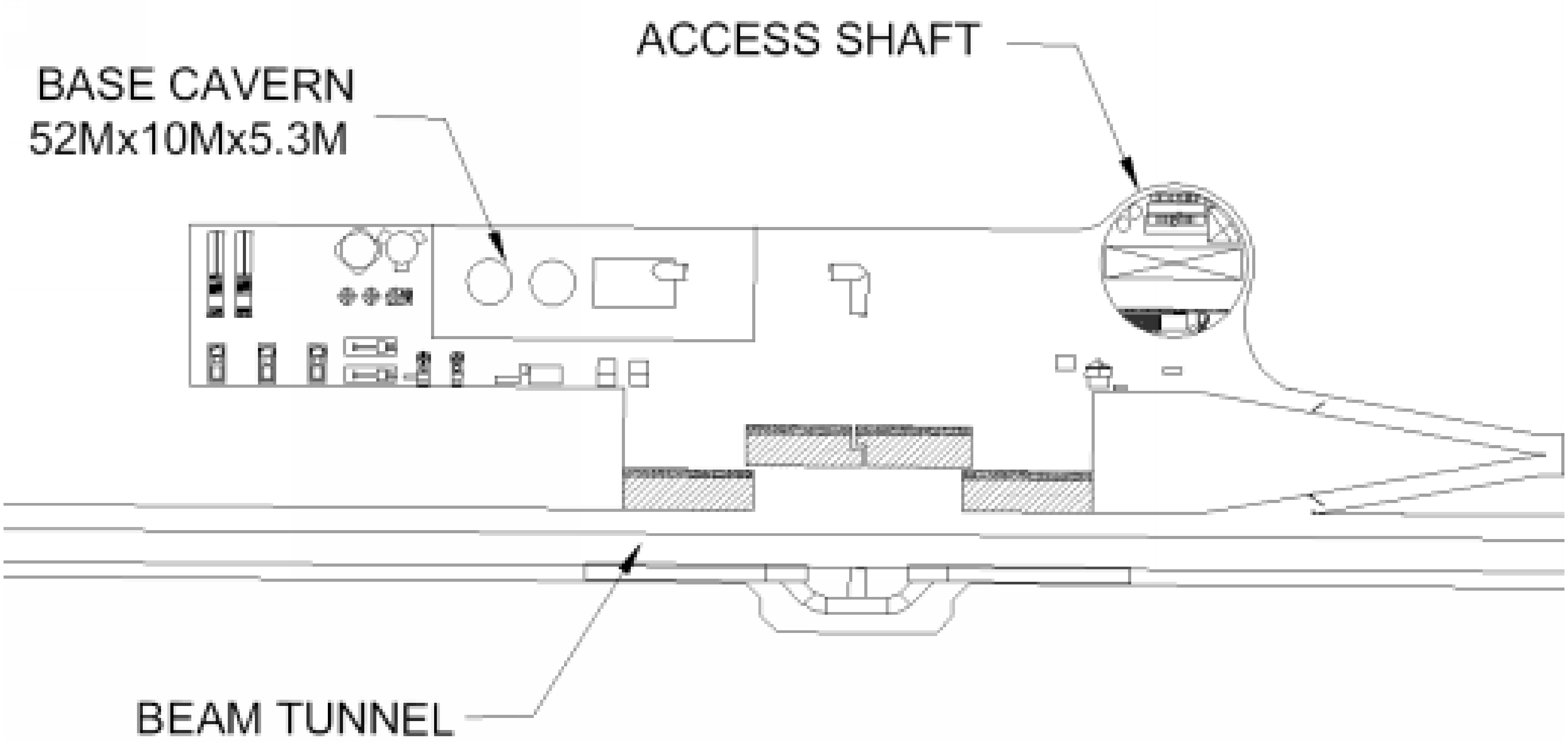
22 m long near-field tunnel section

Fire modeled in center of high-fidelity tunnel section

12.7cm cells – isometric view showing grid

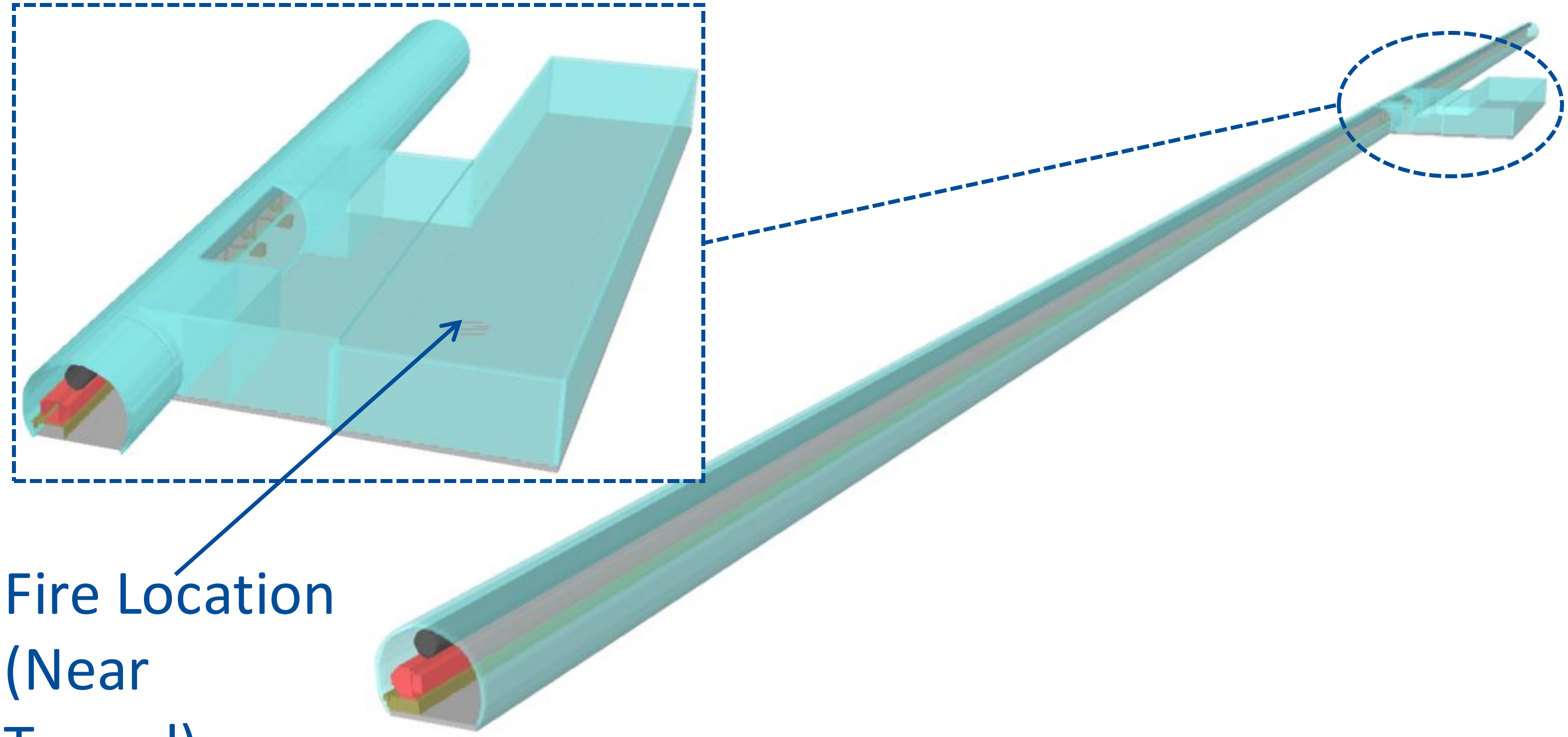
400 m long tunnel section.

# Base Cavern



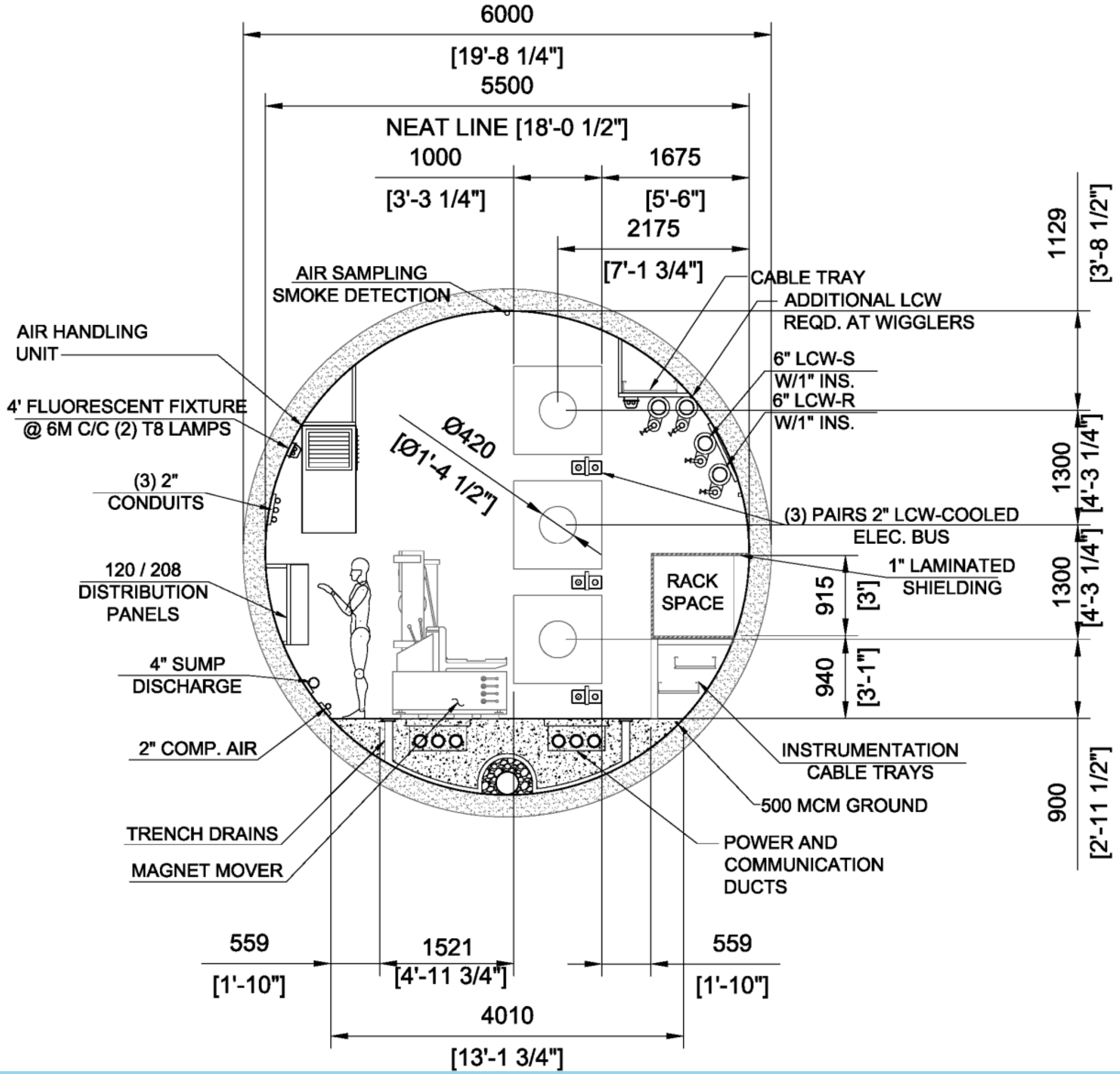
# Base Cavern and Tunnel FDS Geometry

Base cavern height assumed to be approximately the same height as tunnel



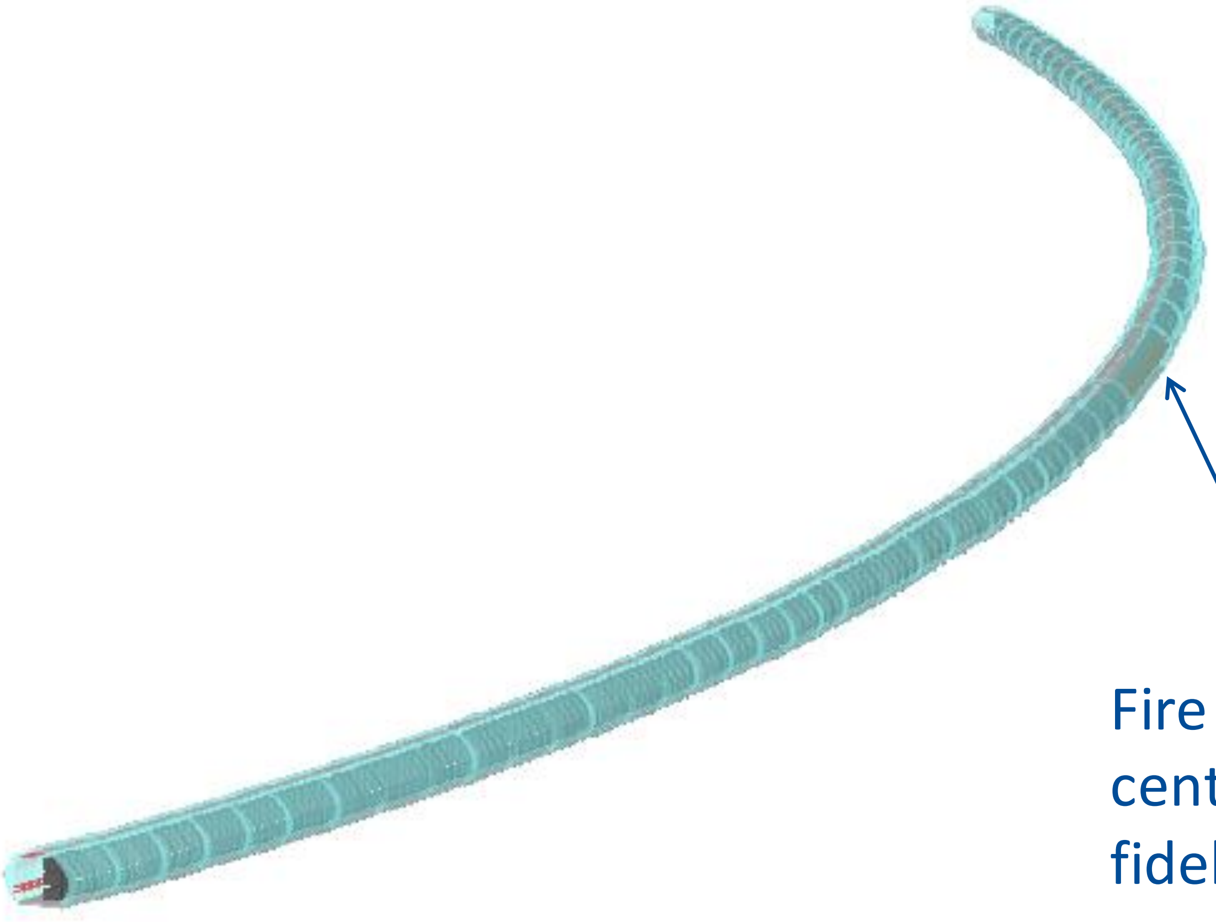
Fire Location (Near Tunnel)

# Damping Ring Drawing Section



# Curved Damping Ring Tunnel FDS Geometry

- Curved and straight tunnel sections modeled



Fire located in center of high-fidelity tunnel section

# Straight Damping Ring Tunnel FDS Geometry

- Curved and straight tunnel sections modeled

Fire located in center of high-fidelity tunnel section

# Occupant Egress

- Occupant load of 50 people per egress area (tunnel space between two shafts)
  - Approximately 70 $m^2$ (753.5 sq. ft.) per occupant
- Given the low occupancy load in the tunnel:
  - Queuing (congestion) would not occur in tunnel during an emergency
  - Occupant travel speeds would be consistent with normal “walking speeds” on uncongested, level pathways
    - **Occupant loadings of lesser density than 3.3 $m^2$ (35.5 sq. ft.) per occupant would not be expected to reduce travel speeds**
- Occupant characteristics
  - Occupants are generally assumed to be able-bodied adults who are awake and aware of their surroundings
  - It is possible that occupants may be injured during an evacuation causing reduced walking speeds

# Walking Speed

- A review of data on walking speeds indicates:
  - Average walking speeds of **1 m/s** to **1.4 m/s** for adults without locomotion disabilities
  - Average walking speed of **0.95 m/s** for adults with crutches or with a locomotion disability requiring no walking aid
  - Average walking speed of **0.72 m/s** for adults with locomotion disability who require pauses for rest
- Walking speed criteria for analysis
  - **1 m/s** to escape from area of fire origin and beyond initial "back-layering" of smoke
  - **0.7 m/s** once the occupant has moved beyond initial "back-layering" to allow for brief rest periods without being overcome by smoke

# Tenability Criteria

- The rate at which tenability decreased in the tunnel was assessed using the following criteria.
  - Quantities measured 1.8 meter (6 feet) above floor
- Visibility is the critical tenability criterion (i.e. visibility is lost before other tenability criteria are exceeded)
  - Results presented in terms of visibility

| Criteria | Limit |
|---|---|
| Temperature | < 76 °C (168 °F) |
| CO Concentration | < 1,200 ppm |
| $O_2$ Concentration | > 17% by volume |
| Visibility | > 10 m (30 ft) |

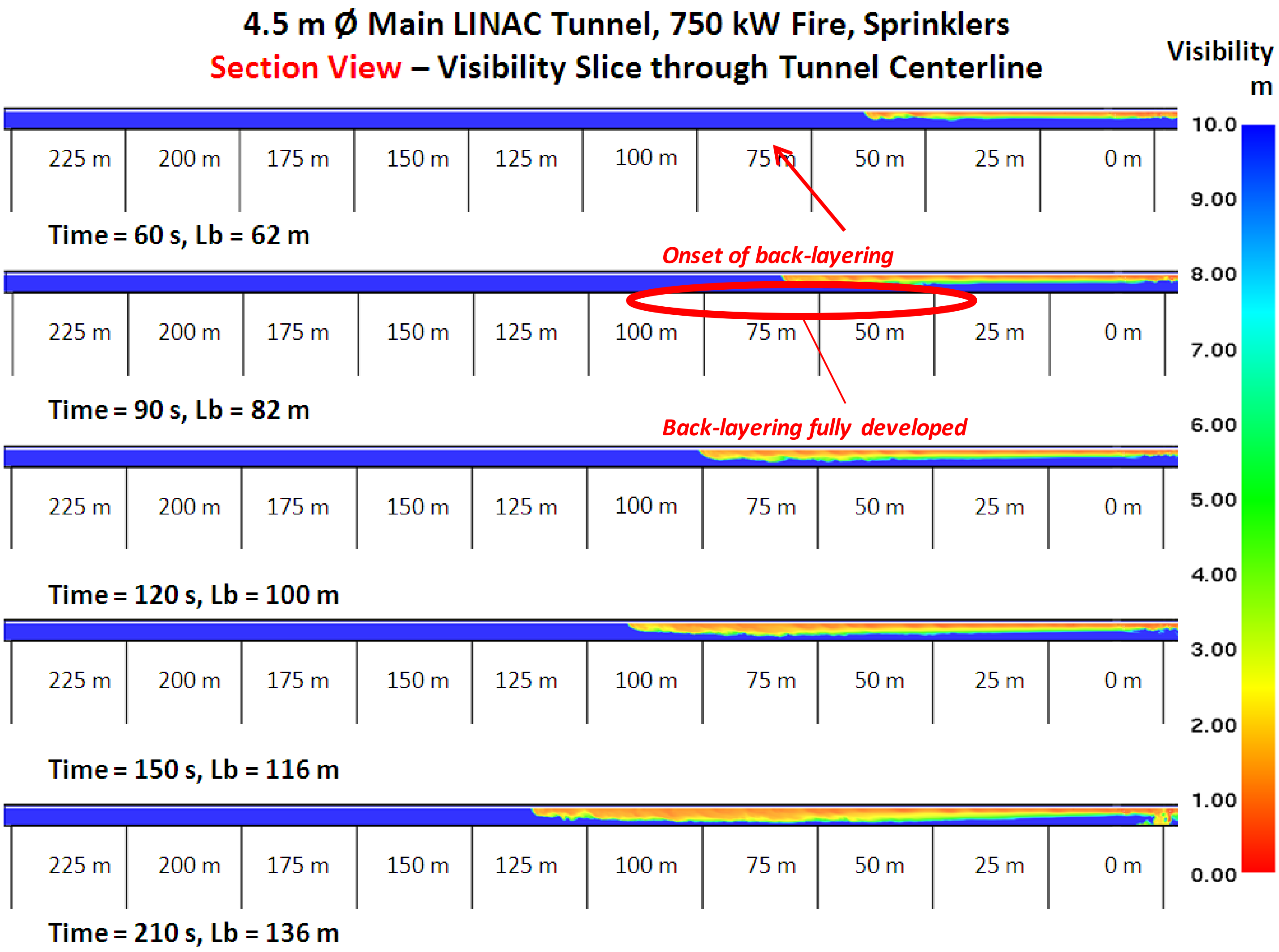
# Results of FDS Modeling

- For each tunnel diameter modeled, the maximum fire size which can be sustained while allowing occupants to outrun smoke was calculated
  - Corresponding pool fire sizes and spill volumes were calculated

- Sprinklers cool the smoke layer but only have a moderate effect on slowing the spread of smoke down the tunnel
  - Sprinklers would be expected to limit fire spread

- Limiting fire sizes calculated for the Main LINAC were the same as those for the straight damping ring sections
  - Fire size is a more important driver than tunnel obstructions

# Main LINAC Tunnel Fire Results



4.5 m Ø Main LINAC Tunnel, 750 kW Fire, Sprinklers

Section View – Visibility Slice through Tunnel Centerline

Time = 60 s, Lb = 62 m

*Onset of back-layering*

Time = 90 s, Lb = 82 m

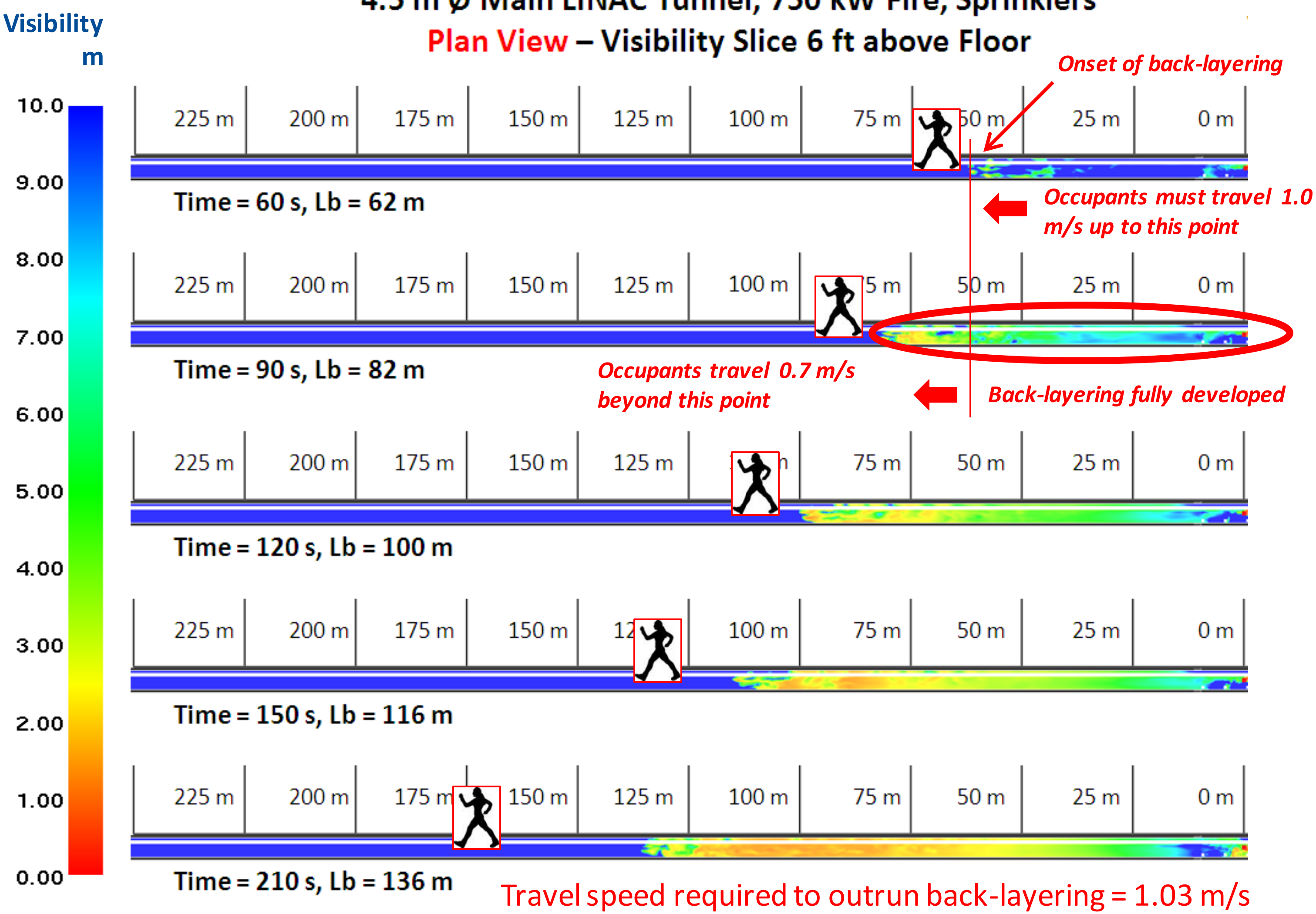
*Back-layering fully developed*

Time = 120 s, Lb = 100 m

Time = 150 s, Lb = 116 m

Time = 210 s, Lb = 136 m

# Main LINAC Tunnel Fire Results


4.5 m Ø Main LINAC Tunnel, 750 kW Fire, Sprinklers

Plan View – Visibility Slice 6 ft above Floor

*Onset of back-layering*

*Occupants must travel 1.0 m/s up to this point*

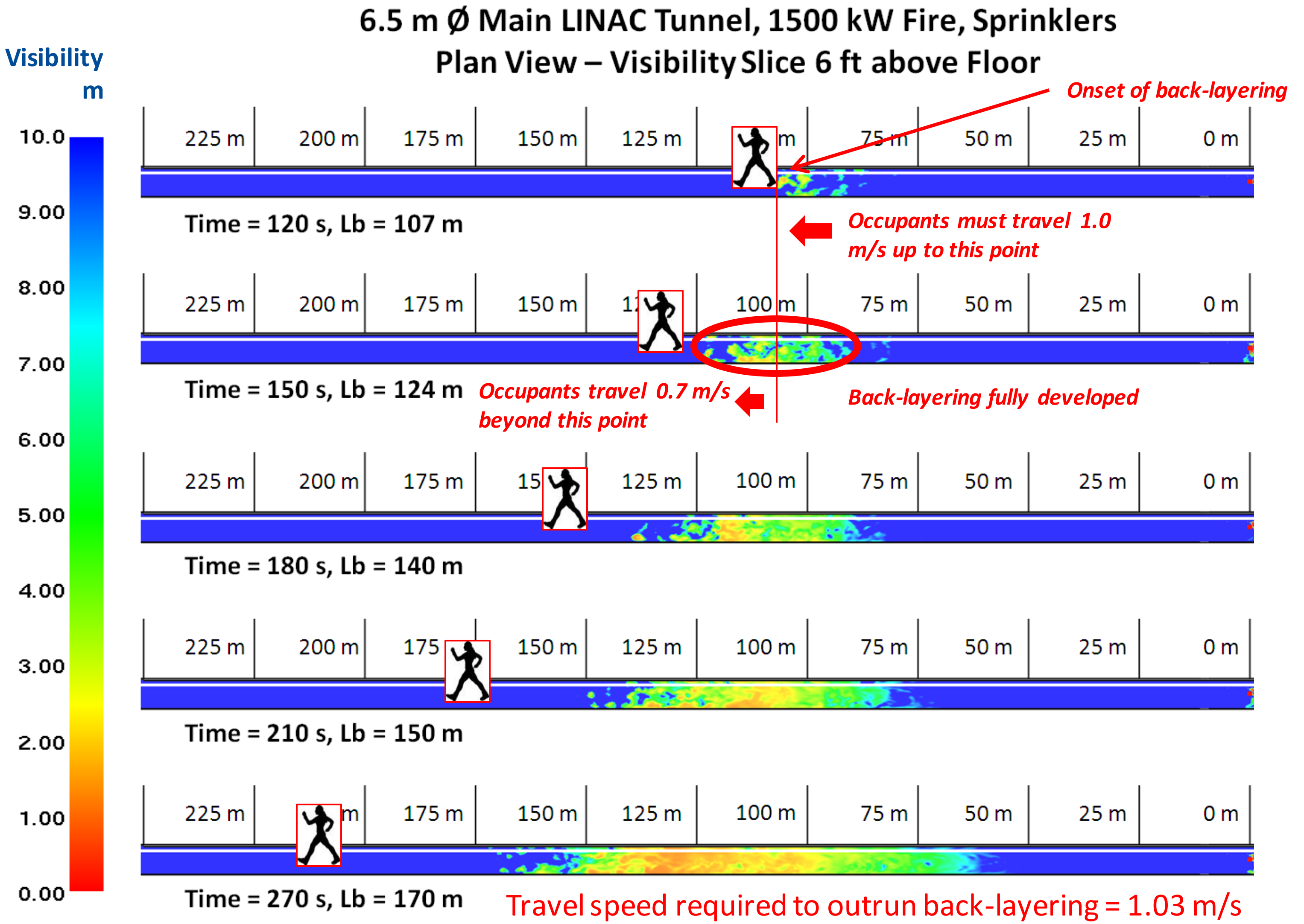
*Occupants travel 0.7 m/s beyond this point*

*Back-layering fully developed*

Travel speed required to outrun back-layering = 1.03 m/s

Travel speed required to stay ahead of smoke layer = 0.63 m/s

# Main LINAC Tunnel Fire Results



6.5 m Ø Main LINAC Tunnel, 1500 kW Fire, Sprinklers

Plan View – Visibility Slice 6 ft above Floor

*Onset of back-layering*

*Occupants must travel 1.0 m/s up to this point*

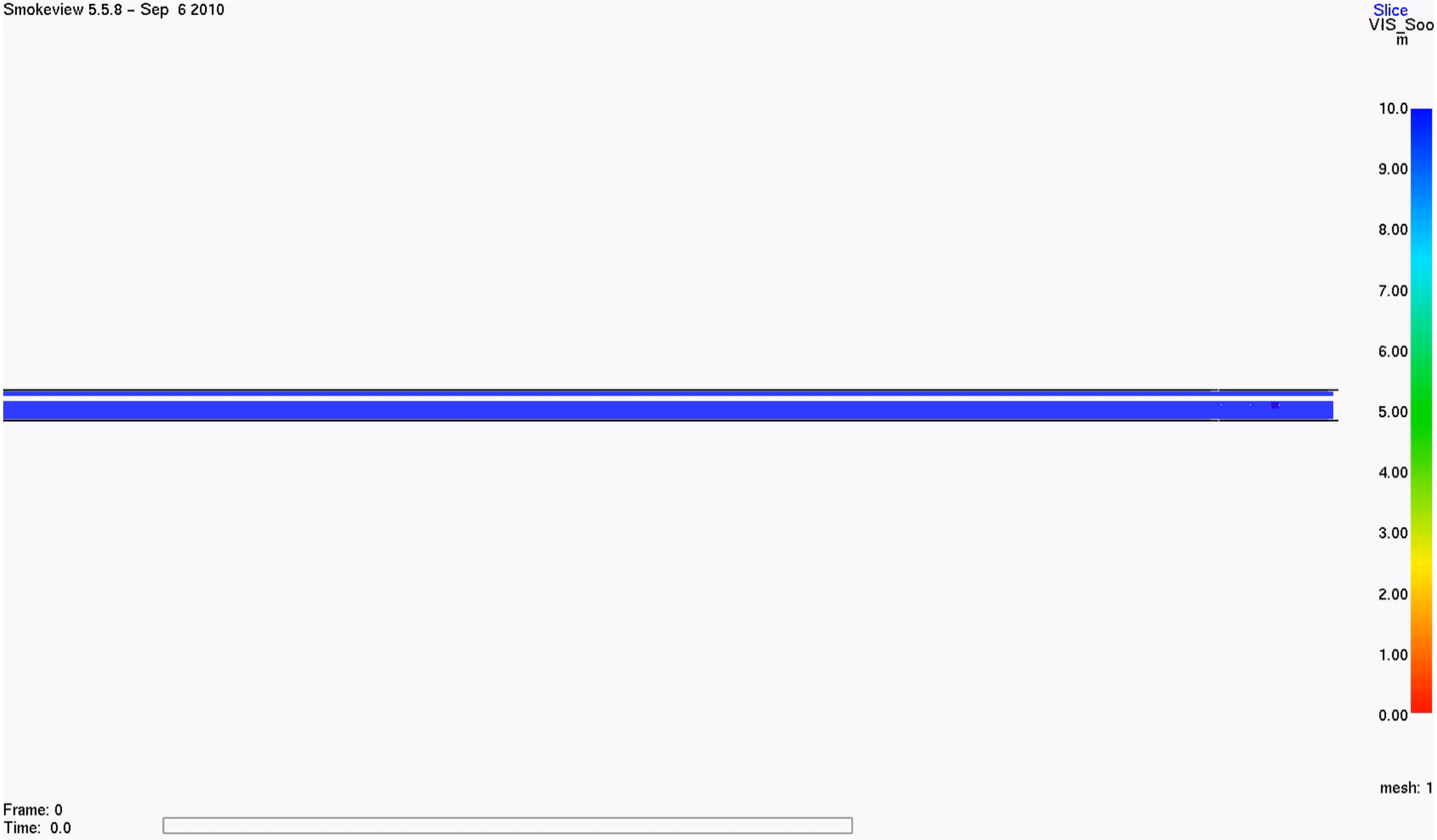
*Occupants travel 0.7 m/s beyond this point*

*Back-layering fully developed*

Travel speed required to outrun back-layering = 1.03 m/s

Travel speed required to stay ahead of smoke layer = 0.63 m/s

# 5m Tunnel Fire Animation 1,000kw Fire Size Plan View



Smokeview 5.5.8 – Sep 6 2010

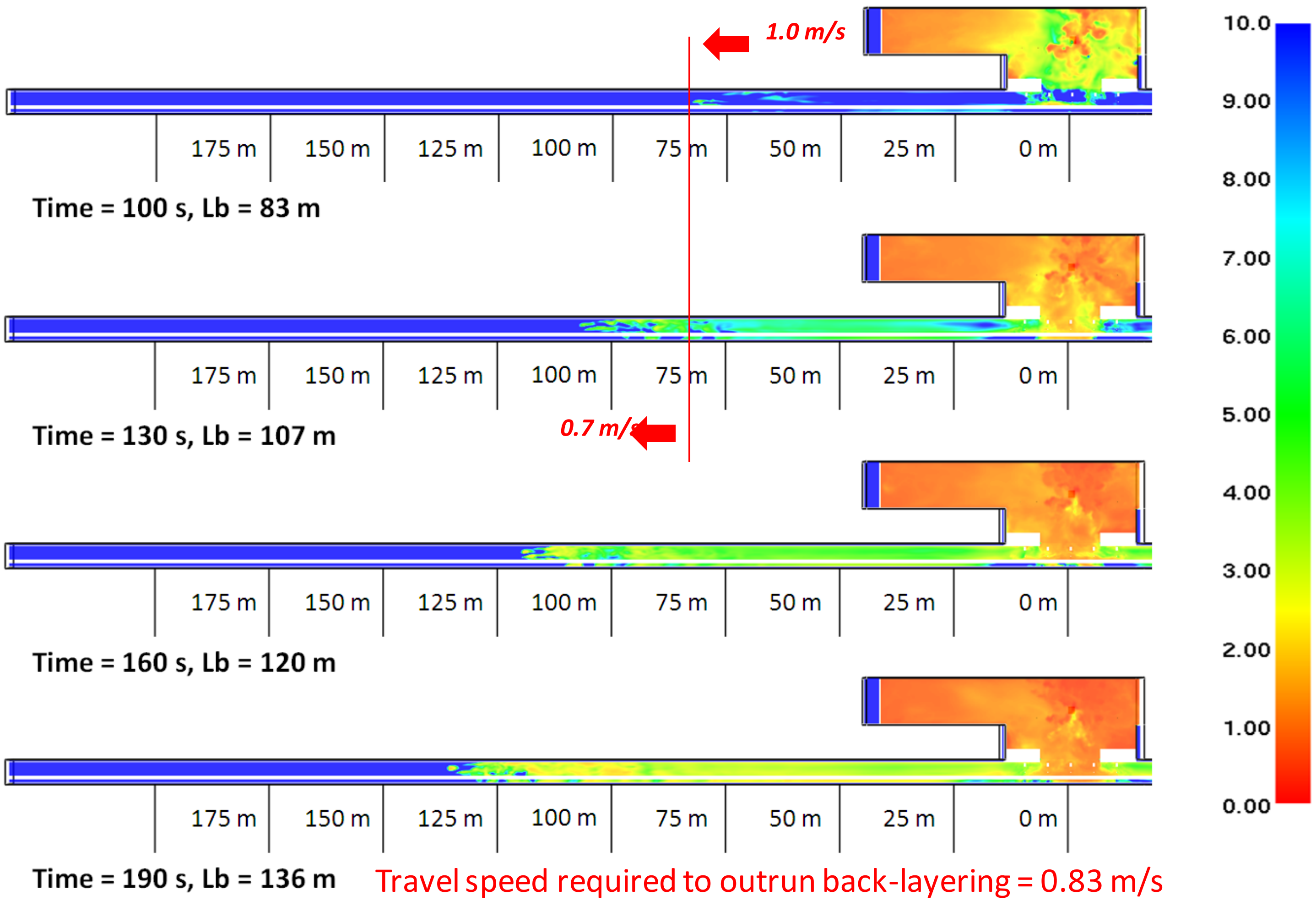
Frame: 0
Time: 0.0

# Summary of Tunnel Fire Results

| Tunnel Diameter (m) | Limiting Fire Size (kW) | Maximum Fuel Spill Area ($m^2$) | Maximum Unconfined Spill Rate (L/min) |
|---|---|---|---|
| 4.5 | 750 | 0.8 | 1.3 |
| 5.0 | 1,000 | 1.0 | 1.7 |
| 5.5 | 1,100 | 1.1 | 1.9 |
| 6.5 | 1,500 | 1.4 | 2.6 |

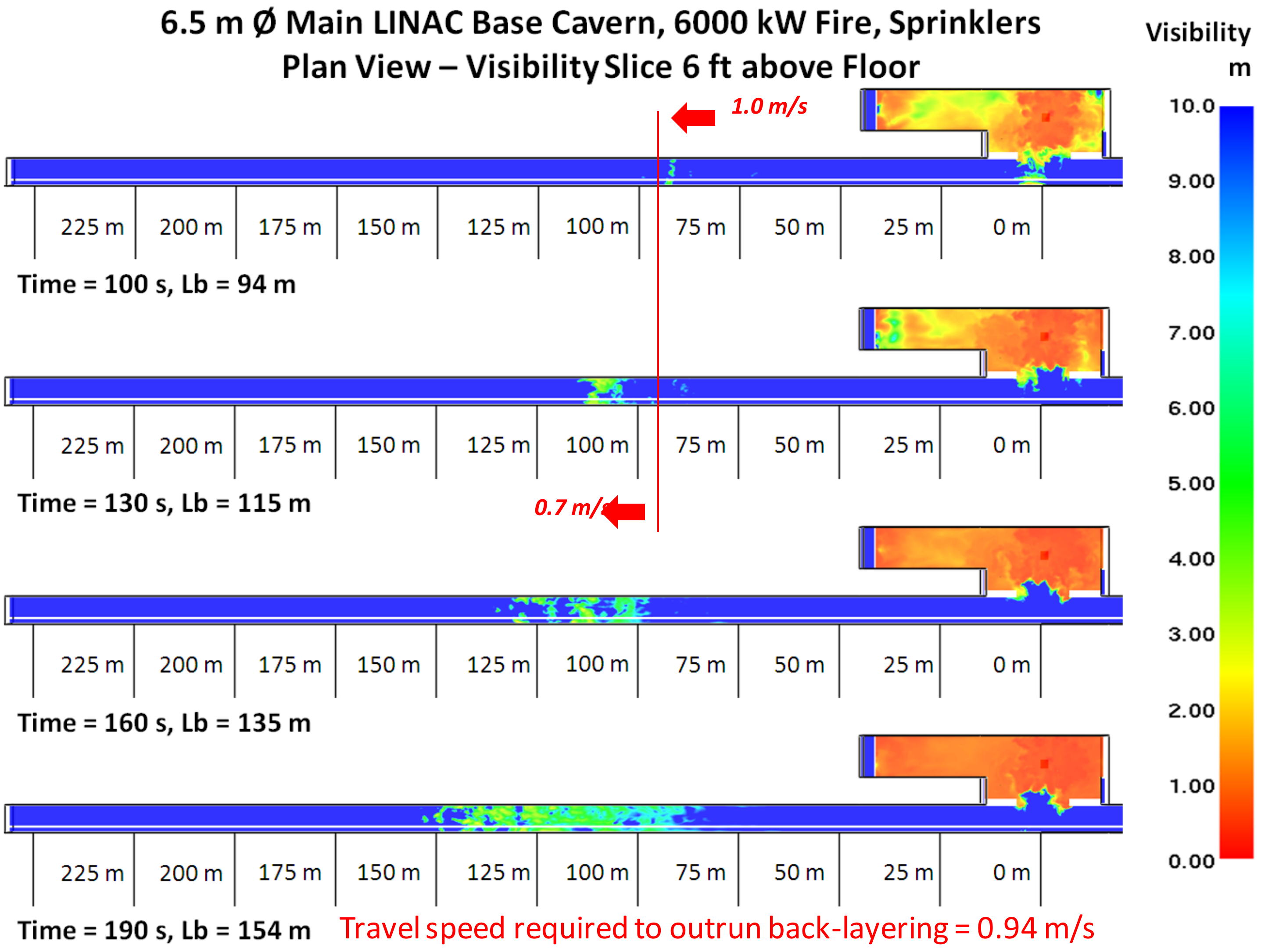
- **Results for Main LINAC apply to straight portions of damping ring tunnel**
  - Smoke movement is essentially the same in straight tunnels of the same diameter. The difference in obstructions between the Main LINAC and damping ring have a minimal effect.

# Base Cavern Fire Results


4.5 m Ø Main LINAC Base Cavern, 3000 kW Fire, Sprinklers
Plan View – Visibility Slice 6 ft above Floor

Travel speed required to outrun back-layering = 0.83 m/s
Travel speed required to stay ahead of smoke layer = 0.62 m/s

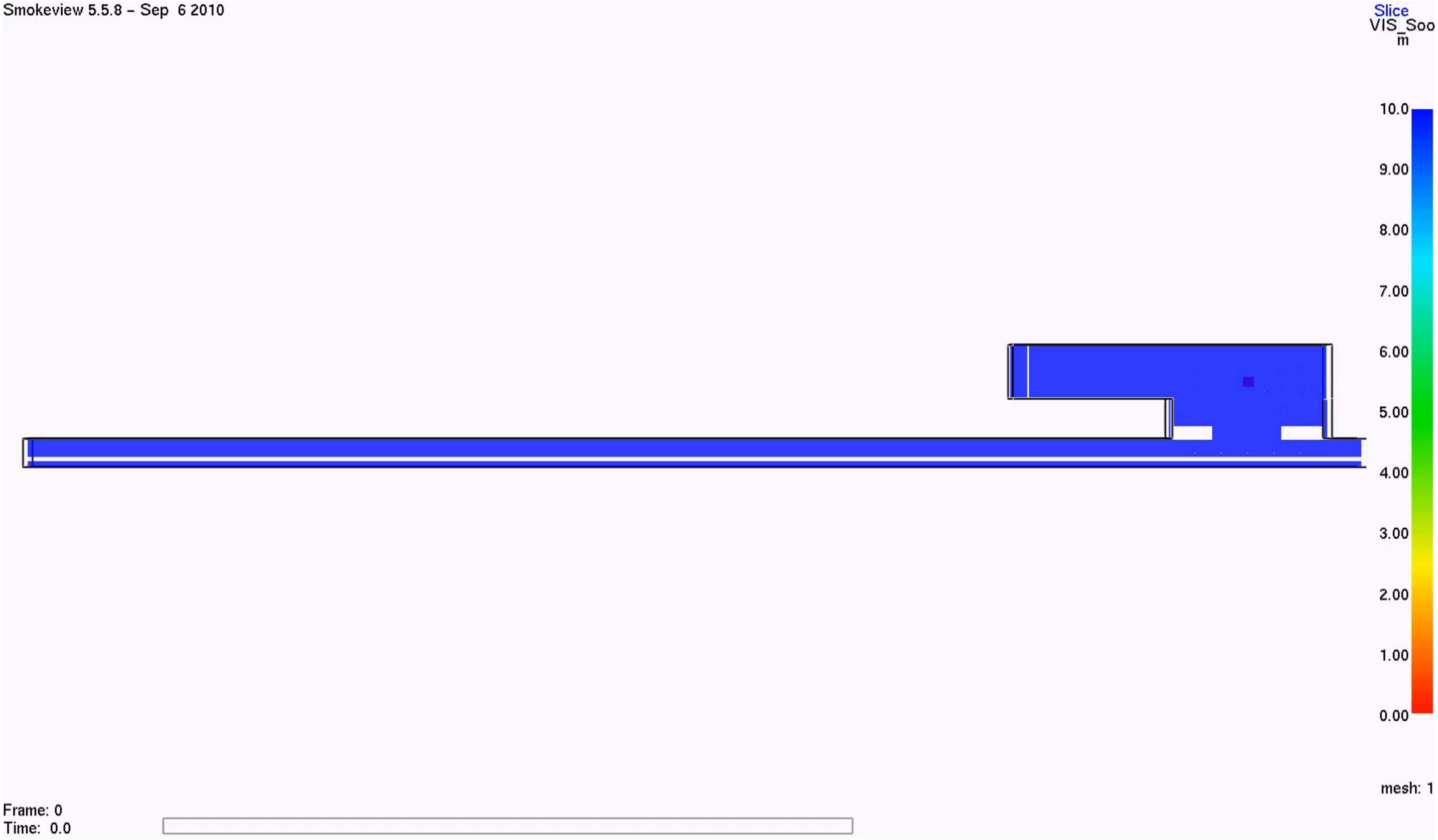
# Base Cavern Fire Results



Travel speed required to outrun back-layering = 0.94 m/s

Travel speed required to stay ahead of smoke layer = 0.73 m/s

# 5m Base Cavern Fire Animation (4,000kw Fire Size) Plan View

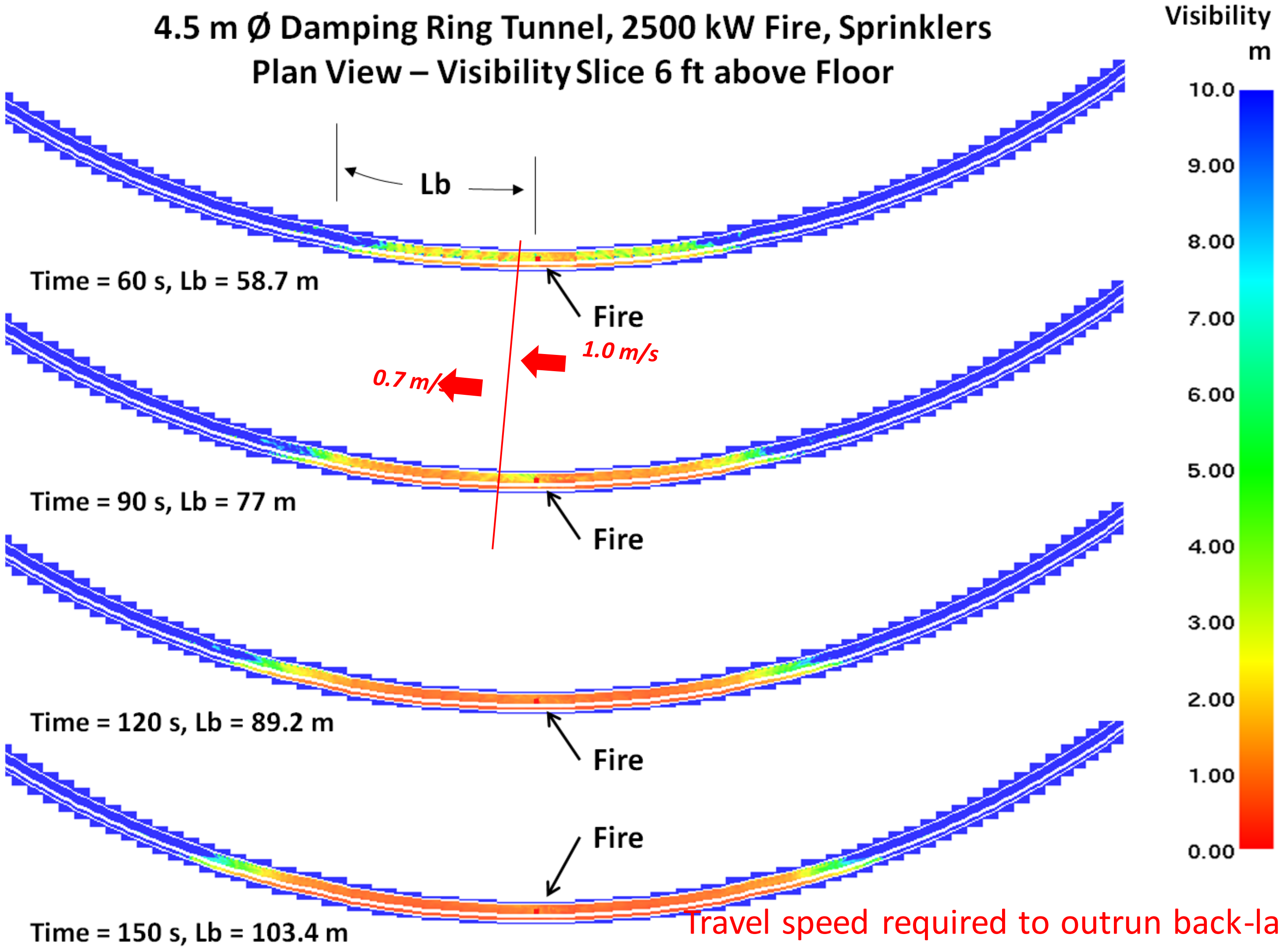


# Summary of Base Cavern Fire Results

| Tunnel Diameter (m) | Limiting Fire Size (kW) | Maximum Fuel Spill Area ($m^2$) | Maximum Unconfined Spill Rate (L/min) |
|---|---|---|---|
| 4.5 | 3,000 | 2.4 | 5.1 |
| 5.0 | 4,000 | 3.0 | 6.8 |
| 5.5 | 4,500 | 3.3 | 7.7 |
| 6.5 | 6,000 | 3.6 | 10.2 |

- Smoke spills out of the base cavern and impacts tunnel walls causing the ceiling jet velocity to decrease

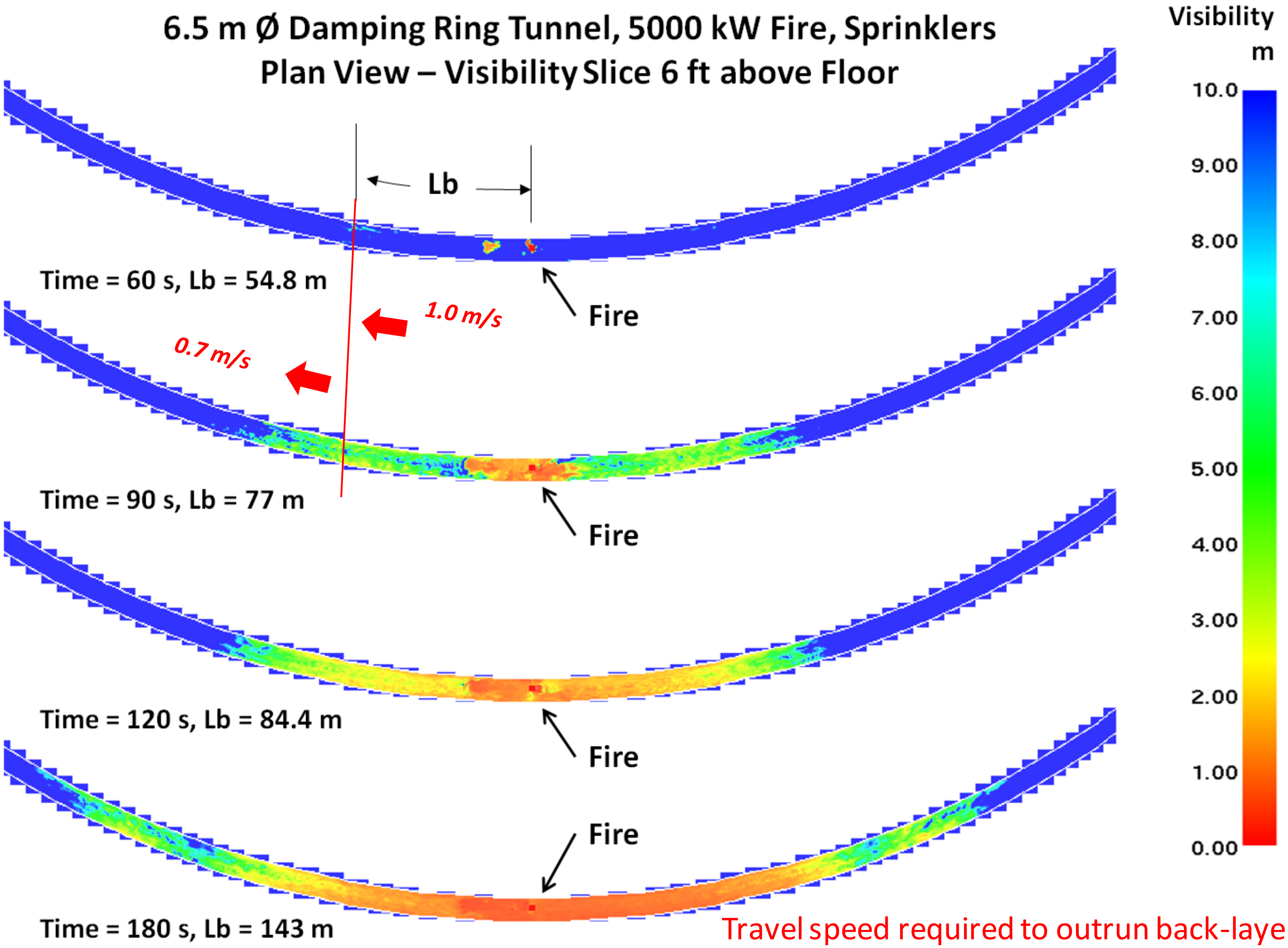
# Damping Ring 4.5m Tunnel Fire Results



4.5 m Ø Damping Ring Tunnel, 2500 kW Fire, Sprinklers
Plan View – Visibility Slice 6 ft above Floor

Travel speed required to outrun back-layering = 0.98 m/s
Travel speed required to stay ahead of smoke layer = 0.5 m/s

# Damping Ring 6.5m Tunnel Fire Results



6.5 m Ø Damping Ring Tunnel, 5000 kW Fire, Sprinklers
Plan View – Visibility Slice 6 ft above Floor

Travel speed required to outrun back-layering = 0.91 m/s
Travel speed required to stay ahead of smoke layer = 0.65 m/s

# Summary of Damping Ring Fire Results

| Tunnel Diameter (m) | Limiting Fire Size (kW) | Maximum Fuel Spill Area ($m^2$) | Maximum Unconfined Spill Rate (L/min) |
|---|---|---|---|
| 4.5 | 2,500 | 2.0 | 4.3 |
| 5.0 | 3,250 | 2.5 | 5.5 |
| 5.5 | 4,000 | 3.0 | 6.8 |
| 6.5 | 5,000 | 3.6 | 8.5 |

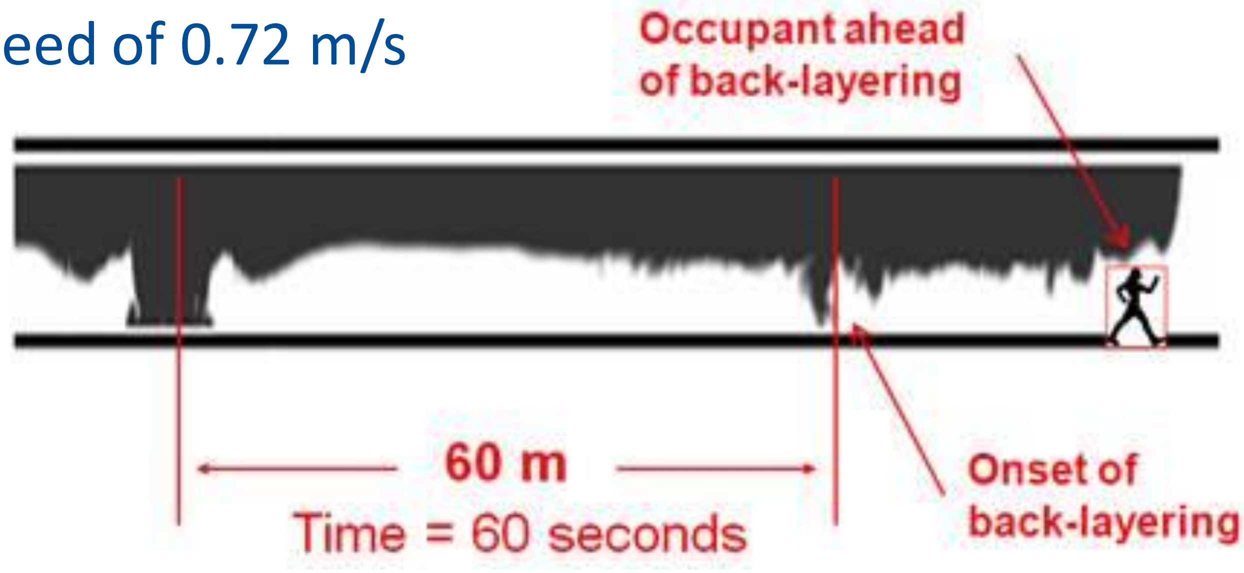
- Results apply to curved sections of damping ring
- Limiting fire sizes in curved section of tunnel increase over straight tunnel section
  - The speed at which smoke descends to head-level decreases due to the curvature of the tunnel
- The straight tunnel sections of the damping ring represent limiting fuel spill quantities for the damping ring

# Compiled Tunnel Fire Results

| Fire Location | Tunnel Diameter (m) | Limiting Fire Size (kW) | Maximum Fuel Spill Area ($m^2$) | Maximum Unconfined Spill Rate (L/min) |
|---|---|---|---|---|
| LINAC / Straight Damping Ring Tunnel | 4.5 | 750 | 0.8 | 1.3 |
| | 5.0 | 1,000 | 1.0 | 1.7 |
| | 5.5 | 1,100 | 1.1 | 1.9 |
| | 6.5 | 1,500 | 1.4 | 2.6 |
| Base Cavern | 4.5 | 3,000 | 2.4 | 5.1 |
| | 5.0 | 4,000 | 3.0 | 6.8 |
| | 5.5 | 4,500 | 3.3 | 7.7 |
| | 6.5 | 6,000 | 3.6 | 10.2 |
| Curved Damping Ring Tunnel | 4.5 | 2,500 | 2.0 | 4.3 |
| | 5.0 | 3,250 | 2.5 | 5.5 |
| | 5.5 | 4,000 | 3.0 | 6.8 |
| | 6.5 | 5,000 | 3.6 | 8.5 |

# Egress Analysis

The Available Safe Egress Time (ASET) was greater then Required Safe Egress Time (RSET) – Visibility is lost at a rate 0.63 m/s travel egress speed of 0.72 m/s



In other words, occupants can comfortably walk faster than smoke can fill the tunnel for a given fire size and can reach the vertical shaft or area of refuge before being exposed to untenable conditions.

# Conclusions

- The travel distances referenced in NFPA 520 are validated, i.e., the maximum travel distance of 610m 2,000ft.) to an exterior access point or area of refuge will allow occupants to evacuate safely
- The size of pool/spill fire (e.g., transformer oil) can be restricted by establishing fuel containment strategies
- Increasing the tunnel diameter allows the combustible fuel loading in a tunnel to be increase without affecting the ability of occupants to evacuate safely
- Administrative controls must be established as part of a combustible management strategy, e.g., transient combustibles may be present in the tunnel

# Questions?