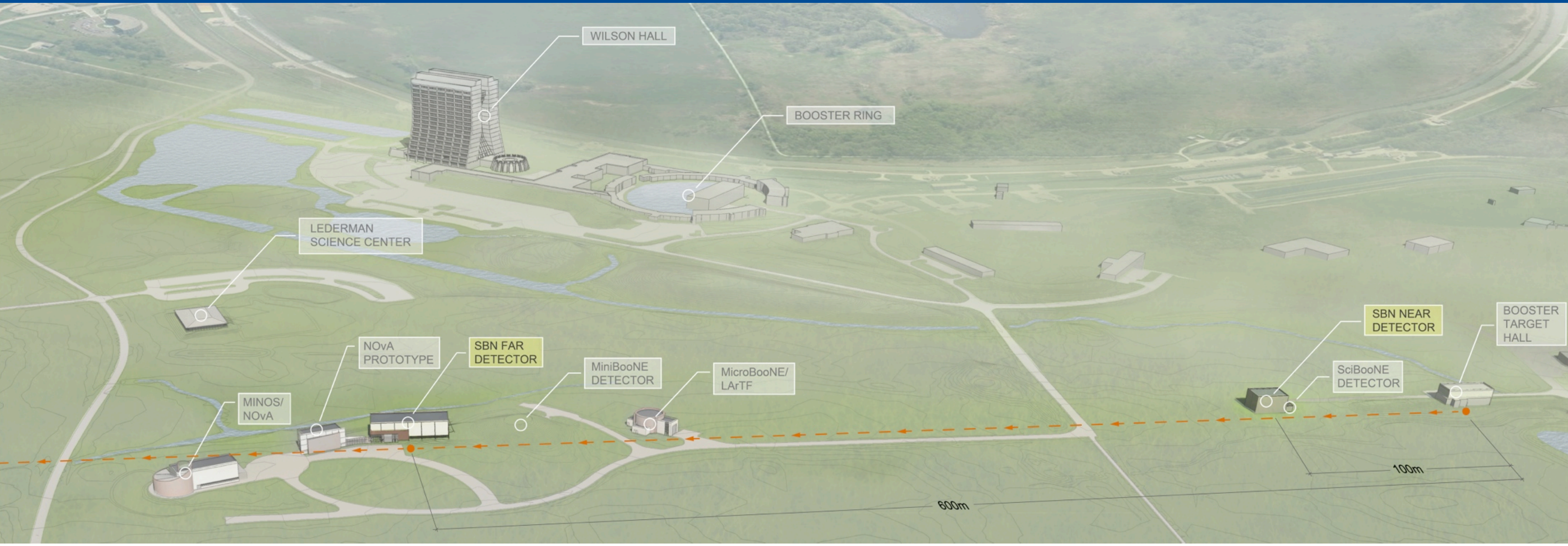

Planning for Safety for SBN cryogenics

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Director's Progress Review of SBN

15-17 December 2015

This presentation answers the question whether ES&H has been properly addressed. The proposed approach is to plan for Safety via Regulatory Safety Environment at Fermilab.

Fermilab is managed by the Fermi Research Alliance LLC for the U.S. Department of Energy Office of Science under Contract No. DE-AC02-07CH11359. As such, Fermilab has to abide by the Appendix I of DOE Orders and Notices, List B, which is so called Fermilab Work Smart Standards. The Work Smart Standards lists a large number of governing documents applicable to the management and operation of Fermilab. For example, ASME codes, PED, 10 CFR 851, and Fermilab ESHM chapters are included.

Specifically, several Fermilab ES&H Manual chapters pertain to the design and operation of cryogenic systems. Each of these chapters specifies the requirements for dealing with a particular hazard or class of equipment, which may affect the safety of a system.

Planning for Safety via Regulatory Safety Environment at Fermilab

Below is a list of FESHM Chapters applicable to the safety of the **argon cryogenic systems**:

2060	Work Planning and Hazard Analysis
4240	Oxygen Deficiency Hazards
5031	Pressure Vessels
5031.1	Piping Systems
5031.2	Inert Gas Trailer Connections and Onsite Filling Guidelines
5031.3	Gas Regulators
5031.4	Inspection and Testing of Relief Systems
5031.5	Low Pressure Vessels
5031.7	Membrane Cryostats (updated as of Nov. 2015)
5032	Cryogenic Systems Review
5032.1	Liquid Nitrogen Dewar Installation and Operation Rules
5033	Vacuum Vessel Safety
5034	Pressure Vessel Testing

Key regulatory requirements for pressure vessels and piping:

- Pressure vessels, i.e. filters or phase separators, per ASME Section VIII (U-stamped) or PED 97/23 (CE marked) – both accepted
- Pressure piping per ASME B31.3 (designed, fabricated and erected)

1. Design calculations per B31.3
   - Verification of materials properties for the range of design temperatures of the piping system
   - Verification of components have working pressures greater than (>) design pressure for the range of design temperatures of the piping system
2. System fabrication and inspection per B31.3
3. The company shall provide documentation packages to show:
   - Pressure ratings for piping components
   - Material certifications for components
   - Welding Procedure Specifications and Welder Performance Qualifications

3. Ideally, a letter from the company stating that the design and fabrication is done per B31.3. If company is ISO9000 certified such a letter is treated as an official statement of compliance.

Key regulatory requirements for cryostats:

- SBN FD cryostats should make every effort to conform to FESHM 5031.5 "Low Pressure Vessels". No MOU between CERN and Fermilab exists yet. The following approach is being proposed:
  - Design of the vessels shall be performed and independently verified per ASME BPVC Section VIII, Div.2 (FEA is an acceptable design method) for external (vacuum) and internal pressure scenarios.
  - Cryostats shall be pressure tested per ASME BPVC, Section VIII:
    - Vacuum test at full vacuum
    - Pneumatic test is performed at internal pressure P_T = 1.15 x Maximum Allowable Working Pressure = 1.15 x 350 mbars
    - Prior to the pneumatic pressure test, all feedthroughs and other external components shall be pressure rated for at least the maximum design pressure of 350 mbarg. The pressure rating shall be obtained through documented qualification process, including design calculations and testing program. Additionally, each feedthrough shall be pressure tested prior to installation into the cryostat in an appropriate setup that is described in a separate document.
  - Reliefs must be sized to have a flow capacity in excess of the largest overpressure scenario. API2000 shall be followed to account for all sources and selection of relief valves.

Key regulatory requirements for cryostats:

- SBND cryostats should make every effort to conform to FESHM 5031.7 “Membrane Cryostats”
- MOU https://edms.cern.ch/document/1554082 between CERN and Fermilab is signed to outline specifics of the Design, Fabrication, Installation and Testing of the LBNF/DUNE and SBND Membrane Cryostats. MOU is written with the intent to satisfy Fermilab ESH Manual.

Additional requirements for “unlisted piping components”, such as feedthroughs:

- Prior to the pneumatic pressure test, all feedthroughs and other external components shall be pressure rated for a design pressure of a least 350 mbarg. The pressure rating shall be obtained through documented qualification process, including design calculations and testing program. Additionally, each feedthrough shall be pressure tested prior to installation into the cryostat (separate test facility is needed).

Preliminary ODH Analysis for SBN buildings

The goal for the SBN detector buildings is to engineer the facilities such that:

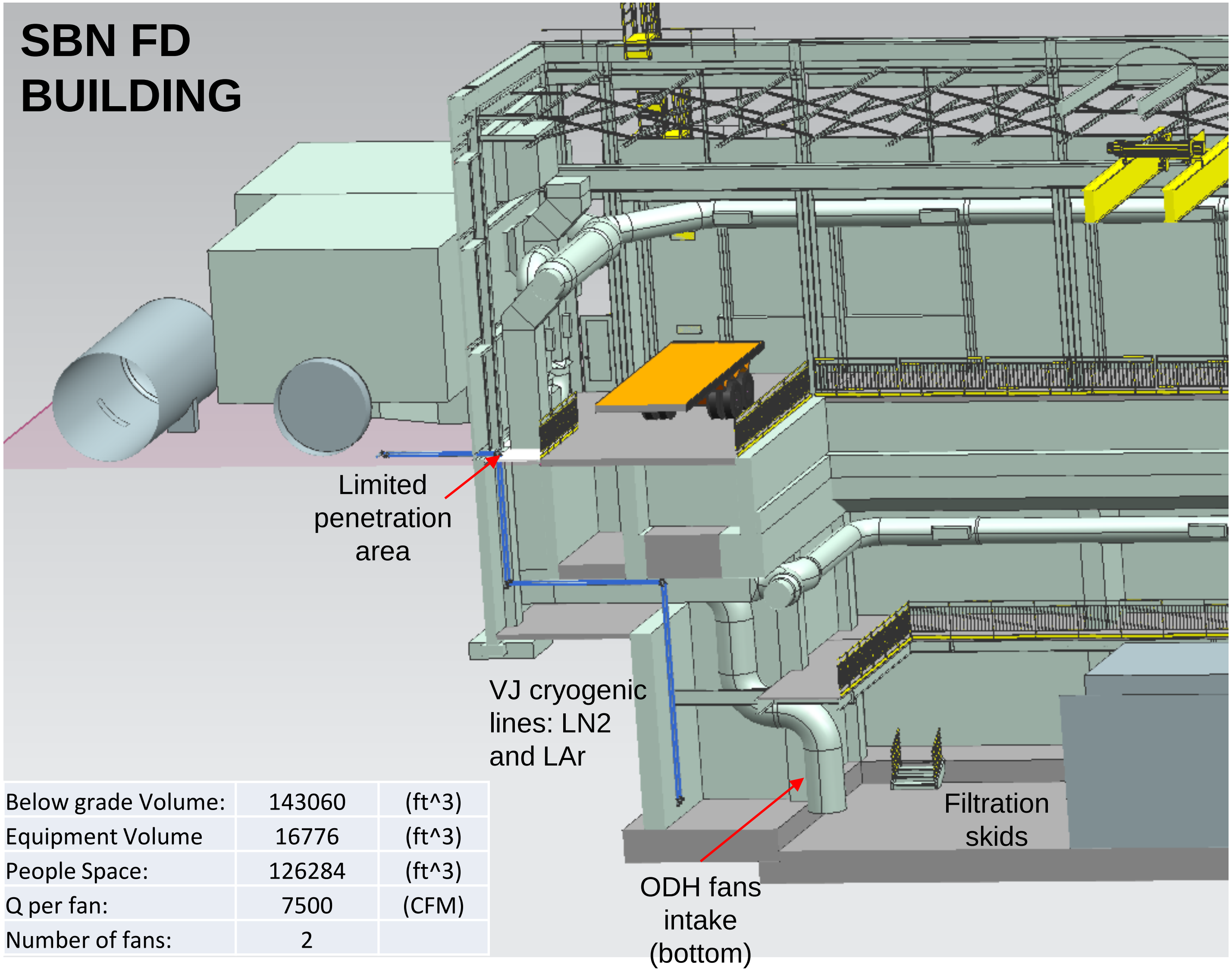
- ODH0 at the grade level
- ODH1 below grade level (mezzanine and pit areas)
- ODH1 in cryo room (SBND)

These ratings will be achieved by:

- Minimizing (or eliminating) cryo equipment and piping at or above grade level
- Apply an industrial standard for safeguarding piping penetrations below liquid level by either the installation of an internal passive quick shutoff valve (Protego©) or a double containment with vacuum jacket vented to outside the building via a parallel plate and relief stack
- Venting all reliefs to the outside the building via relief stack
- Installation of MSA UltimaX Gas Monitors set to alarm at 19.5% O2 at all levels of the building (grade, mezzanine and below mezzanine, pit)
- Continual VFD-driven mechanical ventilation at low rate with inline flow measurement and ramp-up every 24 hours to maximum rate
- Dual ventilation fan system with on-demand ramp to maximum ventilation rate triggered by any ODH cell

Courtesy of K Haaf

Preliminary ODH Analysis for SBN buildings



Below grade Volume:	143060	(ft^3)
Equipment Volume	16776	(ft^3)
People Space:	126284	(ft^3)
Q per fan:	7500	(CFM)
Number of fans:	2	

Total fatality rate
(above grade)

LAr: 1x1.5”, 1x0.5”
GAr: 1x1.5”, 10x0.25”
LN2: 1x1.5”, 1x0.5”
GN2: 1x1.5”, 1x0.25”

Total:	6.68E-08
ODH class:	0

Total fatality rate
(below grade)

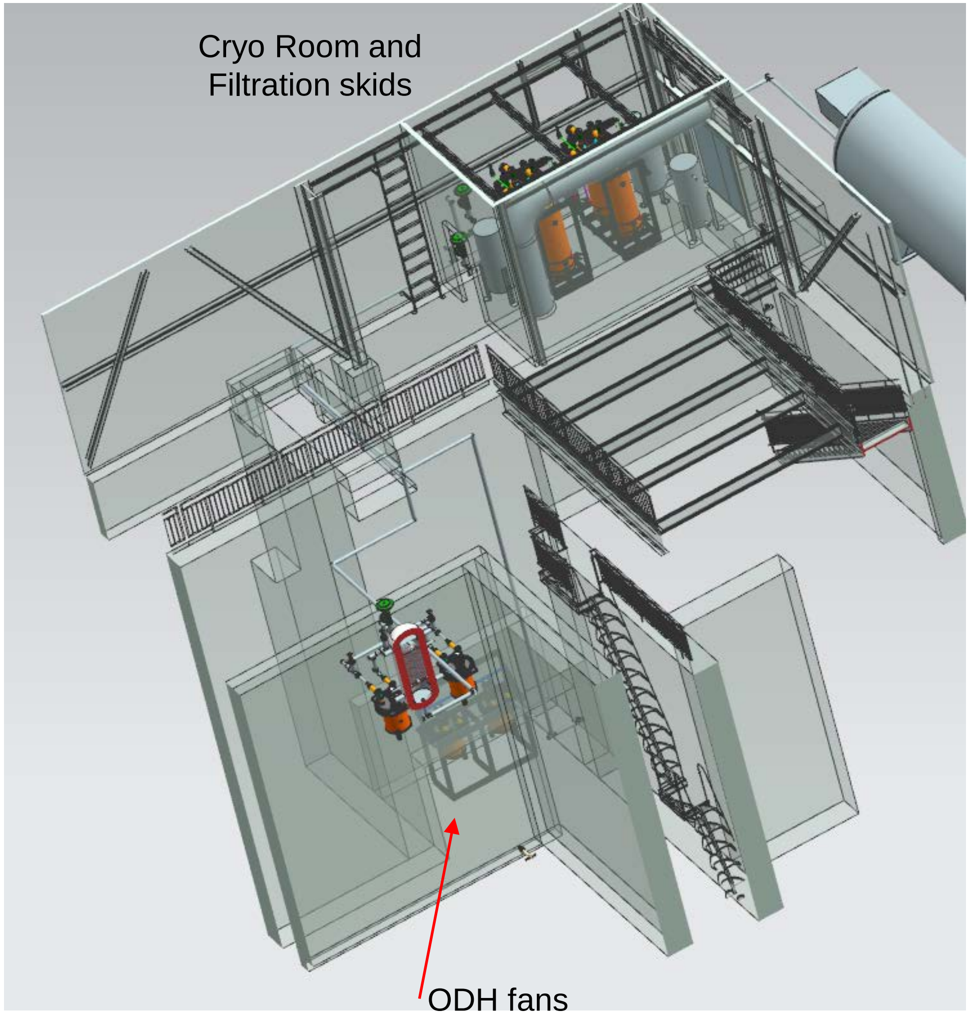
LAr: 10x1.5”, 100x0.5”
GAr: 10x1.5”, 50x0.25”
LN2: 10x1.5”, 100x0.5”
GN2: 10x1.5”, 100x0.25”
LAr vessel: 10
GAr vessel: 10
LN2 vessel: 10
GN2 vessel: 10
Cryostat: 1

Total:	7.91E-07
ODH class:	1

Courtesy of K Haaf

Preliminary ODH Analysis for SBN buildings

SBND BUILDING



Building w/o cryo room

Below grade Volume:	35147	(ft^3)
Equipment Volume	6684	(ft^3)
People Space:	28463	(ft^3)
Q per fan:	5000	(CFM)
Number of fans:	2	

Cryo room

Room volume	3284	(ft^3)
Equipment Volume	820	(ft^3)
People Space:	2464	(ft^3)
Q per fan:	7500	(CFM)
Number of fans:	1	

Total fatality rate (above grade)

LAr: none
GAr: 1x1.5”, 10x0.25”
LN2: none
GN2: 1x1.5”, 10x0.25”

Total:	4.34E-08
ODH class:	0

Total fatality rate (below grade)

LAr: 10x1.5”, 100x0.5”
GAr: 10x1.5”, 50x0.25”
LN2: 10x1.5”, 100x0.5”
GN2: 10x1.5”,100x0.25”
LAr vessel: 2
GAr vessel: 2
LN2 vessel: 2
GN2 vessel: 2
Cryostat: 2

Total:	8.84E-07
ODH class:	1

Total fatality rate (Cryo Room)

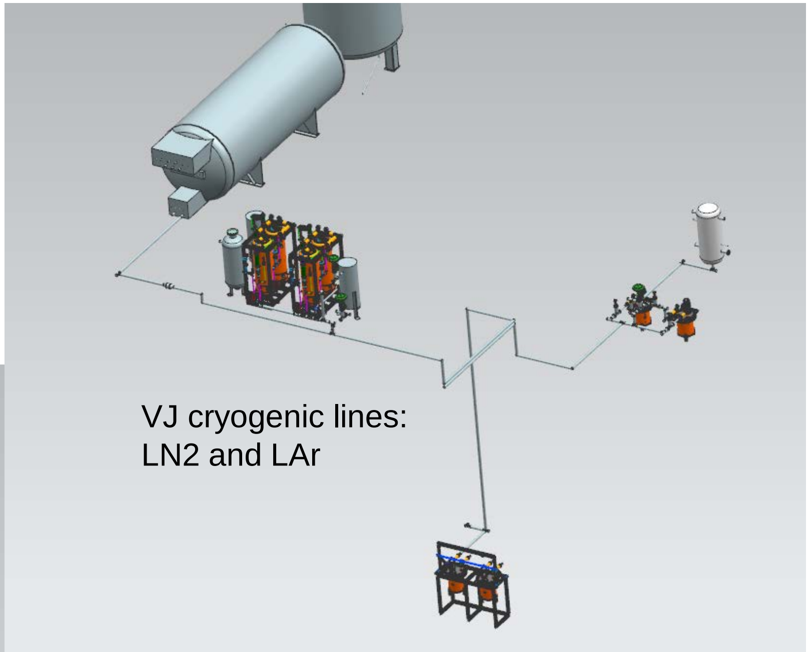
LAr: 5x1.5”, 50x0.5”
GAr: 5x1.5”, 25x0.25”
LAr vessel: 6
GAr vessel: 1

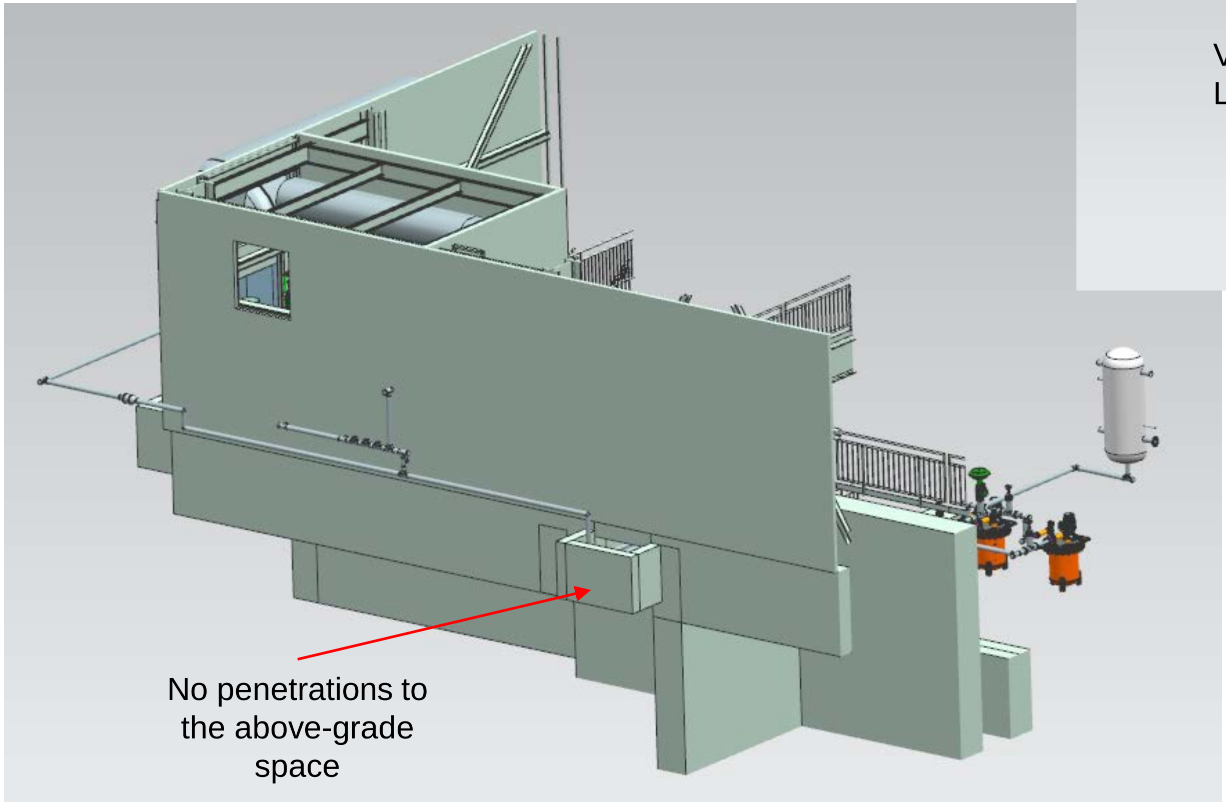
Total:	2.46E-07
ODH class:	1

Courtesy of K Haaf

Preliminary ODH Analysis for SBN buildings

SBND BUILDING





Preliminary ODH Analysis for SBN buildings – Support Slides

- Ventilation scenarios are generated based on failure rates of ODH equipment.
  - For the fans, this depends on the frequency with which they will be tested. For SBN bldgs., the test period is once per day:

$$P_{FOD\_Fan} = \frac{Test_{interval}}{2} \lambda_{fan} = 1.08 \times 10^{-4}$$

  - Provided *n* fans, the probability that *q* of *n* will function on demand is given by:

$$P\left(\frac{q}{n}\right) = \frac{n!}{q!\ (n-q)!} \left(1 - P_{FOD\_Fan}\right)^{q} P_{FOD\_Fan}{}^{(n-q)}$$

- The function of the fans can also be impaired by the failure of the ODH Monitors, or a power failure.
  - The ODH Monitors will be part of an SIL2 system, for which the rate of Failure on Demand is between 10^{-3} and 10^{-2}.
  - The failure of *M* such monitors in a given area is then:

$$P_{FOD_{Monitors}} = 0.01^{M}$$

  - Per Table 1, the FOD rate for power is 3×10^{-4}.

Preliminary ODH Analysis for SBN buildings – Support Slides

- Each scenario is generated simply. At SBND, above ground and in the Cryo Room, there are two ventilation cases:
  - Full ventilation—The single fan operates.
  - No Ventilation—Due to fan failure, ODH monitor failure, or power failure.
- At SBND below ground and for all of SBN-FD, there are three:
  - Full ventilation—Both fans operate.
  - Partial ventilation—One of the two fans operates.
  - No Ventilation—Due to simultaneous fan failures, ODH monitor failure, or power failure.
- In each case, the probability of each scenario depends on the failures, or lack thereof, that can lead to the specified outcome.
  - Below ground at SBND and at SBN-FD, for example, the three scenarios are:

$$P_{Full} = (1 - P_{FOD\_Power})(1 - P_{FOD\_Monitors})P\left(\tfrac{2}{2}\right)$$

$$P_{Partial} = (1 - P_{FOD\_Power})(1 - P_{FOD\_Monitors})P\left(\tfrac{1}{2}\right)$$

$$P_{None} = (1 - P_{FOD\_Power})(1 - P_{FOD\_Monitors})P\left(\tfrac{0}{2}\right) + P_{FOD\_Monitors}(1 - P_{FOD\_Power}) + P_{FOD\_Power}$$

Preliminary ODH Analysis for SBN buildings – Support slides

- Because piping lengths are unknown, they are treated as Cryogenic Fluid Lines per FESHM 4240TA:
  - Leak and Rupture failure rates are given as $5\text{x}10^{-7}$/hr and $2\text{x}10^{-8}$/hr respectively.
  - A very conservative estimate of the number of fluid lines is taken for the Cryo Room and Below Ground areas

- Pipe diameters are assumed to facilitate leak rate calculations:
  - For "Leak" calculations, pipes smaller than 1.5in are assigned a 10mm^2 leak area. Larger pipes are given a 100mm^2 area (the weighted average area between a small and large leak per Table 2).
  - For "Rupture" calculations, it is assumed the flow area is equal to the cross-sectional area of the pipe.
  - In either case, the flow rate in SCFM is given by:

$$\dot{V}_{STP} = C_d A_{leak} \frac{\rho_{fluid}}{\rho_{STP}} \sqrt{\frac{2\Delta P}{\rho_{fluid}}}$$

Where: C_d is the discharge coefficient, assumed to be 0.62. The leak area is that described above. The fluid density is taken at the saturation point for the cryogen at the fluid line pressure and at standard temperature and pressure. ΔP is the difference in pressure between the fluid line and 1atm.

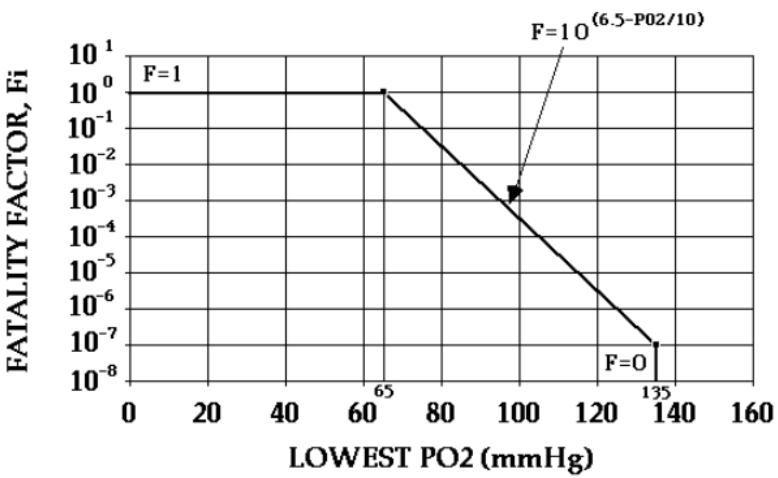
Preliminary ODH Analysis for SBN buildings – Support slides

- For the preliminary calculations, an infinite supply of cryogen is assumed.
  - The oxygen concentration in a space exhausted by a fan rate Q greater than the spill rate R simplifies to:

$$C(t \to \infty) = 0.21\left(1 - \frac{R}{Q}\right)$$

  - In situations where R>Q, presuming an infinite supply of cryogen, the O_2 concentration approaches zero.

- The fatality factor for an individual leak then depends on this O_2 concentration as in Figure 1 of FESHM4240T^·



where $PO_2 = C(t \to \infty)P_{atm}$

Preliminary ODH Analysis for SBN buildings – Support slides

- Finally, the ODH fatality rate is calculated:

$$\Phi = \sum_{i=1}^{N} P_{vent,i} P_{leak,i} F_i$$

  - $P_{vent,i}$ refers to the probability of a given ventilation scenario; for below ground SBND and all of SBN-FD it is either P_{full}, $P_{partial}$, or P_{none}. For above ground and in the cryo room at SBND it is either P_{full} or P_{none}.
  - $P_{leak,i}$ is the probability of a leak occurring in a given type of equipment, e.g., if the probability of an individual cryogenic fluid line leaking is $2x10^{-8}$/hr and 100 such lines are present in the system, $P_{leak,fluidline}=2x10^{-6}$/hr.
  - F_i is the fatality factor associated with the leak event.

Preliminary ODH Analysis for SBN buildings – Support slides

Additional ODH Control Measures will include:

- ❑ SBND pit area may be assigned “confined area” classification due to no easy way of egress
- ❑ Foam insulated 2-ft deep catch-up pans below the cryostats to slow down boil-off of spilled liquid cryogen and allow longer time for egress
- ❑ If a leak occurs and ventilation is unavailable, personnel would have limited time to escape before the space’s oxygen concentration is depleted. If a leak occurs and ventilation is unavailable, personnel would have limited time to escape after an alarm sounds (at C_{normal}=0.195). For this analysis, leaks of 100mm2 are considered.
  - Considering the volume below the mezzanine, and fixing the critical oxygen concentration at C_{crit}=12%, the escape time is: $t_{escape} = \frac{-V}{R} \ln\left(\frac{C_{crit}}{C_{normal}}\right) = \frac{0.49V}{R}$. Escape times for below ground at SBND and SBN-FD are shown below:

Leak type	R (SCFM)	SBND t_{escape}	SBN-FD t_{escape}
LAr – 100mm^2	2600	6.2 minutes	28 minutes
LN_2 – 100mm^2	2800	5.7 minutes	26 minutes