Pollution Prevention Opportunities for Ammonia Emissions in the Food and Beverage Sector

Douglas Reindl, Ph.D., P.E., Professor & Director
Marc Claas, Researcher
John Davis, P.E. Researcher
Todd Jekel, Ph.D., P.E., Scientist
Jake Grayless, Undergraduate Research Intern

Industrial Refrigeration Consortium
University of Wisconsin-Madison

College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

P2 Fugitive Emissions project

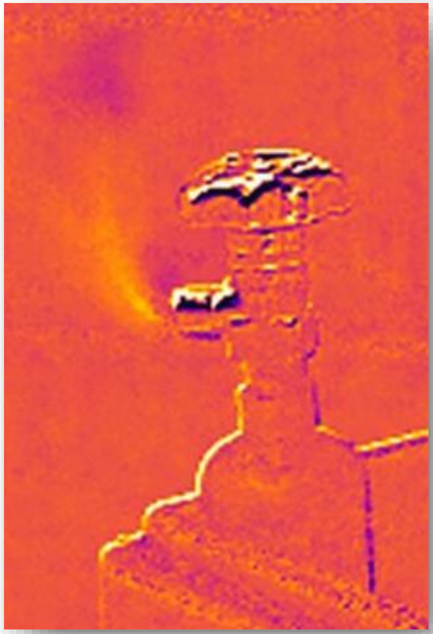
- Goal: reduce fugitive emissions from ammonia refrigeration systems
- Nominal assumption: fugitive emissions are a significant contributor to system refrigerant losses

P2 Fugitive Emissions project

- Approach:
  - Establish guidance for determining refrigerant charge for existing systems
  - Laboratory phase to evaluate/validate methods for identifying gaseous leaks and quantifying leak rates
  - Field phase to apply the lessons learned in the lab to actual systems & characterize fugitive emissions from ammonia refrigeration systems
  - Compile findings & develop recommendations

Fugitive emissions

The undetected or unnoticed loss of refrigerant from a refrigeration system that occurs intermittently or continuously



P2 - Ammonia emissions in the food and beverage sector

- Technology background
- Refrigerant emissions – what's typical?
- Determining refrigerant quantity for existing systems
- Strategies to find refrigerant emissions
- Findings from fieldwork
- Conclusions & recommendations

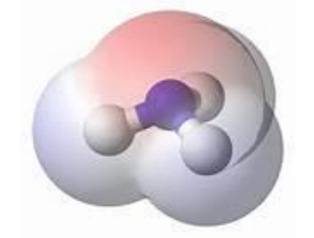
Industrial refrigeration systems

- In the food and beverage sector, reliable refrigeration is integral to the manufacture and distribution of high quality, safe, food products
- Many end-users realize that:
  - no refrigeration = no production
  - no production = no business

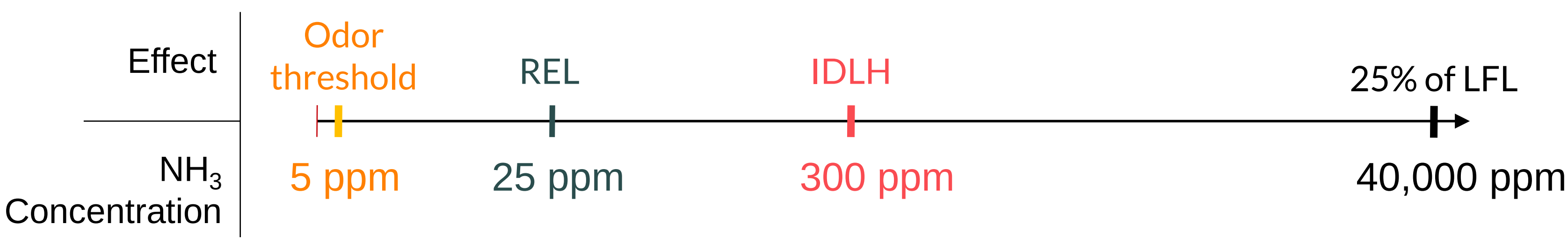
Industrial refrigeration systems

- Key characteristics
  - Utilize anhydrous ammonia as the refrigerant
  - Custom-engineered for the unique needs of the facility
  - Field-erected
  - Large and complex
  - Diversity of components
  - Generally run 24x7

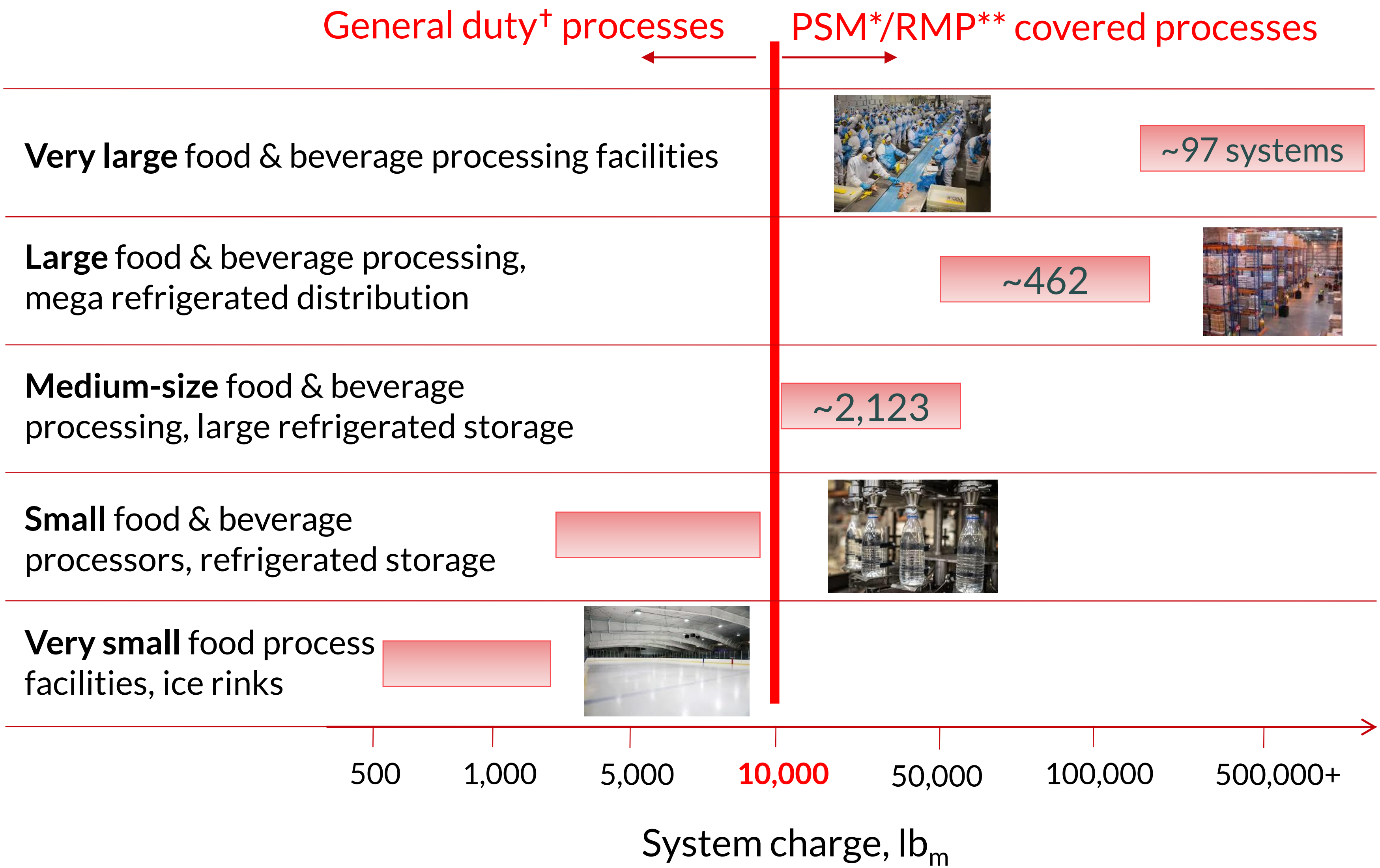
Anhydrous ammonia



- *Why is ammonia widely used in food processing and storage facilities?*
- Because it is a good refrigerant!
  - High thermodynamic performance
  - Low refrigerant cost
  - Zero ODP and GWP
  - Self-alarming



Ammonia refrigeration system refrigerant inventory varies widely



† Clean Air Act Section 112(r)(1)

* Process Safety Management: 29 CFR 1910.119

** Risk Management Plan: 40 CFR 68

Ammonia refrigeration in the U.S.

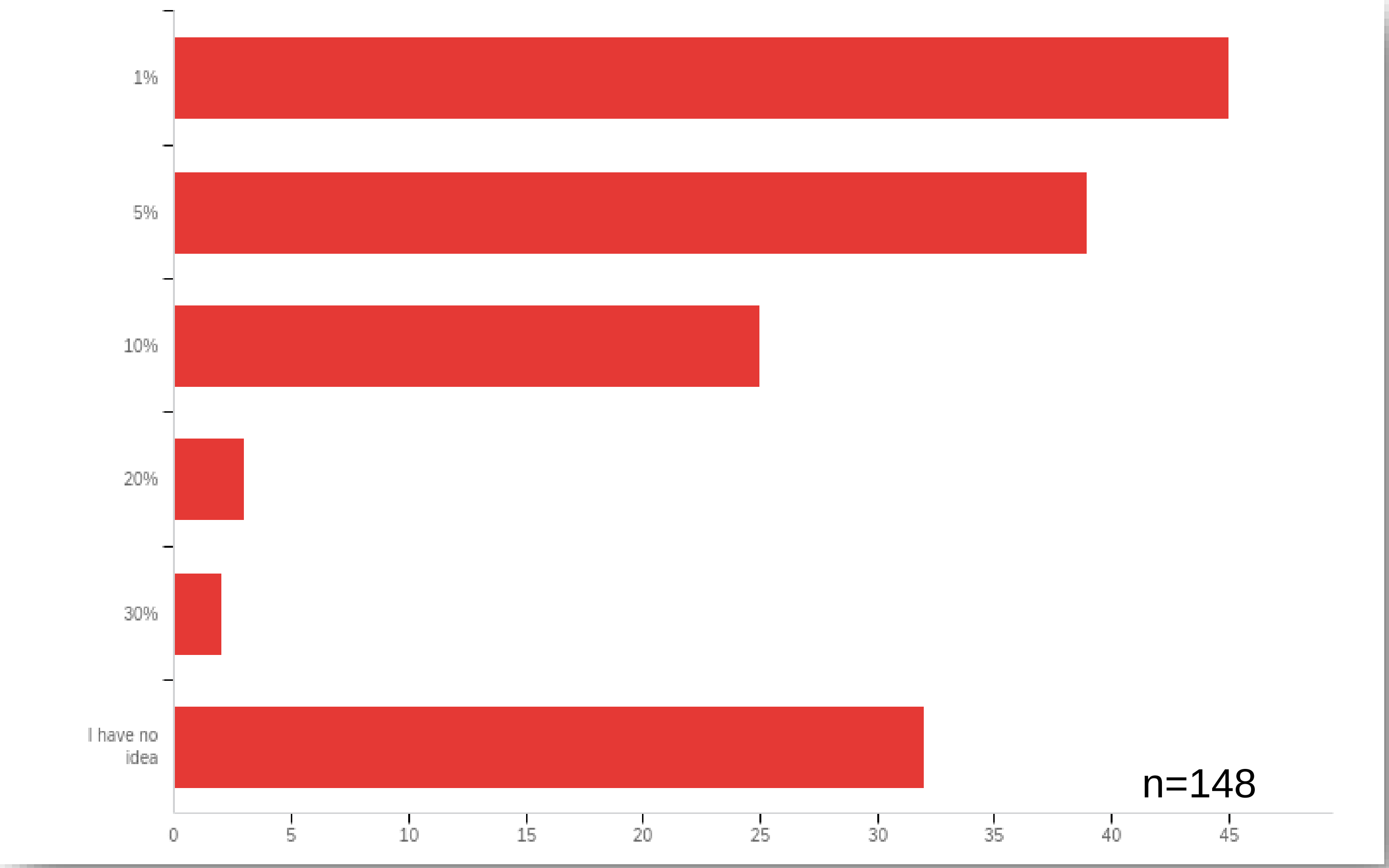
- 2,738* PSM/RMP-covered ammonia systems in NAICS codes: 311, 312, and 493
  - Aggregate quantity of ammonia = 109,291,700 lb_m
  - Average system charge of ammonia ~40,000 lb_m
- Specifically in Region 5, there are 557 facilities
  - Aggregate quantity of ammonia = 20,848,820 lb_m
  - Average system charge of ammonia ~37,400 lb_m
- ~8,000-10,000** non-PSM/RMP ammonia systems

* Source: RMP Database (2020)

** Industry estimate

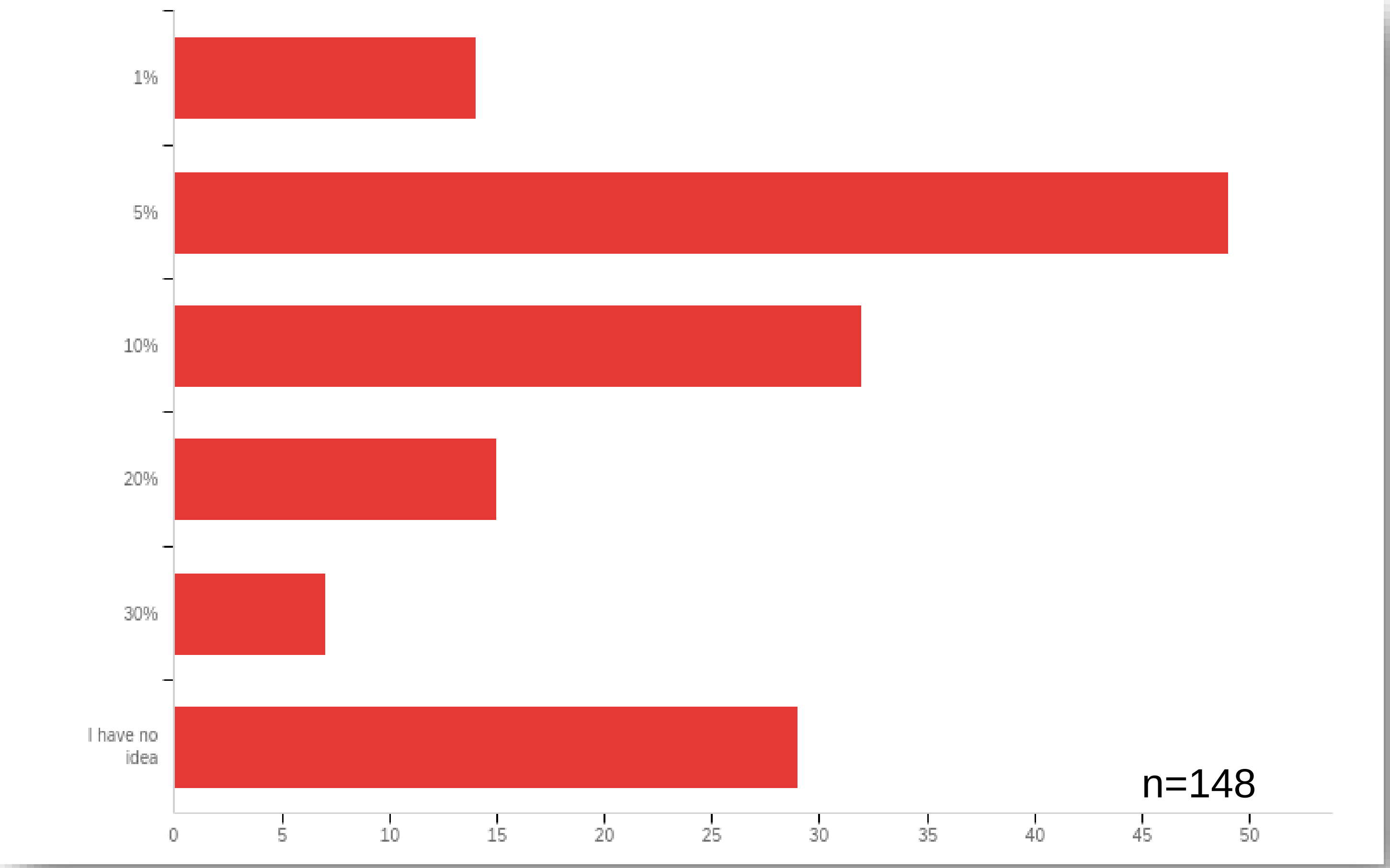
Refrigerant losses – *what do you think?*

What would be a typical annual refrigerant loss rate for an industrial refrigeration system?



Refrigerant losses – *what do you think?*

What annual refrigerant loss rate for an industrial refrigeration system would you consider actionable?



Refrigeration systems leak repairs

- Section 608 of the Clean Air Act applies to refrigeration systems using Class 1 (CFCs) & Class 2 (HCFCs) ozone depleting substances (ODS)
- EPA requires refrigeration owners/operators with equipment containing more than 50 lb of refrigerant to repair leaks if refrigerant annual loss rate exceeds
  - 30% of total system charge for Industrial Process Systems
  - 20% of total system charge for Commercial Refrigeration
  - 10% of total system charge for all others

https://www.epa.gov/section608/stationary-refrigeration-leak-repair-requirements

Refrigeration systems leak repairs

- Section 608 of the Clean Air Act applies to refrigeration systems using Class 1 (CFCs) & Class 2 (HCFCs) ozone depleting substances (ODS)
- EPA requires refrigeration owners/operators with equipment containing more than 50 lb of refrigerant to repair leaks if refrigerant annual loss rate exceeds
  - 30% of total system charge for Industrial Process Systems
  - 20% of total system charge for Commercial Refrigeration
  - 10% of total system charge for all others

Although NH_3 is **exempt** from this requirement, it provides a leak rate benchmark.

https://www.epa.gov/section608/stationary-refrigeration-leak-repair-requirements

Anecdotal evidence from the field

- For more than a decade, we have informally gathered evidence from the field & annual ammonia loss rates have ranged from <1% to more than >100%!

Anecdotal evidence from the field

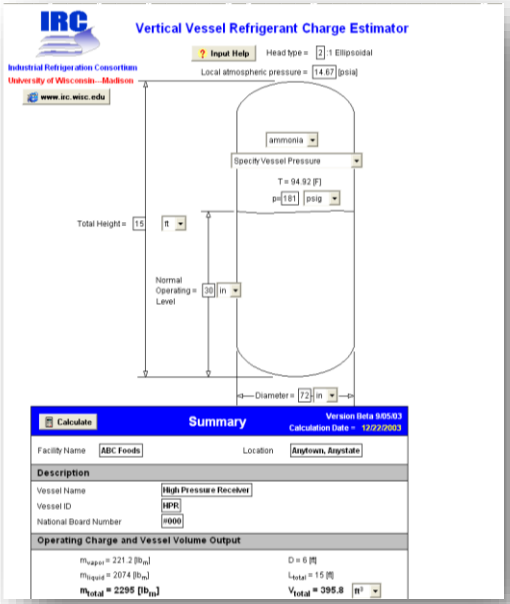
- For more than a decade, we have informally gathered evidence from the field & annual ammonia loss rates have ranged from <1% to more than >100%!
- This raised questions:
  - *Why such a wide range?*
  - *Where are the losses originating?*
  - *Are the losses attributable to fugitive emissions?*
  - *Is there a reasonable loss rate threshold?*

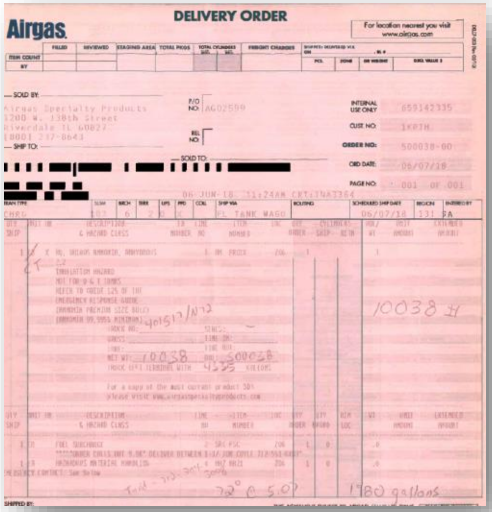
P2 - Ammonia emissions in the food and beverage sector

- Technology background
- Refrigerant emissions – what's typical?
- **Determining refrigerant charge for existing systems**
- Strategies to find refrigerant emissions
- Findings from fieldwork
- Conclusions & recommendations

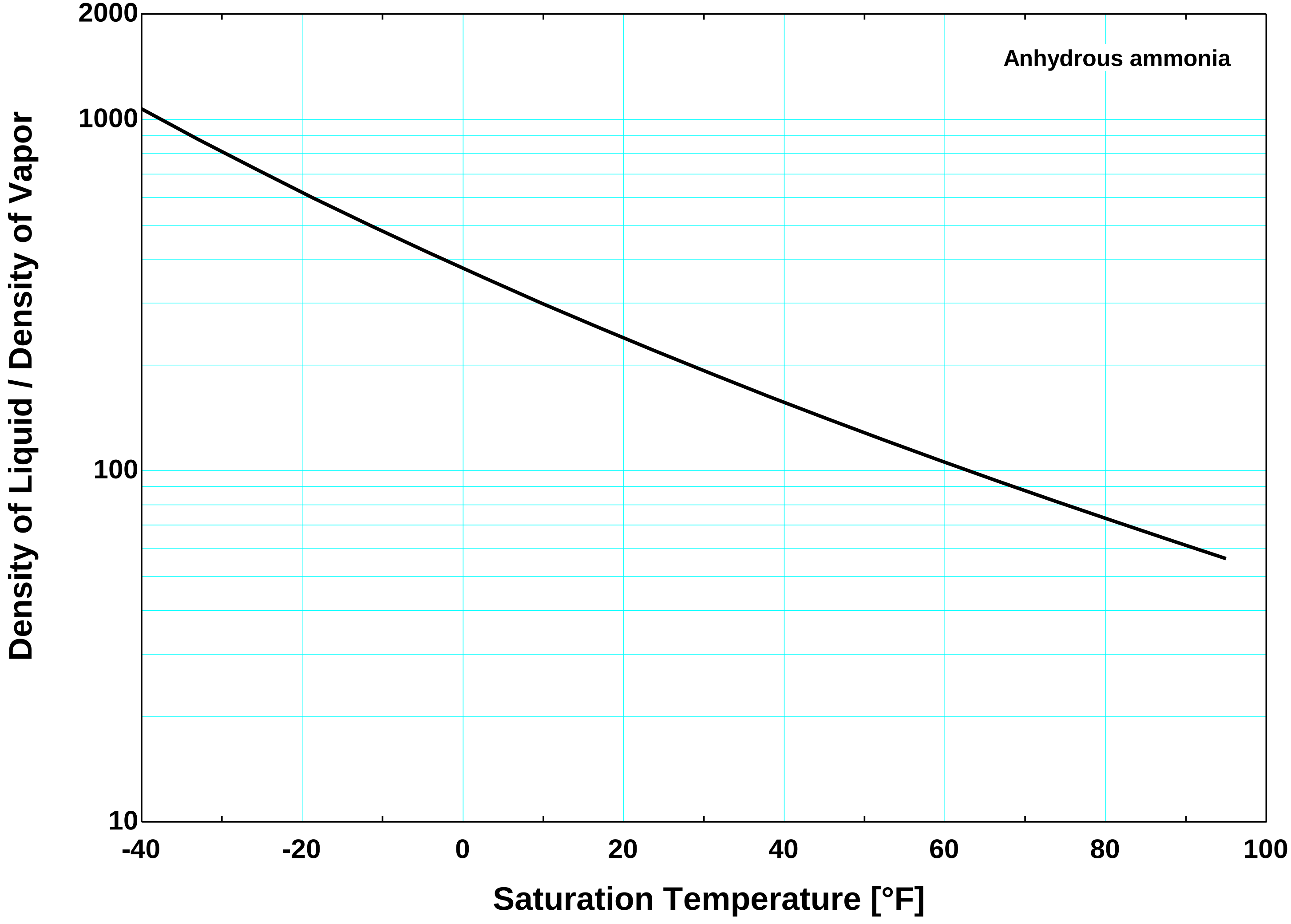
Approaches to determine refrigerant charge

1. Engineering calculations
2. Material receipts (new facilities)
3. Gravimetric (requires a complete system pump-down)





Ratio of liquid to vapor density for anhydrous ammonia



Focus on quantifying components with liquid-phase ammonia.

Refrigeration system charge calculation

1. Determine those locations throughout the system with liquid-phase ammonia
2. Establish the volume of liquid ammonia residing in those component locations
3. Mass = liquid volume x density
4. Sum individual component charge for system total

Details of the engineering calculations are available in a guidance document

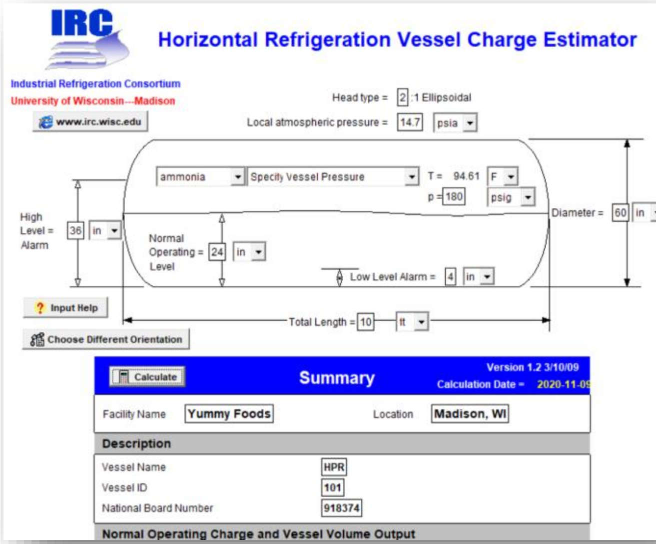

Best Practices for Reducing Fugitive Emissions from Industrial Refrigeration Systems

Industrial Refrigeration Consortium
College of Engineering
Department of Mechanical Engineering
University of Wisconsin-Madison

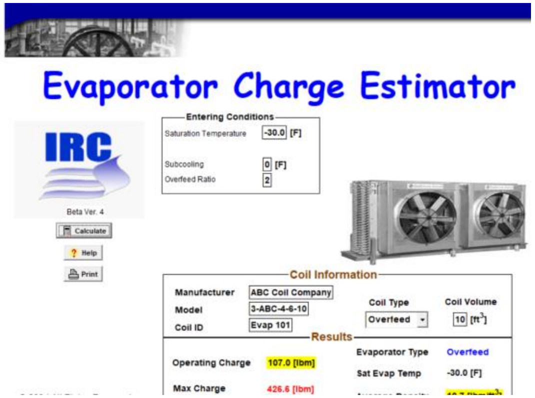
November 2020

Downloadable charge calculators

- Vessels
  - https://irc.wisc.edu/file.php?ID=435
- Evaporators
  - https://irc.wisc.edu/file.php?ID=436
- Compressors
  - https://irc.wisc.edu/file.php?ID=438



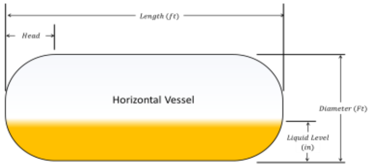
https://irc.wisc.edu/file.php?ID=435

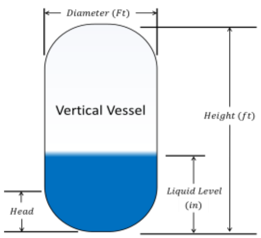


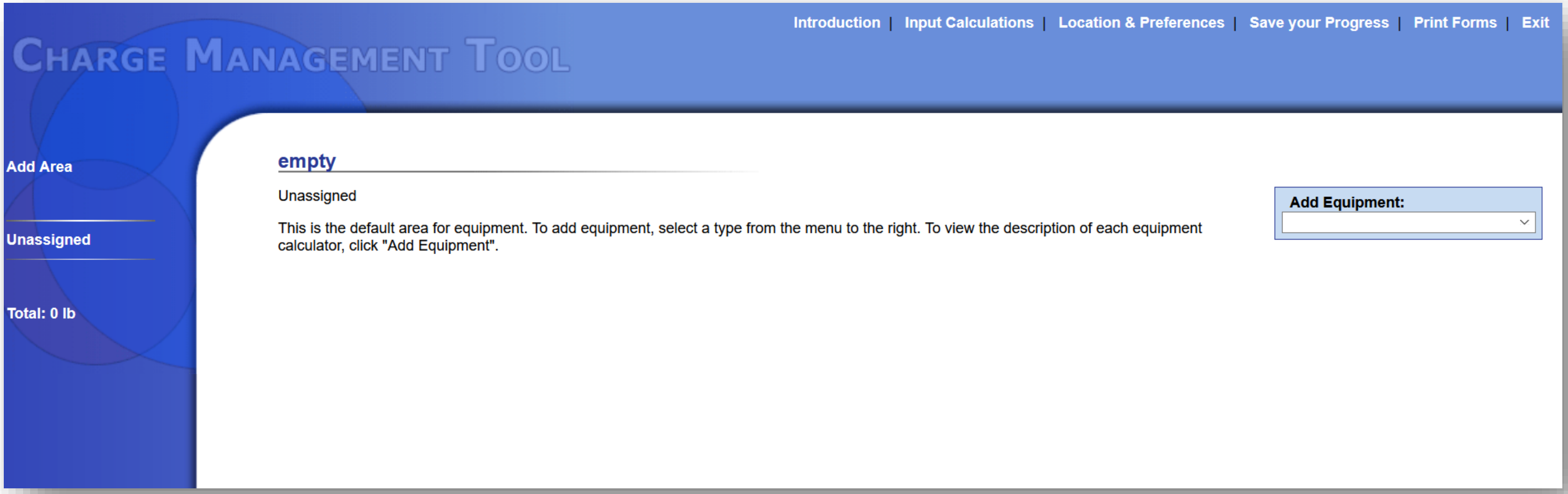
https://irc.wisc.edu/file.php?ID=436

Online charge calculation tool

- Pressure vessels (horizontal & vertical orientations)
- Piping
- Evaporators & condensers
- Compressors







Access online charge calculation tool at: https://irc.wisc.edu/charge2/

P2 - Ammonia emissions in the food and beverage sector

- Technology background
- Refrigerant emissions – what's typical?
- Determining refrigerant charge for existing systems
- **Strategies to find refrigerant emissions**
- Findings from fieldwork
- Conclusions & recommendations

Finding leaks

- Qualitative
  - Odor, self-alarming
  - Sulfur sticks, litmus paper
  - Ammonia detector (hand-held or fixed)
  - Relief vent line sensors
  - Thermography
- Quantitative
  - Component bagging with ammonia detector
  - Ultrasonic

Screening vs. bagging

Screening uses an ammonia sensor with a vacuum pump and probe to sniff for ammonia.

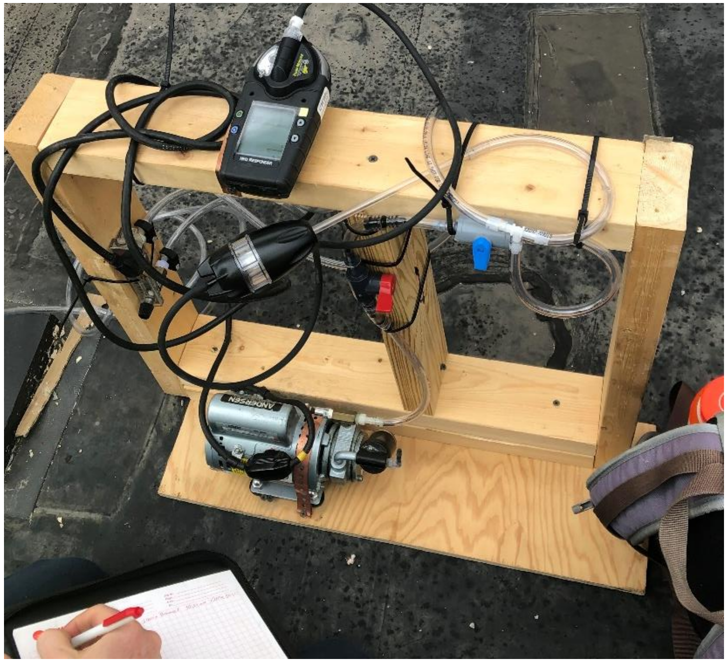
Screening vs. bagging

Bagging temporarily encapsulates the component, capturing any ammonia emissions & enabling measurement of ammonia leak rate.

Handheld vs. vacuum pump leak emission measurement ranges

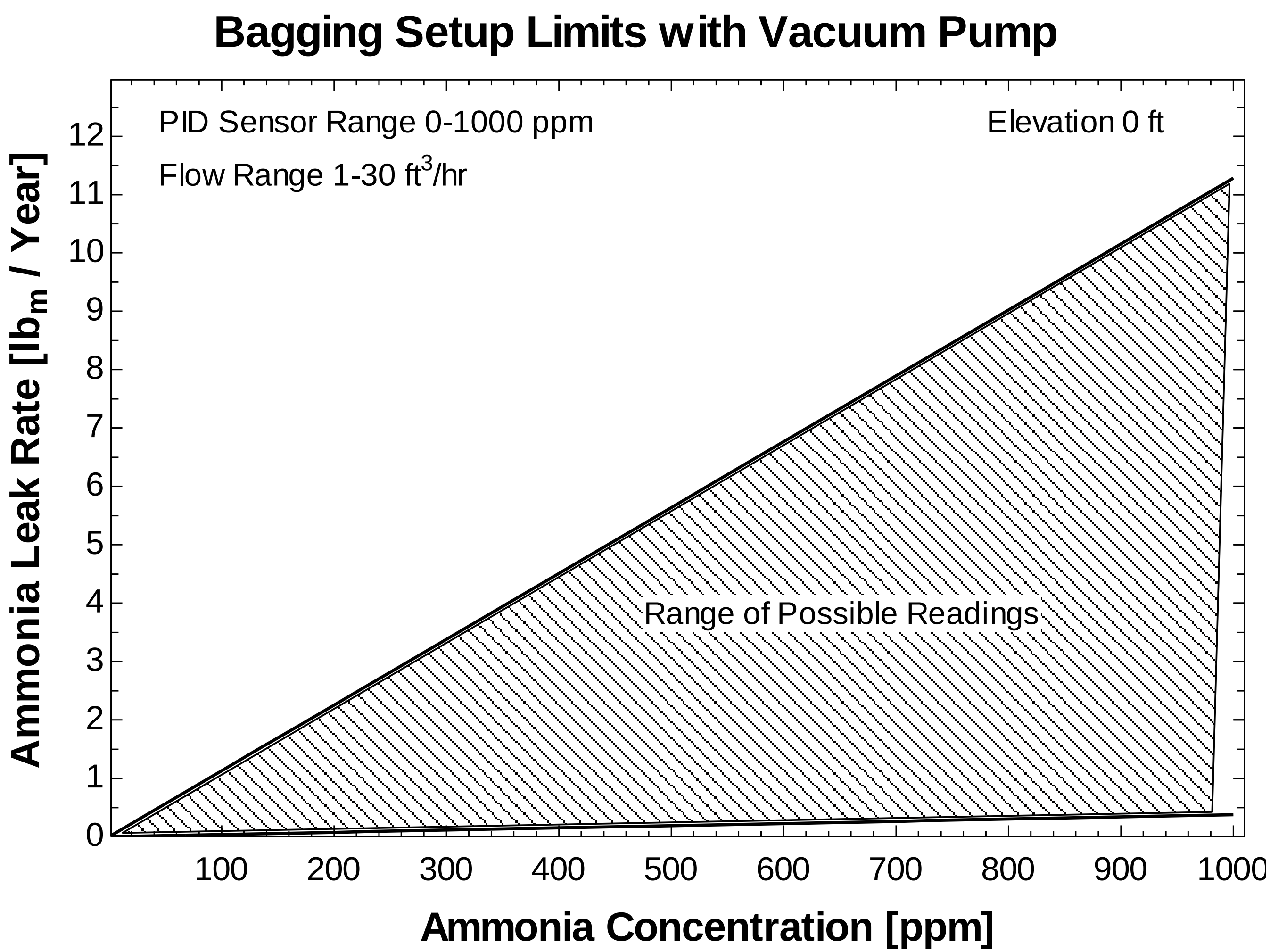
Handheld detector

NH_3 detector with vacuum pump

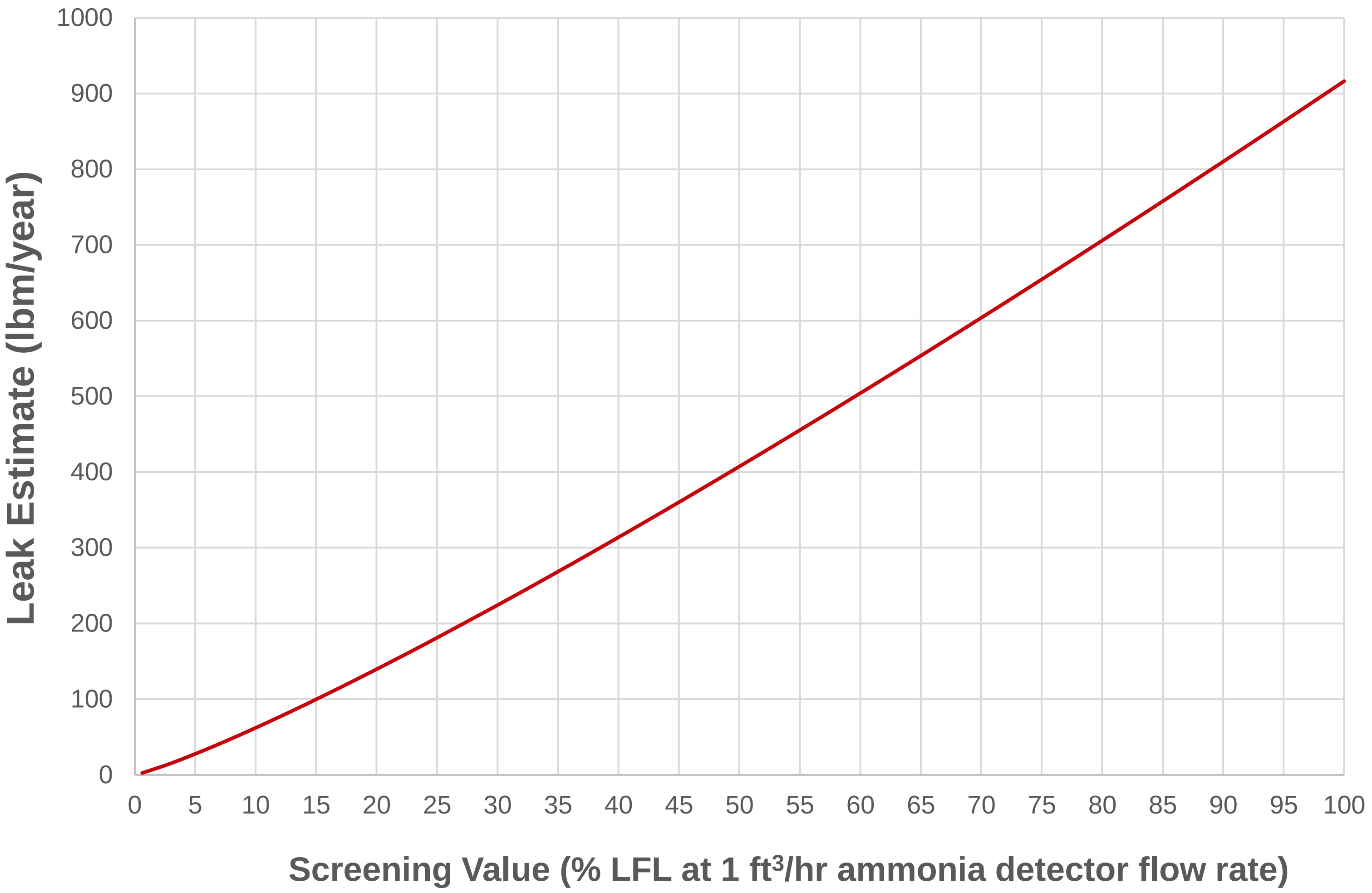


		Leak Rate Measurement Range (lb_m/year)	
Sensor	Detection Range	Onboard Pump (1ft^3/hr)	External Vacuum Pump (1 - 30 ft^3/hr)
PID	0-1000 ppm	0.001 - 0.383	0.001 - 11.3
Catalytic Bead	3-100% LFL (4500-150000 ppm)	2 - 72	2 - 2150

Bagging setup with PID Sensor and Pump



Least Squares Regression of Screening Reading to Leak Rate



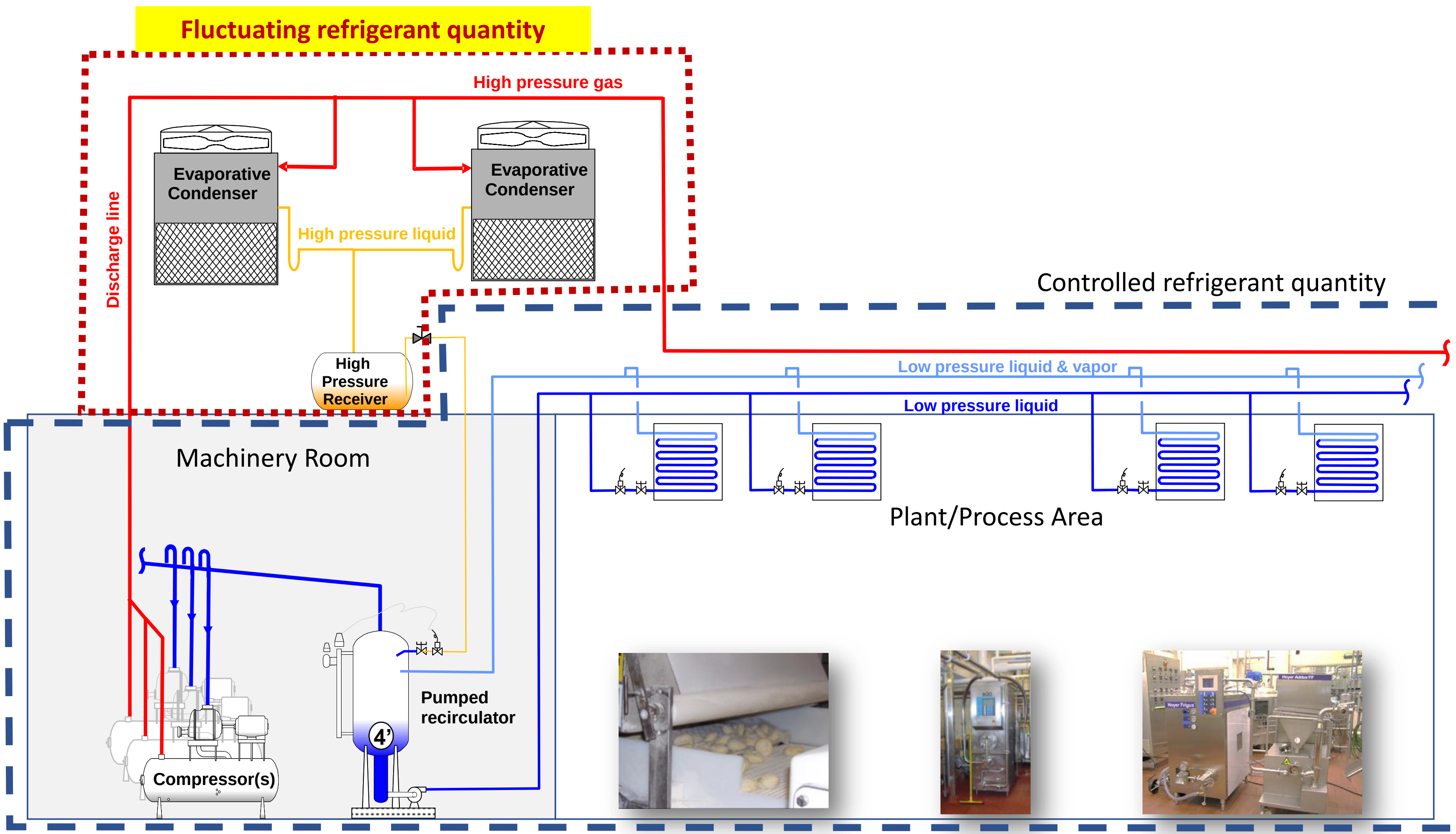
Finding fugitive emissions – best practices

- **Most effective**
  - Odor report with follow-up to pinpoint source using hand-held refrigerant detector or sulfur stick
  - Periodic *screening* of potential leak points
- Less/not effective
  - Ultrasonic
  - Infrared / thermography
  - Relief vent line detectors
    alerts to accidental release but not fugitive)

Dynamic refrigerant charge calculation

1. Divides refrigeration system into
   - “Controlled” refrigerant charge
   - Fluctuating refrigerant charge (usually HPR)
2. Baseline fluctuating component (HPR) quantity
3. Longitudinally track charge of HPR
   - Document temperature and HPR liquid levels during daily rounds with system operation “normal”
   - Track quantity over several weeks
   - Trend quantity to estimate annual loss rate
4. Manage system expansions or decommissioning to adjust baseline charge

Refrigeration system partitioning illustration



Dynamic charge calculation tool

Select vessel orientation

Enter HPR length (height) and diameter

Tool calculates volume

Orientation (H or V)	Length/Height (ft)	Dia (ft)	Head Type	Volume (cuft)	Notes:
Vertical			2:1		

Dynamic Vessel Inventory Calculation Tool

This tool is designed to assist facilities with estimating ammonia refrigerant losses over time by tracking the refrigerant charge of uncontrolled level vessels, most commonly the high pressure receiver.

How to use the tool:

1) In the "Vessel Dimensions" tab select the *Orientation* , and enter the *Length/Height (ft), Diameter (ft), Head Type (2:1 is the most common),* and any notes desired. The *Vessel Volume* will be calculated in cubic feet.

2) In the "Vessel Levels" tab enter the *date* of the reading, the *vessel liquid level (inches)* , and either the *saturation pressure* or *temperature* at the time the level reading was taken. Cell "C1" has a drop down to select temperature or pressure for the conditions column. The refrigerant charge of the vessel is then calculated by the tool.
Possible errors to be aware of are: entering a liquid level greater than the maximum possible, entering an invalid date, or entering a saturation condition outside of the table in columns "J"-"M". Dates must begin in row 2.

3) Periodically enter vessel conditions, ideally daily, however weekly or monthly can be effective as well.

4) Use the "Plot" button in "Vessel Levels" cell "I1" to generate a graph of the vessel charge over time with a trendline to estimate refrigerant losses.

For more information on the strategy of dynamic vessel inventory calculation see the accompaning guidance document,

Vessel Dimensions | Vessel Levels

Tool is available for download at: https://irc.wisc.edu/file.php?ID=508

Dynamic charge calculation tool

Enter longitudinal HPR level and pressure data

	Date	Liquid Level (inches)	Sat. Press (psig)	Liquid Density (lb/cuft)	Vapor Density (lb/cuft)	Liquid Volume (cuft)	Vapor Volume (cuft)	Total Charge (lbs)
2	8/21/2019	21	121	37.9	0.5	47.5	69.8	1830.5
3	8/21/2019	21	119	37.9	0.4	47.5	69.8	1832.1
4	8/21/2019	21	141	37.4	0.5	47.5	69.8	1815.0
5	8/22/2019	21	109	38.1	0.4	47.5	69.8	1840.6
6	8/22/2019	21	120	37.9	0.5	47.5	69.8	1831.3
7	8/22/2019	27	130	37.7	0.5	66.6	50.7	2532.6
8	8/23/2019	27	119	37.9	0.4	66.6	50.7	2546.5
9	8/23/2019	21	115	38.0	0.4	47.5	69.8	1835.2
10	8/23/2019	21	134	37.6	0.5	47.5	69.8	1820.3
11	8/24/2019	27	110	38.1	0.4	66.6	50.7	2558.5
12	8/25/2019	27	109	38.1	0.4	66.6	50.7	2559.9
13	8/26/2019	27	118	37.9	0.4	66.6	50.7	2547.7
14	8/26/2019	21	127	37.7	0.5	47.5	69.8	1825.8
15	8/26/2019	24	133	37.6	0.5	58.6	58.6	2233.6
16	8/27/2019	21	125	37.8	0.5	47.5	69.8	1827.3
17	8/27/2019	21	123	37.8	0.5	47.5	69.8	1828.9
18	8/28/2019	21	110	38.1	0.4	47.5	69.8	1839.7
19	8/28/2019	27	110	38.1	0.4	66.6	50.7	2558.5
20	8/28/2019	21	133	37.6	0.5	47.5	69.8	1821.0
21	8/29/2019	27	110	38.1	0.4	66.6	50.7	2558.5
22	8/29/2019	21	122	37.8	0.5	47.5	69.8	1829.7
23	8/29/2019	21	143	37.4	0.5	47.5	69.8	1813.6
24	8/30/2019	27	110	38.1	0.4	66.6	50.7	2558.5

Plot Data

Vessel Dimensions | Vessel Levels | Chart1

Dynamic charge calculation tool

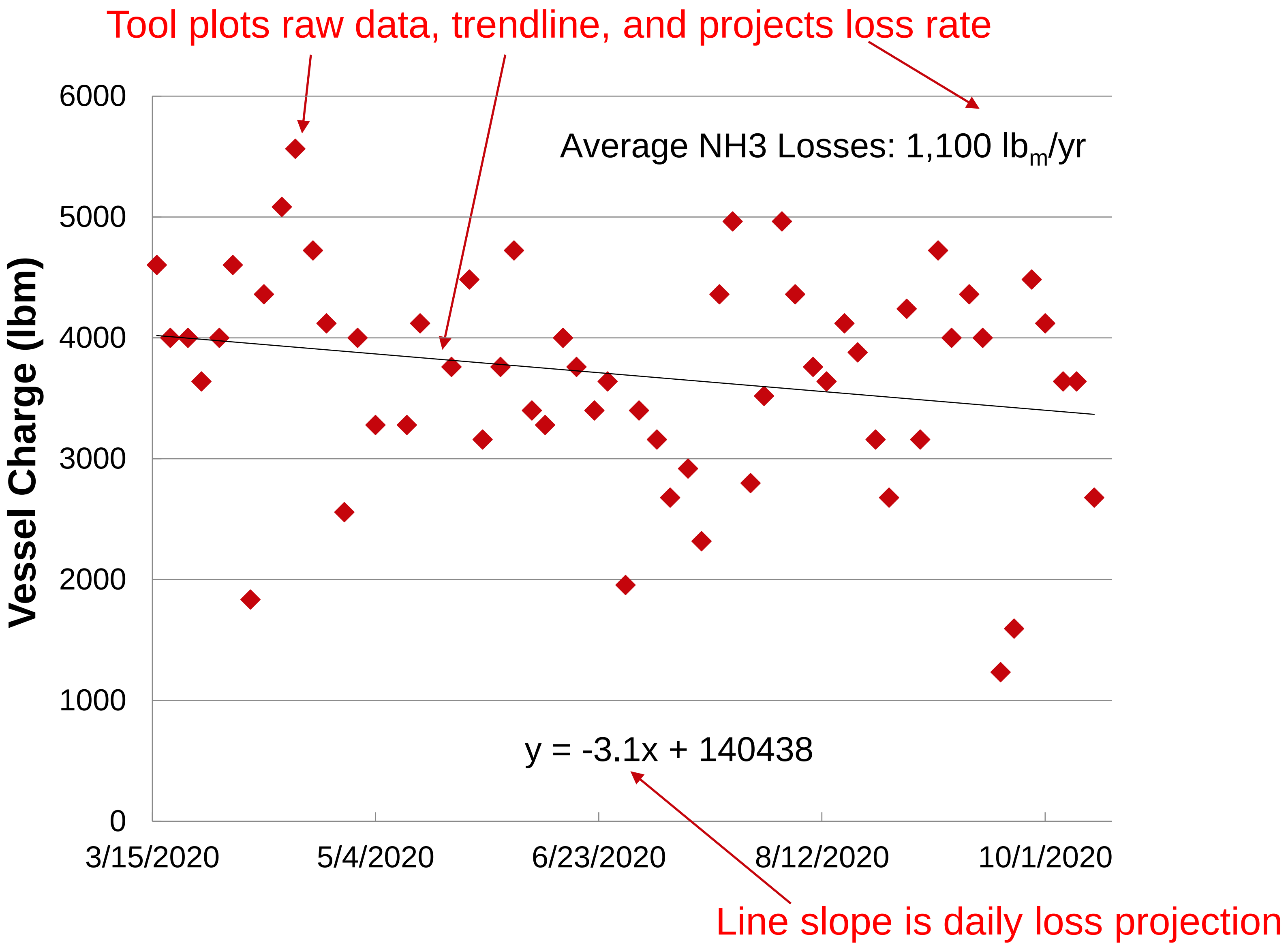
Enter longitudinal HPR level and pressure data

After entering several weeks of data, plot

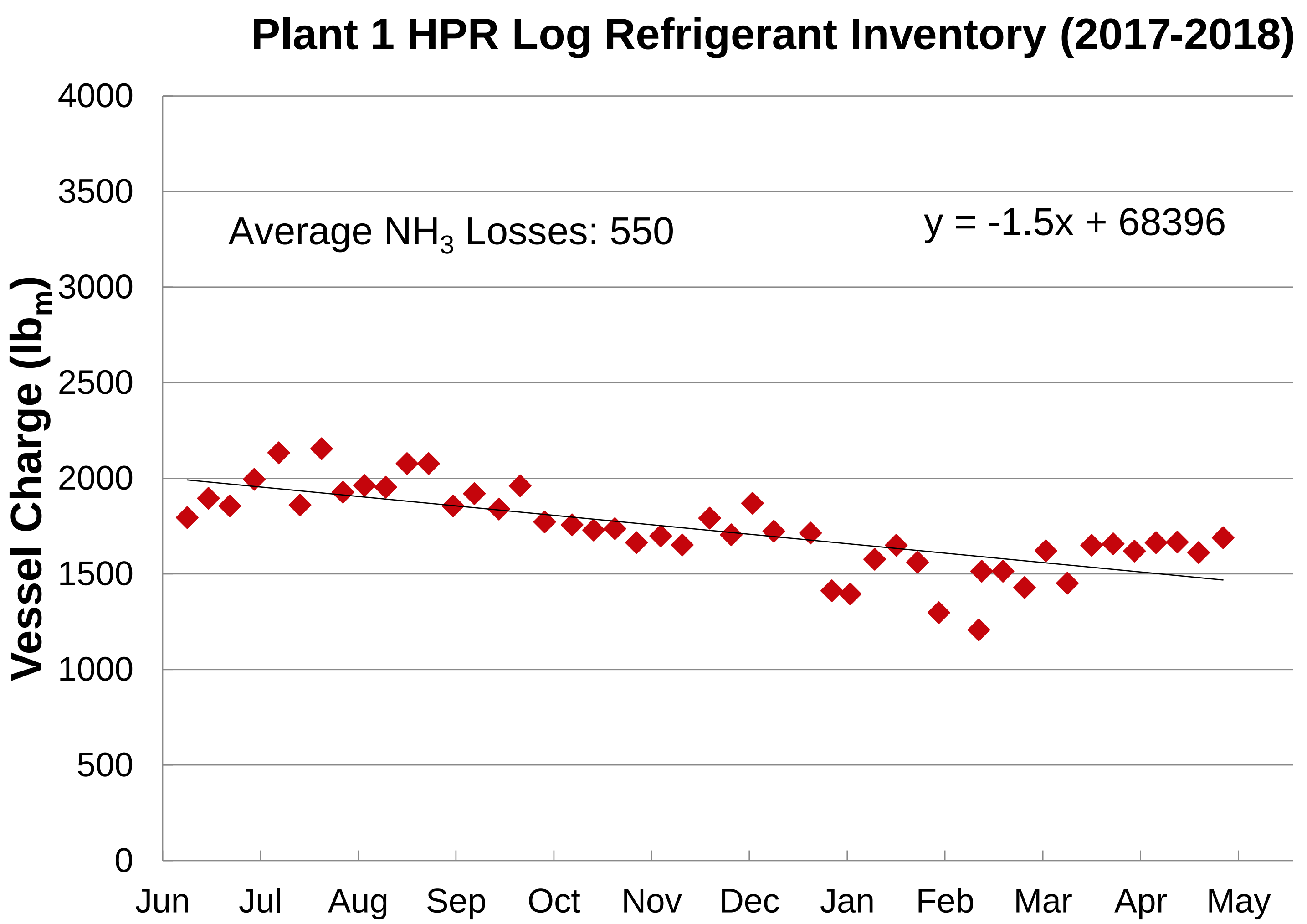
	Date	Liquid Level (inches)	Sat. Press (psig)	Liquid Density (lb/cuft)	Vapor Density (lb/cuft)	Liquid Volume (cuft)	Vapor Volume (cuft)	Total Charge (lbs)	Plot Data
2	8/21/2019	21	121	37.9	0.5	47.5	69.8	1830.5	
3	8/21/2019	21	119	37.9	0.4	47.5	69.8	1832.1	
4	8/21/2019	21	141	37.4	0.5	47.5	69.8	1815.0	
5	8/22/2019	21	109	38.1	0.4	47.5	69.8	1840.6	
6	8/22/2019	21	120	37.9	0.5	47.5	69.8	1831.3	
7	8/22/2019	27	130	37.7	0.5	66.6	50.7	2532.6	
8	8/23/2019	27	119	37.9	0.4	66.6	50.7	2546.5	
9	8/23/2019	21	115	38.0	0.4	47.5	69.8	1835.2	
10	8/23/2019	21	134	37.6	0.5	47.5	69.8	1820.3	
11	8/24/2019	27	110	38.1	0.4	66.6	50.7	2558.5	
12	8/25/2019	27	109	38.1	0.4	66.6	50.7	2559.9	
13	8/26/2019	27	118	37.9	0.4	66.6	50.7	2547.7	
14	8/26/2019	21	127	37.7	0.5	47.5	69.8	1825.8	
15	8/26/2019	24	133	37.6	0.5	58.6	58.6	2233.6	
16	8/27/2019	21	125	37.8	0.5	47.5	69.8	1827.3	
17	8/27/2019	21	123	37.8	0.5	47.5	69.8	1828.9	
18	8/28/2019	21	110	38.1	0.4	47.5	69.8	1839.7	
19	8/28/2019	27	110	38.1	0.4	66.6	50.7	2558.5	
20	8/28/2019	21	133	37.6	0.5	47.5	69.8	1821.0	
21	8/29/2019	27	110	38.1	0.4	66.6	50.7	2558.5	
22	8/29/2019	21	122	37.8	0.5	47.5	69.8	1829.7	
23	8/29/2019	21	143	37.4	0.5	47.5	69.8	1813.6	
24	8/30/2019	27	110	38.1	0.4	66.6	50.7	2558.5	

Vessel Dimensions | **Vessel Levels** | Chart1

Dynamic charge calculation tool

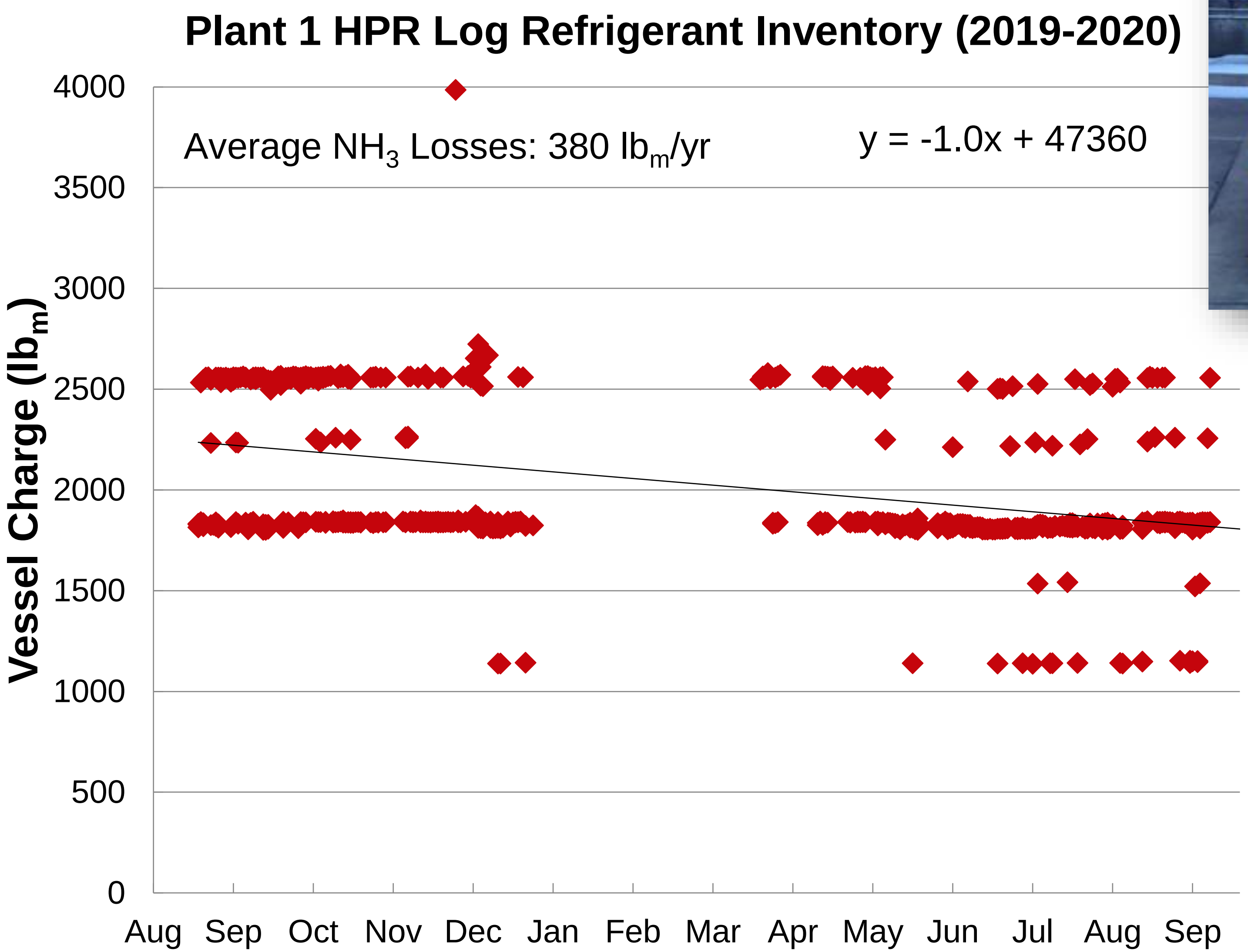


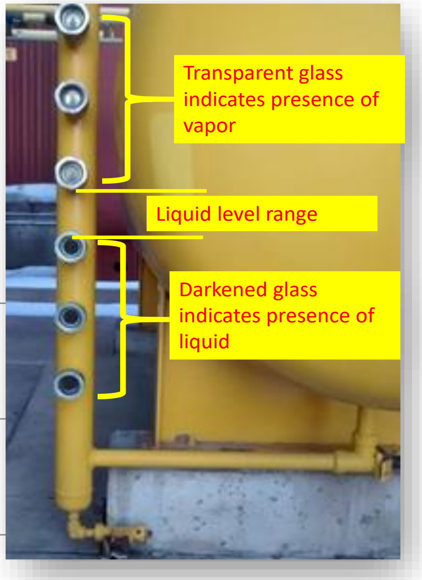
Applying technique to Plant 1



Loss rate based on ammonia purchases 2017-2018, **496 lb_m/yr**

Plant 1 – Post P2 visit





Loss rate based on ammonia purchases 2019-2020, **??? lb_m/yr**

Dynamic charge calc caveats

- Consider how system operation may bias results
  - Portions of plant refrigeration processes operating or shutdown
- Consider how refrigeration system changes will impact the results
  - Decommissioning refrigeration equipment can mask refrigerant loss (false negative)
  - Equipment addition/expansion can suggest refrigerant loss (false positive)

Dynamic charge calculation tool

Orientation (H or V)	Length/Height (ft)	Dia (ft)	Head Type	Volume (cuft)	Notes:
Vertical			2:1		

Dynamic Vessel Inventory Calculation Tool

This tool is designed to assist facilities with estimating ammonia refrigerant losses over time by tracking the refrigerant charge of uncontrolled level vessels, most commonly the high pressure receiver.

How to use the tool:

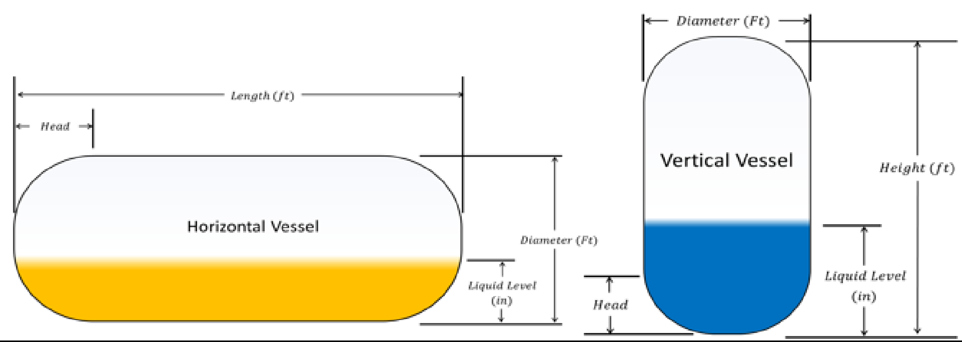
1) In the "Vessel Dimensions" tab select the *Orientation* , and enter the *Length/Height (ft), Diameter (ft), Head Type (2:1 is the most common),* and any notes desired. The *Vessel Volume* will be calculated in cubic feet.

2) In the "Vessel Levels" tab enter the *date* of the reading, the *vessel liquid level (inches)* , and either the *saturation pressure* or *temperature* at the time the level reading was taken. Cell "C1" has a drop down to select temperature or pressure for the conditions column. The refrigerant charge of the vessel is then calculated by the tool.
Possible errors to be aware of are: entering a liquid level greater than the maximum possible, entering an invalid date, or entering a saturation condition outside of the table in columns "J"-"M". Dates must begin in row 2.

3) Periodically enter vessel conditions, ideally daily, however weekly or monthly can be effective as well.

4) Use the "Plot" button in "Vessel Levels" cell "I1" to generate a graph of the vessel charge over time with a trendline to estimate refrigerant losses.

For more information on the strategy of dynamic vessel inventory calculation see the accompaning guidance document, *Estimating Aggregate Refrigerant Losses by Dynamic Refrigerant Inventory Calculations* section.



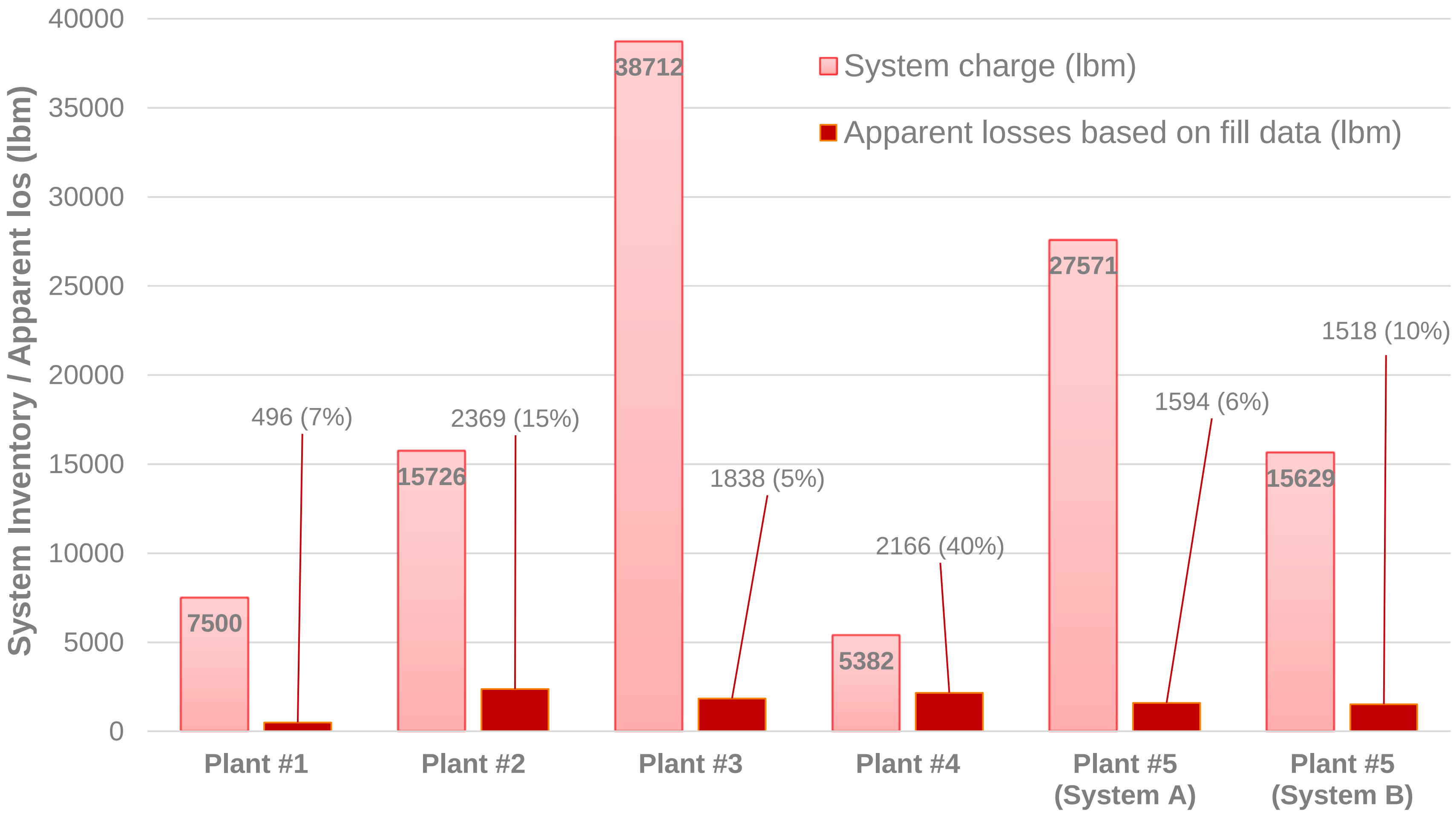
IRC "Guidance Document – Best Practices for Calculating Refrigerant Inventory and Identifying and Reducing Fugitive

Download at: https://irc.wisc.edu/file.php?ID=508

P2 - Ammonia emissions in the food and beverage sector

- Technology background
- Refrigerant emissions – what's typical?
- Determining refrigerant quantity for existing systems
- Strategies to find refrigerant emissions
- **Findings from fieldwork**
- Conclusions & recommendations

Field work – plant summary



Findings from field work

Plant	System Charge (lb_m)	Annual losses (lb_m [%])	Comments
#1	7,500	496 [6.6]	Minimal system changes, reasonable loss est.
#2	15,726	2,369 [15.1]	NH_3 additions due to system expansion biasing apparent loss rate. Estimated steady state loss rate is approximately 4.8%/yr
#3	38,712	1,838 [4.8]	Minimal system changes, reasonable loss est.
#4	5,382	2,166 [40.3]	Plant expansions biasing apparent loss rate. Significant equipment/piping replacements recently expected to reduce annual losses.
#5 (System A)	27,571	1,594 [5.8]	System recently underwent consolidation.
#5 (System B)	15,629	1,518 [9.7]	
Totals	110,520	9,981 [9.0]	Totals are biased high by 3 of 5 plants

Summary of fugitive emissions – field work

- Site visits conducted at 5 separate plants
- A total of 6 refrigeration systems evaluated
  - Detailed charge calculations prepared
  - Assessment of historical ammonia purchases
  - 175 components were surveyed
    - 159 components were screened
    - 110 components were bagged
  - Components surveyed included:
    - Shutoff valves, solenoid valves, sight glasses, threaded connections, unions, flare fittings, flanges, check valves, plugs, pressure relief valves, open-drive refrigerant pump, and purger
  - Pressure levels included "high" and "low"

Summary of fugitive emissions – field findings

- A total of 6 refrigeration systems evaluated, cont.
  - 34 of 175 components surveyed had detectable emissions
    - 21 sight glasses
    - 12 valves
    - 1 twin screw compressor housing
  - Interestingly, no refrigerant emissions were found on the following surveyed components*
    - threaded connections, unions, flare fittings, flanges, check valves, plugs & pressure relief valves

* We do know these components have exhibited refrigerant leaks in other facilities, but they did not exhibit leaks during the field work in the present project.

Field-measured component leak rates

Pressure Level	Average leak rate for components sampled (lb_m/yr)	
	Sampled components triggered by odor	All components sampled
High Side (>80 psig) 105 items	**1.25**	**0.06**
Low Side (<80 psig) 70 items	**N/A**	**0.002**

Although components exhibiting ammonia odor had a component leak rate, the overall annual loss is still low.

Wow, those numbers are small!

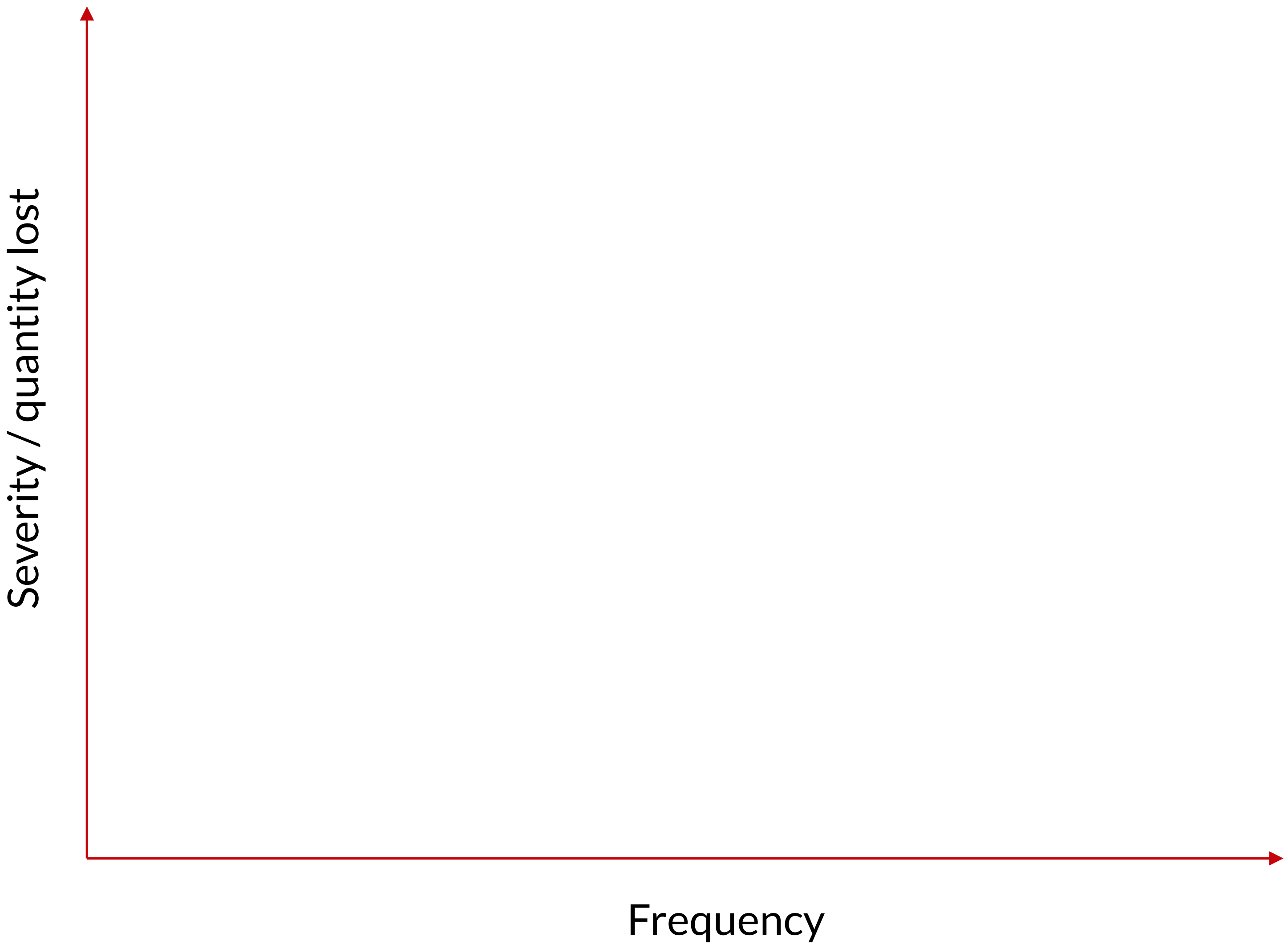
- *So how is refrigerant being lost from systems?*

Wow, those numbers are small!

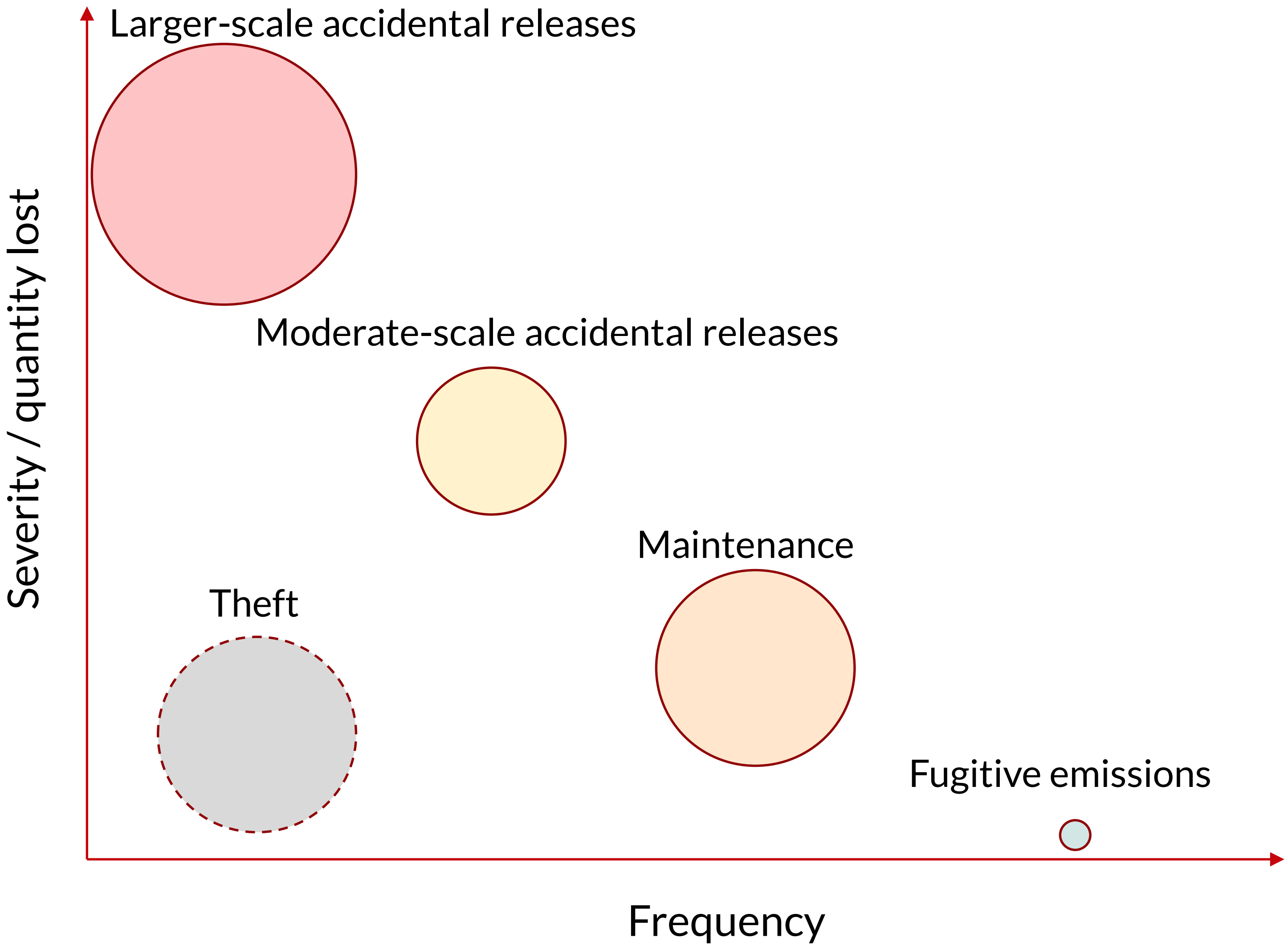
- *So how is refrigerant being lost from systems?*
  - Known (but not always quantified)
    - Intentional: venting as a part of maintenance activities
    - Unintentional: accidental releases due to loss of mechanical integrity, pressure relief valve actuation
  - Unknown
    - Unintentional: accidental leaks that are masked (evaporative condensers, malfunctioning purgers), fugitive emissions

Continuous improvement in plant mechanical integrity programs is the key strategy to decrease accidental releases

Conceptual illustration of refrigerant losses



Conceptual illustration of refrigerant losses



Mechanical integrity (MI)

- Plants covered by PSM/ RMP are required to develop & implement MI programs
- Strong MI programs reduce probability of accidental ammonia releases
- Both OSHA's National Emphasis Program (NEP) and EPA's National Enforcement Initiative (NEI) have found consistent weakness in plant MI programs during inspections

Click here for an EPA-compiled a list of ammonia-related resources.

Conclusions, recommendations, & challenges

- Majority of plants find and fix leaks when discovered (odor response)
- Effectively managing mechanical integrity of industrial ammonia systems is improving but still lagging
- Few plants periodically search for fugitive emissions as a normal part of operations
- Anhydrous ammonia is cheap (~\$1/lb_m) with no ODP or GWP
- Plants do not have refrigerant loss benchmarks that can be used as a trigger to prompt searching for leaks

Threshold of “acceptable” loss rate is not a constant

Plants should target to limit annual loss rates at or below **5%** with total “unknown” losses below **2,000 lb_m/yr**.

Annual loss rate	Daily / Annual loss* quantity (lb_m)		
	400 lb_m system	**40,000 lb_m system**	**400,000 lb_m system**
1%	0.01 / 4	1.1 / 400	11.0 / 4,000
5%	0.05 / 20	5.5 / 2,000	54.8 / 20,000
10%	0.11 / 40	11.0 / 4,000	109.6 / 40,000
20%	0.22 / 80	22.0 / 8,000	219.2 / 80,000

* Does not include system expansion.

Acknowledgements

- Thank you to the end-users who agreed to be a part of the field work associated with this project
- Thank you to EPA Staff for their support:
  - Christine Anderson, P2 Coordinator & our primary contact
  - Antionette Hall, Project Officer

Summary of tools

- Downloadable tools:
  - Component ammonia charge calculations:
    - Vessels: https://irc.wisc.edu/file.php?ID=435
    - Evaporators: https://irc.wisc.edu/file.php?ID=436
    - Compressors: https://irc.wisc.edu/file.php?ID=438
  - Dynamic charge calculation tool:
    - https://irc.wisc.edu/file.php?ID=508
  - Fugitive emissions bagging tool:
    - https://irc.wisc.edu/file.php?ID=509
- Online tool:
  - Ammonia charge calculation tool:
    - https://irc.wisc.edu/charge2/

Summary of additional ammonia refrigeration-related resources

- **IIAR – International Institute of Ammonia Refrigeration** www.iiar.org
  - provides advocacy, education, and standards for the benefit of the global community in the safe and sustainable design, installation and operation of ammonia and other natural refrigerant systems
- **IRC – Industrial Refrigeration Consortium** www.irc.wisc.edu
  - improving the safety, reliability, efficiency, and productivity of industrial refrigeration systems
- RETA – Refrigerating Engineers Technicians Association reta.com
  - dedicated to the professional development of industrial refrigeration operators and technicians

Questions?