Lifecycle Analysis of End-of-Life Management Options for High-Global Warming Potential Gases

Pamela Mathis and Julia Forgie

May 11, 2011

California Air Resources Board
Technical Seminar
Sacramento, California

Acknowledgements

We would like to thank…

- **Glenn Gallagher and colleagues at the California Air Resources Board**
- **Project Team**
  - Stefan Unnasch, Life Cycle Associates
- **Industry stakeholders**

Agenda

- Background
- Project Objectives
- Part I: Household Refrigerators/Freezers
- Part II: Building Foam (Demolition)
- Part III: Disposable Refrigerant Cylinders
- Part IV: Other Stationary Refrigeration/Air Conditioning Equipment
- Part V: Fire Extinguishing Agents & Miscellaneous Gases

Background

- **High-Global Warming Potential (GWP) gases primarily include ozone-depleting substances (ODS) & hydrofluorocarbons (HFCs)**
  - Refrigeration & air conditioning (AC) equipment
  - Foam blowing agents: building insulation, refrigerated appliances, other products
  - Fire extinguishing agents
  - Other: solvents, aerosols, semiconductor manufacture, electrical power systems
- **Very potent GHGs: thousands times greater than CO2**
  - In largest sector, Ref/AC, GWPs range up to 8,100 (based on SAR)
- **Emissions occur primarily through (1) leaking systems and (2) during disposal process**
- **Once released, gases have a long atmospheric lifetime (up to 100 years or more)**

Background

- High-GWP gases ~3% of CA's GHG emissions today, but projected to rise to ~ 8% by 2020

Sector	All High-GWP GHGs			Kyoto Gases Only		
	2020 BAU Emissions ($MMTCO_2eq$)	Percent of BAU	Reduction Potential by 2020 ($MMTCO_2eq$)	2020 BAU Emissions ($MMTCO_2eq$)	Percent of BAU	Reduction Potential by 2020 ($MMTCO_2eq$)
Stationary Refrigeration/AC	45.4	72%	10.3	33.9	73%	7.2
Mobile AC	7.1	11%	3.5	7.1	15%	3.5
Foams	5.8	9%	1.0	1.4	3%	1.0
Fire Extinguishing	0.5	1%	0.1	0.2	0%	0.1
All Other Sources	4.5	7%	1.4	4.2	9%	1.4
Total	**63.3**	**100%**	**16.3**	**46.8**	**100%**	**13.2**

- AB 32 requires annual reductions of 174 $MMTCO_2eq$
  - Several ARB regulations target high-GWP emissions to help achieve goal
- AB 32 Scoping Plan identified recovery & destruction of high-GWP materials as an option for providing further reductions

Project Objectives

Key Questions:

- What are the costs and benefits of reducing high-GWP gas emissions at disposal?
- Which reductions could be achieved through regulatory or non-regulatory measures?

Purpose of Study

- Quantify baseline emissions associated with current EOL management of high-GWP gases
- Quantify lifecycle costs and benefits of alternative EOL management scenarios
- Calculate GHG abatement costs ($/MTCO_2$eq) to inform ARB policy decisions

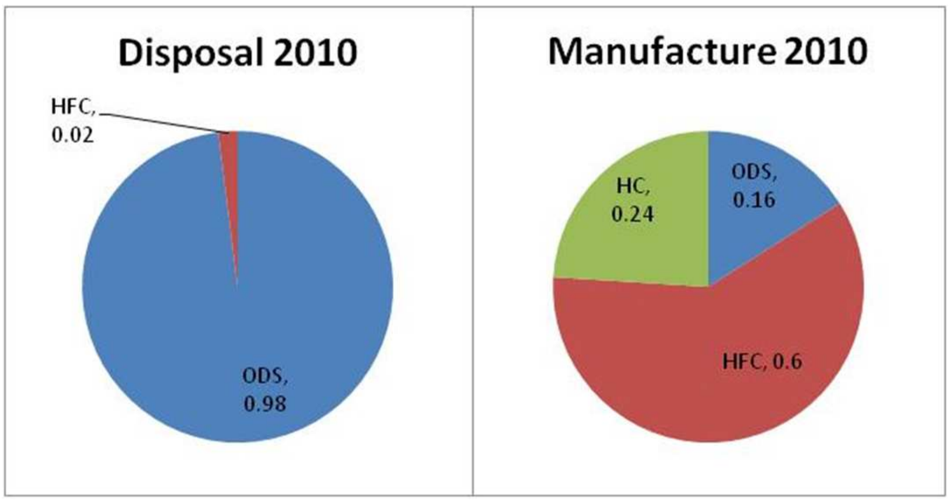
Organization

- Current situation
- Alternative management options
- GHGs avoided
- Cost effectiveness

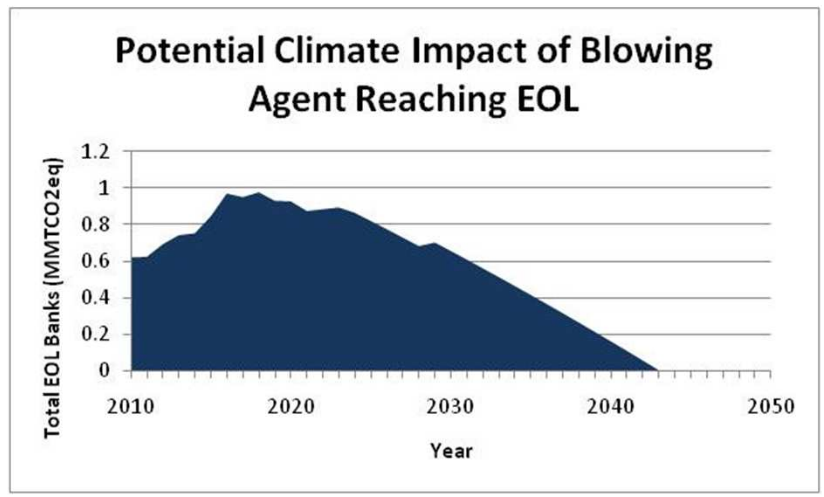
Part I:
Household Refrigerators/Freezers

Current Situation

- Nearly 1 million refrigerators/freezers disposed annually in CA
  - Units contain ODS/HFC refrigerants (~0.5 lb) and foam blowing agent (~2 lbs)
- At disposal, federal law requires proper handling of refrigerant and other hazardous substances
  - No requirements for foams
- Depending on date of equipment manufacture, foam contains CFC, HCFC, HFC, or HC blowing agents



Increasingly, units will transition to HCs & other low-GWP agents



EOL banks peak in 2018

(on carbon-weighted basis)

Current Situation

- Since 2006, only a Certified Appliance Recycler (CAR) may remove materials that require special handling from appliances in CA
- Over 170 CARs operate in CA
  - Most dispose of units as follows:
    - Refrigerant: recovered & reused/destroyed
    - Metals, plastics, glass: recycled
    - Foams: put in auto shredder then landfilled
  - 3 dedicated appliance recyclers (DARs) remove foam manually
    - Primarily for utility DSM programs
    - 15% of units in CA handled this way

Question: What are the lifecycle costs and benefits of different foam handling procedures?

Alternative Management Options: 100% Foam Recovery

1. **Manual foam recovery at existing CA facilities**
   - BAU
     - 85% at existing CARs, using handheld saws
     - 15% at existing DARs, using handheld/automated saws

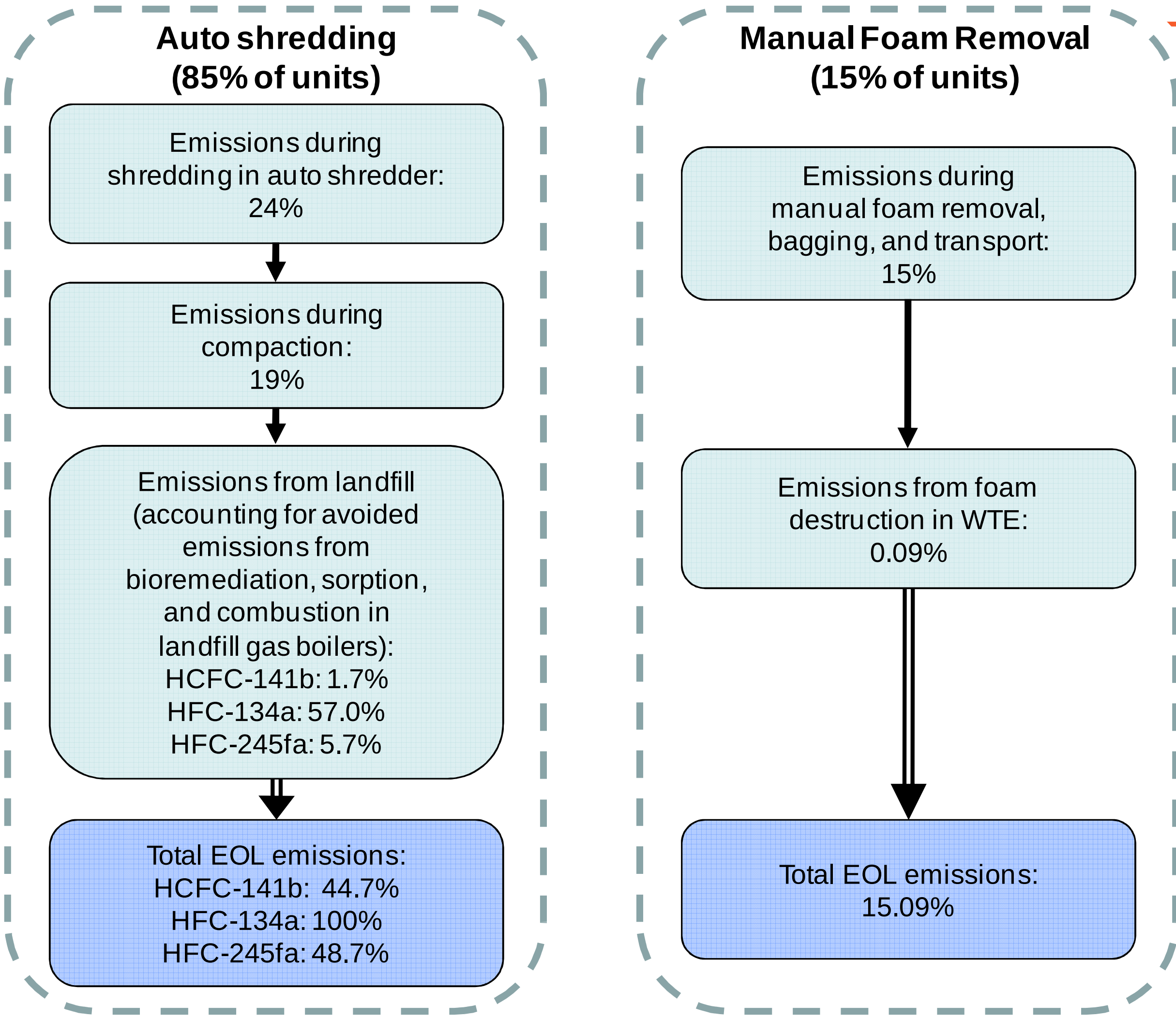
2. **Manual foam recovery at dedicated appliance recycling facilities**
   - Current 3 DARs + 7 new facilities in CA
     - Recovery using handheld/automated saws

3. **Fully-automated foam recovery at dedicated appliance recycling facilities**
   - More advanced technology used in Europe, Japan, elsewhere
     - High capacity; would require 5 new facilities in CA

Key Parameters

- **Boundary of Analysis**
  - Units containing ODS and HFC foams only
  - Focus on foam treatment (not the handling of other components)
- **Emissions Analyzed**
  - Blowing agent (based on foam treatment)
  - Energy consumption during foam handling
  - Transport
- **Costs Analyzed**
  - Transport fuel
  - Labor: transport and foam handling
  - Energy consumption
  - Operations and maintenance
  - Foam disposal
  - Capital costs of facility rental and equipment purchase

BAU Foam Disposal Assumptions

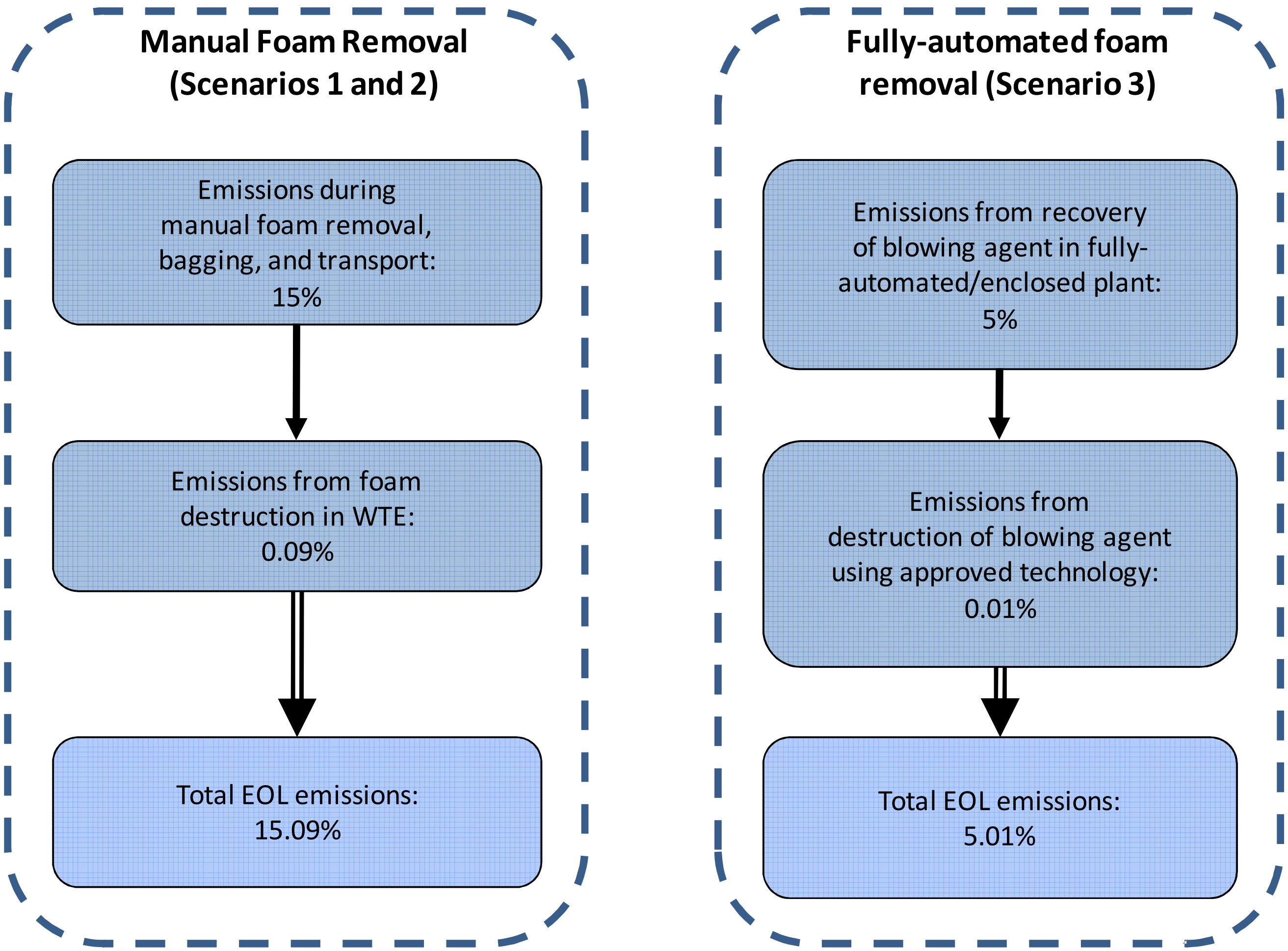


Areas of uncertainty:

- Emissions avoided in landfill can vary
  - Relied on published literature, CAR protocol, industry experts
- Emissions from manual recovery; studies vary between 5% -24%
  - Relied on published literature, industry experts
- Conservative assumptions used

Key Assumptions in Alternative Management Options

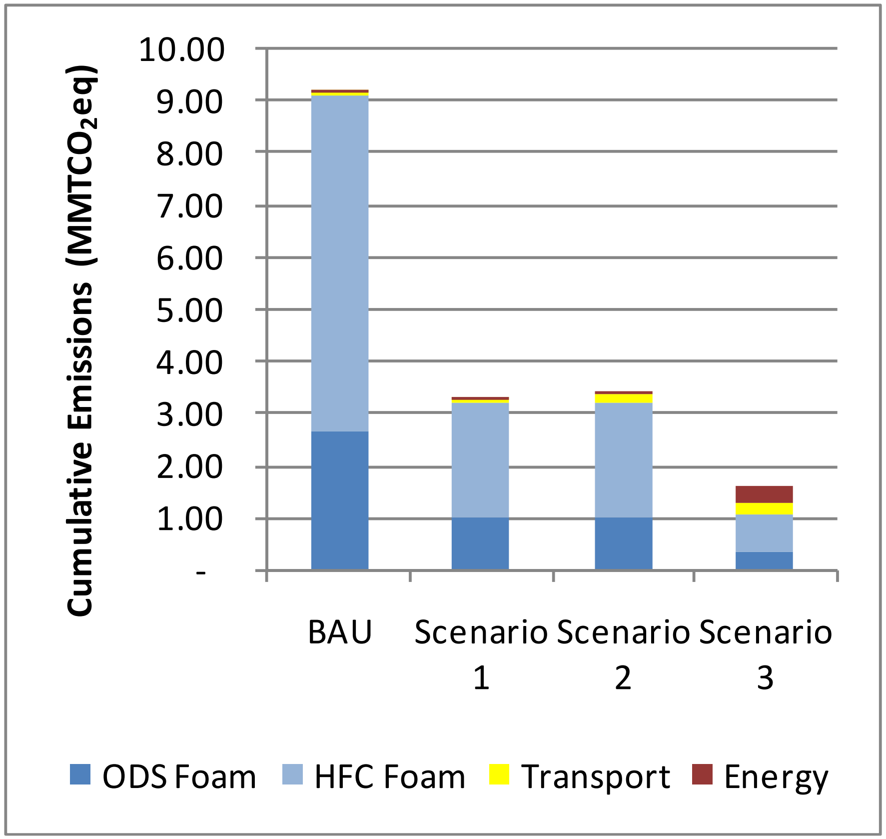
Percent of Foam Remaining at EOL



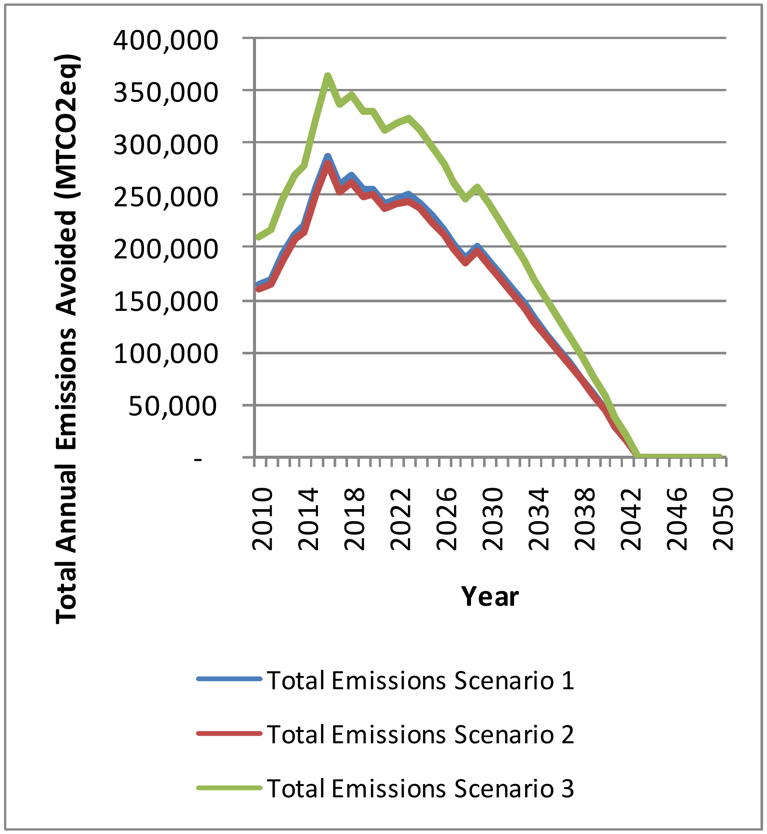
- 10% more foam capture using more sophisticated technology
- But greater transport required for destruction of concentrated blowing agent
  - Facilities located in AR, UT, TX

Results: GHG Emissions Comparison

Cumulative GHG Emissions ($MMTCO_2eq$), 2010-2050



Annual GHG Emissions Avoided ($MTCO_2eq$)



Results: Cost Effectiveness

Per Unit Costs (2010)

Activity or Stage	Costs ($)			
	BAU	Scenario 1	Scenario 2	Scenario 3
Total Per-unit Costs	**$12**	**$29**	**$55**	**$49**
Estimated total per-unit costs including metal recycling and refrigerant recovery	($8)	$9	$35	$28
Total Incremental Per-unit Costs	**NA**	**$17**	**$43**	**$37**

Total Costs (2010-2020)

Total Costs and GHG Emissions Avoided (2010-2020)	HFC-Containing Units			Total		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
NPV Incremental Cost ($ millions)	$28	$69	$64	$171	$421	$387
Average Cost per $MTCO_2eq$ Avoided	$23	$58	$42	$67	$170	$119

- Cost to reduce HFC emissions range from $23- $58/$MTCO_2eq$, depending on method used
- Fully-automated foam recovery costs less than manual recovery—on per unit and $MTCO_2eq$ basis

Findings

- Fully automated foam recovery results in greatest emission savings
  - ~0.2 MMTCO2eq can be reduced from HFC-containing units in 2020
- Manual recovery using existing CAR facilities also results in GHG savings—and at lowest cost
  - \$23/MTCO_2eq for HFC-containing units
- Great uncertainty associated with emissions avoided in landfills; if emissions not avoided, results are significantly different:
  - Reductions would more than double: 0.5 MMTCO_2eq in 2020 (HFC units)
  - Cost effectiveness would be less than half: \$11/MTCO2eq (HFC units)
- Best opportunity to reduce emissions from appliance disposal is in near-term, before high-GWP gas-containing appliances reach retirement

Part II:
Building Foam
(Construction & Demolition-C&D)

Current Situation

- Caleb Management Services prepared foams inventory for ARB in 2010; looked at current practices
- At EOL, C&D foam typically combined with other non-hazardous waste and landfilled
- No precedent for recovery of C&D foam for safe disposal in US/CA, but some in Europe
  - Polyurethane (PU) sandwich panels—which contain foam between two facing materials (usually steel panels)—can most easily be recovered from C&D waste

Question: what are the lifecycle costs and benefits of recovering C&D panel foam in CA, where feasible?

BAU: Disposal of Panel Foams

- **According to Caleb (2010):**
  - 80% of panel foam is open shredded, then landfilled; 20% directly landfilled
  - 1st year of disposal is 2016

Blowing Agent (MT) in PU Panels in CA Buildings Reaching EOL

Year	CFC-11	HCFC-141b	HFC-245fa	HCs
2010	-	-	-	-
2015	-	-	-	-
2020	1.5	-	-	-
2025	2.0	2.0	-	-
2030	-	91.5	-	-
2035	-	19.2	57.6	51.2
2040	-	-	256.9	256.9
2045	-	-	472.5	472.5
2050	-	-	667.1	667.1
Total	**32.6**	**688.7**	**6,256.8**	**6,212.4**

Alternative Management Options

- **Separation and recovery of blowing agent from (a) 25% or (b) 50% of C&D panels reaching EOL**
  - PU panel foam separated from other C&D waste and trucked to appliance recycling facility
  - Blowing agent separated from foam panel fluff in fully-automated/ enclosed appliance shredder
  - Blowing agent sent for destruction in hazardous-waste permitted destruction facility

Key Parameters

- **Emissions**
  - Foam blowing agent (BA)
  - Energy consumption for foam treatment
  - Transport
- **Costs**
  - Foam separation/collection (alternative scenario only)
  - Incremental transport
  - Foam handling: shredding vs. processing for BA recovery (energy and labor)
  - Foam/blowing agent disposal (landfilling vs. destruction of BA)

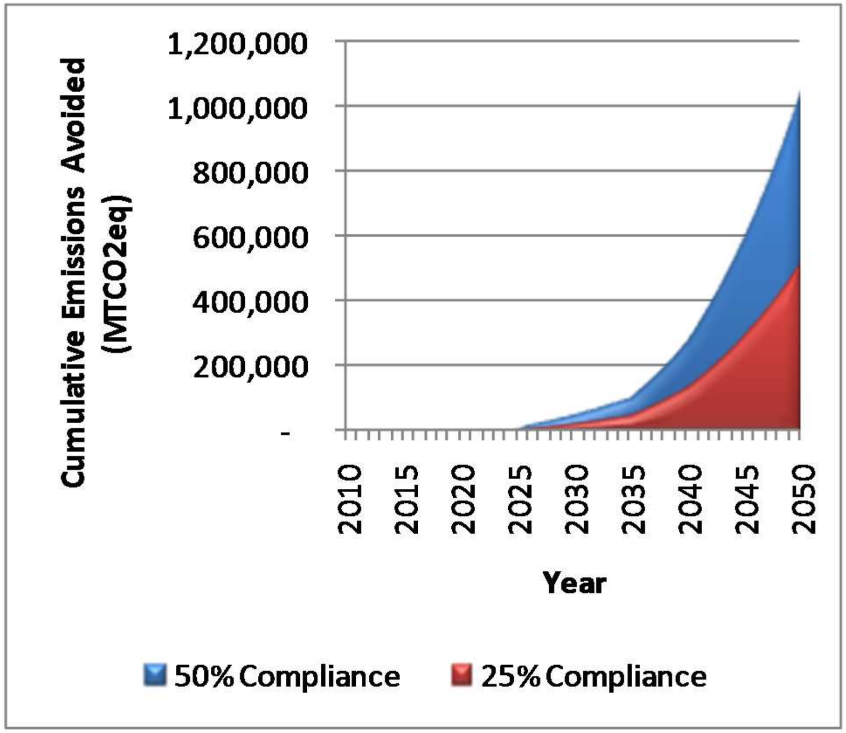
Foam Emission Assumptions

Blowing Agent	BAU							Alternative
	Shredding/Landfilling (80%)				Direct Landfilling (20%)			Blowing Agent Recovery and Destruction
	Shredding	Compaction	In Landfill	Total	Compaction	In Landfill	Total	
CFC-11	24%	19%	0.3%	43%	19%	0.5%	19%	10%
HCFC-141b	24%	19%	1.7%	45%	19%	2.3%	21%	10%
HFC-245fa	24%	19%	5.7%	49%	19%	8.1%	27%	10%

- Uncertainty about BAU emissions avoided in landiflls
  - To be conservative, high rates of landfill bioremediation/sorption/combustion assumed
- As a result, alternative management scenario only reduces between 9-39% of BAU emissions, depending on BA type

Results: GHG Emissions Avoided

- Significant emissions reductions possible
- GHG reductions partially offset by increased emissions associated with transport and energy consumption for foam processing
- 50% adoption rate: 1.04 $MMTCO_2eq$ reduced by 2050 (HFC & ODS)
- Avoided emissions of HFCs are zero through 2030; no HFCs projected to reach EOL until 2031



Results: Cost Effectiveness

Cost Effectiveness ($/MTCO$_2$eq)

	25% Compliance			50% Compliance		
	ODS	HFC	Total	ODS	HFC	Total
Costs, 2010-2050 ($ million)	$10.0	$43.4	$53.4	$20.1	$86.8	$106.9
Cost Effectiveness ($/MTCO2eq)	$242	$90	$102	$242	$90	$102

- Benefits and costs not incurred until 2016 for ODS; 2031 for HFCs
- Cost effectiveness is $90/MTCO$_2$eq for HFCs under optimal BAU landfill conditions
    - Assuming zero emissions avoided in landfills, cost effectiveness ~$33/MTCO$_2$eq

Findings

- No precedent for C&D foam recovery in CA
- No GHG emission benefits to be realized until ~2030
- In later years, small but significant GHG reductions can be achieved
  - In 2050, recovery of HFC panel foams could reduce 0.1 $MMTCO_2eq$
- Additional research needed to assess:
  - Infrastructure needed to support alternative scenario considered
  - Other methods of PU panel foam handling, which may be more cost-effective

Part III:
Disposable Refrigerant Cylinders

Current Situation

- ~732,000 disposable 30-lb. cylinders used annually in CA to service refrigeration/AC equipment
  - Stationary equipment: HCFC-22 and R-410A most common
  - Mobile: HFC-134a most common

- Two concerns:
  1. Refrigerant "heel" emissions
     - When deemed "empty," cylinders contain a "heel" of ~1.1 lbs of refrigerant/cylinder (~4%)
  2. Metal recycling or disposal vs. reuse
     - Recycling of metals common (~6.5 lbs of steel)

Current Situation

- High-GWP refrigerant heel can have significant GHG impacts
  - e.g., 0.03 $MTCO_2eq$. per R-410A cylinder

- January 1, 2011: CA's Refrigerant Management Program took effect
  - Requires evacuation to 15-inch mercury vacuum prior to cylinder disposal (California Code of Regulations §95390)
    - Remaining heel ~0.2% (~0.05 lbs/cylinder)

- GHG impact of refrigerant heel emissions:
  - Full compliance w/ RMP: ~0.03 $MMTCO_2eq$/year
  - Non-compliance w/ RMP: ~0.50 $MMTCO_2eq$/year

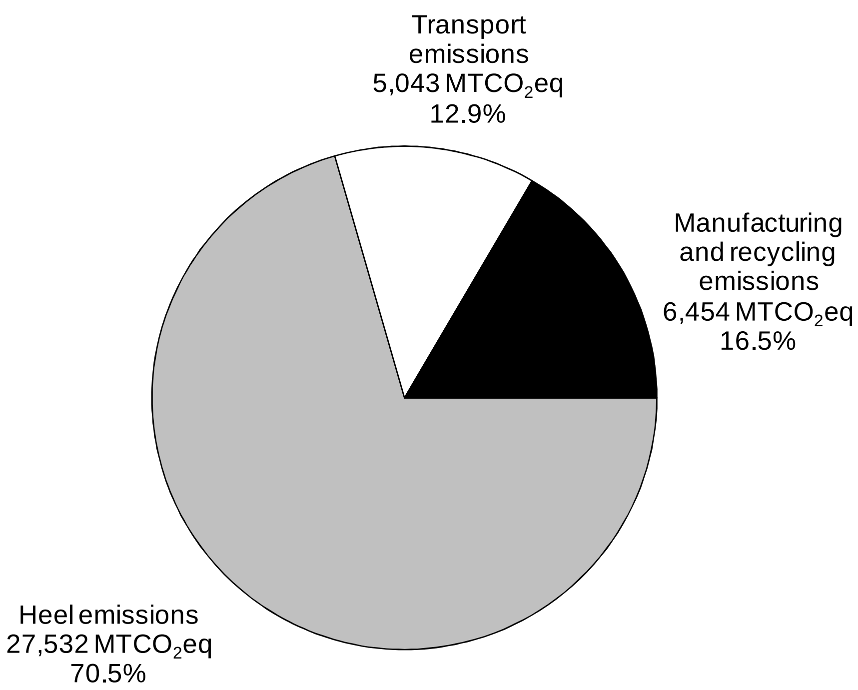
Alternative Management Option

- **Replace disposable cylinder fleet with reusables, 5-year phase-in**
  - Assume producer responsibility scheme: refillable cylinders are returned to refrigerant manufacturer
  - Ensures heel not released, cylinders refurbished and reused for 20 years

Key Parameters

- **Emissions**
  - Cylinder manufacture and reuse/ recycling/ disposal
  - Heel
  - Transport
- **Costs**
  - Cylinder manufacture
  - Labor: for heel evacuation, transport
  - Metal recycling (savings)
  - Cylinder refurbishment (for refillables)
  - Transport fuel
  - No capital costs

Annual BAU Emissions



Annual Emissions:

0.039 $MMTCO_2eq$

BAU…

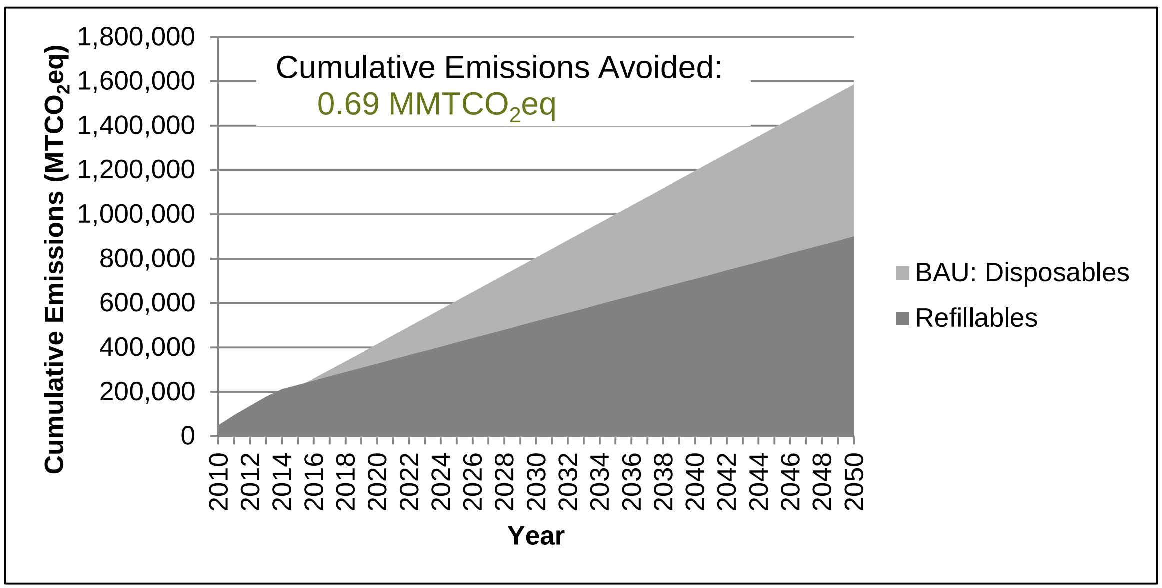
- Assumes full compliance with evacuation requirements
- 75% of cylinders recycled

Annual emissions assuming <u>no</u> compliance with RMP:
0.50 $MMTCO_2eq$

Results: GHG Emissions Comparison

	GHG Emissions Avoided ($MTCO_2eq$)					
	Direct		Indirect			Total
	ODS Heel	HFC Heel	Transport	Manufacturing	Recycling Credits	
2010-2020	48,269	142,725	(48,244)	(55,163)	717	19,924
2010-2050	48,269	803,505	(198,693)	29,835	3,108	686,023

Cumulative Net GHG Emissions (2010-2050)



If non-compliance with cylinder evacuation:

- Cumulative emissions avoided by 2050: 14.0 $MMTCO_2eq$

Cost Effectiveness

Costs per Cylinder Used Annually, Post-2015

Disposables	Refillables
$13.16	$25.25

Cost Effectiveness of Alternative Management Scenario ($/MTCO2eq), 2010-2050

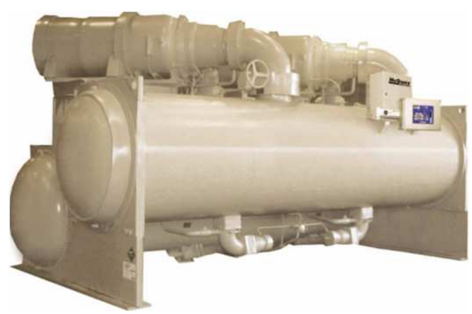
Total Costs	HFC Only	Total (ODS + HFC)
Full compliance with cylinder evacuation	$254	$387
Non-compliance with cylinder evacuation	$14	$20

Findings

- Transition to refillable cylinders could reduce GHG emissions from refrigerant heels, in spite of higher transport
  - Reductions are significant if low levels of compliance with heel evacuation in BAU

- Costs to achieve reductions are high assuming compliance with RMP (\$254/MTCO_2eq for HFCs)
  - But very reasonable otherwise: \$14/MTCO_2eq

Part IV:
Other Stationary Refrigeration/AC Equipment

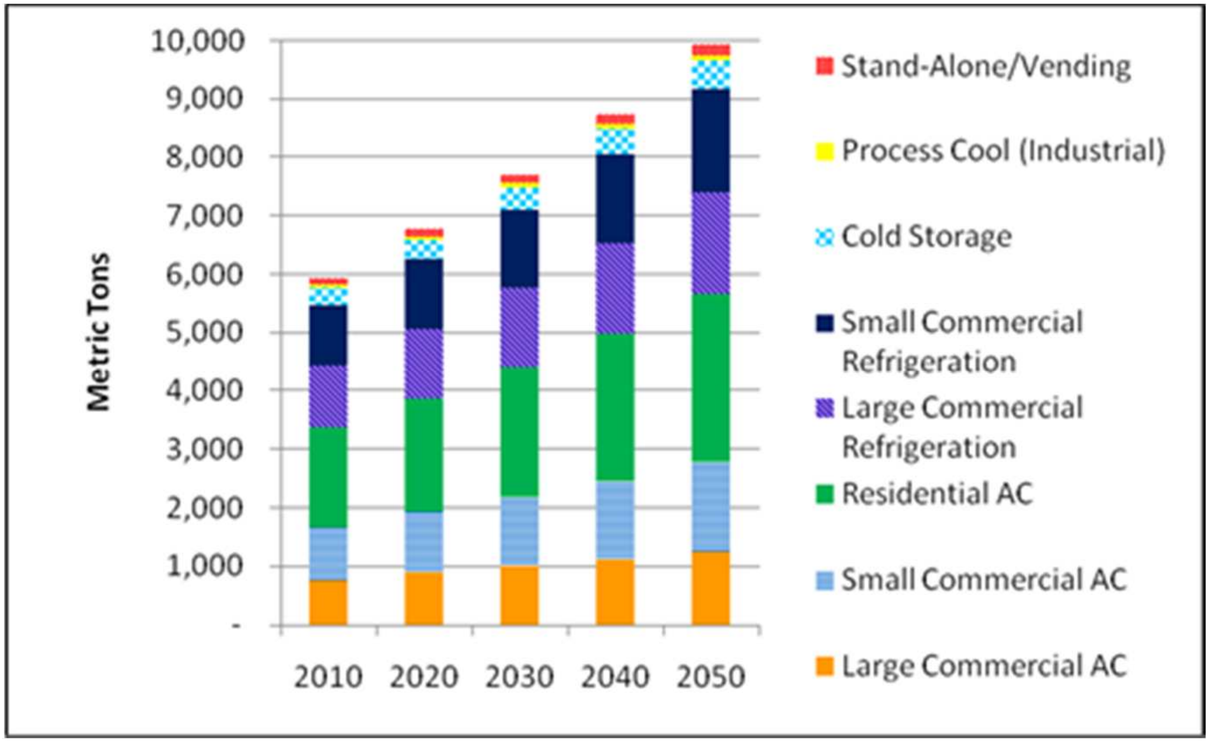


Current Situation

- Apart from household refrigerators, ~17 million units of other stationary refrigeration/AC equipment are installed in CA
- Federal law requires that refrigerant be recovered at equipment EOL and either stored, recycled, reclaimed, or destroyed
  - Not always cost-effective—especially for equipment with small charge size and/or refrigerants with low market value
  - Compliance is difficult to enforce
- ARB's Refrigerant Management Program focuses on reducing emissions during operation of stationary equipment; does not directly address EOL issues

Question: What are the lifecycle costs and benefits of complying with federal regulations at equipment EOL?

Quantities Reaching EOL (MT)



Source: CARB (2010)

- Based on ARB inventory, greatest quantities reaching EOL are from: residential AC, commercial refrigeration, and small commercial AC

Alternative Management Options

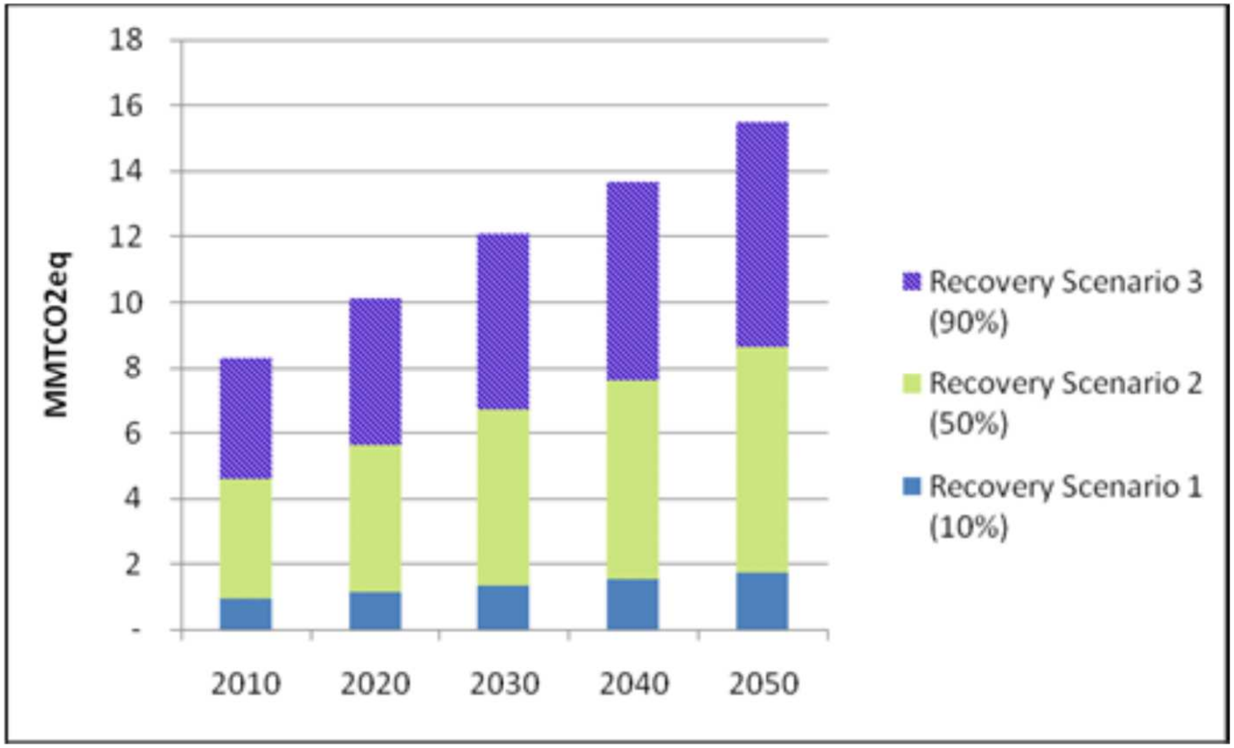
- **Assess lifecycle costs & benefits for:**
  - Various levels of compliance and recovery efficiency
    - 10%, 50%, and 90% refrigerant recovery scenarios
    - Assumes 100% of charge available at EOL
  - Various refrigerant fates
    - Recovery [+ Storage]
    - Recovery + Reclamation
    - Recovery + Destruction

Key Parameters

- **Emissions**
  - Refrigerant avoided
  - Transport to reclamation or destruction facilities
  - Energy consumption for reclamation
- **Costs**
  - Transport: fuel and labor
  - Refrigerant recovery
  - Refrigerant savings for reclamation
  - Energy consumption for reclamation
  - Refrigerant destruction

Assumptions based on previous LCAs, augmented with information from refrigerant reclaimers

Results: Annual GHG Emissions Avoided

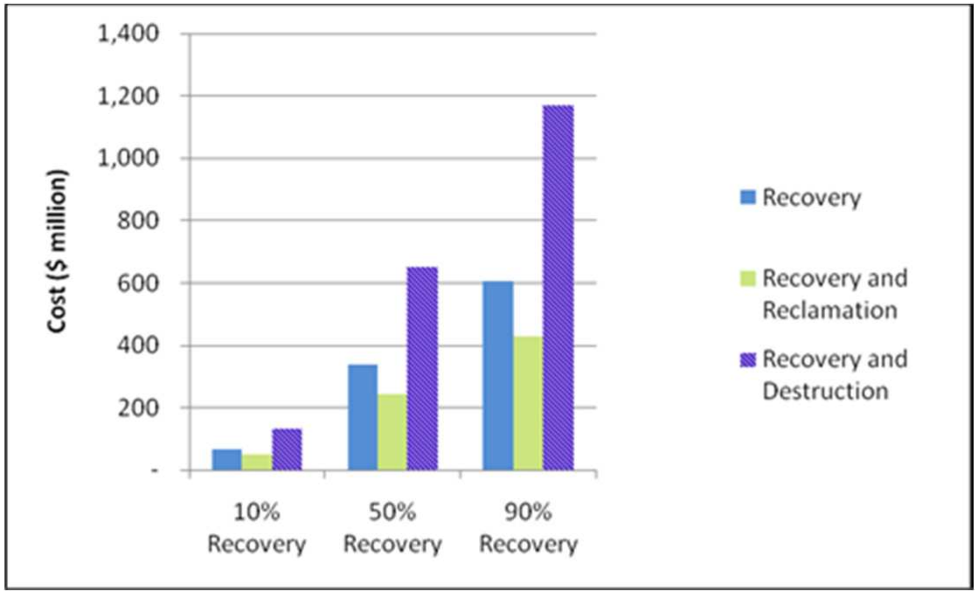


- For HFCs alone, a 10% increase in recovery can reduce 7 $MMTCO_2eq$ from 2010 to 2020
- By 2020, 90% recovery can reduce
  - 99 $MMTCO_2eq$ from HFC/ODS

Results: Cost Effectiveness

- **Low-cost GHG reductions**
  - $1-$5/ $MTCO_2$eq
  - Reclamation is lowest cost
  - Cost effectiveness increases over time, as HFCs are phased in

Cumulative Costs (2010-2050)



Incremental $/$MTCO_2$eq 2010-2050 (NPV, 5%)

Year	HFC Only			Total		
	Recovery	Recovery/ Reclamation	Recovery/ Destruction	Recovery	Recovery/ Reclamation	Recovery/ Destruction
2010-2020	$2.13	$1.54	$4.11	$2.60	$1.88	$5.01
2010-2050	$1.06	$0.76	$2.04	$1.25	$0.90	$2.40

Findings

- Significant GHG savings can result from recovery from ref/AC equipment at EOL
  - Even with only 10% recovery, >1 $MMTCO_2eq$ could be reduced in 2020 from ODS/HFC equipment; 11 $MMTCO_2eq$ from 2010-2020
  - Recovery most critical from residential AC, commercial AC, large commercial refrigeration
- Cost effective GHG reductions (<$2.50/$MTCO_2eq$)
- Actual recovery levels will depend on number of technicians performing recovery, recovery practices employed, and quantities remaining at EOL
- Approaches for increasing recovery could include:
  - Regulatory enforcement
  - Fee/tax on refrigerant sales
  - Producer responsibility schemes

Part V:

Fire Extinguishing Agents & Miscellaneous Gases

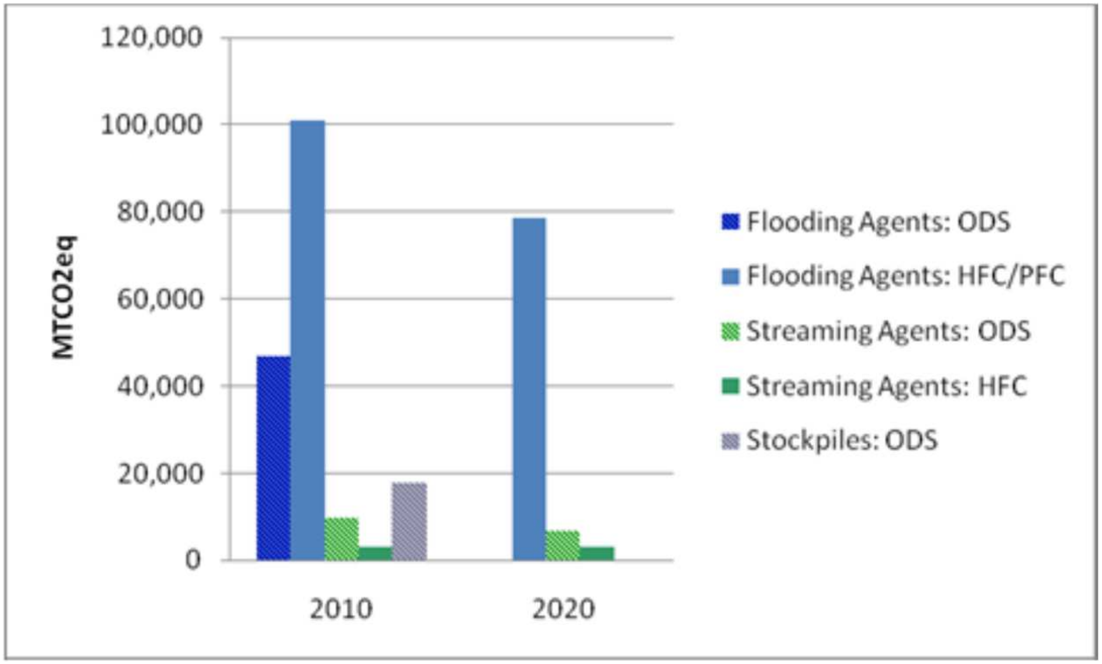
Current Situation

- **Institute for Research and Technical Assistance (IRTA) estimated inventory of high-GWP gases in CA from fire sector and misc. stockpiles**
  - Fire protection sector: total flooding systems & portable extinguishers
  - Stockpiles: ODS solvents
- **At EOL, federal law requires that these gases be recovered and stored/recycled/reclaimed/destroyed**
  - Recovery and reuse at EOL is common in the fire sector
  - Fate of stockpiles highly uncertain; long-term storage could lead to slow leakage

Question: what are the lifecycle costs and benefits of complying with federal regulations?

Estimated EOL Banks: 2010, 2020

- Quantities reaching EOL calculated based on IRTA banks & equipment lifetime assumptions
  - Flooding: 20 yrs
  - Streaming: 12 yrs



Alternative Management Options

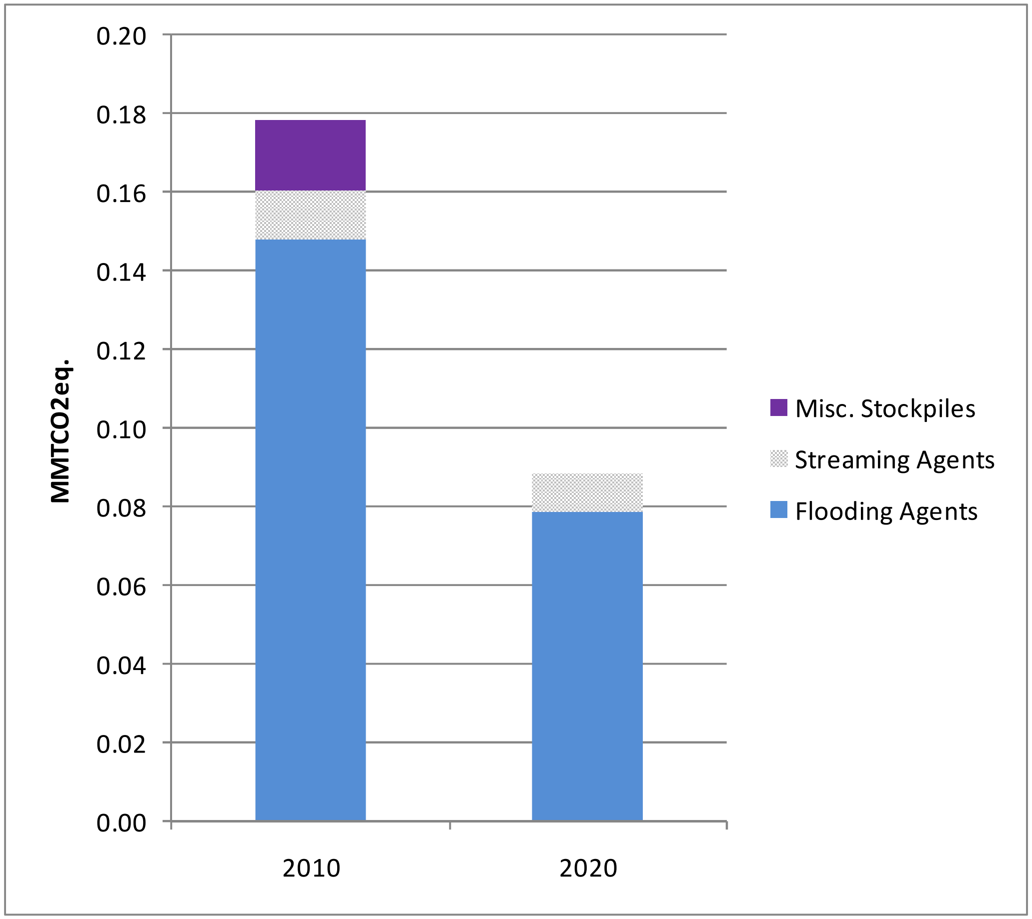
- **Assess costs & benefits for**
  - Recovery [+Storage]
  - Recovery + Reclamation
  - Recovery + Destruction

Key Parameters

- **Emissions**
  - High-GWP gases
  - Transport to reclamation or destruction facilities
  - Energy consumption for reclamation
- **Costs**
  - Transport of refrigerant to reclamation/destruction facilities
  - Labor for transport
  - Agent savings (for reclamation)
  - Energy consumption

**Assumptions consistent with other LCAs; additional information obtained from reclaimers of fire extinguishing agents.*

Results: Annual GHG Emissions Avoided



- By 2020, potential to avoid ~1.5 $MMTCO_2eq$ from recovery of fire equipment & stockpiles
- Indirect GHG emissions associated with reclamation and destruction reduce GHG savings by 0.1% - 1.1%

Results: Cost Effectiveness

Incremental \$/MTCO_2eq, 2010-2020

Year	HFCs/PFCs Only			Total		
	Recovery	Recovery/ Reclamation	Recovery/ Destruction	Recovery	Recovery/ Reclamation	Recovery/ Destruction
Flooding	\$1.94	(\$1.20)	\$4.06	\$1.70	(\$1.05)	\$3.56
Streaming	\$0.79	(\$0.49)	\$1.66	\$3.79	(\$2.34)	\$7.93
Stockpiles	-	-	-	\$1.79	(\$1.11)	\$3.75

- Reclamation reduces GHGs at cost savings
- Recovery and/or destruction reduces emissions at low cost (<\$4/MTCO_2eq for HFCs/PFCs)

Findings

- Proper management of ODS stockpiles and fire equipment at EOL could avoid nearly 1.5 $MMTCO_2eq$ from 2010 – 2020 at low or negative cost (<$5.00/$MTCO_2eq$)

- Fire protection sector: majority of emission reductions expected in BAU
  - Options could be considered to promote destruction of phased out gases (i.e., halons)—instead of reuse

- Solvent stockpiles: uncertainty over fate of stockpiles; eventual leakage a concern
  - Options could be considered to promote reclamation or destruction → e.g., stakeholder outreach/education, take-back programs, economic incentives

Wrap-Up

Conclusions

Proper EOL management of high-GWP gases can lead to significant GHG reductions

- Pursuant to AB 32 goals, additional HFC emission reductions could be realized from foam recovery
  - Near term: refrigerators/freezers
  - Long term: C&D PU panels
- Compliance with existing regulations is key to ensuring GHG reductions from stationary ref/AC, disposable cylinders, and fire equipment
  - Regulatory or voluntary measures could enhance compliance
- No regulations governing proper management ODS stockpiles
  - Outreach and/or financial incentives could be pursued

Conclusion

- Further research needed to
  - Explore technical and logistical options for C&D panel foam recovery in CA
    - Innovative approaches used in other countries and lessons learned
    - Unique infrastructure and markets in CA
  - Assess measures to promote compliance with federal and CA refrigerant recovery regulations at EOL
    - Stationary ref/AC
    - Disposable cylinders

Q&A

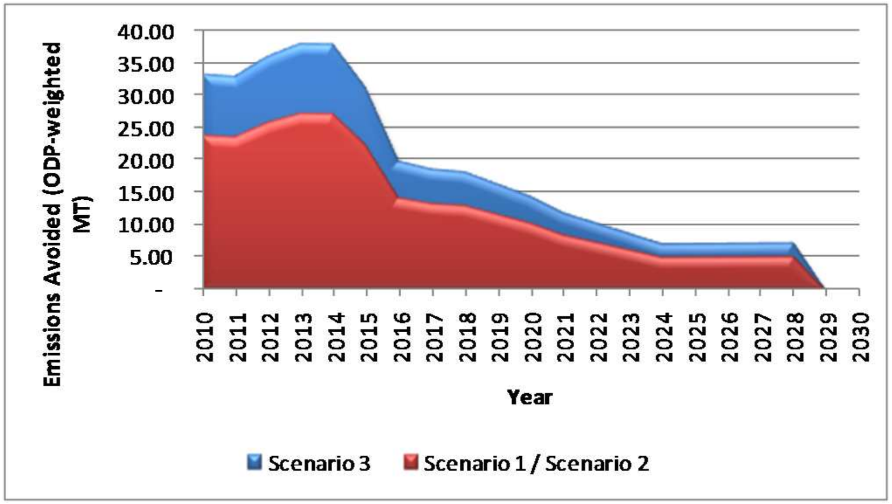
More Information

Pamela Mathis
pmathis@icfi.com
415-677-7193

Additional Slides

Appliance LCA: Other Emissions Avoided

Annual ODS Emissions Avoided (ODP-Weighted MT)

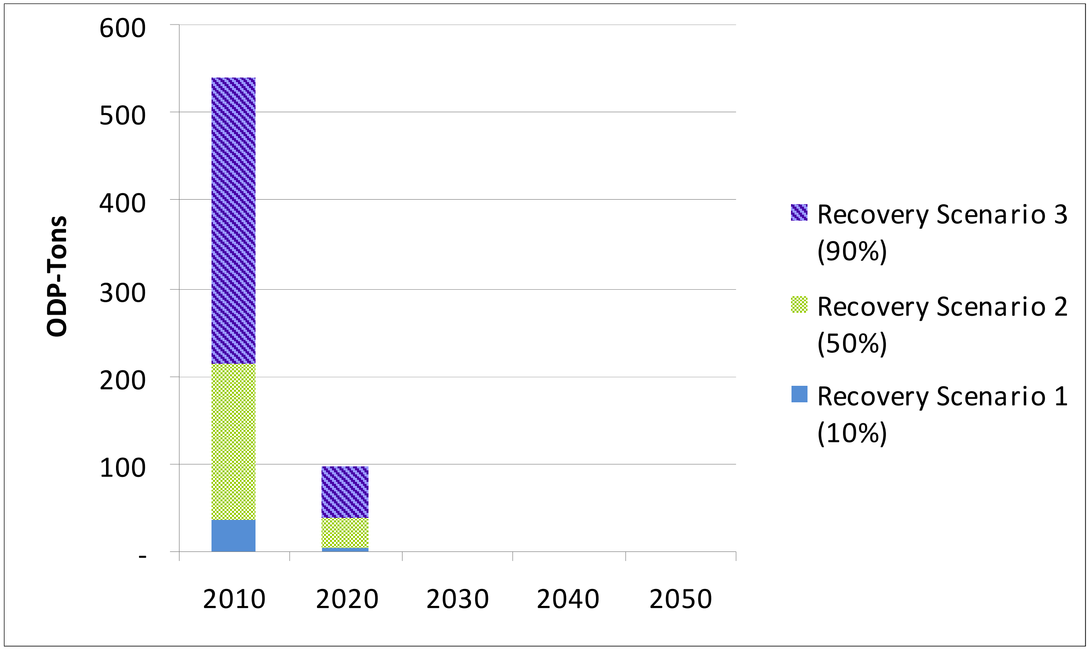


- **ODS emissions**
  - Emissions savings until 2029, then ODS fully retired
  - Scenario 3 results in greatest emissions savings due to foam capture efficiency
  - Total BAU ODS emissions (2010-2028): **417 ODP-weighted MT**

- **Criteria Pollutants**
  - Scenarios 2 and 3 result in very small incremental criteria pollutant emissions from transport and energy consumption

Other Stationary Ref/AC: Other Emissions Avoided

- **Ozone Benefits**
  - Potential to avoid 1,667 ODP tons by 2020 (at 90% recovery)
  - ODS refrigerants virtually phased out by 2020
- **Criteria Air Pollutants**
  - Slight increases in NO_x, SO_x, PM_{10}, $PM_{2.5}$ associated with increased transportation



Disposable Cylinders: Other Emissions Avoided

- **ODS emissions will be reduced by 1.77 ODP-weighted MT from 2010-2019, until the phase-out of HCFC-22.**

- **Incremental, but insignificant criteria pollutant emissions from transport and cylinder manufacture.**

C&D Foams: Other Emissions Avoided

- **ODS emissions are avoided from 2016 through 2035, after which all ODS panel foam is phased out**
  - 25% compliance: 8 ODP-weighted MT avoided, 2010-2050
  - 50% compliance: 16 ODP-weighted MT avoided, 2010-2050

- **Incremental criteria pollutant emissions from transport and energy consumption during foam shredding and blowing agent recovery**

Fire & Misc. Stockpiles: Other Emissions

- **Ozone Benefits**
  - Potential to avoid 508 ODP tons by 2020

- **Criteria Air Pollutants**
  - Slight increases in NO_x, SO_x, PM_{10}, $PM_{2.5}$ associated with increased transportation