Transport Refrigerators
Technology Assessment

September 3, 2014
Sacramento, California

California Environmental Protection Agency
Air Resources Board

Overview

- Background
- Key Performance Parameters/Development Goals
- Technologies Evaluated
  - Costs/Economics
  - Deployment Challenges
- Conclusions and Recommended Next Steps
- Contacts

Background

- Definition, Population, Manufacturers

TRU Background

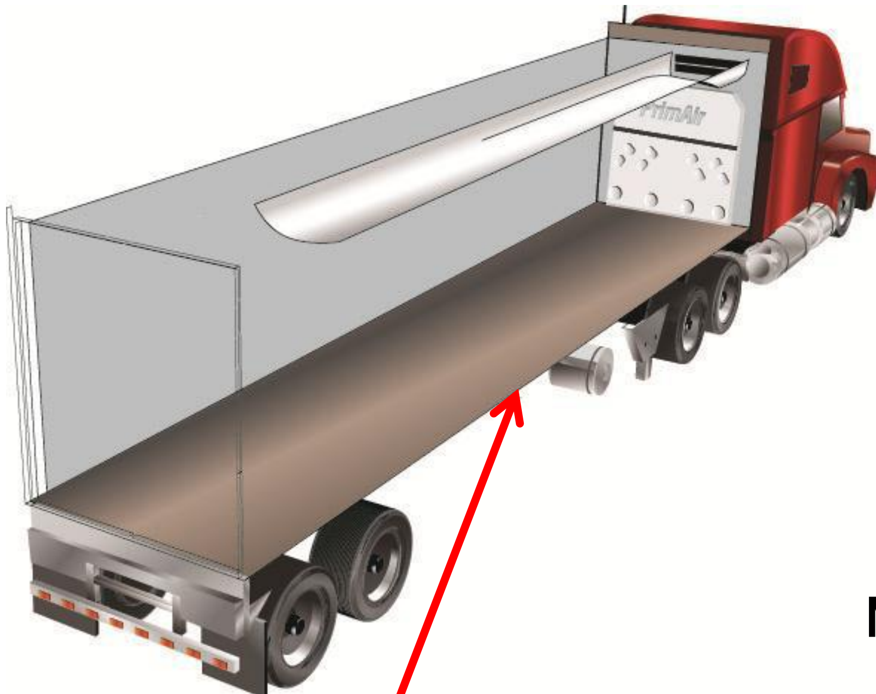
- What is a TRU?

- What is a TRU Genset?

TRU Background

- Operational Characterization – TRUs
  - Powered by integral diesel engine (8 to 38 hp)
  - Capable of cooling or heating
  - Programmable for continuous or start-stop
- Fleet Characterization
  - Private Carriers (groceries, foodservice)
    - Short-haul
    - Regional
  - Commercial Carriers (truckload, LTL)
    - Regional
    - Long-haul
  - Leasing/Rental

TRU Background

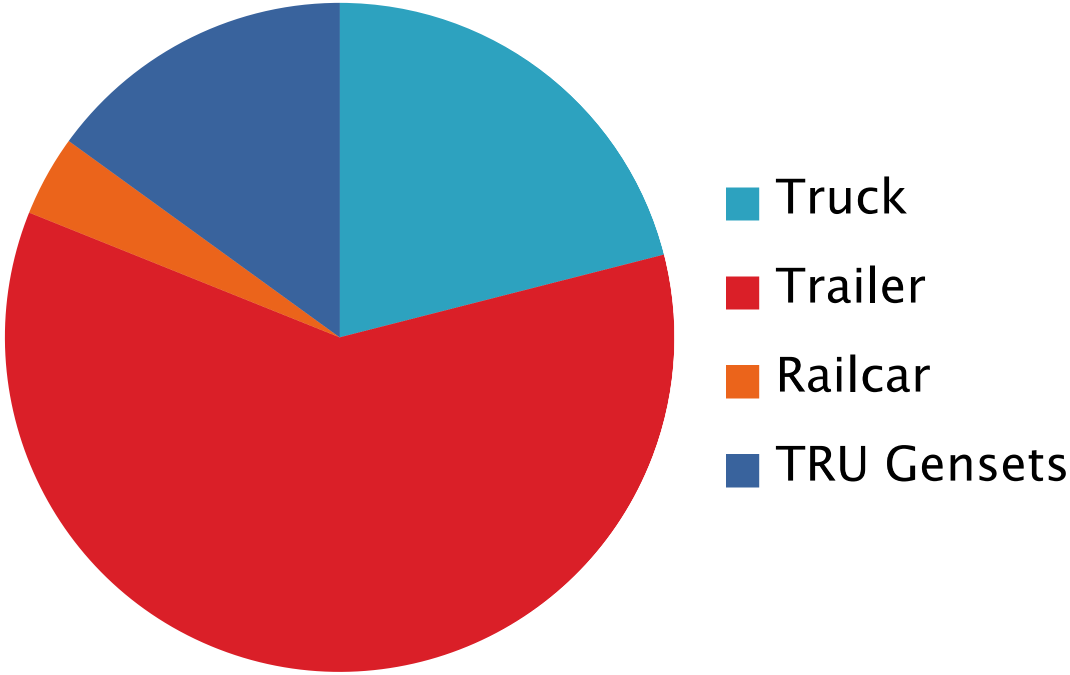


Multi-Temp, Multi-Compartment
Refrigerated Trailer

Single-Temp, Single-Compartment
Refrigerated Trailer

California TRU Population

Truck TRUs	7,000
Trailer TRUs	20,000
Railcar TRUs	1,300
TRU Generator Sets	5,000
Total:	33,300



Manufacturers

- TRU Manufacturers
  - Carrier Transicold (~50% market share)
  - Thermo King (~50%)
  - Kingtec (<1%)
  - Zanotti (<1%)
- TRU Genset Manufacturers
  - Carrier Transicold (unknown market shares)
  - Thermo King
  - Hewitt Equipment
  - MEC

Key Performance Parameters

- Development Goals

Key Performance Parameters

- Duty cycle
- Noise
- Durability/Reliability
- Range
- Payload Impacts
- Fuel Infrastructure
- Cost/ROI
- Safety

Technologies Evaluated

- How They Work, Technology Readiness, Cost/Economics, Advantages, Key Performance Parameters Issues and Deployment Challenges for Each

Green Technologies Evaluated

- All-Electric Plug-In/Battery Transport Refrigerators
  - Used historically (plug-in without batteries) as refrigerated trailer cold storage at distribution centers and grocery stores
  - Cold plate temperature control extends range
- Hydrogen Fuel Cell Power – electric power for:
  - All-Electric Transport Refrigerators
  - Refrigerated Shipping Containers
- All-Electric Battery/Plug-In/Solar Transport Refrigerators

Green Technologies Evaluated (cont'd)

- Cryogenic Temperature Control (Liquid N_2, CO_2)
- Alternative-Fueled Engine Transport Refrigerators
  - Compressed Natural Gas (CNG)
  - Liquefied Natural Gas (LNG)
  - Liquefied Petroleum Gas (LPG)
- Advanced Power Plants
  - HCCI/PCCI
- Tier IV+ New Off-Road CI Engine Emissions Standards for <25 hp categories

All-Electric Plug-In/Batteries

How Does It Work?

- All-Electric Transport Refrigerator
  - OEM All-Electric Models
  - Diesel TRU Conversions to All-Electric
- Electric Power Plug Infrastructure at DC
  - Stationary cold storage
  - Charge batteries
  - Freeze eutectic cold plates for on-road operation
- On-Road Operation – powered by vehicle alternator, batteries/inverter

Electric Power Plug Infrastructure

Parking Space Plugs

Loading Dock Plugs

Batteries

Absorbed Glass Mat Deep Cycle Batteries

- Lead-Acid
- Heavier
- Lower cost

Advanced Batteries

- Lithium-Ion
- Higher energy density (lighter/smaller)
- Higher cost (but coming down fast)

Eutectic Cold Plates

- Sheet metal shell
- Refrigerator evaporator coil inside shell
- Filled with eutectic salt solution/gel
- Sized around van size & intended cargo
- Mounted in cargo area
- Refrigerator freezes eutectic solution/gel
- Electric fans blow air across plates to absorb heat load

Technology Readiness

- **All-Electric Truck Refrigerators – commercially available**
  - Manufacturers: Thermo King (model B-100)
  - Capable of stationary (plug-in) and on-road operation (vehicle alternator and batteries)

- **All-Electric Trailer Refrigerators – commercially available**
  - Carrier Transicold (Vector 8100), Electric Reefer Solutions (conversions)
  - Capable of stationary operation (plug-in)
  - On-road operation (umbilical power from tractor in design/demonstration phase)

Technology Readiness (cont'd)

- **Cold Plates – commercially available**
  - In use for over 20 years, unknown number in use in CA (less than 1%)
  - Manufacturers: Dole Refrigerating Co. (USA), many foreign companies
  - Numerous suppliers: Johnson Truck Bodies, Kidron/Hackney, others
- **Advanced Batteries – commercially available**
  - Recent rapid technology advances due to electric vehicle, consumer electronics, power tool, medical, and defense markets
  - Longer life, greater energy density, reduced weight
  - Higher cost (coming down fast)
  - >99% made with lithium ion (Li-ion) chemistry
  - Use in demonstration in transport refrigeration in planning phase

All-Electric TRs

Economics – Truck

- **Conventional truck TRU costs**
  - Capital cost: $12,000 to $18,000
  - Fuel Cost: ~$3,744/yr at 0.6 gal/hr, 1560 hr/yr, $4/gal
  - Maintenance: ~$1,650 per year at $0.90/hr, 1560 hr/yr
- **Technology Costs**
  - Capital Costs: Depends on customer application
    - OEM all-electric models: Unknown
    - Conversions: ~$6,000 more (installed, with AGM batteries)
  - Fuel Cost for Generator Load: ~$624
  - Maintenance: ~$390 per year
  - Electric plug infrastructure: Unknown
- **Savings**
  - Operating Cost savings: ~$4,380/yr

Economics – Trailer

- **Conventional trailer TRU costs**
  - Capital cost: $20,000 to $30,000
  - Fuel cost: $6,400/yr at 0.8 gal/hr, 2,000 hr/yr, $4/gal
  - Maintenance: ~$1,700 per year at $0.85/hr, 2000 hr/yr
- **Technology Costs**
  - Capital Costs: Depends on customer application
    - OEM all-electric models: Unknown
    - Unit Conversions: $10,000 – $13,000
    - Advanced batteries: $500 per kW-hr
  - Maintenance: ~$390/yr
  - Electric plug infrastructure:
    - ~$6,000 per loading dock space
    - ~$7,200 per parking area pedestal
- **Savings**
  - Fuel/energy: ~40% to 70% reduction
  - Maintenance: ~$1,300/yr

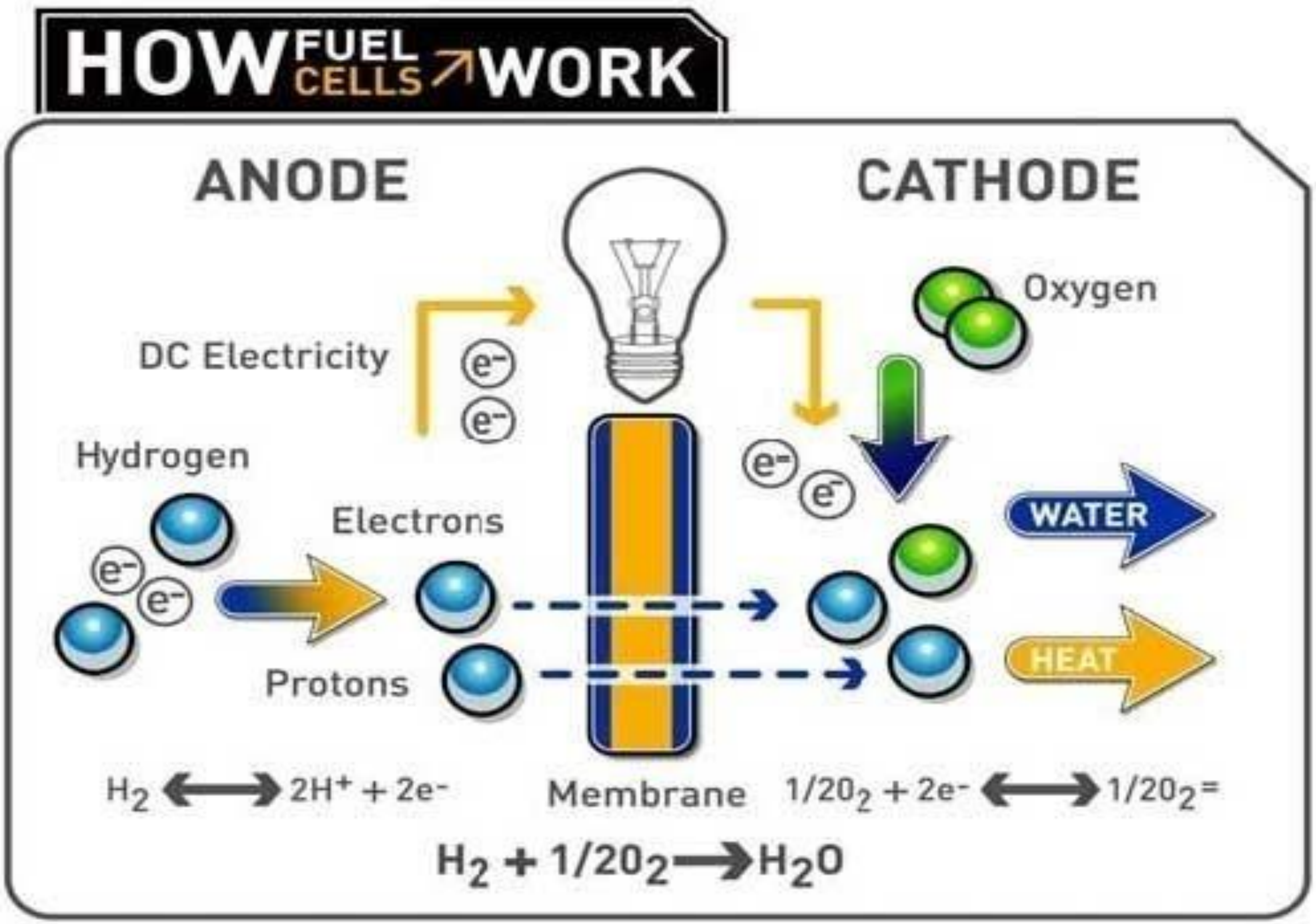
Technology Advantages

- Quiet Operation
- Fewer Moving Parts ➔ Reduced Repair, Maintenance, and Downtime
- Zero Tail Pipe Emissions
  - Zero GHG
  - Zero criteria pollutants

Key Performance Parameter Issues & Deployment Challenges

- Range – Limited to return-to-base fleets
- Electric Power Infrastructure Costs
- Charge Time (batteries and/or cold plates)
- Cargo Space Impacts (cold plates/fans)
- Cargo Weight Impacts (cold plates and/or batteries)
- ROI/Payback – More data needed
- Safety Procedures (high voltage power plugs)
- All-Electric Trailer Refrigerator Needs System Integration for On-Road Operation

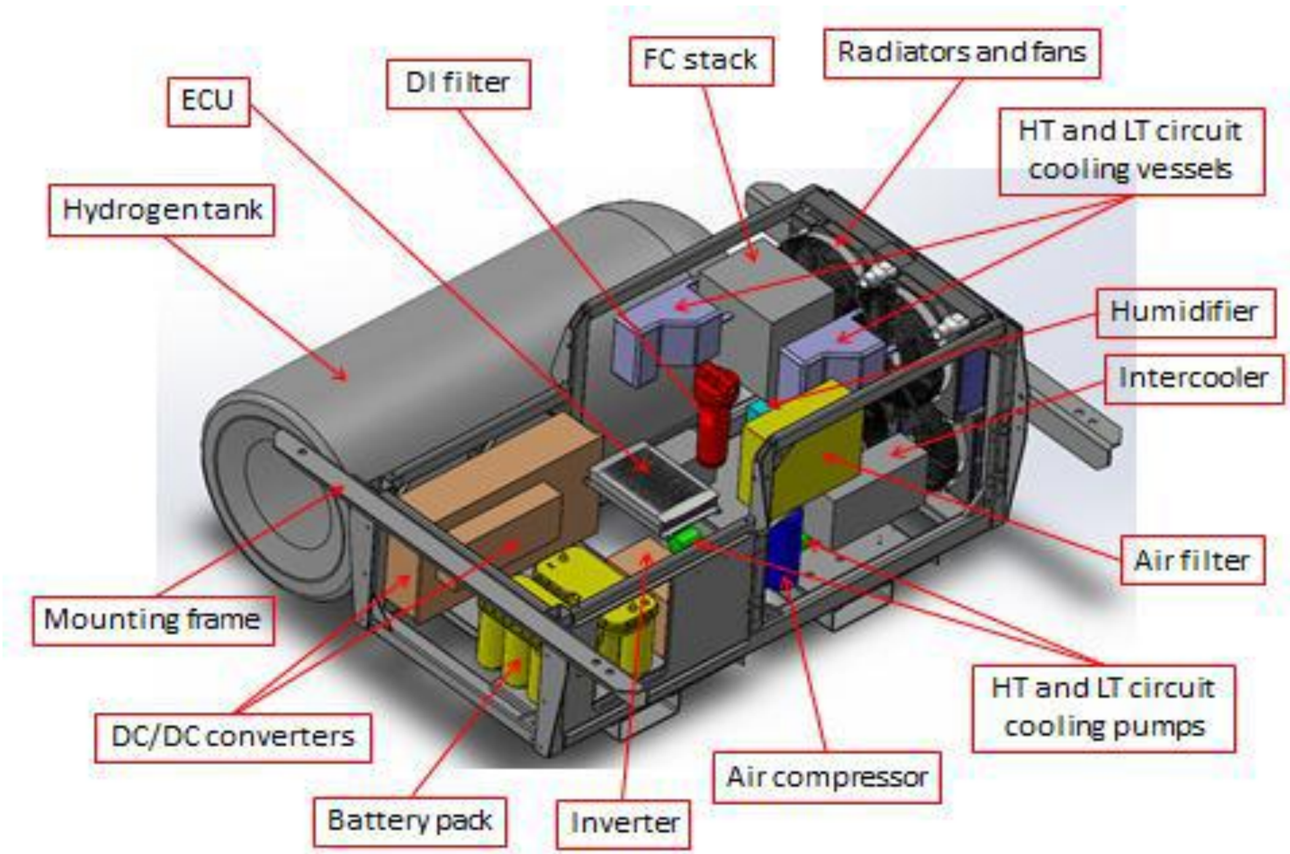
Hydrogen Fuel Cell–Power



How Does it Work?

- Hydrogen fuel cell stack
- Balance of plant components
  - ECU
  - Radiators, fans, filters
  - Air compressor, intercooler, humidifier
  - DC/AC Inverter
  - DC/DC converters
- Hydrogen storage tank for full day operation
- All-electric transport refrigerator

Nuvera Fuel Cell System for Trailer



Technology Readiness

Pilot Demonstration Phase

- Pacific Northwest National Laboratory – FC Power Units for All-Electric Trailer Refrigeration
  - Nuvera Fuel Cells – Fuel cell system & on-site hydrogen reformer
    Thermo King – Refrigeration system
    Sysco Foodservices – Riverside, CA & HEB Grocery, San Antonio, TX
    Report due mid-2015
  - Plug Power – Fuel cell system
    Carrier Transicold
    Sysco Foodservices – Long Island, NY
    Air Products (hydrogen produced off-site, supplied via tube trailer)
    Report due mid-2015
- Sandia National Laboratories – Containerized Portable FC Gensets for Multiple Refrigerated Shipping Containers
  - Hydrogenics Corp. – Fuel cell system
    Young Bros./Foss Maritime Co. – Port of Honolulu
    Hydrogen supply – TBD
    Report due mid-2015

Economics

- **Costs** – will be clearer when demonstrations are completed
  - Capital cost
    - Per unit – unknown
    - Fueling infrastructure (additional) – unknown
  - Federal investment tax credit (30%) available until 2016
  - Maintenance – unknown, less than diesel TRU
- **Savings**
  - Fuel consumption – 2X more efficient than diesel engine
  - Maintenance – expected to be less than diesel engine
- **Return on Investment**
  - Payback period – unknown

Technology Advantages

- **Quiet Operation**
- **Fewer Moving Parts → Reduced Repair, Maintenance, and Downtime**
- **Zero Tail Pipe Emissions**
  - Zero GHG
  - Zero criteria pollutants

Key Performance Parameter Issues & Deployment Challenges

- Limited to return-to-base fleets until broader hydrogen fueling infrastructure available
- Cost/ROI/Payback unknown until demonstrations completed
- Need second generation design demonstrations
- Need funding for large-scale distribution center demonstration
- Need infrastructure development along major transportation corridors to support regional and long-haul deployment

All-Electric/Battery/Plug-In/Solar

How Does it Work?

- Solar panels cover van roof
- Solar charge controller
- On-Board battery system (AGM)
- DC to AC Inverter
- High efficiency all-electric transport refrigerator
- High thermal efficiency van construction

Technology Readiness

Pilot Demonstration Phase

- Pilot demonstrations completed in UK
  - University of Southampton/Sainsbury Groceries
  - Three units tested (1997-2000)
- Next generation demonstration in the U.S.
  - Currently in planning phase
  - Need system integration and optimization with updated higher efficiency components

Economics

- **Conventional trailer TRU costs**
  - Capital cost: $20,000 to $30,000
  - Fuel cost: $6,400/yr at 0.8 gal/hr, 2,000 hr/yr, $4/gal
  - Maintenance: $1,700/yr at $0.85/hr, 2,000 hr/yr
- **All-electric, solar costs**
  - Capital cost: ~$50,000 (UK demonstration included high-efficiency refrigerator and van insulation, batteries)
  - Electric power infrastructure (battery charger) – unknown
  - Energy cost: ~$1,000-$1,200/yr
  - Maintenance: ~$400/year (UK demonstration)
- **Savings**
  - Fuel energy savings: ~$5,300/yr
  - Maintenance: ~$1,300 per year

Technology Advantages

- Quiet Operation
- Fewer Moving Parts → Reduced Repair, Maintenance, and Downtime
- Zero Tail Pipe Emissions
  - Zero GHG
  - Zero criteria pollutants

Key Performance Parameters & Deployment Challenges

- Range: Limited to return-to-base fleets
- High capital costs
- Electric power plug infrastructure costs
- Cargo space impacts (thicker van insulation)
- Cargo weight impacts (added insulation, batteries and PV panels may not be offset by engine removal)
- Needs high-efficiency refrigerator and high thermal efficiency van construction (insulation)
- Long payback period expected

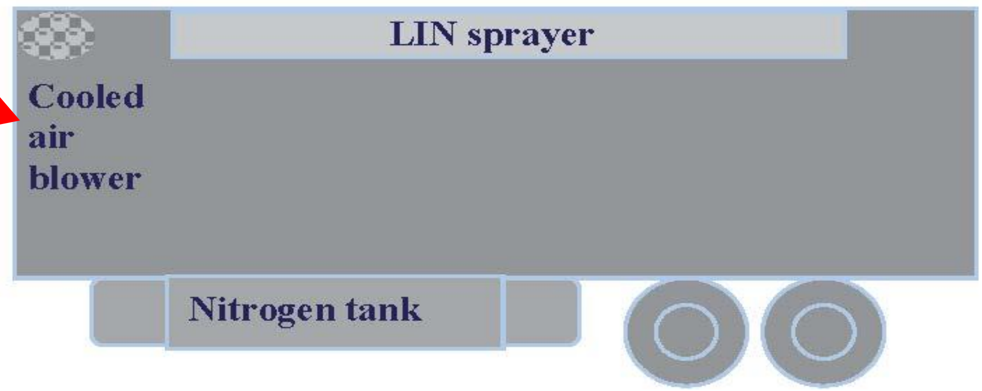
Cryogenic Temperature Control

How Does it Work?

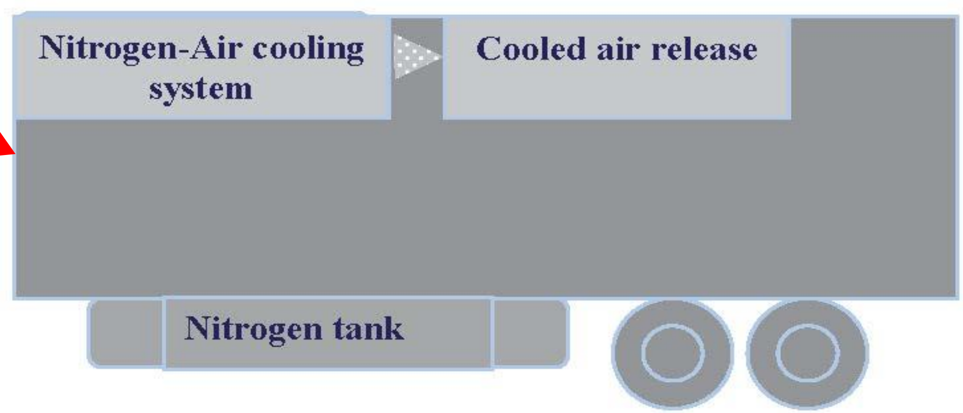
- Cryogenic Fluid Cooling
  - Usually liquid N_2 (R-728) or CO_2 (R-744)
  - Vents to atmosphere
  - Direct injection into cargo space, or
  - Indirect cooling via heat exchanger
- Components
  - Sprayers (direct) or heat exchangers (indirect)
  - Fans circulate air
  - Cryogen tank (330 to 1100 liters)
  - Controls & flow regulators

Direct Verses Indirect Systems

Direct cryogenic refrigeration with liquid nitrogen <u>sprayer</u>



Indirect cryogenic refrigeration with <u>heat exchanger</u>



Technology Readiness

- Widely Available in Europe
  - Over 2,000 units in use from 5 manufacturers
- Pilot Demonstrations in US
  - In-N-Out Burger tested indirect system (1999 to 2000 SCAQMD funded study)
  - Sysco Foods-Texas tested indirect system (2000)
  - Safeway-Northern California tested both indirect and direct systems (early 2000's) – still operating
  - Produce and frozen dairy fleets in Utah demonstrated indirect system (2013 to 2014) – test phase in-progress
- Manufacturers: Air Liquide (Blueeze), Reflect Scientific (Cryometrix), ecoFridge (natureFridge), Linde (Frostcruise), Thermo King (CryoTech)

Economics

- **Conventional Trailer TRU Costs**
  - Capital cost: ~$20,000 to $33,000
  - Fuel cost: $6,400/yr at 0.8 gal/hr, 2,000 hr/yr, $4/gal
  - Maintenance: ~$1,700 per year at $0.85/hr, 2,000 hr/yr
- **Technology Costs**
  - Capital cost: $15,000 to $35,000 per unit
  - Fuel infrastructure cost: $1,500/mo (single station lease)
  - Fuel cost (cryogenic fluid): $3,840 to $14,400/yr at 24 to 40 liters/hour, 1,600 to 2400 hours/year, and $0.10–$0.15/liter
  - Maintenance: ~$100/yr at $0.05/hr, 2,000 hr/yr
- **Savings:**
  - Fuel: Depends on cryogenic fluid cost
  - Maintenance: ~$1,600/yr

Technology Advantages

- Very quiet operation
- Rapid cool downs
- Rapid temperature recovery after door openings
- Less product dehydration
- No high GWP refrigerant
- Fewer Moving Parts ➔ Reduced Repair, Maintenance, and Downtime
- Minimized defrosting needs
- Reduced emissions (criteria and GHG)

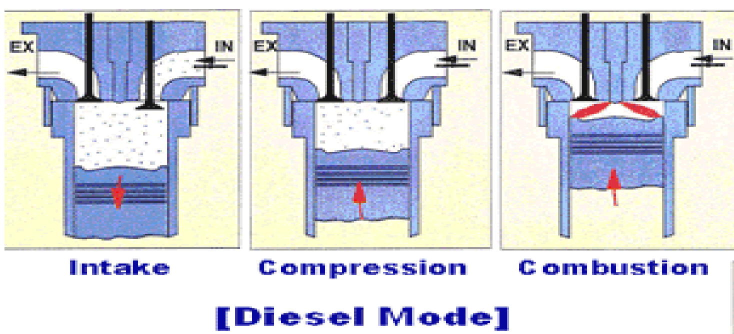
Key Performance Parameter Issues & Deployment challenges

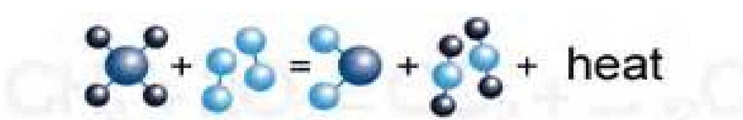
- Range: Limited to return to base operations
- Cost and availability of cryogenic fluid
- Cost of cryogenic "fuel" dispensing infrastructure
- Refueling of cryogenic fluid tanks takes longer than conventional refueling
- Need power source for fans
- Direct systems produce oxygen deficient atmosphere in the van (safety systems/procedures required)

Alternative-Fueled Engine

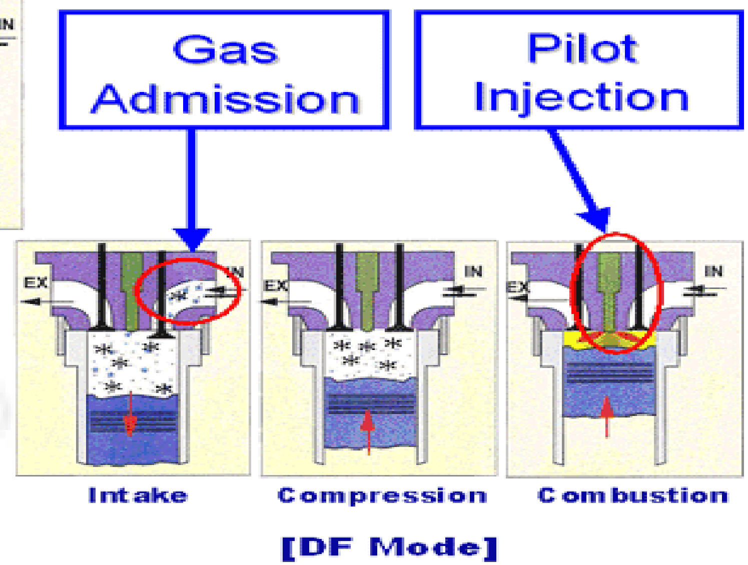
How Does it Work?

- Various configurations:
  - Dedicated fuel designs (spark-ignited)
  - Dual fuel pilot injection
  - After-market conversion kits





$CH_4 + 2O_2 = CO_2 + 2H_2O$



Alt-Fuel-Powered TRs

Technology Readiness

Pilot Demonstration

- LNG:
  - CR England – Truck tractor demonstration (end of 2014)
- CNG:
  - Kohler Engines – truck TRU field demonstration (2015)
  - Kwik Trip – Negotiating with Thermo King & Carrier Transicold
  - North America Repower – Adapting from tractors to TRUs
- LPG:
  - Lister Petter – Interested in TRU market

Economics

- **Costs:**
  - Capital cost – $9,000 to $15,000 for rebuild (includes fuel tank)
  - Fueling infrastructure – $800,000 to $1,845,000
  - Maintenance – Less soot and metal in lube oil
    - Less frequent oil changes
    - 30% to 40% longer engine life
- **Savings:**
  - Fuel consumption – 20% to 35% lower
  - Maintenance – Expected to be less than diesel engine
- **Return on Investment:**
  - Payback period – More data needed

Natural Gas Fueling Stations

Publically Accessible Natural Gas Stations (Heavy Duty)

- CNG (490)
- LNG (57)

Technology Advantages

- Reduced Emissions
- 20% to 35% Lower Fuel Cost
  - Offset by 8% greater fuel consumption (diesel gallon equivalent basis)
- Quieter
- Meets Duty Cycle
- 30% to 40% Longer Engine Life

Key Performance Parameter Issues & Deployment Challenges

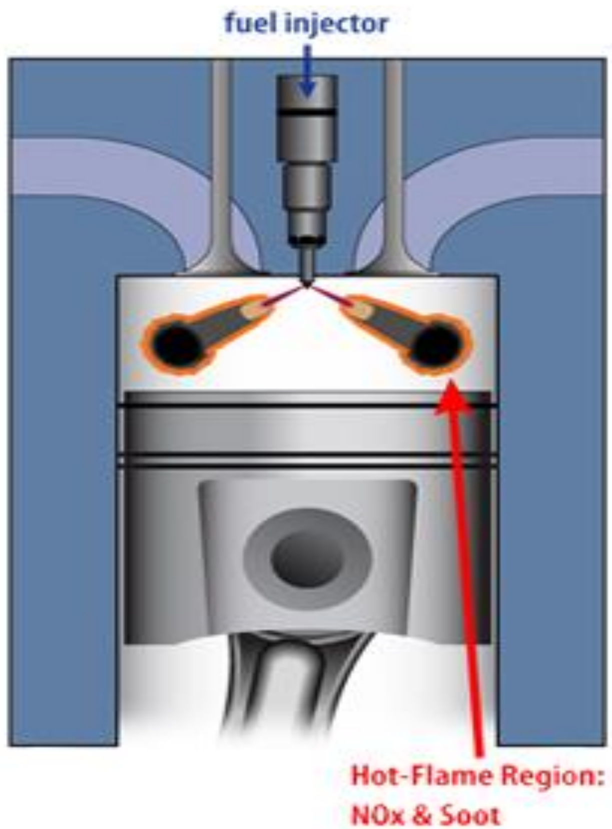
- Cost and space required for fuel tanks
- Range – limited by on-board fuel tank size
- Cost of home-base fueling infrastructure
- Limited to return-to-base fleets
  - Fuel infrastructure on transportation corridors inadequate for long-haul
- Potential payload impact for dual-fuel systems
  - Requires two fuel tanks (weight)
- Not currently available for trailer transport refrigeration
  - Smaller engines available for trucks

Advanced Power Plants HCCI/PCCI

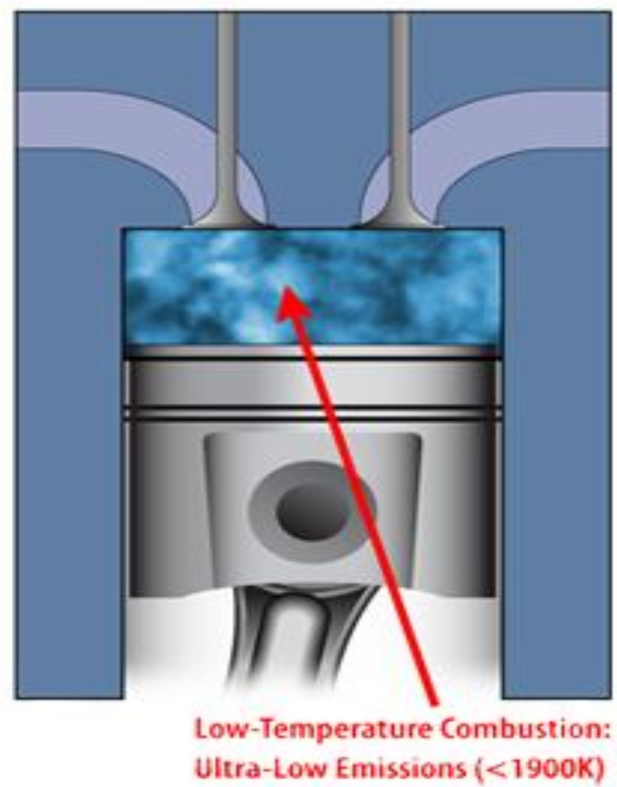
How Does it Work?

- Homogeneous charge compression ignition (HCCI): thermal auto ignition of a premixed air-fuel without flame propagation
- Aka Premixed charge compression Ignition (PCCI)
- Low combustion temperatures produce extremely low nitrogen oxides (NO_x) emissions
- Lean premixed combustion results in near zero particulate matter (PM) depending on the fuel used

How It Works

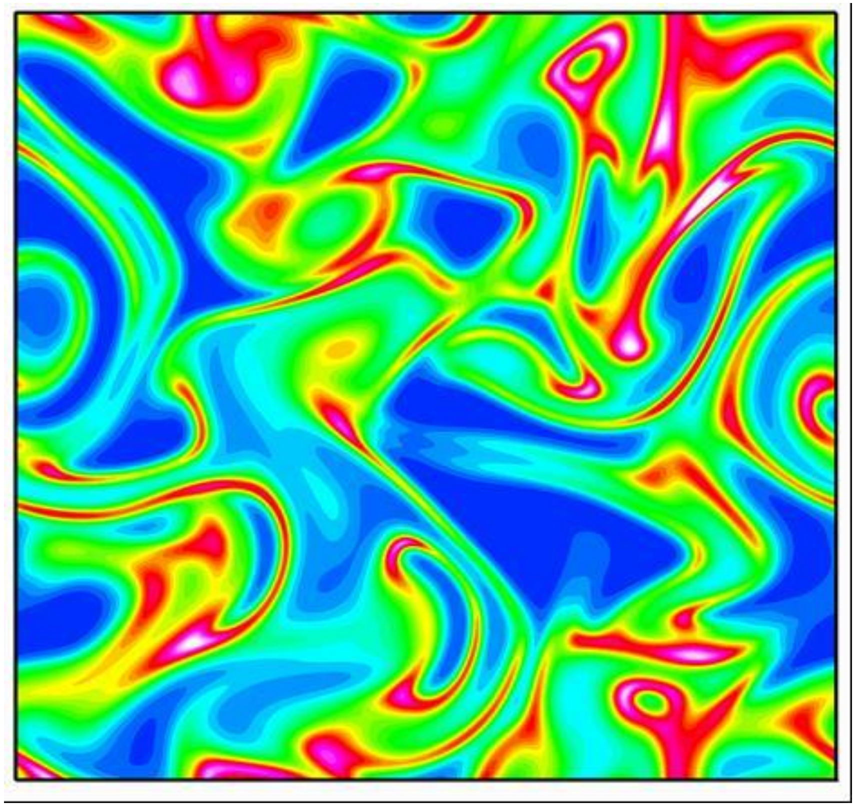


Conventional Diesel



HCCI/PCCI

Not Homogenous



Colors represent imperfect fuel air mixture within HCCI event
(homogenous would be single color)

Technology Readiness

Bench Phase

- Sandia National Labs
  - Fundamental modeling
- Lawrence Livermore National Labs
  - Conversion of single-cylinder engine to HCCI to develop controls for six-cylinder engine using CNG
- Lawrence Berkeley National Labs
  - Conversion of single cylinder diesel CI to diesel HCCI
  - Demonstrate capability for the TRU application
  - Expected to begin Q4 of 2014
  - Results estimated for 2015

Economics

- Costs
  - Capital cost – unknown
  - Maintenance – unknown
- Savings
  - Fuel consumption – More data needed; however, tests show greater efficiency with HCCI
  - Maintenance – unknown
- Return on Investment
  - Payback period – unknown
  - Expected to be similar to current engines

Key Performance Parameter Issues & Deployment Challenges

- Cold start HCCI requires heated air intake
- Instable with quick load changes
- Auto-ignition event controls needed
- Prone to knock
- High in-cylinder peak pressures
- High HC and CO emissions
- Bench and pilot demonstrations needed

Tier IV+ New Off-Road CI Engine Emissions Standards for <25 HP

- Current Tier 4 standards for PM do not meet TRU ATCM's Ultra-Low-Emission TRU In-Use Performance Standards (ULETRU)
- ARB research contract to evaluate feasibility, cost-effectiveness, and necessity of advanced PM and NO_x after-treatment
  - Report due in 24 months
- Results important to TRU program
  - Need near-zero criteria pollutant emissions for all TRU engine horsepower categories

Conclusions

- Most Promising TR Technologies, Next Steps

Conclusion: Most Promising TR Technologies

- Hydrogen fuel cell-powered refrigerator
- All-Electric high-efficiency refrigerator and AC/DC alternator with power control unit, shore power plugs, and batteries
- Cryogenic temperature control

Recommended Next Steps

- Hydrogen Fuel Cell All-Electric Transport Refrigerators
  - Monitor ongoing field demonstrations
  - Coordinate with US EPA/US DOE
- All-Electric Transport Refrigerators
  - Encourage trailer system integration/demonstrations for on-road operations
- Cryogenic Temperature Control
  - Monitor U.S. demonstrations in progress
  - Encourage infrastructure development and quick fill technologies
  - Encourage control systems and safety procedures

Contacts

- Truck Sector Lead:
  - Kim Heroy-Rogalski kheroyro@arb.ca.gov
- Transport Refrigerator Team:
  - Rich Boyd rboyd@arb.ca.gov
  - Rod Hill rhill@arb.ca.gov
  - Renee Coad rcoad@arb.ca.gov
  - Carolyn Craig ccraig@arb.ca.gov
  - Ziv Lang zlang@arb.ca.gov
  - Chris Popovich cpopovic@arb.ca.gov

  - Submit comments by Oct. 1 to: http://www.arb.ca.gov/msprog/tech/comments.htm