Solid-State Pulsed Electric Field (PEF) Overview
Technology and Markets

Presentation Summary

- Introduction to DTI
  - Core Technology
- Introduction to PEF
  - Major PEF Subsystems
    - Treatment Chambers for Fluid
    - Treatment Chambers for Bulk Products
  - PEF System Goals
  - Basic Sizing Relationships
  - PEF Commercialization History
  - PEF R&D Status
  - PEF Regulation
  - PEF System Manufacturers
- Overview of PEF Applications
  - Rationale for PEF
  - Non-Thermal Pasteurization
    - Cost Comparisons
  - Extraction
  - Drying Acceleration
  - Material Modification
  - Wastewater Treatment
- DTI Equipment
  - Laboratory Scale PEF System
  - Industrial Scale PEF System
  - PEF Costs

- Founded 1987 by Dr. Marcel Gaudreau (MIT)
  - Located in Bedford, MA, USA
  - 60 Employees
  - 6 PhDs (EE, Physics, Aero)
  - Diverse Technical Background
  - 33,000 Square ft
- Products
  - Solid State Modulators, Power Supplies
  - RF Transmitters
  - PEF Systems
- Primary Business Areas:
  - High Power Electronic Systems
  - System Design and Integration
  - Manufacturing/Process Automation Systems
  - Consulting Engineering

Core Technology – HV Solid-State Switches

Very Fast High Current, HV Solid-State Switches

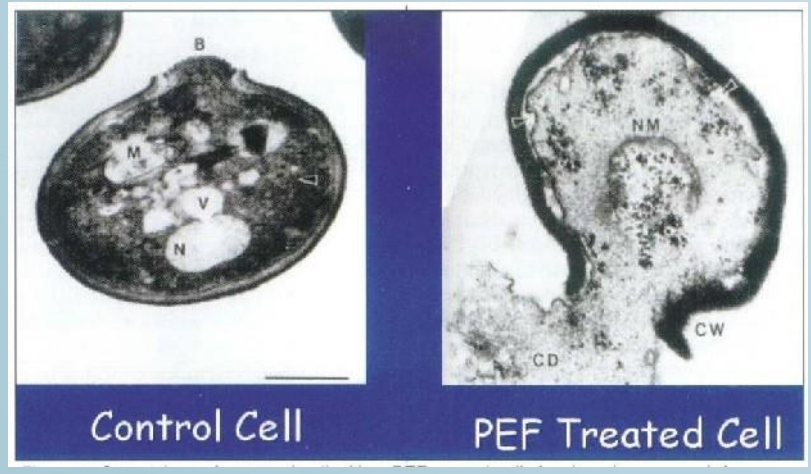
- Series String of Transistors
  - All Operate Synchronously
  - Patented Design
- Very High Voltage and Current Demonstrated
  - Up to 500 kV (500,000 Volts)
  - Up to 20 kA (20,000 Amperes)
- Extremely Uniform & Reliable Pulses
  - Sub-Microsecond Switching
  - Arbitrary Pulsewidth & Frequency
  - 1 nS – CW; > 300 kHz Continuous

Solid-State Switch Modules

60 kV, 250 kW Power Supply

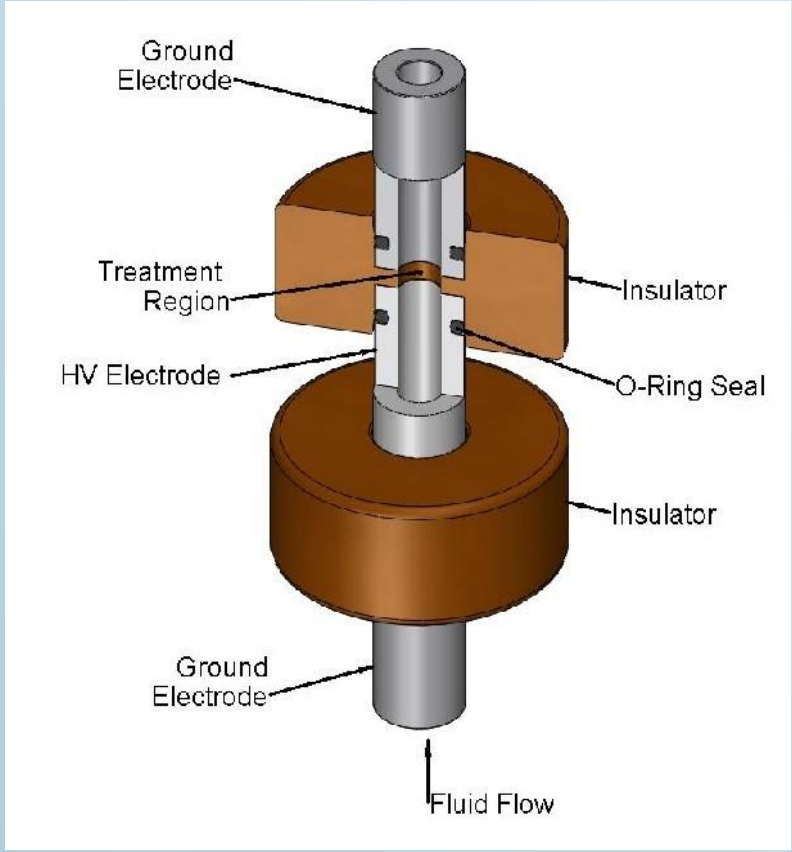
Pulsed Electric Field (PEF)

- Uses Short, High Voltage Pulses to Perforate Cell Membranes
  - 'Electroporation'
  - Similar to Gene Therapy Processes, at Larger Scale
- Short = microseconds
- High Voltage = 1 – 50 kV/cm
- Instantaneous Penetration through Tissue
- Permanently Damages/Breaks Cell Membrane
- Very Low Energy



Major PEF Subsystems

- DC Power Supply
  - Converts Wall Power into High Voltage DC Power
  - Rated in Average Power (Watts)
- Pulse Modulator
  - Stores and Releases Average Power in High Peak Power Pulses
  - Key Parameters – Peak Voltage and Peak Current
- Treatment Chamber
  - Applies Voltage Pulse to Product
  - Fluids / Non-Thermal Pasteurization (R)
  - Fruits, Vegetables in Water Bath

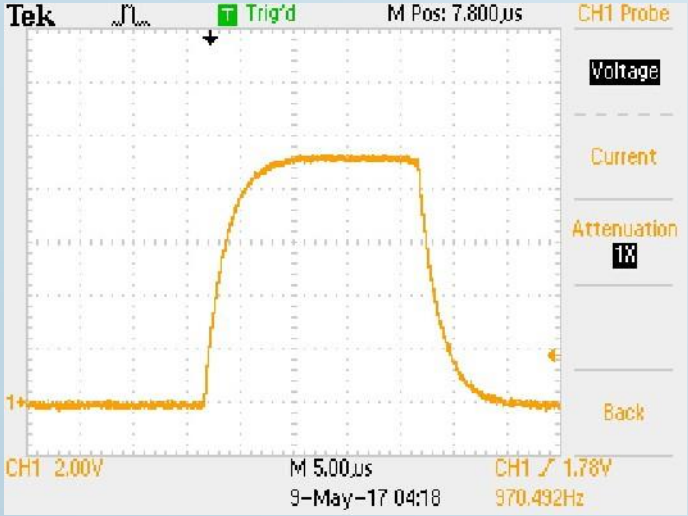


PEF for Bulk Products

- Product in Water Bath
- Conveyor / Flume
  - Move Product
  - Apply HV Pulses
- Very High Throughput
  - Microsecond-Scale Treatments
  - No Holding Time
  - In-Line at Tons / Hour

PEF System Goals

- Apply Very Short, High Voltage (HV) Pulses to Product
  - PEF Requires Very High Fields
  - Pulses vs Continuous Power
    - Avoid Boiling
    - Prevent Arcing
- Consistent and Controllable
  - Field Strength (kV/cm)
  - Treatment Time (μS)
- Adapt to Changing Product Attributes



Basic Sizing Relationships

- Inputs: Field Strength, Dose, Conductivity
  - Flow Rate Determines Average Power (Power Supply)
  - Treatment Chamber Gap Determines Pulse Voltage
  - Pulse Current:
    - Voltage x Conductivity x Chamber Size (Area / Gap)
  - Pulse Power = Voltage x Current
- Switch Size / Cost Determined by Pulse Power
- Other Trade-Offs:
  - Pressure vs Voltage vs Chamber Diameter
  - Peak Power vs Pulse Frequency
  - Multiple Treatment Chambers

PEF Commercialization History

- First Commercial Scale System 2000 (DTI for OSU / DUST, right)
- First Commercial PEF NTP Products 2005 (Genesis Juice)
  - Genesis Sold (Financial Issues) 2007
  - Many Believed PEF Was at Fault
  - Reality – Products Were Popular and Sales Were Increasing Faster Than Genesis Could Support
- Financial Crash 2008
  - Limited Interest For 4 - 5 Years
- Renewed Commercialization ~ 2012
  - Primarily Europe, Shelf Life Extension
  - Increased Interest Last Two Years

PEF R&D Status

- Over 1,000 Peer Reviewed Papers
- Research at Numerous Institutions Around the World
- Significant Data Available
  - Pulsed Electric Field: 887k Google Hits
  - Pulsed Electric Field, Juice: 70k Google Hits
  - PEF, Orange Juice: 29k Google Hits
  - 21 Books on Amazon; Over 50 on Google
  - Over 100 Patents / Applications Worldwide (~ 40 US)

- Significant R&D Background for PEF

PEF Regulation

- PEF Has Been Approved in the US For Juices by FDA
  - 5-log Reduction in Pathogens Required
  - Genesis Juice Met this Standard
  - Perceived Risk - No one Else is Doing It
- Several Examples of PEF Processed Juice In Europe
  - Shelf-life Extension vs Food Safety
  - Sold As Fresh Juice (Unlabeled)
  - Lower European Threshold vs Other Markets?

by Hoogesteger

- Regulation is an Issue, Especially in US

PEF System Manufacturers

- Diversified Technologies, Inc. (USA)
- DIL / ELEA (Germany)
- +4 Additional European Companies

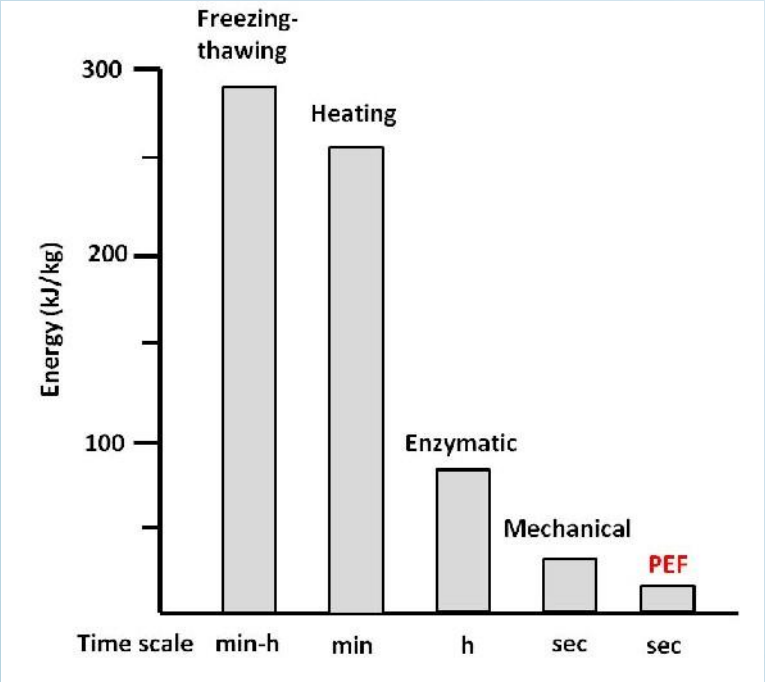
- Primarily Solid-State Pulsed Power Systems
- 4 – 300 kW + Average Power
- Range of Applications and Installations

Overview of PEF Applications

- Non-Thermal Pasteurization
  - Juices
  - Slurries (Salsa, Salad Dressing)
- Extraction
  - Algal Oil and Intracellular Materials
  - Fruit & Vegetable Juices
  - Starches & Sugars
- Drying Acceleration
  - Plant Tissue
- Material Modification
  - Slicing/ Peeling
  - Frying
  - Fermentation Improvement
  - Reduced Freezing Time
  - Others?
- Wastewater Treatment
  - Disinfection
  - Pre-Digestion
  - Denitrification

Rationale for PEF

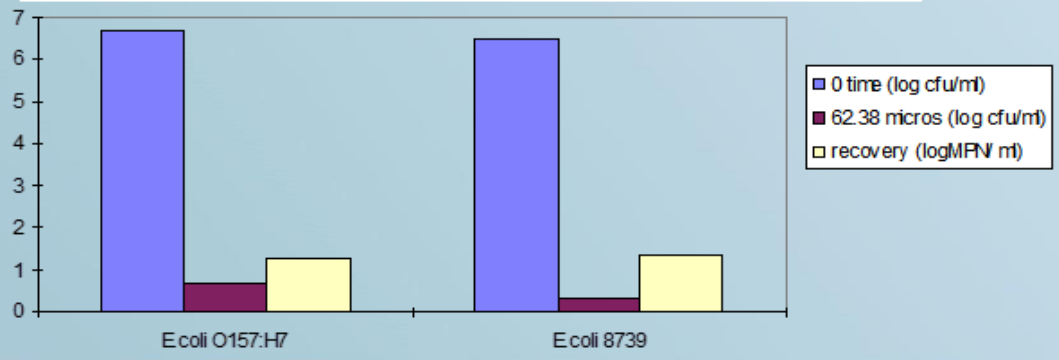
- Premium Product (Non-Thermal Pasteurization)
  - Better Taste
  - Less Denaturation
- Economic
  - Lower Cost (Extraction, Slicing, Drying)
  - Higher Yield (Extraction)
  - Higher Efficiency (Digestion, Separation)
- Indirect Effects
  - Elimination of Other Processes/Chemicals
  - Lower Oil Uptake in Frying
  - Absorption of Additives
  - Less Breakage During Slicing
  - Access to Intracellular Compounds
  - More to be Discovered!



PEF Application – Non-Thermal Pasteurization

- Non-Thermal Pasteurization
  - Researched for Over 20 Years
  - Electroporation Kills Microbes
  - Pasteurization Equivalence at Low Temperature
  - Typically 25 – 40 kV / cm Field Strength
  - Continuous Flow

Inactivation of *E.coli* O157:H7 and *E.coli* 8739 by OSU-3 System. Treatment conditions: flow rate: 1.33ml/s, pulse repetition rate 1000 Hz, pulse duration 3μs, electric field strength 42.04 kv/cm for both *E.coli* O157:H7 and *E. coli* 8739



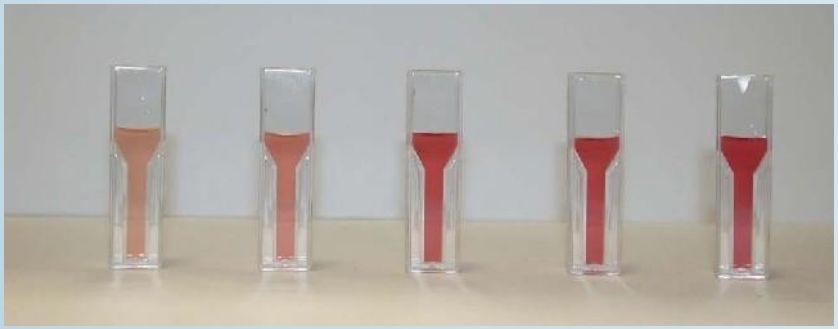
PEF Cost Comparisons for Non-Thermal Pasteurization

- Typically Estimated at $0.02 – 0.05 / liter
- From Sampedro:
  - PEF $0.037 / liter (Orange Juice)
  - Thermal Pasteurization $0.015 / liter (~ 1/3 PEF Cost)
  - HPP $0.107 / liter (~ 3X PEF Cost or More)
- Other Direct Comparisons Show Similar Scaling
- Industrial Applications Vary Wildly
  - Key Is Existing Cost Without PEF
  - Energy / Time / Equipment Savings With PEF
- Cost Does Not Appear to be a Limiting Factor

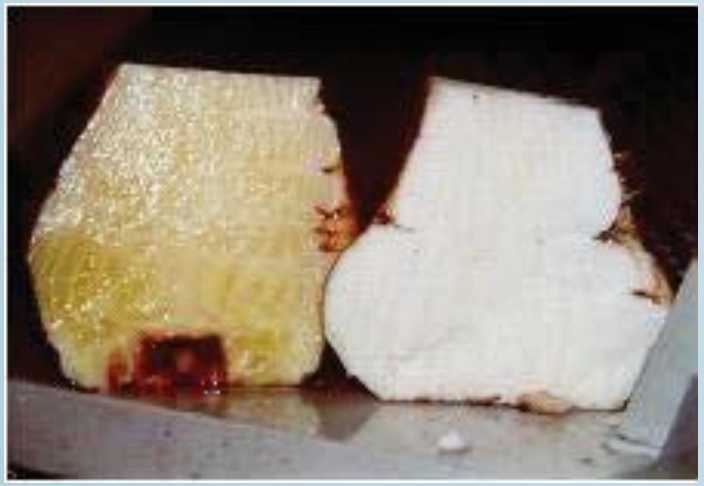
COST ANALYSIS AND ENVIRONMENTAL IMPACT OF NONTHERMAL TECHNOLOGIES, Sampedro, F. et al 2013

PEF Application - Extraction

- Higher Yield / Lower Energy
- Increased Nutrients
- Sugar Beets
  - Yield More than Doubles
  - Better Quality / Less Water
  - Much Lower Energy Costs
- Olive Oil: Up to 54% Higher
- Grape Polyphenols: 3X Higher
- Wet Extraction of Lipids
  - Faster
  - No Drying Costs
  - Less Hazardous Solvents

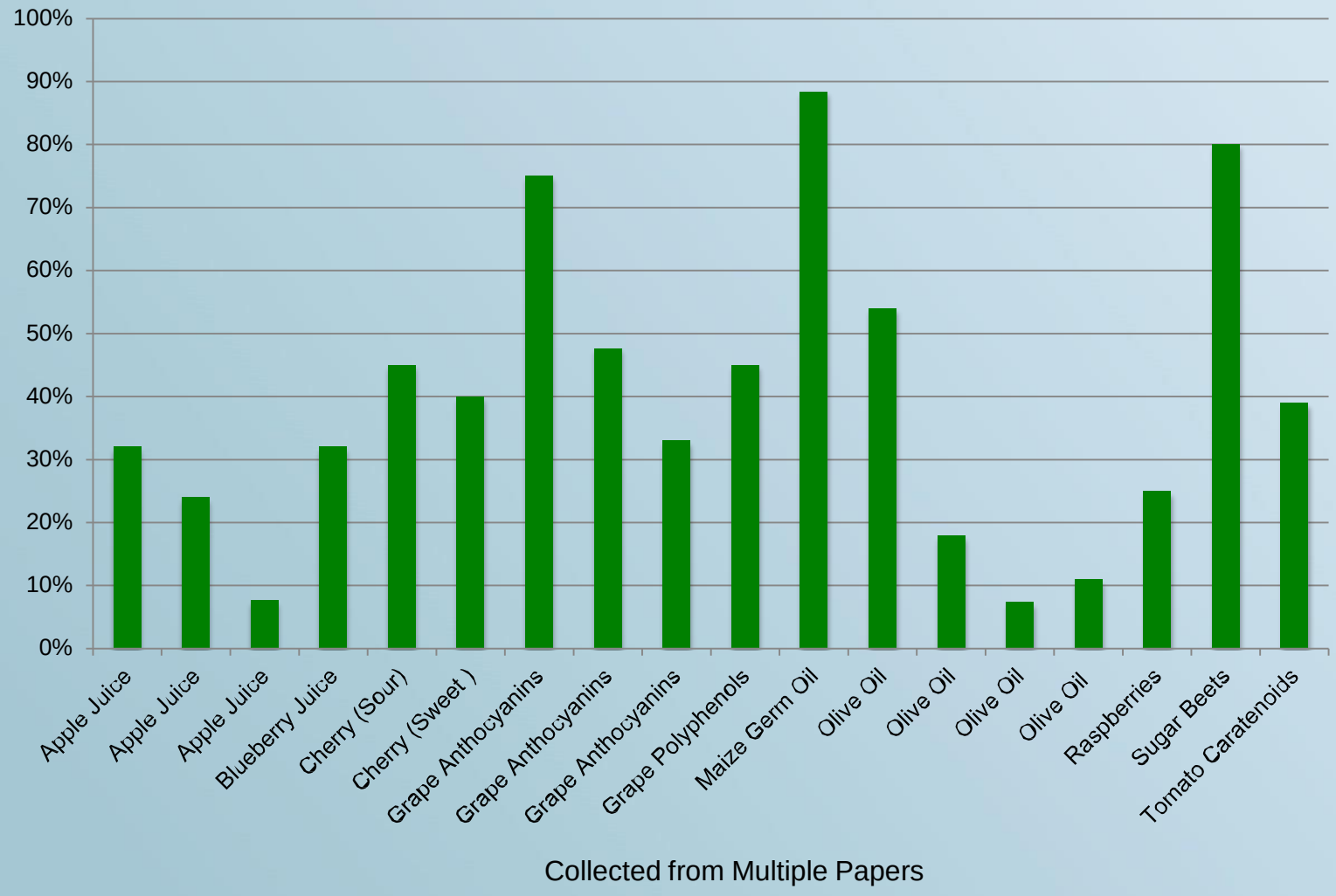


Grape Maceration – 1 Day = 1 Week



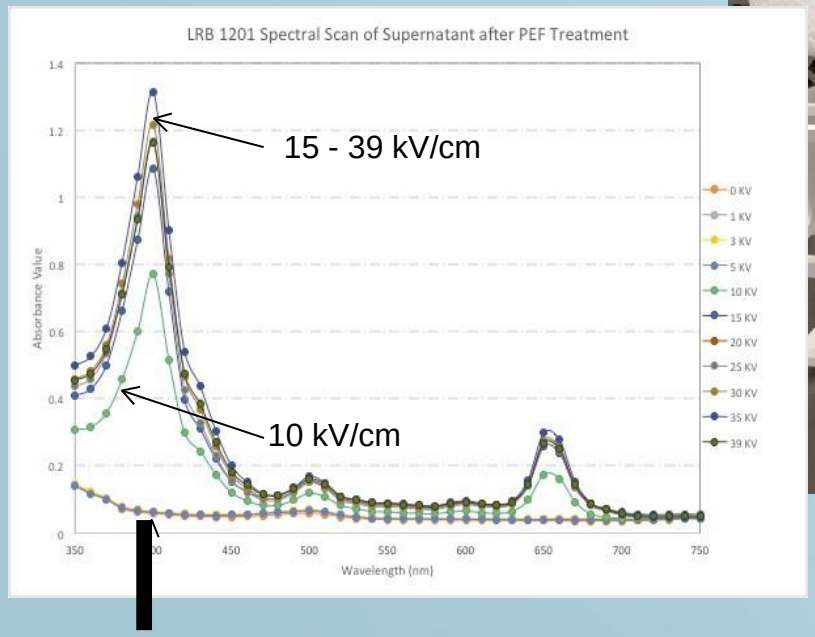
Sugar Beets

Extraction Yield Improvement

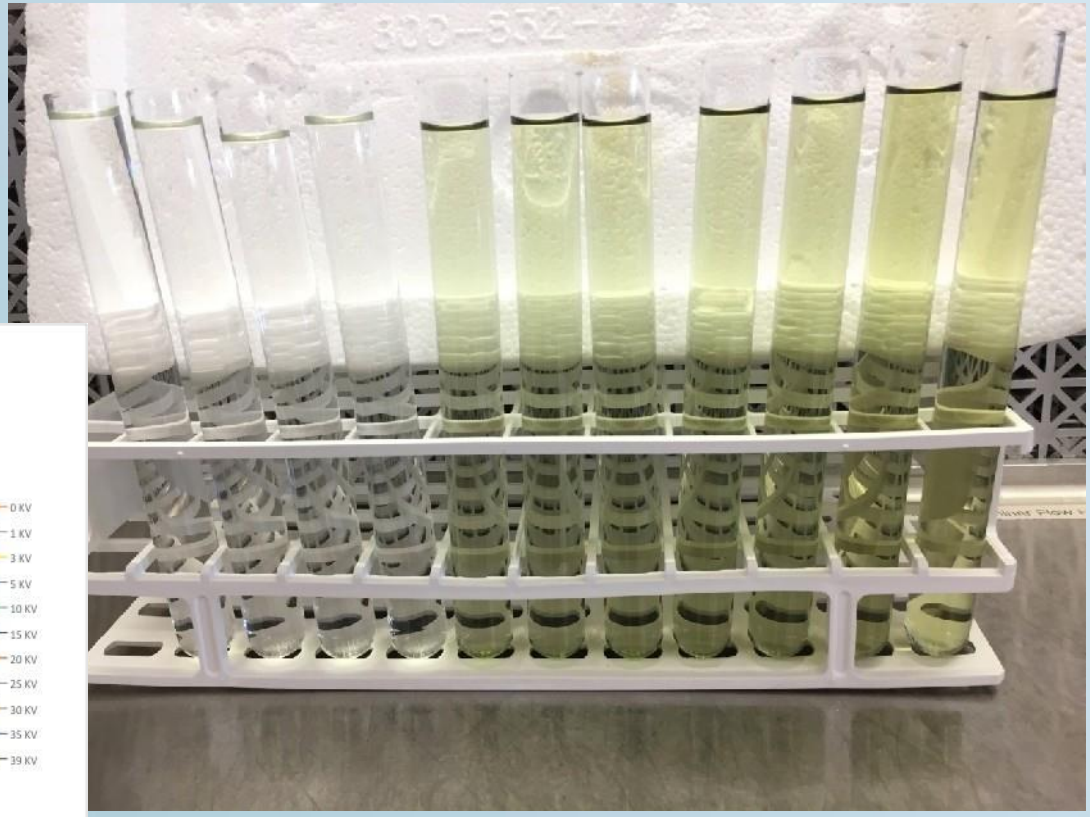


Collected from Multiple Papers

Extraction for Algae (*Chlorella vulgaris)*



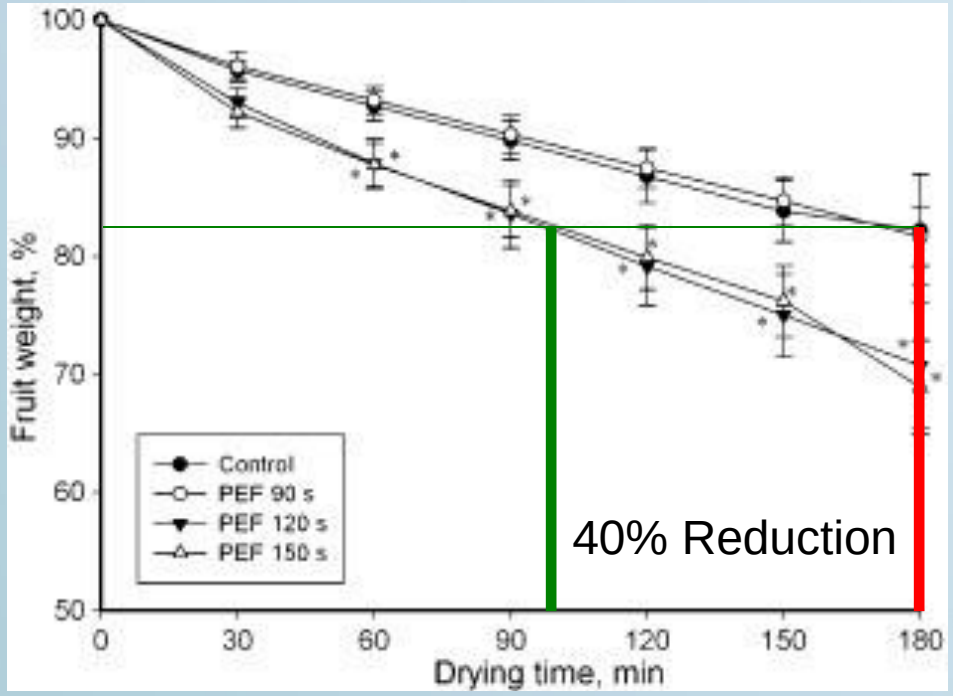
Control – 5 kV/cm



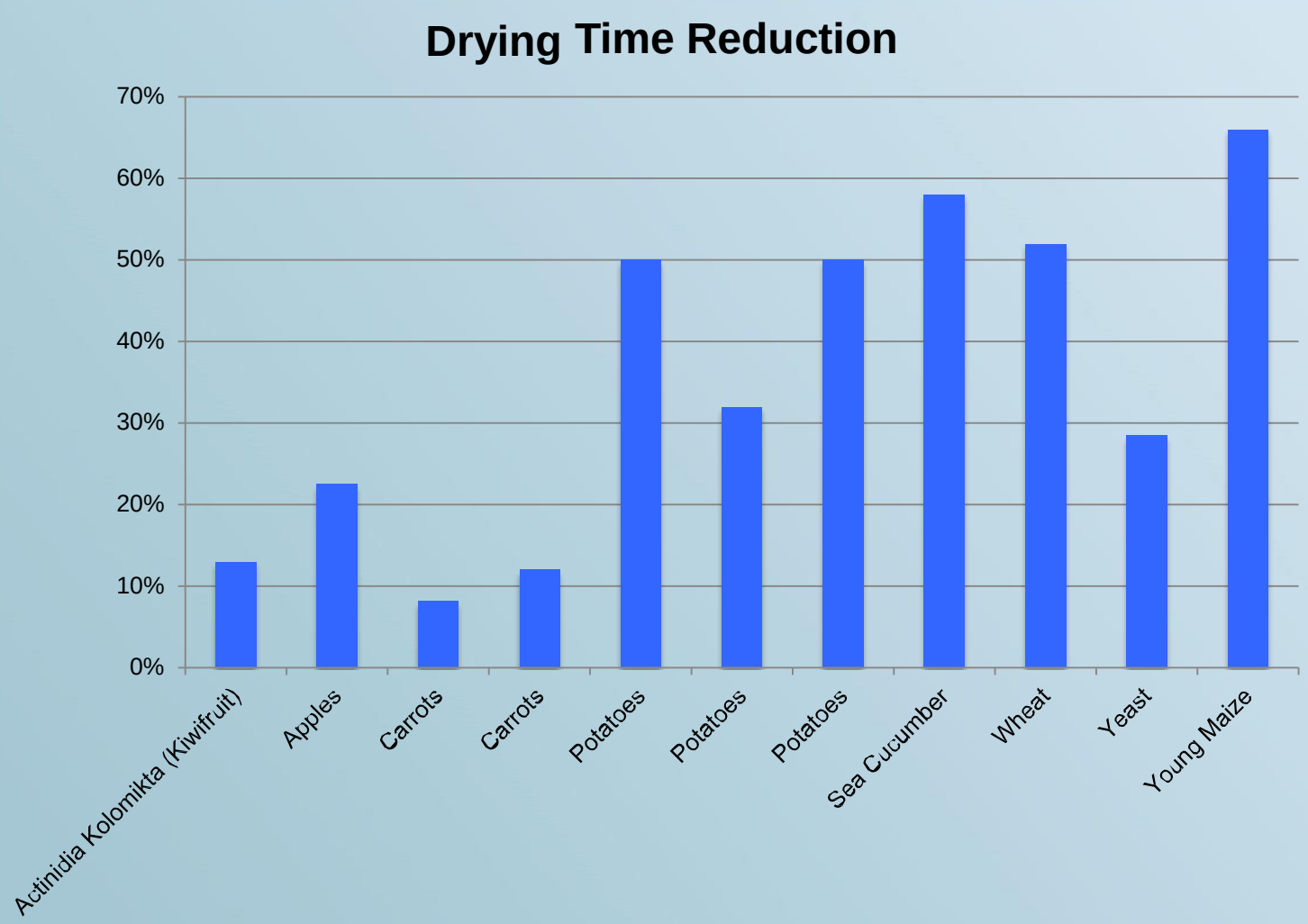
Post-PEF and Centrifuge
(0 - 39 kV/cm, 20 μs)
Visible Release > 10 kV/cm

PEF Application – Drying Acceleration

- Plant Tissue
  - Faster = Lower Energy
  - Potatoes: 25% Reduction
  - Carrots: 50% Reduction
  - Fruit: 40% Reduction
- Larger Pieces – Greater Improvement
  - Intracellular Liquids Available
  - Longer Path to Surface for Water



Plant Drying



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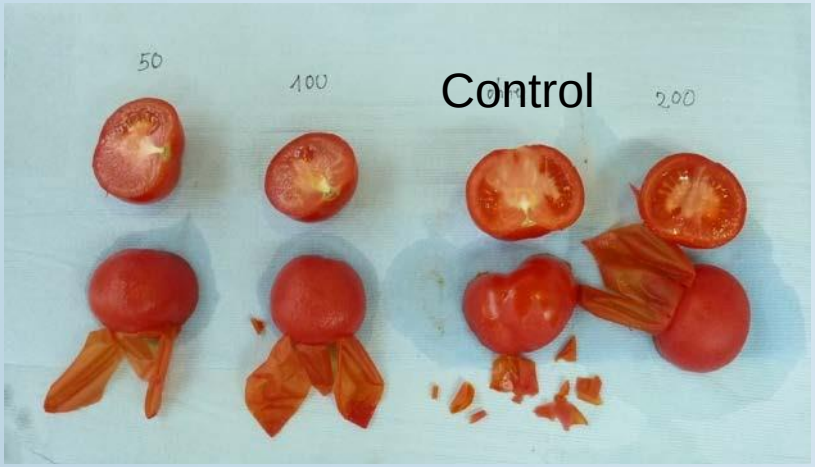
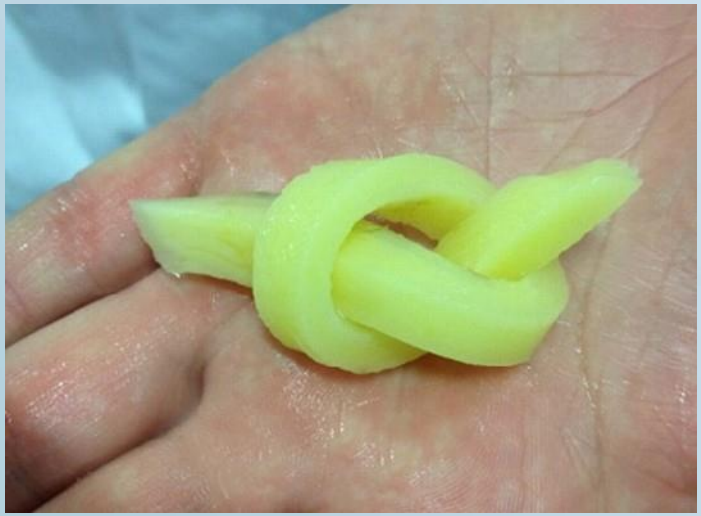
PEF Application – Material Modification
Cutting / Peeling

- Reduced Energy: 20 – 50%
- Faster Than Thermal Blanching
- Less Breakage / Waste

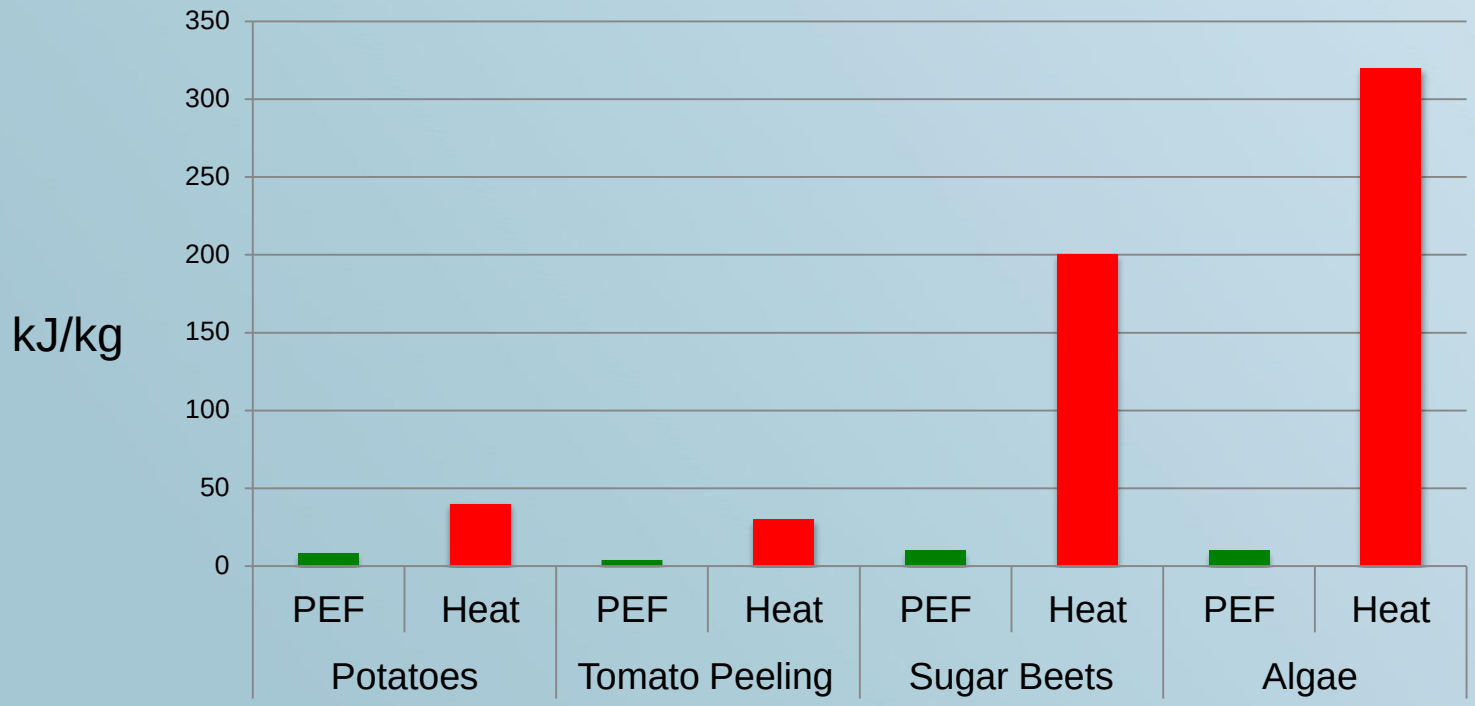


- Major PEF Application – Potatoes For Fries / Chips
  - Reduced Energy
  - Significantly Reduced Oil Uptake
  - < 6 Month ROI Reported
  - Approximately 50 PEF Systems Fielded to Date



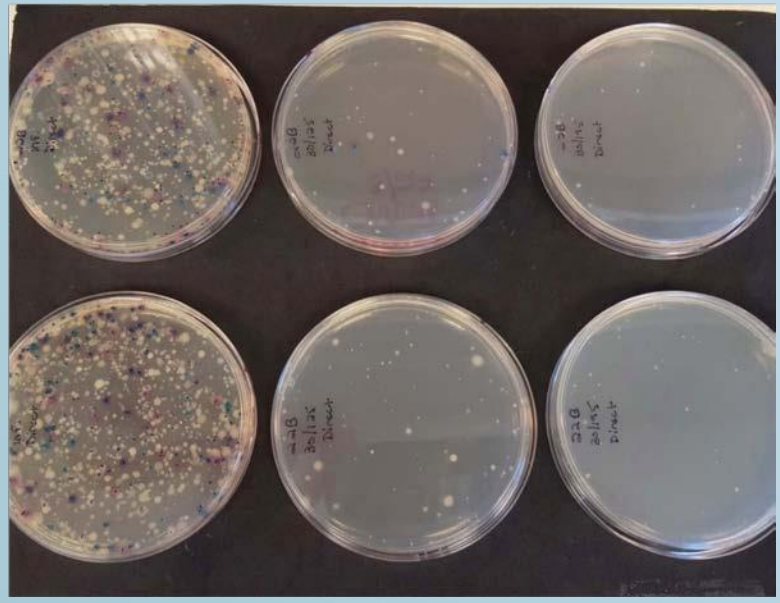
Energy Usage (kJ/kg)

- Data From Actual Trials / Similar End Results
- Only Energy Usage – Excludes Yield Improvements
- Cost Delta is Somewhat Lower (Oil or Gas vs Electricity)



PEF Application – Wastewater Treatment

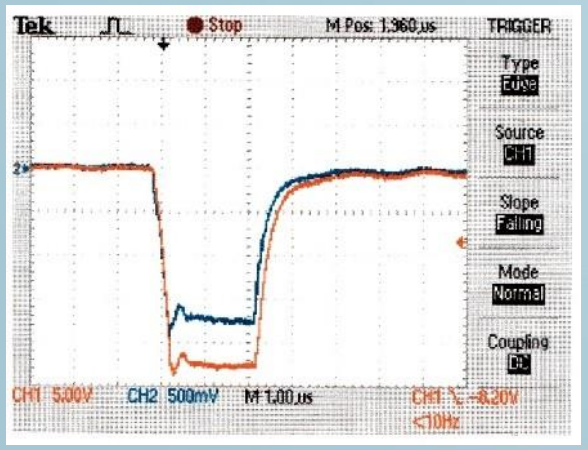
- Pre-Digestion (Increased Methane / Decreased Solids)
- Hospital Wastewater Treatment
  - Kill Antibiotic Resistant Strains Before Discharge
  - No Holding time (Unlike UV/Chlorine)



Control; 30 kV/cm, 125 µs; 30 kV/cm, 195 µs

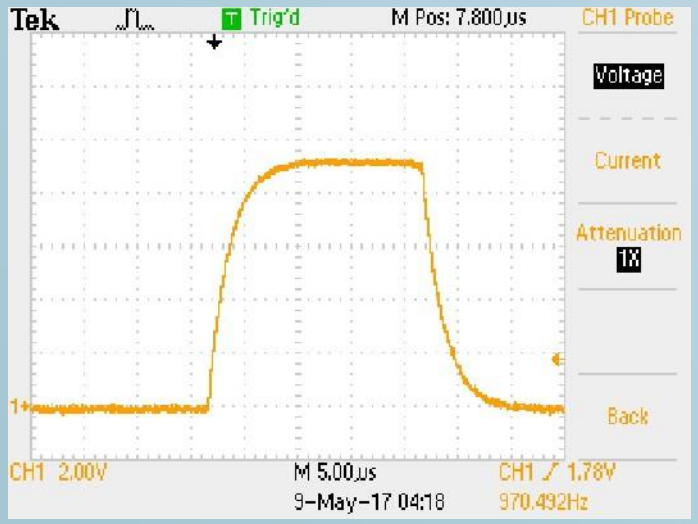
Laboratory Scale PEF System

- Mono-Polar
- 10 - 20 kV, 100 A Pulses
- Pulse Frequency Up to 1400 Hz
- 5 - 10 kW Average Power
- ~ 50 liters/hr
- $85k USD with Pump and Single Treatment Chamber



Industrial Scale PEF System

- Scalable to Tons / Hour
  - 50 – 600 kW Average Power
  - 10 – 50 kV Pulses @ 500 A Peak
  - Multiple kHz Pulse Frequencies
- Compact
- Fully Automated / Integrated Controls
- Up to 10,000 liters (tons) / hour
- Solid-State Series Switch



15 kV, 500 A, 15 µs Pulse

PEF Costs

- Primary Cost - Power
  - Power is a Function of V^2 (Tissue Modification <<<< NTP)
  - Power Scales With Throughput (for Given Treatment Protocol)
  - Efficiency Is Key
    - PEF System Typically 85 – 95% Efficient (Wall Plug to Electrode)
    - Pulse Shape Critical (Square Pulse is most Efficient)
  - 100 kW ~ $100k Annual Electric Cost (at $0.10 / kWhr)
- Capital Equipment $1.50 - $3 per Watt
  - For 50 kW and Above
  - Excludes Material Handling (Pumps, Conveyors, etc.)
- Electrode Costs Are Minimal
- Maintenance – Very Low for Solid State Systems