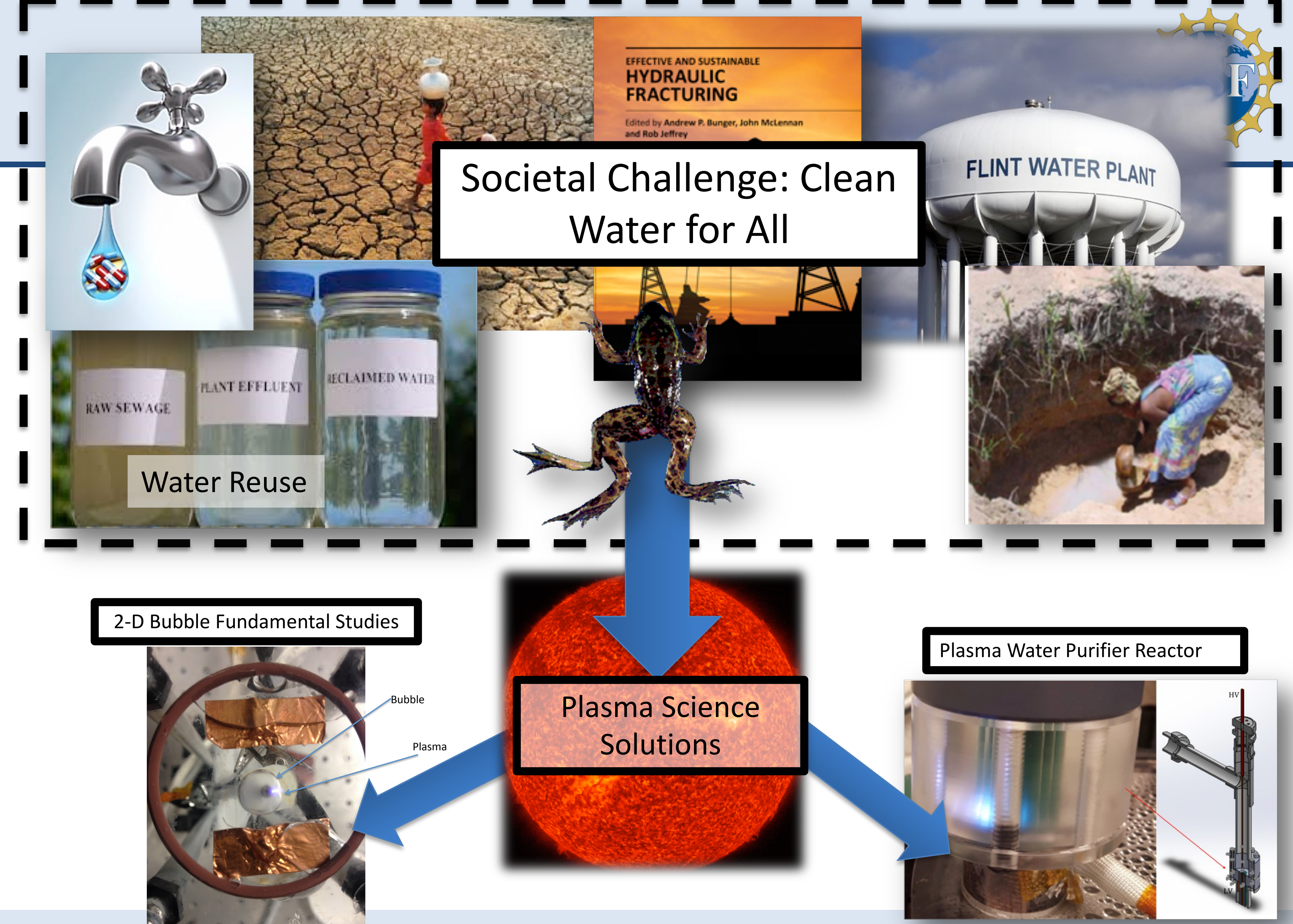
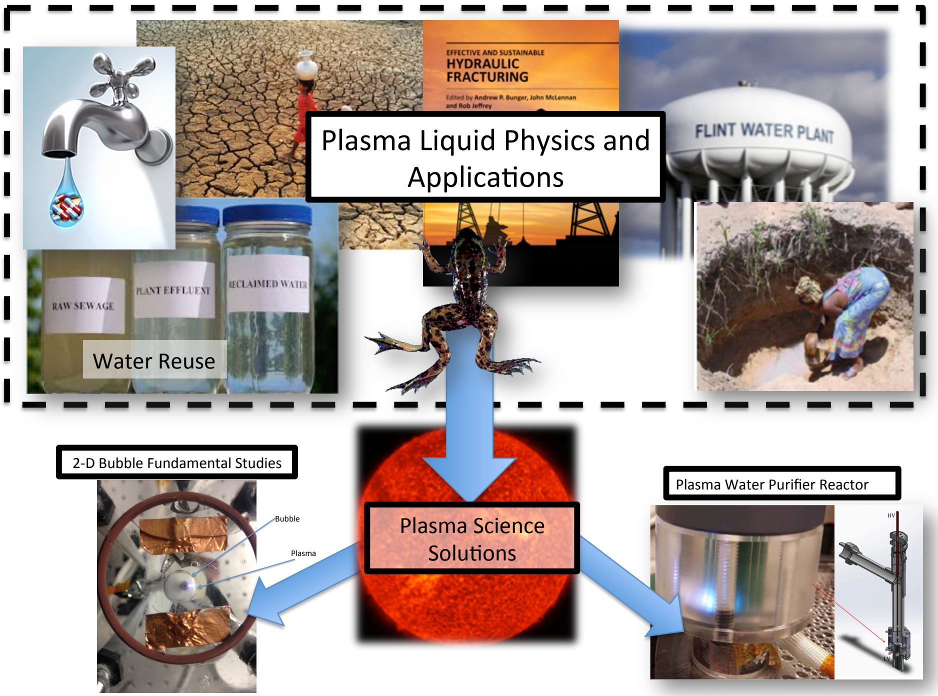

Societal Challenge: Clean Water for All
EFFECTIVE AND SUSTAINABLE
HYDRAULIC FRACTURING
Edited by Andrew P. Bunger, John McLennan and Rob Jeffrey
FLINT WATER PLANT
RAW SEWAGE
PLANT EFFLUENT
ECLAIMED WATER
Water Reuse
2-D Bubble Fundamental Studies
Bubble
Plasma
Plasma Science Solutions
Plasma Water Purifier Reactor
HV
LV

Towards a scalable plasma water treatment reactor via the optimization of reactions and transport at the plasma liquid interface

PIs Foster and Kushner

- **Title:** Scalable plasma water treatment methodology via optimization of of plasma liquid interaction surface
- **PIs:** J.E. Foster and M.J. Kushner, University of Michigan
- **Outcome/Deliverable**: Using a combination of small scale guiding experiments, simulation, and hardware development, demonstrate operation of plasma reactor with the capacity for piloting applications at modest throughput (>5 gal/min)
- **Impact:** Introduction of a scalable advanced water treatment method that has potential to address a range of industry relevant contaminants and water treatment needs at reduced cost and system complexity
- **Project Duration, Budget**: 18-24 months, ~$200 k-$250k



University of Michigan
Institute for Plasma Science & Engr.

Need and Industrial Relevance

Municipal

Agriculture
*80 percent of consumptive use

Resource Extraction

Figure 1. Total water withdrawals by category, 2010.

Water Use (withdrawals) and Waste Water production in the US is spread over many sectors

Industrial processing

Energy Production

Need and Industrial Relevance

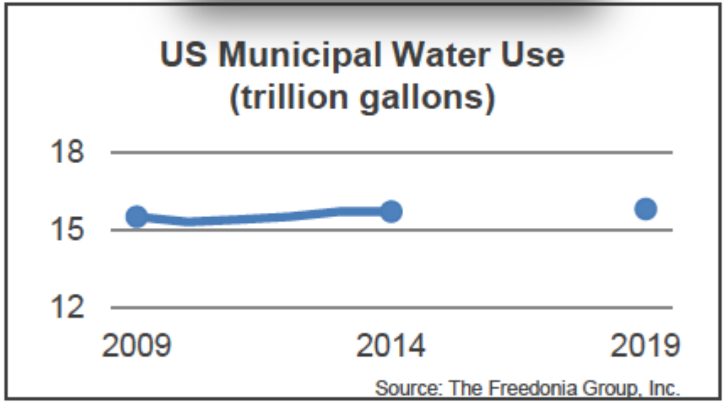
Advanced Treatment Methods Enable Water Reuse

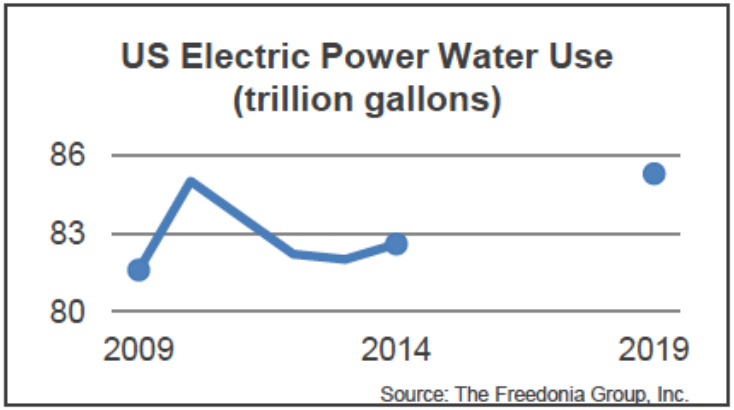
- Freshwater is a scarce commodity and thus it is in the interest of all stakeholders to manage the resource in a sustainable fashion
- Reuse necessarily becomes the simplest most practical solution
  - Addresses climate change limitations to availability
  - Address ground water depletion and salt intrusion
  - Addresses pollution control
  - Addresses sustainability
  - Addresses regulatory requirements
  - Addresses hidden “cost of water”
- Advanced Technologies are necessary to enable reuse
  - Involves treating waste with via advanced methods to remove contaminant levels to the point where it can actually be reused
  - Current advanced methods include combination of **Reverse osmosis and Advanced oxidation**

Cost of water goes beyond water and sewer bill

Customer Segments in need of advanced solutions: U.S. Water Treatment Equipment Demand

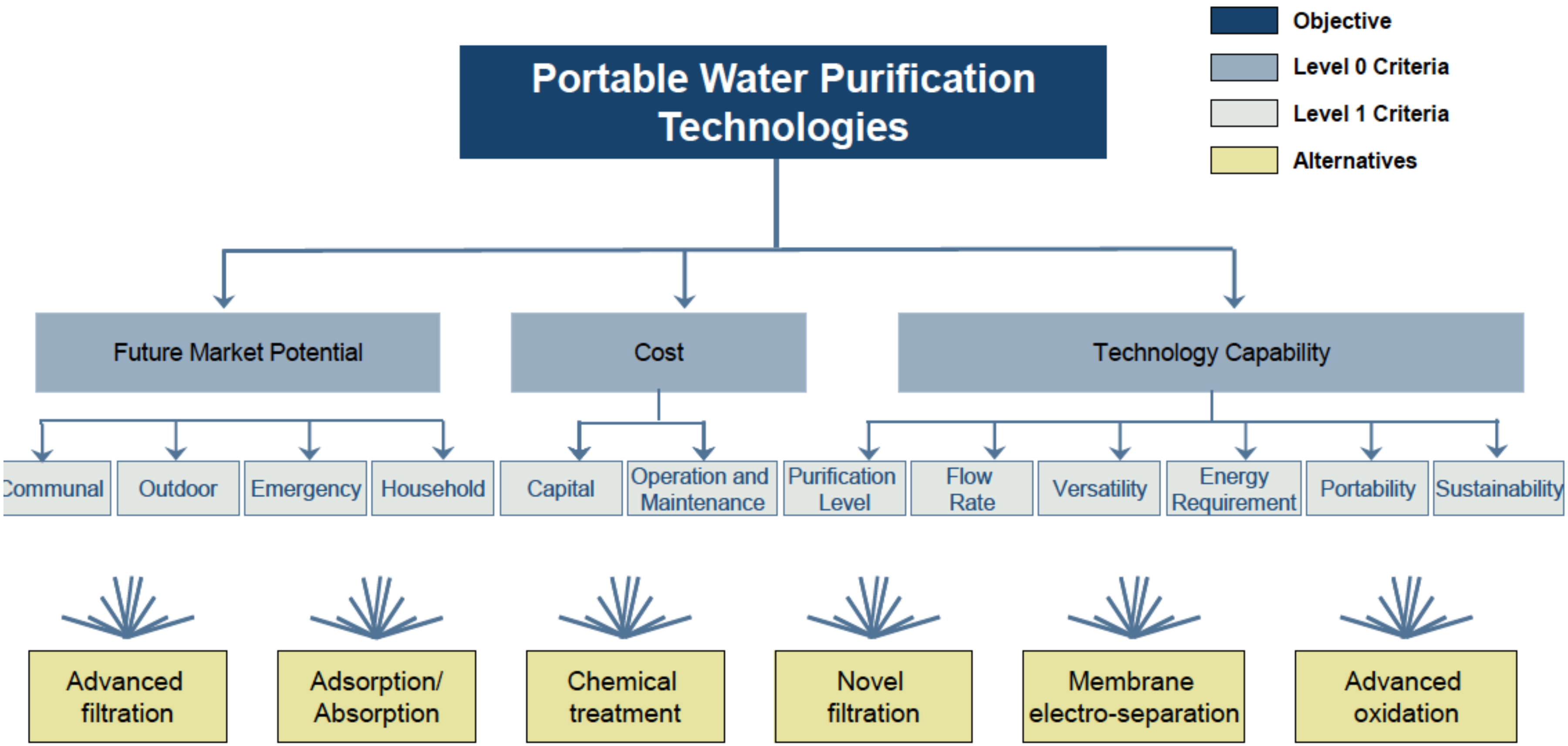
- **Municipal demand**
  - Increase of 4.4% annually to $7.5 Billion by 2019
- **Commercial and Residential Sectors (point of entry systems)**
  - Rise of ~6% annually to $1.8 Billion by 2019
- **Manufacturing sector**
  - Expected to increase ~6% annually to $ 3.1 Billion by 2019
    - Sector needs are not always satisfied by municipal sources (chlorine and disinfection byproducts bad for beverage or semiconductor industry)
    - Tragic water crisis in Flint and Ford Motor
- **Resource Extraction Sector (Oil/Gas/Mining)**
  - expected to grow ~8% annually to $1.9 Billion by 2019
- **Power Generation Sector**
  - Expected to grow 2.4 % annually to ~$500 Million
  - Water use decline due to advanced reuse tech
- **Other markets-ballast water, agriculture, zoos, ect**
  - 6.1% growth per year to $~210 M by 2019





Freedonia Focus Group Reports, May 2015.

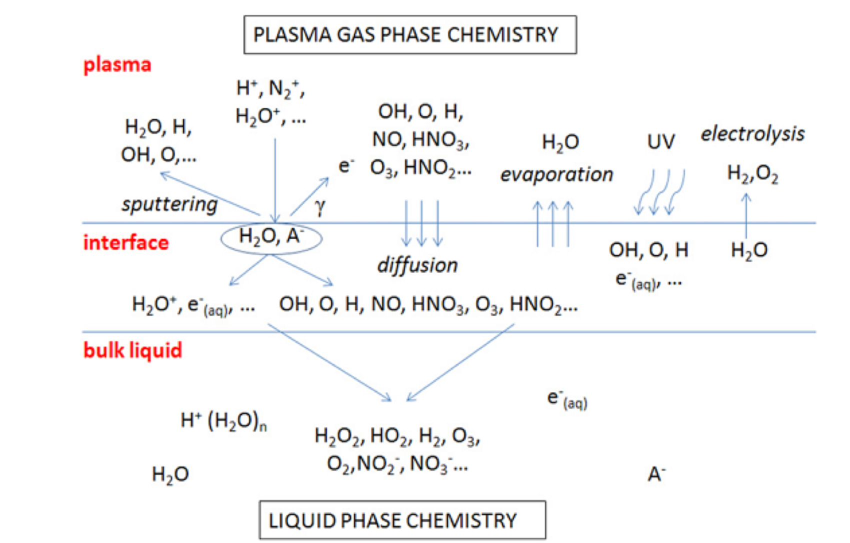
Portable Point of Use Drivers



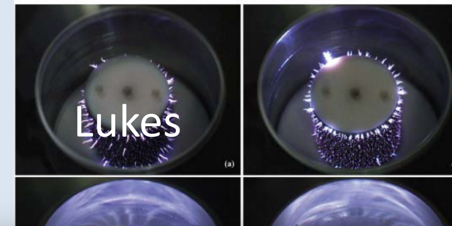
Source: Frost & Sullivan Analysis

Approach-Plasma as an Advanced Oxidation Method

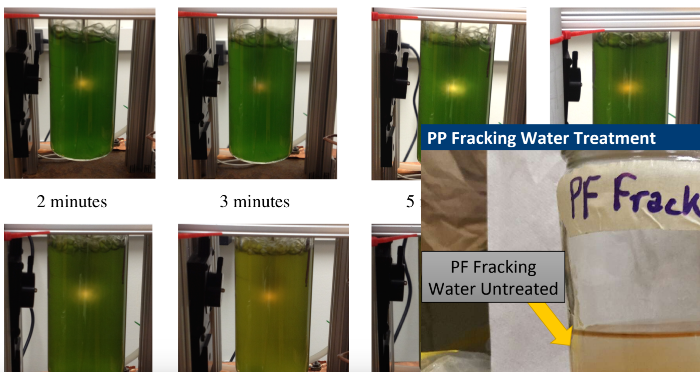
- The Plasma **Value Proposition**
  - Produce a range of advanced oxidation processes at once (OH, Peroxide, Ozone, Ultrasound, UV…)
    - Indiscriminate decomposition of organic contaminants
    - Potential for higher decomposition rates than conventional methods
  - Does not require consumables
    - Onsite Oxygen or Peroxide not needed
  - Power requirements estimated to be less than conventional methods (UV/Peroxide or RO)
- Plasma purifiers can be applied as point of use for areas w/o treatment infrastructure
- Technology is modular—allows for incorporation into existing infrastructure

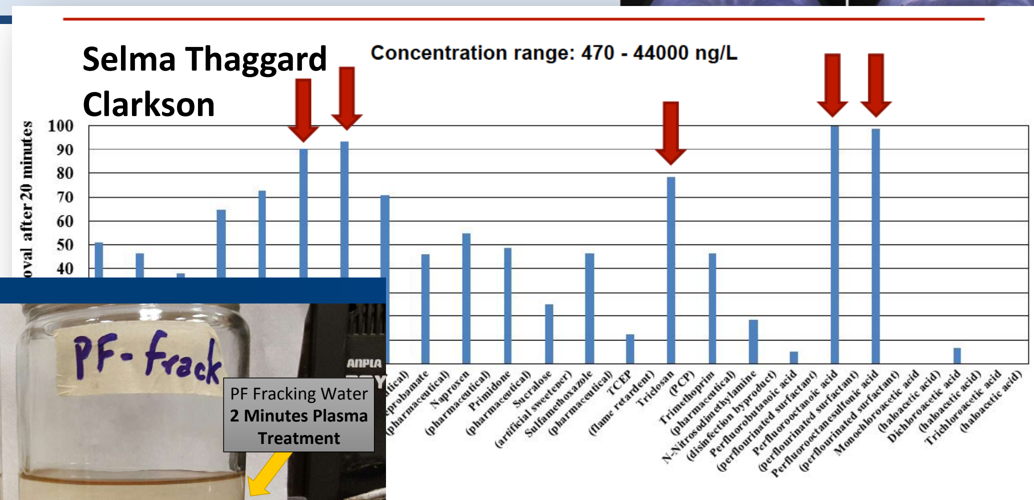


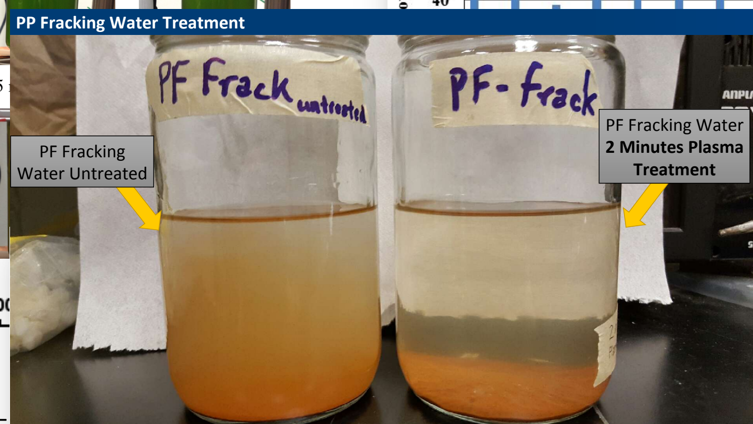
Demonstration of Scientific Feasibility: Done!



- Literature abounds in laboratory scale demonstrations of the advanced oxidation power of plasmas







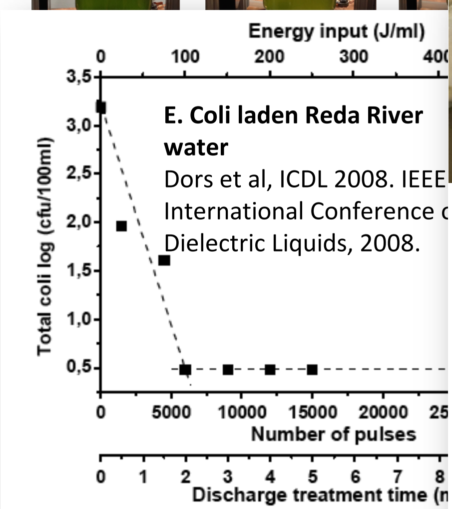


Fig. 4. Total coli disinfection during coron... as a function of applied specific energy...

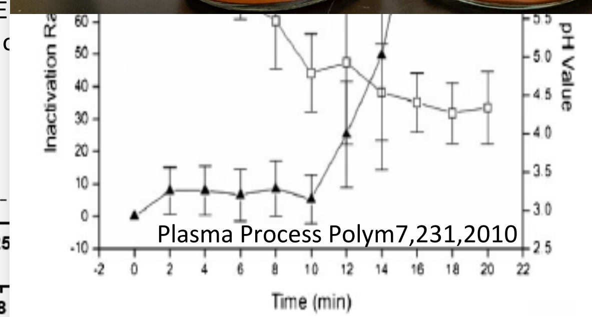
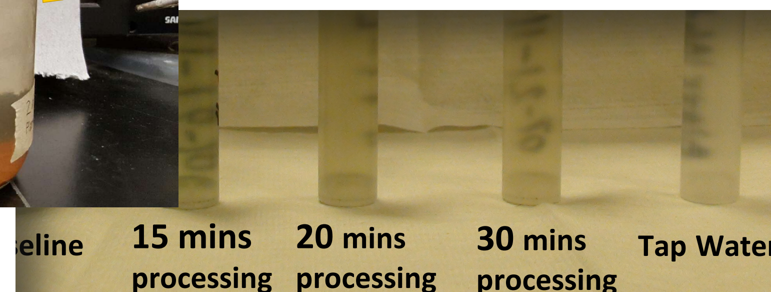


Figure 6. Inactivation rate of *S. aureus* treated with a PMJ in water plotted together with the change in the pH value of the liquid as a function of plasma exposure.



Microcystin removal/UM

Treatment time (min)	% removal
5-6min	~40%
10-15min	~99%
20-30min	>99%

Plasma based Water Purification: Challenges to Realization

- Two hurdles must be surmounted before plasma based water purification can be realized in practice
  - Technical feasibility demonstrated…but…
    - Must be scalable
    - Must demonstrate ease of integration
    - Must satisfy state EPA log reductions
  - Economic feasibility requires demonstration
    - Must be competitive with existing technologies
    - Power systems must be affordable
    - Must add some form of additional value
      - No consumables
      - Effectiveness independent of initial water quality

Advanced Treatment, It Costs

- Average cost in US to conventionally treat 1000 gallons of drinking water: ~2.5 dollars (adjusted for inflation)
  - Treatment accounts for 15% of this cost
  - Average American uses 100 gallons a day!
- RO cost ~4 dollars/1000 gallons
  - 15 kW hours per 1000 gallons
- Advanced oxidation costs variable 2 dollars/1000 gallons(ozone) to $90 for ultrasound
  - Contaminant specific

Requirements

- **Plasmas have demonstrated the capacity at the beaker-scale that they are effective at decomposing organic contaminants and pathogens in solution**
- **Currently water reuse requirements are dictated by California Standards as stated in Reuse Framework**
- **Plasma based purification methods must be competitive with conventional methods to be taken seriously as a solution**
  - **Effectiveness**
  - **Energy costs**
  - **Scalability**

Energy costs ~3.5 kWhr/1000 gallon

Table 4.2. Microbial Reduction Criteria for AWTF Treatment Trains[a]

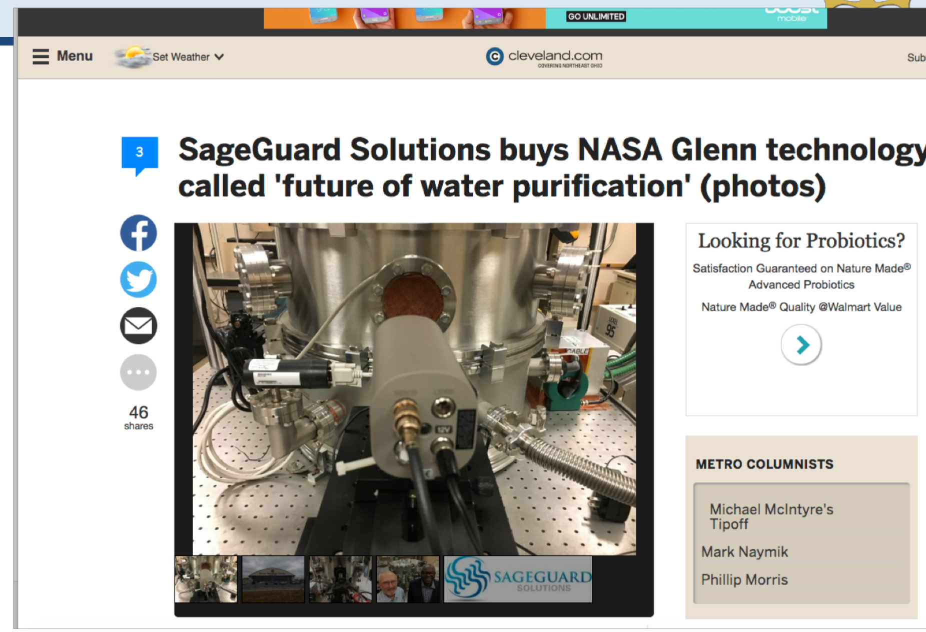
Microbial Group	Criterion (Minimum Log Reduction)	Possible Surrogates
Enteric virus	12	MS2 bacteriophage
Cryptosporidium spp.[b]	10	Latex microspheres, AC fine dust, inactivated *Cryptosporidium* oocysts, aerobic spores
Total coliform bacteria[c]	9	Not applicable

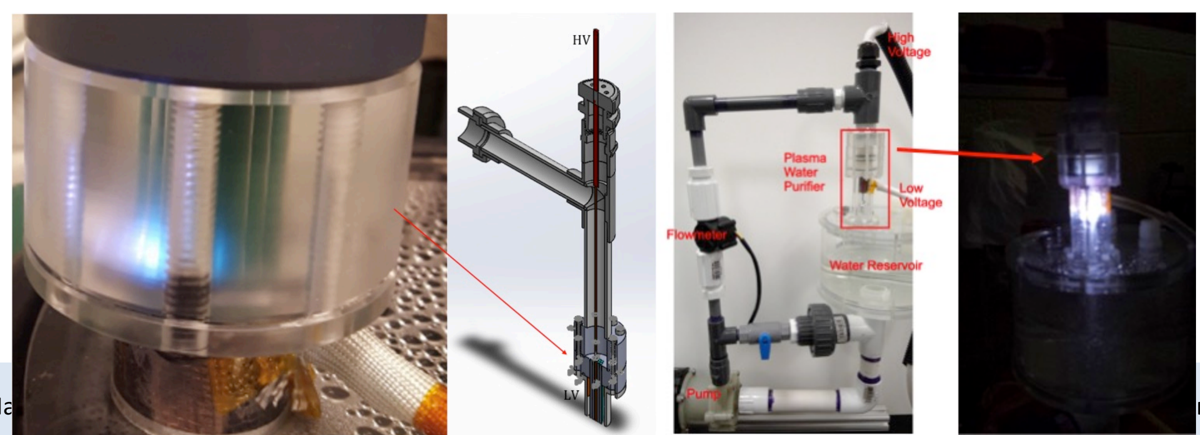
Notes: [a]Reduction criteria for ATWF, including secondary treatment; [b]Addresses *Giardia* and other protozoa as well; [c]Addresses enteric pathogenic bacteria, such as *Salmonella* spp.
Source: Adapted from NWRI (2013)

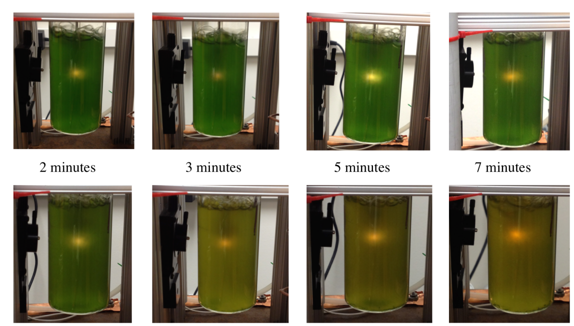
Chemical Type	Example
Industrial chemicals	1,4 dioxane
Steroid hormones	17Beta-estradiol
Pharmaceuticals	Pain relievers

Plasma Reactors for Water Purification

- Two types of reactors have been designed and tested based insight gleaned from prior NSF grant
  - Devices optimize plasma surface interaction without appreciably compromising throughput
  - Reactors can produce controllable peroxide and ozone concentrations levels in solution competitive with conventional systems, which require actual consumables







2 minutes 3 minutes 5 minutes 7 minutes

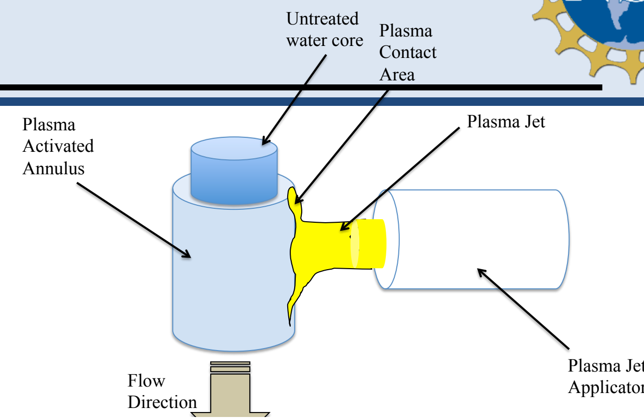
9 minutes 13 minutes 19 minutes 30 minutes

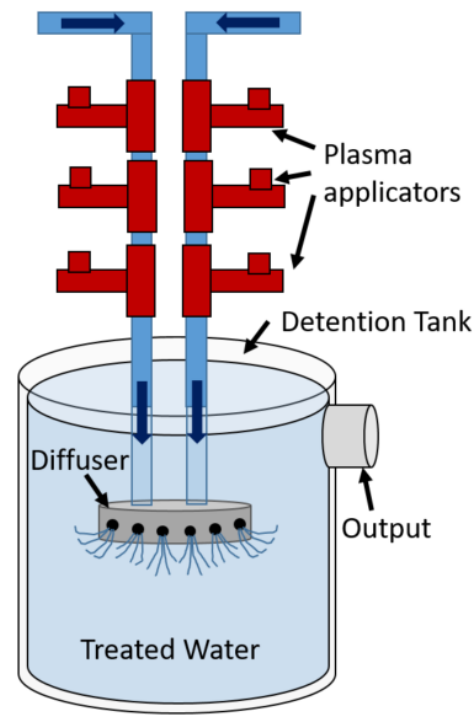
Achieving Scale: Underwater DBD

- **Inline jets can be used in flow through geometries as well.**
  - **Source can be inserted directly into flow to essentially dose passing liquid**
  - **Unsteady bubble tear off disperse longer lived species deeper into the flow**
- **Nature of dosing depends on water quality, water flow rate and plasma power**
- **Batch like mixing can be achieved using an appropriately sized detention tank**
- **Combination of detention with multiple applicators on multiple lines is a pathway to achieving a quasi-batch treatment arrangement**
- **One can estimate the concentration of degraded contaminant C in subsequent stages:** $\frac{dC}{dt} = 0 = C_0 - C - \frac{V}{nQ} \cdot kC$

$$C_n = \frac{C_0}{\left[1 + \frac{V}{nQ} \cdot k\right]^n}$$

in steady state C is constant in a given stage

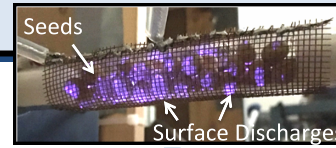




Achieving Scale: Packed Bed Discharge

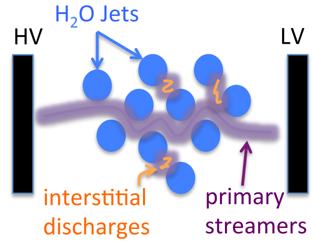
- **Since thin sheets of water are more amenable to dosing, then water can be disposed into a series of thin water streams**
- **Water streams can be treated as leaky dielectrics and thus can be made to operate as a multilayer dielectric barrier discharge (packed bed-like)**
- **Discharge formed in such a geometry would include surface ionization waves and direct stream attachment**
- **Plasma produced at surface and in interstitial space is source of ROS and RNS**
    - **Multi-mode way of dosing water**

Packed Bed Dielectric Barrier Discharge (PBDBD)



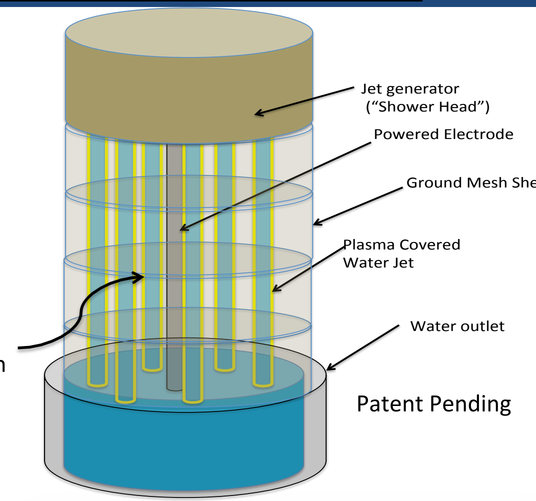
Engeling, 2016

Water Dielectric in Context of PBDBD

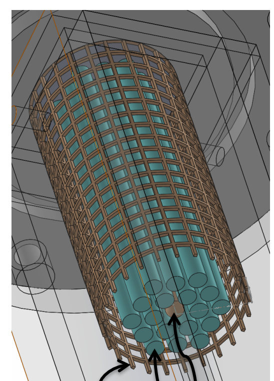


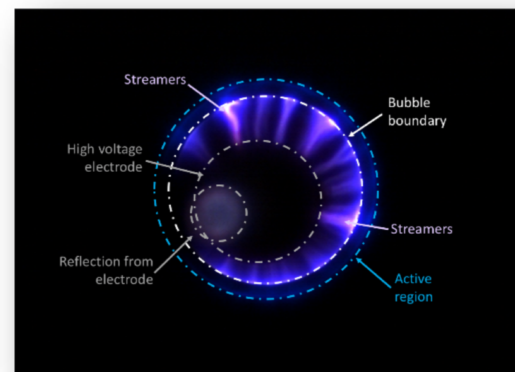
Foster, 2018, JPhysD

Plasma Water Reactor (PWR)



Patent Pending





Evidence of surface ionization waves

The Role of Plasma in the Water Food Energy Nexus