Bipolar Plate Cost and Issues at High Production Rate

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DOE Workshop on Research and Development Needs for Bipolar Plates for PEM Fuel Cell Technologies

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Bipolar Plate (BPP) Presentation Outline

- Overview of Recent Activities
- BPP Cost Breakdown
- Factors that Affect BPP Cost
- Issues and Limitations
  - Forming, Coating, Joining
- Ideal BPP Operation
- GLWN Report Findings
  - Observations
  - Supply Chain Readiness and Potential
  - Actions to Improve Competitiveness

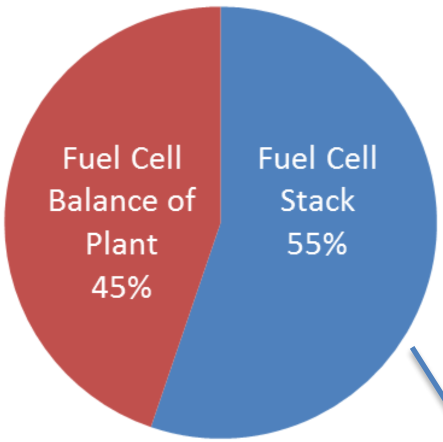
Recent Activities

- Design for Manufacture and Assembly (DFMA) Studies
  - Annual SA reports on 80kWe (auto) and 160kWe (bus) systems
    - Identify a manufacturing process train detailing the specific materials, machinery, labor, utilities, and processing conditions
  - BPP analyses:
    - Forming Metal Plates
      - Progressive Stamping, Conventional Hydroforming, Borit's Hydrogate^{TM} Process (hydroforming)
    - Coating
      - TreadStone Gen 1-3(PVD process), Amorphous Carbon (on Ti & SS), Au Nanoclad
    - Sealing/Joining
      - Laser welding
- Supply Chain & US Competitiveness Analysis
  - Team: GLWN (Prime), SA, E4Tech, DJW Technology
  - 35 interviews with OEMs and Suppliers
  - Report: U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competitiveness Analysis
      - Global Fuel-Cell Trade-flows
      - Supply Chain Evolution
      - Global Component Cost Comparison
      - Global Supply Chain Strategies
      - US Competitiveness Analysis and Suggested Actions

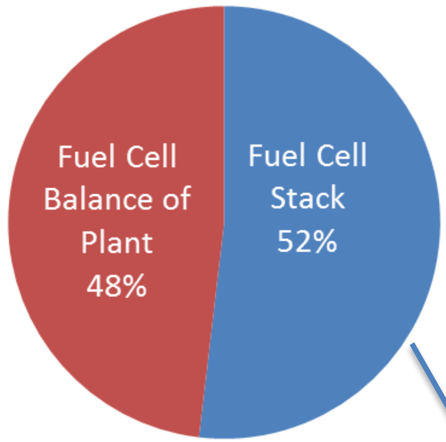
Draft report with DOE for review

Bipolar Plate Cost as Fraction of System Cost

Total $90/kWnet
10,000 Systems/Year



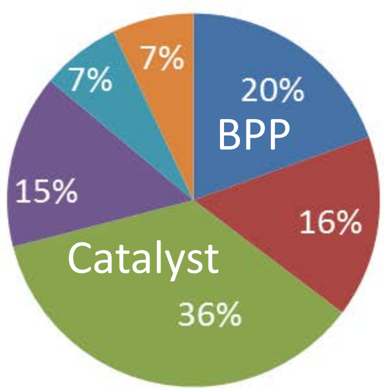
Total $53/kWnet
500,000 Systems/Year



FC System Cost Breakdown

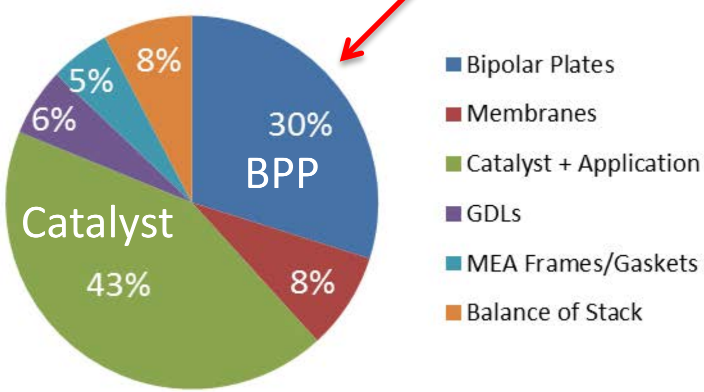
FC Stack Cost Breakdown

10,000 Systems/Year

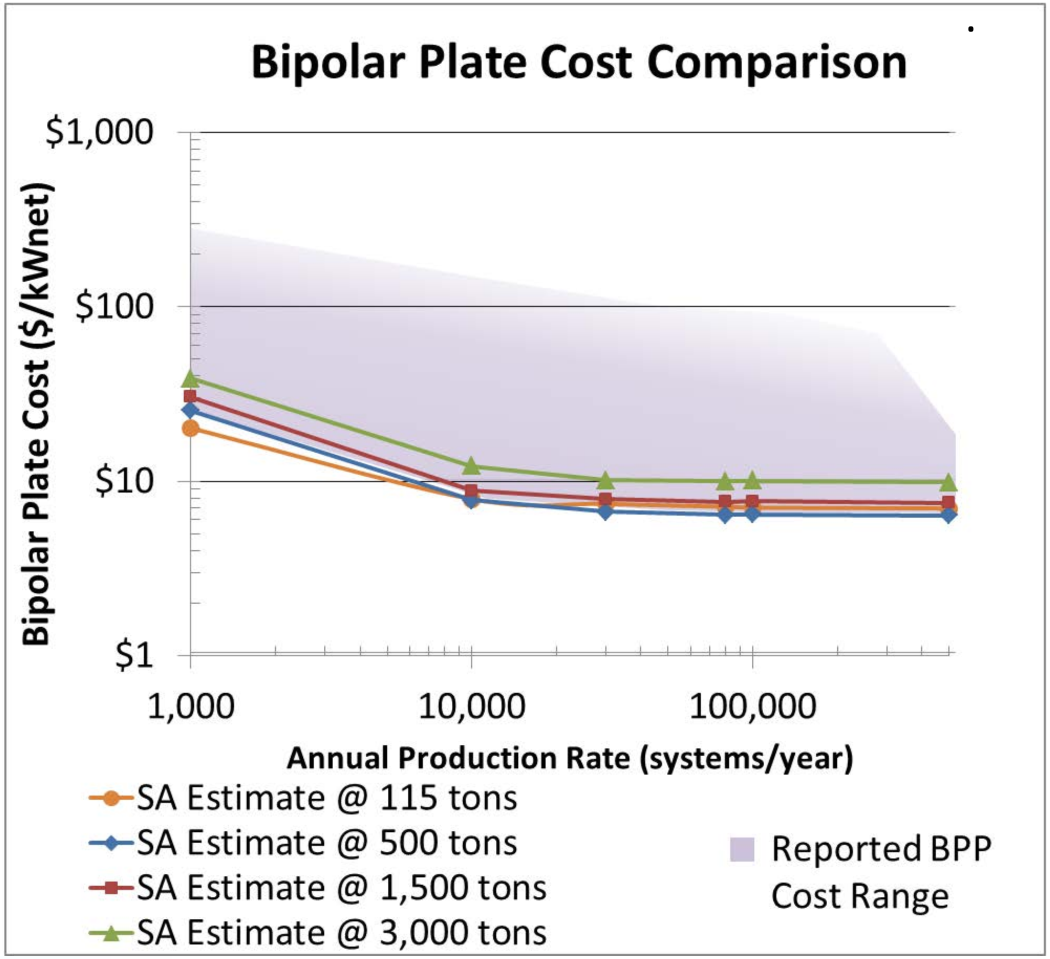


500,000 Systems/Year

BPP Assy. ~$8/kWnet



Wide range in OEM/Supplier BPP Price Estimates



(SA cost estimates for stamped SS316 plates from SA 2015 Cost Analysis Report)

Cost uncertainty may stem from misalignment of reporting:

- Does cost include forming, coating, and joining?
- Does it include gaskets?
- At what production rate?
- Costs quoted in $/kW but at what power density?
- Costs quoted in $/plate but at what plate size an active/total area ratio?
- Per BPP or BPP assembly?

Factors that Affect BPP Cost

- **Forming**
  - **Material**
    - SS316($3.50/kW$_{net}$), SS304, titanium, carbon
  - **Power Density & Active/Total Area Ratio**
  - **Plate Design**
    - Flow Field Design
      - Fine Features (<1mm)
      - Course Features (>2mm)
      - "Fine Mesh" (Toyota)
    - Forming Force (1,000 to 2,000 tons)
      - Cost correlates with force
      - Strokes/min correlates with force
      - Coining vs. Bending
- **Coating**
  - Cycle time
  - Use of precious metals
- **Sealing/Joining (of the two BPP halves)**
  - Cycle time
  - Matching rates with forming and coating
- **Quality Control and Leak Testing**

SA Projected High Volume Process

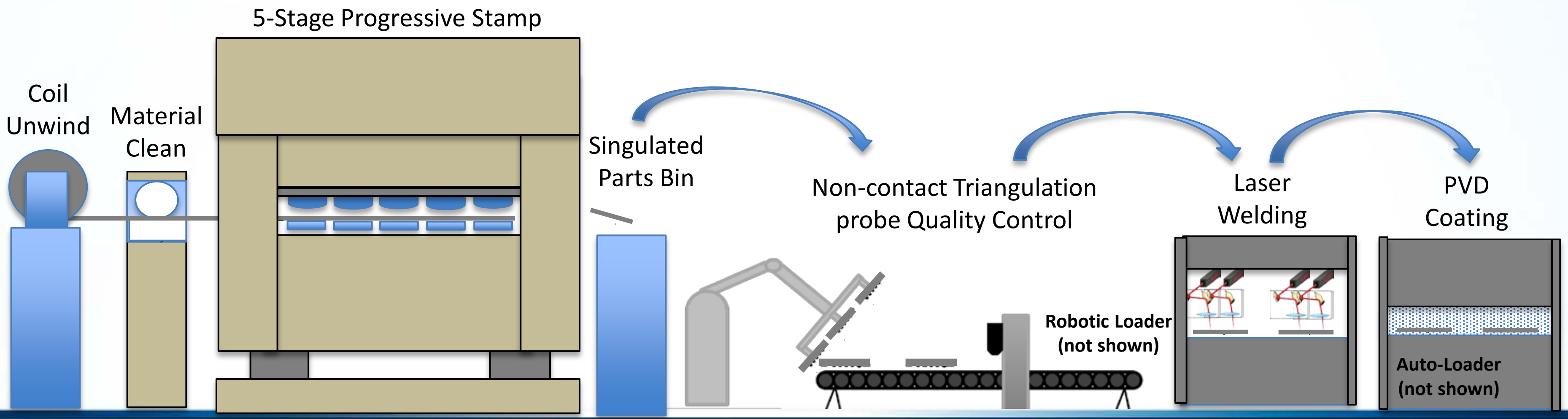
DFMA studies based on:

- SS 316L metal plates
- Progressive die stamping
- Laser welding
- Treadstone PVD coating (outer faces of welded assembly)

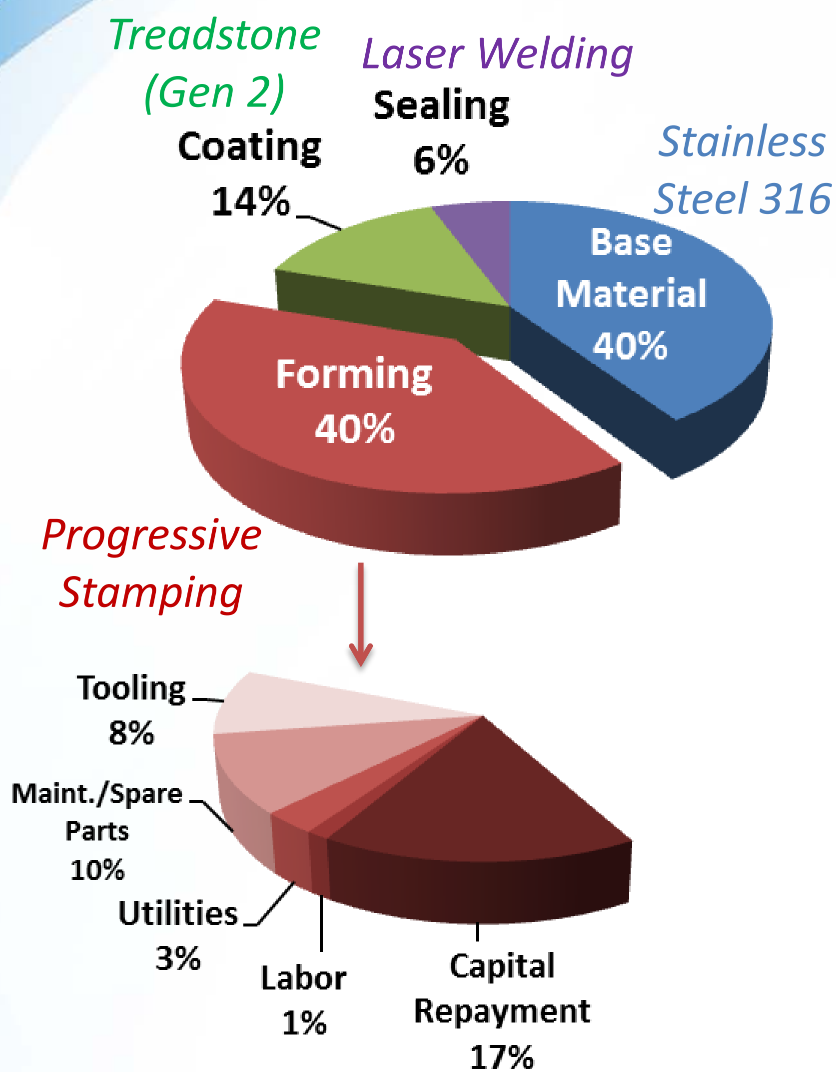
GLWN Study found:

- Metal plates expected to dominate for auto FCVs
- Europe leads in BPP technology
- Coatings can be pre or post forming
- Laser welding most prevalent
  - Toyota is exception
- Concerns about welding and coating times and costs

SA's Baseline BPP Manufacturing Process Steps



SA Projected High Volume Cost Estimate



This is unsatisfactory. Need a faster process!

2016 Baseline Estimate

- 380M Plates/year (500k vehicles/year)
- 110 simultaneous processing lines needed for forming (30 lines if 24/7, no roll change-out time)
- Materials/manufacturing only (no markup included in estimate)
- $8/kWnet, ~30% of FC stack cost
- ~$3.40/kWnet (stamping only)

GLWN Project Interviewees report that parallel production lines are undesirable/unacceptable due to quality control concerns.

Stamping vs. Hydrogate Parameters

	SA Baseline (5-stage Progressive Die Stamping)	Borit Hydrogate
Plate Active Area	312 cm^2	312 cm^2
Plate Total Area	500 cm^2	500 cm^2
Plates per stamp	1	4
BPP Forming Force	16,000kN or 1,600 tons	41,200 kN or 4,200 tons (2,000 bar over active area)
Plate Material	316SS, 3 mils	316SS, 3 mils
Forming Machine Capital Cost	\$1.8M (Prog. Stamp) \$2.1M total system	\$1M (Hydrogate) \$89k (Cutting Press) \$1.2M total system
Forming Rate	2.47sec per plate	7.5 sec per 4 plates (1.88 sec/plate)
Labor	0.25 workers per press (min)	0.25 workers per press (min) (oversees Hydrogate & stamping)
Stamping Die Set Lifetime	10M cycles	10M cycles (Cutting die)
Stamping Die Set Cost	\$662k	\$100k (Cutting die)
Hydrogate Die Set Lifetime	Not applicable	10M cycles
Hydrogate Die Cost	Not applicable	\$60k

Issues and Limitations with Current Forming Methods

- Progressive Stamping
  - Difficult to maintain flatness for laser welding
  - +/-5µm tolerances (possibly requiring temp controlled room)
  - More complex flow fields require higher press force
    - Slower cycle time (2.5 sec/plate)
    - Higher capital cost (~ $1k/ton)
  - High tooling cost (>$600k, 1,000s of hours to fabricate)
  - High # of simultaneous lines to meet capacity (100+)
  - BPP geometry limited by wall thinning issue
- Hydroforming
  - Must form more than 4 parts simultaneously to meet capacity (70+ lines for 4 parts/form)
  - Requires extra stamping to cut manifold holes and parts separation

GLWN project reports that only a few worldwide companies have capacity to be credible high-volume BPP supplier to OEM

Suppliers voice a concern

Multiple parts per operation appears to be key step in improving cost and cycle time

Coating of Metal Bipolar Plate

Coating

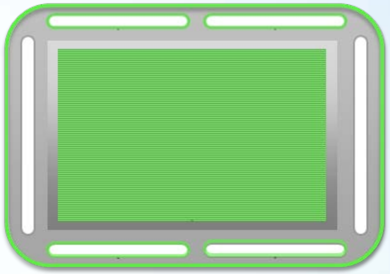
- **Two Purposes**
  - Increase Conductivity
  - Anti-Corrosion
- **Approaches**
  - Sub-Atmospheric/Vacuum Deposition
    - TreadStone Gen 1-3 (PVD process)
    - ImpactCoating (PVD)
    - PECVD Amorphous Carbon (on Ti plates for Toyota)
  - Atmospheric Deposition
    - Nitriding (ORNL)
  - Special alloys
    - Custom alloys with innate corrosion resistance
  - Liquid processes
    - Pickling
    - Polymer Matrix (Dana Reinz patents*)
  - Others ?

Issues

- **Cycle time**
  - ~2- 30 minutes
- **Batch vs. Continuous**
  - Parts per batch
    - a few to 100's of parts
  - Can process be continuous?
- **Sputtering Targets**
  - Can add surprising amount of cost (beyond material price)

* US Patent 8,053,141 B2 (2011),
DE Patent Application 10235598 A1 (2002),
DE Patent Grant 10235598 B4 (2005)

Metal BPP Joining Issues



- **Laser Welding**
  - Welding length
    - Perimeter & around manifold holes
    - Portion of active area (to connect BPPs for electrical contact)
  - Welding speed can be high (7-80 meters per min)
  - But total on-beam time still 0.2-5 min per BPP assembly
  - **Engineering solutions can be developed**
    - Multiple plates per station
    - Multiple stations
    - Multiple lasers per station
    - Multiple galvos per laser

Effective cycle time can be ~2 seconds per BPP assembly

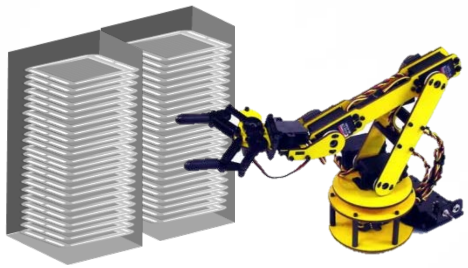
- **Adhesives**
  - Practiced by Toyota/Mirai
  - Seals can fail (more frequently than welding)
  - Can be done R2R before part singulation
  - R2R can be very fast

Effective cycle time can be <2 seconds (at 20m/min.)

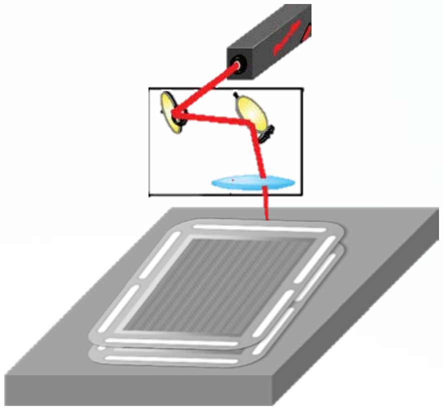
Laser Welding Considerations

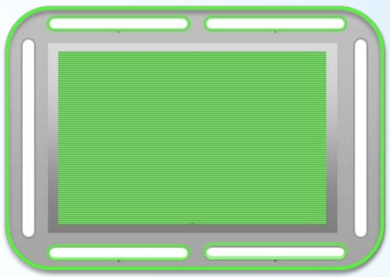
Low Volume Scenario

Stamped individual anode/cathode BPPs stacked in magazine



Pick-and-Place robot picks up and orientates anode and cathode BPPs into welding single fixture, then removes after welding.
(20 seconds)



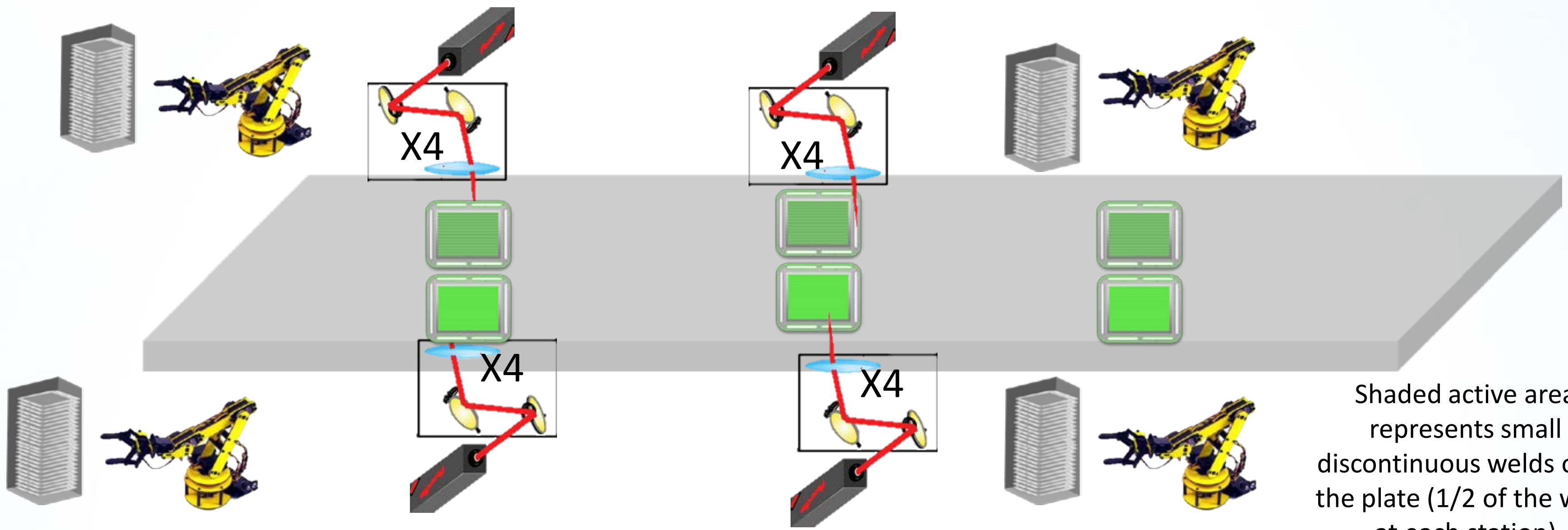


Manifold and perimeter welding time: ~30sec
Active Area Flow field welding time: 35sec
(for 5% of the flow field length)

High Volume Scenario

Welding Station #1

Welding Station #2



Shaded active area represents small discontinuous welds over the plate (1/2 of the weld at each station)

2 stations each with 2 plates, 2 lasers, and 4 galvos/laser to progressively weld the plates
Effective welding time: 1.8sec/station + index time 2.5s/station => total 4.3s/ two plates =>2.2s/welded plate assembly

Ideal BPP Fabrication

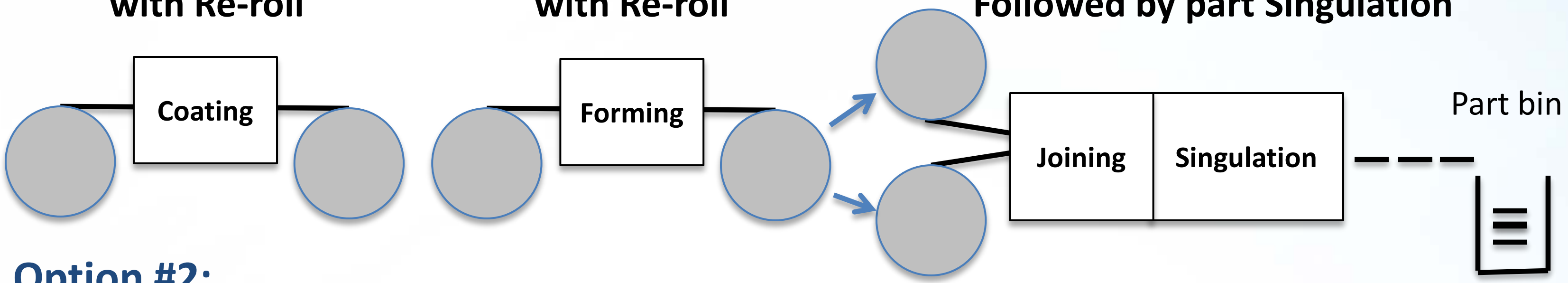
(inspired by Nissan concept)

Option #1:

Coating from Coil with Re-roll

Forming from Coil with Re-roll

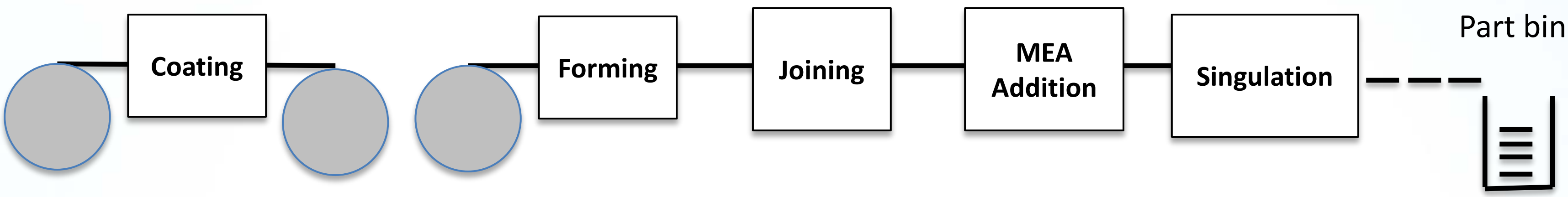
Joining from Coil Followed by part Singulation



Option #2:

Coating from Coil with Re-roll

Forming/Joining/MEA-Addition/Sing. All on Continuous Line



Key Points:

1) Delay singulation as long as possible.
2) Re-roll of formed plates would be an enabling technology.
3) Flow-field formation on the MEA would be an enabling technology.
4) R2R creation of a unitized cell (BPP plus MEA) would be an enabling technology.
5) Numerous configurations are possible.

Required Line Speed to Achieve 500k systems/yr

- Ideal line speed for BPP roll-to-roll processing and assembly
  - 380M parts/yr at 6,000 hrs/yr* and 10 lines =>0.57sec/part
  - Lines speed for single-wide BPP line =>26cm x 19cm (down length)
    - (0.19m/part) / (0.57s/part) = 0.33m/s or **~20m/min**
  - Line speed for double-wide BPP line => 52cm x 19cm (down length)
    - (0.19m/part) / (1.14s/2 parts) = 0.167m/s or **~10m/min**

For 10 lines: Required line speed is ~10-20 m/minute.

For 1 line: Required line speed is ~100-200 m/minute.

* Assumes high utilization: 20 h/day, 300 days/year.

(Draft) Bipolar Plate Observations

(Consensus comments from interviewees)

- **Bipolar plates will likely be supplied as welded and coated assemblies**
  - Gaskets/seals were not included as a key component but were noted as a significant challenge and cost item during interviews
  - Gaskets can be included on bipolar plate assembly or as a separate framed MEA with sub-gasket
- **3-5 suppliers worldwide are currently capable of producing bipolar plates with the quality and reliability required by OEMs at high volume**
  - While stamping and welding technology is (in many ways) mature, achieving the required precision, quality control, and volume production dramatically limits the number of suppliers
  - New production houses can be developed but it will require years to establish themselves as viable automotive suppliers
- **Factory likely to be sited near stack integrator/OEM at high volume**
  - At high volume, labor is not a cost driver
  - However, shipping costs are very low
  - Coating and forming/welding are different competencies, so these two operations may be separated

(Draft) Actions to Improve Competitiveness

High Priority Manufacturing Opportunities (generally applied research)

Opportunity #5: Development of (near-)continuous, high-speed process for BPP fabrication

- Sequential, roll-to-roll formation, coating, and joining of BPP assemblies
- Delay of part singulation so as to minimize part handling
- Develop processes capable of <1 sec per plate processing time (~3m^2/min (based on total plate area))

Opportunity #6: Program to characterize and assess the problem of thinning of metal in BPP

- Investigate limitation of conventional sheet metal stamping due to metal elongation limits and thinning issues.

Opportunity #7: Development of alternate forming techniques that solve the metal thinning limitations of conventional stamping.

- Identify/Devise solutions to these limits so as to enable advanced BPP designs consistent with expected future stack performance (high power density, improved water management, low-pressure drop, low stoichiometric flow rates, etc.).

Manufacturing R&D/Demonstrations

Opportunity #8: Demonstration of high-speed, high accuracy, geometry-neutral fuel cell stacking system

- Equipment is needed by all vendors
- Provides quality control at high processing rates.

Opportunity #9: Demonstration of low-cost, high-speed, high-accuracy, geometry-neutral BPP welding systems

- Equipment is needed by multiple vendors.
- Current systems are costly due to low welding and indexing speeds.
- Desired system would leverage existing U.S. capabilities in welding and system automation to develop high-speed, high-accuracy automated systems that could be used by any fuel cell vendor.

Thank you.

Questions?