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ME 481 FDP:
"The Design of a Polymer Electrolyte Membrane (PEM) Fuel Cell."

Design Objective:

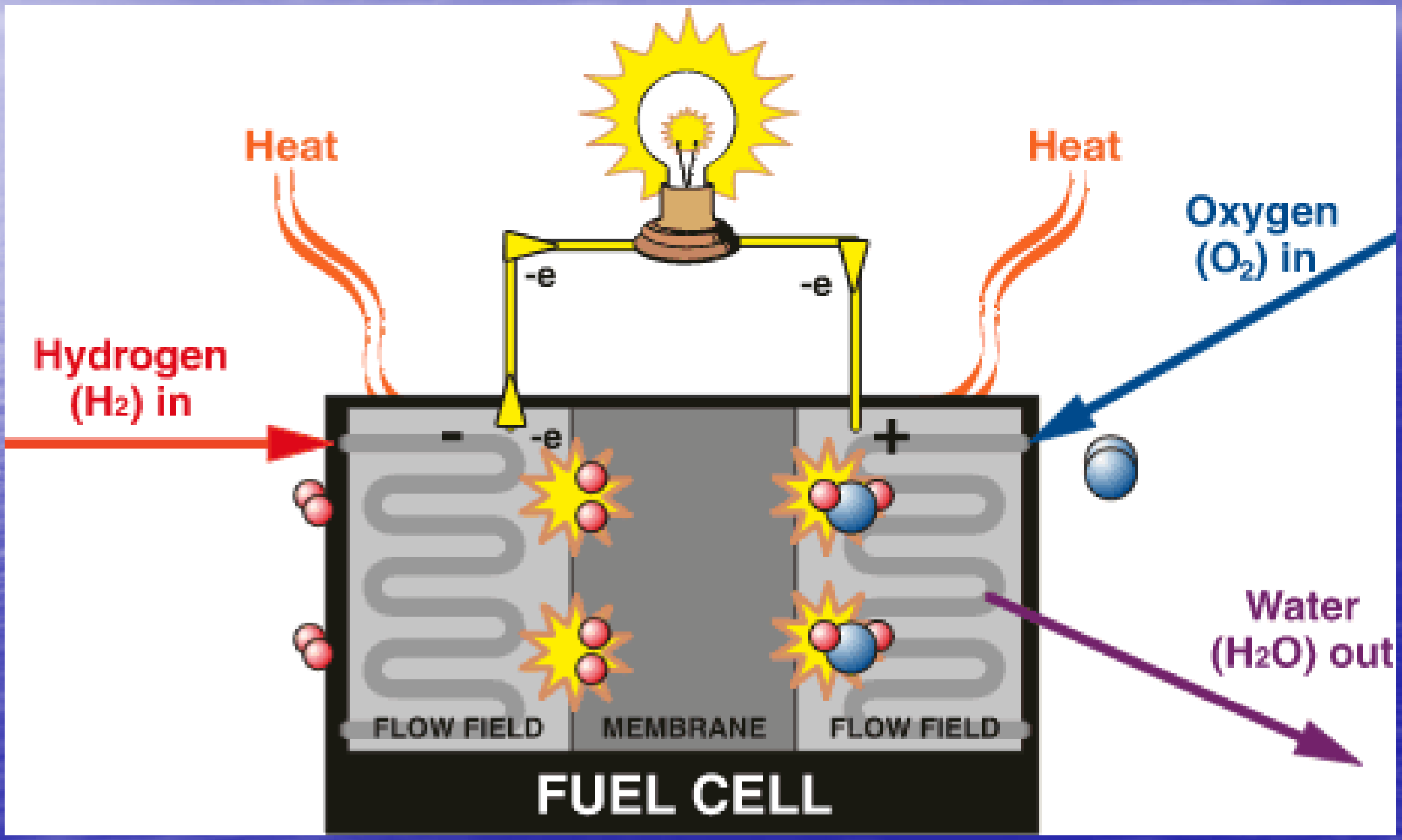
- *A 100 cm^2 active area PEM fuel cell must be designed and built.*
- *The project objective is to design and build a fuel cell that is fully functional and not necessarily fully optimal.*

The Design Purpose

To equip UW undergraduate engineering students with:

- Education
- Experience
- Employment

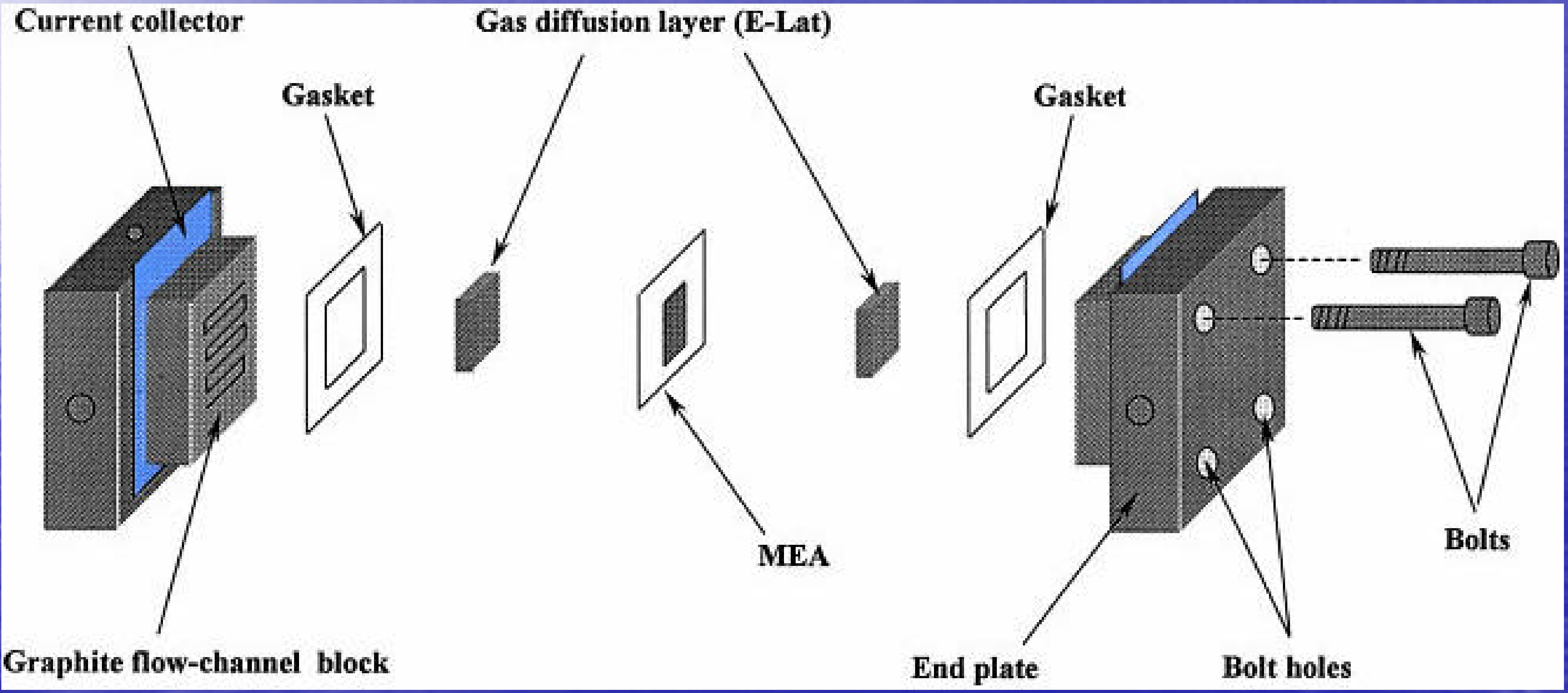
The Design Process



Design Constraints

- Built at University of Waterloo
- Cost of less than $2600 USD + MEA
- 100 cm^2 active area MEA
- Maintained at 80°C
- Should not operate > 100°C
- Form of alignment
- Durable

Deliverables: Exploded view



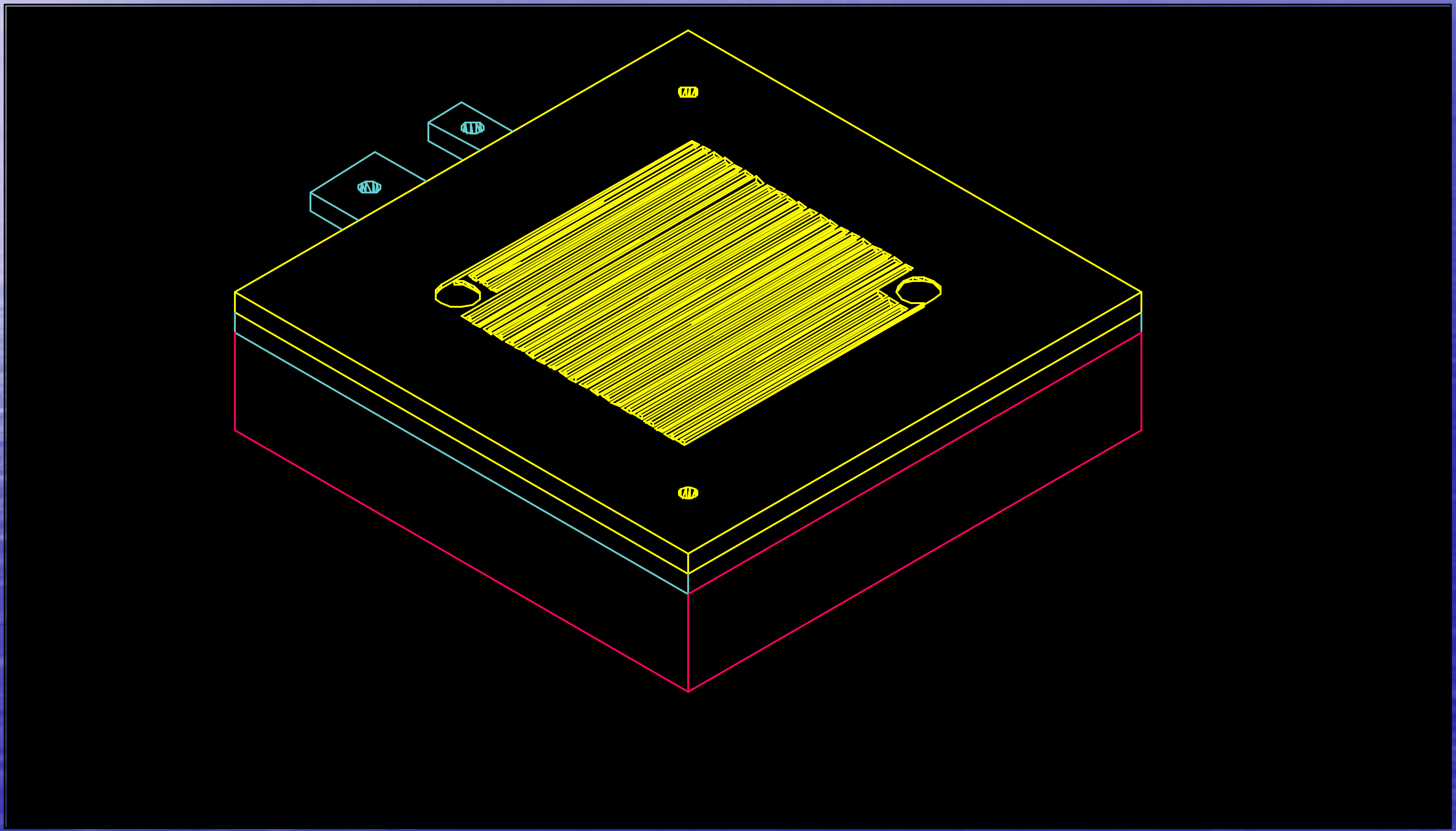
Design Approach

1. Optimize each individual sub-design within the fuel cell
2. Analyze the compatibility of sub-designs:
   - Will it function?
   - Cost
   - Flow characteristics
   - Thermal compatibility and compressibility
   - Pressure loss
3. If incompatible, go back to (1) and determine where a suitable compromise can be made
4. If fully compatible, final design is completed

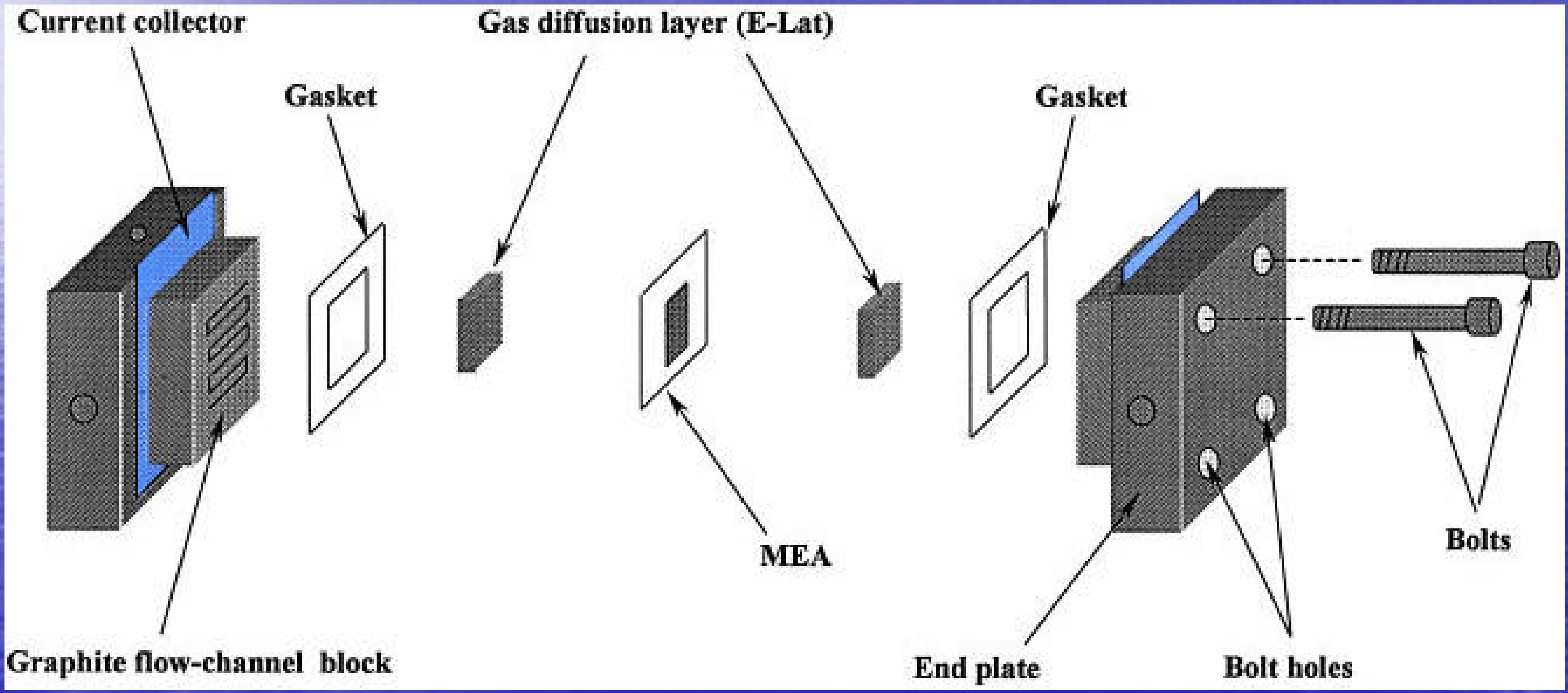
SHAPE & SIZE

- Constrained by 10 cm x 10 cm active area
- Use typical square shape
- Use minimal amount of material
  - Cost
  - Contact pressure
- Make 17 cm x 17 cm overall cell

SHAPE & SIZE



END CAP



Current collector
Gas diffusion layer (E-Lat)
Gasket
Gasket
MEA
Bolts
Graphite flow-channel block
End plate
Bolt holes

END CAP

Aluminum or Stainless Steel

Criteria:

- Structurally stable
- Ease of fabrication
- Low cost
- Suitable size and thickness

END CAP

Aluminum

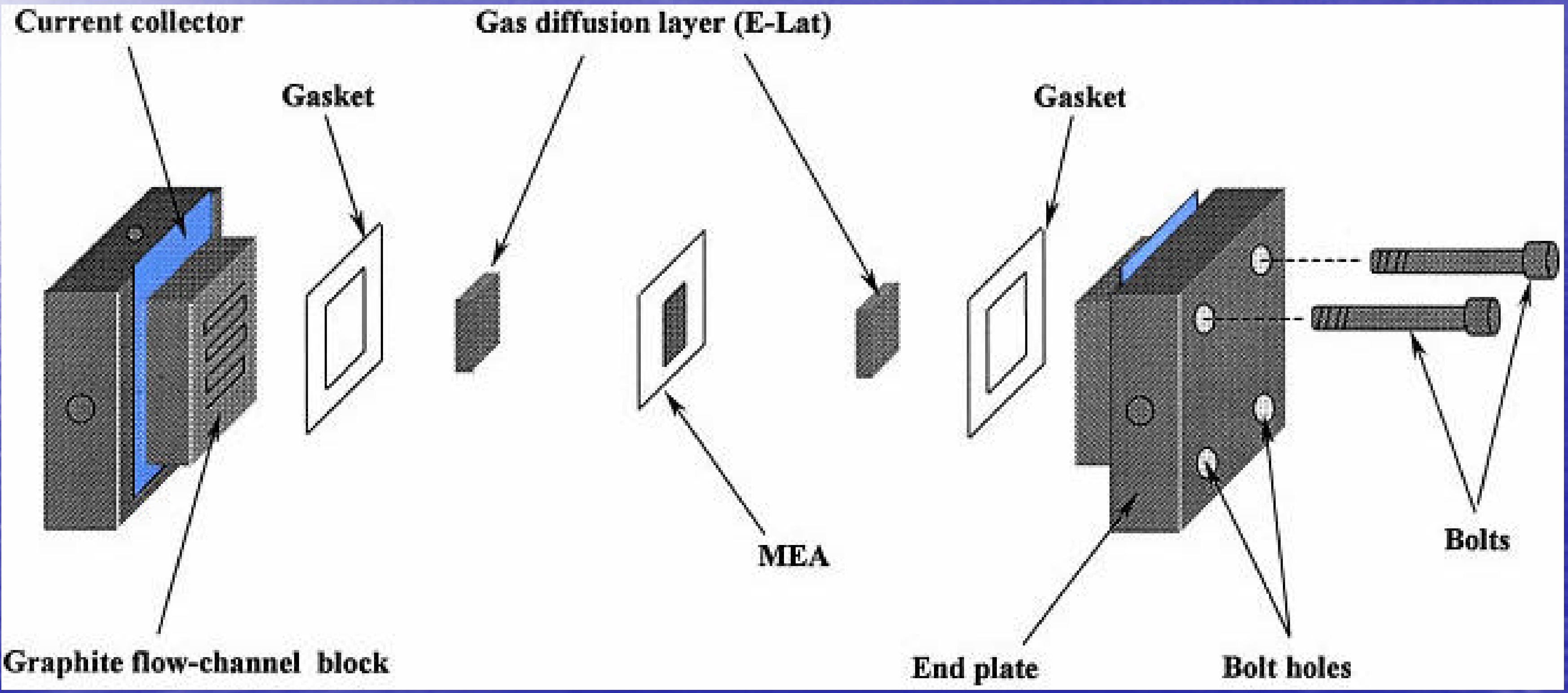
17 cm x 17 cm x 1.25” = $27-$30

304 Stainless steel

17 cm x 17 cm x 1.25” = $26

Purchased outside of school

CURRENT COLLECTORS



CURRENT COLLECTORS

Copper, Brass, or Gold-plated S.S.

Criteria:

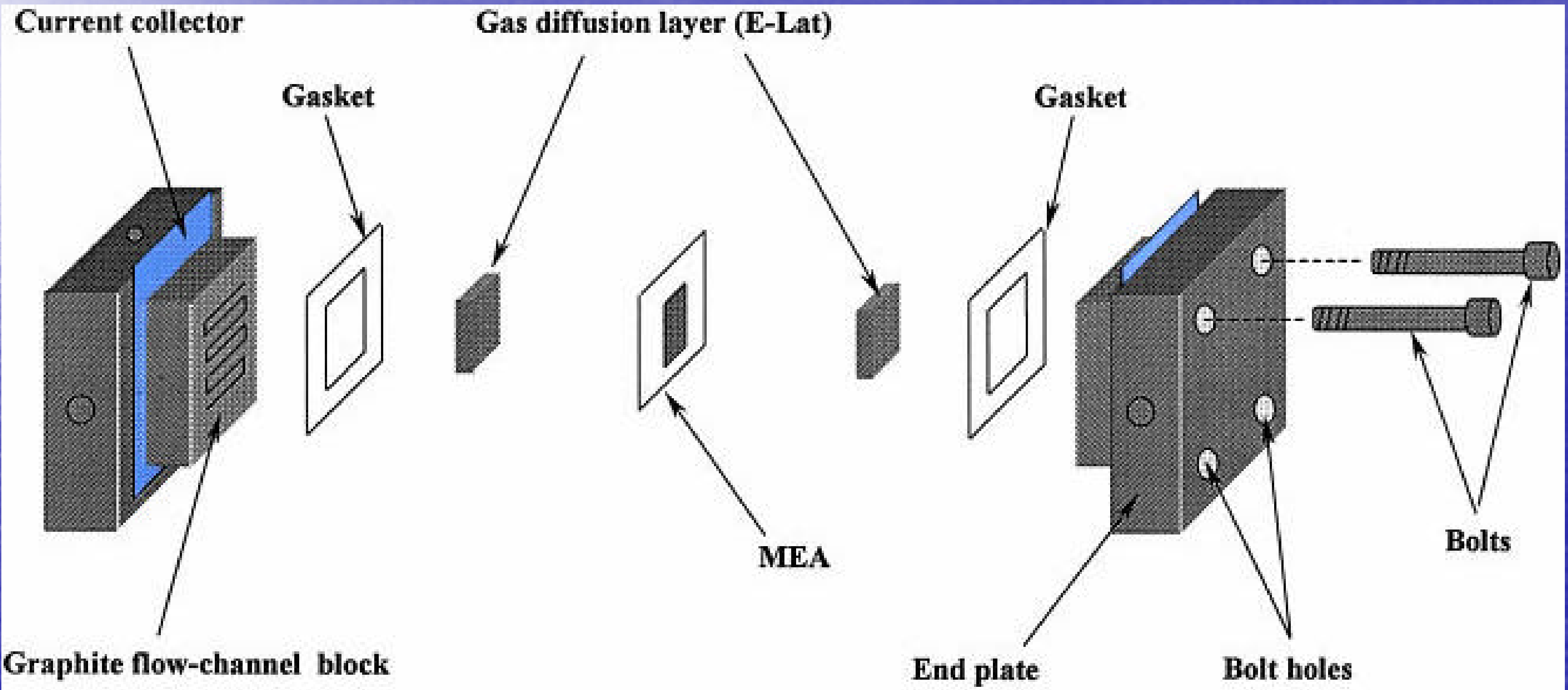
- High conductivity
- Ease of manufacture
- Ease of building a connector
- Low cost

Electrical Conductivity

Material:	**Electrical Conductivity (% IACS)**
Aluminum alloys (68-212ºF)	27 – 61%
300 stainless steels (32-212ºF)	2.3 – 2.5%
Brass	12 – 37%
Graphite	0.22%
Copper (68-572ºF)	100%

Cost → approx. $100 for brass, copper

FLOW FIELD PLATES



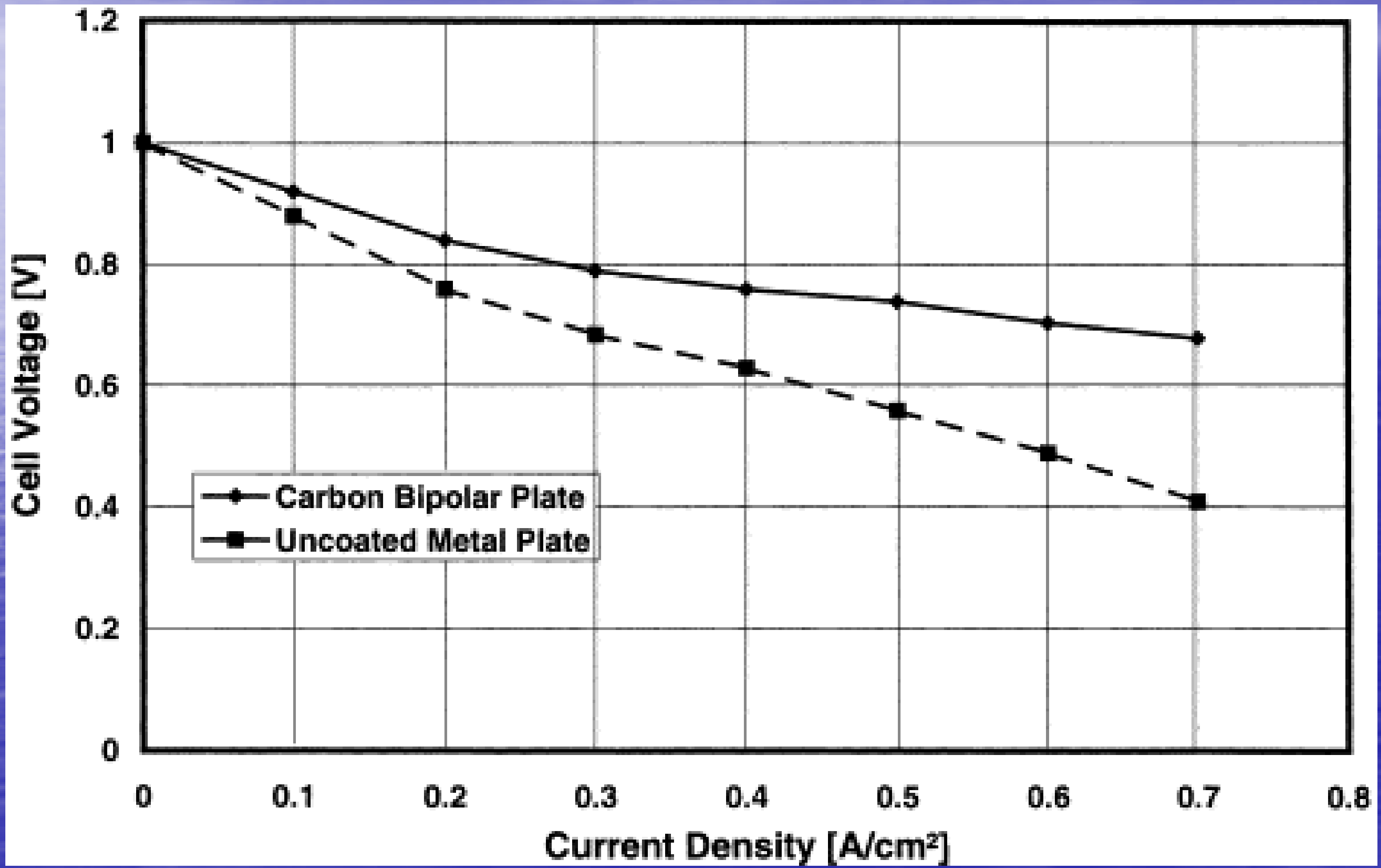
FLOW FIELD PLATES

Graphite, Stainless Steel, or Coated S.S.

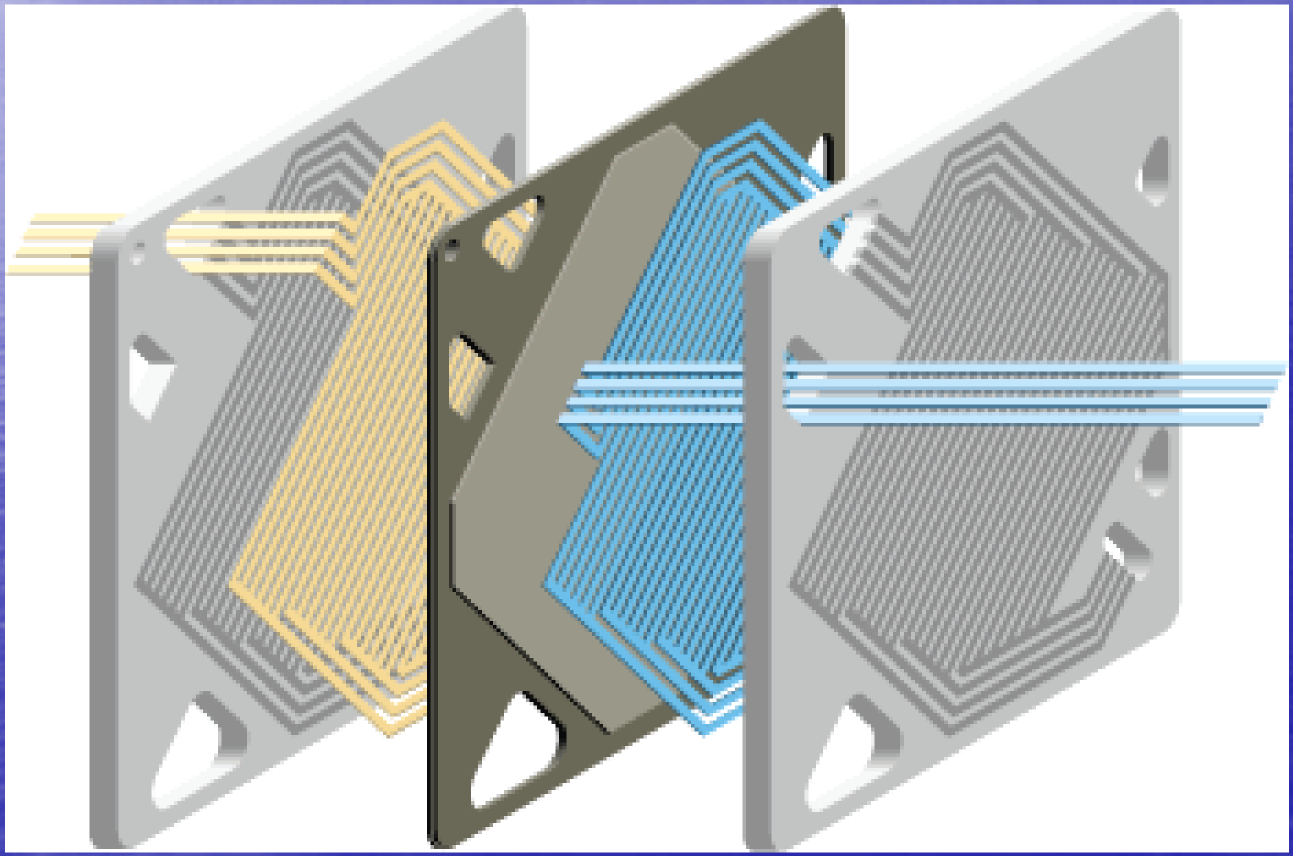
Criteria:

- High conductivity
- Impermeable
- Suitable thickness
- Suitable size
- Distribution of reactants
- Machinability
- Corrosion-resistant
- Low cost
- Ease of fabrication

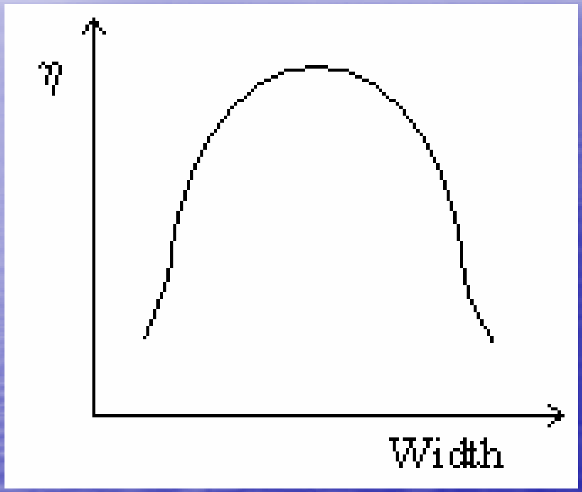
FLOW FIELD PLATES

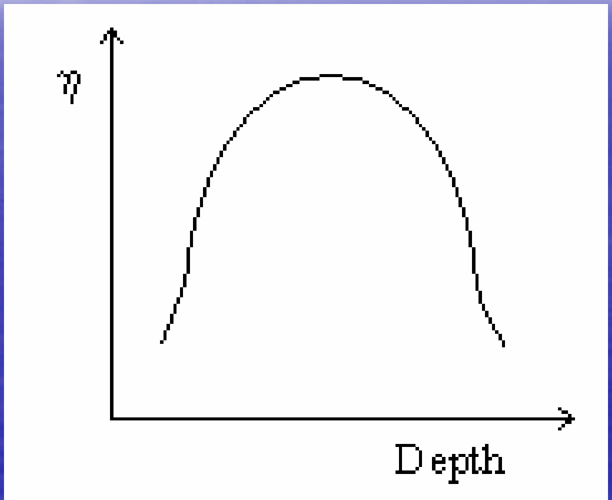


The Flow Field Channels



FLOW FIELD CHANNELS





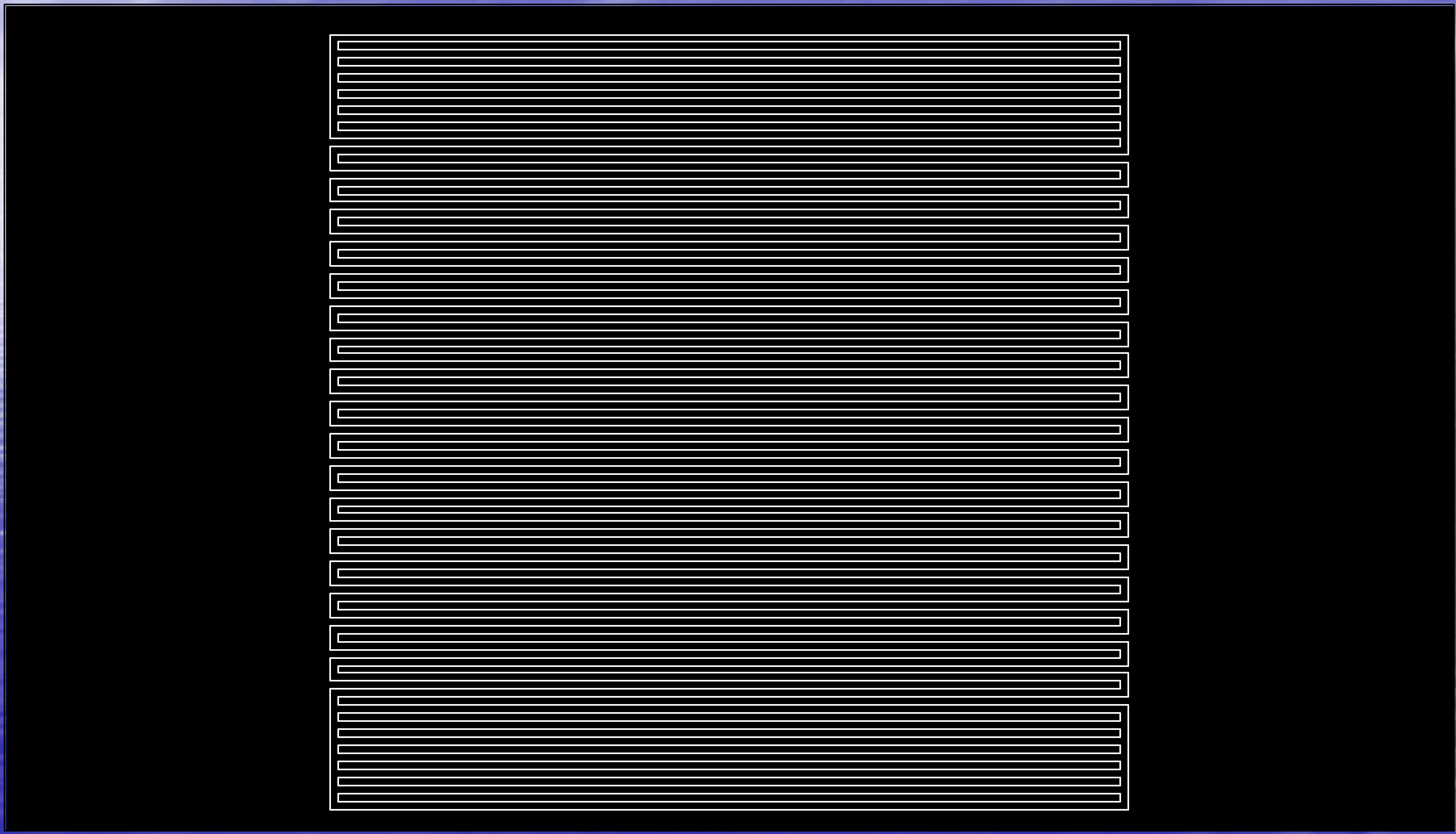
- Increasing # channels → increases pressure loss
- Flow channels too wide → GDL swells and blocks flow
- Flow channels too deep → inefficient
- Optimize? → Through experiments

FLOW FIELD CHANNELS

- E. Hontanon from Madrid, Spain
  - "Fuel consumption increases when decreasing the width"
  - "Channels narrower than 1 mm are not viable in practice"
- Watkins et al.

  - "Optimum width for ridges and gas channels ranges are from 0.89-1.4 mm and from 1.14-1.4 mm, respectively, and the optimum depth for gas channels is between 1.02-2.04 mm"
- Test cell in lab uses 1 mm x 1 mm
- Professor X. Li
  - "It will work."

FLOW FIELD CHANNELS



Flooding Not Required

Half Reaction: $H_2 \rightarrow 2H^+ + 2e^-$

For an 83.3% utilization rate of hydrogen (stoichiometric ratio of 1.2:1):

(using Faraday's, since 1 A = 1 C/s)

$$n_{H2} = (100.0\ \text{A})\left(\frac{1\ \text{coulomb/sec}}{1\ \text{A}}\right)\left(\frac{1\ \text{equivalence of } e^-}{96{,}487\ \text{coulombs}}\right)\left(\frac{1\ \text{g mol } H_2}{2\ \text{equiv. of } e^-}\right)\left(\frac{100\ \text{g mol } H_2 \text{supplied}}{83.3\ \text{g mol } H_2\ \text{consumed}}\right) = 6.22\ \text{E-4}\ \frac{\text{g mol}}{\text{sec}}\ H_2$$

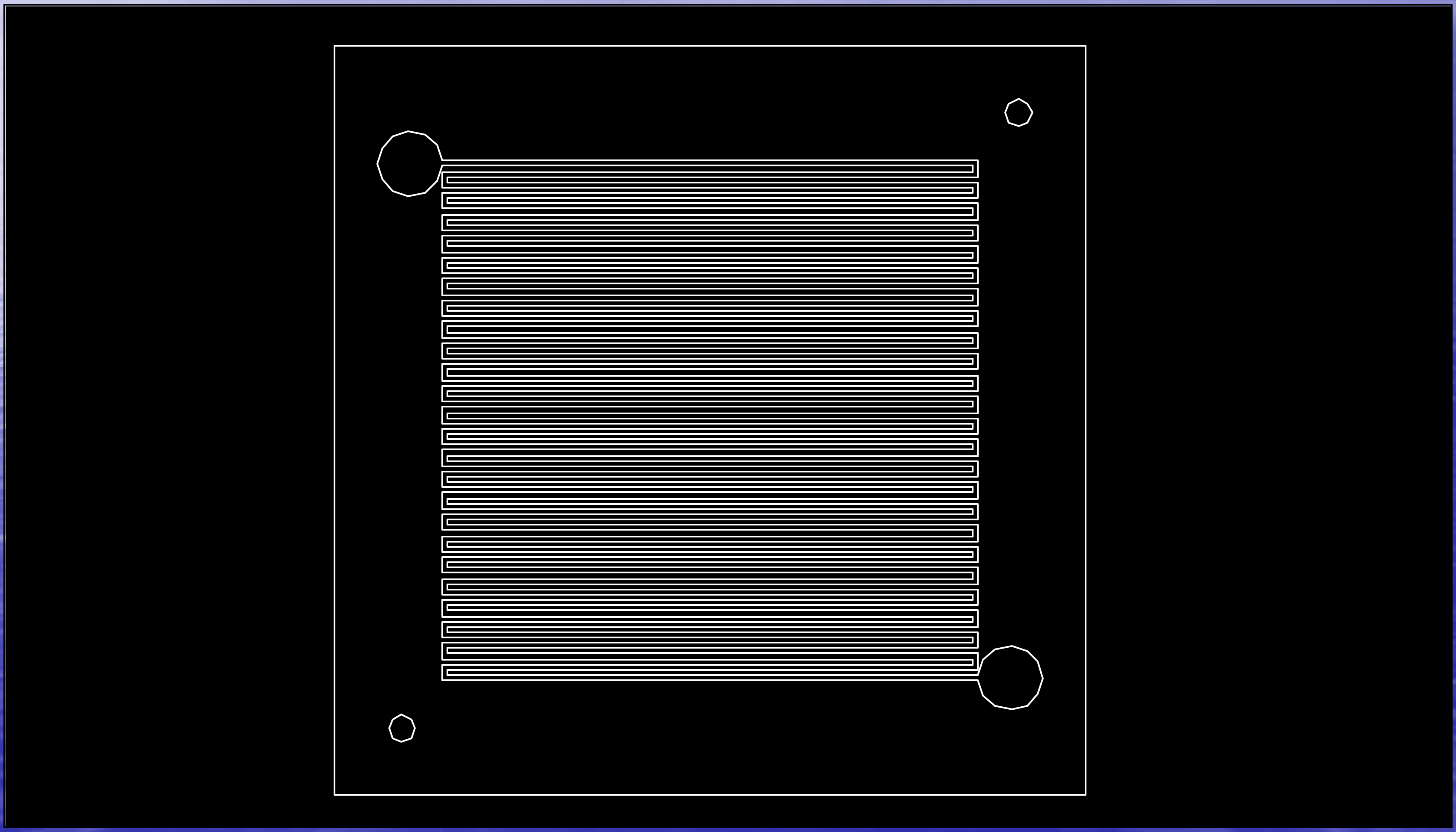
$$m_{H2} = \left(6.22\ \text{E-4}\ \frac{\text{g mol}}{\text{sec}}\ H_2\right)\left(\frac{2.0158\ \text{g}}{1\ \text{g mol } H_2}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 1.25\ \text{E-6}\ \frac{\text{kg}}{\text{sec}}\ H_2$$

$$m_{H2O} = \left(6.22\ \text{E-4}\ \frac{\text{g mol}}{\text{sec}}\ \text{H2O}\right)\left(\frac{18.01\ \text{g}}{1\ \text{g mol H2O}}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 1.12\ \text{E-5}\ \frac{\text{kg}}{\text{sec}}\ \text{H2}$$

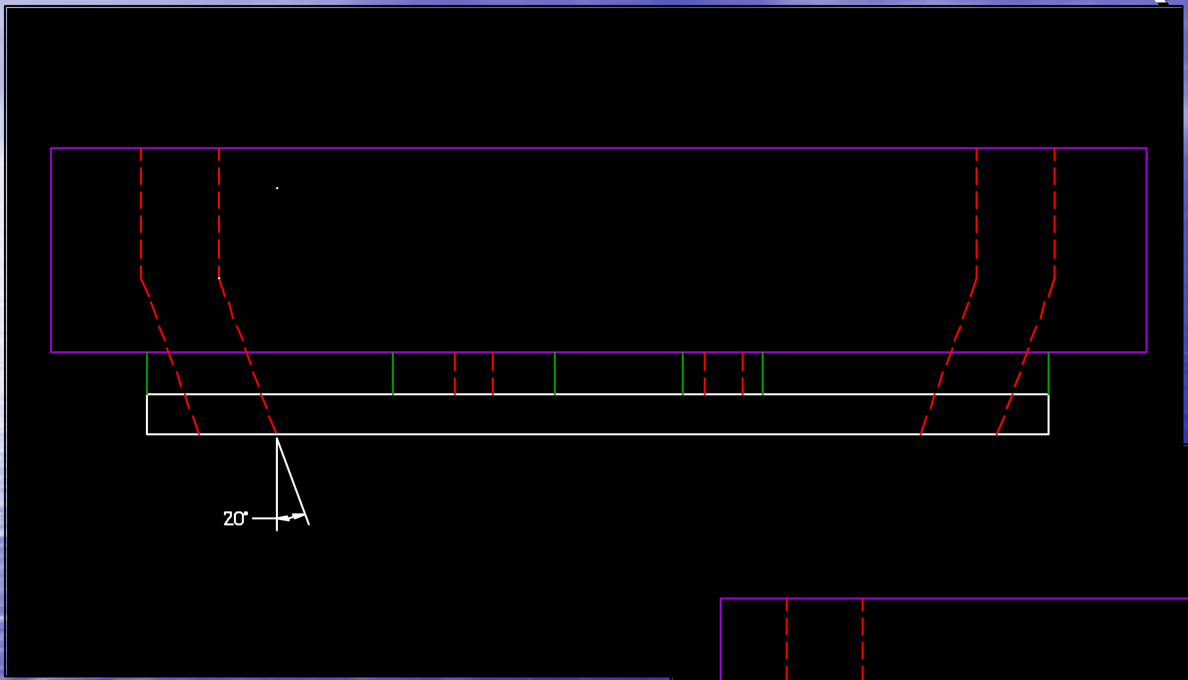
For a 50% utilization rate of oxygen (stoichiometric ratio 2:1):

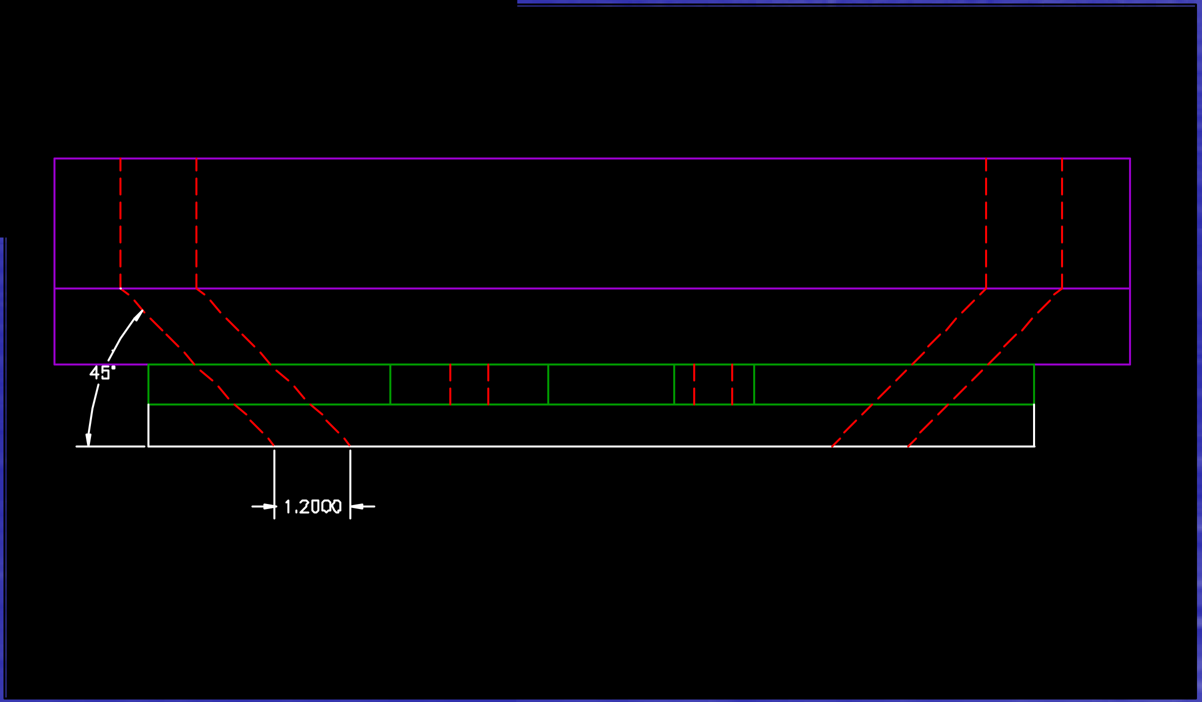
$$m_{air} = \left(2.99\ \text{E-3}\ \frac{\text{g mol}}{\text{sec}}\ \text{wet air}\right)\left(\frac{28.74\ \text{g}}{1\ \text{g mol wet air}}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 8.60\ \text{E-5}\ \frac{\text{kg}}{\text{sec}}\ \text{air}$$

FLOW FIELD INLET (A)

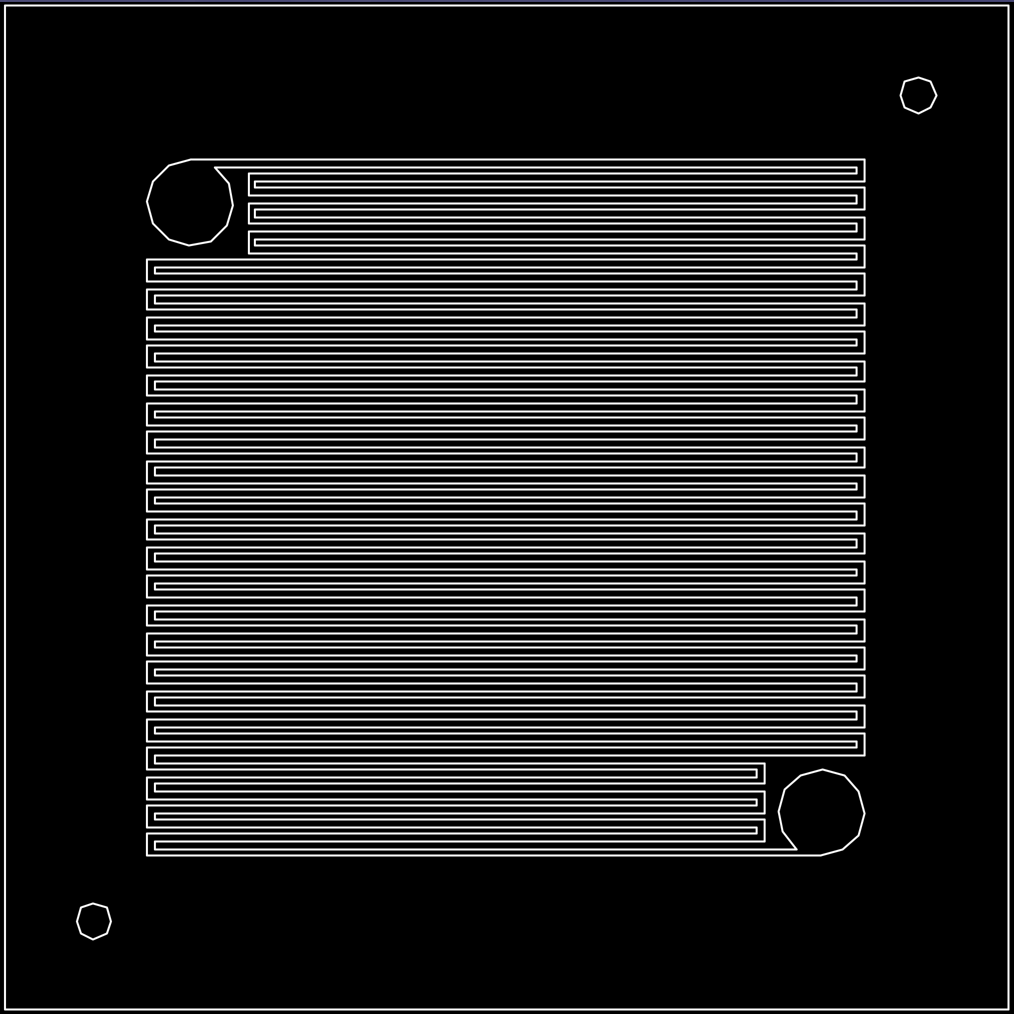


FLOW FIELD INLET (B) & (C)





FLOW FIELD INLET (D)



Force on the membrane

Anode side $F = m'_{H2}\, v = (1.25\ E\text{-}6\ kg/s)(0.64\ m/s) = 8.00\ E\text{-}7\ N$

Cathode side $F = m'_{air}\, v = (8.60\ E\text{-}5\ kg/s)(3.06\ m/s) = 2.63\ E\text{-}4\ N$

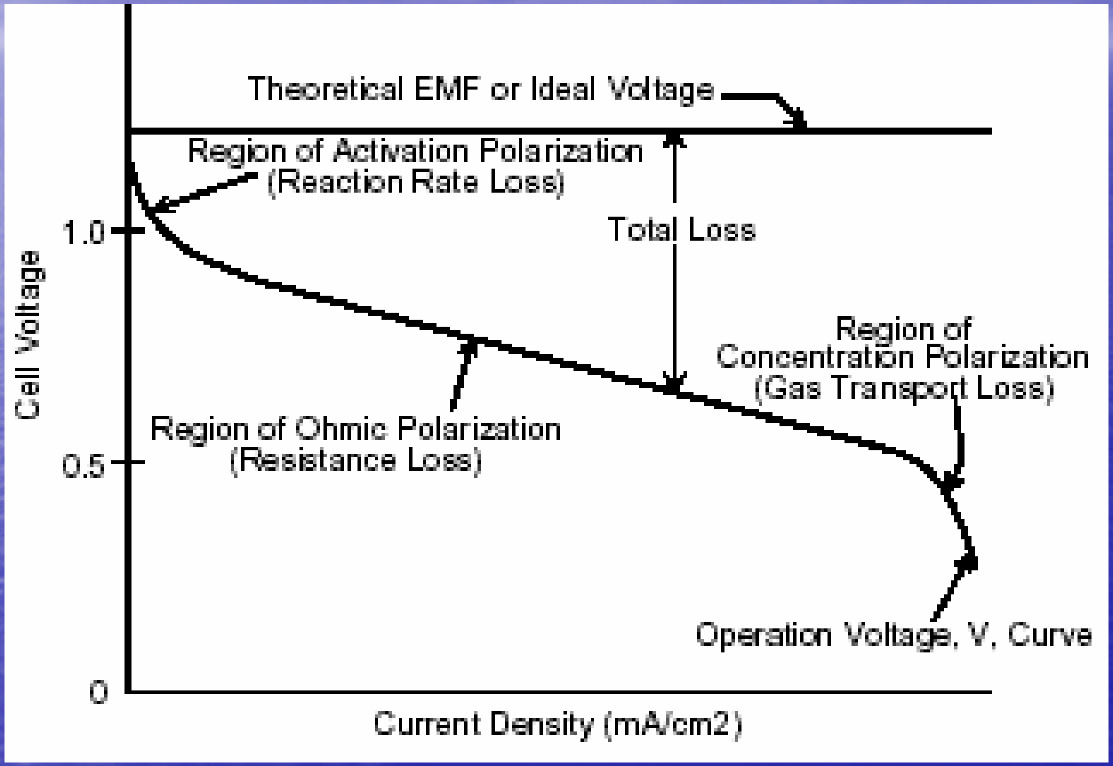
Anode side $F / [\pi(D/4)^2] = (8.00\ E\text{-}7\ N)/(28.27\ mm^2) = 2.80\ E\text{-}8\ N/mm^2$

Cathode side $F / [\pi(D/4)^2] = (2.63\ E\text{-}4\ N)/(28.27\ mm^2) = 9.30\ E\text{-}6\ N/mm^2$

The tear strength of Teflon is 29-39 N/mm^2 at 23ºC and 14-20 N/mm^2 at 150ºC.

Therefore, it can be assumed that the MEA can more than adequately resist the force on it.

Maintaining the cell at 80°C



ΔG_{max} = nFEº = (2 electrons / 1 mol H_2)((96,487 C)(1.229 V)
= 237,165 J/mol H_2

Heat produced

ΔG_{actual}

$= (1 - ?)\ \Delta G_{max}$

$= nF(E^o - E_{actual})$

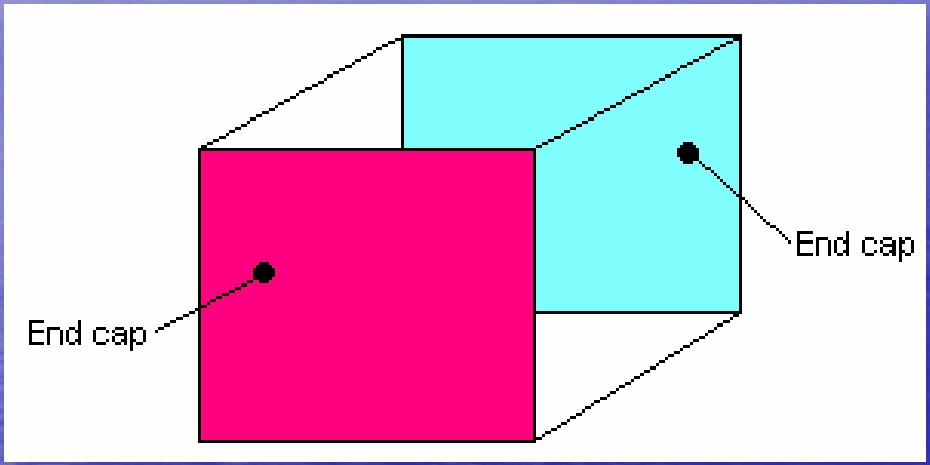
$= (2 \text{ electrons} / 1 \text{ mol } H_2)(96{,}487 \text{ C})[1.229 \text{ V} – (0.83)(0.6 \text{ V})]$

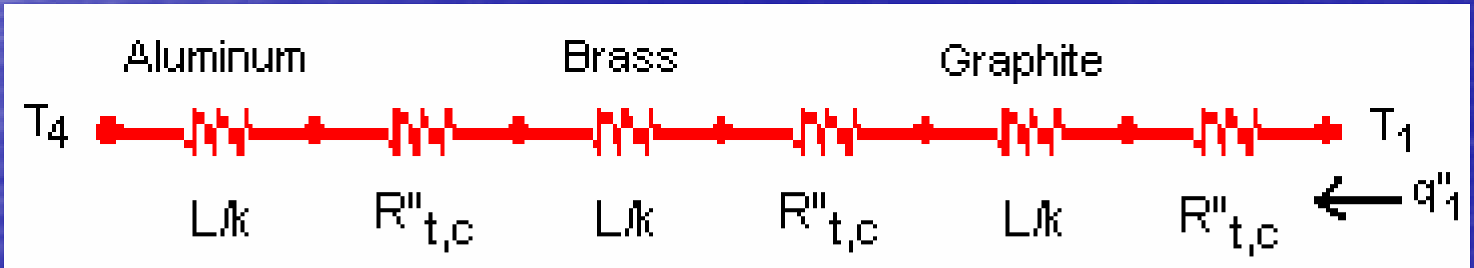
$= 141{,}064 \text{ J/mol } H_2$

$q_{gen} = \Delta G_{actual}\ (6.22 \text{ E-4 mol } H_2/s) = 87.7 \text{ J/s} = 87.7 \text{ W}$

$q'' = q / A = (87.7 \text{ W}) / (0.01 \text{ m}^2) = 8{,}770 \text{ W/m}^2$

Assuming perfect insulation





Approximate Temperature Drop

$q''_1 = U\,\Delta T = U(T_1 - T_4)$

$U = 1 / (R_{tot}\,A)$

$= 1 / (L_{graphite}/k_{graphite} + L_{brass}/k_{brass} + L_{Al}/k_{Al} + R''_{t,c1} + R''_{t,c2} + R''_{t,c3})$

$= 1 / [(0.03175\text{m})/(80\ \text{W/m.K}) + (0.00635\text{m})/(127\ \text{W/m.K}) + (0.00635\text{m})/(181\ \text{W/m.K}) + 0.72\ \text{E-4 m}^2\text{.K/W} + 0.02\ \text{E-4 m}^2\text{.K/W} + 0.08\ \text{E-4 m}^2\text{.K/W}]$

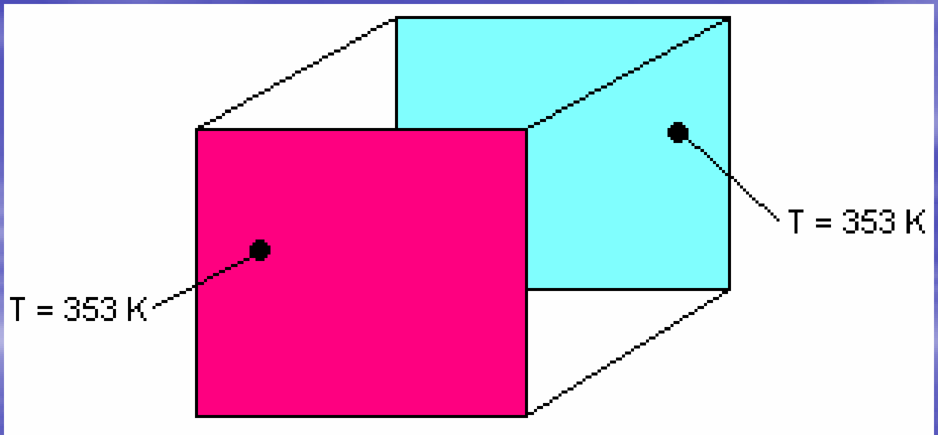
$= 1{,}773.2\ \text{W/m}^2\text{.K}$

Thus, $T_4 = T_1 - (q''_1 / U)$

$= 80.0^oC - (8{,}770\ \text{W/m}^2) / (1{,}773.2\ \text{W/m}^2\text{.K})$

$= 75.1^oC$

Heat Required



$q''_{loss,\ conv} = 2\ h_{air}(T_s - T_{surr}) = 2\ (100\ W/m^2.K)(80°C - 25°C)$
$= 11{,}000\ W/m^2$

Heat required = Heat loss – Heat generation

$q''_{req'd} = 11{,}000\ W/m^2 - 8{,}770\ W/m^2$
$= 2{,}230\ W/m^2$

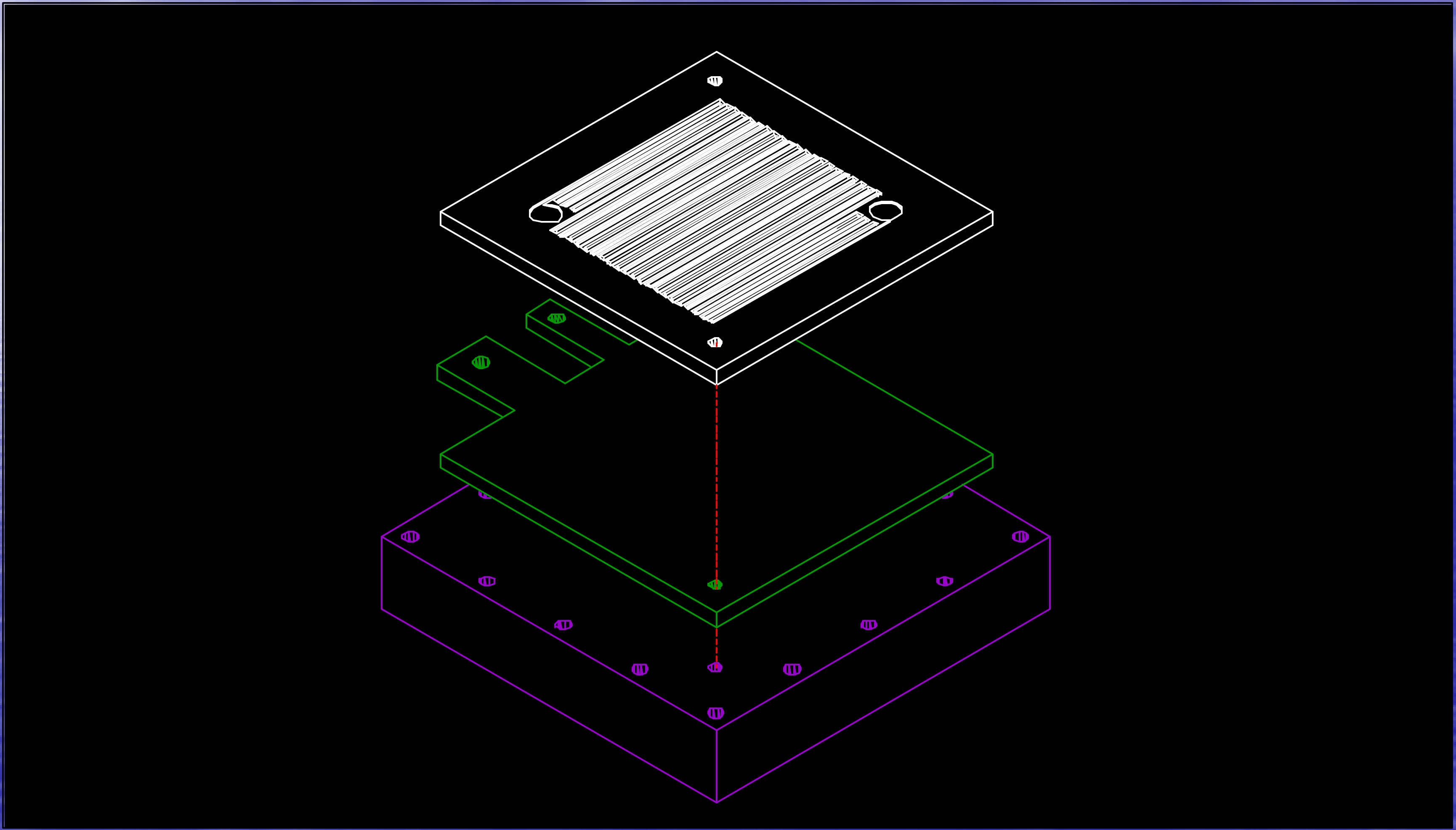
$q_{req'd} = q''\ A = (2{,}230\ W/m^2)(0.0196\ m^2) = 43.7\ W$

ANALYSIS

Thermal Compatibility

Material:	**a (1/ºC)**
Aluminum alloys (68-212ºF)	22.3 – 24.1 (x 10^{-6})
300 stainless steels (32-212ºF)	14.9 – 18.7 (x 10^{-6})
Brass	19.0 (x 10^{-6})
Graphite	7.0 – 8.8 (x 10^{-6})
Copper (68-572ºF)	16.7 – 17.6 (x 10^{-6})

Reducing area of CCs and FF plates



Compressibility

- System under 30 psi of pressure
- Metals possess good compressive strength
- Graphite possesses ample compressive strength of 7,151 psi to 11,020 psi

Laminar Flow in Flow Field Inlets

$m' = ?vA$ → $v = m' / ?A = m' / [?p(D/4)^2]$

$v_{H2} = (1.25\text{ E-6 kg/s}) / [(0.06924\text{ kg/m}^3)(p)(0.012\text{ m} / 4\text{ m})^2]$

$= 0.64\text{ m/s}$

$v_{air} = (8.60\text{ E-5 kg/s}) / [(0.9950\text{ kg/m}^3)(p)(0.012\text{ m} / 4\text{ m})^2]$

$= 3.06\text{ m/s}$

$Re = ?vD / \mu$; < 2100 → laminar

> 4000 → turbulent

$Re_{H2} = (0.06924\text{ kg/m}^3)(0.64\text{ m/s})(0.012\text{ m}) / (98.8\text{ E-7 N.s/m}^2)$

$= 53.8$

$Re_{air} = (0.9950\text{ kg/m}^3)(3.06\text{ m/s})(0.012\text{ m}) / (208.2\text{ E-7 N.s/m}^2)$

$= 1,754.9$

Flow through Flow Field Channels

$Q = v_1 A_1 = v_2 A_2$

Re_{H2} = (0.06924 kg/m^3)(18.10 m/s)(0.012 m) / (98.8 E-7 N.s/m^2)
= 1,522.2

Re_{air} = (0.9950 kg/m^3)(86.51 m/s)(0.012 m) / (208.2 E-7 N.s/m^2)
= 49,612.4

Taking into account an average of fuel consumption:

Re_{H2} = 1,827

Re_{air} = 37,209

Acceptable Pressure Losses

P_1 + ½ ?v_1^2 + ?gz_1 = P_2 + ½ ?v_2^2 + ?gz_2 + Sh_L

?P_{anode} = ½ ?(v_2^2 - v_1^2) + Sh_L

= 11.34 Pa + 22,271.00 Pa

= 22.28 kPa = 7.8% P_1

?$P_{cathode}$ = ½ ?(v_2^2 - v_1^2) + Sh_L

= 4.83 Pa + 25,359.17 Pa

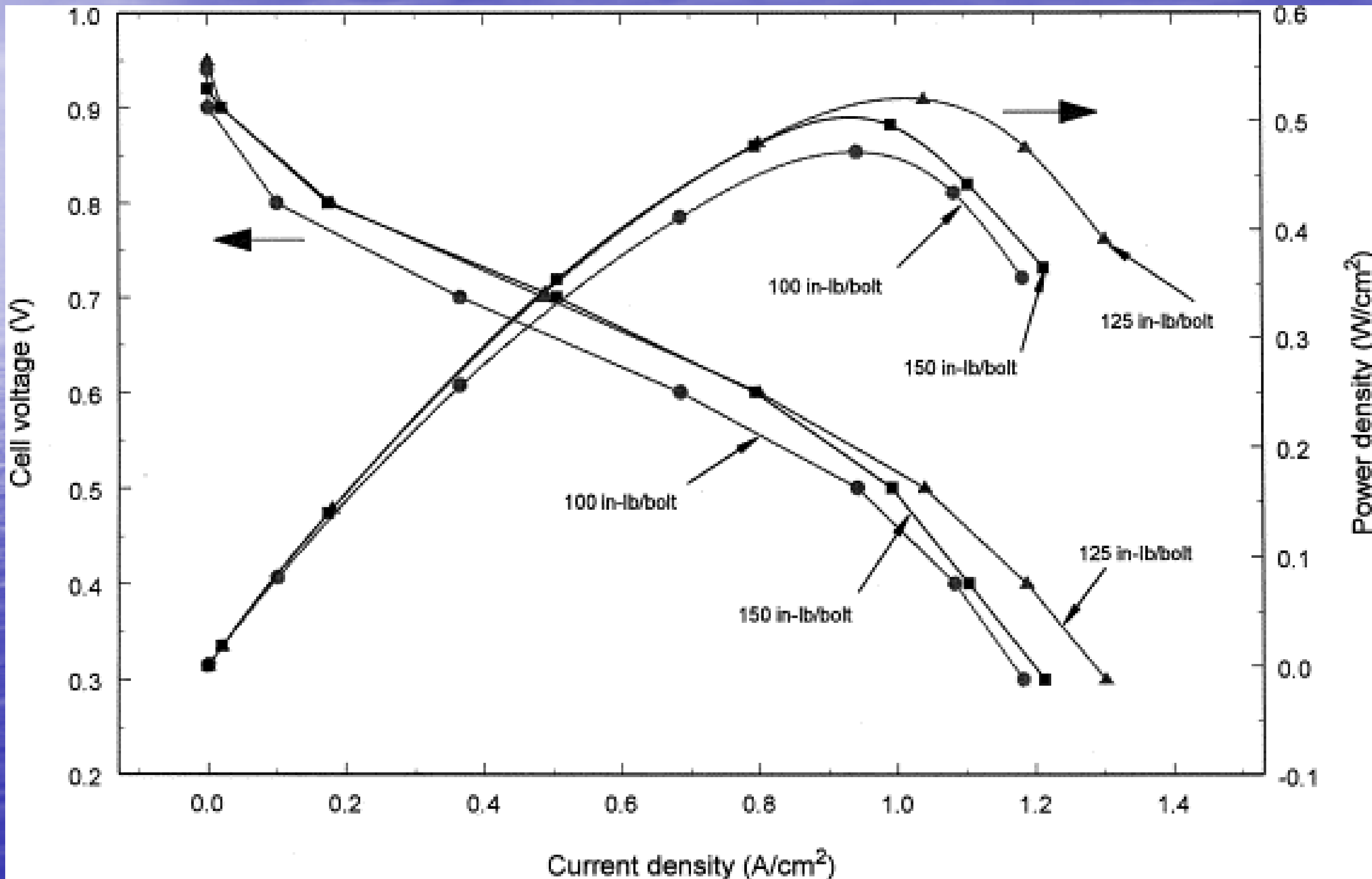
= 25.36 kPa = 8.9% P_1

SEALING & COMPRESSION

Suitable bolts and pressure

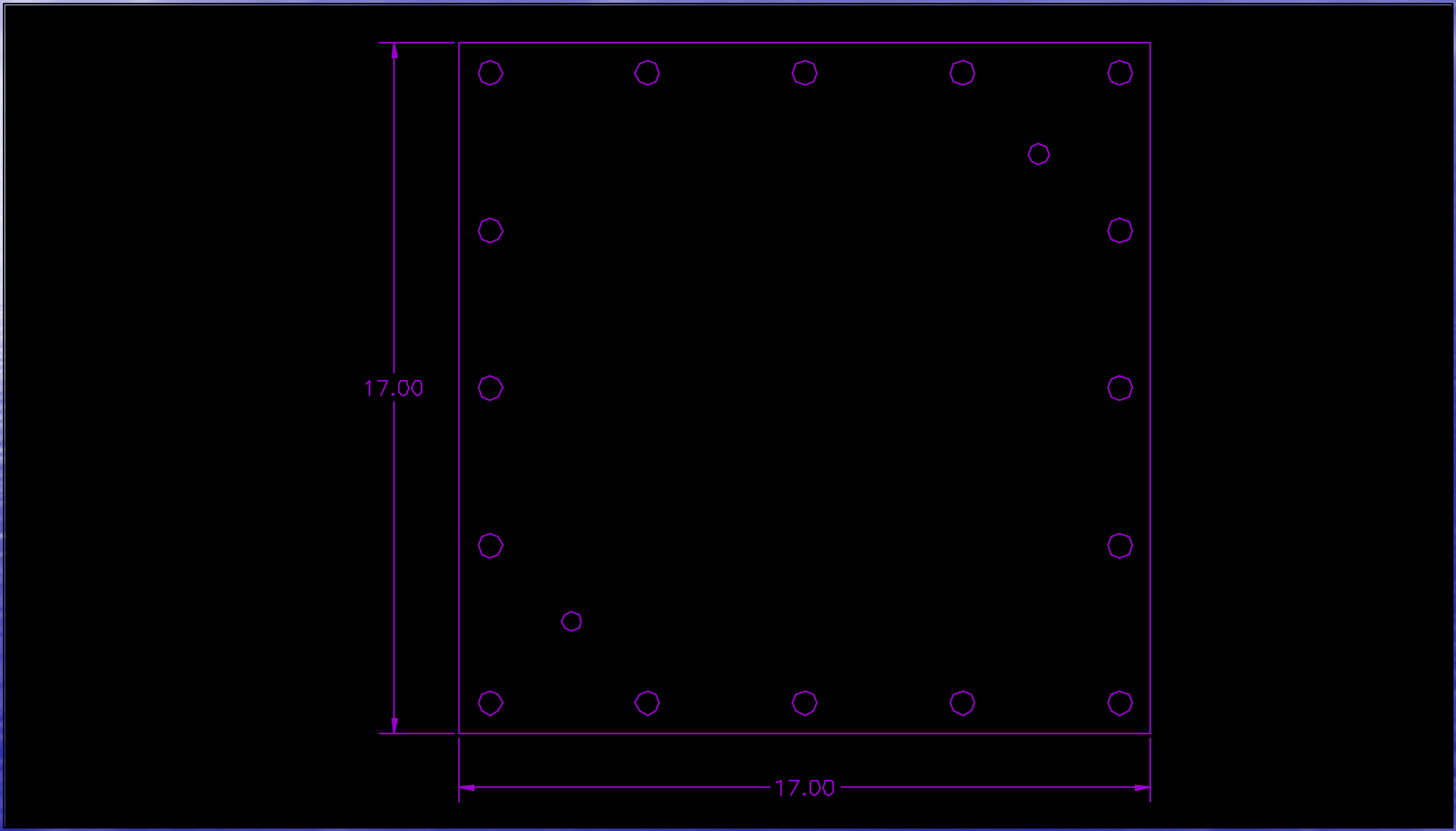
- – Prevent leakage
- – Minimize contact resistance
- – Maximize electrical conductivity
- – Maximize reactant diffusion
- – Uniform distribution of pressure
- – Optimize pressure through experiments

Bolt Torque



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Cell voltage (V)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
Power density (W/cm2)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Current density (A/cm2)
100 in-lb/bolt
125 in-lb/bolt
150 in-lb/bolt
100 in-lb/bolt
125 in-lb/bolt
150 in-lb/bolt

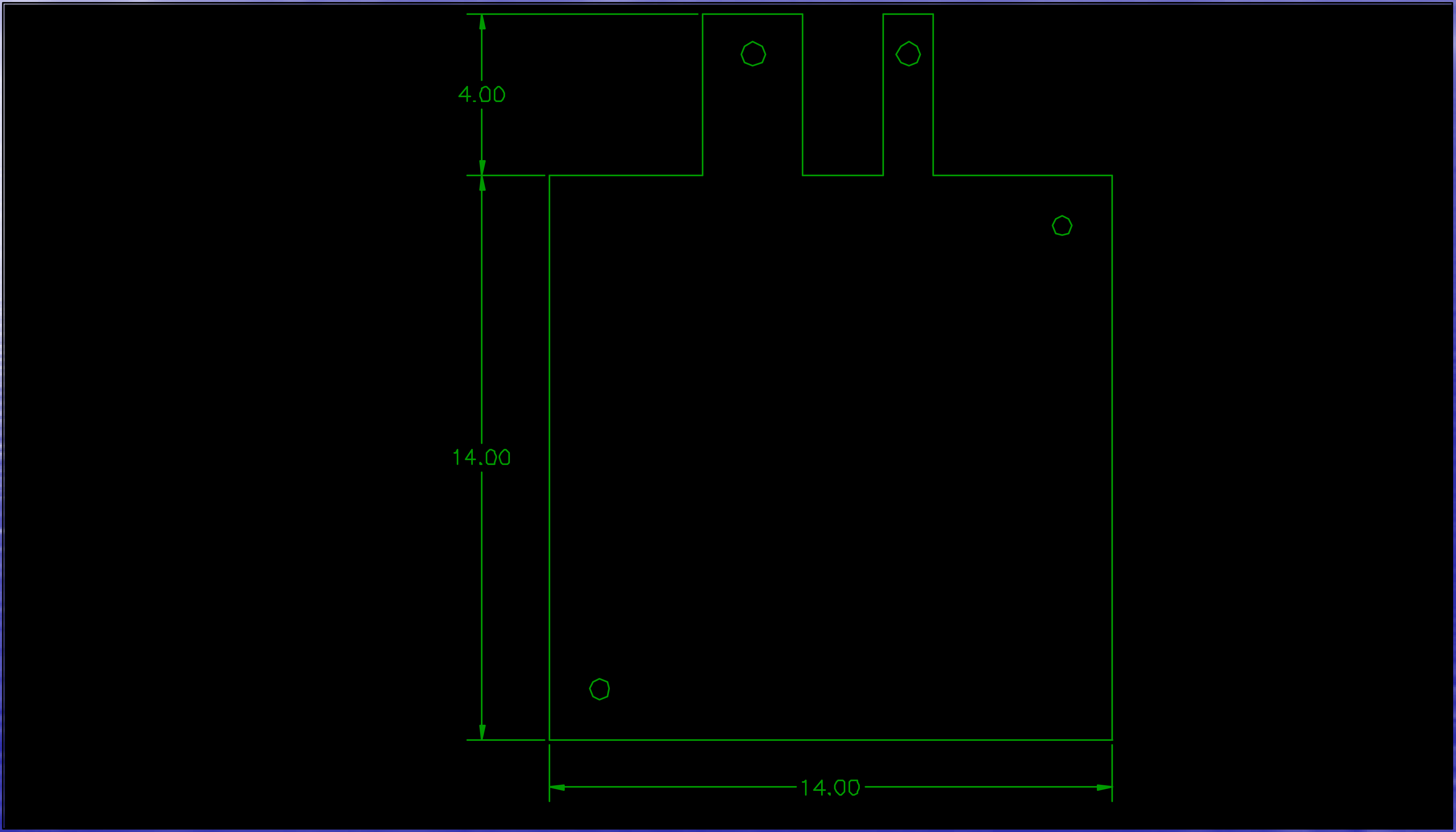
Aluminum End Caps = $60



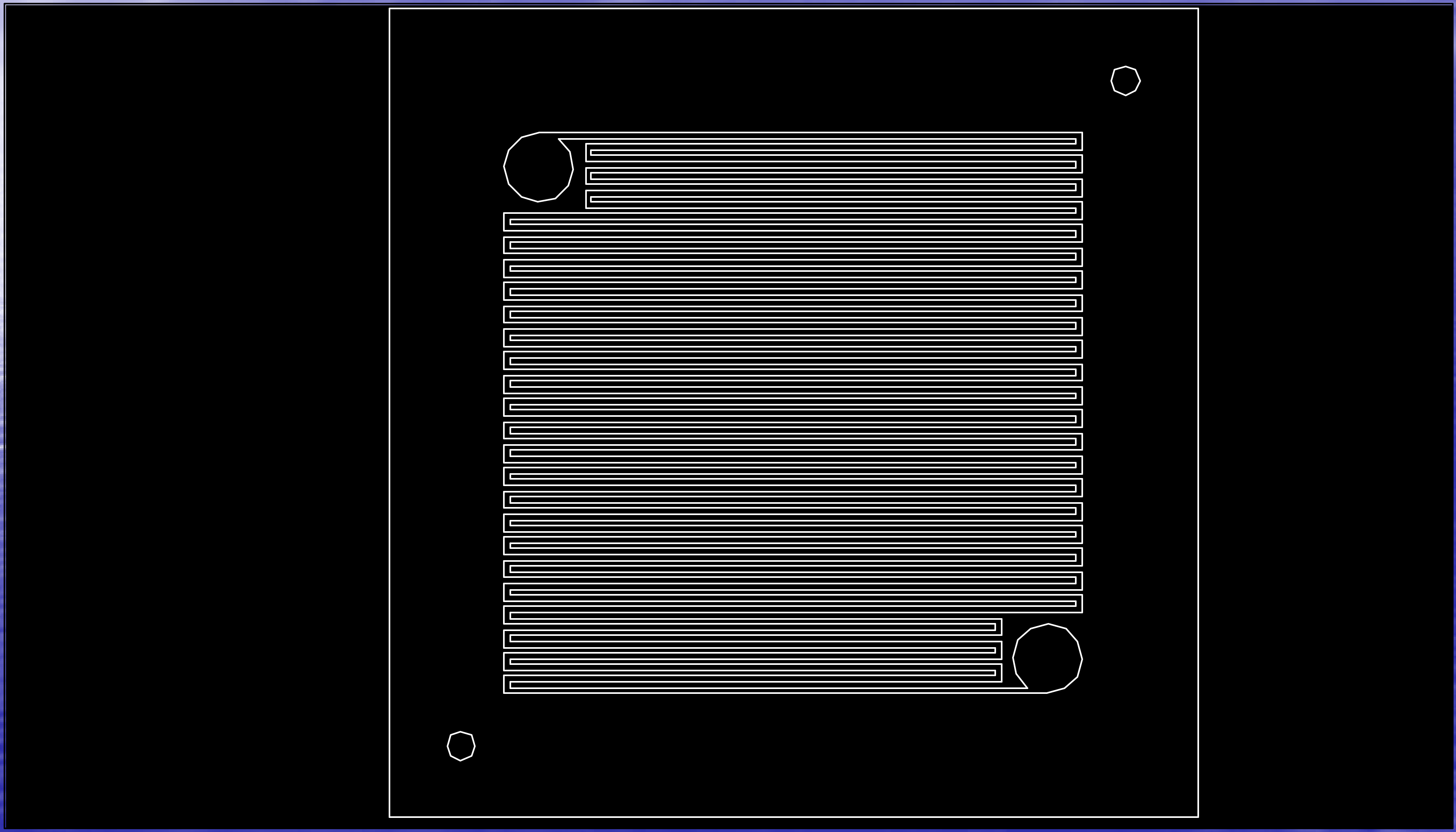
Miscellaneous costs ~ $100

- Gasket
- Hardware
- Swagelok
- Insulation

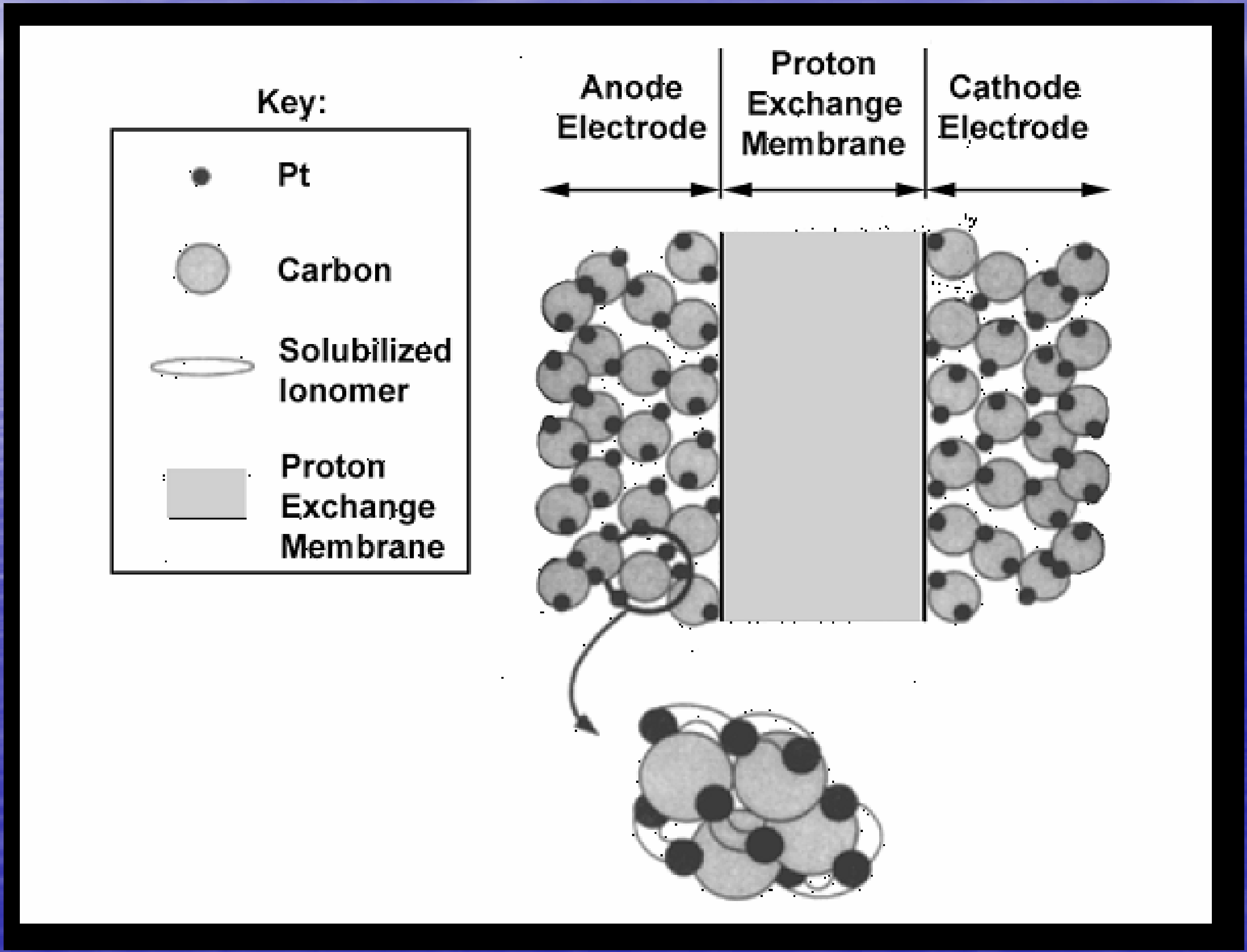
Copper Current Collectors = $160



Graphite plates = $212



MEA and GDL = $1200



Having a fuel cell that works?

Priceless.

Thank you.

Questions?