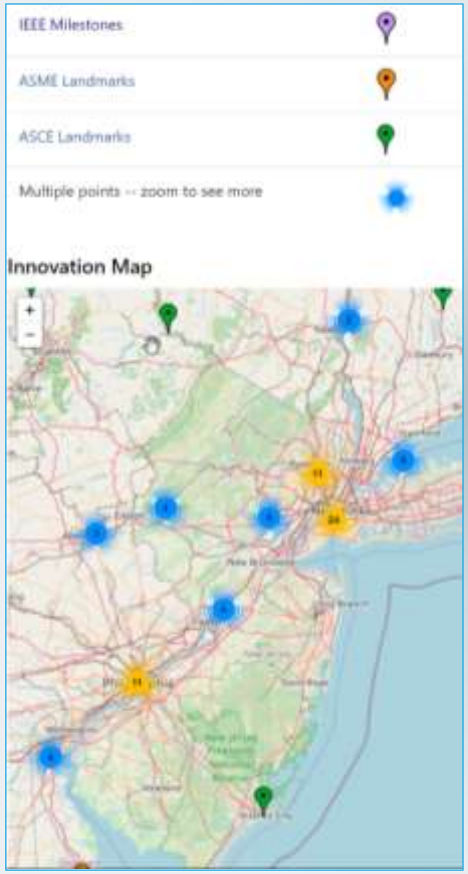
Power Electronics Hardware Design For Manufacturability

Thursday September 15th, 2022

Agenda

- Introduction to PPPEAC and Magna-Power Electronics (MPE)
- History, role of MPE products in test and measurement space
- Presentation focus engineering targeting manufacturing and mass production
- External Manufacturing – Constraints and design rules.
- Printed circuit board design w/ emphasis on high power.
- Internal Manufacturing – Competency, feedback, efficiency.
- Design for automation
- Record keeping and tracking: Issues, BOMs, firmware, revision/versions
- Firmware and testing
- Electronic and mechanical packaging

Princeton-Philly Power Electronic Advancement Consortium (PPPEAC)

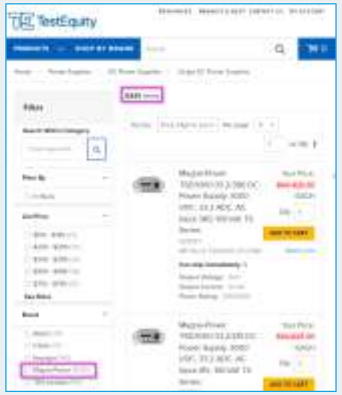


https://ethw.org/map

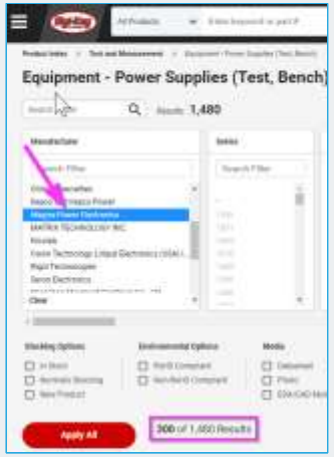
- Founded in 2019
- Joint **Chapter**: IAS/PELS chapter
- Joint **Section**: Princeton and Philadelphia
- Joint **Region**: R1and R2
- Visit us at www.*ieee-pppeac.org* to register for the newsletter.
- **Factory Tour and General Meeting**

  Friday September 16th, 4 - 6pm ET
  39 Royal Road
  Flemington, NJ 08822
  https://bit.ly/3S9PLbM

Who is Magna-Power Electronics?



TestEquity (Moorpark, CA)



Digi-Key

NaturalShrimp, Inc.

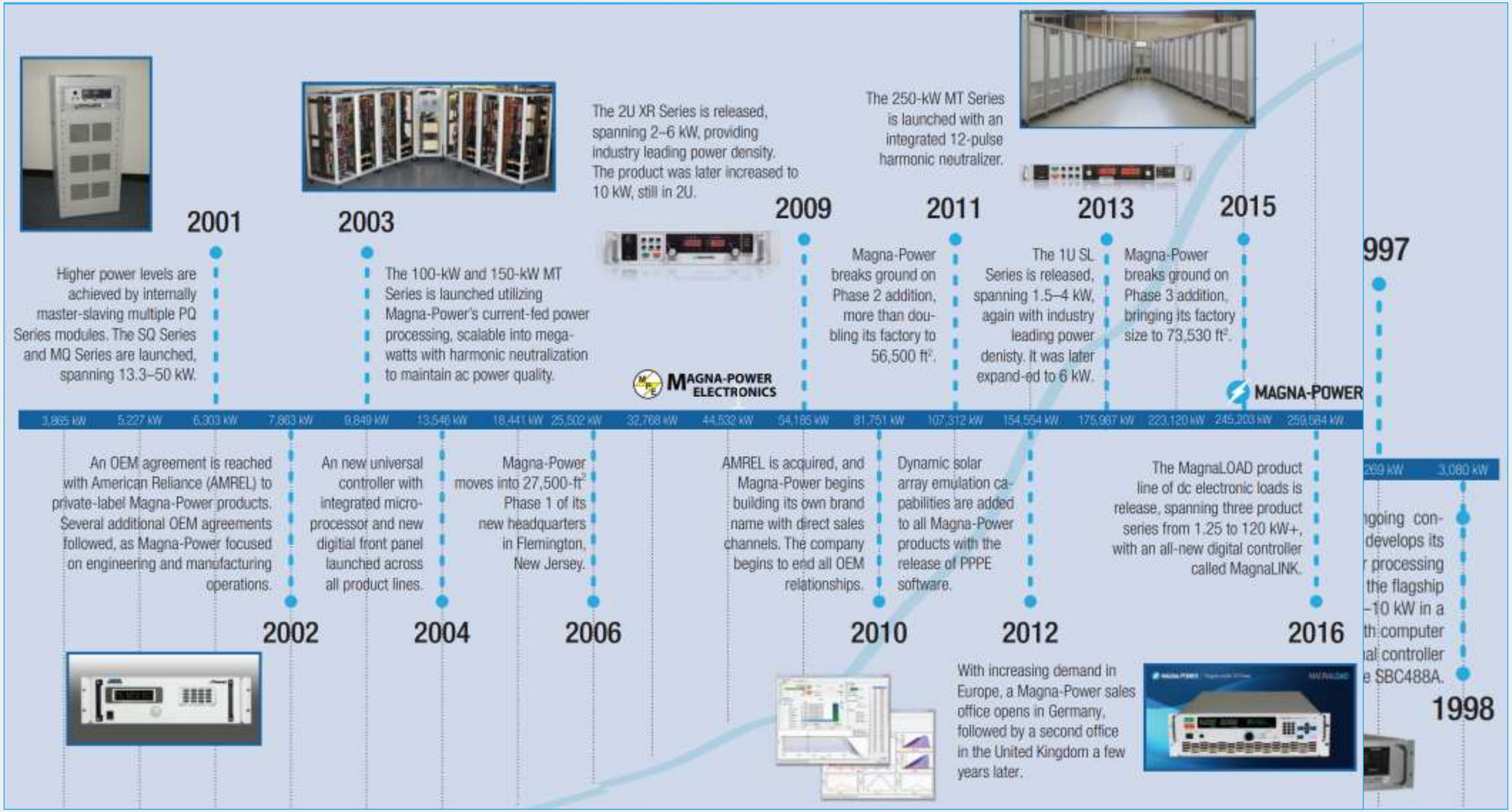
- Offers the largest selection of COTS programmable ac-dc power supplies (350,000+) designed for and shipped around the world.
- Rack mount and floor standing power finds applications in automotive, chemical processes, military, academia, renewable, fusion, … animal science.
- Other power-specific specialty products: electronics loads, blocking diodes, high-accuracy linear regulators, and even cables.

The Team 2022 @ Magna-Power Electronics, Inc. HQ, Flemington, New Jersey

Bloomberg @ General Fusion

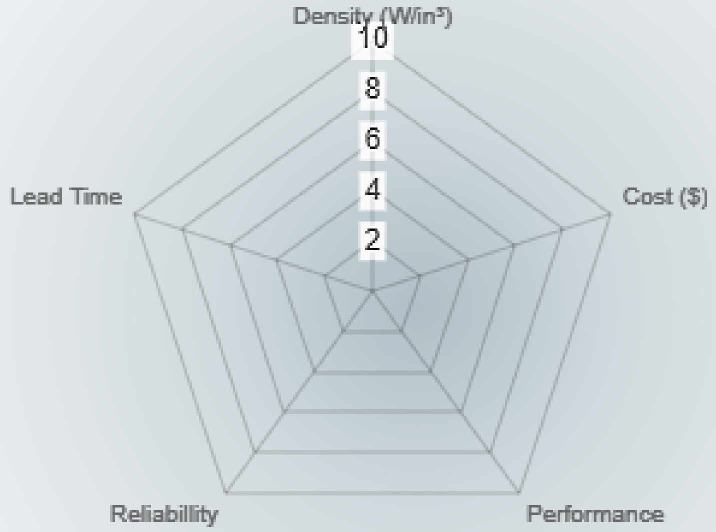
President Biden @ NREL

History[2] 1998-2016



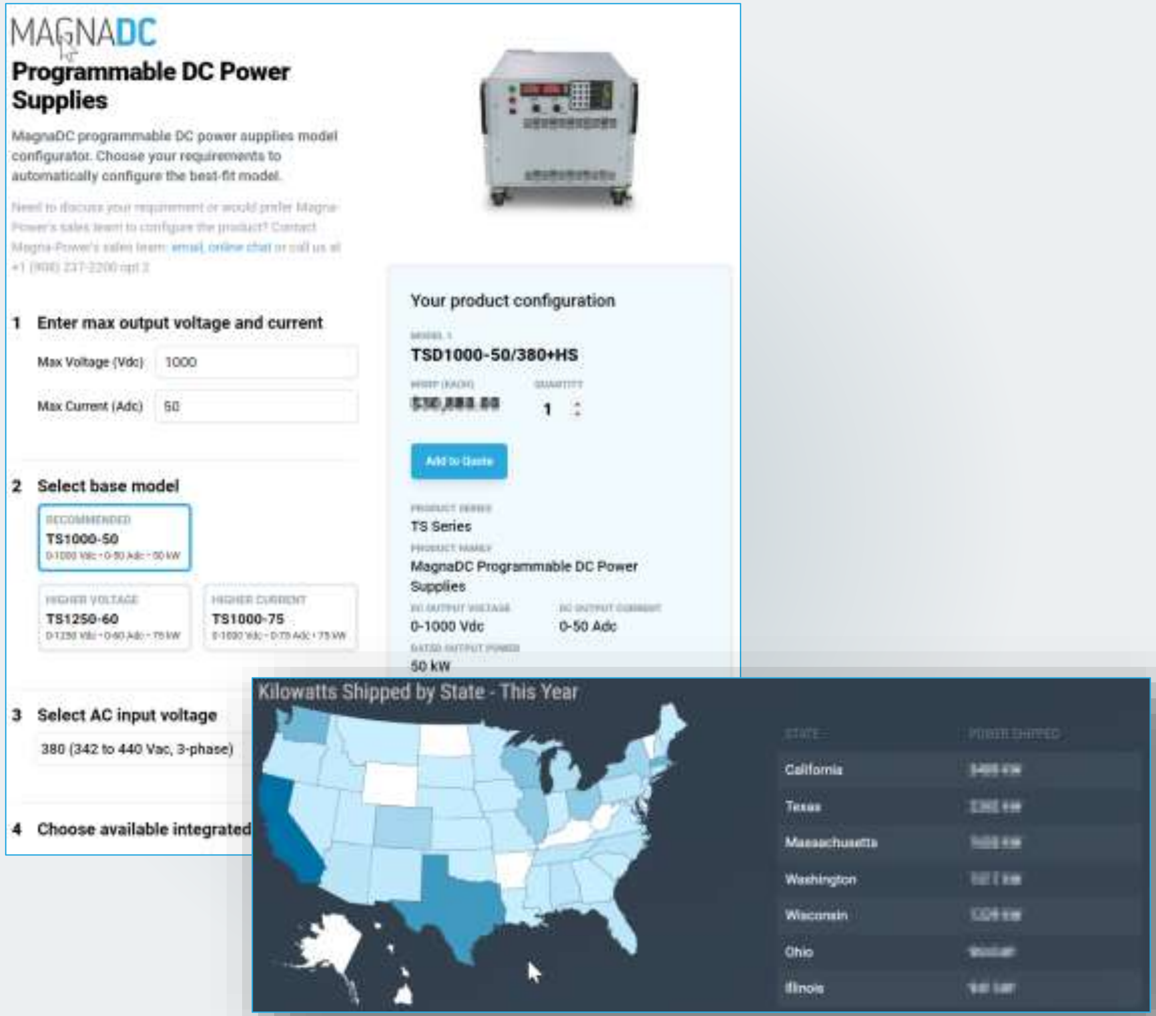
1. A. Pitel and G. Pitel, "The History of Magna-Power Electronics: The Path to a Vertically Integrated U.S. Electronics Manufacturer [History]," in IEEE Industry Applications Magazine, vol. 23, no. 1, pp. 7-13, Jan.-Feb. 2017, doi: 10.1109/MIAS.2016.2614392.

Power Supply Manufacturing



- Before MPE, high-power supplies were custom designs with the same formula.
  (1) Find a power-electronics engineer/firm;
  (2) allow one to two years time to design, test;
  (3) outsource manufacturing.
- MPE rewrote the formula
  - Listen to customers. Create a base design that hits the largest customer demographic.
  - Parametric BOM definitions
  - Parametric testing routines
  - Parametric drawings
  - Flexible, vertical-integrated production processes and staff. Low-volume high-mix manufacturing.
  - Learn from mistakes, iterate, improve, and repeat.

Engineering Challenges



- Expansive BOMs and datasets
  - GIT, ERP, and lots of custom software.
- Rule/parameter-based design and quoting
- Low lead times mean quick response needed form planning, production, and engineering to address materials shortages or missing drawings
- First-time builds may fail test
- Managing product compatibility
- Designing and selecting parts for reuse in multiple assemblies.
- Legacy support

Software Design Constraints in Action

- Power electronics specific PCB design [2]
- For high current, more copper weight introduces drastic tolerance changes in the etching and masking processes.
- For high-voltage, design must manage clearance/creepage distances.
  - Line-to-line, line-to-chassis, and floating
  - Be wary of over constraint and constraint ordering
  - Understand and enable as many design rules as possible

2. G. Pitel and A. Pitel, "Power Electronics Hardware Design for Manufacturability: Employing design principles to ensure manufacturability of complex designs at high-voltage and high-current extremes," in IEEE Power Electronics Magazine, vol. 8, no. 4, pp. 16-22, Dec. 2021, doi: 10.1109/MPEL.2021.3123832.

High-Voltage Clearance / Creepage Rules

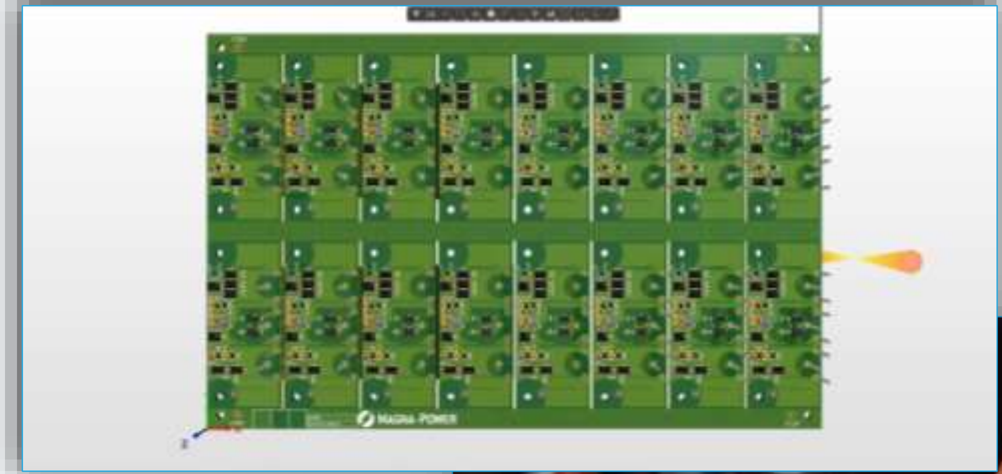
- Default to generous clearances (IPC-2221)
- Apply specific rules when tighter spacing is needed
- Leverage software to store and enforce design rules. Inter-layer violations are hard to see/calculate and sometimes non-obvious.

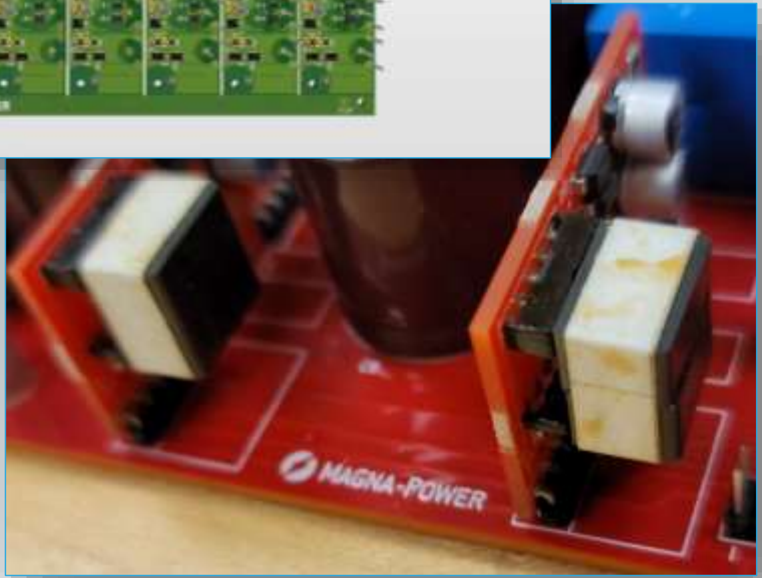
Voltage Between Conductors (DC or AC Peaks)	Minimum Spacing						
	Bare Board				Assembly		
	B1	B2	B3	B4	A5	A6	A7
0-15	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]
16-30	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.25 mm [0.00984 in]	0.13 mm [0.00512 in]
31-50	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	0.6 mm [0.024 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.4 mm [0.016 in]	0.13 mm [0.00512 in]
51-100	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	1.5 mm [0.0591 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.5 mm [0.020 in]	0.13 mm [0.00512 in]
101-150	0.2 mm [0.0079 in]	0.6 mm [0.024 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
151-170	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
171-250	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	6.4 mm [0.252 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
251-300	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	12.5 mm [0.4921 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]
301-500	0.25 mm [0.00984 in]	2.5 mm [0.0984 in]	12.5 mm [0.4921 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]	1.5 mm [0.0591 in]	0.8 mm [0.031 in]
> 500 See para. 6.3 for calc.	0.0025 mm /volt	0.005 mm /volt	0.025 mm /volt	0.00305 mm /volt	0.00305 mm /volt	0.00305 mm /volt	0.00305 mm /volt

B1 - Internal Conductors
B2 - External Conductors, uncoated, sea level to 3050 m [10,007 feet]
B3 - External Conductors, uncoated, over 3050 m [10,007 feet]
B4 - External Conductors, with permanent polymer coating (any elevation)
A5 - External Conductors, with conformal coating over assembly (any elevation)
A6 - External Component lead/termination, uncoated, sea level to 3050 m [10,007 feet]
A7 - External Component lead termination, with conformal coating (any elevation)

	Condition	Pollution Degree 1	Pollution Degree 2
Creepage (in equipment)	Basic Insulation, 300V, Category 1, CTI >100	0.7mm	3.0mm
Creepage (on PCB)		0.7mm	1.4mm
Clearance		0.5mm	0.5mm
Creepage (in equipment)	Basic Insulation, 150V, Category 1, CTI >100	0.3mm	1.6mm
Creepage (on PCB)		0.22mm	0.35mm
Clearance		0.1mm	0.2mm

Board House and Stencil Fabricators

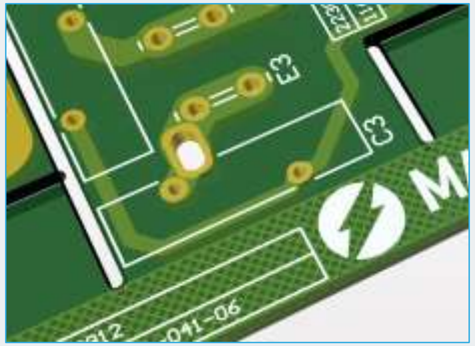


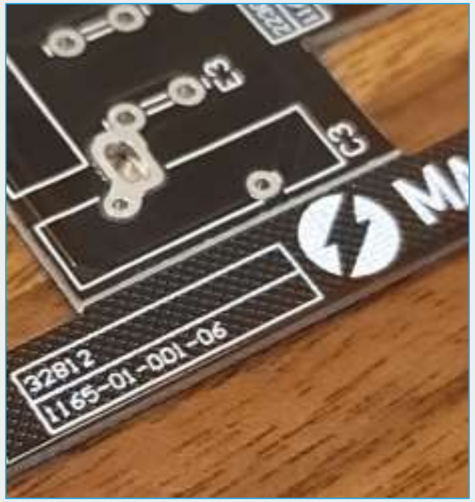


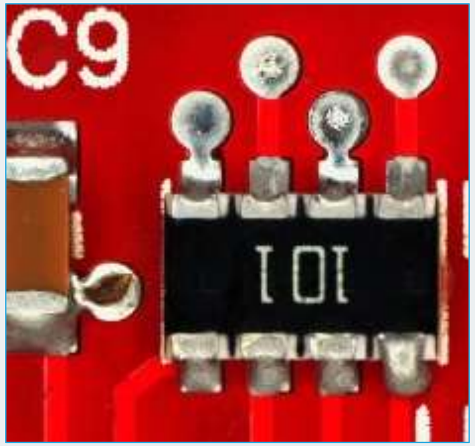
- Due to fab limitations, solder mask tolerances and minimum trace widths grow with copper weight.
  - 1 oz -> 5 mil minimum trace width
    4 oz -> 15 mil minimum trace width
  - Prevents the mixing of high current with dense logic on the same PCB.
  - Different layers stacks have different design rules.
- Avoid fabrication delays by putting as much details about the build on the Gerber artwork (drill guides, layer stack, stencils, ...)
- Mindful of language barriers and regional holidays
- Run DFM checks before sending
- Keep a healthy and inquisitive dialog with board house.
- Translate their years of experience into design rules.
- Upfront time investment for long-term time savings.

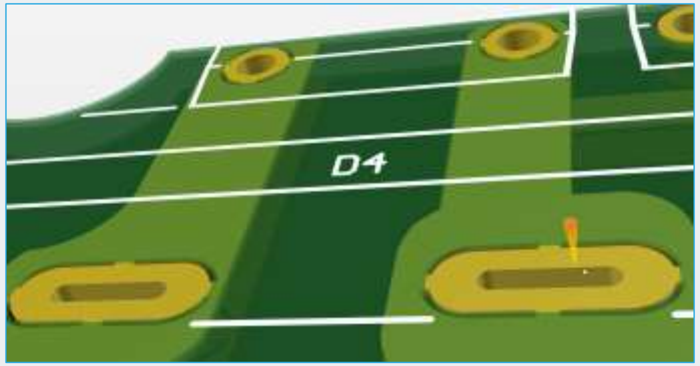
Soldering and Reflow

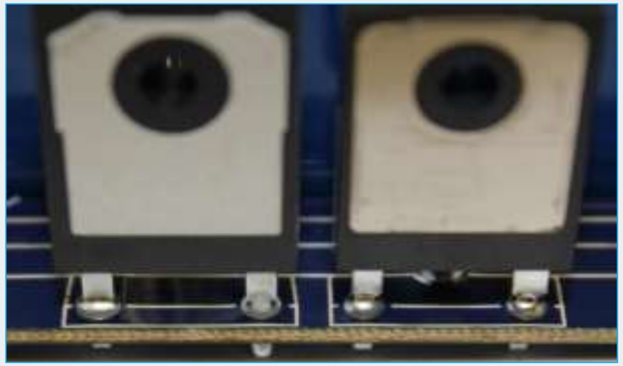
- Solder mask slivers starve joints of solder.
  - Bad joints and bridges flagged by AOI
  - Rework increases labor costs and lead times
- Reflow and wave solder process expose all joints to the same temperature and dwell time.
  - Thermal reliefs increase thermal resistance that evens heat distribution and improves solder wetting.
  - Balance electrical conduction and thermal conduction





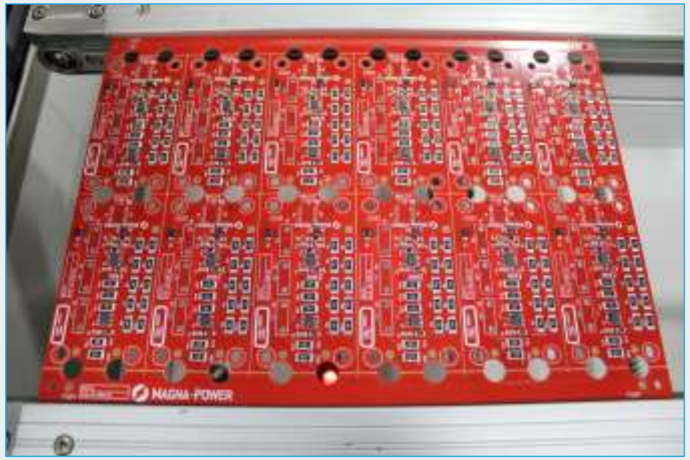




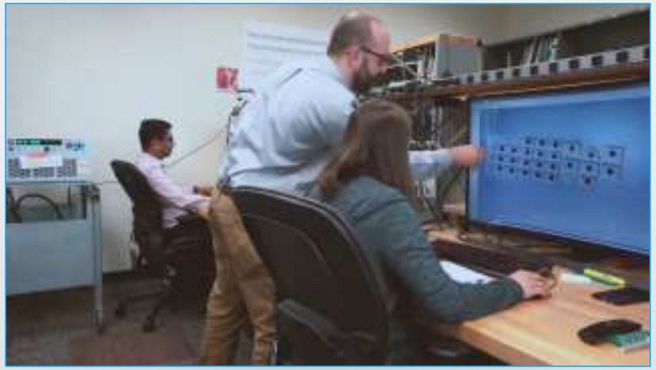


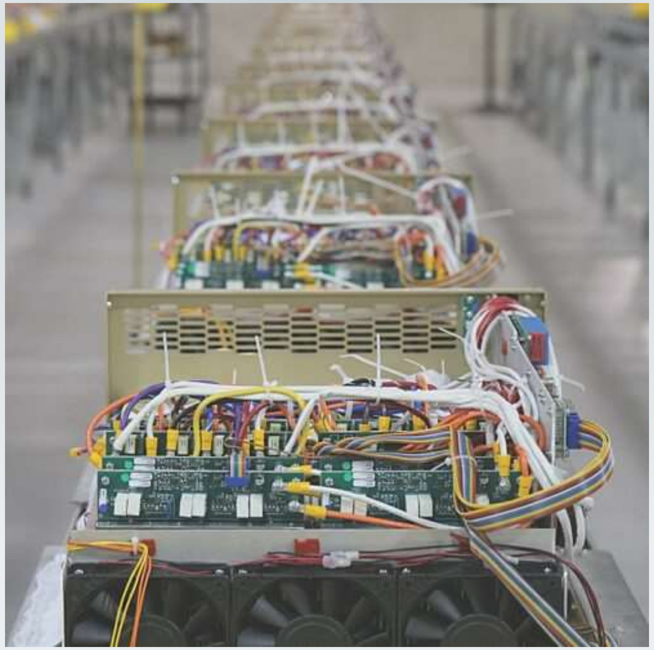
Automated Assembly

- Be mindful of labor and equipment (benefits of insourcing)
- Alignment fiducials, bad board marks, tooling holes.
- Array PCB designs to reduce handling and tool change time.
- Assembly likely traveling by conveyor
  - Include rails for griping
  - Watch for gaps/obstructions on leading edge
- Edge-of-board clearance for de-paneling and mechanical inserts.
- Board flex, bounce back



Engineering Prototype Management

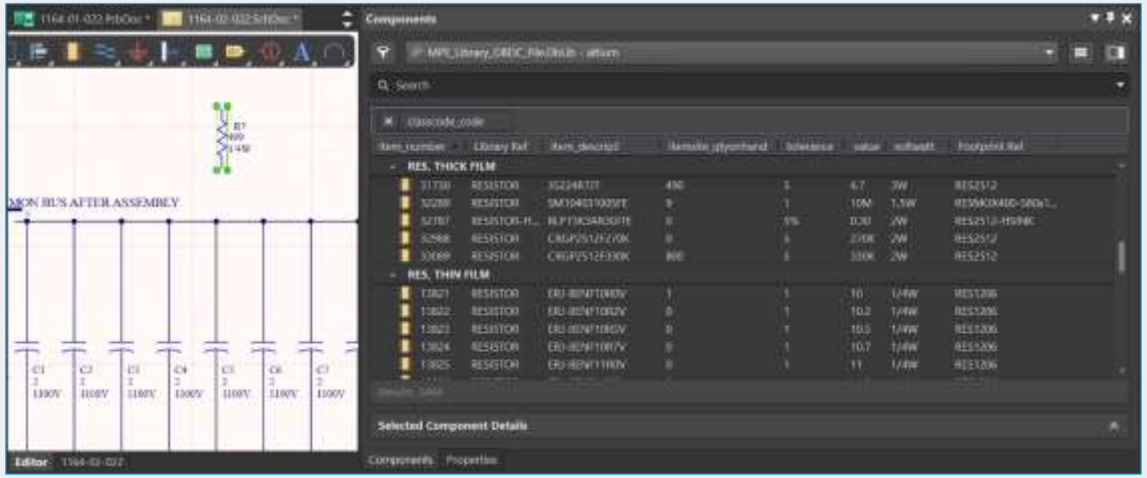




- Nature of the business requires regular prototype runs.
  - Treat as standard production board to accelerate completion
- Differentiate from normal work orders
  - Tracking: Issue tickets, color router holder, work order notes
  - Revision numbers, revision states (active, pending, inactive)
  - May have incomplete work instructions, operations, missing/wrong materials
- Quick turn needed to clear blocks in design validation
  - Escalate in job work queue
  - Expedite purchase parts
  - Engineer responsible for clearing any obstacles
- Bring prototypes (BOMs, drawings, etc.) to a near production-ready state.
  - Exercises documents to identify problem with design or production process
  - Low-volume runs to test out recipes, tooling, and machine programming.
  - Material purchasing and kitting follow standard processes – all handled for engineering

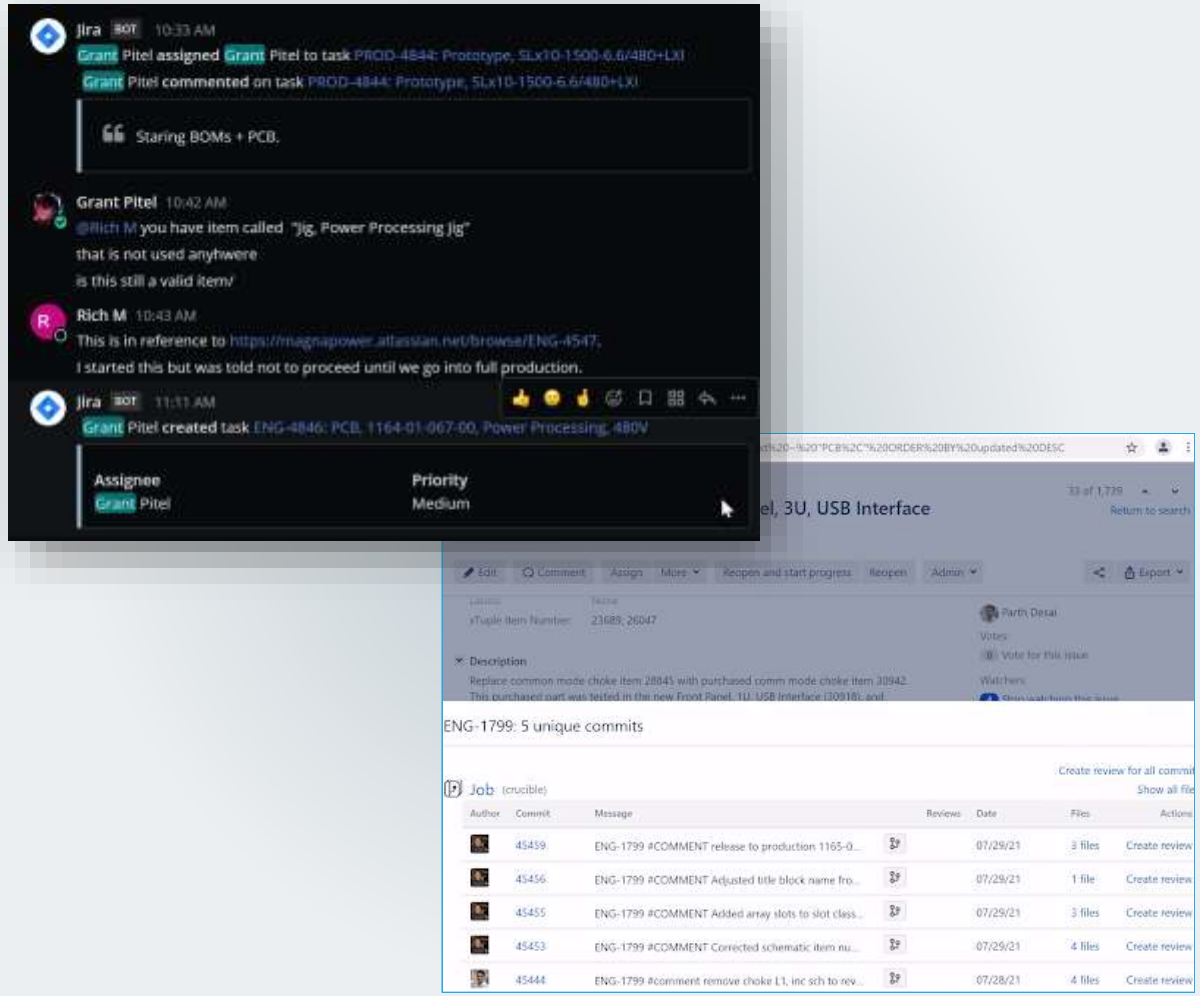
Data Driven Engineering and Prototype Planning

- Single central database. Sophisticated queries on production, sales, and engineering.
- API exposure to engineering design software
- Export design to production software (AOI, P&P)
  - Recipe construction and on-the-fly component-level validation.
- Labor tracking identify bottle necks.
- ERP – Manage purchasing, jobs, shipping



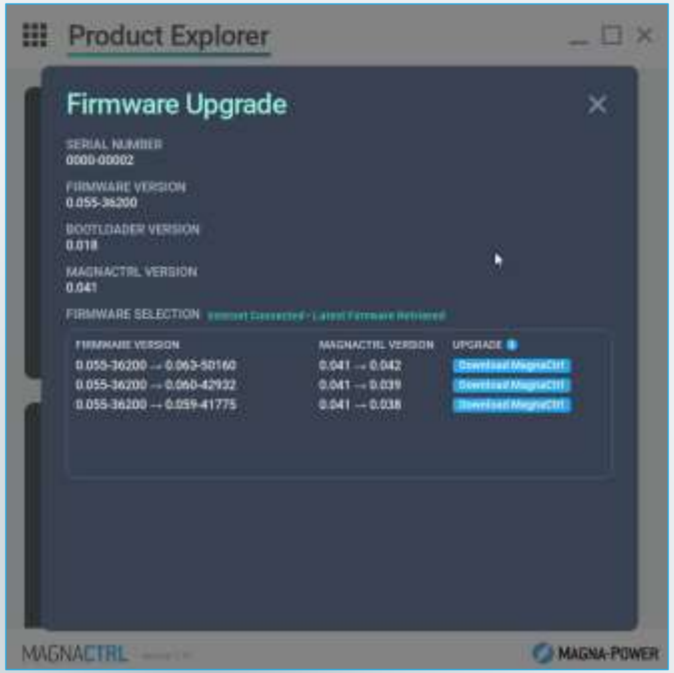
- Encourage intelligent component reuse
  - Volume pricing
  - Reduced vendor/manufacture vetting effort
  - Inventory/planning simplifications
  - Job optimization reduces tool change over
- Automate record keeping processes when possible.

Document and Software Management



- Adopted the tracking/processes used by software developers
- When production or customer encounter an issue.
  - Document problem and how to repeat it in an issue tracking system.
  - Issues are searchable visible to all within the company. Tied to multiple tertiary services. Stays in system until closed.
  - Issues can pass freely from support, engineering, production, and testing.
  - Ticket evolves. Establish accountability, priority, and ownership.
  - Resolving file change(s) linked together with issue.
- Permanent record of problem and resolution (source for many of the images in this presentation)

Hardware-Firmware-Software Compatibility



- #1 Required launch feature – firmware flashing
- Platform, future proofing, support continuous improvements
- Firmware, hardware, and software features.
- Manage changes/fixes in hardware, protocol, and EEPROM.
- Multi-chip, multi-product flashing
- Forward compatibility, Backwards compatibility
- Cross-product compatibility (ALx, DBx, SLx ….)
- Compatibility breaks ☹

Items	Changes	Date	Snapshot
23080R27, 23717R10, 23742R5, 23746R6, 24283R16, 25040R14, 25750R7, 25768R3, 25769R6, 25912R10, 28206R0.012, 28207R0.045, 28208R0.024, 28431R0.014, 29448R0.023, 29468R0.101	hw: change transceiver U2 to a SSOP16 package to address … hw: fix footprints TH1, VR1, C22, remove C34, remove +48V connection on JA2 hw: common mode choked added cg2: bootloader can respond to status message requests cg2: fan speed turns off gently to prevent aux power reset cg2: fix rheostat mode tripping by changing order of linear module … cg2: prevent shorting switch from turning on during initialization ivi: first release (built through cis)	2019-02-26	36
23080R28, 23717R10, 23742R5, 23746R6, 24283R16, 25040R15, 25750R7, 25768R3, 25769R6, 25912R10, 28206R0.012, 28207R0.046, 28208R0.025, 28431R0.014, 29448R0.024, 29468R0.101	hw: digital IO buffers controlled by gatedrv only hw: increased current to power rocker opto hw: input capacitance to flyback reduced to speed up startup hw: current increased to opto to improve turn on cg2: bootloader can respond to status message requests	2019-03-19	37

Design for Test

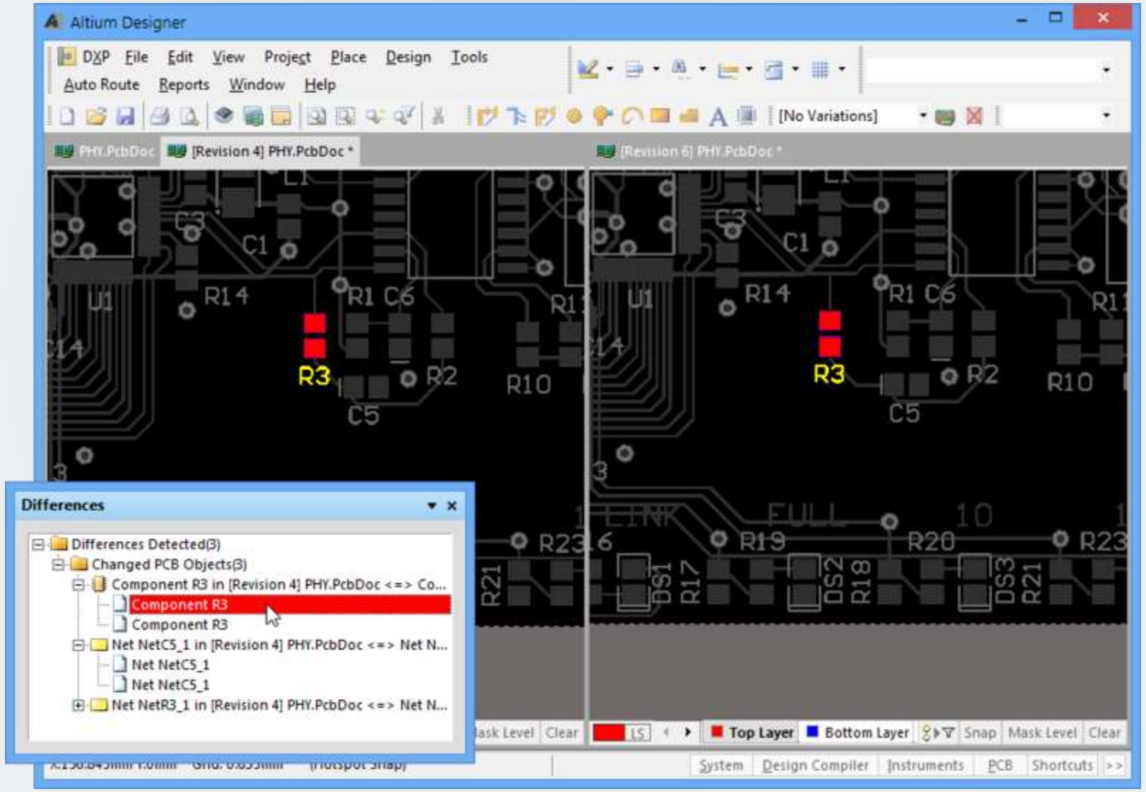
- Provide simple visual debugging for testers (inexpensive)
- Consider test point accessibility and visibility
- Prevent redundancy in testing (functional vs electrical)
- Balancing
  - Test duration
  - Probability for failure
  - Time needed to address problem
- Configurable products need configurable testing.

Extensible Testing

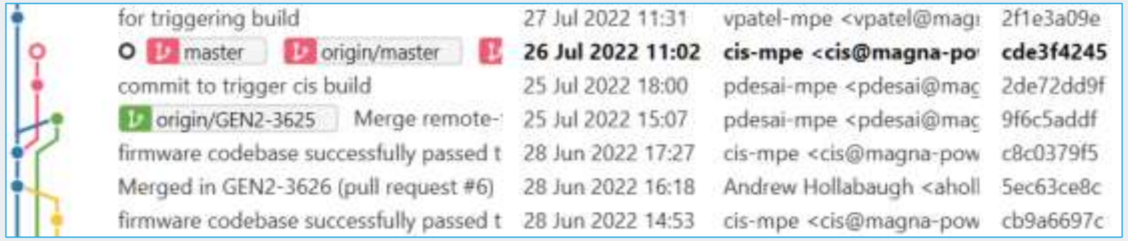
- One testing station many combinations
- Sales order acts as inputs for tests.
- Tests automatically added or removed from suite based on those inputs.
  - Extra tests loaded for detected firmware
    or hardware changes, when breakage is most probable.
  - Discover feature breaks before shipment.
- Object orientated test programming

```python
def test_analog_output(self):
    """Measure voltage on all analog output pins at various set points. Checks each set point satisfies a certain error threshold."""
    ratedVoltage = float(self.get_input(instruct='Product rated voltage', ask='What is the product rated voltage (V)', inpParamKey=InputParameterSet.RatedVoltProduct))
    self.write_eeprom_value(EMemSetting.aOPin, FixedPointNumber([PinOptionAO.vTerminal.value, PinOptionAO.vTerminal.value, PinOptionAO.vTerminal.value, PinOptionAO.vTerminal.value, 0, 0, 0, 0], NumType.Arr8_Q0_16_0))
    # cycle through four steps of voltage within the voltage range of the unit
    if not self.ats.piDaq.isConnected:
        self.assertTrue(self.get_input(instruct='Connect I/O test fixture to External User I/O connector.',
                                       ask='Ready to test analog output voltage', choices=['Y', 'N']))
    for idx, pin in enumerate(self._aOPins):
        self.ats.powerSupply.change_setpoint(voltage=(ratedVoltage / float(idx + 1)), current=1.0)
        time.sleep(10)          # wait for voltage to settle down
        value = self.ats.get_uut_analog_output(pin, measureDevice='meter')
        self.assertLess(abs(value - (10.0 / (idx + 1))) / 10.0, 0.0075, "Error of %0.2f percent in analog output voltage exceeds the allowed bounds of 0.75 percent" % (100.0 * abs(value - (10.0 / (idx + 1))) / 10.0))
```

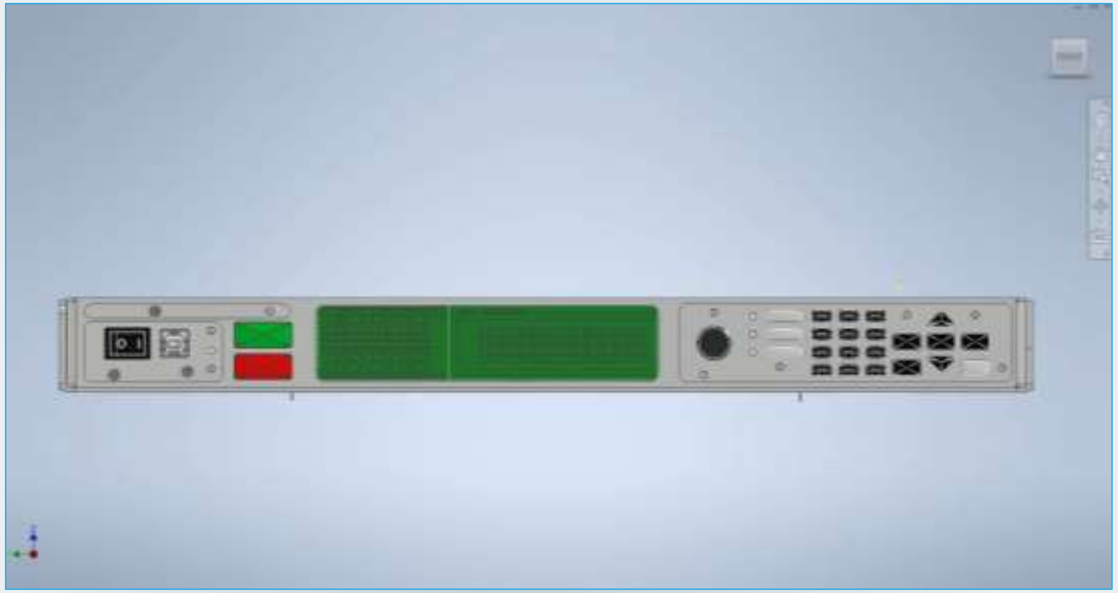
Version Control for Engineering Documents



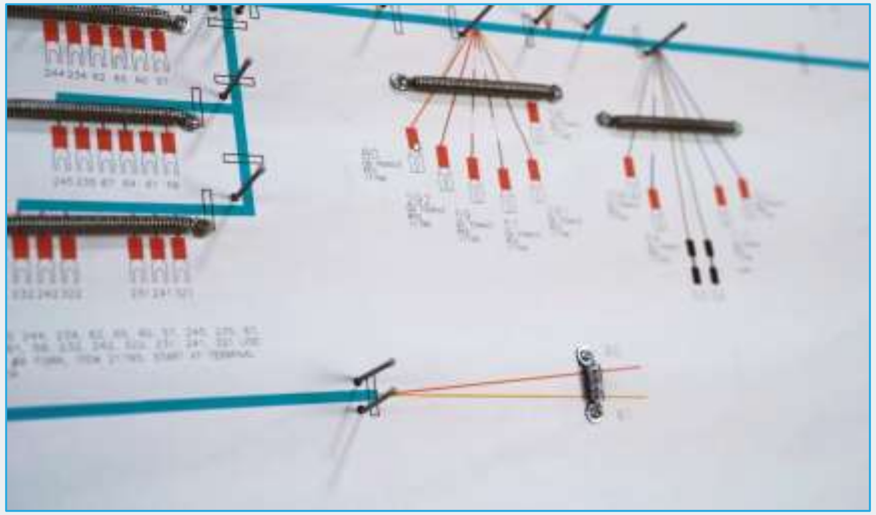
- Common practice for software development – facilitate parallel effort
- Trace when and who made changes. Help production direct questions.
- Backup, recovery, and centralized access
- Most engineering files binary (schematic, layouts, and drawings) limited support conflict resolution.
- Careful selection on when to tag/version engineering documents in production process.
    - Layouts, transformers, and metal
- Compare between versions to trace/identify cause of defect.



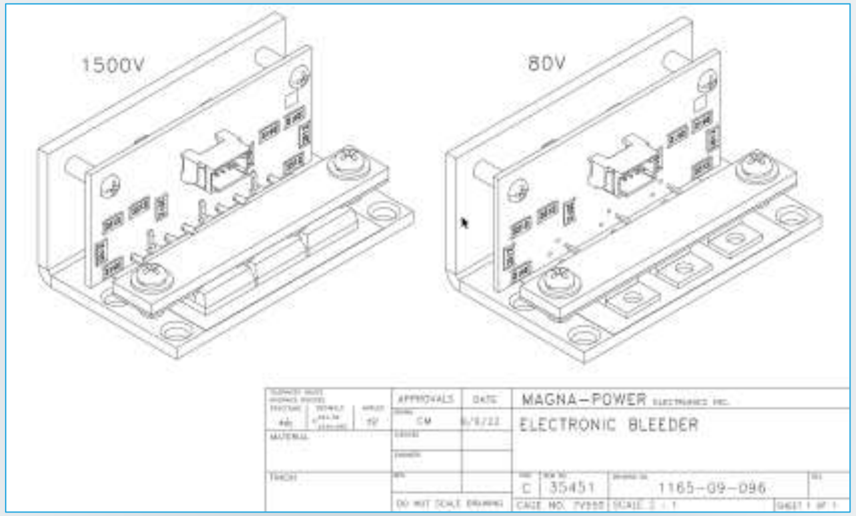
Electronic and Mechanical Packaging



- Parametric (solid) modeling (new to MPE)
- More complicated drawings (keypad)
- We find ~¾ of the component manufacturers provide 3D models
- Check form/fit before physical prototype
- Boost working efficiency between electrical and mechanical teams.
- Assembly drawings for production
- Configurable drawings
- Importance of clearly defined wire harnesses.



Prototype Production



- Treat as standard production (drawings, BOMs, identification), limited communication -> faster builds
- In past relied heavily on past designs, pictures, and back-and-forth communications with engineering and production.
- Has become at lot less laborious to create assembly drawings for production
  - High availability of 3D component models from manufacturers
  - Evolution of internal part libraries
  - Build up of new models
- CAM and bends embedded in solid model
- Keep prototype volumes low, heavily scrutinized, and be conservative with revision status.
  - Active = Ready for Mass Production

Conclusion & Questions

Looking for critical feedback on talk, please reach out:
gpitel@magna-power.com

Factory Tour and General Meeting
Friday September 16th, 4 - 6pm ET
39 Royal Road
Flemington, NJ 08822

https://bit.ly/3S9PLbM