3D Printed Micro-channel Heat Sink Design Considerations

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Motivation / Background

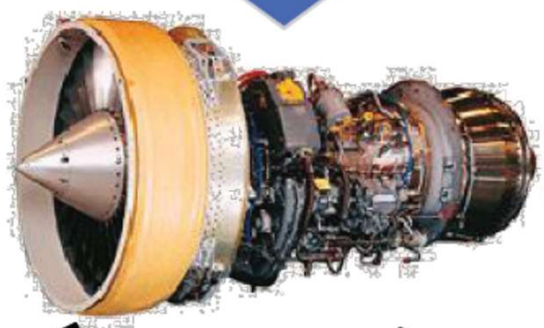
- New generation of airplanes becoming “More Electric”
  - Traditional pneumatic and hydraulic systems on airplanes are being replaced with electrical devices
  - More electrical equipment is being added to airplanes
- Most airplane equipment requires DC power to operate, while generation and distribution is done through 3-phase AC power
- Therefore, AC power needs to be converted into DC power
  - This is done with power conversion equipment
- AC-DC power conversion units are influencing airplane’s generator, wire and filter sizes
- Bulky magnetics in AC-DC converters for distribution power and high power motor loads are difficult to cool – driving size and weight
- Liquid cooling becomes a necessity.

Traditional Airplane

Pat Wheeler, “ The More Electric Aircraft, Why Aerospace Needs Power Electronics”, University of Nottingham, Nottingham, UK

Jet Fuel

200kW Electric Power



Propulsion Thrust (≈ 40MW)

Electrical	Pneumatic	Hydraulic	Mechanical
Gearbox driven generators	High pressure air “bled” from engine	Gearbox driven hydraulic pump	Fuel pumps and oil pumps on engine
200kW	1.2MW	240kW	100kW

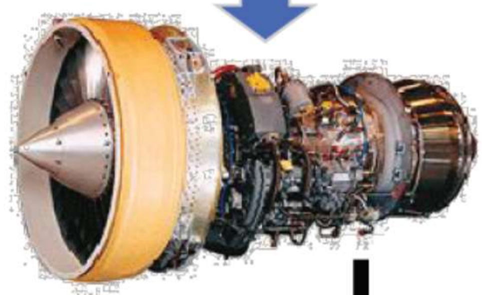
Total “non-thrust” power ≈ 1.7MW

More Electric Airplane

Rationalization of power sources and networks

“Bleedless” engine

Jet Fuel



Propulsion Thrust (≈ 40MW)

Pat Wheeler, “ The More Electric Aircraft, Why Aerospace Needs Power Electronics”, University of Nottingham, Nottingham, UK

Engine driven generators

Expanded electrical network

Existing electrical loads

ELECTRICAL
Cabin pressurisation
Air conditioning
Icing protection

ELECTRICAL
Flight control actuation
Landing gear/ Braking
Doors

ELECTRICAL
Fuel pumping
Engine Ancillaries

New electrical loads

Electrical system power ≈ 1MW

Majority of load demand on more electric aircraft is from high power motor loads sourced from HVDC (270 Vdc or 540 Vdc)

Liquid Cooling Options

- Liquid-air heat exchanger
- Liquid immersion
- Individual component cooling
- Spray cooling/jet impingement
- Heat pipe
- Cold plate
  - Tubes
  - Machined/casted/3D printed channels

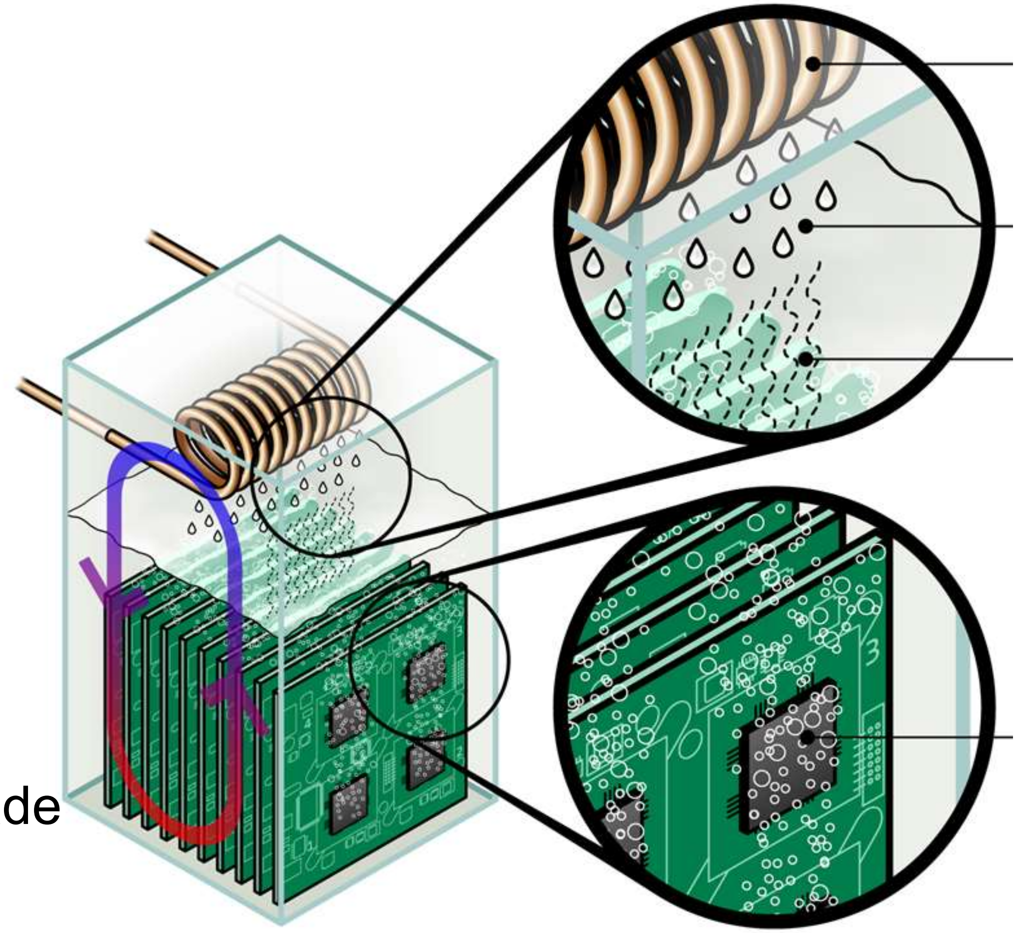
Liquid Cooling Options: Liquid Immersion

Advantages:

- COTS assembly
- Great thermal performance

Disadvantages:

- Lack of reliability
  - Contaminations
  - Leaks
  - Chemical reactions
- More difficult to maintain
- Challenging to repair/upgrade
- Weight issues



http://www.allied-control.com/immersion-cooling

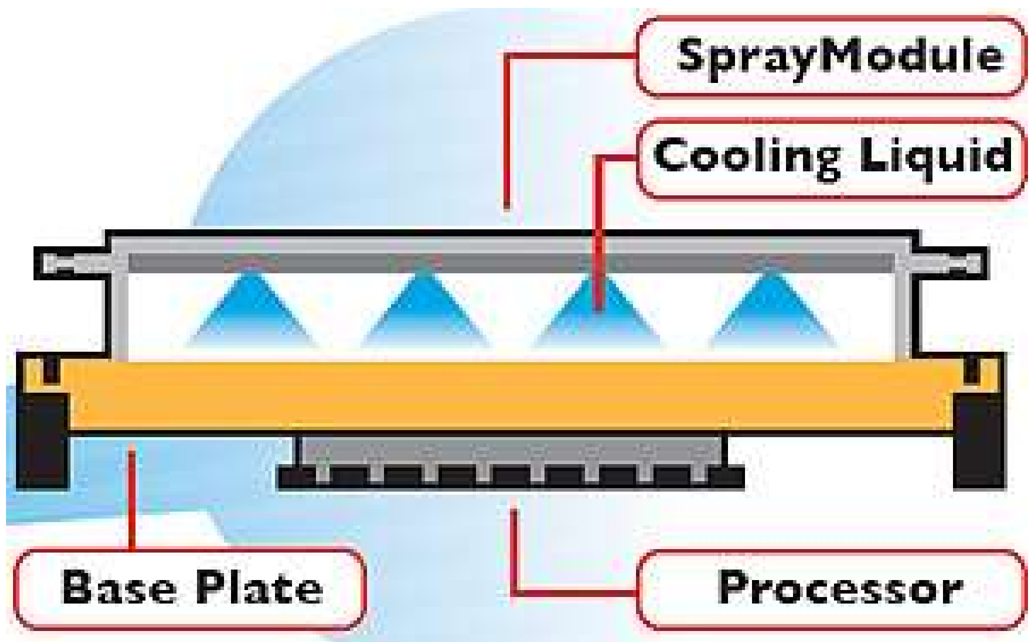
Liquid Cooling Options: Spray Cooling/Jet Impingement

Advantages:

- Great for cooling COTS assembly
- Lower weight
- Hot spot cooling

Disadvantages:

- Lack of reliability
  - Contamination
  - Small pumps
  - Nozzles
  - Leaks
  - Chemical reactions
- More difficult to maintain
- Challenging to repair/upgrade



http://www.frostytech.com/

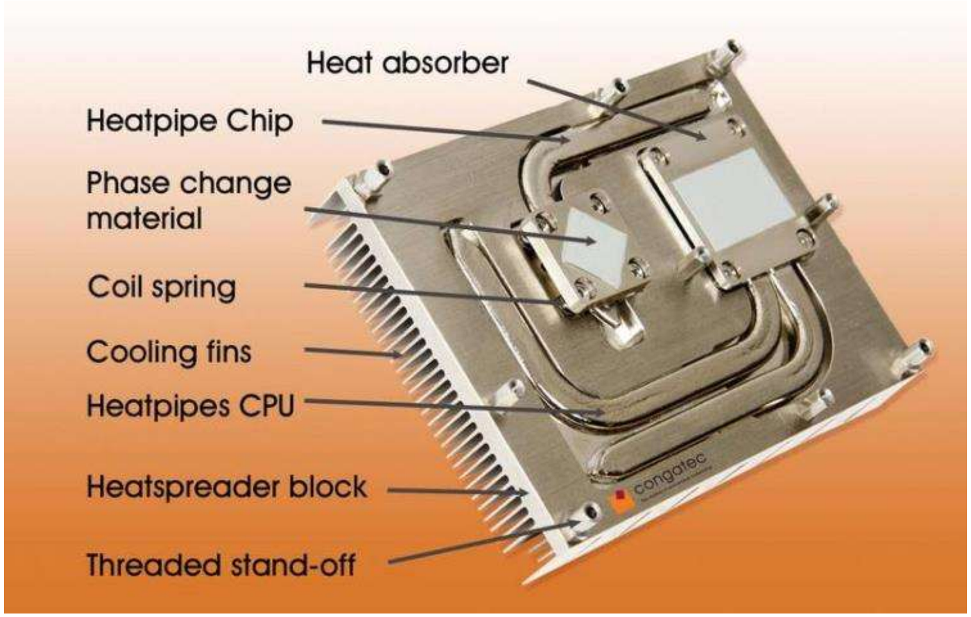
Liquid Cooling Options: Heat Pipe

Advantages:

- Lower Weight
- Simple
- Passive

Disadvantages:

- Cannot transfer heat to longer distance
- Less long-term reliability
- Potential for freezing
- Need additional heatsink



http://www.congatec.com/

Liquid Cooling Options: Cold Plate

Cold plate types:

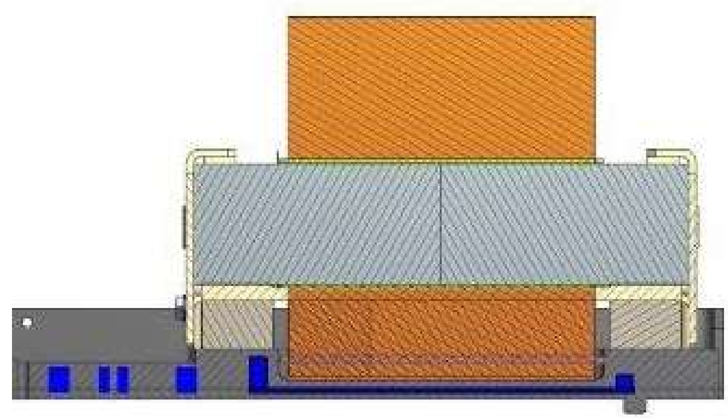
- Tubes
- Machined/cast channels
- Serial
- Parallel

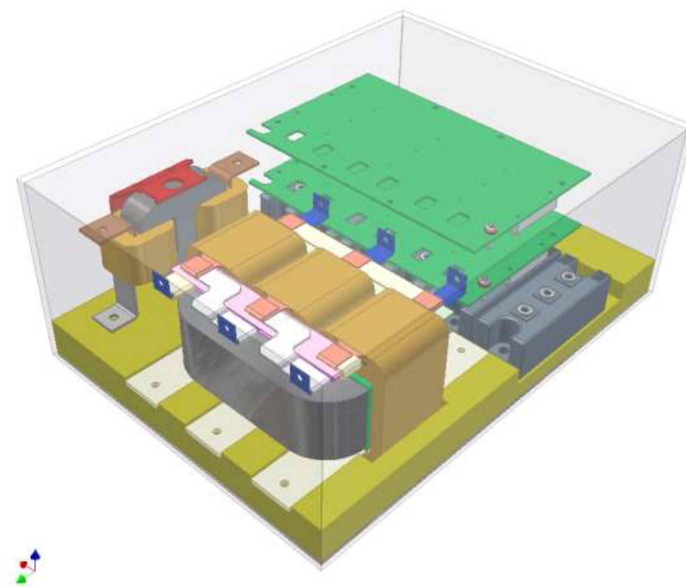
Advantages:

- High Reliability
- No restrictions to liquid
- Can carry structural load
- Easier to maintain, repair, and overhaul

Disadvantages:

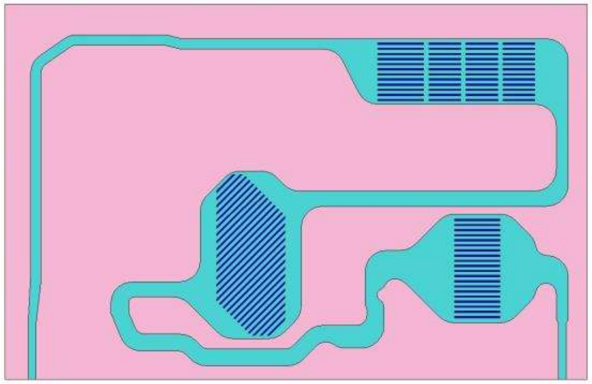
- Need conduction paths
- Position sensitive (see later slides)



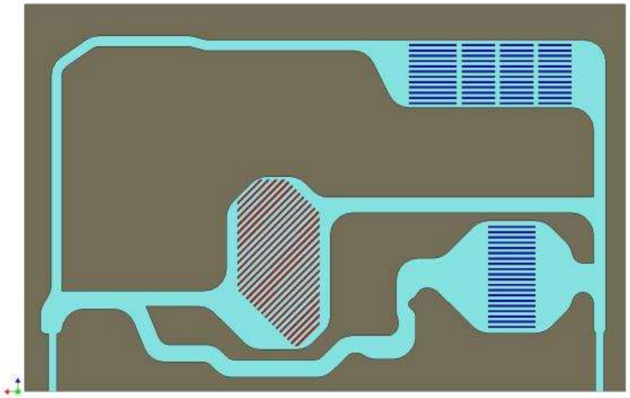


Cold Plate Issues

- Serial channel cold plate
  - Harder to route
  - Fluid channel's dimension is larger
  - Higher pressure losses
  - Liquid temperature rises
  - Cannot provide point of thermal load cooling
  - Relies on solid cold plate material conduction

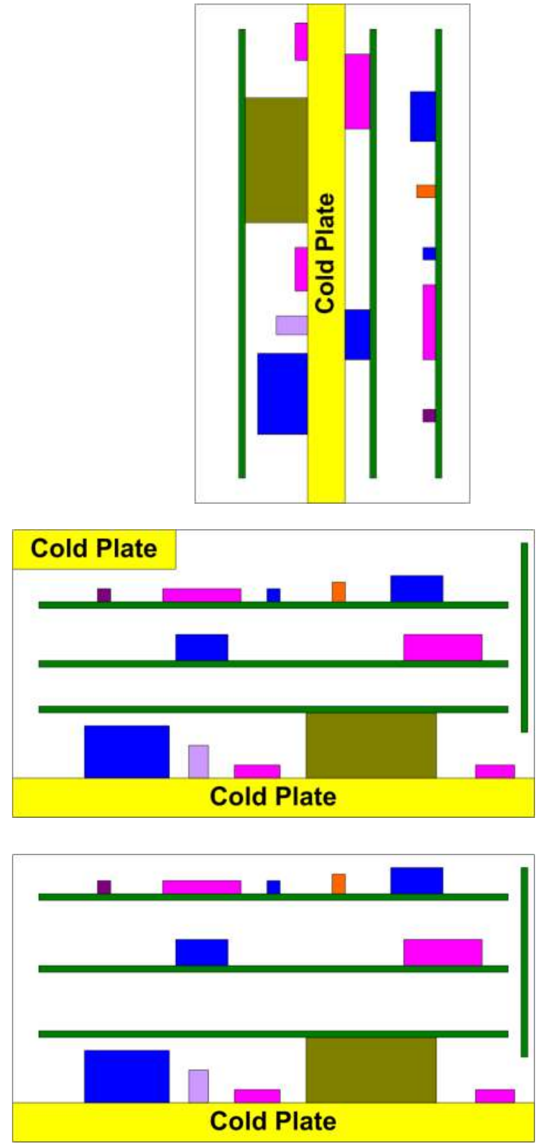


- Parallel Channeled Cold Plate
  - Complicated calculation and design
  - Need higher precision production (for pressure balance)
  - Need to balance the pressure losses
  - Lower heat exchange rate

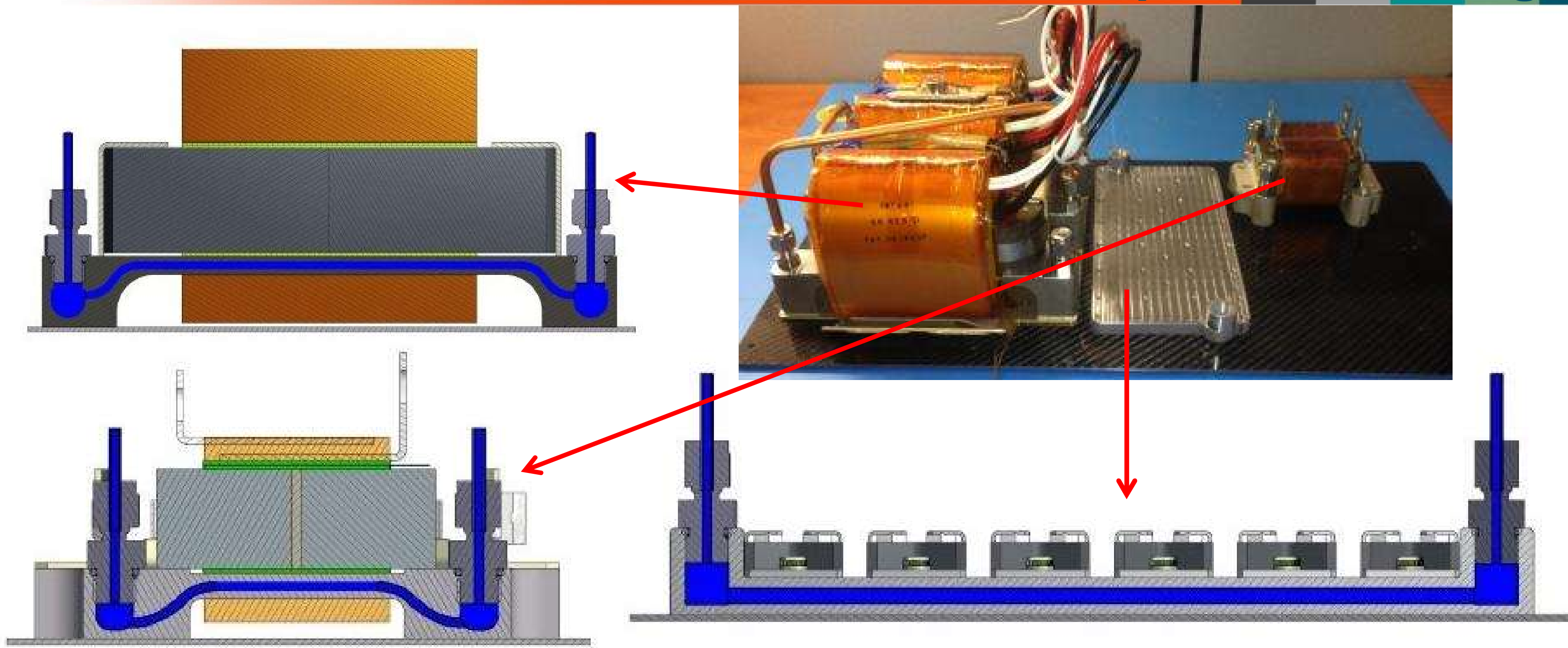


Cold Plate Issues (Internal Air)

- Internal air temperature of liquid cooled electronics is often ignored
- Not all heat dissipating components are thermally coupled to cold plate
- The upper surfaces of the thermally coupled components are also releasing heat into internal ambient air
- Components with very small heat dissipation can end up very hot in liquid cooled electronics if not thermally coupled to the cold plate
- Heat released into the internal (box) ambient air needs to be addressed
- If not designed properly, the heat can be released to EE bay from liquid cooled electronics
- Smartly positioning the cold plate as shown can address these problems



Liquid Cooling Options: Individual Component Cooling



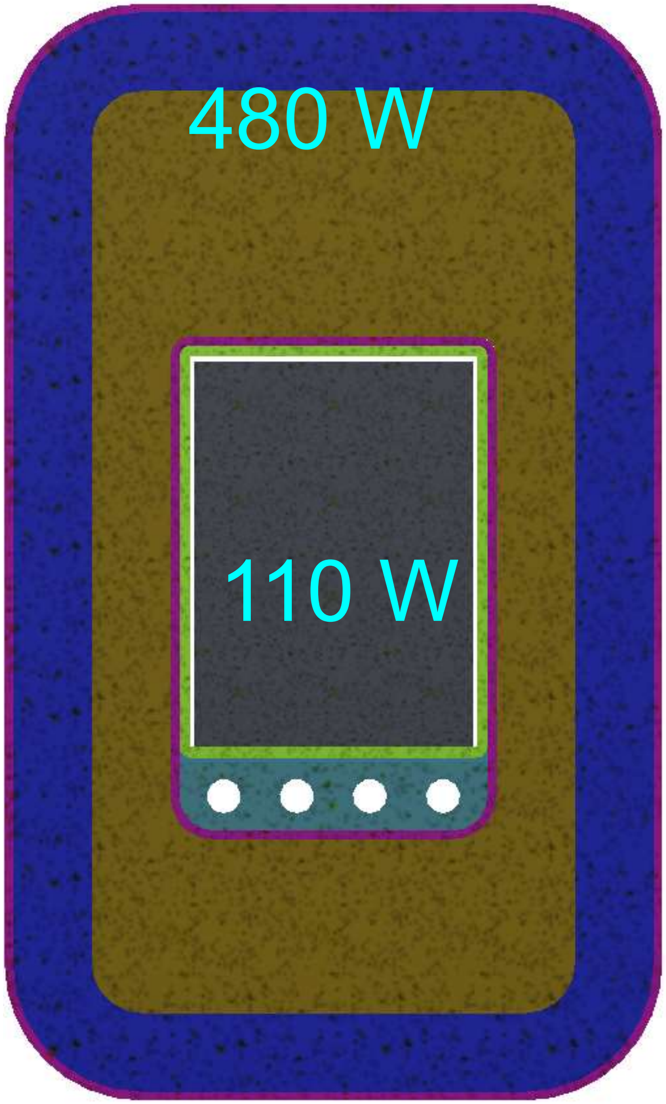
Advantages:

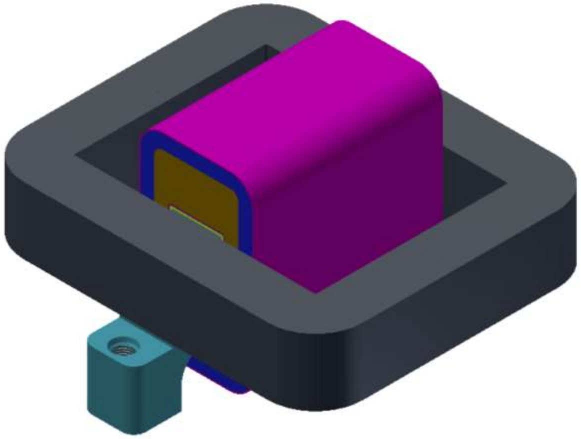
- Light weight
- Small
- Efficient

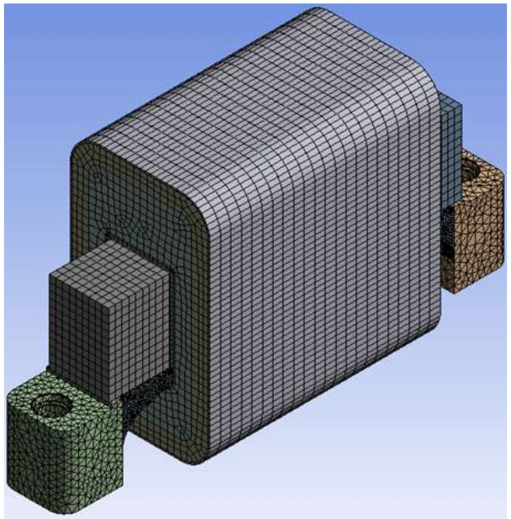
Disadvantages:

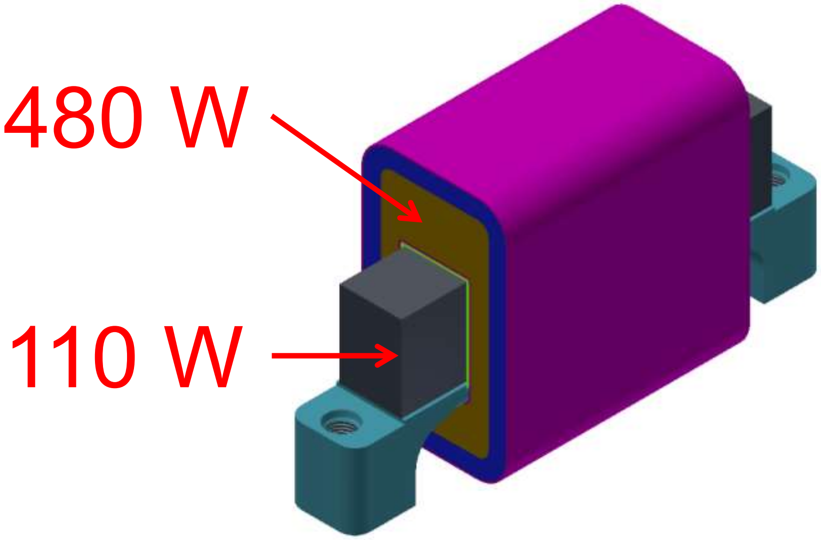
- Connections
- Availability
- Complexity

Liquid Cooled Coil Construction



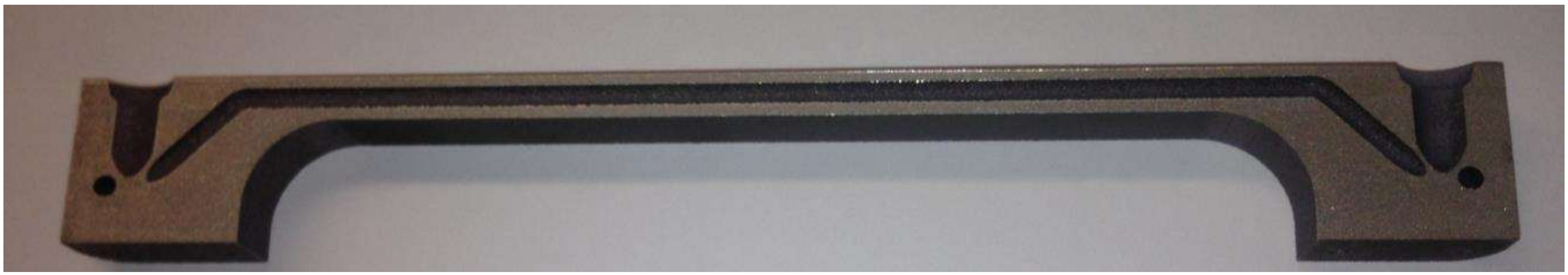


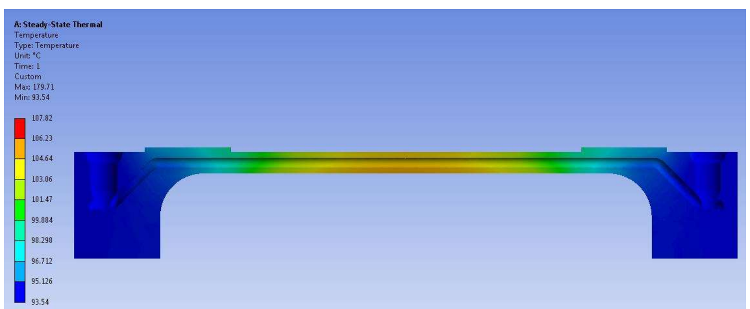


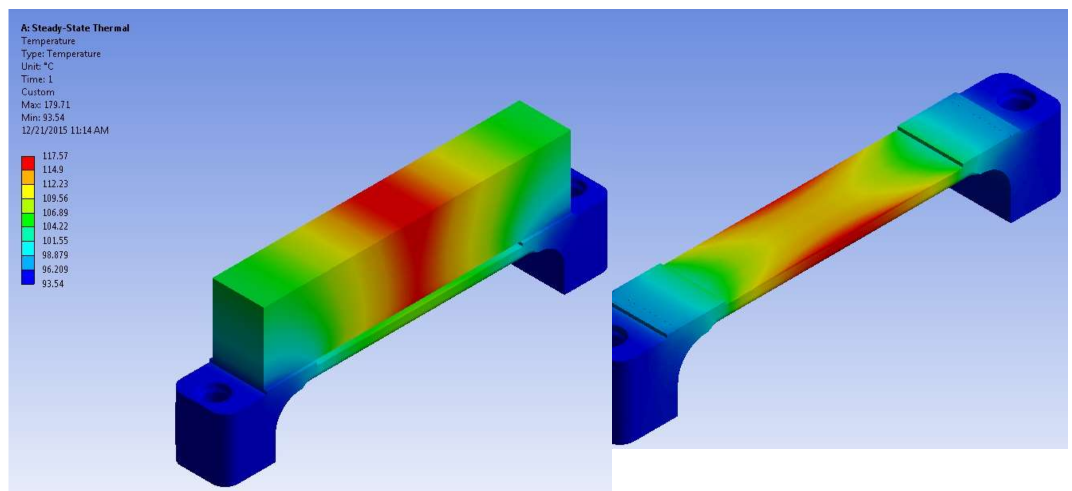


Thermal Analysis

Internal “rough” surfaces enhance the heat transfer co-efficiency to liquid







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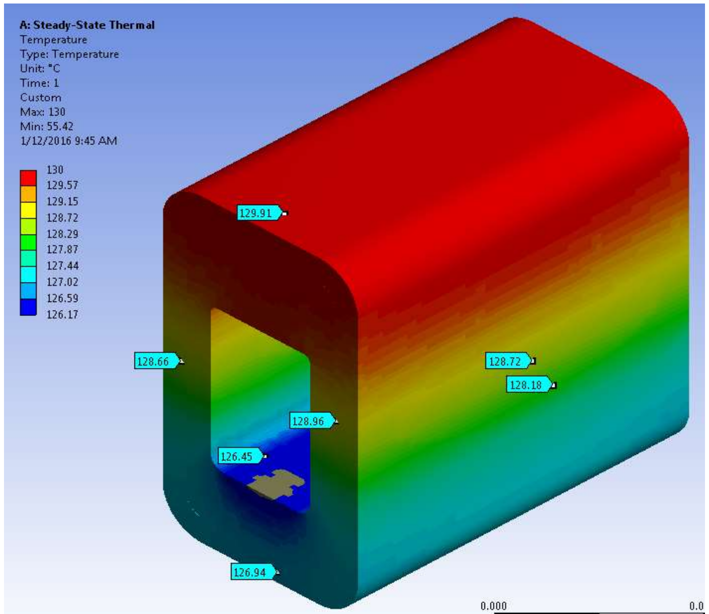
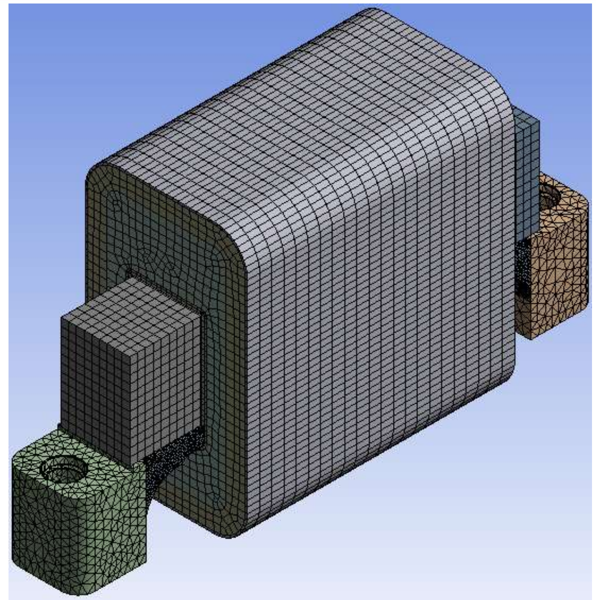
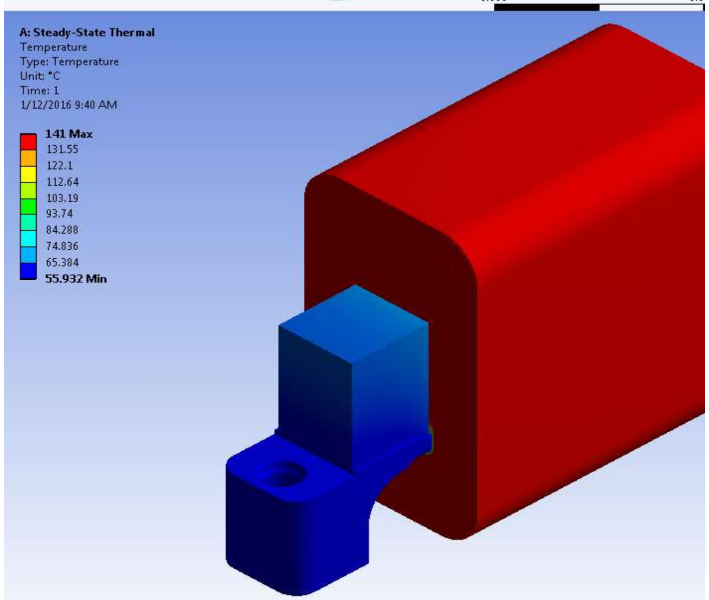
Thermal Analysis





Transformer coil internal cooling creates uniform temperature distribution. This reduces the hot spot temperature and extends the reliability of the transformer.



Transformer Temperature Comparison (Component Function Descriptions)	Cold Plate Cooling	Individual Component Cooling
Coil Outer Surface	116 C	130 C
Coil Center	140 C	130 C
Core Surface	72 C	72 C
Core Center	78 C	78 C

Weight Benefit

- Since the large metal cold plate is no longer necessary, the structure load can be carried by carbon fiber epoxy material.

Weight Comparison Carbon Fiber Epoxy Chassis versus Cold Plate Metal Chassis	Cold Plate Cooled ATRU Weight	ATRU with Carbon Chassis Weight
Electrical Connectors (4 X) and Handles (2X)	1%	1%
Total Chassis	24%	11%
Rectifiers Cooler		3%
Transformer	43%	46%
Rectifiers X 12	2%	2%
Input Filter	6%	6%
Output Inductor	6%	5%
Output Capacitor	6%	6%
Status & Output High Frequency Filter CCA	1%	1%
Bus Bar & Interconnect	4%	4%
Fluid 62% EGW	1%	1%
Miscellaneous, Hardware, and Fluid fittings	5%	5%
Total Weight	100%	90%

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Why 3D printing technology?

- Freedom in Design
  - No longer bound by traditional machine capabilities
  - Can produce far more complicated geometries
  - No restrictions in hollow structures
  - Small features are possible
  - No crack, void or any other type liquid passages
- Shorter Development Cycles
  - Short lead time in manufacturing
  - No tooling is needed
  - Less programming and setup times
- Future Technology
  - Additive Manufacturing technology is fast evolving
  - With new technologies and vendors emerging, the cost of production will reduce rapidly
  - Many new possibilities in design

Existing 3D Printing Technology

- Fused deposition modelling (FDM)
- Electron Beam Freeform Fabrication (EBF3)
- Direct metal laser sintering (DMLS)
- Electron-beam melting (EBM)
- Selective laser melting (SLM)
- Selective heat sintering (SHS)
- Selective laser sintering (SLS)
- Plaster-based 3D printing (PP)
- Laminated object manufacturing (LOM)
- Stereo Lithography (SLA)
- Digital Light Processing (DLP)
- New additive manufacturing technologies are emerging

Technologies and Manufacturers

Technology	Manufacturer(s)
Laser Sintering	3D Systems Corp., U.S.A.
Direct Metal Laser Sintering (DMLS), a trademark name for laser sintering tech	EOS,Germany (privately held)
Selective Laser Melting (SLM)	Renishaw,U.K. (listed on London Stock Exchange)
	SLM Solutions,Germany (privately held)
Electron Beam Melting (EBM)	Arcam, Sweden
LaserCUSING, a laser sintering tech	Concept Laser, Germany (privately held)
Digital Part Materialization (DPM), or what the ASTM considers binder jetting	ExOne, U.S.A.
Laser Engineered Net Shaping (LENS)	Optomec, U.S.A. (privately held)

Direct Metal Laser Sintering (DMLS)

- Parts are grown micro-layer by micro-layer, with an average thickness of 30 microns.
- The powdered material is distributed by a sliding metal arm on to the printing platform.
- The 3D file directs the 400 W fiber laser to heat the powdered substance layers together at specific points, fusing the particles and transforming the material into solid form.
- The powdered metal is precisely distributed across the build platform with a re-coater arm.
- Proprietary software slices the engineered 3D files into micro-thin layers and controls a 400W fiber optic laser to sinter the exposed layer to the layer before it, fusing the particles and transforming the material into solid form.

Additive Manufacturing Design Considerations

- The misconceptions of 3D printing are that anything, any design, can be printed
  - There are limitations of 3D printing technologies
  - These limitations are different from technology to technology
  - Not all materials can be used
  - Powder based system have more design challenges than wire based
  - Liquid bases systems can only print polymers
  - Thermoplastic is an easier material to print
  - Polymers are much easier to deal with than metal
  - Not all metals can be "printed"
  - Metal printer needs to be protected by inert gas (Argon)
  - Nitrogen is cheap, however, it can change metal properties

DMLS Design Considerations

- Metals
  - DMLS can only print metal materials
  - Not all metal materials can be used
  - For a heatsink, metal is the best choice
  - CTE, thermal conductivity, etc
  - Materials that can be welded by laser are the best candidates
- Material “growth” Direction
  - This is one of the most important factors during the design
  - Think about how to add materials over a part
  - Sintered material need to “stick” together
  - Laser may penetrate through the metal powders
  - How is the finished part separate from the base matters

Laser Weldability of Materials

Material	Comment
Carbon steel	Welds well. If carbon content > 0.2 % brittle welds.
Stainless steel	300 series welds well except alloys with S > 0.05 % 400 series welds brittle
Copper	High refectivity requires high peak power
Cu-Be	Welds well but particles hazardous
Bronze (Cu/Sn)	Reasonable welds
Brass (Cu/Zn)	Outgasing of zinc prevents good welds
Aluminium	Pure Al (1xxx) welds well, only a few alloys weld crack free (2219, 3003). Filler material 4047 or combination of alloys may improve result (e. g. 6061 with 4047),
Titanium	Welds well. Very good shielding with inert gas necessary
Gold, Silver, Platinum	High reflectivity requires high peak power
Nickel	Welds well
Ni based super alloys	Welds well if Ti + Al content < 4 %
Kovar	Welds well
Tantal	Welds well. Very good shielding with inert gas necessary
Molybdenum	Usually welds brittle – may be acceptable where high strength is not required

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DMLS Design Considerations

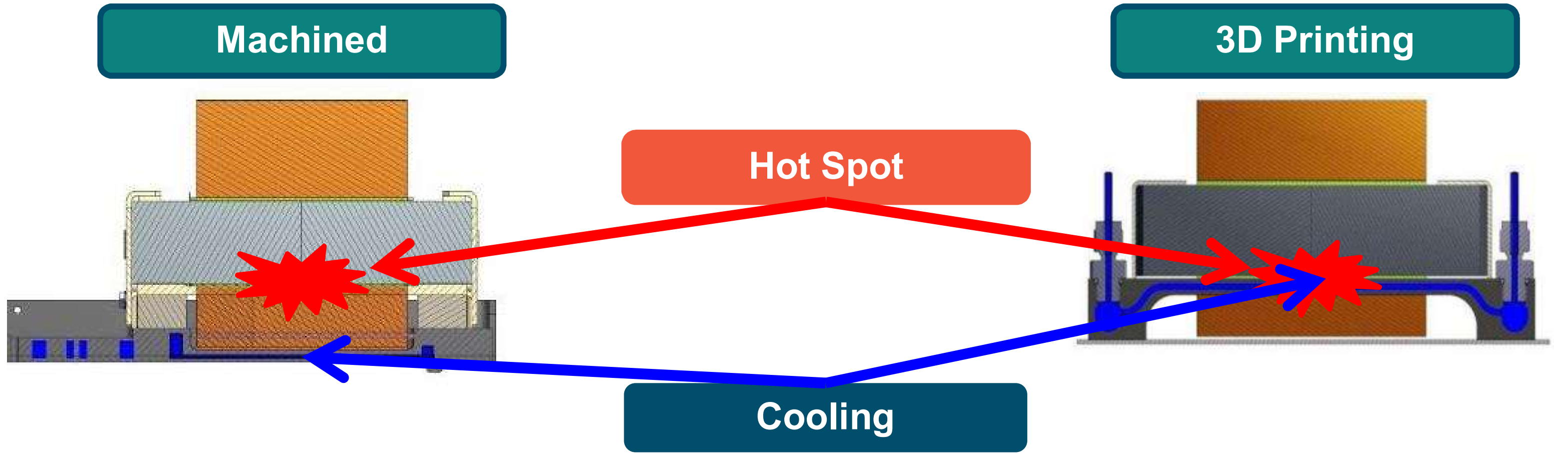
- Cavity Supports
  - Can powder support the sintered materials?
  - Will a laser penetrate through the powder?
  - 45 degree rule is typical
  - If holes are not aligned with gravity, diameter of the holes matter
  - Recommending dome shaped cavity
    - Top of the dome needs to be rounded
- Surface Roughness and small features
  - The finished part surface roughness is similar to casting
  - 3D print fine threaded hole is not practical due to roughness
  - Sharp corners are not practical
- Post Process
  - Particle blasting, chemical cleaning, machining
  - Drill and tap threaded features
  - Smooth surface polishing

Additive Manufacturing Method Discussions

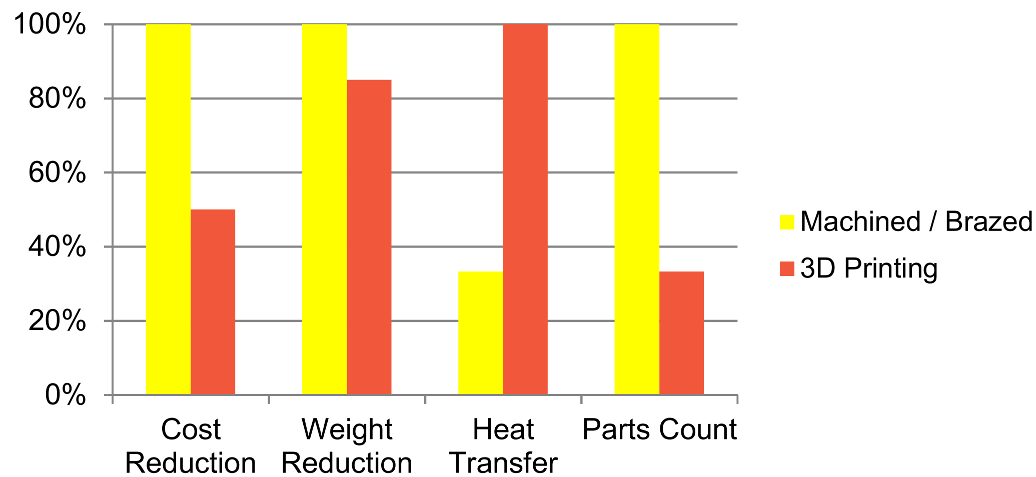
- Additive manufacturing method (or 3D printing) will revolutionize the design and manufacturing
- We are at the early stage of this revolution.
- The "Direct Metal Laser Sintering" may be the best technology today. It will not be the best technology tomorrow.
- There is no "best" technology in additive manufacturing. Only better technology exists.
- The next step in additive manufacturing will be the technology that can produce the part in multiple materials.
- 3D print a traditional design is not the right way to move forward.
- We should rethink about the designs that can take full advantages of the new technology.

Summary – Better Results using 3D Printing

High Power Product Example

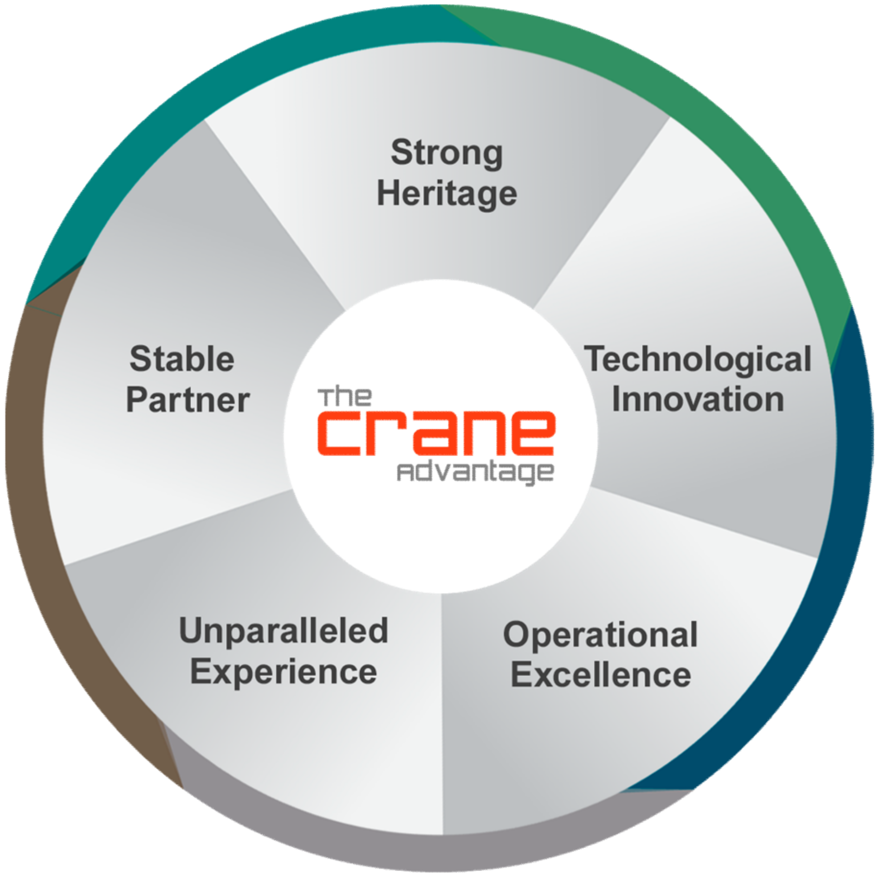


- Individual component liquid cooling offers the lowest weight solution that will be attractive to airborne hardware electronics industry



Lower cost, weight & part count.
Dramatically improved heat transfer

The Crane Advantage!



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