Cryogenic system options for a superconducting aircraft propulsion system

C2OrH

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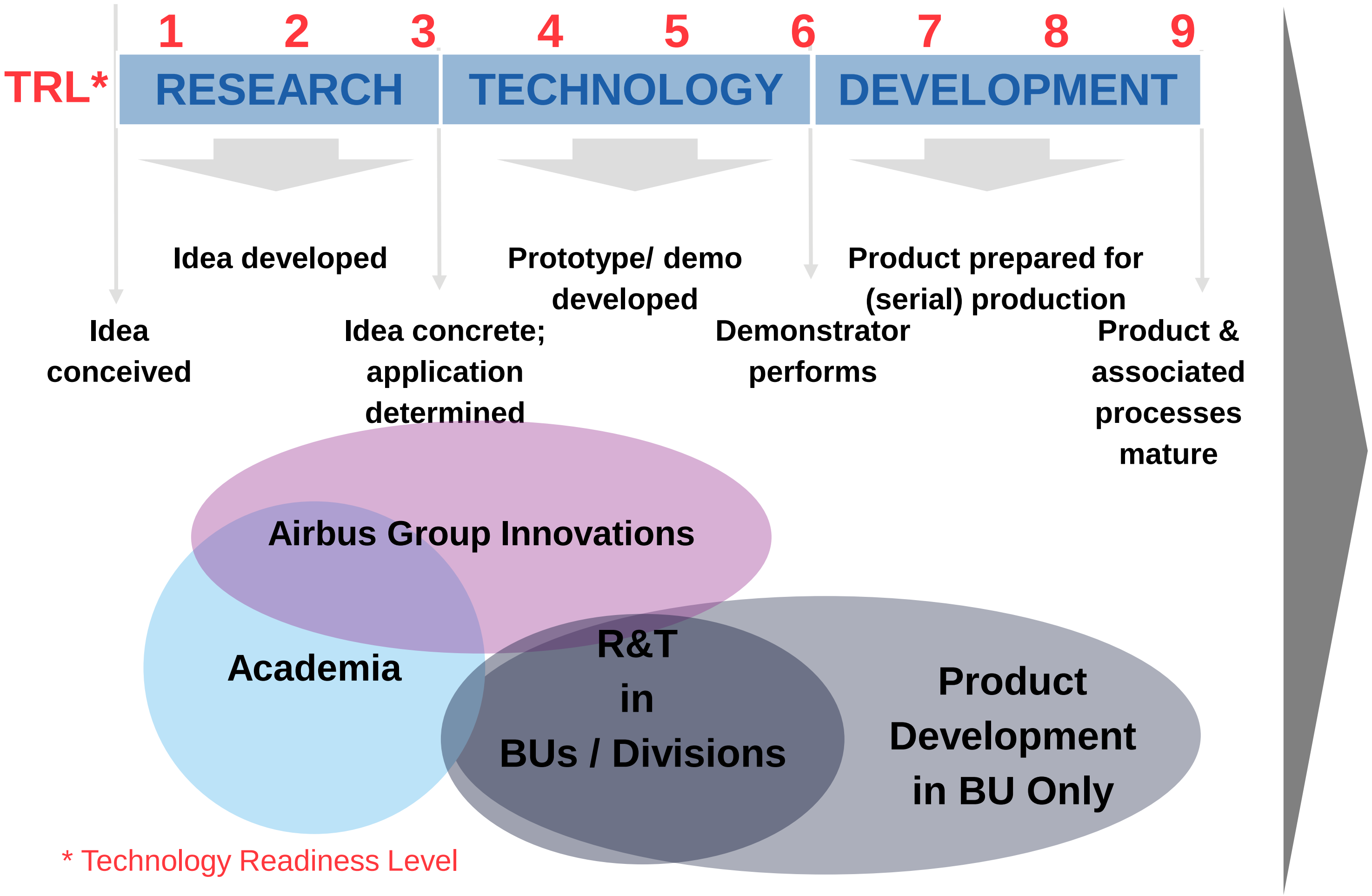


* Technology Readiness Level

Introduction
DEAP project

- Distributed Electrical Aerospace Propulsion part-funded by UK Technology Strategy Board

AIRBUS GROUP   Cranfield UNIVERSITY   Rolls-Royce

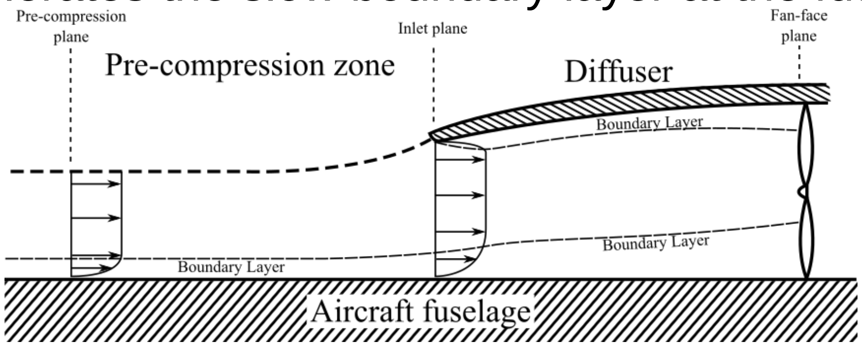
- 2-year project: March 2013 – March 2015

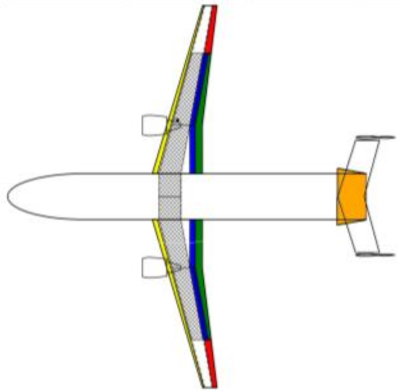
- Research area is in distributed propulsion, boundary layer ingestion and the enabling electrical system with superconducting machines and power distribution

Introduction

Context in aircraft

- Need for disruptive aircraft configurations to improve fuel efficiency in the future
- Distributed propulsion is one possible way of producing thrust more efficiently, e.g. by enabling boundary layer ingestion (BLI)
- BLI re-accelerates the slow boundary layer at the fuselage in order to reduce drag

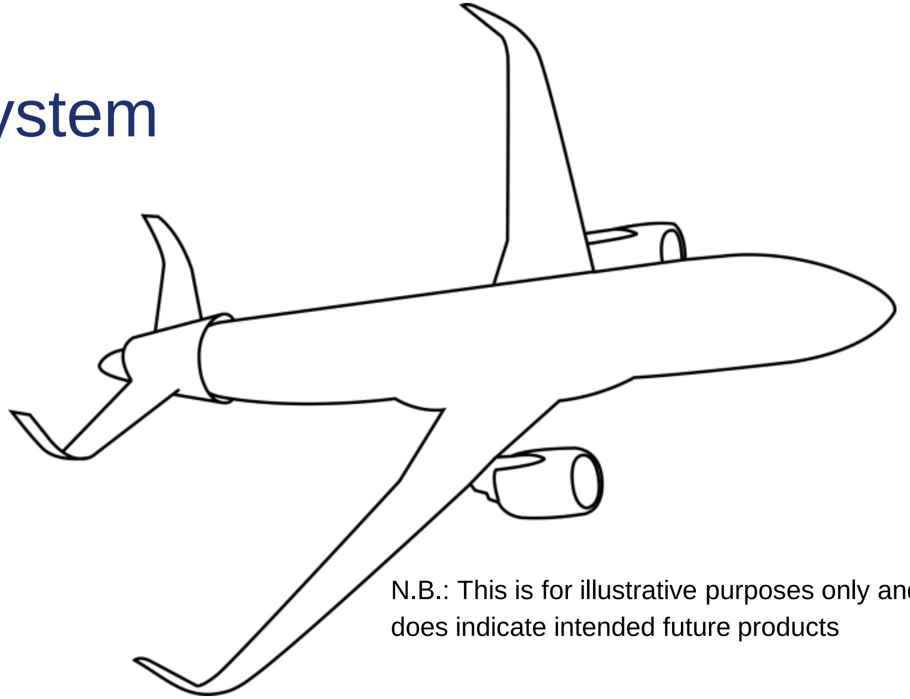




- Example aircraft electrical system power levels:

Conventional twin-aisle: ~300 kW | More-electric aircraft: ~1 MW | Future hybrid/all-electric aircraft: 5 – 100 MW

Superconducting aircraft propulsion system



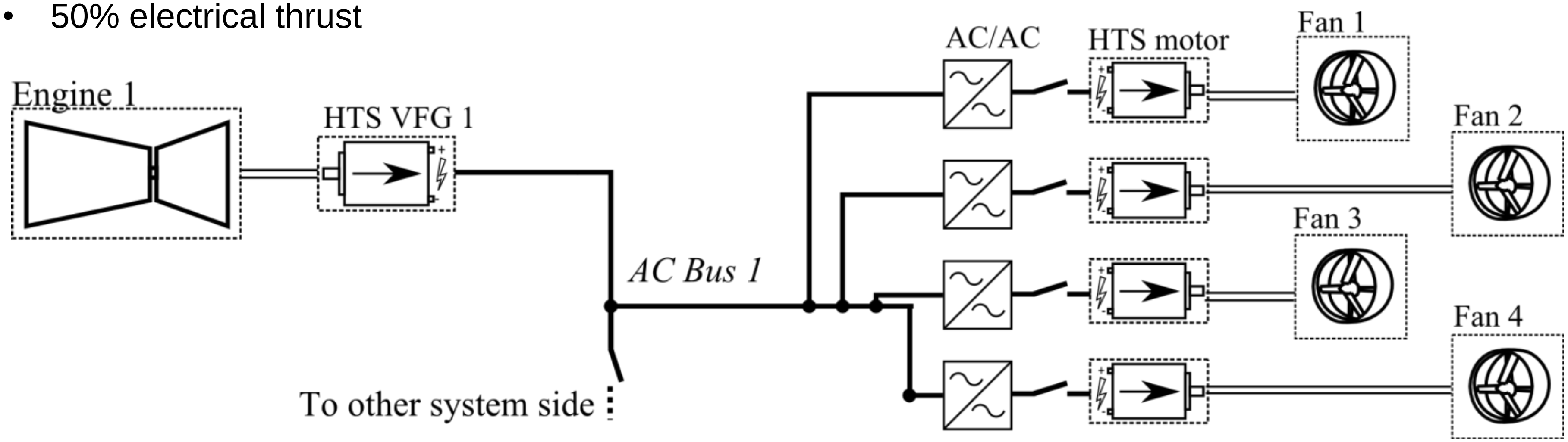
N.B.: This is for illustrative purposes only and does indicate intended future products

Aircraft propulsion

- 2 turbofans under wings
- 8 ducted fans around rear fuselage

Electrical system

- 2 generators, 8 motors
- Superconducting machines
- Superconducting AC transmission
- Cryogenic power electronics (~100 K)
- Contiguous cryostat
- 50% electrical thrust

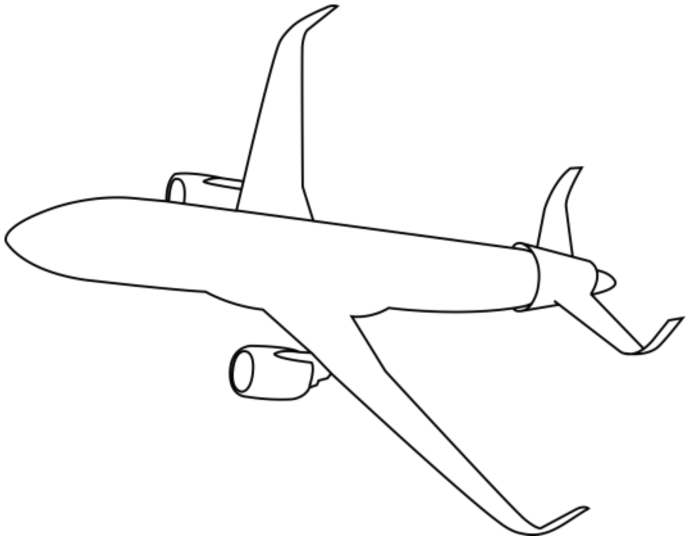


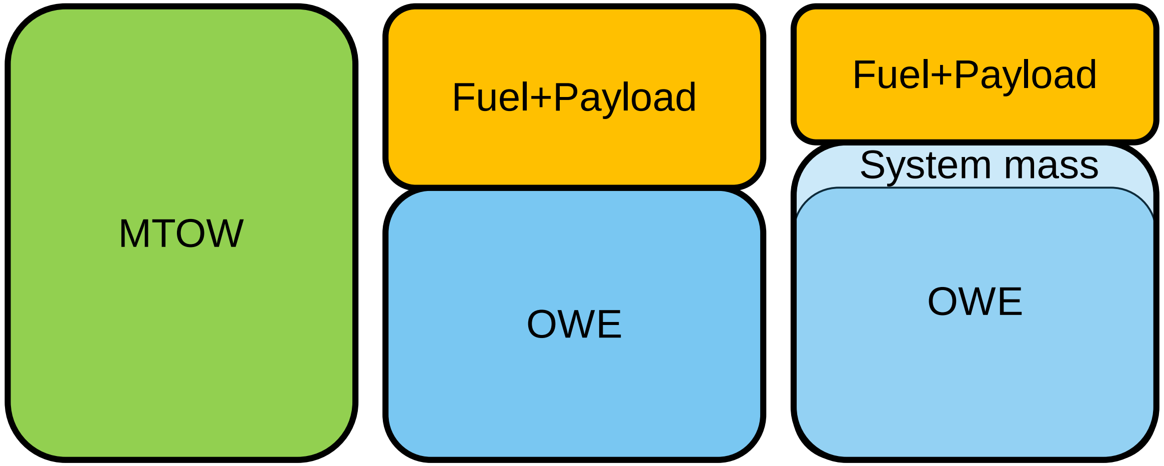
System-level targets

- **Still a subject of ongoing research!**

- Aerodynamic/propulsion efficiency benefits in literature: 10-20% fuel burn savings
- Conversion and transmission system efficiency must be better than 90%
- Superconducting system may need to be better than 95% efficient to be attractive
- ~3% of electrical power available for cryogenics

- Aircraft Maximum Take-Off Weight (MTOW) sizes major components (landing gear, wings, high-lift devices)
- Reduced fuel requirements can offset additional system mass
- Operating weight empty (OWE) should aim for less than 10% increase
- Cryogenics maximally 2/3 of electrical system mass





Cryogenic system options
Main architectures, operating temperature

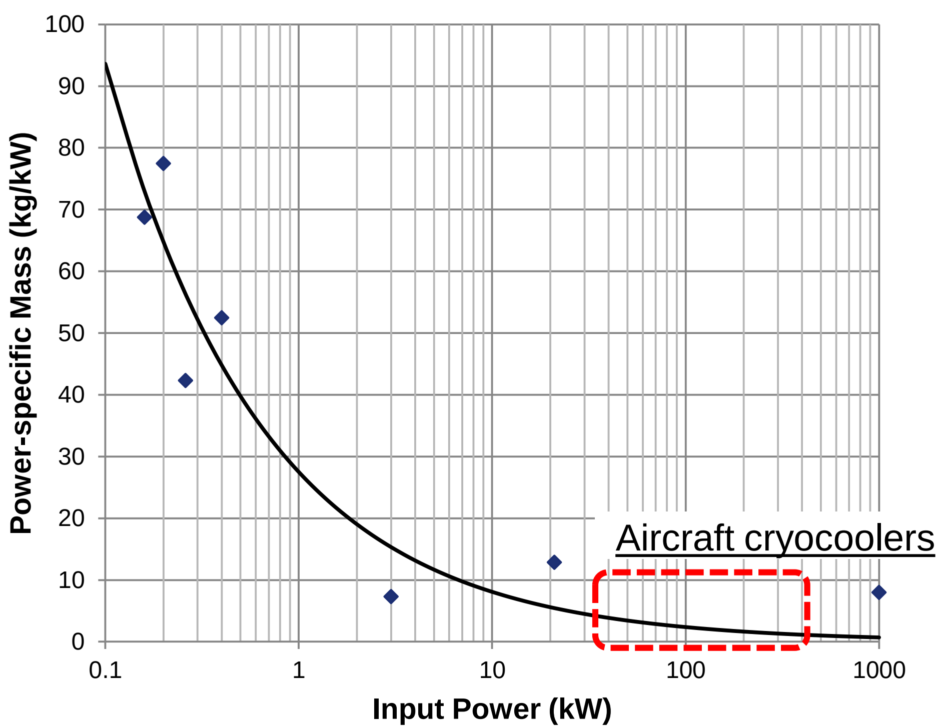
Main cooling system philosophies:

Fully decentralised: Each machine or subsystem has a closed cooling loop with a cryocooler.

Partly centralised: Central coolers provide medium-temperature circuit and local cryocoolers provide final cooling

Fully centralised: large cryocoolers maintain a closed loop of cold fluid at the superconducting operating temperature. Reverse-Brayton cycle most likely (scalability, reliability)

Reverse-Brayton cryocooler survey [1]



Operating temperature

- Materials carry higher current with lower temperature
- Temperatures below 50 K likely to be needed for light machines using YBCO/BSCCO
- MgB2 is promising for making windings and suppressing AC losses. Temperatures below 30 K needed
- 20-30 K target temperature is current assumption

[1] Palmer et al. “Modelling of Cryogenic Cooling System Design Concepts for Superconducting Aircraft Propulsion”, IET Journal, Submitted for publication 2015

Cryogenic system options
Heat sinks

- Independent aircraft operation required up to ~350 K
- Cryocoolers less efficient -> heavier with higher ΔT
- Drag and icing a possible issue with air heat exchange

Main heat sink contenders:
Liquid methane/LNG and liquid hydrogen
  - Useful temperatures
  - High latent heat
  - Good potential as fuels to displace kerosene

LCH4:
- Engine alterations small for LCH4/LNG combustion
- LCH4 combustion is clean and efficient

LH2:
- LH2 more expensive, harder to handle, high volume
- but... Lower temperature, higher energy per kg
- Less simple to combust (may need separate fuel cell/engine)

TH = 300 K

eta_fc	0.1	0.2	0.3	0.4	0.5
T_c (K)	Power demand (% of system power)				
60	8.0%	4.0%	2.7%	2.0%	1.6%
50	10.0%	5.0%	3.3%	2.5%	2.0%
40	13.0%	6.5%	4.3%	3.3%	2.6%
30	18.0%	9.0%	6.0%	4.5%	3.6%
20	28.0%	14.0%	9.3%	7.0%	5.6%
15	38.0%	19.0%	12.7%	9.5%	7.6%

TH = 225 K (32,000 ft.)

eta_fc	0.1	0.2	0.3	0.4	0.5
T_c (K)	Power demand (% of system power)				
60	5.5%	2.8%	1.8%	1.4%	1.1%
50	7.0%	3.5%	2.3%	1.8%	1.4%
40	9.3%	4.6%	3.1%	2.3%	1.9%
30	13.0%	6.5%	4.3%	3.3%	2.6%
20	20.5%	10.3%	6.8%	5.1%	4.1%
15	28.0%	14.0%	9.3%	7.0%	5.6%

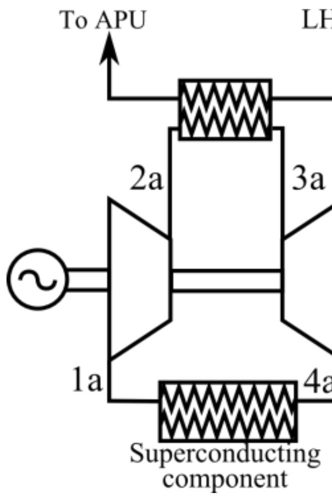
TH = 111 K (LCH4)

eta_fc	0.1	0.2	0.3	0.4	0.5
T_c (K)	Power demand (% of system power)				
60	1.7%	0.9%	0.6%	0.4%	0.3%
50	2.4%	1.2%	0.8%	0.6%	0.5%
40	3.6%	1.8%	1.2%	0.9%	0.7%
30	5.4%	2.7%	1.8%	1.4%	1.1%
20	9.1%	4.6%	3.0%	2.3%	1.8%
15	12.8%	6.4%	4.3%	3.2%	2.6%

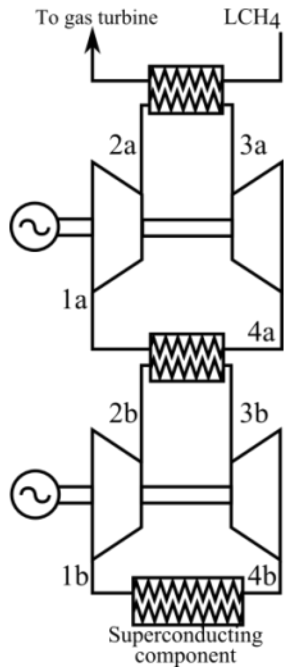
Sensitivity analysis
Systems under investigation

- Helium gas closed loops throughout

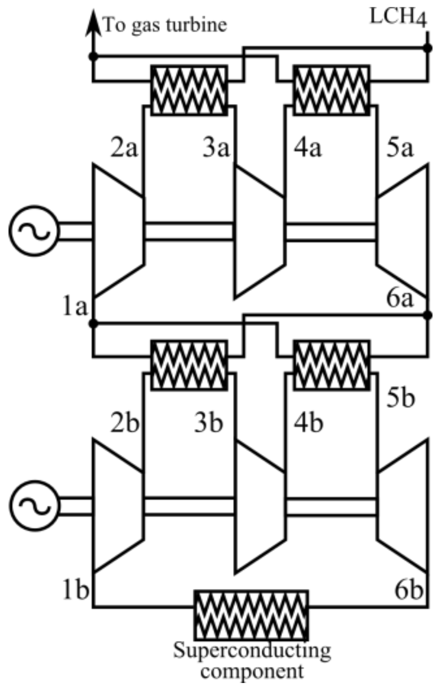
- LH2 coolant
- Single-stage RB cryocooler



- LCH4 coolant
- Two-stage RB cryocooler



- LCH4 coolant
- Two-stage RB cryocooler
- Intercooling in ‘parallel’ configuration



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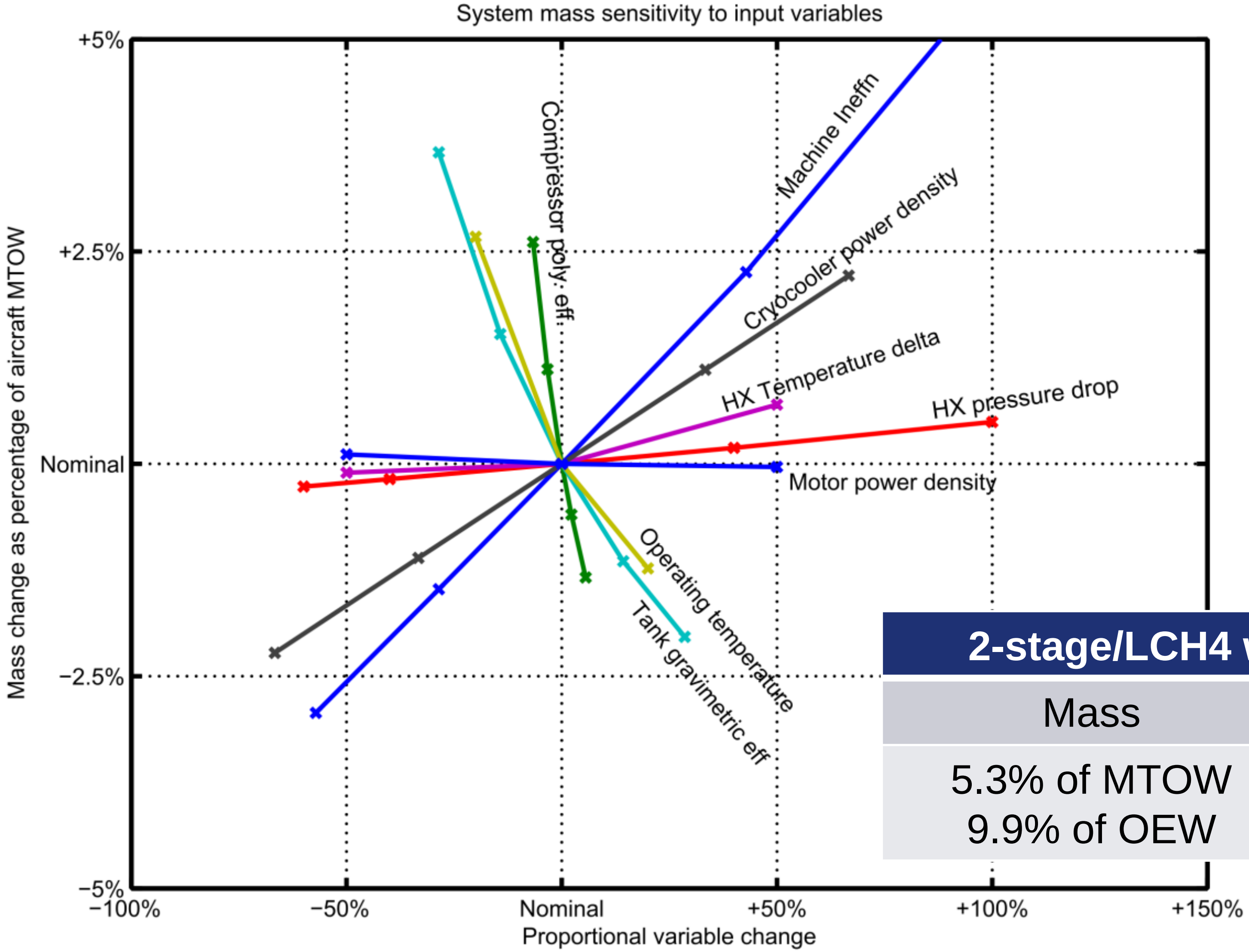
Sensitivity analysis
Variables

- Algebraic/Static models developed for three cryocoolers
- Models are subject to the main parameter assumptions below
- Nominal values in bold
- Range of possible outcomes considered in sensitivity study
- 5-hour cruise +10% safety margin assumed for coolant requirements
- Losses at cold temperature determined by machine electrical inefficiency only

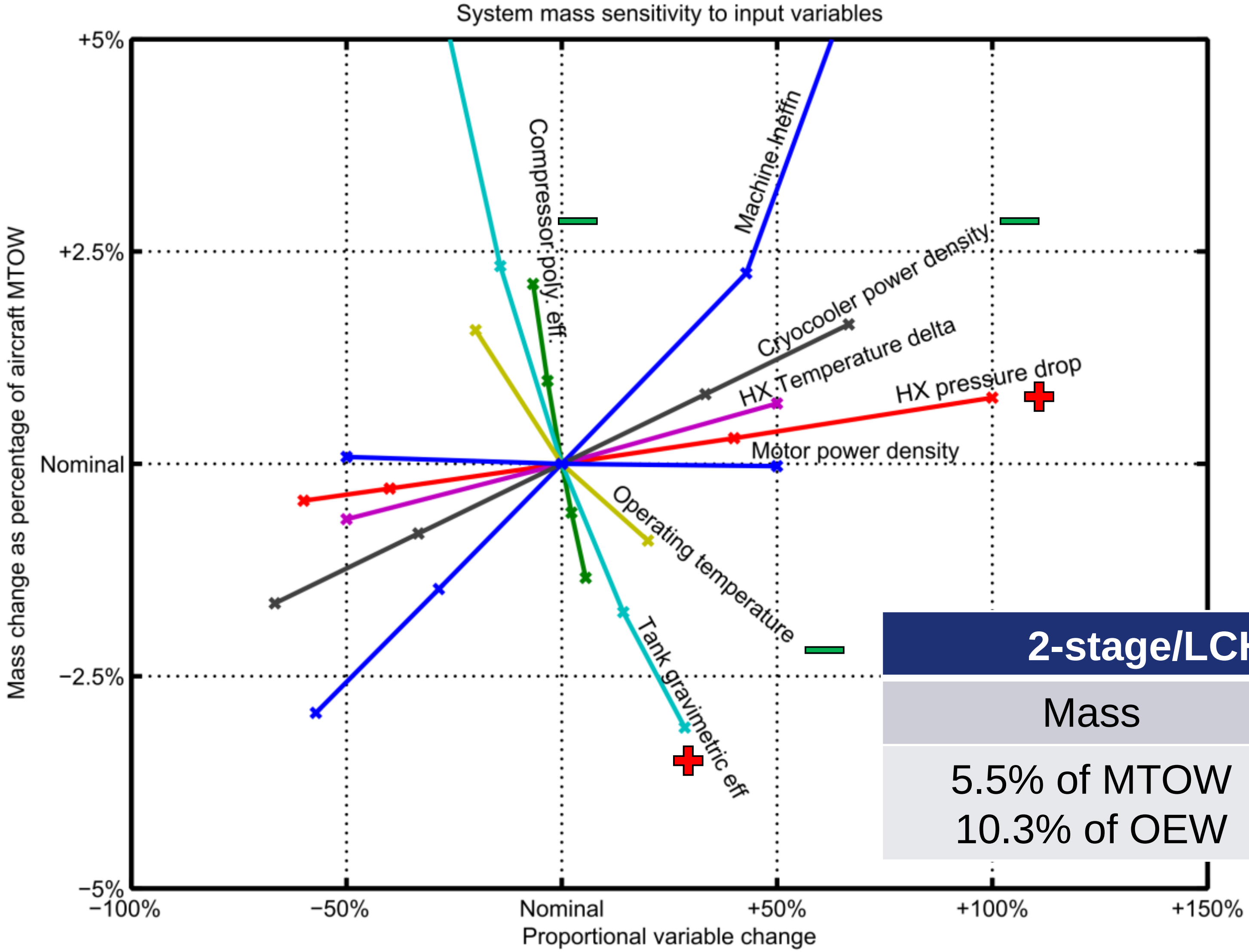
Parameter		**Units**	**Values**
Machine inefficiency at cold temperatures		%	0.03, 0.05, **0.07**, 0.1, 0.2
Compressor polytropic efficiency (Turbine +3%)		%	84, 87, **90**, 92, 95
Heat exchanger pressure drop		%	10, 7, **5**, 3, 2
Heat sink tank gravimetric efficiency	LH2	%	20, 30, **40**, 50, 60
	LCH4	%	50, 60, **70**, 80, 90
Heat exchanger minimum hot to cold side temp. differential		K	5, **10**, 15
Maximum component operating temperature		K	20, **25**, 30
Cryocooler total power density		kg/kW	5, 4, **3**, 2, 1
Motor power density		kW/kg	5, **10**, 15

Sensitivity results: 2-stage with LCH4



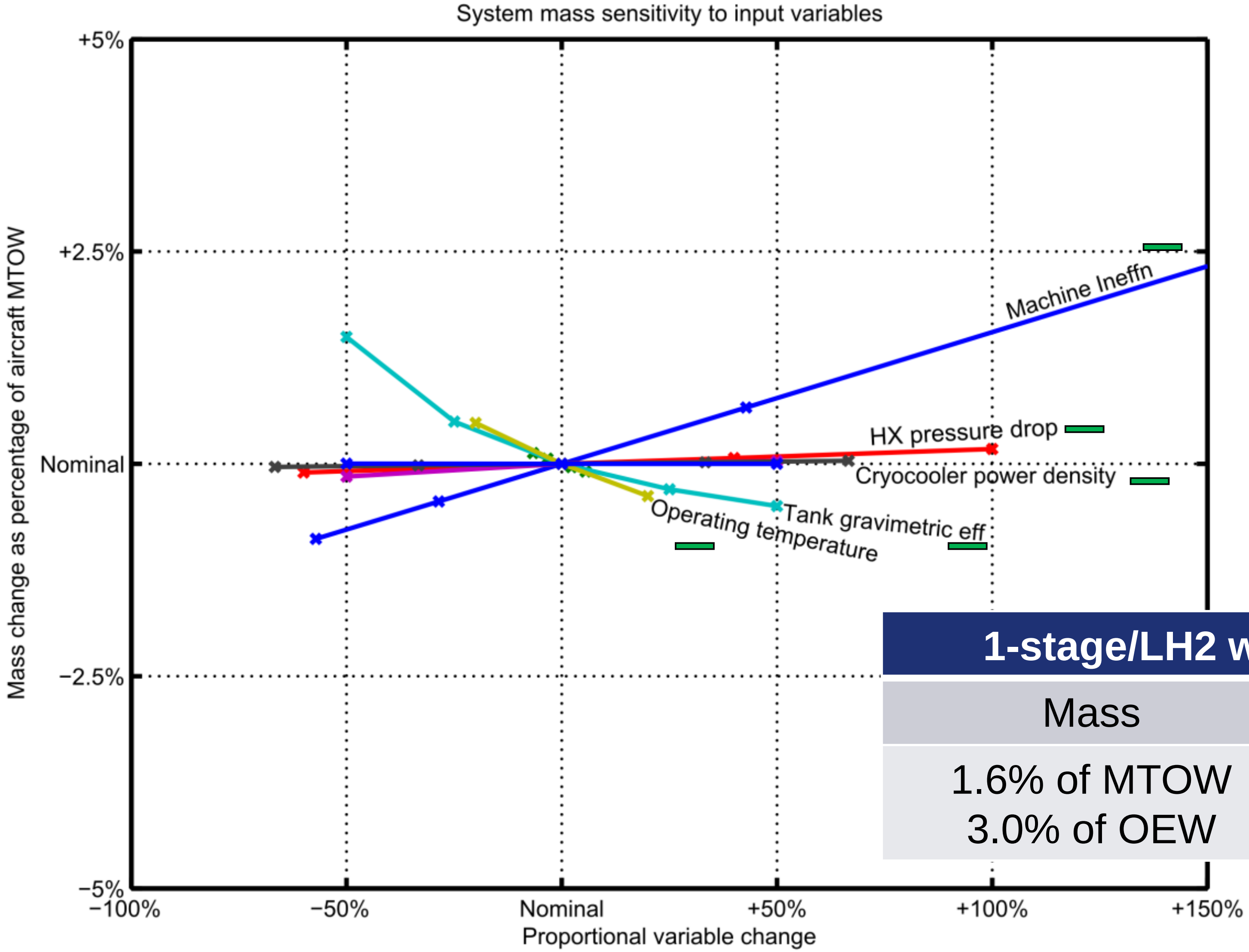
2-stage/LCH4 with nominal values	
Mass	Power
5.3% of MTOW 9.9% of OEW	5.5% of system power

Sensitivity results: 2-stage with intercooling



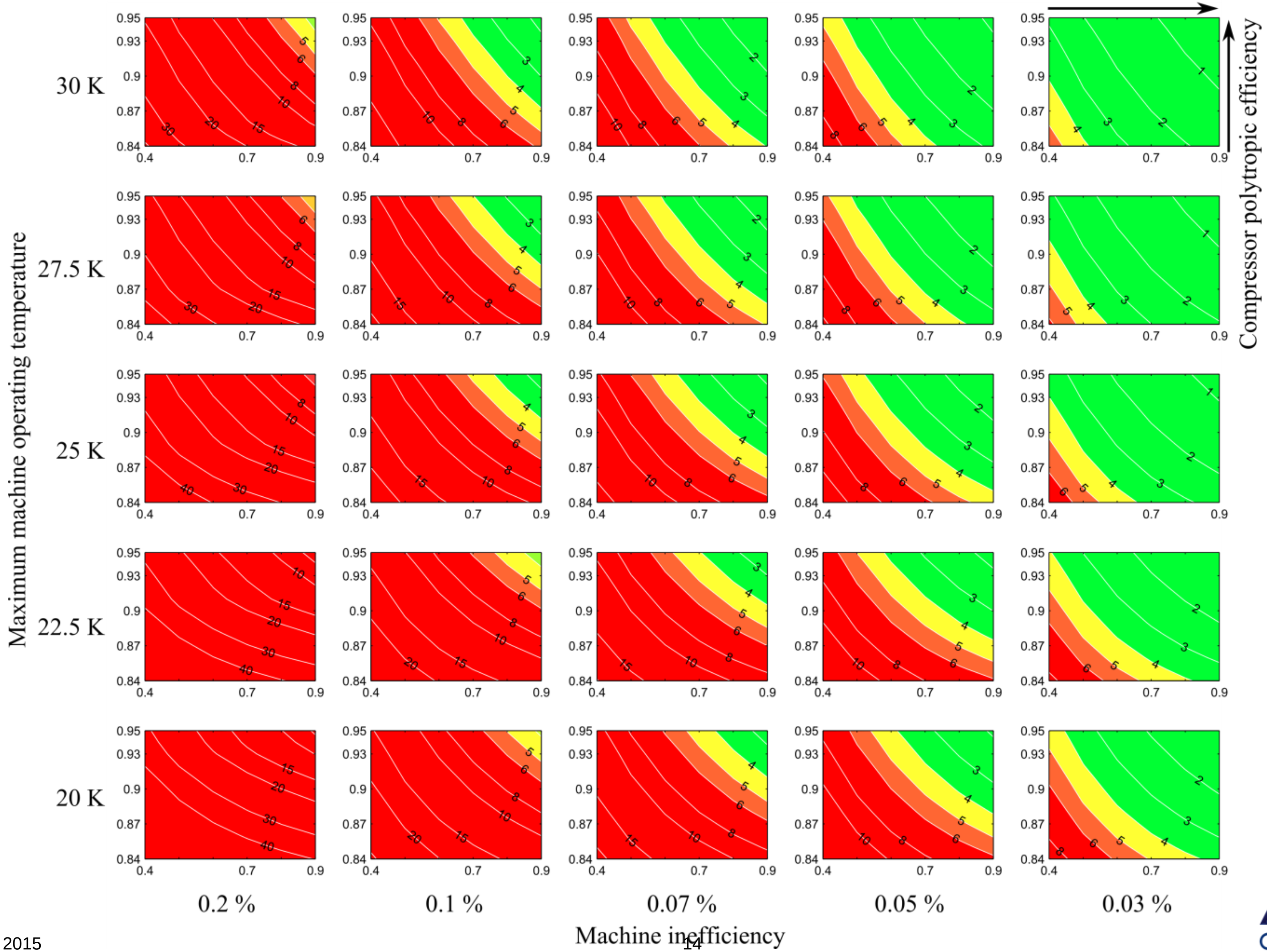
2-stage/LCH4 + intercooling	
Mass	Power
5.5% of MTOW 10.3% of OEW	4.2% of system power

Sensitivity results: 1-stage with LH2



1-stage/LH2 with nominal values	
Mass	Power
1.6% of MTOW 3.0% of OEW	0.1% of system power

Sensitivity results: 2-stage with LCH4



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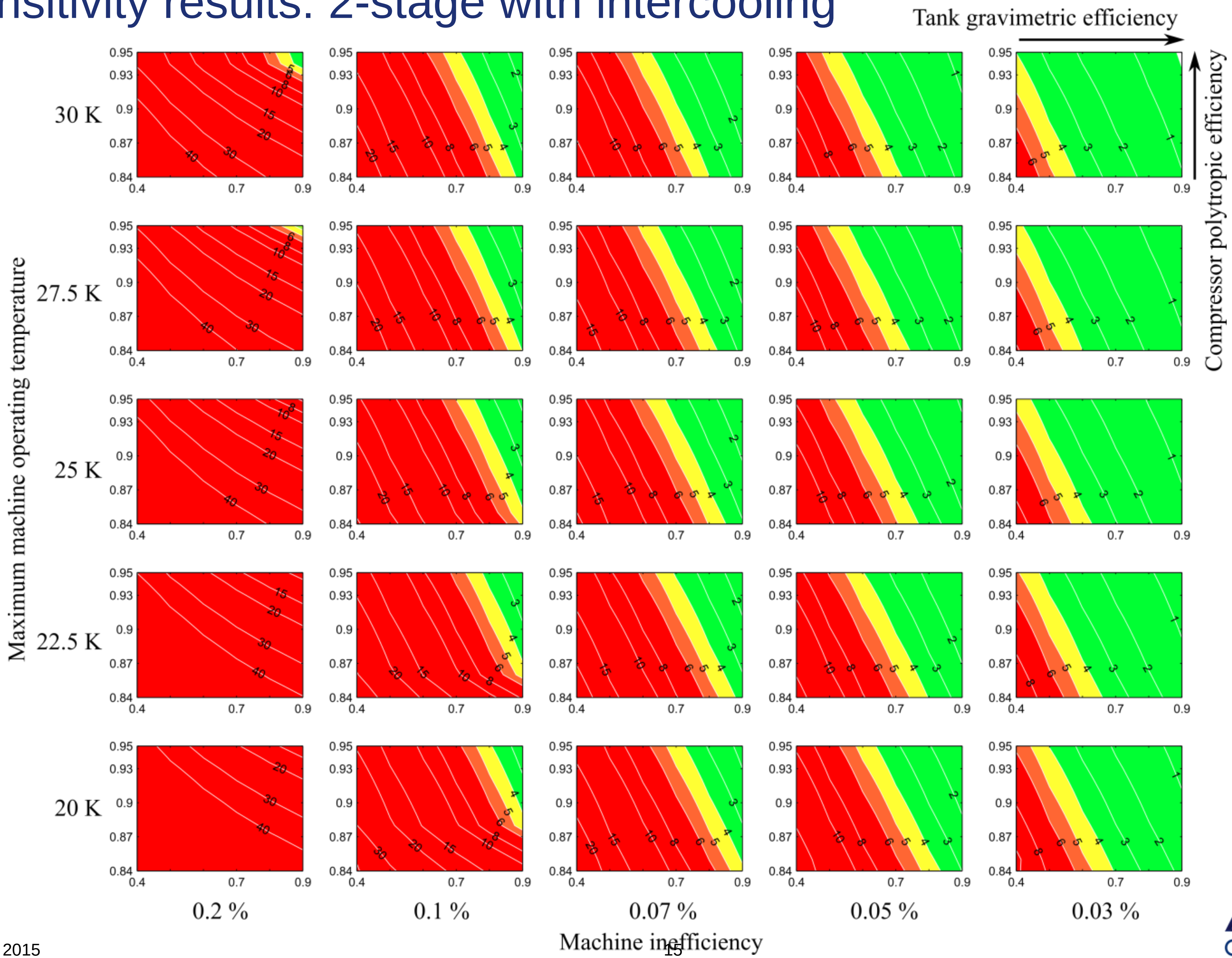
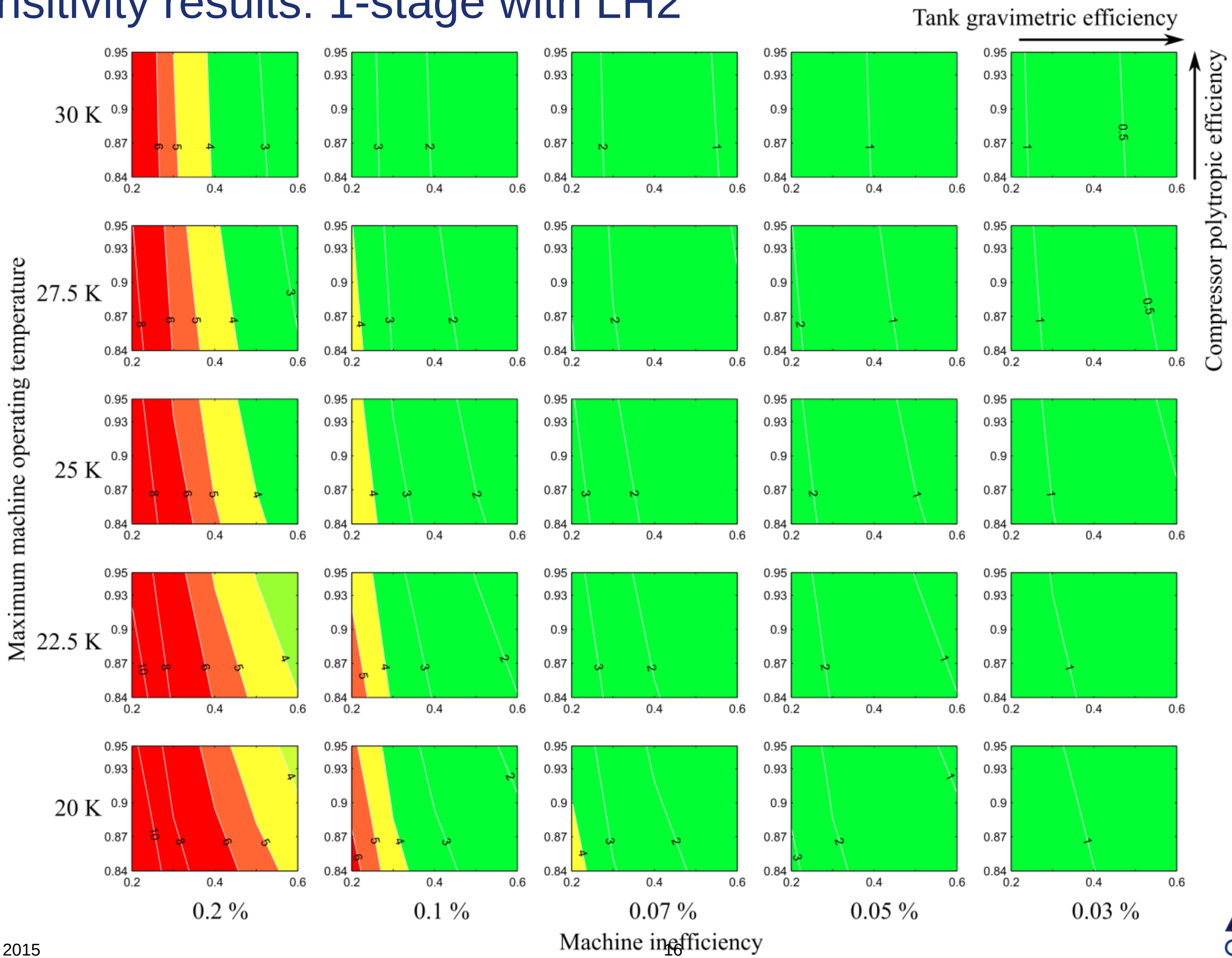
Sensitivity results: 2-stage with intercooling



Sensitivity results: 1-stage with LH2



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Outcomes

- Values and ‘acceptability’ are relevant to the example system – other aircraft may vary
- Results are subject to simplification and hence only guides to further research

- Most sensitive parameters:
  - Compression/expansion polytropic efficiencies
  - Operating temperature
  - Cryogen tank gravimetric efficiency
  - Superconducting machine inefficiency

- LCH4 solutions need technology better than nominal values

- LH2 solution may be required if technology is below nominal values but is limited by volume, infrastructure, handling, expense

- Intercooled option requires less power, but system is very sensitive to LCH4 use and is thus heavier

Conclusions

- Centralised cooling system preferred
- Reverse-Brayton coolers considered best choice
- LCH4 or LH2 heat sink likely to be required
- Target temperatures currently 20-30 K

Research baselines subject to change and discussion

- Stringent technology targets required to find acceptable solutions
- Research is needed on all aspects of the superconducting and cryogenic systems
- Further work is required on the aircraft applications to this technology

- Functional solution can only be found by close working relationship between the airframer and the superconductivity and cryogenics communities

Thank you