TCT Project Board

June 2013

Exec Summary

- Since the last Project Board modelling of tunnel heat build up and modelling / testing of ACM fibre release have been carried out.
- This information will inform a project “go / no go” decision today.
- An operational window for heating has been established, at reduced cleaning effectiveness.
- No cleaning can be delivered within the ACM limit.

Back story of Heat

Item	Evidence
1. October 2011 – Concept Design Review – Trevor Jipson queries power use of the machine and effect on local temperature in tunnels.	1. CDS
2. CTT (Mark Gilbey) engaged to investigate. Confirmed that 907kW would overheat rapidly in LU tunnels and by extrapolation would also overheat at lowest power.	2. CTT Report
3. 2x independent calculations confirmed CTT conclusion	3. JM & SW calcs
4. SK offer 329kW minimum power design, interpolation says this will overheat in 5 minutes.	4. MG emails
5. Ansys commissioned to carry out 3D CFD modelling of TCT at 329kW. Findings confirm overheat and validate MG suggestion of 200kW limit.	5. Ansys report
6. MG interpretation report offers confirmation of findings and possible mitigations.	6. MG report
7. SK further reduced minimum power with more extensive re-design, giving options of 207kW and 233kW, featuring measures to improve thermal tolerance of sensitive equipment.	7. SK report
8. SK conduct tests to demonstrate cleaning effectiveness at low power limits.	8. Images & video

Back story of ACM

Item

1. During the feasibility stage Occupational Health advised that dust is classified as "nuisance" not hazardous. Dust samples from the old TCT showed no asbestos, conversations with TransPlant confirmed that regular testing was undertaken and supported this conclusion. The project was authorised on the basis that the dust was free of asbestos and proceeded past feasibility on that basis.
2. As part of the VLU, cleaners were used to control dust. They had been instructed to stay away from certain assets as there was a risk of disturbing ACMs. The Asbestos Control Unit (ACU) were consulted and stated "it will not be possible to clean where there is asbestos". At the time the project believed this was a misunderstanding: the TCT generates air movements an order of magnitude lower than a service train at line speed, therefore it is hard to understand why the TCT could be unacceptable while service trains are safe.
3. During Concept Design Asbestos Duty Holders confirmed that there is a real risk. Two ACMs were selected for testing, thought to represent the highest risk, a meeting was held to discuss the results. The scope of the problem increased as the meetings progressed and more stakeholders became involved. It soon became clear that the behaviour of ACMs in air flows is not well understood within the business and is a complex subject.
4. A TCT Asbestos Control Strategy was agreed with the Duty Holders as a way to demonstrate that the TCT could clean without disturbing ACMs.
5. Project team worked with ACU/HMU to arrange testing as per the strategy. The tests revealed that fibres are released at speeds much lower than the TCT design for all ACM types in both suction and blowing modes.
6. Extensive validation testing has confirmed ACM limits at 20m/s blow and 14m/s suck. Testing on SK rig and modelling has been used to determine the feasibility of cleaning within these constraints.

Evidence

1. "FW. TCT Update" - email
2. Emails between 4.01.11 to 14.03.11.
3. Minutes of ACM meetings
4. TCT Asbestos Control Strategy
5. 4-Rail test reports
6. SK, 4-Rail and Ansys reports

Conclusions from Previous Board

1. Work to date has defined new constraints on the project;

- ACMs constraints remove the capability to clean 34% of the network.
- ACMs further constrain the cleaning capability on 64% of the network, only 2% is unconstrained.
- Heat constraints further limit the delivery of the cleaning capability to ~12% of what was planned.
- It is technically possible to recover a proportion of the capability lost due to heat constraints.
- At this time the project is not able to influence the loss of capability due to asbestos constraints.

2. Benefits still remain;

- It will be possible to achieve a small amount of cleaning with the existing design, however this is unlikely to justify the expenditure on the project.

3. Fundamental risks still remain;

- The asbestos duty holders, during their review of the results to date, requested testing on damaged samples of ACMs. These tests may yield results that limit the air flows yet further and effectively render the project infeasible.
- The temperature modelling techniques used, though cutting edge, may be inaccurate. It will only be possible to guarantee performance by building the machine and running it.

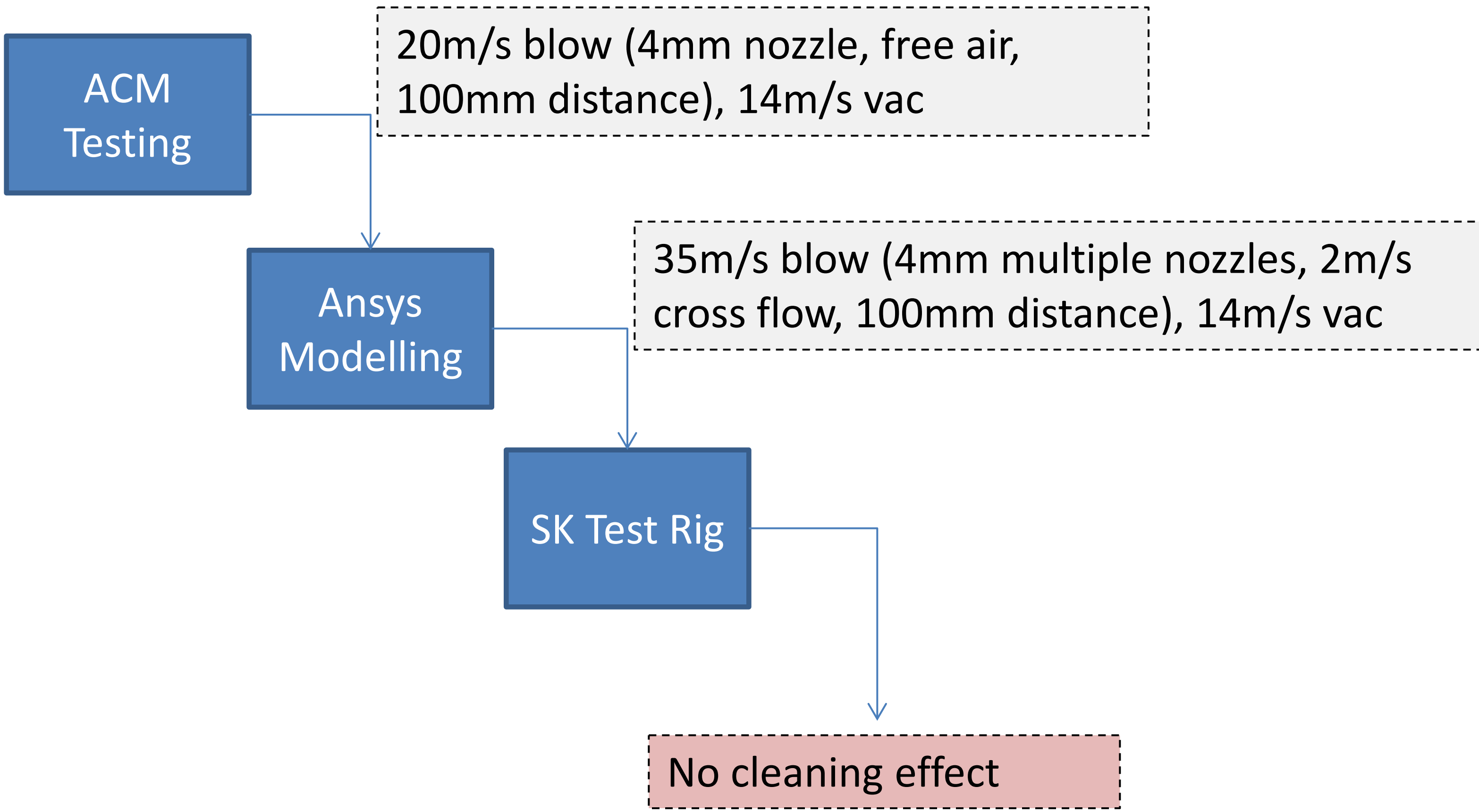
PCN - Heat & Power

- Schorling's CDS machine (907 – 329kW) was investigated further but is not viable as it overheats in 5 minutes.
- Schorling's other machines use far more power (highest is 1.7MW) but are more heat-tolerant, using diesel engines.
- Schorling do not accept LU's heat model but have offered a 620 – 207kW machine.

PCN - Heat & Power

- If LU are willing to pay for the design, Schorling will build the 620kW machine but LU will have to agree to the performance losses.
- Having witnessed the performance on the test rig, the project team believe cleaning of dust from cable runs and track bed is available.
- The heat issue can be resolved at a cost of ~£250k with additional delay and reduced cleaning effectiveness.

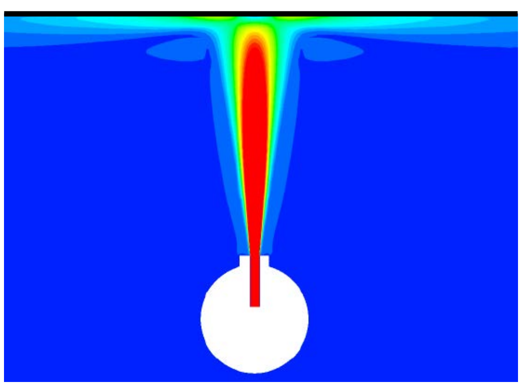
PCN - ACM

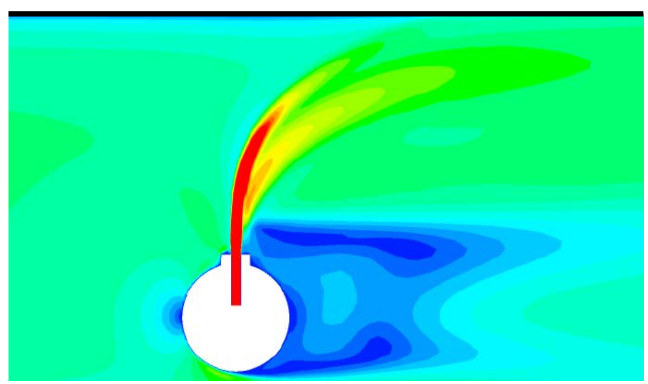

ACM Testing
20m/s blow (4mm nozzle, free air, 100mm distance), 14m/s vac
Ansys Modelling
35m/s blow (4mm multiple nozzles, 2m/s cross flow, 100mm distance), 14m/s vac
SK Test Rig
No cleaning effect

PCN - ACM

- Further to the above;
  - When set to operate at "full vacuum" of 14m/s at the hood there will be significantly lower vacuum flows at points local to other cleaning heads.
  - The location and magnitude of these turbulent flows cannot be reliably predicted.
  - When a high blowing nozzle coincides with a low suction flow the blowing speed at the wall will be undiminished.
  - It will therefore be necessary to set the machine to blow at the free air maximum ACM limit.

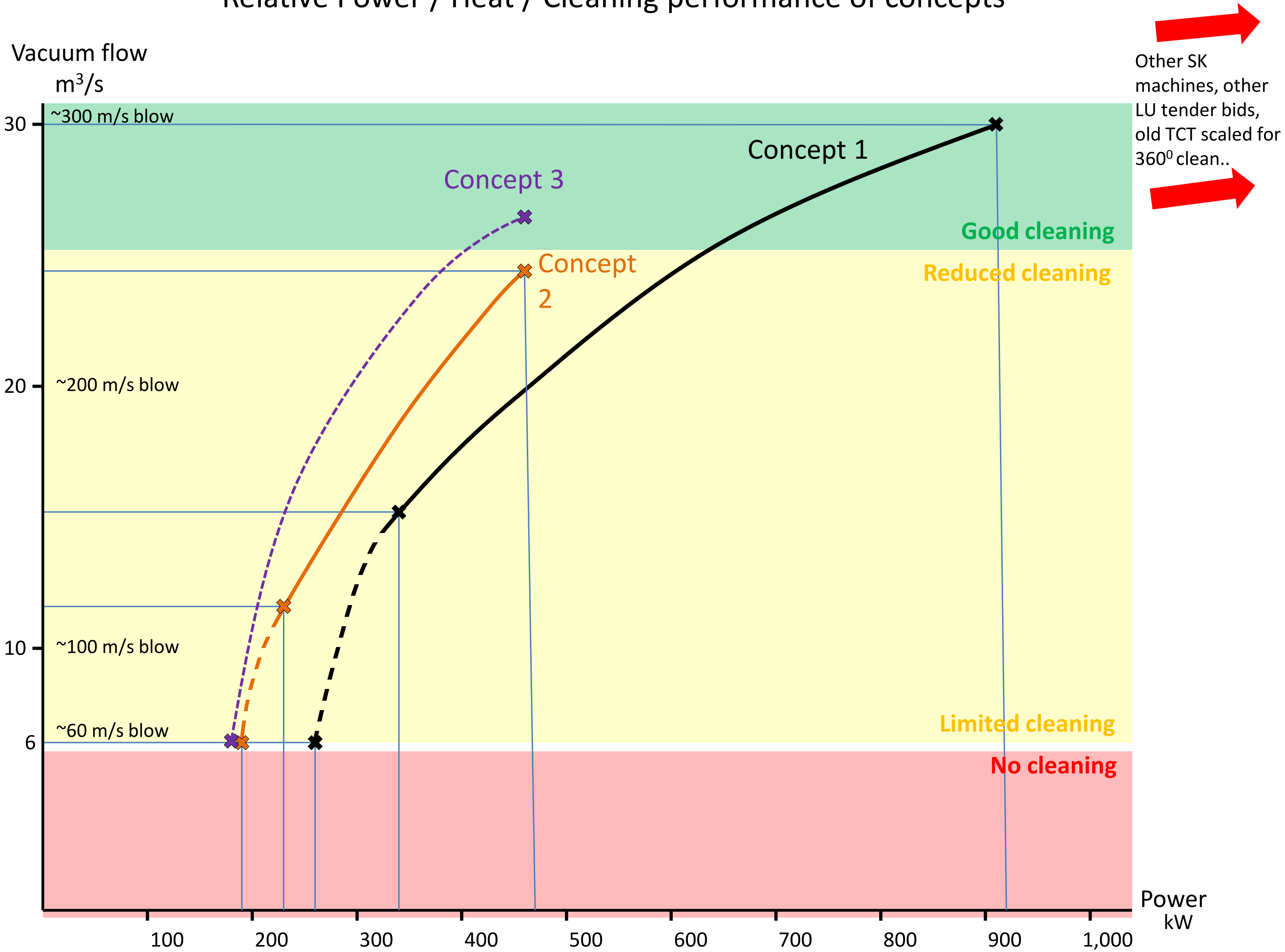
Free Air





Including vacuum flow

Relative Power / Heat / Cleaning performance of concepts



Conclusions from PCN

1. Work to date has defined the constraints on the project and their implications;

- Heat constraints limit the cleaning capability but can be resolved in exchange for a reduction in the peak cleaning performance.
- ACMs constraints were known to remove the capability to operate on 34% of the network but now further constrain the cleaning capability on another 64% of the network to levels so low that no cleaning can be delivered - **only 2% of the network can be cleaned.**
- The project is not able to influence the loss of capability due to asbestos constraints.

2. Benefits;

- The MPU and the section switch at Northfields will be beneficial if followed to completion.
- 2% of the original benefits remain, based on original scope.

3. Fundamental risks remain in delivery;

- If the calculations, testing or modelling done on the asbestos are wrong or misleading LU may be operating in breach of the law for extended periods with no way to detect that this was occurring.
- The temperature modelling techniques used, though cutting edge, are not validated. It will only be possible to guarantee performance by building the machine and running it.

Project decision implications

- **PROJECT ‘GO’ – BUILD TCT WITHIN HEAT CONSTRAINTS;**
  - Only operate machine in tunnels with no asbestos
    - TCT area of operation limited to 2% of tunnels
    - Extension of area of operation dependent on removal / encapsulation of ACMs which requires Company commitment to £100s million spend over 20+ years

- **PROJECT ‘NO GO’ – DO NOT BUILD TCT**
  - Commits LU to:
    - Long term manual cleaning of tunnels
    - Steady state management of ACM risks
    - Special measures to mitigate risks associated with new fleet introduction

Going forward (1)

- The business imperative has not changed, dust continues to gather.
- Manual cleaning removes <200kg of dust per kilometre where the old TCT removed 600-1,000kg/km.
- Options to proceed are limited:
  - **Do nothing:** Cancel project and continue manual cleaning.
  - **Continue delivery:** Change ACM strategy and use operating controls to obtain some beneficial use.
  - **Change the rules:** Seek a change to the legislation.

Going forward (2)

- **Do nothing:** Cancel project.
  - Use savings to develop better manual cleaning tools?
  - Intensify the manual cleaning regime?

Going forward (3)

- **Continue delivery:** build one of the "heat tolerant" designs.
  - Cleaning operation depending on;
    - Change to agreed ACM strategy. Machine must be configurable to specific sites. Risk of wrong config resulting in fibre release.
  - Requires
    - Extensive management controls to "lock" the train into certain areas, with configuration specific to each area to ensure no ACM release / collection.
  - Enables
    - Clean 360 on JLE
    - Clean 360 on Heathrow T5 loop
    - Possible cleaning of sections of tunnel roof on Picc / NL / CL
    - Possible cleaning of wall and 4' sections of above & Bak / Vic / SUP where there is no troughing or cables.

Going forward (4)

- **Change the rules:**
  - Obtain a change to the legislation allowing TCT to operate at full power within heat limit (will disturb fibres).
  - Attempt to derive a safe system of work within the updated law, which mitigates all arising fibre release issues.
  - This will take a lot of time and may invalidate the SK concept. In this case, the TCU procurement should be paused.

Going forward (5)

Even if “no go”, benefits may still be delivered;

- Section switch at Northfields for plant delivery.
- The Motive Power Units could be used as:
  - Motive power for the new Rail Grinder (£250k, 6-9months)
  - Materials delivery to platforms to support escalators, air con plant, PEDs. (£200k, 6-9months)
  - Staff train (£100k, 6-9months)
  - Gauge train (£300k, 12months)
  - Weed killer (£75k, 6-9months)
  - Targeted ATMS (£1M, 12 months)
  - Signals & systems test bed (funded under Plant Development programme)

Questions & discussion

Appendix 1 – Detail of Heat

Heat

- Schorling have offered two new options to meet the LU heat constraints;
- Concept 2:
  – 620kW, machine remains “DC-hydraulic”
  – Reduced air flow from smaller fans
  – New minimum power is 207kW
  – Sufficient thermal stability for LU tunnels when operating at 207, given forced cooling of Inverters
  – Lower peak power reduces cleaning capability

Heat

- Schorling have quoted £250k and two months to validate Concept 2:
  - Effectiveness / reliability of forced cooling system in LU environment
  - Rework of existing concept design documentation and assurance work
- LU must assess the impact on benefits of the reduced cleaning capability

Heat

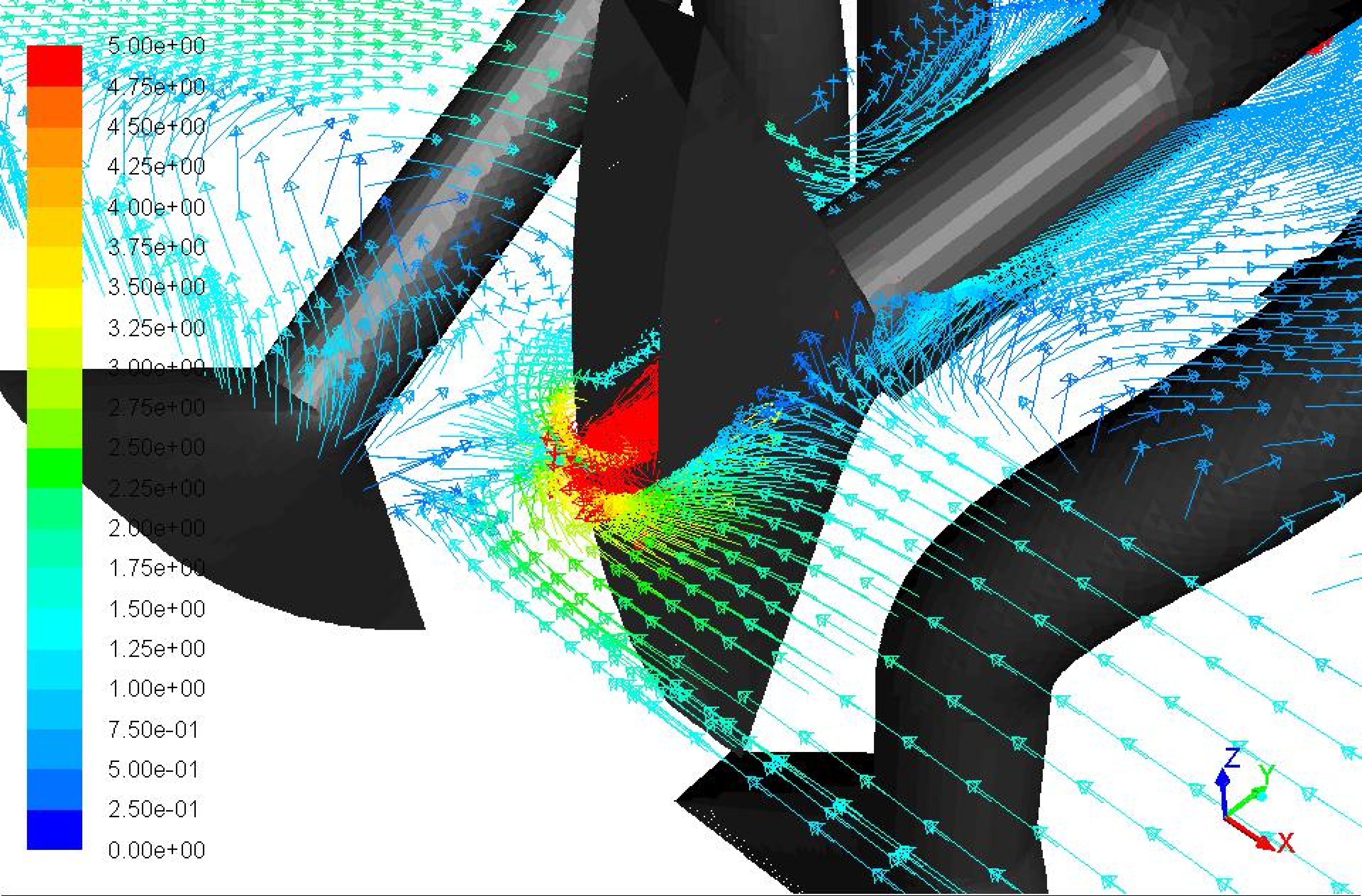
- Concept 3:
  - ~620kW, fundamentally revised concept of "AC direct-drive" features a shift from hydraulic power.
  - New minimum power is ~207kW
  - 6 fewer compressors, 4 fewer inverters, replaced by AC direct drives and controllers
  - Higher efficiency than Concept 2 maintains cleaning capability of Concept 1 despite peak power reduction.
  - Does not require forced cooling of equipment

Heat

- Schorling have quoted £500k and four months to validate Concept 3, including;
  - The EMC implications of AC power
  - The accuracy of their power predictions
  - RAMS and safety work to the same level as the existing concept.
  - Revised physical packaging of equipment
  - Revised equipment control design

Heat

- The conclusion to the Heat & Temperature "emerging issue" is as follows;
  - Schorling do not accept the modelling and wish to build their original concept, however;
  - LU can choose to implement one of two alternative concepts at our cost
  - Both alternative options appear feasible, albeit both are subject to costs and delays



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Jun 07, 2013

ANSYS Fluent 14.5 (3d, pbns, rke, transient)

Appendix 2 – Detail of ACM

ACM

- Woven cable results were suspected to be wrong. This has been confirmed.
- The new "limiting material" is troughing. This restricts the permissible air flow to 20m/s blow, 14m/s vacuum. There are no reasons to suspect that these figures are incorrect.
- Caulking has been tested and releases fibres at speeds in line with troughing, but appears to be more friable in a vacuum flow.

ACM

- The limits of 20m/s blow, 14m/s vacuum can only be raised further by either avoiding these assets, encapsulating or removing them
- Costs to remove troughing is estimated at £1M to £1.2M for the network and taking 18 - 24 months from order
- Caulking would cost many tens of millions to remove or several million to encapsulate, requiring many years in both cases

ACM

- Further ballast sampling to produce the “ACM prohibited map” has revealed additional “prohibited zones”.
- These can only be identified to the TCT Operators by blocking out station-station runs, which further constrains the operational area of the TCT.
- The new ballast restrictions are on the Bakerloo, Northern and Jubilee Lines

ACM

- Tests on the Schorling factory test rig and simulations using the computer model both confirm that the ACM compatible “blowing” air flows cannot penetrate the incoming air flow.
- Theoretically CAD modelling could yield a “compensated ACM” blowing rate to compensate for the incoming air flow; however the test rig demonstrated that the current design cannot be set up to comply with precise air flow limits.

ACM

- TCU air limit compliance;
  - Ensuring that the maximum air speed is reliably below the ACM limit at any one of the 900 individual nozzles will mean that the average speed needs to be significantly reduced.
  - In order to set the limit for any one nozzle, its position relative to the air inlet and its distance from the suction hood must be related to its closest approach to the tunnel and the “depth” of the under-pressure flow in that area.
  - All of the above must be set for the worst case nozzle so a significant safety factor will be required.

TCT Update – June '13

- On the test rig;
  - Due to the many variables the highest air speed would need to be set significantly lower than the "compensated ACM limit" to ensure that the limit could never be breached .
  - This would mean that many of the nozzles received virtually no air flow and were unable to clean.
  - The machine would not deliver even the most basic cleaning capability.

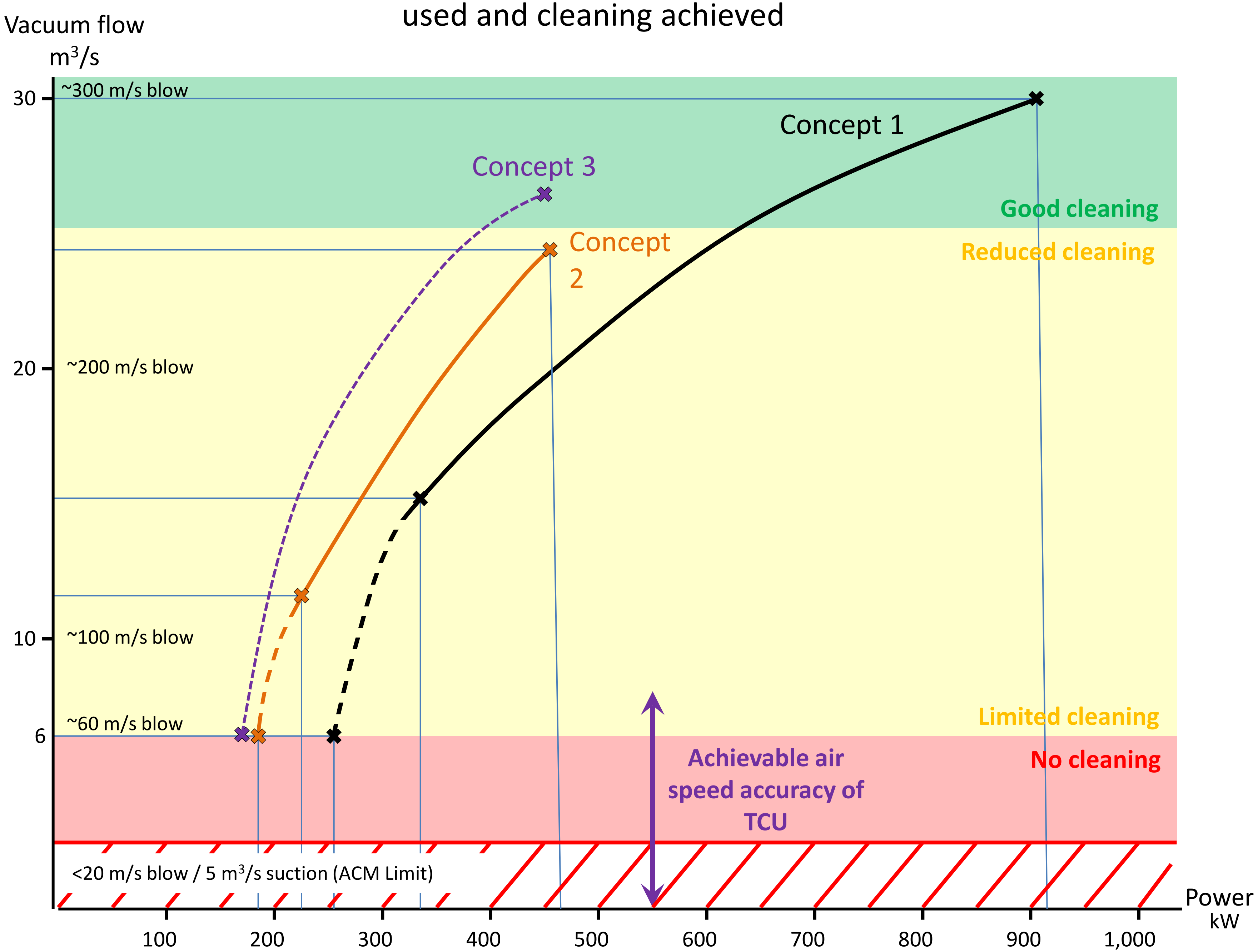
TCT Update – June ‘13

- Even if this can be done;
  - The industrial air compressors on the TCU are not designed to provide a constant air flow. They feed a reservoir, cutting in and out as necessary to maintain a target pressure band.
  - This reaction is delayed to prevent damage to the compressor, the delay results in “surges” and “lulls” in the air supply.
  - Swings of +/-70m/s were routinely observed.
  - To guarantee <20m/s “surge”, the duration of the “lulls” become very long. In this time the nozzle air flows fall to zero.

TCT Update – June '13

- Going forward;
  - Modifications to the design to enable greater control accuracy of blowing speeds may be possible, but these are not high integrity, will not be reliable and many "wrong-side" failure modes exist.
  - Significant further work is required to understand how the design could be altered to reliably deliver any cleaning at such finely defined low levels.
  - The cost and timescale implications are not easily defined.

Relationship between vacuum flow, power used and cleaning achieved



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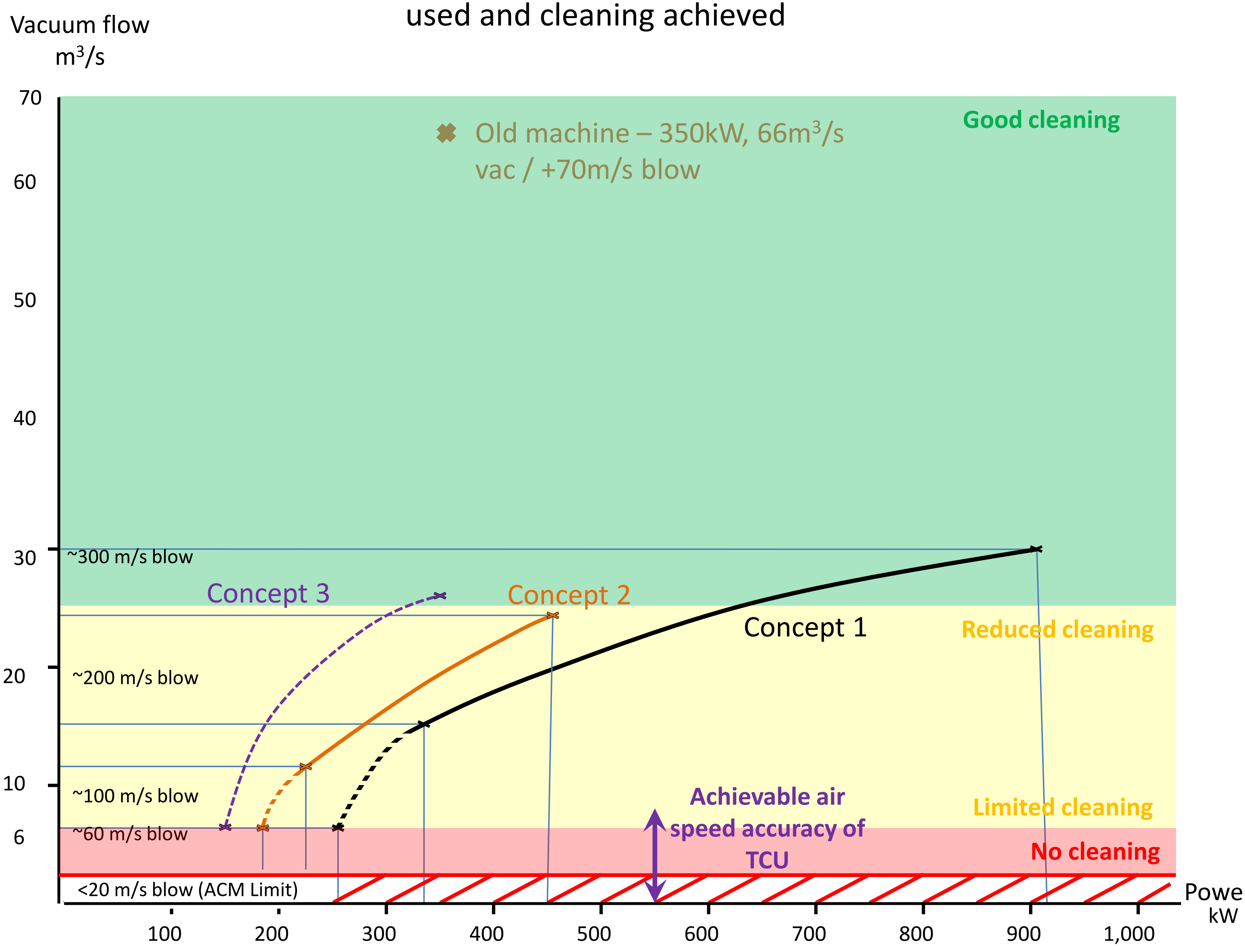

PCN - ACM

- In summary;
  - At present there is no solution to achieve cleaning within the asbestos limits, it may be the case that there can be no solution.
  - Attempting to find a solution will require further time and money.
  - If a solution could be found it would not be guaranteed by the supplier.
  - Even a high integrity solution may one day result in a significant ACM release under failure conditions.
  - There is no way to detect such a failure.