Keck Adaptive Optics Note 902

Near-Infrared Tip-Tilt Sensor

Camera Thermal Design

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Thermal requirements

KAON 894, *Detector Performance Characterization,* presents measurements of the degradation of noise performance as temperature increases. For the range of frame rates required for the near-infrared (NIR) tip-tilt sensor (TTS) (~50Hz-1000Hz), the noise histogram is degraded acceptably by dark current provided that the detector temperature remains below about 135K.

Black body emission from the camera optics is reduced to negligible levels by cooling this optic path to similar temperatures. Inverse ray tracing (see KAON 892) showed that it was only necessary to maintain the cooling of the optical path and surrounding baffles as far forward as the camera entrance window. In the NIR TTS camera the collimating lens preceding the filter is also cooled, intercepting the thermal radiation from the area adjacent to the window so that the filter is not warmed by the window. Keeping the filter cold may be important since the filter emissivity peaks at the edges of the passband where the interference filter passes from being transmissive (low emissivity) to reflective (low emissivity).

Apart from cooling the detector and optics to reduce Poisson noise from dark current and black body radiation respectively, the thermal control system must bring the detector to operating temperature quickly without violating the safe limits for thermal slew rate for either the detector or the optics. Teledyne maintain their old 0.5 K/min specification, which is known to be very conservative, since they now test at much higher rates.

NIR TTS camera temperature stability requirements are looser than is typical of a science sensor due to the shorter exposure. With video offset voltage sensitivity being typically 800 e-/K, the 0.5 K/minute limit on thermal slew rate translates to 7 e-/s, thermally induced "signal", which becomes negligible for frames rates 10 Hz and above. The thermal control system should keep short-term errors far below this. Long term temperature drift requirements are driven by the desire to subtract dark current accurately. If we set a requirement for 1% residual error after dark current subtraction, for a 2.5 μm cutoff detector, this leads to a requirement for long term temperature drift less than 53 mK if operating at ~130 K, which is easily met by the Lakeshore temperature controller.

We have adopted the 0.08 K/min cooling rate used by MOSFIRE for BaF_2, *without analysis of the effect of the smaller lens size (probably good) and smaller number and area of epoxy bonds (possibly bad).*

The Infrasil lenses experience similar slew rates but are not a concern, since they are both less brittle, have lower CTE, and are housed in pockets without being bonded so that the thermal contact to the lens cell will not be as good.

The refrigeration system must not produce significant vibration or heat on the AO bench. This requirement has not been quantified.

The system must not present an unacceptable hazard to personnel or equipment. The principal concern here is flammability of the refrigerant gas, or toxicity.

Cooling system and Refrigerant Selection

Liquid Nitrogen cooling with an autofill system is technically feasible, but deemed logistically undesirable. The small thermal load ~4 W would have required infrequent fills, and the fixed dewar orientation would have allowed an autofill system which would have only required replacement of the storage dewar every 10-14 days. The low heatsink temperature would have made the thermal design easy since the large temperature differential between detector and heat sink permits more series resistance in the thermal circuit and thus less concern about thermal resistance in joints. Lower operating temperature would have allowed us to avoid the expense of exploring detector performance at elevated temperatures. However the use of liquid Nitrogen was considered undesirable by the observatory, due to the liquid Nitrogen transport and handling overheads, and the risk of accidental warm up.

The closed cycle coolers considered are shown in Table 1. Stirling, Gifford-McMahon, and pulse tubes were ruled out due to the vibration, and/or heat dissipation on the atmospheric side. The remaining choices were Joule Thomson coolers which exhibit very low vibration, comparable to liquid Nitrogen (Figure 1 and 2)[1]. A Polycold Compact Cooler (Brooke's Automation) with high performance head was selected initially since it was more compact (~2.5" shorter) than the Advanced Research Systems "Orca".

[1] *Throttle Cycle Cooler Vibration Characterization*, Dennis Hill, APD Ctryogenics, Allentown PA 18103, USA.

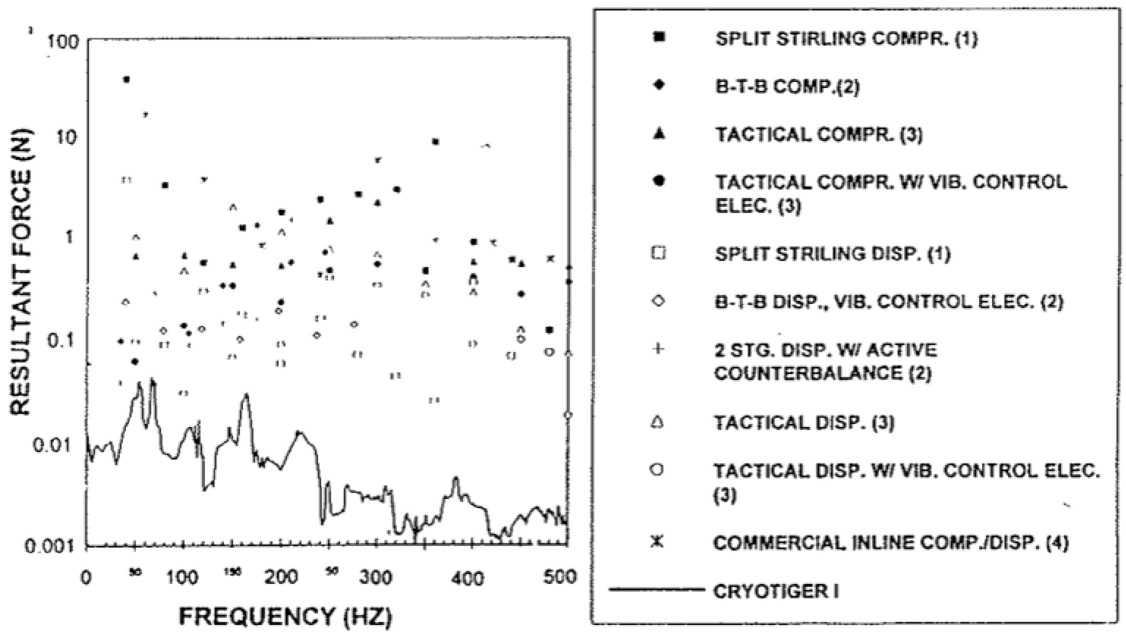

Figure 1: Comparison of vibration caused by Cryotiger with other closed cycle coolers.

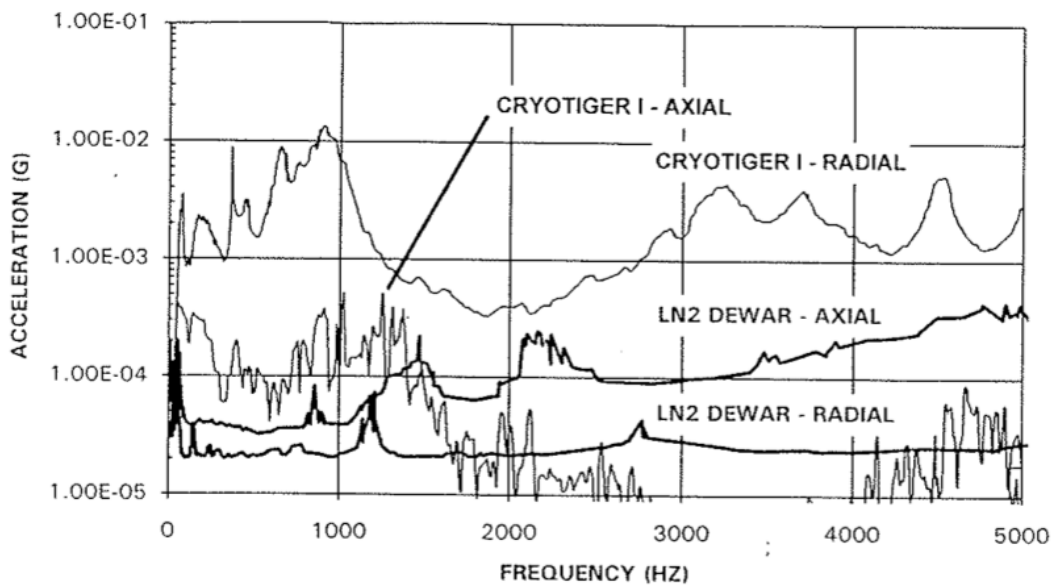

Figure 2: Comparison of vibration caused by Cryotiger with a similar liquid Nitrogen cooled system.

Table 1: Cryocooler options considered for NIR TTS.

PCC Polycold Cryotiger	* Low-vibration heat removal system * Compact size for small footprint * Remote cold end and minimal connections for optimal flexibility * Closed cycle compressor uses patented gas blends and innovative oil management for quiet, reliable performance * Cooling to -203° C * Elimination of the cost, inconvenience and risks of liquid nitrogen

Advanced Research Systems Orca™ Mixed Refrigerant Cooler	* Cryogen Free * Nonflammable Non-Toxic Mixed Gas Refrigerant * JT-Cooler, No moving parts in the cold head * Low Vibration * Operates in any orientation * AIr Cooled Compressor
Crymech PT-10 Pulse Tube	Helium working fluid choice of liquid or air cooled compressor
Thales Pulse TUBE Linear Pulse Tube Cryocooler LPT 9710	Linear Pulse Tube Cryocooler LPT 9710 * MTTF: > 20000 hour * Compressor dimensions: 140x300 mm * Cold finger / approx. dewar bore: 34 mm * Mass: < 16.0 kg * Cooling power @ 80K/23°C: 15000 mW * Input power: < 350 W * Cool down time to 80K @ 6000J: < 20 min. * Operating temperature range: -30/71 °C * Input voltage: 55 VAC
Thales Linear Stirling cooler Linear Stirling Cryocooler LSF 9320	Linear Stirling Cryocooler LSF 9320 Properties * MTTF: > 20000 hour * Compressor dimensions: 90x204 mm * Cold finger / approx. dewar bore: 22 mm * Mass: 6.5 kg * Cooling power @ 80K/23°C: 7200 mW * Input power: < 150 W * Cool-down time to 80K @ 2150J: < 10 min. * Operating temperature range: -52/71 °C * Input voltage: 28 VAC
Sunpower stirling cooler	* Heat rejection options Waste heat must be rejected from the cryocooler, maintaining a reject temperature (at the external cryocooler reject surface) not exceeding 70°C. This can be done conductively with a standard unit. Sunpower can provide air cooling fins or a liquid cooling jacket to make it easier for the customer to manage the heat rejection. * Controller The CryoTel® includes a 24 VDC input controller. 110V, 60 Hz and 230V, 50 Hz AC controllers are also available, but the AC controllers do not have temperature feedback. * Vibration absorber A passive balance unit is standard with the CryoTel® CT, GT and MT. Sunpower also offers an active (drivable) balance unit for stringent vibration control.

Cryomech - Gifford McMahon Single Stage AL10	1st Stage: 14W @ 80K Minimum Temperature: 0W @ 20K Type: GM Cooling: Air or Liquid
Liquid nitrogen with autofill system from 70 Gallon dewar	Stable 77 degree temperature no vibration non explosive gas

Cooling power curves are shown in Figure 3 for a variety of Polycold refrigerant gases. PT13 or PT14 were originally preferred (by Caltech) since their low final temperature allowed more relaxed thermal design parameters (larger resistances) and a large safety margin for detector dark current. However Polycold indicated that the refrigerants may be flammable or even explosive in some concentration levels. They provide a specification[2] for the room volume into which the entire gas charge may be vented without risk of ignition, 10 m^3 for ANSI/ASHRAE 15 standard, or 15 m^3 for using standard EN 378. Unfortunately Polycold's desire to keep the gas formulation secret leads them to define a single safety requirement for all refrigerant options even though the ones which reach lower temperature are likely to have lower flammable gas content given the limited range of compounds which are still gaseous at such low temperatures.

The volumes into which the cryocooler and compressor might vent exceed those required to dilute the refrigerant gases to levels at which they become non-flammable, however the observatory safety office recommended against the use of these gases on the basis of their flammability; in the event of needing to use these flammable gases he recommended additional safety measures. The non-flammable NF48 refrigerant from Polycold was therefore the preferred choice.

[2] Polycold Compact Cooler Operating Manual, Document Number 825133-00, Revision A

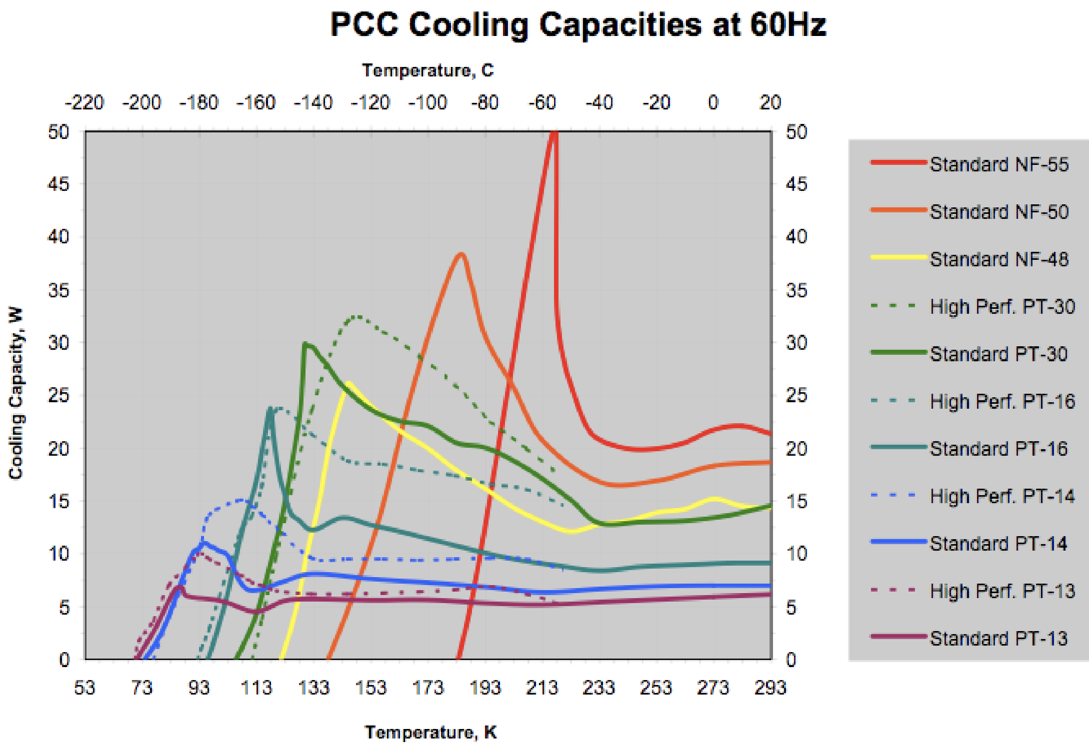

Figure 3: Cooling power versus cold head temperature for Polycold Compact Coolers (AKA Cryotigers) for various proprietary refrigerant gases. "High Performance" refers to a slightly longer cold head unit. PT-xx gases contain some flammable components, while NF-xx gases do not.

A detailed thermal model (to be described in detail later) shows that the cooling curve (when using the Polycold NF-48 refrigerant), Figure 4, exhibits significant slope change during cooling (Figure 5). This is primarily due to the steep increase in cooling power at low temperature for the NF-48 gas (Figure 13), but is exacerbated by the drop in heat capacity of most materials at these temperatures (Figure 14). Most conductances also drop at these temperatures (Figure 15), but the slew rate is dominated by "cooling power divided by heat capacity", not by the RC time constant.

The thermal slew rates at the detector are well below the (already conservative) 0.5 K/min recommendation by Teledyne. However the peak negative slew rate for the lenses with the Polycold NF-48 refrigerant is ~0.22 K/min, which is about three times the 0.08K/min limit adopted by the MOSFIRE project for Barium Fluoride. We have not (yet) performed the detailed analysis required to determine permissible slew rate for the lens size and mounting geometry used in the NIR TTS camera, and therefore we have adopted the MOSFIRE requirement.

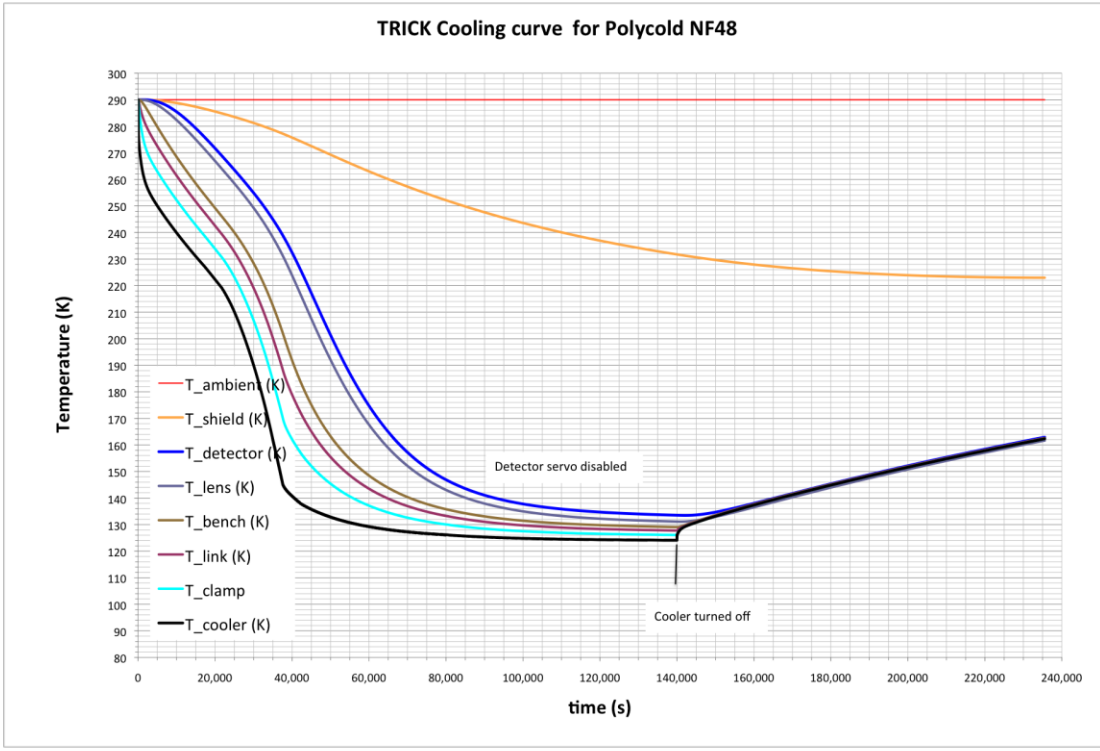

Figure 4: Cooling curve for Polycold NF-48 refrigerant, dewar wall emissivity 0.08, shield emissivity 0.06, typical contact resistance 0.5 K/W. Detector heater is disabled to show a final temperature ~134 K. Warm up is passive

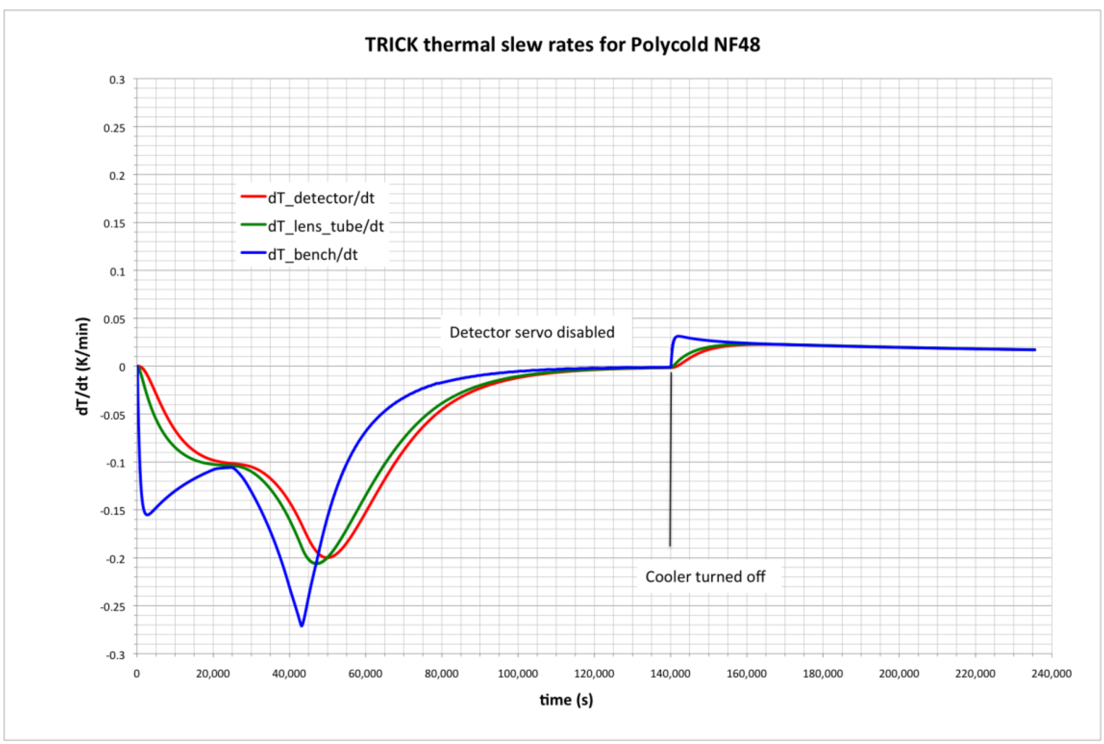

Figure 5: Thermal slew rate for Polycold NF-48 refrigerant, dewar wall emissivity 0.08, shield emissivity 0.06, typical contact resistance 0.5 K/W, and detector heater disabled. Passive warm up is <0.02K/min. Peak cooling rate (0.27K/min) occurs when cooling power peaks.

The following potential approaches have been identified to control the thermal slew rate:

1. Increase the thermal resistance between the cold head and lenses to create a dominant time constant. To avoid an increase in detector operating temperature, the thermal circuit would need to be modified to provide a parallel path from the detector to the cold head bypassing the lens tube and bench. The attachment of this thermal strap would make it difficult (impossible?) to remove the detector and lens tube without fully disassembling the dewar. We did not want to lose this good feature of the present design and therefore looked for other options.

2. Add ~10 kg more mass to the bench to slow down the cooling rate. Apart from the undesirability of the added mass, this not only slows the maximum rate but also the minimum so the cool down time to 138 K is extended to 235,000 s, nearly 3 days. This long thermal cycle time would increase commissioning and servicing costs and was deemed unacceptable.

3. Actively control the slew rate using the bench heaters, and the Lakeshore temperature controller's slew rate control function. This would be a good solution except that a failure to activate or execute the temperature control correctly would result in possible destruction of the optics. This was deemed too risky.

4. Change the cooler to version with lower and flatter power curve. This is the option proposed.

5. Reexamine slew rate limit based on a detailed FEA models of the BaF_2 lenses and in the actual cells, to determine whether the MOSFIRE specification is in fact too stringent when applied to smaller optics.

Just prior to the Detailed Design Review, it was realized that the "Orca", Joule Thompson cooler made by Advanced Research Systems, uses *non-flammable and non-toxic* refrigerants. The MR80 and MR90 refrigerants deliver fairly flat power curves for constant slew rate with the correct magnitude without modification to the thermal circuit. The lower cold head temperature (compared to the Polycold NF-48) allows for higher thermal resistances and less dependence on low thermal resistances in joints.

The peak slew rate for the MR80 refrigerant is below 0.08 K/min without active control (Figure 9), but at the expense of longer cooling time (Figure 8). The MR90 refrigerant cools to 90 K (Figure 10) with slew rate slightly greater than the goal (Figure 11). It is proposed that the bench temperature servo (which is needed anyway for warm up) be used to slow the MR90's slew rate to 0.08K/min, with the knowledge that a loss of servo control will only result in a slew rate which is ~20% higher than is ideal.

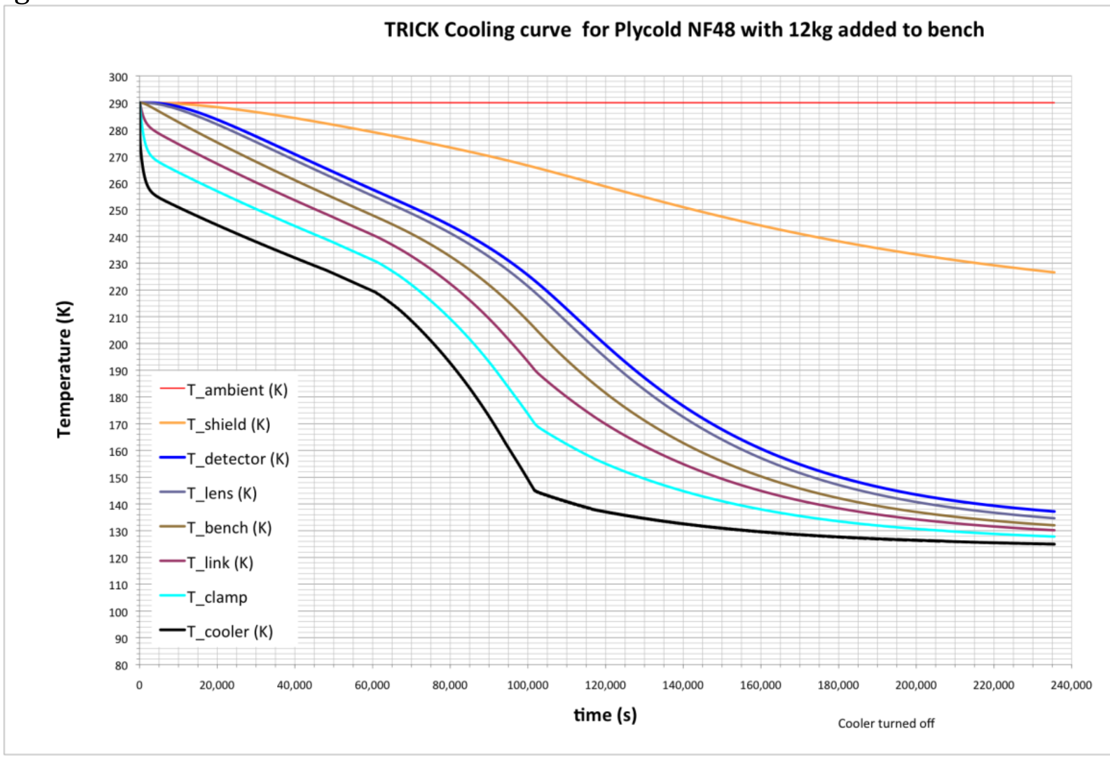

Figure 6: Cooling curves slowed by adding 12 kg of Aluminum to the bench, but it now takes 235,000 s to reach 138 K. The detector temperature servo has been disabled in this simulation.

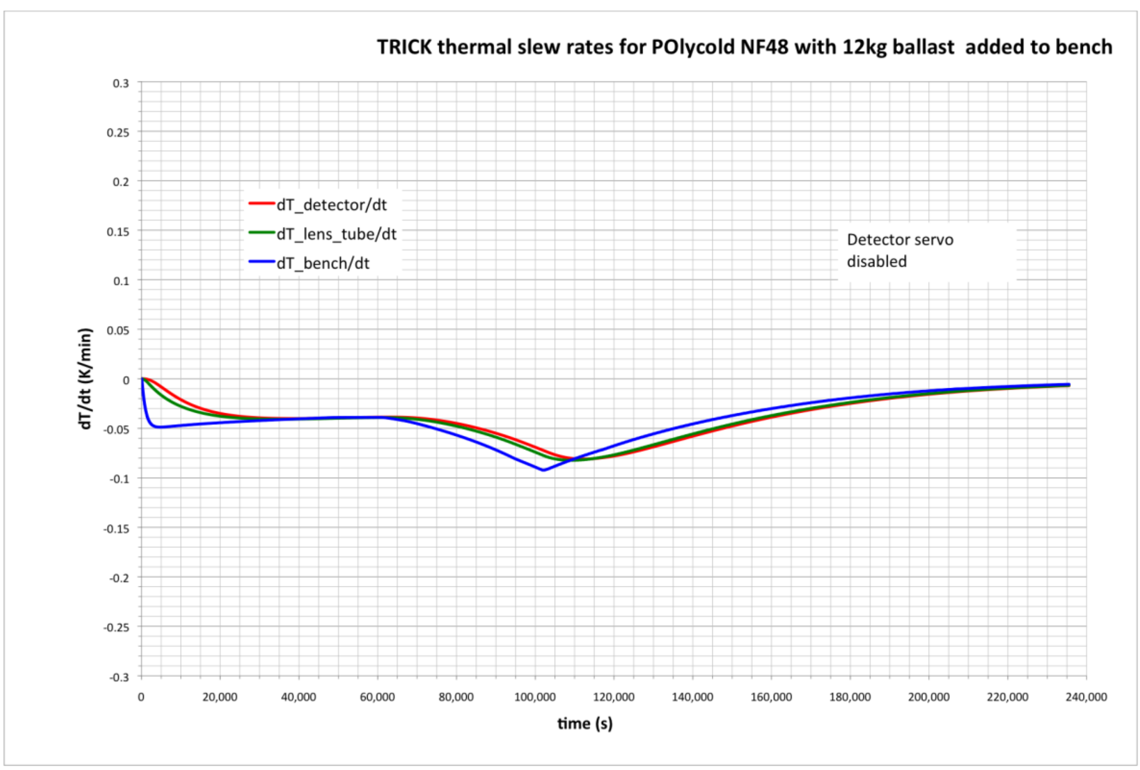

Figure 7: Thermal slew rates slowed by adding 12 kg of Aluminum to the bench, but it now takes 235,000 s to reach 138 K. The detector temperature servo has been disabled in this simulation.

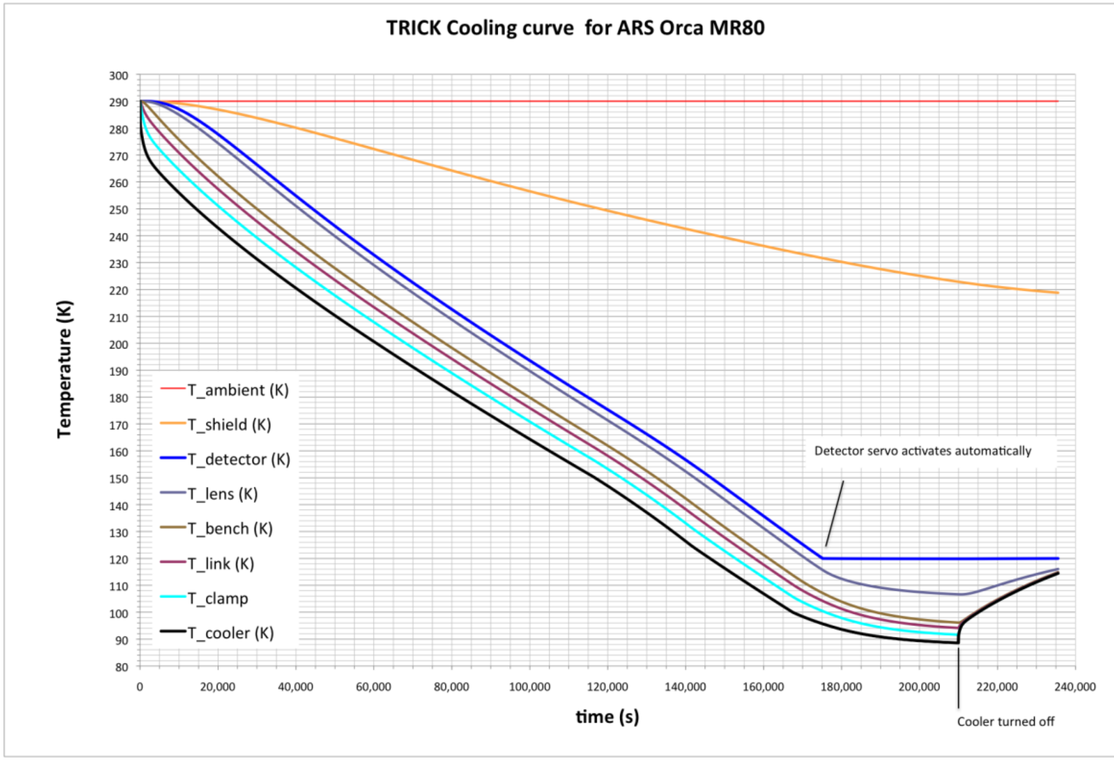

Figure 8: Cooling curve for ARS Orca with MR80 refrigerant, and detector servo enabled with 120 K setpoint.

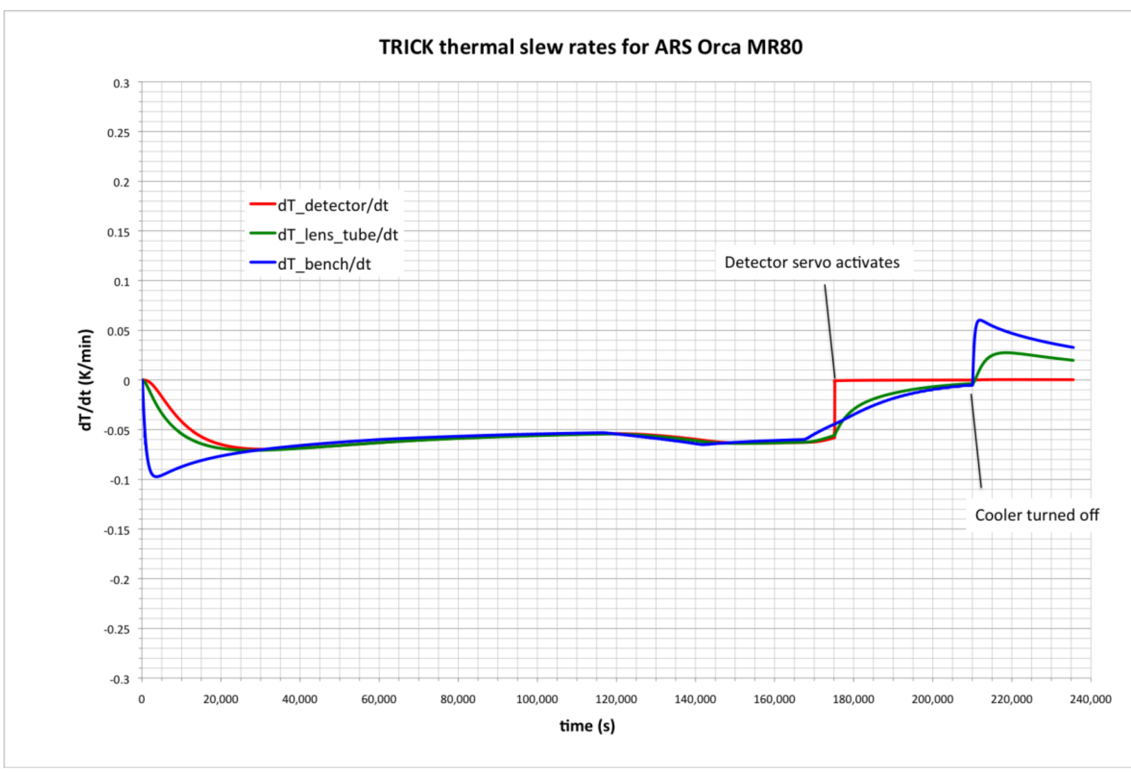

Figure 9: Thermal slew rate for ARS Orca with MR80 refrigerant, and detector servo enabled with 120 K setpoint. This is much flatter than the Polycold NF-48, but the slew rate is lower than the limit so that the cooling time is longer than necessary.

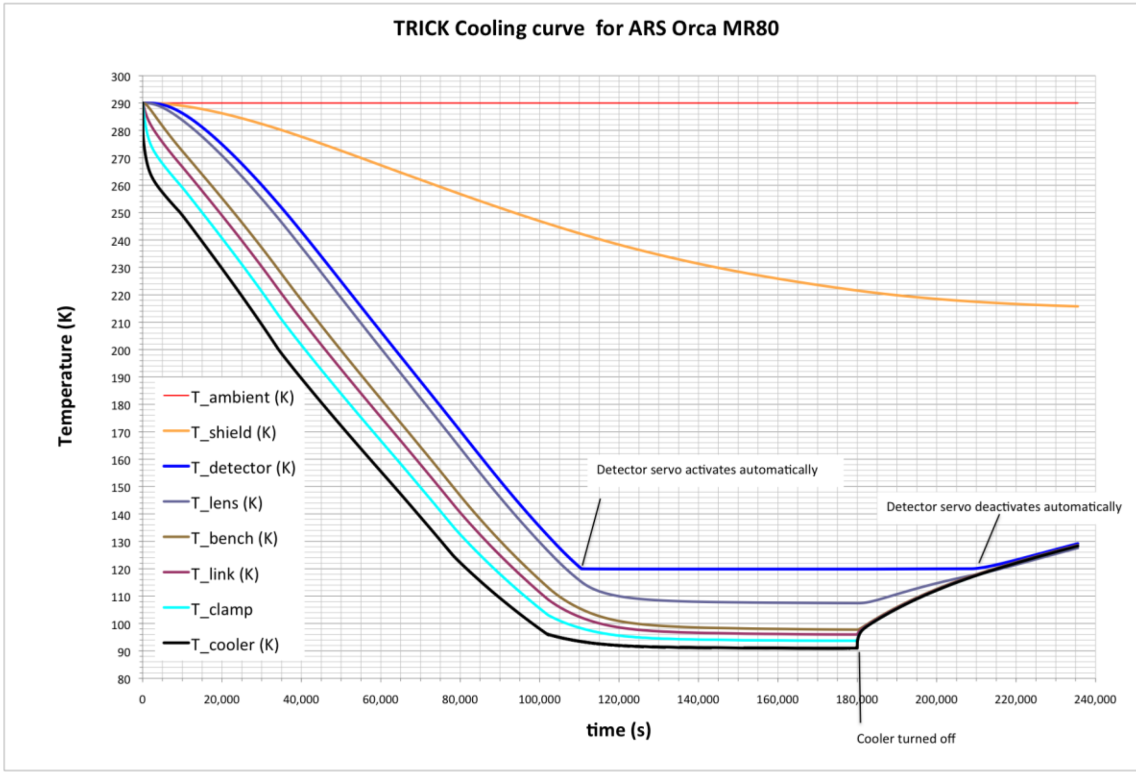

Figure 10: Cooling curve for ARS Orca with MR90 refrigerant (the plot title is wrong), and detector servo enabled with 120 K setpoint. The higher cooling capacity accelerates cool down. Cooling time is much shorter.

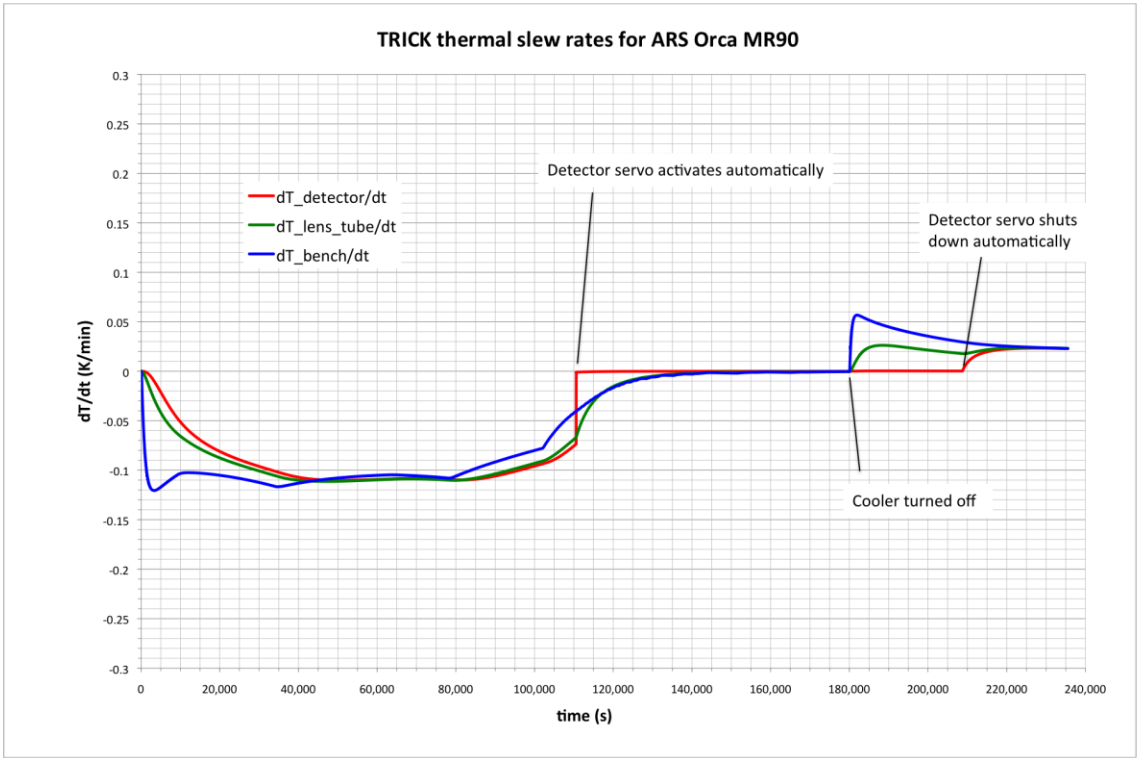

Figure 11: Thermal slew rate for the ARS Orca JT cooler with MR90 refrigerant.

Thermal Model

The thermal circuit used to model performance is shown in Figure 12. The physical locations corresponding to nodes in this circuit are shown in Figure 16. The distributed thermal resistances and heat capacities have been approximated by dividing the circuit into a reasonably large number of components and by splitting many into two resistances with capacitance placed in the middle.

A finite difference model was generated as an excel spreadsheet, "TRICK thermals.xls" with ~8000 rows, each representing a point in time, spanning 240,000 s at 30 s per row. Approximately 20 columns contained temperatures at each node and power flows shown as "current source" symbols in the circuit diagram. These power flows are computed as a function of the temperatures in the previous row and include radiative transfer (following the Stephan Boltzmann relation), the cooling power versus cold tip temperature for any one of the refrigerator options or the proportional control equations of the detector or bench heaters. The time at which various refrigerators turn off and the bench heater turns on are programmable.

The numerical simulation is constructed as follows. For capacitance a new temperature is predicted by a linear approximation:

$$T_n = T_{n-1} + \Delta t * dT/dt$$

By analogy to the familiar electrical equation for capacitance,

$$\Sigma I = C * dV/dt,$$

Then,

$$dT/dt = \Sigma \text{ (power flows into node) } / \text{ heat\_capacity\_of\_node}$$

Each row of the spreadsheet contains new temperatures and power flows based on the temperatures in the previous row so that there are no circular definitions. The time increment must be made small enough to make the linear approximation valid and to minimize non physical oscillations caused either by overshoot in the simulation of feedback loops or quantization caused by table lookup.

Refrigeration power versus temperature is implemented as a lookup table recorded manually from the data sheet but with values interpolated on 0.1 to 0.2 degree increments to minimize the quantization by Excel's VLOOKUP function. Lookup tables or polynomials are also used to model the dependence of specific heat on temperature for each material (Figure 14). The dependence of conductance on temperature (Figure 15) has not been implemented since its impact on performance is minor. Instead fixed values have been manually adjusted to those expected at the final operating temperature.

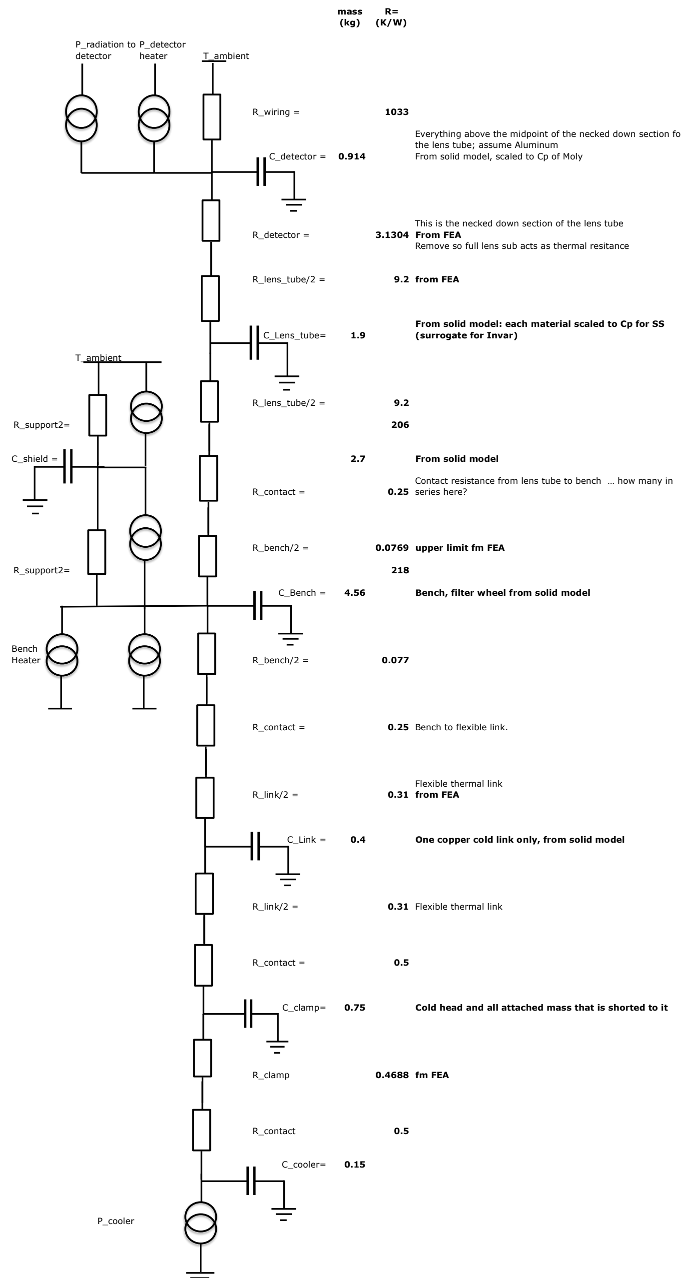

Figure 12: Equivalent circuit used for thermal modeling. Current sources represent temperature dependent power flows such as cryocooling, radiative transfer, heaters used to servo control detector and bench temperatures. Capacitances are also temperature dependent.

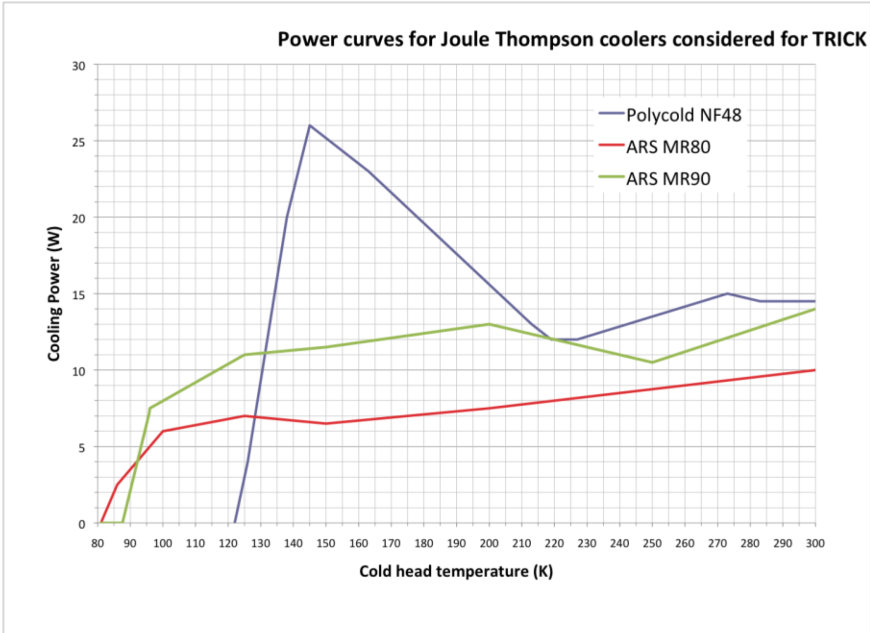

Figure 13: Cooling power versus cold head temperature for candidate JT coolers. These plots use data in the lookup table used by the simulation and have been read form manufacturers data sheets. Real performance will be a smoother function of temperature.

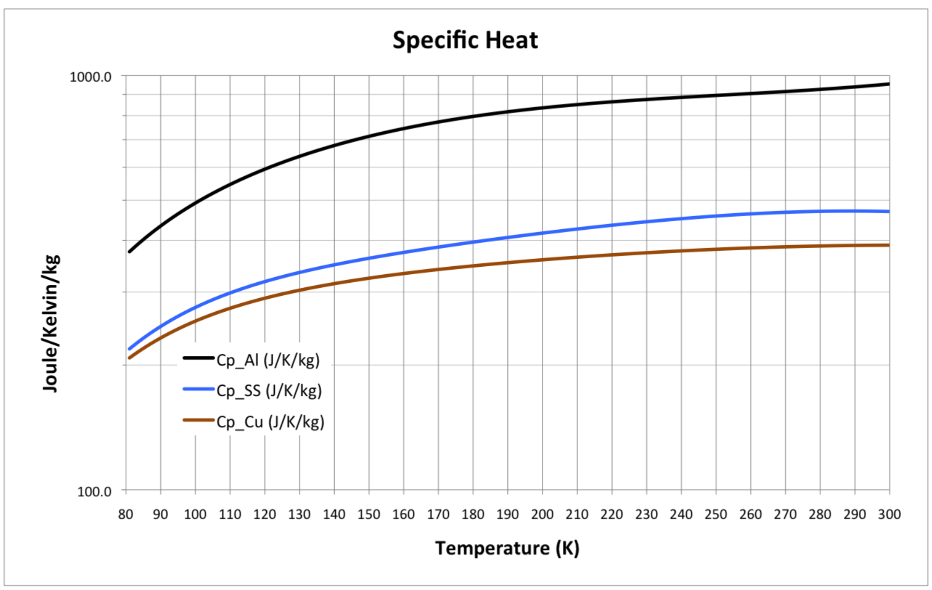

Figure 14: Temperature dependence of specific heats used in thermal model.

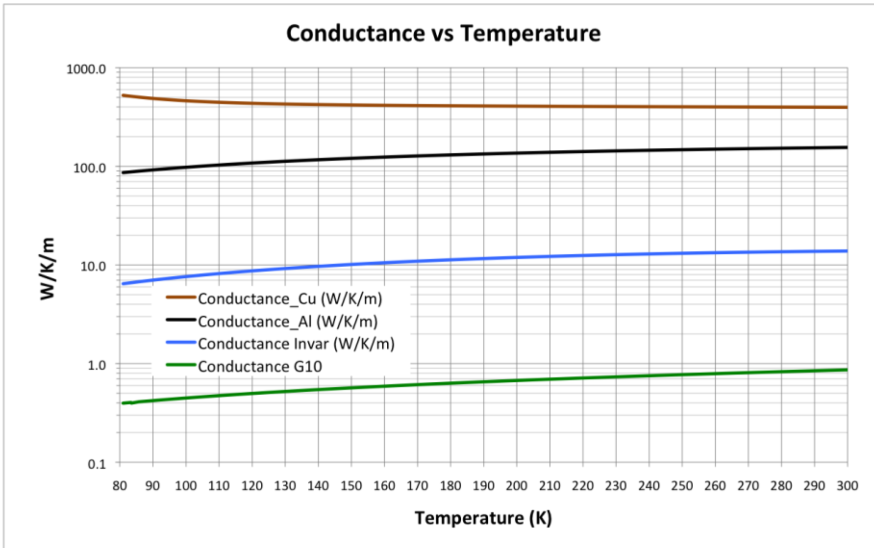

Figure 15: The thermal model uses fixed values taken from these curves at the operating temperature.

Where properties vary within a component due to gradients in temperature across the component (e.g. the thermally insulating supports), an average value is used. Since the power flowing though these components is minor, the error is negligible.

Masses used for calculating heat capacities were predicted for the final design using SolidWorks. Fasteners have been neglected.

Resistances were estimated from Finite Difference modeling with token heat flows and boundary conditions as follows:

- Cold head temperature = 80 K
- Detector power = 0.325 W, applied at three mounting points of detector.
- Detector heaters = 0.25 W
- Radiation to outer diameter cylinder of cold plate = 1.375 W
- Radiation to lower surface of cold plate = 1.25 W

Temperature drops between thermal circuit nodes were inferred from the colors shown in Figure 16 and divided by the power flows based on the numbers above. While the temperatures cannot be read very accurately from the figure due to the small number of colors and low contrast, this only results in a slight partitioning error between resistances in series and no cumulative error.

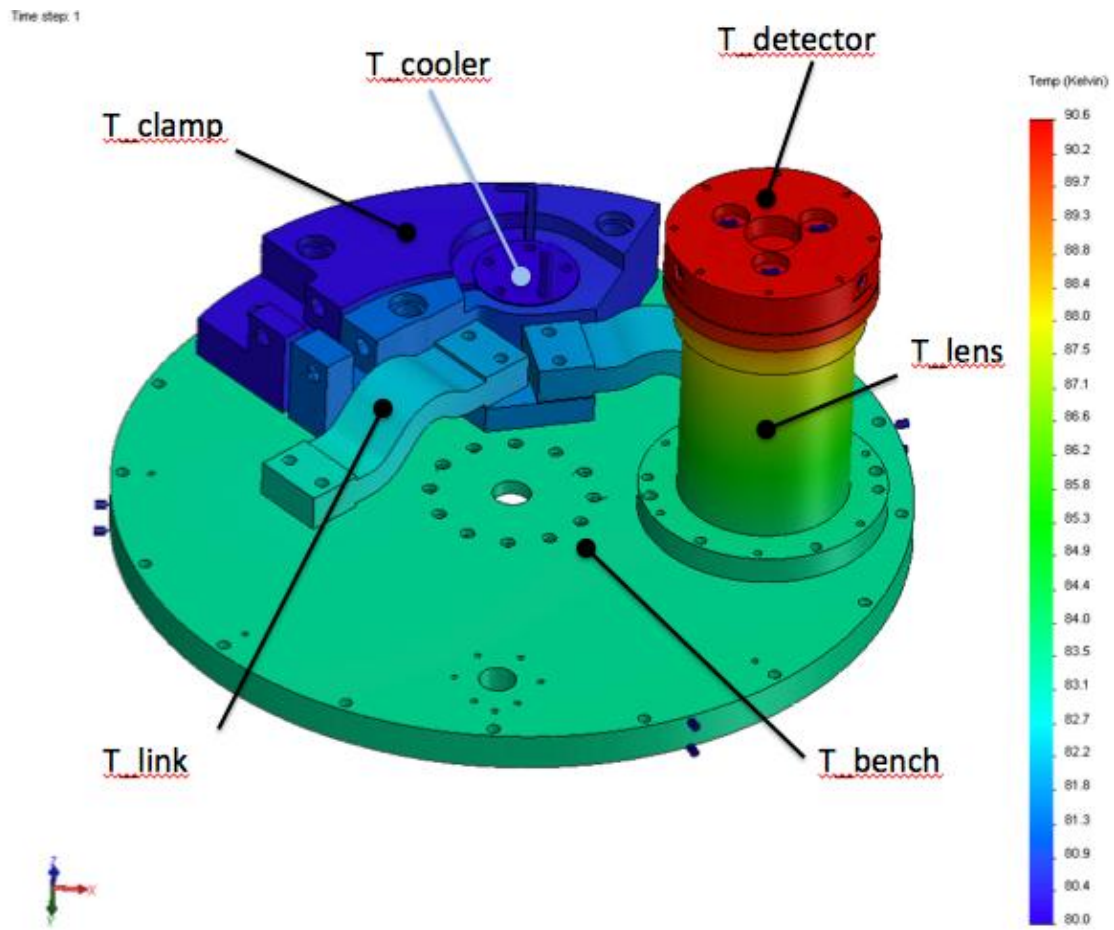

Figure 16 Finite difference analysis of the temperature distribution. The cooler temperature and power flows are somewhat arbitrary since this was only used to estimate the equivalent lumped resistances to be used in the thermal circuit used in the more complete model implemented as an Excel spreadsheet. The nodes for that model are labeled here.

The least well-defined model parameters are contact resistances and emissivities These are much less critical for the ARS Orca Coolers than the Polycold NF-48 due to the increased difference between cooling head temperature and detector temperature, which can accommodate a rise in cooling head temperature due to the higher power flow when emissivity is degraded or due to temperature drops across joints. These effects are discussed below, after examining the overall results.

Masses used to calculate heat capacities, and thermal resistances, are shown in Figure 12 while other parameters used in the model are shown in Table 2.

Surface	Emissivity	area	diameter	length
		(m^2)	(m)	(m)
dewar interior	0.08	0.427	0.315	0.274
shield exterior, upper	0.06	0.283	0.297	0.142
shield exterior, lower	0.06	0.283	0.276	0.025
shield interior	0.06	0.567		
bench	0.5	0.177	0.265	0.08
detector mount	0.3	0.004	0.071	

t_stop cooler	180,000	s
t_2nd_det_setpoint	200,000	s
t_start_Bench heater	220,000	s
T_bench_setpoint	300	K
max bench_heater_power	5	W
bench servo gain	10	W/K
T_1st_det_setpoint	120	K
T_2nd_det_setpoint	300	K
max det_heater_power	1.3	W
det servo gain	6	W/K

Table 2: Parameters used in the thermal model in addition to component values shown in Figure 12

Detector heater

The maximum detector power available from the Lakeshore 336 temperature controller (25 W) greatly exceeds requirements and could generate dangerous slew rate in the event of hardware, software or operator error. To prevent this, detector heater resistance will be chosen to dissipate only 1.3 W at the maximum output voltage so that the highest detector temperature slew rate will be limited to 0.5 K/min. Fortuitously this also limits the lens slew rate caused by the detector thermal transient to 0.08 K/min (Figure 18).

Warm up

Simply shutting off the cooler results in only 0.02 K/min initial warming rate, given the emissivities of the dewar and shield ~0.04. This rate drops further as room temperature is approached due to lower conductive and radiative loading. As a result it will take a week or more for the dewar to reach room temperature if no additional power source is employed.

The use of an additional power source is also desirable to minimize cryopumping by the detector as the other parts of the dewar begin to desorb contaminants.

Without additional power, the warming rate for the bench drops to 0.02 K/min by the time the detector reaches room temperature even when running the detector heater at full power during warm up. A constant 0.08 K/min slew rate will be enforced during warm up by generating ~5 W with the bench heaters. This will reduce the warm up time to ~42 hours, the shortest possible without exceeding the limit for the optics.

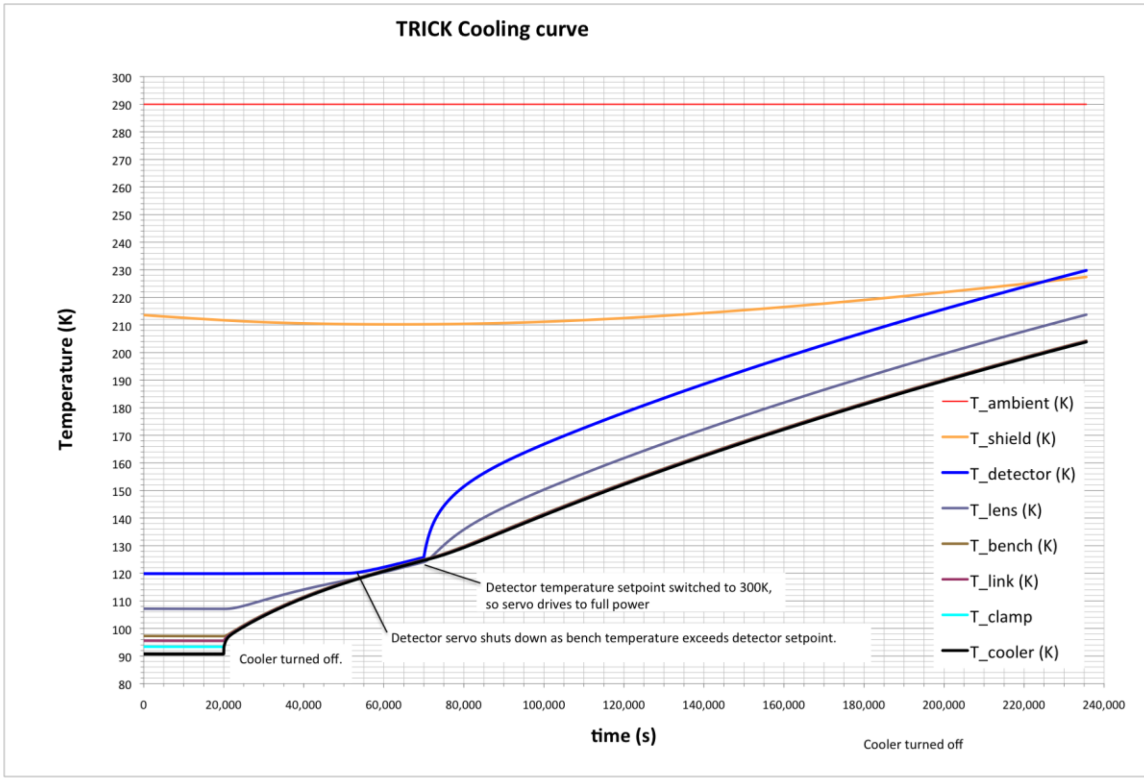

Figure 17: Warm up curves starting with equilibrium temperatures for ARS Orca MR90 cooler and detector setpoint at 120 K. The cooler is switched off then the detector setpoint is changed to 300 K after the detector servo has shut down. This generates the largest possible thermal slew rate at the detector. Warm up is much too slow with the detector heater alone.

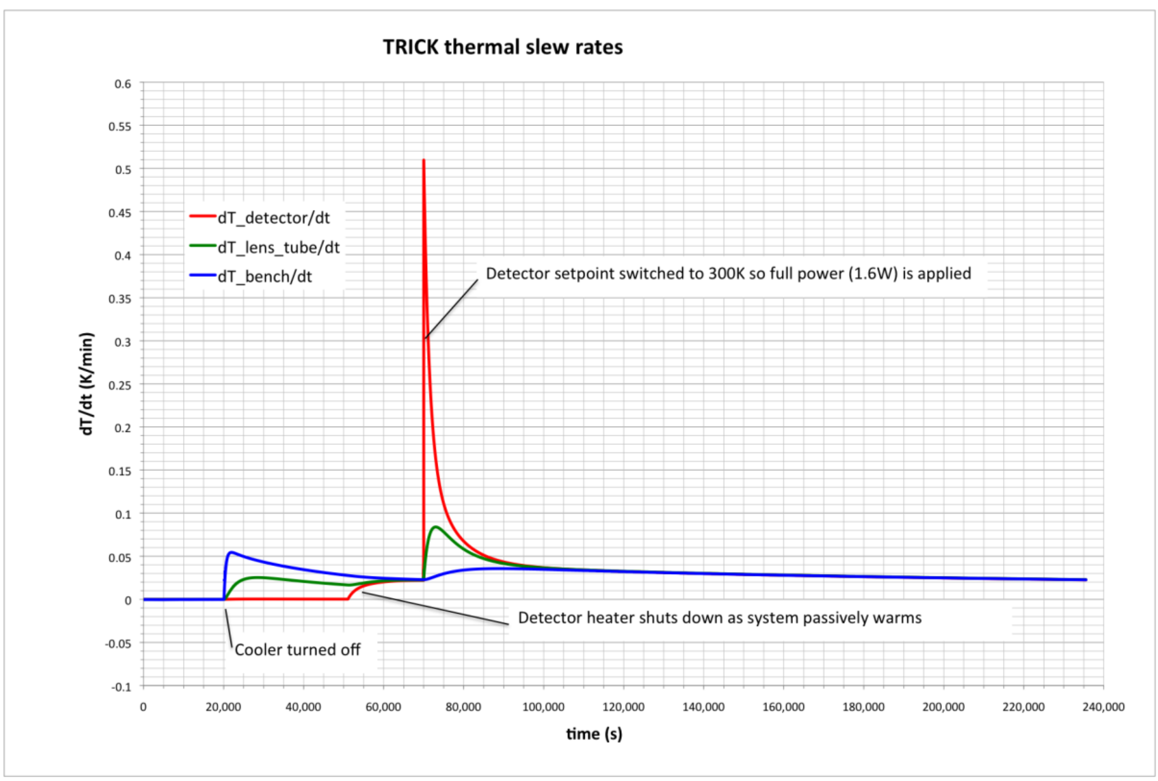

Figure 18: Thermal slew rates when detector servo switches from zero to full power at low temperature.

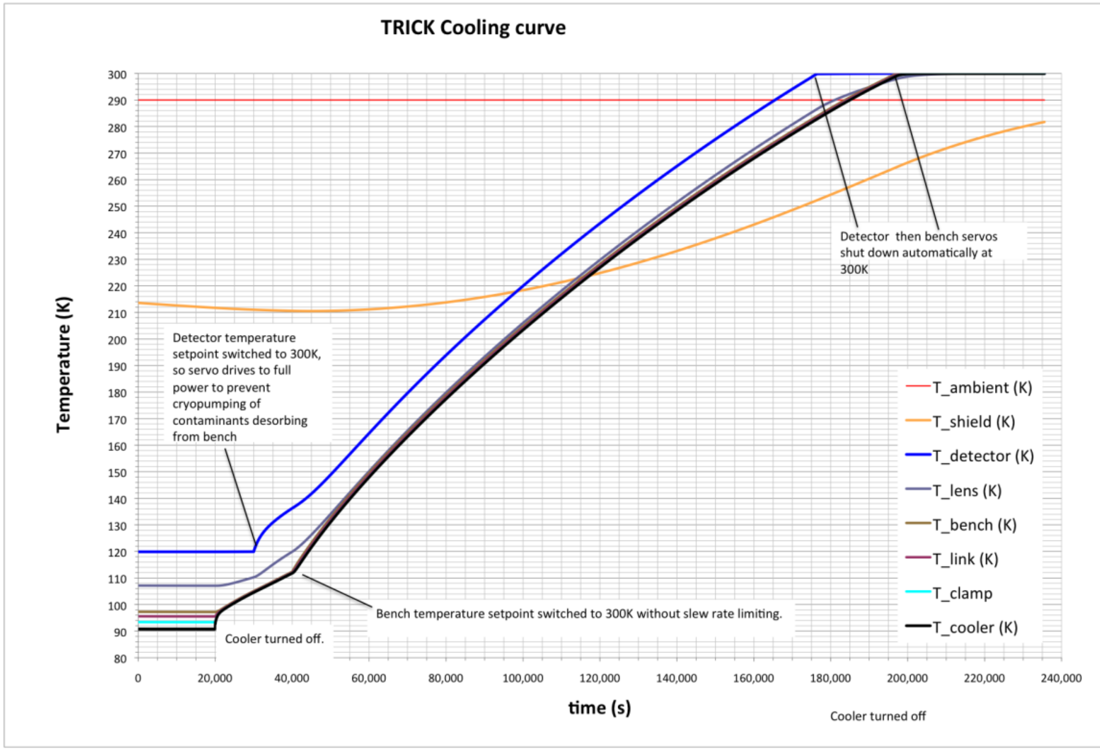

Figure 19: Warming curves starting with equilibrium for ARS Orca MR90 cooler and detector setpoint at 120 K. The cooler is shut down, then both bench and detector setpoints are switched to 300 K simultaneously generating 1.3 W at the detector and 5 W on the bench.

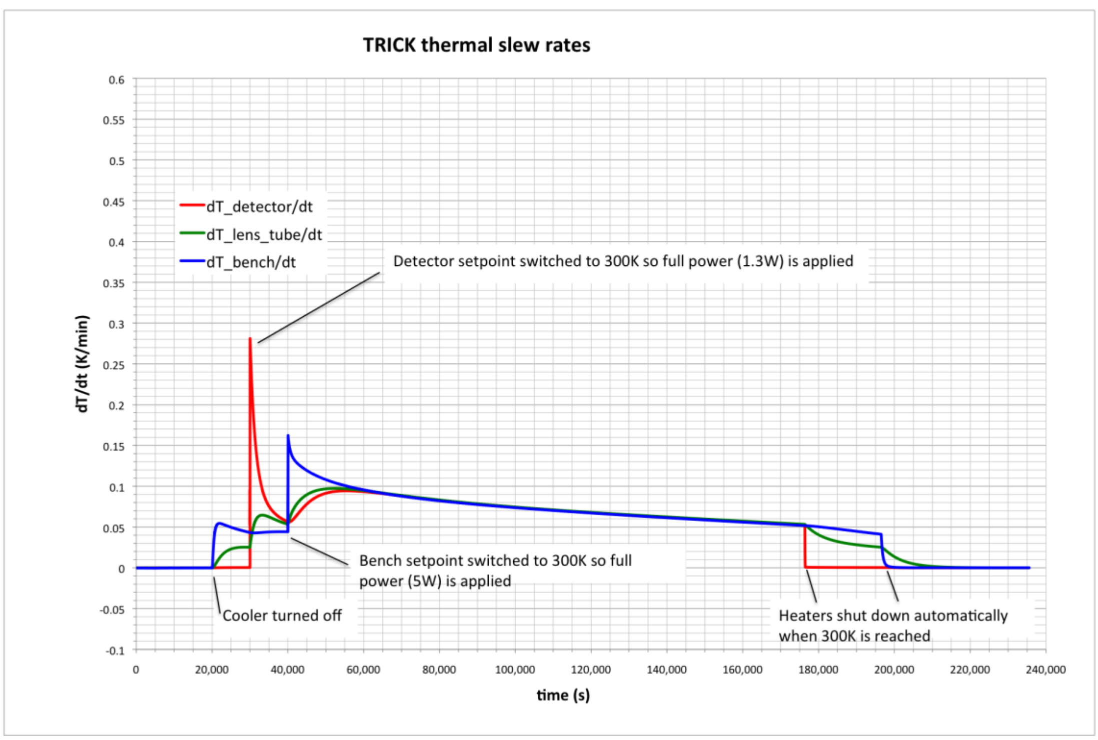

Figure 20: Slew rates during warm up with bench heater at full power. In reality the servo will actively restrict slew rate to 0.08 K/min instead of applying full power as shown here.

Fault protection

As discussed at length above, excessive cooling rate is prevented primarily by limiting the power available. The small (20%) power margin will be compensated, if needed, by application of the bench heaters during cool down. Excessive positive slew rate during warm up is limited by selecting bench heater resistors so that even in the event of the controller driving to the maximum voltage during a fault, the power dissipated will be acceptable.

A temperature controller fault or erroneous setpoint value for either the detector or bench servos could easily drive the detector beyond maximum permissible temperature. "Microtemp" thermal fuses will be placed in series with both servos to cut the power if the temperature exceeds 47 C. The threshold temperature is set above ambient to avoid accidental tripping of the fuse, which has to be replaced once tripped. 47C is the lowest threshold available and is below the temperature at which the detector or epoxy bonds are damaged. These have fuses been used extensively for this purpose at Caltech and NOAO and have been highly reliable.

Loss of thermal contact between heater resistors and the heated surface can cause power resistors to overheat, melt and even explode. To prevent the more violent outcomes very heavy wire will be used between resistors providing a heat sink to the neighboring resistor. The detector, optics and filters are fully enclosed except for small venting holes, with the heating elements on the outside of these spaces, and any vapors produced will freeze out upon contact with cold surfaces providing a final level of protection, unless the camera is warm.

To provide a soft fail in the event of an open circuit, a more common failure mode sometimes resulting form thermal stresses in the heater resistor, all heaters will be wired as a network of series-parallel resistors, so that the heater will continue to function if any one element becomes an open or short circuit.

Contact resistance modeling

Contact resistances in the range from 2 K/W to the highly optimized 0.2 K/W have been modeled, but these are only guesses. Low contact resistance requires high forces in dry joints, or for joints to be wetting over large areas by adding indium, or a thin film of vacuum grease or epoxy to the joint. Where possible joints in the lens *tube* have been designed to experience large compression forces due to differential thermal contraction caused by nesting the lower CTE material within the higher CTE material. This also serves to remove the centration error created by the clearance fit at high temperature. (None of these forces are transmitted to the lenses.)

The permissible contact resistance depends on the power flow. Typical values are:

- ~0.4W through supports,
- ~0.15W through wiring
- ~0.8W from shield to the bench (highly dependent on dewar and shield emissivities) and

- ~0.4W from the window (independent of emissivities).

See Figure 23 for an example of the time dependence of some of these power flows.

Keeping all parameters the same as in Figure 4 but increasing contact resistance from 0.5K/W to 2 K/W, we see in Figure 21 that operating temperature has to be increased (from 136K in Figure 4) to 145K. This would impact dark current and noise performance and thus require one of the special joints treatment noted above.

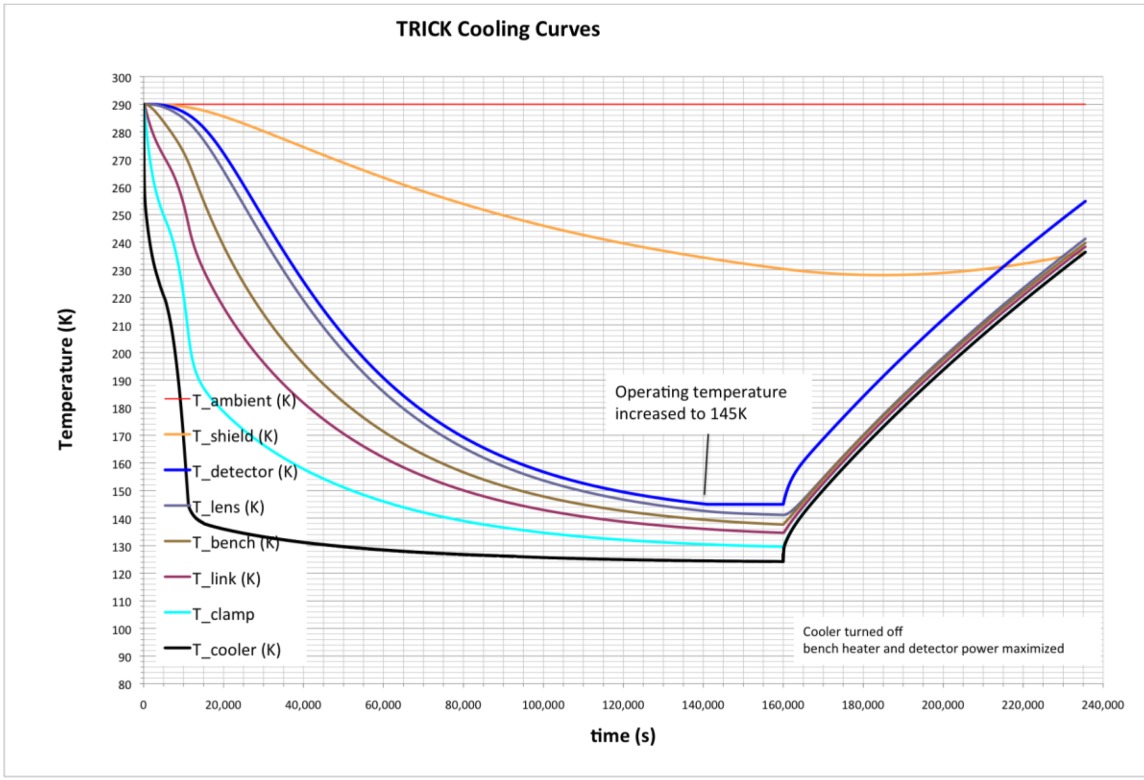

Figure 21: Polycold JT cooler with NF48 refrigerant, with resistance of bolted contacts increased to 2K/W, but emissivity unchanged. Detector temperature setpoint had to be increased from 136K to 145K.

Emissivity modeling

Emissivity values at 10 µm and longer, where the black body emission is peaked, are typically 0.025 for gold over polished metal, 0.04 for freshly polished and clean aluminum, or 0.06 for polished nickel which is more stable over time than bare aluminum. Emissivity for the dewar interior has been set to 0.08 in all cases unless notes, to allow for some ageing of polished Aluminum, while the shield emissivity has been set to 0.06 assuming polished nickel rather than gold. The internal parts such as the bench and lens tube are assumed to have emissivity = 0.5 to be on the safe side even though they should be moderately polished too and well cleaned.

Figure 4 shows the Polycold cooler NF-48 cooling curve for the above emissivities and low contact resistance. Figure 22 shows the corresponding case where emissivity is degraded to 0.1 for both dewar and shield: the higher power flow both raises the cold head temperature and the increases the temperature drops across all series resistances. Provided that contact resistances are small this only results in a small (2K) increase in detector temperature. Figure 24 shows the combined effect of increased emissivity and inferior contact resistance.

Figure 26 shows the detector temperature is unaffected for the ARS Orca MR90 refrigerant even when both emissivity and contact resistance are degraded. Compare to Figure 10.

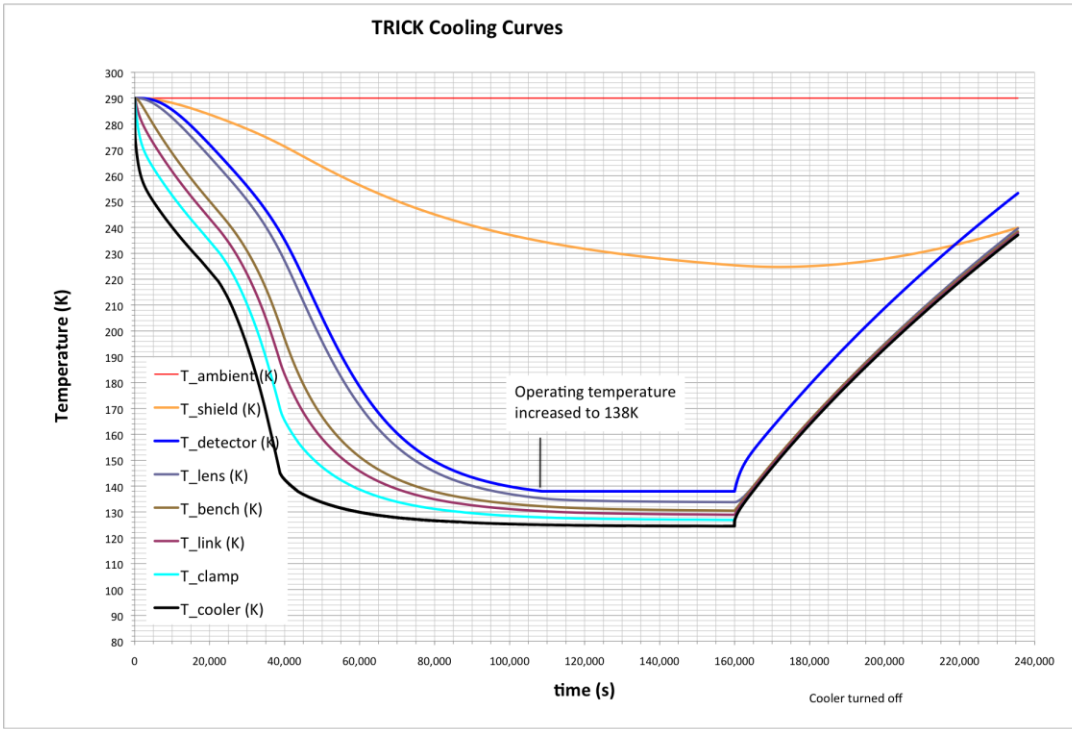

Figure 22: Polycold NF 48 with emissivity increased to 0.1 for dewar, shield exterior and interior, for low contact resistances (0.5K/W). Detector temperature setpoint had to be increased from 136K to 138K. (In this example, to warm up, the cooler is shut down and detector heater and bench set-points are switched to 300K simultaneously.)

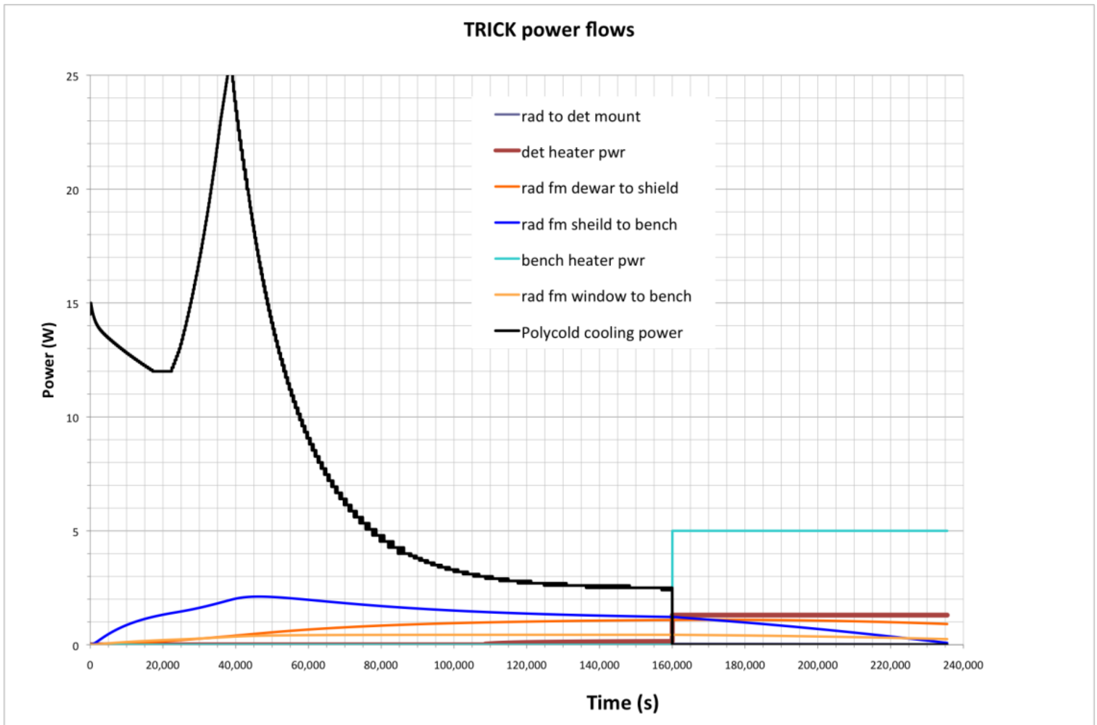

Figure 23: Radiative, cooling and heating power flows corresponding to Figure 22. The conductive flows from ambient (~0.15W in wiring and ~0.4W in supports at operating temperature) are not shown.

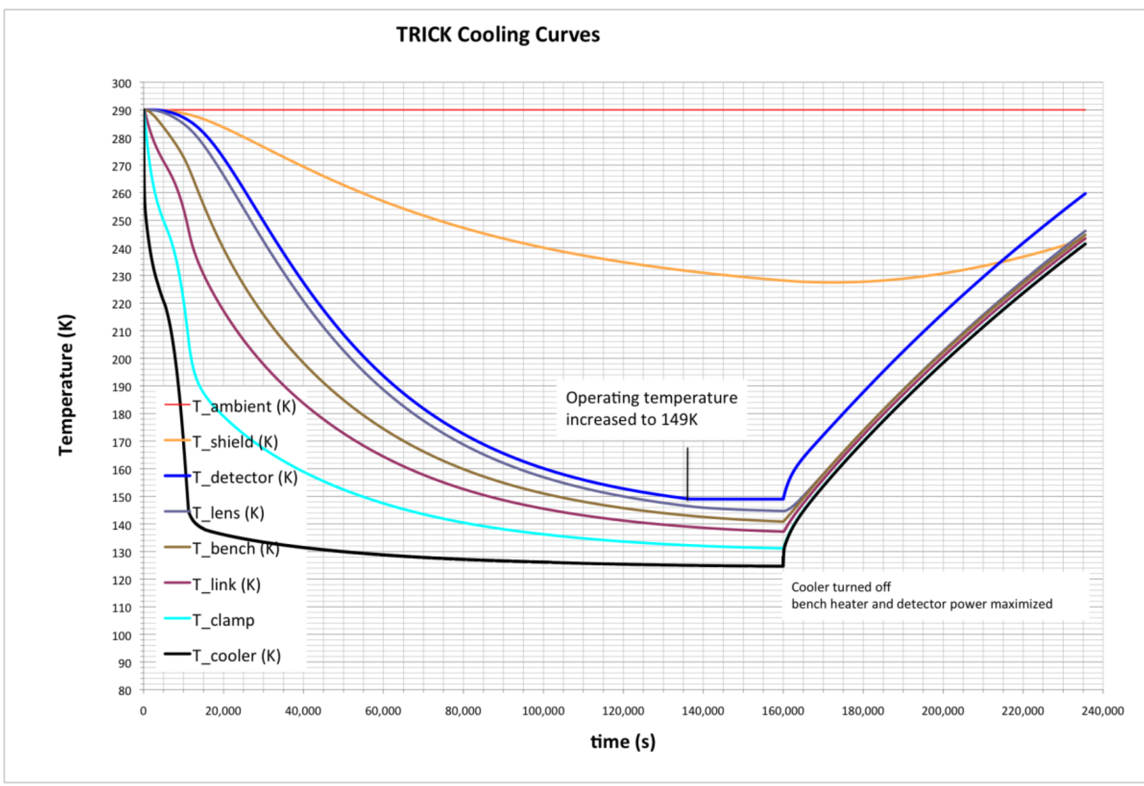

Figure 24: Polycold NF 48 with emissivity increased to 0.1 for both dewar and shield interior and exterior, for higher contact resistances (2 K/W). Detector temperature and cooling time are both increased.

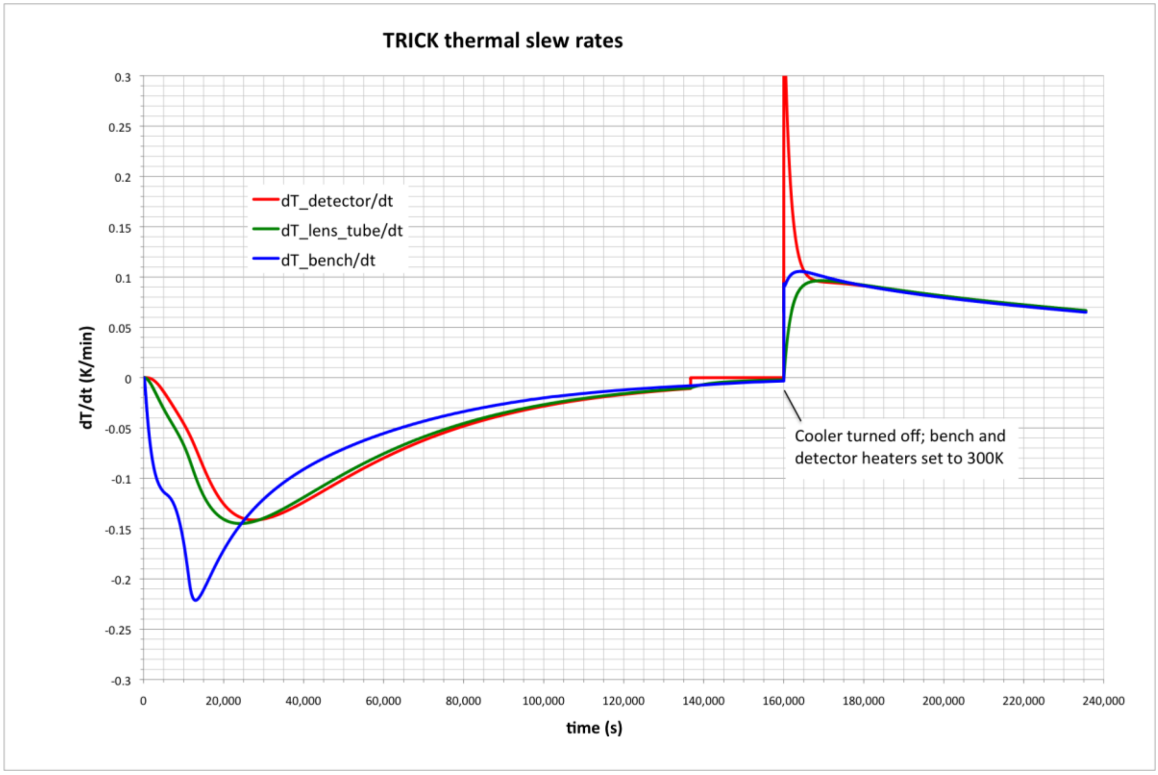

Figure 25: Slew rate for NF48 cooler with 0.1 emissivities. The 2K/W contact resistance partially mitigates the excess slew rate of the NF48 refrigerant.

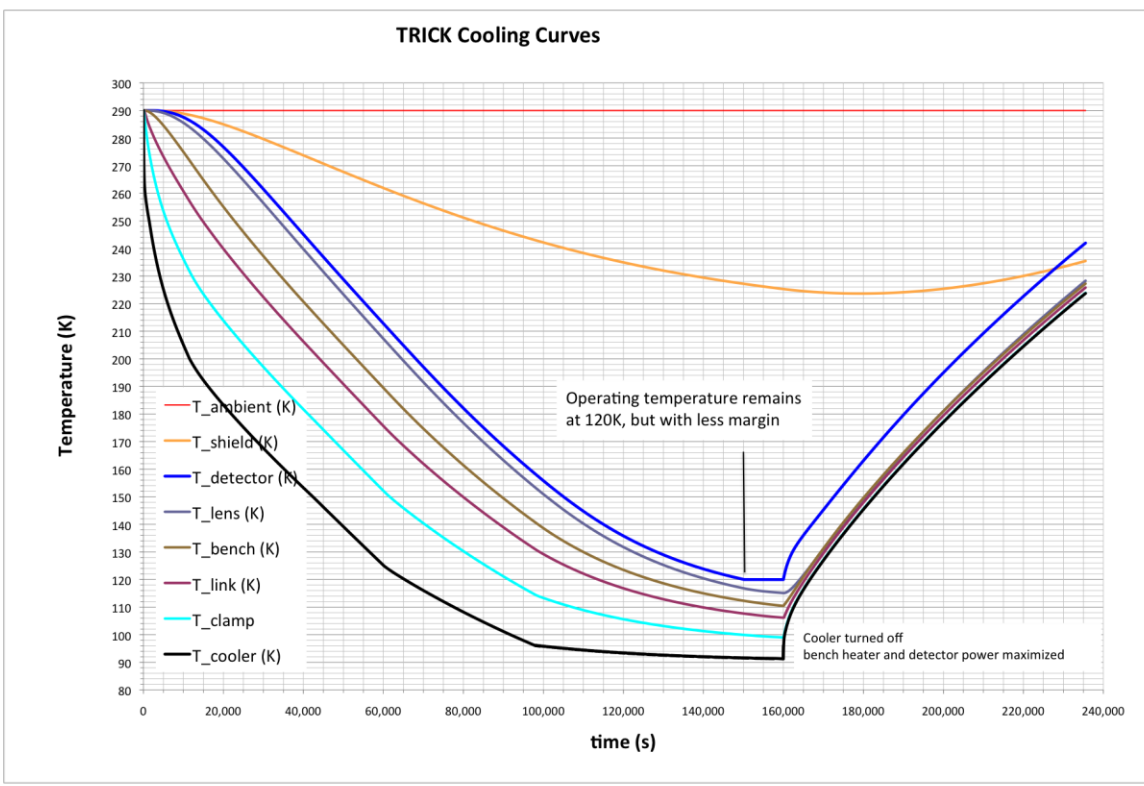

Figure 26: Cooling curves for ARS Orca MR90 with high emissivity (0.1) and high contact resistance showing that a low detector temperature can still be achieved under these less than ideal conditions.

Sensitivity to ambient temperature

Radiative power transfer scales as the fourth power of the ambient temperature, while conduction scales linearly. The curves presented above are for a 290K ambient temperature. Comparing Figure 27 to Figure 4 shows how a lower initial temperature (270K) both reduces cooling time, and reduces the cold head temperature slightly due to the lower radiative and conductive loads. Since the change in cold head temperature is small, the detector servo easily compensates. The detector temperature setpoint may be able to be set a few degrees lower due to the low ambient temperature on Mauna Kea.

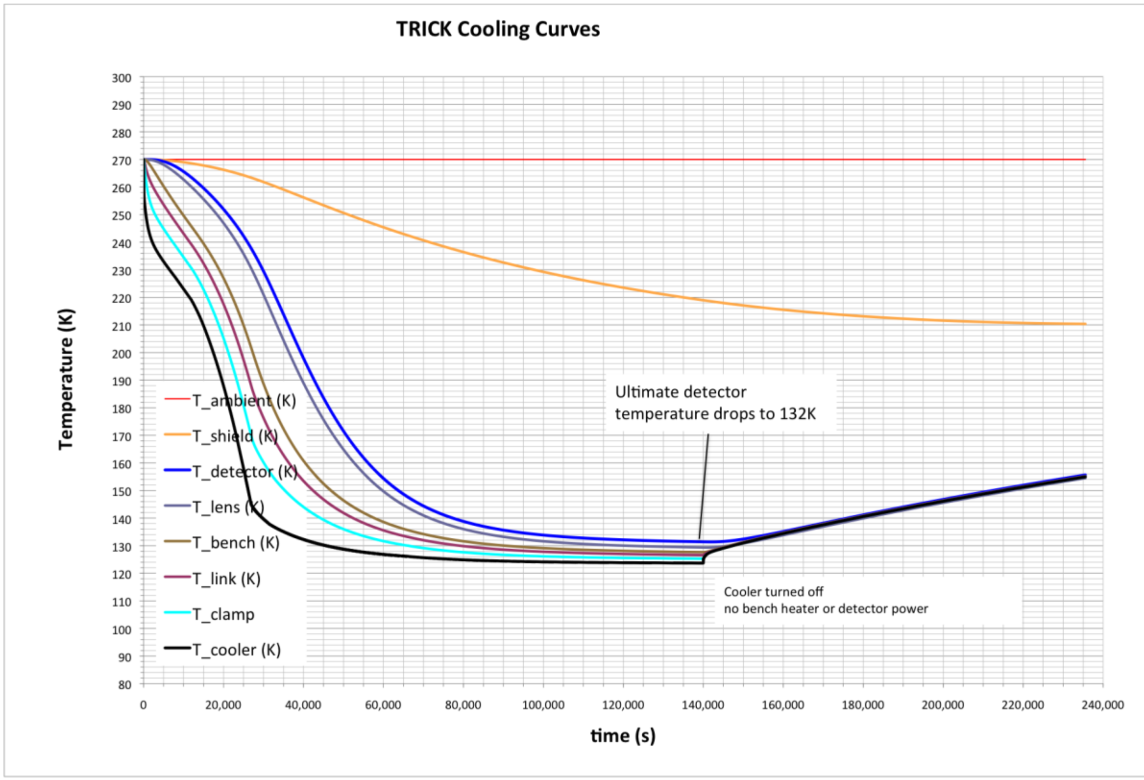

Figure 27: Cooling curve for Polycold with NF48 refrigerant when ambient temperature is 270K, for low (0.5K/W) contact resistance and standard emissivities (0.08, 0.06). Compare with the same case for 290K shown in Figure 4.

Summary

The adoption of the Orca Joule Thompson Cooler made by Advanced Research Systems Inc., with their MR90 refrigerant provides almost constant cooling rate for the shortest possible thermal cycle, while matching the power level to the heat capacity to avoid thermal shock to the optics. Fortunately, the Orca costs about \$10K, half the price of the Polycold, and the mechanical design mods required are of order 3 man days so the design change is assured to provide a net saving.

Ample power margin and low cold head temperature accommodate cheaper (higher emissivity) surface treatments and make the design less vulnerable to modeling errors which commonly occur due to “shape factor” being neglected in radiative transfer calculations, unaccounted gaps in shields, misestimation of contact resistances, etc., and due to residual errors due to the lumped circuit approximation.

The above choices provide ample safety margin for detector operating temperature (thus low dark current) and good thermal stability under all environmental conditions.

Warm up time has been reduced to the minimum possible within the thermal slew rate constraint (42 hours). Cryopumping by the detector during warm up has shown to be avoidable by maximizing detector heater power during warm up.

Safety concerns have been addressed by using an inflammable refrigerant, which is also non-toxic. Risk to equipment due to slew rate or excess have also been addressed.

It remains to be resolved whether the 0.08 K/min slew rate limit adopted from MOSFIRE is in fact safe. The much smaller lens diameter and mass in the NIR TTS camera, compared to MOSFIRE, must surely provide some relief, but the smaller contact area may reduce that advantage. We have identified the necessary tools but have not yet done the analysis. Another approach would be to identify an analogous implementation.

We had hoped to resolve this with an experiment in which a BaF_2 flat was cooled after bonding to a representative cell (including flexures) but looking back on that experiment now it is clear that the cooling method used (contact with cold gas) was radically different to the NIR TTS case and the cooling rate was not well enough documented. In that test, one of the three epoxy 3 pads “cored out” a piece of the BaF_2 so we really don't yet know the maximum permissible cooling rate.