Active Versus Standby Redundancy for Improved Cryocooler Reliability in Space

R.G. Ross, Jr.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Long-life space cryocooler applications, such as NASA's Atmospheric Infrared Sounder (AIRS) instrument, require that the cryocooler system possess a very high level of reliability. This need for high reliability not only demands that high reliability coolers be used, but often requires that some form of redundancy be incorporated. One common implementation is standby redundancy; however, active redundancy is another equally viable choice. Recently, experience with both types of redundancy has been gained with the AIRS instrument. The AIRS cryocoolers were initially designed and launched as standby redundant units; they were then switched over to active redundancy after six months of in-space operation.

This paper examines the performance trade for the two redundancy approaches with explicit treatment of the effect of operational level (off, versus low power, versus high power) on the reliability of the redundant and primary unit. This is accomplished through the derivation and use of a new reliability model that explicitly includes the probability of failure both prior to and after the time of a cooler failure. Also presented, is a discussion of the effect of the two redundancy approaches on the overall space-instrument system including input power level, robustness to transient single-event shutdowns, and robustness to in-space load increases—such as from in-space contamination of cryogenic surfaces. The active redundancy approach is shown to have advantages in terms of improved reliability as well as improved overall system performance.

INTRODUCTION

One key means of improving the reliability of systems required to provide continuous cooling during multi-year space missions is to incorporate redundant components to protect against individual failures. There are many options for incorporating redundancy; four common ones, highlighted in Fig. 1, have been analyzed previously by this author with respect to their total systems advantages and disadvantages.[1] Although most space cryocooler missions to date have not incorporated redundancy, the 'dual coolers with dual electronics and no switches' approach in the lower left corner of Fig. 1 was adopted by the NASA AIRS mission, which was launched in May 2002.[2-5] The original analysis of the reliability of that configuration utilized the classic equations for the reliability of a two-parallel redundant system as noted in Eq. 1. This classical equation describes the reliability (R_{clrsys}) of the two-cooler system over (T) years of operation as:

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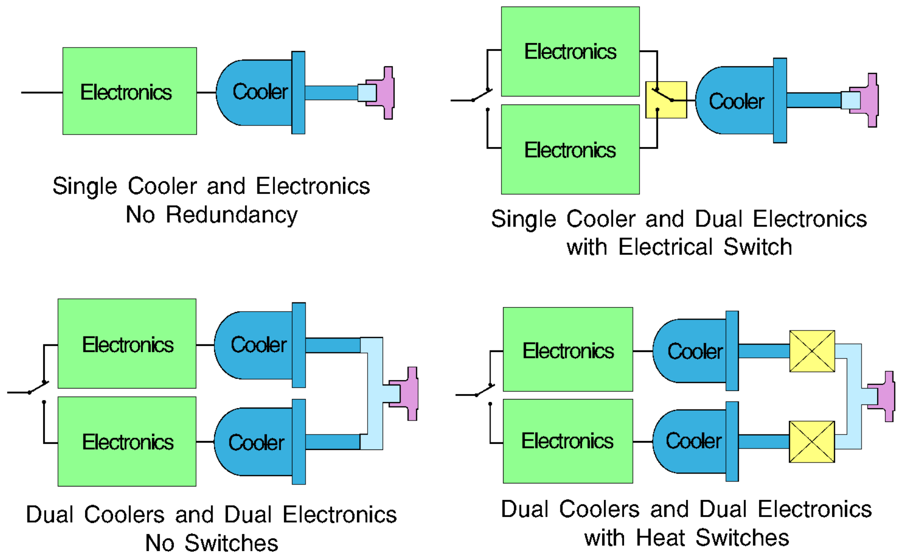

Figure 1. Example cryocooler redundancy options.

$$R_{clrsys} = 1 - (\dot{P}_u \cdot T)^2 \qquad (1)$$

where P_u is the probability of failure per year of each integrated cooler unit (mechanical cooler plus electronics). Given that the electronics and mechanical cooler are in series (i.e. both must work for the integrated cooler unit to work) we get that

$$\dot{P}_u \approx \dot{P}_e + \dot{P}_m \qquad (2)$$

where $\dot{P}_e$ is the probability of failure per year of the electronics and $\dot{P}_m$ is the probability of failure per year (failure rate) of the mechanical cooler. This simplified equation assumes that the probabilities of failure are small ($\dot{P} \ll 1$). More accurately

$$\dot{P}_u = \dot{P}_e + \dot{P}_m - \dot{P}_e\dot{P}_m \qquad (3)$$

Also imbedded in these classical equations for series/parallel redundancy are assumptions as to how the coolers are operated. For example, is the redundant unit 'on' or 'off' while the second unit is operating, and what is the effect of whether it is on or off on its probability of failure?

For the AIRS instrument, an operational strategy referred to as *standby redundancy* was initially selected. With this approach, the second, or redundant cooler, was assumed to be not operating while the primary unit was operating; this minimizes the chance of failure of the backup unit during operation of the primary unit. A second operational strategy available with the AIRS cooler configuration was to operate both coolers at reduced power until one fails, then to depend on the remaining good cooler to operate alone for the rest of the mission life, or until it fails. This is referred to as *active redundancy.*

For either operational strategy, each cooler must be sized to carry both the active cooling load of the instrument as well as the parasitic cooling load caused by heat conduction through the turned-off cooler. For the AIRS cryogenic system, the parasitic load through the off-cooler represents nearly half of the total load on the operating cooler.[3] Thus, when two coolers are sharing the load, they have only about one quarter of the load carried when a single cooler is operating.

To properly quantify and understand the reliability of these two operational strategies, one must explicitly address the effect of operational level (off, versus low power, versus high power) on the reliability of the redundant and primary unit during all periods of the mission. This requires an analytical formulation for reliability that is considerably more complete than the classical representation presented above in Eqs. 1 to 3. Also, when considering the merits of the two operational strategies, it is important to consider the effect of the two redundancy approaches on the overall space-instrument system including input power level, robustness to transient single-event shutdowns, and robustness to in-space load increases—such as from in-space contamination of cryogenic surfaces.

This paper first addresses this comparison through the derivation and use of a new reliability model that explicitly includes the probability of failure, both prior to, and after the time of a cooler failure. This is then followed by an examination of the effect of the two redundancy approaches on the overall space-instrument system.

RELIABILITY MODEL DERIVATION

To understand the reliability of the complex operational scenario associated with active redundancy it is necessary to examine the details of what it takes to survive the mission. Let us assume that there are two parallel cooler units (A and B), and that cooler A fails first, and then cooler B continues on until cooler B fails. Successful outcomes include both:

a) Those cases when cooler A never fails and operates for the complete mission, and

b) Those cases where cooler A fails, cooler B is still functional when cooler A fails, AND cooler B does not fail for the remainder of the mission.

Examination of the above indicates that there are three failure-rate terms that govern the system-level reliability: 1) the probability of failure per year ($\dot{P}_A$) of cooler A prior to its failure, 2) the probability of failure per year ($\dot{P}_{B1}$) of cooler B prior to the failure of cooler A, and 3) the probability of failure per year ($\dot{P}_{B2}$) of cooler B after the failure of cooler A. Introducing these three distinct failure-rate probabilities ($\dot{P}_A$, $\dot{P}_{B1}$, and $\dot{P}_{B2}$) allows us to assign different failure rates to the two coolers before and after the switch-over to the redundant unit.

Stepping back to basic principals, we can now calculate the reliability of the complete system over mission length (T) as the fraction of successful outcomes out of all possible operational outcomes. Successful outcomes include: 1) cases where cooler A never fails, and 2) all cases where cooler A fails at time (t), cooler B is still functional (has not failed) at time (t), AND cooler B continues to run for the remainder of the mission (T- t).

Mathematically, the fraction of possible outcomes where cooler A never fails is given by the reliability of cooler A, i.e.

$$R_A = 1 - \dot{P}_A T \tag{4}$$

For all other possible outcomes, consider the calculational process schematically illustrated in Fig. 2. Here, we divide up the mission duration (T) into numerous time intervals Δt, each defined by the time (t) since the start of the mission. For each of these time intervals we ask what is the probability of a cooler A failure during this interval, and what is the fraction of these failure cases where cooler B successfully completes the mission. This fraction of cases where cooler B works successfully can be most easily computed as one minus the probability of cooler B failing either before or after the switch-over. Thus, the fraction of successful outcomes for each Δt interval at each time (t) is given by

$$R_t = \dot{P}_A \Delta t \left(1 - \dot{P}_{B1} t - \dot{P}_{B2}(T - t)\right) \tag{5}$$

where $\dot{P}_A \Delta t$ is the probability of a cooler A failure during time interval Δt, $\dot{P}_{B1} t$ is the probability of cooler B failing prior to time (t), and $\dot{P}_{B2}(T - t)$ is the probability of cooler B failing after time (t).

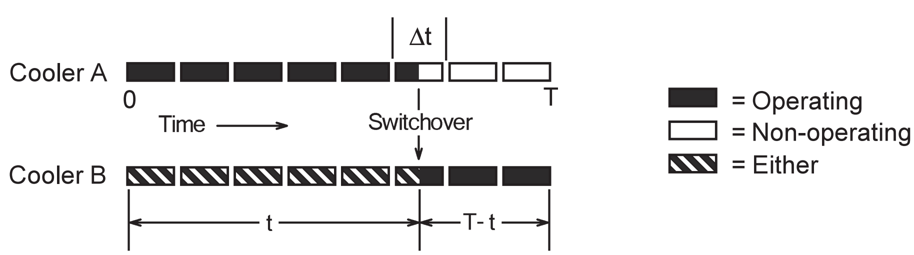

Figure 2. Schematic illustration of reliability calculation interval (Δt) of mission life (T).

Now, the complete mission reliability (the fraction of successful outcomes out of all possible operational outcomes) is just Eq. 4 plus the sum of Eq. 5 over all possible Δt's from 0 to T, i.e.

$$R_{clrsys} = 1 - \dot{P}_A T + \sum_{t=0}^{T} R_t \tag{6}$$

Converting this to an integral for a vanishingly small Δt we get

$$R_{clr} = 1 - \dot{P}_A T + \int_{t=0}^{T} \dot{P}_A \left(1 - \dot{P}_{B1} t - \dot{P}_{B2}(T - t)\right) dt \tag{7}$$

which gives

$$R_{clrsys} = 1 - \tfrac{1}{2} T^2 \dot{P}_A (\dot{P}_{B1} + \dot{P}_{B2}) \tag{8}$$

or

$$P_{clrsys} = \tfrac{1}{2} T^2 \dot{P}_A (\dot{P}_{B1} + \dot{P}_{B2}) \tag{9}$$

where

R_{clrsys} = reliability of cooler system over T years operation
P_{clrsys} = probability of failure of cooler system in T years
$\dot{P}_A$ = probability of failure/year of cooler A + electronics A, where unit A is the first to fail
$\dot{P}_{B1}$ = probability of failure/year of cooler B + electronics B in period before unit A fails
$\dot{P}_{B2}$ = probability of failure/year of cooler B + electronics B in period after unit A fails

In the above, recall that the probability of failure of the mechanical cooler plus electronics is given by Eqs. 2 and 3. For example, for cooler A

$$\dot{P}_A \approx \dot{P}_{mA} + \dot{P}_{eA} \tag{10}$$

Comparing Eq. 9 with Eq. 1, we see that Eq. 1 assumes that $\dot{P}_{B1} = \dot{P}_{B2} = \dot{P}_A$, i.e. that cooler B's probability of failure is independent of whether it is operating or not, or whether cooler A has failed or not. Equations 8 and 9 now provide access to these important functional dependencies.

SYSTEM IMPLICATIONS OF ACTIVE VERSUS PASSIVE REDUNDANCY

Equations 8 and 9, provide one means for providing visibility into the reliability strengths and weaknesses behind active versus passive redundancy. However, before conducting numerical comparisons it is useful to first explore the system level implications of the two redundancy options; this can provide insight into additional reliability factors that may need to be addressed.

Important distinctions between active versus passive redundancy include:

- The drive level (power, piston stroke, speed) associated with each cooler, both before and after a first cooler failure, and how the drive level reflects into the projected failure rate of the coolers and their electronics
- The impact of two-cooler operation on the total input power required from the spacecraft and the amount of heat that must be rejected from the spacecraft heat rejection system
- Possible implications of two-cooler operation on closed-loop temperature control of the cryogenic load
- Possible implications of two-cooler operation on such things as closed-loop cryocooler vibration suppression systems and limits on allowable input ripple current to the spacecraft power system
- The extent to which two-cooler operation minimizes thermal cycling of the overall cryogenic load to elevated temperatures during the mission due to things such as spurious safety trip-outs and warm-ups required to boil-off contamination condensed on cryogenic surfaces

Each of these is discussed below.

Implications on Required Range of Cooler Drive Levels

With active redundancy, both coolers (the primary and the backup) run simultaneously until one of the two coolers fails. From an input-power perspective, the impact of simultaneous two-cooler

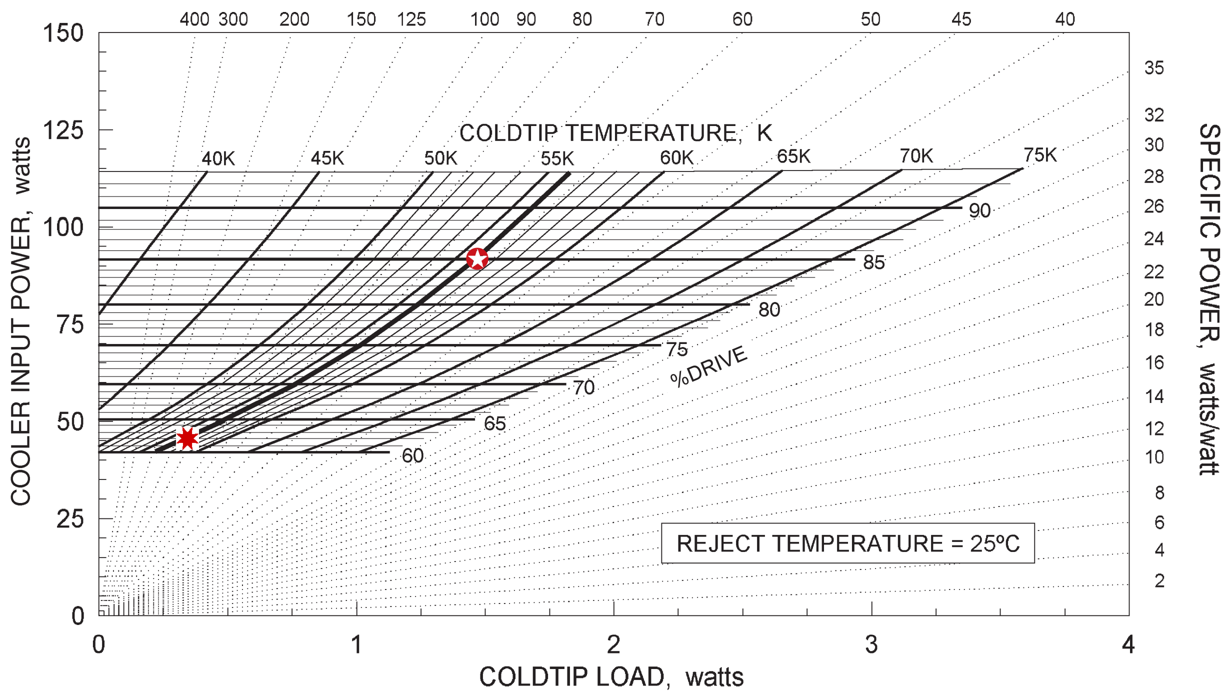

Figure 3. Cryocooler operating point in the AIRS instrument with single cooler operating ✪ and with load shared by two coolers in active redundancy mode ✷.

Table 1. Cooler drive status for the three operating regimes.

Redundancy Implementation	Cooler Drive Level		
	Cooler A Before Failure	Cooler B Before Cooler A Fails	Cooler B After Cooler A Fails
Standby Redundancy	85% drive	unpowered	85% drive
Active Redundancy	62% drive	62% drive	85% drive

operation may be greatly alleviated by the fact that, with some cooler designs, as much as 50% of the total cryogenic load may be the parasitic load of the non-operating redundant cooler.[3] Specifically, with both coolers operating, the parasitic load of the standby cooler disappears, and the total cooling load shared by the two operating coolers may be only half of the load carried by a single operating cooler. This can result in each of the operating coolers in an active redundant system carrying only one quarter of the cryogenic load of the single operating cooler in a standby redundant system, and cause the required spacecraft power for the active redundant system to be comparable to that for the passive redundant system.

As an example, Fig. 3 illustrates the operating points of the pulse tube cryocoolers in the AIRS instrument in both standby redundancy mode (single cooler operating) and active redundancy mode (both coolers sharing the load until one cooler fails). Table 1 summarizes the resulting drive levels for this application in both the standby and active-redundancy implementations. For the AIRS cooler, '%-drive' is the relative input drive level that is commanded to the power amplifier; for the mechanical unit, it roughly equates to the percent of maximum available piston stroke.

Implications of Cooler Drive Level on Failure Probabilities

As shown in Table 1, active versus standby redundancy leads to significantly different drive levels (stroke levels) on the coolers prior to a first cooler failure. Specifically, the trade is between a single, heavily-loaded cooler plus a non-operating standby unit and two lightly-loaded coolers. Estimating the failure rates associated with these drive levels depends heavily on the specific cooler design and must draw upon test experience and understanding of the governing physics underlying the individual failure mechanisms.

Table 2. Failure rate (%/year) vs. input power level for example cryocooler mechanical unit.

FAILURE MECHANISM	0% Power 0% Stroke	40% Power 65% Stroke	60% Power 75% Stroke	75% Power 85% Stroke	100% Power 95% Stroke
Coldend blockage by Internal Contamination	0.05	0.05	0.08	0.15	0.22
Leakage from Seal or Feedthrough Failure	0.15	0.15	0.15	0.15	0.15
Comp. Flexure Spring Breakage from Fatigue	0	0.02	0.03	0.05	0.07
Comp. Motor Wiring Isolation Breakdown	0.05	0.12	0.15	0.25	0.35
Compressor Piston Wear or Seizure	0	0.06	0.09	0.15	0.22
Compressor Piston Position Sensor Failure	0	0.04	0.06	0.10	0.14
Wear and Leakage of Internal O-ring Seals	0	0.06	0.09	0.15	0.20
Total Failure Probability (%)	**0.25**	**0.50**	**0.65**	**1.00**	**1.35**

Table 3. Failure rate (%/year) vs. input power level for example cryocooler drive electronics.

FAILURE MECHANISM	0% Power 20°C	40% Power 25°C	60% Power 28°C	75% Power 30°C	100% Power 33°C
Transient/Peak Voltage-Current Stress	0	0.20	0.25	0.30	0.40
Arrhenius Time-Temp-Voltage Mechanisms	0.15	0.25	0.30	0.35	0.45
Thermal-cycle Fatigue Stress	0.05	0.10	0.15	0.20	0.25
Long-term Radiation Damage	0.15	0.15	0.15	0.15	0.15
Total Failure Probability (%)	**0.35**	**0.70**	**0.85**	**1.00**	**1.25**

Tables 2 and 3 provide examples of mechanism-level failure-rate estimates for both the mechanical cooler and its drive electronics. Such estimates, based on the methodology published previously by this author,[1] allow the effect of drive level to be explicitly observed. These particular estimates were generated by first scaling the mechanism failure rates at the 85% stroke level (which equates to a 75% power level) to give a total probability of failure of 1%/year; this corresponds to a 95% reliability after five years—which is felt to be a representative value. To scale the probabilities for different drive levels, the mechanisms were categorized by their underlying physics into those that had minimal dependency on drive level (such as leakage and parts radiation damage), those with a strong dependency on stroke level (such as flexure fatigue, contamination, and O-ring wear), and those with an Arrhenius-like temperature dependence on case temperature (such as many electronic-parts failure mechanisms). Included in the column headings is an estimate of the variation in total cooler input power, the percent of maximum piston stroke, and electronic part case temperature associated with the various drive levels; these data were drawn from the AIRS cooler application.[3,4]

For the stroke-sensitive failure mechanisms, the failure probability was assumed to increase 10x for each factor of two increase in stroke level (S), i.e. $\dot{P}_S = \dot{P}_{75\%} \times 10^{\alpha}$, where $\alpha = \log (S/S_{75\%})/\log 2$ and $\dot{P}_{75\%}$ and $S_{75\%}$ are the failure rate and stroke for 75% power. This is representative of the power-law dependence of fatigue life on strain level and is felt to perhaps be a useful model for piston-generated contamination and piston-head O-ring wear, since piston forces and compression space temperature both increase rapidly with increasing compressor stroke and input power. For Arrhenius mechanisms, where log failure rate is linearly proportional to inverse absolute temperature, P was assumed to increase 2x for each 10°C increase in case temperature (T), i.e. $\dot{P} = \dot{P}_{75\%} \times 2^{\beta}$, where $\beta = (T - T_{75\%})/10$. Note that these assumptions result in a significant reduction in failure probability at low drive-levels for both the cooler mechanical unit and its electronics.

Implications on Closed-loop Temperature Control, Vibration Control, and EMI

Another class of considerations that must be addressed in trading-off passive versus active redundancy is the effects on various control functions of running two coolers simultaneously. Specifically, closed-loop temperature control of the cryogenic load and closed-loop vibration suppression of cooler-generated vibration. The effect of ripple current fed back to the spacecraft power subsystem and AC magnetic fields of two coolers running simultaneously are additional considerations.

Closed-loop Temperature Control. For most space cryocooler applications, closed-loop control of the temperature of the cryogenic load is an extremely important function of the cooler system. Therefore, accommodating closed-loop temperature control with either one or both coolers operating is an important consideration in selecting cooler redundancy. As an example, with the AIRS cooler system, each of the two coolers is connected to the focal plane load with its own flexible braid that has a finite thermal impedance. This thermal impedance between the controlled cold tip and the focal plane allows the two coolers to run simultaneously, each with its own independent closed-loop temperature control. Thus, either active or standby redundancy is possible with this system.

Closed-loop Vibration Suppression. The closed-loop control of cooler-generated vibration is another common requirement of space cryocooler applications. Distinguishing between the vibration output of two simultaneously-operating coolers and applying the appropriate suppression feedback often requires special design features and control algorithms that must be specifically addressed in light of the cooler redundancy approach.

Generated EMI. A third area affected by the redundancy approach is control of ripple currents fed back into the spacecraft power bus from the drive electronics as well as the magnetic fields radiated from the compressor drive motors. Since two coolers running at partial load are likely to have offending current and magnetic field levels similar to a single heavily-loaded cooler, EMI is probably not a decision driver, but is a difference that should be considered at the systems level.

Implications on Payload Thermal Cycling

Cycling the cryocooler off for any reason will generally result in warm-up of the cryogenic payload elements such as focal planes, and require a cooldown and re-stabilization period that adversely impacts payload operational time. The resulting thermal cycling can also lead to mechanical fatigue of payload elements, with serious reliability consequences. Thus, the manner in which standby versus active redundancy influences the likelihood and number of payload warm-ups can be an important consideration.

With the AIRS instrument,[5] two types of cooler outages were found to be significant during the first few months of space operation: 1) planned warm-ups to decontaminate the cryogenic load elements and cooler coldend of high-emittance surface films (water ice), and 2) unplanned warm-ups associated with spurious safety trips caused by single event effects (SEEs) associated with passage through the South Atlantic Anomaly (SAA) during times of exceptionally severe radiation levels.

Implications of Redundancy on Deicing Warm-ups. Gettering of frozen contaminants on the cryogenic surfaces of the payload is a common space-instrument problem often addressed by planned periodic warm-ups to defrost the critical surfaces.[6] When the problem of contaminant buildup is solely an issue of cooler load increase, as opposed to degradation of optical or science performance, then a second active-standby cooler may be able to share the increased load and greatly extend the time between required decontamination events. In contrast, a single cooler in standby-redundant mode may be quickly overwhelmed by the contaminant-induced load increase and require frequent decontamination shutdowns. Over the mission life the rate of recontamination gradually diminishes, so the initial higher-power operation is likely to be well matched to the availability of the redundant unit and coincide with the availability of excess spacecraft power early in the mission.

As an example, Fig. 4 highlights the large reduction in payload warm-ups of the AIRS instrument following the switch-over from standby-redundant operation to active-redundant operation in November 2002. Since the switch-over, there has been only a single warm-up—that a precautionary shutdown of the entire instrument prior to the arrival of the radiation from a 100-year worst case solar storm spotted on the surface of the sun around the first of November 2003.

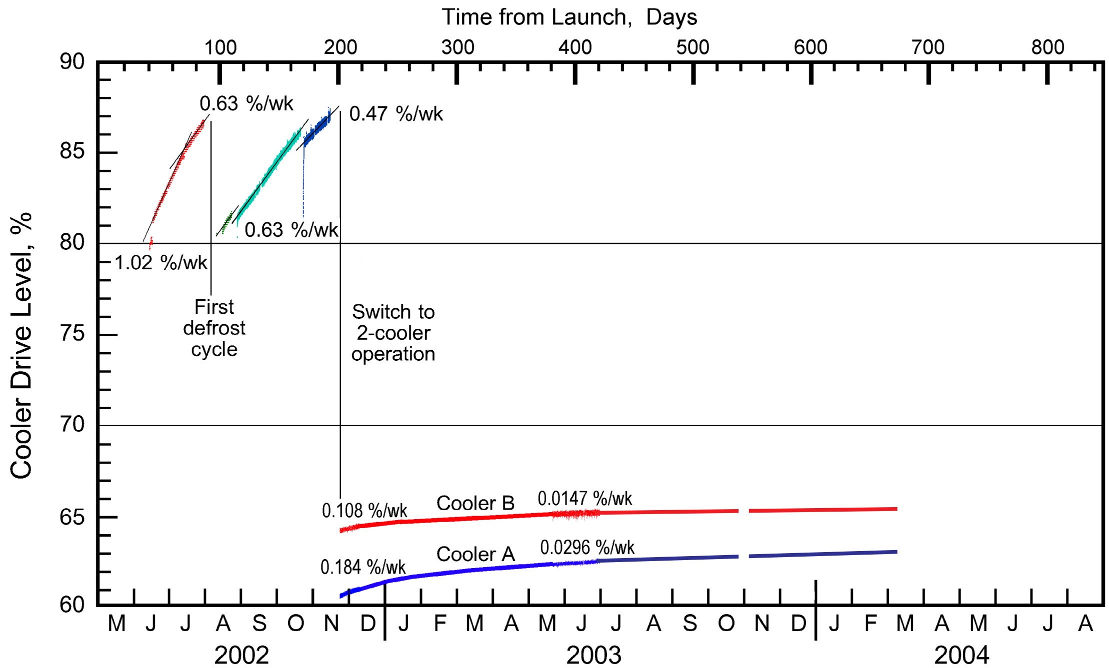

Figure 4. Overall summary of AIRS cooler drive level over the first two years of operation.

Implications of Redundancy on Safety Shutdowns. Random safety shutdowns are a possibility with any cooler due to such things as radiation hits received by the cooler electronics when passing through particularly severe radiation environments. With a single cooler operating in standby redundant mode, the safety shutdown is likely to cause a complete payload warm-up as the failure data is reviewed and a decision is made to resume cooler operation. By the time thermal equilibrium is returned, several days of operation may have been lost.

With active redundancy, the coolers may be programmed so that the second, unaffected cooler simply picks up the total load while the tripped-out cooler is being analyzed and restarted. For some applications, the reduced stroke and power associated with load sharing may also make the operating coolers less susceptible to shutdown events.

TWO-COOLER SYSTEM-LEVEL RELIABILITY ANALYSIS

With the reliability equations derived earlier and the system-level implications noted above, we are now prepared to work a numerical example assessing the reliability of the two redundancy approaches. To the earlier equation (Eq. 9) we now add the dependency of a focal-plane failure rate on thermal cycling, and the additional probability of a cooler unit failing during launch. This launch failure risk is not a function of operating time, so it is added as a discrete new term. Thus:

$$P_{sys} = P_{clr} + P_{FP} = (\dot{P}_A T + P_L)(\dot{P}_{B1} T/2 + \dot{P}_{B2} T/2 + P_L) + \dot{P}_{FP} T \qquad (10)$$

where

P_{sys} = probability of failure of total cryogenic payload system in T years
P_{clr} = probability of failure of the redundant cryocooler system in T years
$\dot{P}_A$ = failure rate for cooler A + electronics A, where unit A is the first to fail
$\dot{P}_{B1}$ = failure rate for cooler B + electronics B in period before unit A fails
$\dot{P}_{B2}$ = failure rate for cooler B + electronics B in period after unit A fails
P_L = probability of failure of a cooler/electronics unit during launch
$\dot{P}_{FP}$ = failure rate per year for focal plane (assumed not redundant)

Table 4 summarizes example values for the above failure probabilities. The cooler failure rates were derived from those in Tables 2 and 3 for the appropriate drive levels, while the focal plane failure rates are representative values selected for illustrative purposes.

Table 4. Example failure probabilities for cooler system components.

Cooler Drive Level	Focal Plane Thermal Cycling	Mechanical Cooler	Cooler Electronics	Focal Plane
Cooler at 85% stroke	extensive	0.010/yr	0.010/yr	0.010/yr
Cooler at 65% stroke	minimal	0.005/yr	0.007/yr	0.002/yr
Cooler unpowered	n/a	0.0025/yr	0.0035/yr	n/a
Launch Environment	n/a	0.01	0.01	n/a

Active Redundancy. Using the values from Table 4 for the case of active redundancy, and defining a cooler unit as a mechanical cooler plus its drive electronics gives:

$\dot{P}_A$ = failure rate for unit A in operation = 0.005 + 0.007 = 0.012/year
$\dot{P}_{B1}$ = failure rate for unit B *before* unit A fails = 0.005 + 0.007 = 0.012/year
$\dot{P}_{B2}$ = failure rate for unit B *after* unit A fails = 0.010 + 0.010 = 0.020/year
$\dot{P}_{FP}$ = failure rate for focal plane = 0.002/year
P_L = probability of a cooler unit failing during launch = 0.01 + 0.01 = 0.02

Entering these numbers into Eq. 10 for a mission duration of T=5 years gives:

$$P_{Active} = (0.012\times5 + 0.02)(0.012\times2.5 + 0.02\times2.5 + 0.02) + 0.002\times5$$
$$= 0.0080 \text{ (for coolers)} + 0.010 \text{ (for focal plane)} = \boxed{0.018} \quad (11)$$

Noting that the system reliability is just one minus the probability of failure, we get

$$R_{Active} = 1- 0.018 = \boxed{98.2\%}$$

Standby Redundancy. Using the values from Table 4 for the case of standby redundancy, and again defining a cooler unit as a mechanical cooler plus its drive electronics gives:

$\dot{P}_A$ = failure rate/year for unit A in operation = 0.01 + 0.01 = 0.020/year
$\dot{P}_{B1}$ = failure rate/year for unit B *before* unit A fails = 0.0025 + 0.0035 = 0.006/year
$\dot{P}_{B2}$ = failure rate/year for unit B *after* unit A fails = 0.010 + 0.010 = 0.020/year
$\dot{P}_{FP}$ = failure rate/year for focal plane = 0.010/year
P_L = probability of a cooler unit failing during launch = 0.01 + 0.01 = 0.02

Entering these numbers into Eq. 10 for a mission duration of T=5 years gives:

$$P_{Standby} = (0.02\times5 + 0.02)(0.006\times2.5 + 0.02\times2.5 + 0.02) + 0.01\times5$$
$$= 0.0102 \text{ (for coolers)} + 0.050 \text{ (for focal plane)} = \boxed{0.0602} \quad (12)$$

and

$$R_{Standby} = 1- 0.0602 = \boxed{94.0\%}$$

Interpretation of the Results

First, ignoring the contribution of the focal plane reliability, the numbers in Eqs. 11 and 12 indicate that the analyzed coolers configured with active redundancy are around 20% more reliable than the same coolers configured in a standby redundancy configuration. However, when the effect of reduced thermal cycling on the focal plane is also included, the reliability of the active redundancy system is seen to be vastly superior. Thus, adding the systems considerations into the cooler reliability analysis can be an important factor in selecting the optimum cooler redundancy approach.

SUMMARY

This paper has examined the performance trade between active and standby redundancy through the derivation and use of a new reliability model that explicitly includes the probability of failure of the redundant unit both prior to and after the time of a cooler failure. This allows the explicit treatment of the effect of operational level (off, versus low power, versus high power) on the reliability of the redundant and primary unit. Also presented, is a discussion of the effect of the two redundancy approaches on the overall space-instrument system including input power level, robustness to transient single-event shutdowns, and robustness to in-space load increases—such as from in-space contamination of cryogenic surfaces. The active redundancy approach is shown to have advantages in terms of improved reliability as well as improved overall system performance.

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