Micro Miniature Rotary Stirling Cryocooler for Compact, Lightweight and Low Power Thermal Imaging Systems

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ABSTRACT

Novel compact and low power consuming cooled infrared thermal imagers as used in gyro-stabilized payloads of miniature unmanned aerial vehicles, Thermal small arms sights and tactical night vision goggles often rely on integral rotary micro-miniature closed cycle Stirling cryogenic engines.
Development of EPI Antimonides technology and optimization of MCT technology allowed decreasing in order of magnitudes the level of dark current in infrared detectors thus enabling an increase in the optimal focal plane temperature in excess of 95K while keeping the same radiometric performances as achieved at 77K using regular technologies.
Maintaining focal plane temperature in the range of 95K to 110K instead of 77K improves the efficiency of Stirling thermodynamic cycle thus enlarging cooling power and enabling the development of a mini micro cooler similar to RICOR's K562S model which is three times smaller, lighter and more compact than a standard tactical cryocooler like RICOR's K508 model.
This cooler also features a new type of ball bearings and internal components which were optimized to fit tight bulk constraints and maintain the required life span, while keeping a low level of vibration and noise signature. Further, the functions of management the brushless DC motor and temperature stabilization are delivered by the newly developed high performance sensorless digital controller.
By reducing Dewar Detector thermal losses and increasing the focal plane temperature, longer life time operation is expected as was proved with RICOR's K508 model.
Resulting from this development, the RICOR K562S model cryogenic engine consumes 1.2 - 3.0 W_{DC} while operating in the closed loop mode and maintaining the typical focal plane arrays at 200-100K. This makes it compatible with very compact battery packages allowing further reduction of the overall thermal imager weight thus making it comparable with the compatible uncooled infrared thermal imager relying on a microbolometer detector in terms of power consumption and bulk.

Keywords: Micro Miniature, Cryocooler, Stirling, COP, Deawr, FPA, RICOR.

1. INTRODUCTION

1.1. Trends in Novel Thermal Imaging Systems

Miniature unmanned aerial vehicles are becoming more and more common in military operations, in particular miniature low altitude aircrafts. Thermal imaging allows the aircraft to fly in total darkness and detect fast moving targets in the dynamic infrared battlefield. Since a lightweight UAV is normally powered by batteries, the weight and bulk of the infrared payload are of concern.
Typically, the payload is mounted inside the aircraft's nose, pointed forward and angled down for reconnaissance and navigation missions.
Based on the characteristics of miniature unmanned aerial vehicles, several key requirements are important to consider when dealing with gyro-stabilized sensor payloads.

Weight - One of the most important requirements for a sensor payload in this application is weight. A heavy sensor may shift the center of gravity and requires a counterbalancing weight to be added to compensate for the added weight in the nose.

Bulk - small size is imperative because of the implications on drag characteristics. The same parameters affected by weight – maneuverability, airspeed, and flight duration are generally affected even more so by drag. Another compelling advantage of a small sensor is that it offers more potential for a multi-sensor payload.
Low power consumption - Minimizing power consumption of an on-board sensor reserves more battery capacity for the aircraft's propulsion system and wireless link. A low-power thermal imager thus contributes to longer flight duration and longer range.

Portable thermal hand held and tactical night vision goggles also need to be small and lightweight so that they can easily be carried in the field by commanders, forward observers, fire controllers and reconnaissance teams.
A typical hand held camera relies on the battery power supply, hence the power consumption budget becomes critical for the mission duration. Lightweight and low power hand held thermal imagers allow improving camera features by accommodating additional sensors like laser rangefinders, target markers or laser pointers.

1.2. Trends in Novel Cooled Infra Red Detectors

Whatever the technology used (MCT, InSb or other) the operating temperature is a key parameter for the cooled infrared detector. The main performances like dark current, sensitivity (NETD), number of defective pixels and stability are linked to the operating temperature of the FPA. Lower FPA temperature is better for cooled IR detector performances, but on the other hand reduces the cooler thermodynamic efficiency. As a result an oversized cooler is needed with disadvantages in terms of power consumption, bulk, acquisition cost and time between the battery recharges.
The MCT technology enables increasing the operating FPA temperature of detectors, especially in the mid wave range [3]. In the InSb technology, diodes fabricated in InSb epitaxial layers grown on InSb substrates achieved significant reduction in the dark current compared to diodes made by a standard process. InAlSb diode technology based on Antimonide Based Compound Semiconductors (ABCS) achieved reduction in the dark as well [2].
The results of the advances in IR detectors technologies have allowed decreasing in order of magnitudes of the level of dark current in infrared detectors thus enabling an increase in the optimal focal plane temperature in excess of 95K up to 110K while keeping the same radiometric performances as achieved at 77K using regular technologies.
The technology approach of increasing FPA temperature improves cooler thermodynamic efficiency and enables developing a novel low power and compact micro miniature cooler optimized for FPA temperatures above 95K.

2. MICROMINIATURE CRYOCOOLER DESIGN ASPECTS

2.1. Miniaturization Evaluation Review

During the nineties, miniature cryocoolers developed throughout the world for tactical IR detectors operated at an FPA temperature of 77K. RICOR's miniature K508 model was designed to fit mainly mid format arrays while covering military specifications for various applications. As a result the K508's cooling power is above 1/2W at 71°C ambient with 138cm^3 volume and 450gr weight.
At the beginning of this century a new approach was achieved for cryocooler miniaturization, still for tactical IR detectors operating at 77K. RICOR's developed miniature models K560, K561 and K563 are mainly for low power hand held thermal imagers with a cooling power of up to 0.3W at 71°C ambient, 75cm^3 volume and a 290gr weight.
As a result in the last few years of development advanced IR detector technologies operate above 95K and also approach in cooler mechanical miniaturization, new micro miniature coolers developed throughout the world.
RICOR's new family of 0.2W at 71°C ambient K562S with 40cm^3 volume and 185gr weight and K562 with 145gr weight.
The main challenge encountered during the K562S development was to dramatically reduce size, bulk and weight comparable to K561and K563 models without impact on cooler reliability, and to achieve enough cooling power with reasonable margins in order to meet full environmental requirements for a tactical IR detector operated at 95K and above.
Cooler miniaturization mainly achieved by mechanical design of the bearings, piston – cylinder assembly, driving assembly and sensorless motor.

Cost objective was also a key factor in order to meet global market trends and to be compatible with uncooled infrared imager relying on a microbolometer detector.

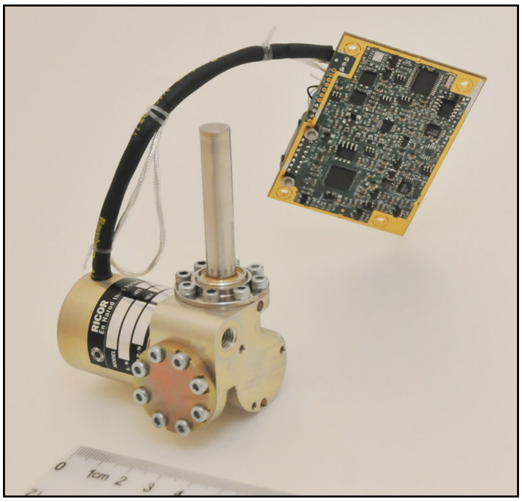

Figure 1 – K562S Micro Miniature Cryocooler with Digital Controller

2.2. Cooling Optimization

FPA Temperature
The FPA temperature is a key parameter for Stirling thermodynamic efficiency and for cooler optimization. The exact FPA temperature for advanced IR detectors is derived from the following parameters:

1. Photons Flux – derived from the system characteristics and from the application. An IR Detector with a low F-number can absorb a high level of photon flux hence the detector is less sensitive (high signal to noise ratio) and then the FPA temperature could be increased. On the other hand, an IR Detector with a high F-number absorbs a low level of photon flux hence the detector is more sensitive and then the FPA temperature should be decreased.

2. Defective Pixels – the number of defective pixels increased while the FPA temperature increased. Determining the threshold for the percentage of defective pixels derived from the application requirements.

3. Cooler Power Consumption - The higher the FPA temperature the better the thermodynamic efficiency hence low input power. The regulated power consumption limitation is derived from the system power source limitations and from the mission duration period.

Cooler Efficiency
The COP (Coefficient of Performance) of the cooler is the ratio between the amount of heat Qe absorbed by the expander and the amount of heat Qc rejected from the compressor (which is also equal to the work input Wc)

$$COP_{Stirling} = Qe / W = Qe / (Wc - We) = Te / (Tc - Te)$$

The overall COP is a product of partial efficiencies of three subsystems: thermodynamic Stirling cycle efficiency, motor assembly efficiency and driver controller efficiency. The higher the FPA temperature (Te), the higher the COP and the lower the power consumption and consequently the lower the operational cost.
K562S operating at 110K with a typical Dewar of 145mW could reach up to 10% efficiency which is about 17% of Carnot efficiency.

Cooling Power

The cooling capacity of the cooler Qe is proportional to the compressor swept volume (Vc, in cm^3), the mean fill charge pressure (Pm, in atm), the coldtip temperature (Te, in K), and the operating frequency (f, in Hz)

$$Qe = (f/2)\ TePmVc \times 10\text{-}5\ (\text{Watts})$$

For reliability considerations, in order to decrease the mechanical load on the bearings, the fill pressure (Pm) was limited to a relatively lower value - about 20bar. The swept volume (Vc) and the regenerator were optimized by the mechanical design in order to achieve enough cooling power Qe (about 0.2W @71°C ambient) with a reasonable margin in order to meet typical IR detector operating requirements at Te>95K.

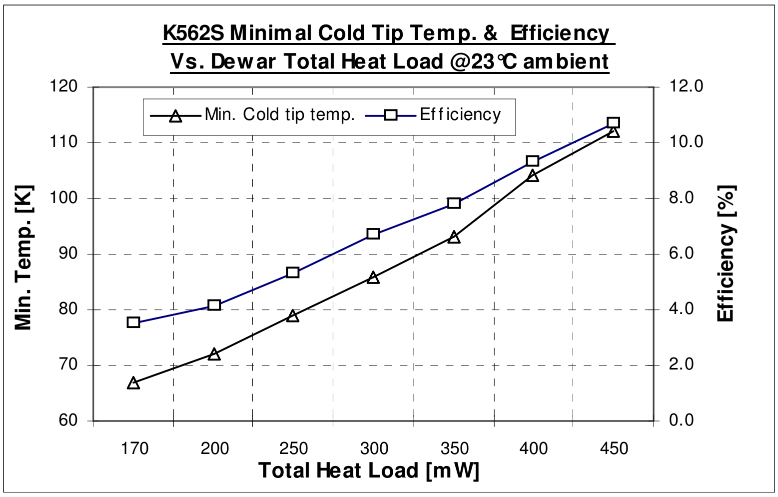

Figure 2: K562S Minimal Cold Tip Temp. & Efficiency Vs. Total Heat Load

Cool Down Time

One of the main design challenges was to achieve very short cool down time for system readiness. Besides the influence of the Dewar Joule mass (Part of the IR manufacture design), the trade-offs between power consumption at steady state, fill pressure, maximum power consumption, boost level and cool down time duration were well studied.

Form reliability considerations in order to reduce the load level on the cooler bearings , K562S designed to operate with a low fill pressure and therefore the main efforts were focused on optimizing the booster unit (part of the controller) in order to accelerate the operating frequency during cool down only.

As a result of the optimization, the boost level was well defined and an appropriate motor winding was designed with a digital controller driver that includes booster components. The cool down time finally achieved by the K562S model is lower than 3 minutes from 23°C ambient to 110K for a typical Dewar with a 155J thermal mass.

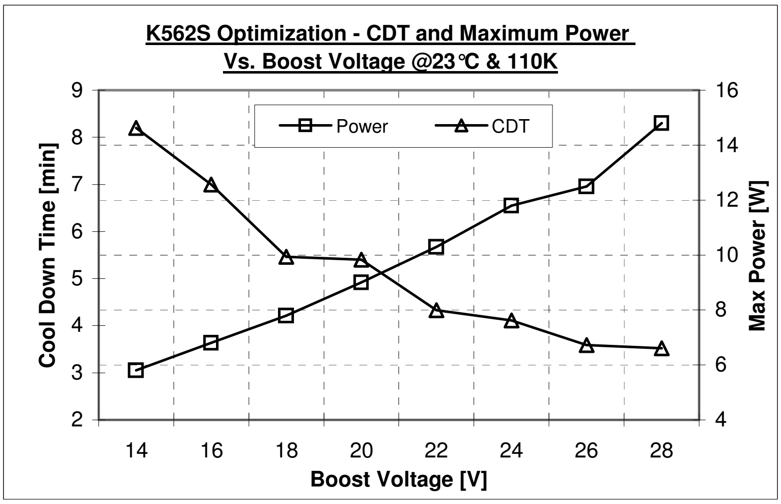

Figure 3: K562S Cool Down Time Optimization (1)

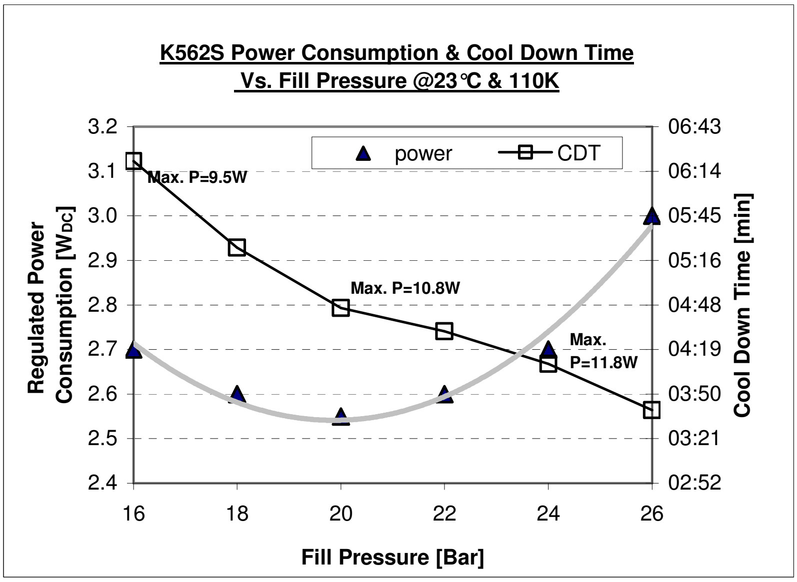

Figure 4: K562S Cool Down Time Optimization (2)

Remark: The Dewar thermal mass used for the optimization (figure 3 and figure 4) was relatively higher than a typical Dewar detector.

2.3. Reliability

The reliability prediction of the operational MTTFF (Mean Time to First Failure) and MTBF (Mean Time Between Failures) is based on the similarity between the K562S model and the K560 model. It has employed the following approach:

1. Assessment of the K560 operational life characteristics based on laboratory life test data of 3 K560 units at weighted temperature of 36°C were analyzed, while assuming two parameters Weibull life distribution with an unknown β shape parameter. The analysis has yielded:
   a) Point estimate of the Weibull shape parameter: $\beta \cong 7.5$
   b) Point estimate of the Weibull scale parameter: $\alpha = 5780$ hours
   c) Point estimate of the coolers MTTFF: 5430 hours
   The environment conditions of this test were considered by us as GF (Ground Fix).

2. Projection of K560 operational life characteristics on K562S operational life characteristics taking into account the differences in the coolers design.
   In general the K562S is a smaller version of the K560, with a ratio of 14/11=1.27 between the diameters of the compressor pistons, or a ratio of 1.62 between the piston areas. This fact yields lower stresses on the K562S bearings by the latter factor. Based on common bearings life models, the effect of the reduced stress is an increase in the bearings life by a factor of $1.62^3 = 4.25$.
   However, there is uncertainty regarding the net effect of the cooler miniaturization on its life relative to the life of the K560.
   We have therefore assumed that the K562S operational life will be increased by factor A considered a random variable in the range 1- 4.25 with a probability function as following:

$$f_A(a) = 0.61532 - 0.1893(a-1), 1 \leq a \leq 4.25$$

   Namely, $f_A(a)$ is a right-angled triangle probability function, bestowing higher probabilities to low values of a.
   The expected value of A, E(A) is ~2.08.

   The projected MTTFF figures of the K562S is 11,000 hours (@36°C & GF)

As a complementarily activity, an accelerated life demonstration test is planned for a few K562S units in order to approve cooler reliability and to let the customer know about actual reliability in the early stages of system design.

2.4. Cold Finger Design

As cooler miniaturization has some impact on cooling power abilities, therefore Dewar heat load balance becomes more critical and each component in the Dewar needs to be optimized in order to operate the cooler up to 71°C ambient with a reasonable margin.
Heat load balance includes radiation of the environment on Dewar components, conduction through the electrical readout connections, conduction inside the Dewar through the cold finger due to temperature gradient and power dissipation from the signal processor.
The trade offs between cold finger stiffness, low heat load by conduction and rugged mechanical design is able to sustain mechanical environmental conditions led to a study of cold finger construction and wall thickness optimization that was finally defined to be 80µm.
New technology for cold finger manufacturing is based on a laser welding process implemented in the K562S model. In the near future this technology will replace RICOR's traditional technology based on a brazing process.
As complementary activities, IR manufacturers are also making a lot of efforts to miniaturize Dewar volume, resulting in reduction in external radiation and Dewar weight as well. In addition, signal processors based on advanced silicon technology designed for economical power consumption.

2.5. Sensorless Digital Controller

Sensorless

Traditionally, BLDC (Brushless DC) motors are commutated in a six-step pattern with commutation controlled by position hall sensors. These hall sensors consume electrical power, increase the size and the cost of the motor and a special mechanical arrangement needs to be made for mounting the sensors. These sensors also limit the operation of the motor in low voltages and potentially reduce motor reliability. In a Brushless DC motor, only two out of three phases are excited at one time, leaving the third winding floating. The back EMF voltage in the floating winding is measured (without the need to sense the rotor position) to establish a switching sequence for commutation of the power device.

The development copes with the challenge to commutate in such a way that the current is in phase with the phase back EMF to get the optimal control and maximum torque/ampere. Since the shape of back EMF indicates the rotor position, the commutation timing is well determined. The zero crossing of the phase back EMF is measured, and then it's known when to commutate the current.

Digital Controller

As a result of adapting sensorless technology, a new digital controller based on a main processor was designed in order to drive a sensorless motor for the K562S. The design is mainly focused on the accuracy level of cold tip temperature means ±0.2K stability at constant conditions and up to a ±0.5K drift over the full range of ambient temperatures.

Leveraging the abilities of the main process on board, new approaches have been achieved for rotary Stirling driving and functionality:

- As the battery of a hand held IR camera is limited by the level of current, soft start is implemented by software to eliminate inrush current.
- As each type of IR hand held camera copes with the trade offs between maximum power consumption in transient mode and cool down time duration until stabilization, booster voltage can be tuned for better optimization.
- Accumulating operating hours and counting the number of on/off is done by software instead of a mechanical device.
- FPA temperature is tuned by software communication instead of setting a potentiometer hence better for controller reliability.
- The operating voltage range is increased to 4.5-18V in order to cope with the worldwide trend of voltage operation reduction for electronic devices, while the result is a saving power in losses from voltage transformation at camera level.

Motor optimization

A part of the development phase focused on miniaturizing the motor in order to reduce volume and size. At the first step, a miniature motor weighing was about 20gr was developed for a cooler model named K562 while the total cooler weight reached 135gr. By studying the power consumption fractions for the K562 model while the cooler operates with self heat load only, it was learned that about 90% of the power consumption related to the motor & rotor assembly operates in idle current only. The conclusion from the study was that power consumption could be improved by optimizing motor & rotor assembly and also it is understood that the K562 is an optimal solution for applications where bulk and weight are of concern and less suitable for low power consumption applications.

The next step in the study led to develop an additional motor & rotor assembly with an additional 50gr weight hence the cooler weight reached 185gr and was called the K562S model. The efficiency of the motor improved by about 30% and had a dramatic impact on cooler efficiency finally leading to a real breakthrough in micro miniature string coolers power consumption – 2.2W DC (including controller) @110K @23°C with a typical Dewar of 145mW at room ambient conditions.

2.6. Induced Forces and Acoustic Noise

The micro miniature integral rotary cooler is designed for IR applications which are inherently sensitive to a vibration export developed by the imbalanced motion of the cooler's components. Theoretically, full dynamic balancing of the fundamental component of vibration export can be achieved.

By recurrently modifying the mass of the displacer and geometry of the balancer flywheel, the vibration export at the driving frequency may be practically eliminated. From experiment test results, the vibration export is lower than 12gr rms at a driving frequency of ~40Hz, in all three axes.

The micro miniature integral rotary cooler is quite a sophisticated piece of machinery, comprising numerous moving components and it is their mechanical motion which produces periodic micro collisions radiating wideband vibration and noise.

During the development of the K562S special effort was made to reduce the acoustic noise level by optimizing micron clearances, radial play of bearings, preloading bearings and optimizing the mechanical arrangement. As a result, a very low acoustic noise was achieved at a cooler level of <25dB from a distance of 5 meters measured while the cooler stabilized at room ambient temperature.

As complementary activity, essential vibration isolation between the cooler and the system over mid- and high-frequency bands could be designed based on RICOR's center of excellence novel solutions, finally achieve aural undetectability from 10 meters.

2.7. Performances Screening

In order to properly adapt the K562S to advanced IR detectors operating at a FPA temperature of >95K, test experiments were performed during the development phase in order to monitor the power consumption in different scenarios.

As a result, for available IR detectors the K562S operates at 110K with a Dewar heat load of 145mW and could reach lower than 2.5WDC (including the controller) at steady state while the ambient temperature is 23°C.

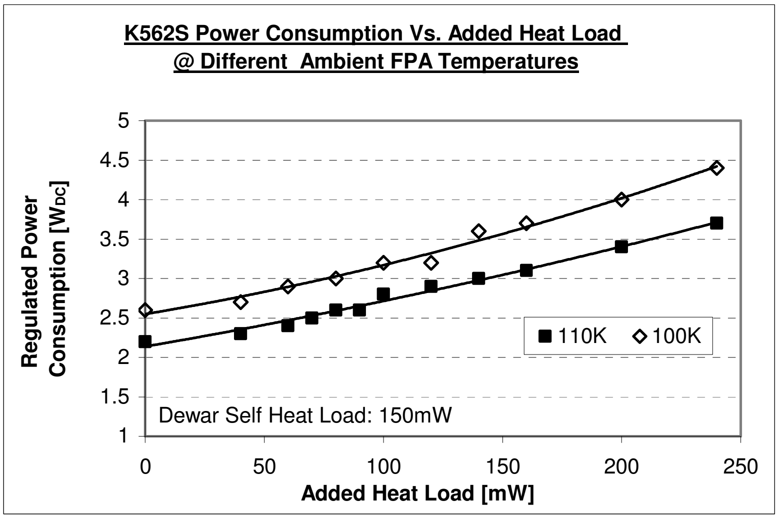

Figure 5: K562S Power Consumption Vs Added Heat Load at Different FPA Temp.

A test for the future detector generation was also performed from 120K up to 200K FPA temperature in order to evaluate the K562S power consumption abilities. The cooler reached about 1.2WDC @200K (including the controller) at steady state while the ambient temperature was 23°C.

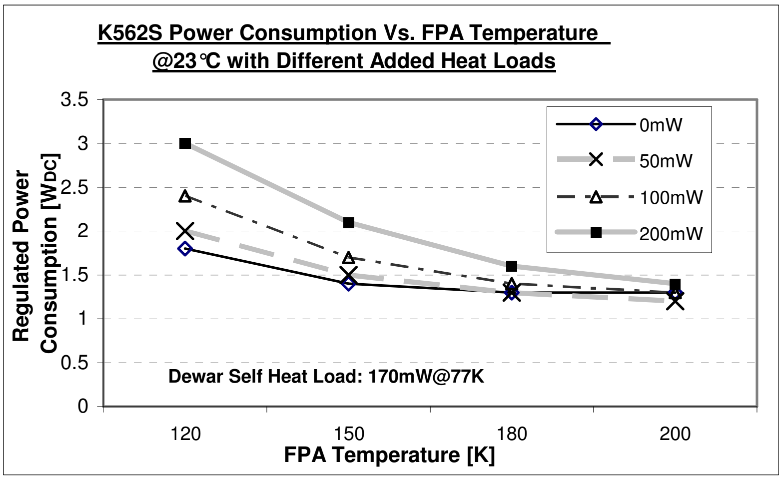

Figure 6: K562S Power Consumption Vs. FPA Temp. at Different Added Heat Loads

3. SUMMARY

A new approach was achieved in the range of micro miniature coolers development thanks to optimized mechanical design and adapting new technologies such as sensorless motors and IR detectors operated at 95K FPA temperature and above.

The reduction achieved by the K562S model in size, weight and power consumption without impact on cooler reliability is a real breakthrough for a Stirling cryocoolers.

Reducing the regulated input power to a range of 1.2-3WDC (for 200-100K FPA temperature) makes K562S compatible with very compact battery packages and allows further reducing of the overall thermal imager weight. As a result the K562S becomes compatible with the new generation of cooled infrared thermal imagers and is competitive with uncooled infrared imagers as well.

As complementary activities an accelerated life demonstration test and qualification program will be performed during the second half of 2009 as a final phase for production readiness in high volume.

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