AIM Space Cryocooling System Qualification

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ABSTRACT

IR-Space applications require very long life in conjunction with high cooling performance at minimum energy consumption, compact and low weight design, and robust environmental resistance. Depending on satellite design, mission life, and orbital conditions each on-board subsystem is subject to specific qualification procedures at different levels.

Since 2007, AIM has been developing and delivering Integrated Detector Cooler Assemblies (IDCA) including corresponding electronics for different space programs. The cooling systems of such IDCA's typically consist of a long-life cryocooler with AIM Flexure Bearing Moving Magnet (FBMM) compressor, a ½"-pulse tube coldfinger with buffer volume, and a fully redundant Cooler Drive Electronics (CDE). All components and manufacturing processes of AIM cryocoolers are based on volume production and meet the highest quality and reliability requirements. In a former article of ICC 16 [1], two space programs involving AIM cryocooler hardware were introduced, and their qualification procedures were presented.

This paper gives an overview of the latest space qualification activities involving AIM cryocoolers and cooler drive electronics. Key mechanical and electrical environmental qualification requirements and respective performance results are presented and discussed in detail. Emphasis is placed on the current life test results for different long-life cryocoolers used within AIM space programs.

INTRODUCTION

As an IR system manufacturer, AIM started in 2007 with the development of a Long Wave Infrared (LW-IR)-Detector System for low earth orbit operation consisting of an Integrated Detector Cooler Assembly (IDCA), the detector electronics (FEE), and the Cooler Drive Electronics (CDE). To fulfill typical space mission requirements in terms of reliability, mechanical resistance, and irradiation hardness, the AIM cooler division has developed a pulse tube cryocooler with flexure bearing moving magnet compressor technology and a radiation hardened, redundant cooler electronics. In the past two years, several qualification activities have been conducted, resulting in the flight model delivery in the first half of 2012. In addition, a Short Wave Infrared (SW-IR)-Detector System with a smaller compressor and an advanced version of the CDE is currently in development for flight.

AIM's Long Wave Detector System is based on the SF400 flexure bearing compressor. Because of the higher detector temperature of the Short Wave System, there a SF100 compressor was choosen. The following sections give an overview of the cooling system design and the environmental qualification of the cooling system as part of the Long Wave IDCA. Example results are shown for both cooler and electronics.

Cryocoolers 17, edited by S.D. Miller and R.G. Ross, Jr.

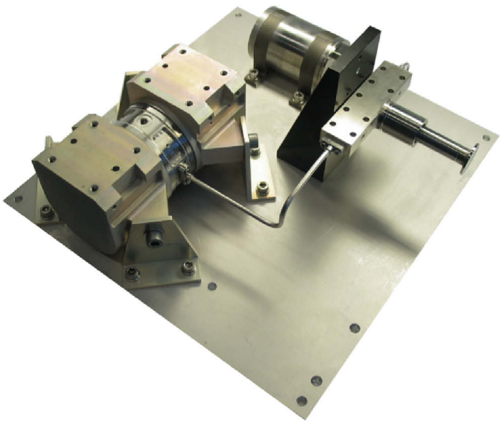


Figure 1. SF400 pulse tube cooler with cold tip flange (left); CDE box, Aeroglaze-coated (right)

COOLING SYSTEM DESIGN

Pulse Tube Cryocooler

Both AIM space cryocoolers are based on serial production design consisting of a long-life flexure bearing compressor, a ½" co-axial pulse tube coldfinger as part of the dewar-detector assembly, and a buffer volume. The mentioned components are connected via tubes and freely placeable relative to each other (considering maximum allowable tube lengths).

The long-life flexure bearing compressors with moving magnet design combine the highest reliability due to minimized failure potential and optimum performance due to the variety of three compressor sizes. The co-axial pulse tube is designed to replace standard AIM Stirling coldfingers and also the inner dewars of AIM Integrated Detector Cooler Assemblies. However, for the thermal connection to an optical bench a ½" Pulse Tube version with a flange at the coldtip is also available (see Figure 1, left). The buffer volume combines the inertance tube and its gas volume and can be placed independently near the pulse tube.

Thermal, mechanical, and electrical interfaces are designed according to customer's system architecture and to provide in-orbit capability. The dimensions and masses of the cryocooler components (excl. harness) are shown in Table 1. Components with values shown as "smaller than" exist in different designs. Detailed information on the SF070 and SF100 compressor designs can be found in [2] and [3]. The cryocoolers are designed for in-orbit lifetimes >50,000 hours and lifetimes in excess of 10 years including storage.

A typical performance map of the fully qualified and delivered space cooling system is shown in the following section. In Figure 2, the cooling performance of the SF400PT cooling system is plotted for a rejection temperature (compressor and cold finger) of 308 K. Typical applications can be found in LW-IR single IDCA systems operating at 80 K as well as Short Wave (SW)-IR multi detector systems at cooling temperatures of 180 K.

Table 1. Dimensions and masses of cooling system components

	Compressor			Pulse Tube	Buffer Volume	Connecting tubes	CDE
	SF070	**SF100**	**SF400**				
Length [mm]	113	145	163	min. 105	93	acc. need	280
Width [mm]	44	81	128	min. 27	57	acc. need	180
Depth [mm]	44	84	84	min. 19	57	acc. need	65
Mass [kg]	1.0	2.3	3.9	< 0.4	< 0.4	< 0.1	4.0

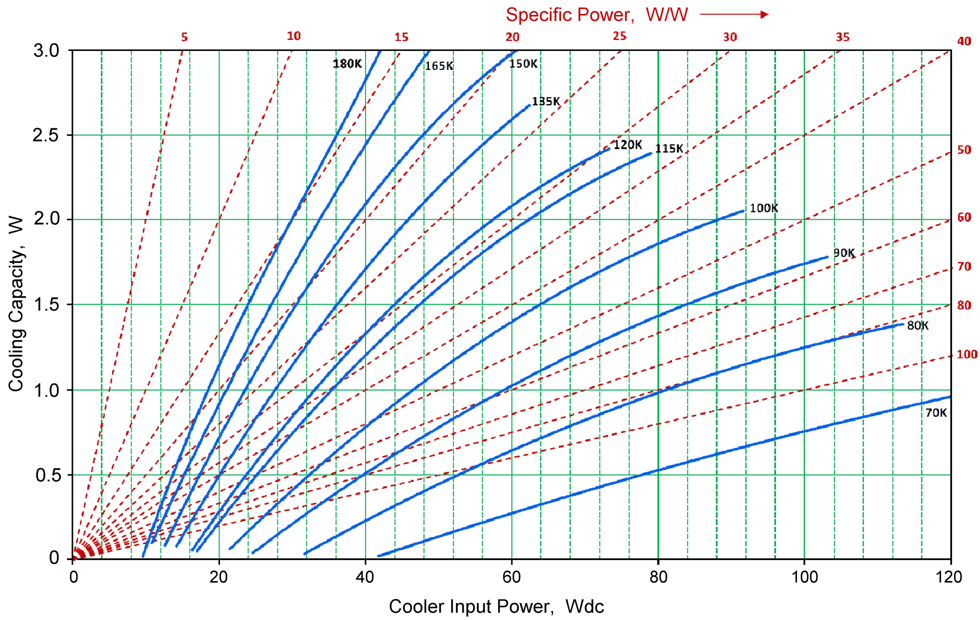

Figure 2. Cooling performance of SF400 pulse tube cooling system at Trej = 308K

Cooler Drive Electronics (CDE)

The purpose of the Cooler Drive Electronics (CDE) is to stabilize the IR-Detector operating temperature to a preset temperature value. The CDE is designed such as to survive the nuclear and heavy ion environment that is present in space orbit. This is done by proper selection of rad-hard EEE-parts and appropriate in-situ measurements in the circuit design. A latch-up protection is implemented in order to shut-down the electronics in case of SEU effects.

The Cooler Drive Electronics senses the detector temperature via a temperature sensor diode 2N2222, thermally coupled to the detector array, and drives the flexure bearing compressor via a pulse width modulated (PWM) full bridge with controlled electrical energy in order to stabilize the detector temperature at the nominal operating temperature. Depending on the cooler type, the linear motor of the flexure bearing compressor (moving magnet design) can be operated within the frequency range between 30 Hz and 70 Hz.

The following functions are provided through the CDE to the IR-FPA

- Driving the cooler system of the IR-detector hybrid with the required temperature stability.
- Stabilize the operating temperature within the specified operational temperature range and tolerances (in conjunction with the pulse tube cooler)

The core of the CDE is based on a hybridized electronics in an approved and reliable analogue design. Several thousand electronics with this design have been build for tactical cooler applications at AIM so far. Only minor modifications of the assembly of the military hybrid design ensure the functionality of the complete CDE assembly. Using hybrid design for active power-carrying circuit parts are designed on Al_2O_3 for high reliability, passive parts, e.g. input and output filter, are assembled on printed circuit boards.

Meeting the demand of high reliability space components, the CDE consists of a nominal and a redundant electronics in a single housing. With the usage of mixed technology, a space qualified, highly integrated cooler drive electronics was built up and qualified at AIM. The outline dimensions of the CDE are 280×180×65mm at a total weight of 3960 g.

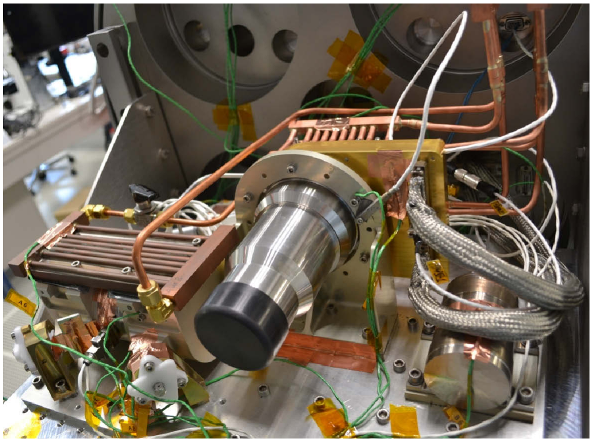

Figure 3. IDCA integrated in the TV-chamber

THERMAL TESTING

The capability of the cooling system to perform at operating conditions and to survive at non-operating temperatures has been tested at AIM. The thermal vacuum (TV) test facility is equipped with two cylindrical chambers (DN630, length: 600 mm) each with two oil-free, cryogenic vacuum pumps. The chambers contain thermal plates (540×490 mm^2) as well as a huge number of feedthroughs for thermal, power, and measurement connections.

The installed cooling system provides interface temperatures from -40°C to +80°C. Figure 3 shows the IDCA installed in the TV-chamber and equipped with chiller and instrumentation. Both IDCA and CDE were eight times cycle tested including nominal, minimum, and maximum operating and non-operating temperatures. The test cycle shown in Figure 4 has been recorded during CDE TV testing. For this specific test the cryocooler has been placed outside the vacuum chamber exposed to 35°C I/F temperature. The grey line represents the interface temperature at the CDE bottom plate. The black solid line shows the CDE input power; the black dashed line describes the detector temperature. The CDE was switched 'on' at ambient temperature ±1°C. During cool dow

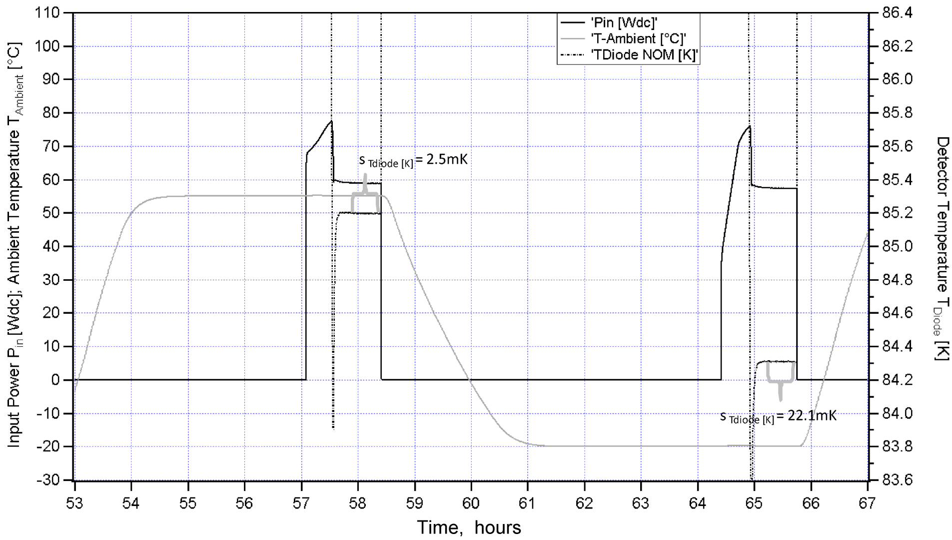

Figure 4. Temperature cycle test of the CDE

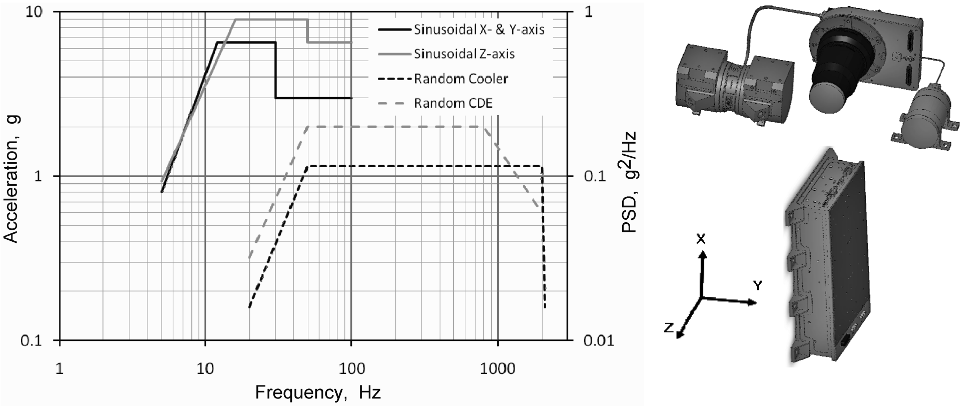

Figure 5. Launch vibration levels of IDCA and CDE; Sinusoidal test levels relate to the left scale in g's, while the random vibration levels relate to the right power spectral density (PSD) scale in g^2/Hz.

the detector temperature is carried from CDE to around 85 K and was held constant during operation time. During high (+55°C) and low temperature (-20°C) operation, the setpoint stability is calculated with a standard deviation (1-SIGMA) of 2.5 mK at high temperature and 22.1 mK at -20°C.

MECHANICAL QUALIFICATION

Launch Vibrations

On-board cryocooling systems are heavily exposed to vibration from the launch vehicle engines during launch. Depending on the spacecraft and launch vehicle type, and the position of the payload, vibration requirements can be quite different.

The cooling system has been qualified and acceptance tested in two steps due to different vibration requirements. The cryocooler has been qualified as part of the IDCA. That means the cold finger is part of the detector-dewar with its specific mechanical support. The tests have been performed at the vibration laboratory of Astrium GmbH, Friedrichshafen (Germany). In Figure 5, the vibration levels of the IDCA and the CDE are summarized. After each axis, system health and mechanical integrity were verified by 0.3g low level sine sweeps and functional tests. Solid lines show the sinusoidal levels, which are equal for IDCA (cooler) and CDE. Dashed lines stand for random vibration levels for the cooler (black) and the CDE (grey).

Pyro Shock

Pyro shock tests were performed at the Institute for Space Systems of the German Aerospace Center (DLR), Berlin (Germany), along the three orthogonal axes as shown in Figure 5. The SRS spectra that were used are indicated in Table 2. The cryocooler and CDE passed the pyro shock tests by showing unchanged cooling performance and structural integrity.

Table 2. SRS spectra for cooler and CDE

	Cryocooler		**CDE**	
Axis	Frequency	Level	Frequency	Level
All three axes	100 Hz 1,000 Hz 10,000 Hz	21 g 400 g 400 g	100 Hz 980 Hz 10,000 Hz	21 g 498 g 498 g
Shocks per axis	2		3	
Attenuation	5% / Q=10			
Resolution	1/6 octave			

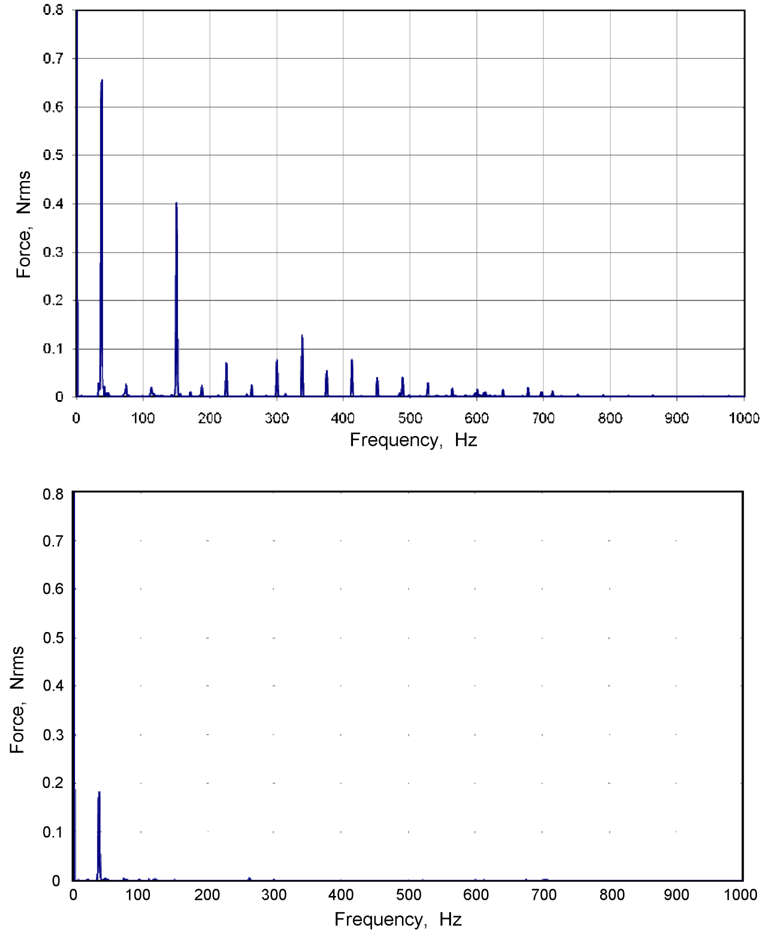

Figure 6. Vibration output force of the cryocooler without (top) and with (bottom) flexible brackets at the compressor I/F.

Cryocooler Micro Vibrations

Micro vibrations induced by the movement of the motor drives inside the compressor are greatly undesired since they generate disturbances in the optical path of the detector and the payload. In order to minimize vibration exported from the cooler to the optical system, the compressor mechanical I/F is mounted in flexible brackets that are specifically designed for its application. Vibration output measurements were conducted at the AIM cooler development lab using a Kistler dynamometer.

Figure 6, top shows the vibration force of the cooler mounted without damping elements in a rigid fixture in the compressor longitudinal axis (piston moving axis, Y-axis in Figure 5). The cooler is in temperature-controlled mode at ambient conditions. The graph shows the vibration force exported to the dynamometer platform in the 1 kHz range. As can be seen, the maximum output force occurs at the fundamental frequency of 36 Hz followed by decreasing levels at higher harmonics.

The same frequency and force range is displayed in Figure 6, bottom for the same operating conditions of the cooler. However, flexible brackets are used to damp and suppress the forces exported from the compressor to the mounting platform. The compressor is suspended with a *Zero-g*-device in order to simulate in-orbit conditions. The maximum output force can be reduced to levels < 0.2 Nrms.

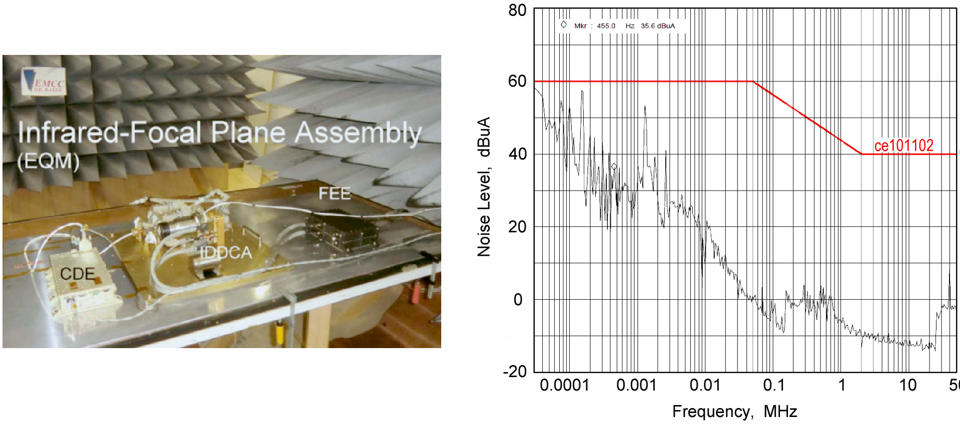

Figure 7. CDE EMI measurement assembly with conducted emission in common mode.

EMI AND IRRADIATION

During operation in space orbit, the electronic parts are exposed to extreme irradiation. The electronics are designed to withstand both the permanent effect on electronic parts from gamma radiation and the transients induced by heavy ions. Irradiation tests of Proton irradiation up to 45 krad and Gamma irradiation up to 30 krad was tested with the complete design. To serve the requirements for space applications, radiation tested parts are used.

Due to the included input and output filter for differential and common mode, the cooler drive electronics is tested compliant to MIL-STD-461E. Based on the design of the motor driver, the conducted emission has to be specifically considered. The common mode is shown in Figure 7. The differential mode result depends directly on the input power of the compressor.

The electronics was found to be insensitive to radiated susceptibility due to its reliable analog design, and therefore no influences on the detector temperature stability were measured.

COOLING SYSTEM LIFE TIME VERIFICATION

Although cooling system life time can be predicted by analytical approaches, life time testing is an essential part of system qualification. In early project phases, AIM started tests of three representative cooler samples each consisting of equal cooler components and the driving electronics, which acts as a basis for flight hardware. The test samples operate on-bench in open-loop-mode. The maximum input power is set to be 1.5 to 3 times higher than that expected under nominal operating conditions. Thermal interface temperatures are typically in the order of 50°C and thus round about 25K above the nominal rejection temperatures of compressor, cold finger warm end, and electronics. In addition, high temperature operating cycles are performed regularly. As a result, the chosen lab test conditions in terms of temperature and input power are much more demanding than real in-orbit conditions. Due to the tightened environmental conditions, a safety factor can be detected easily. Cooling performance and Helium leakage tests are conducted at regular time steps to check performance and life time stability.

Table 3 shows the coolers in test with their achieved life time and their latest status. Each cooler is controlled by a tactical, military electronics which achieved the given cooler lifetime without maintenance or replacement.

In order to verify required lifetimes in excess of 50,000 hours, a life time analysis has been performed. This analysis is based on the failure mechanisms stated by R.G. Ross [4]. In [1], internal working gas contamination due to organic materials inside the gas vessel has been identified to be the only relevant degradation source for the cooler type used. Hence, the proposed accelerated life time test has been conducted. As a result, it was shown that the amount of organic material inside

Table 3. Summary on AIM life time test coolers

Cooler type	Coldfinger type	S/N	Operating hours	Status
SF070	¼" Stirling	032	2,412	Running, no performance degradation observed yet
SF070	¼" Stirling	033	2,565	
SF070	¼" Stirling	005	31,471	
SF100	13mm Sirling	0012	10,423	Stopped for He-gas analysis
SF100	13mm Sirling	0013	34,323	Running
SF100	13mm Sirling	0015	32,640	Stopped due to displacer wear out after 10% Performance degradation
SF100	½" Pulse Tube	0046	33,202	Running, no performance degradation observed yet
SF100	½" Pulse Tube	0047	33,229	
SF100	½" Pulse Tube	0048	33,711	
SF400	½" Pulse Tube	0013	13,245	Running, no performance degradation observed yet
SF400	½" Pulse Tube	0014	13,485	
SF400	½" Pulse Tube	0018	13,556	

the cooler helium vessel is negligible in terms of cooling performance degradation. Even most of the organic molecules diffuse within the outgassing periods prior to cooler assembly.

Whereas the cooler lifetime prediction has influences from different parameters that depend on the respective design, the lifetime calculation of electronic parts is conducted with constant failure rate. For further evidence, the ECSS [5] specifies an accelerated lifetime test of 1,000 hours. The CDE has performed during its qualification at highest ambient temperature and maximum input power.

SUMMARY AND CONCLUSION

In the past 5 years, AIM has developed, assembled, qualified, and delivered a space qualified cryocooling system as part of a LW-IR Detector Assembly. Cryocooler and CDE have been tested according to thermal, mechanical, electrical, and radiation requirements. A number of respective qualification test results for cooler and/ or CDE were presented. An overview of on-going life time tests was given and analysis results were discussed briefly.

Building on this heritage, qualification activities for the EnMAP SW-IR program consisting of the smaller SF100 pulse tube cooler and an advanced version of the CDE are in progress.

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