DESIGN OF A 0.5 WATT DUAL USE LONG-LIFE LOW-COST PULSE TUBE COOLER

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ABSTRACT

The design of a 0.5 Watt Dual Use Pulse Tube Cooler discussed in this paper is based on the analyses of a Hybrid Refrigerator Model (HRM) which is similar in nature to a third order model that has been validated extensively against various Stirling and Pulse Tube Coolers in the literature[1-8]. Together with BEI's experience with the Stirling refrigerators and the introduction of flexure bearings, the design of a long-life and low-cost cooler emerges. The cooler should have a lifetime of at least five years with high reliability and is capable of producing 0.5 Watt of cooling power at 80 Kelvin with a total input power of less than 15 Watt and with a cooler heat sink temperature of 310 Kelvin. The system should also deliver 0.3 Watt of cooling at 65 Kelvin with the same input power and heat sink temperature. The cooler is also light-weight, weighing less than 1 Kg.

INTRODUCTION

BEI has developed a family of "tactical" cryocoolers based on the U.S. Army Night Vision Electronics Directorate (NVESD) specifications. These units are of split Stirling cycle variety, employing opposed piston compressors and reciprocating regenerator displacers. The first step in designing the Long-Life Low-Cost Cooler (L^3C^2) required the identification of the compressor needed to drive the Pulse Tube. The current design of the BEI B512 cooler meets all the thermodynamic requirements of the L^3C^2 cooler described in this paper (see Reference 9).

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However there are two major concerns in using the B512 Compressor as the driver. First, in order to meet the 5+ year of life time requirement, the springs of the compressor have to be replaced by flexure bearings. Due to the size limitation, the incorporation of flexure bearings in the B512 compressor might present a problem. Second, thermodynamic analyses showed that the B512 compressor does not have enough power to drive a 0.5W pulse tube. Thus it was concluded to use the B600 compressor instead.

A schematic diagram of the Dual Use L^3C^2 Cooler is presented in Figure 1. The pulse tube and regenerator are designed to fit within the current design of an existing BEI coldfinger. For the sake of easy packaging, a concentric design of the pulse tube is adopted. Four hundred mesh screens made of stainless steel are used for the regenerator material. For reasons to be discussed later, etched foils might be used as regenerator material instead. In this paper, the results of an orifice pulse tube are discussed. Due to the fact that concentric pulse tubes are less efficient than their linear cousins, the double-inlet and/or multi-bypass configuration might be used to make up the difference between the theoretical and actual performance of the cooler.

PREDICTED PERFORMANCE

Due to the stringent requirements of this cooler, (0.5 W cooling per 15W input power at 80K), it is important to perform a thorough thermodynamic analysis to determine the configuration of the cooler and the operating conditions. The model used for the design of this L^3C^2 cooler is similar to a third order model that has been validated extensively against various Stirling and Pulse Tube coolers in the literature[2-8]. This new model is know as the Hybrid Refrigerator Model[1] (HRM) which uses second order analysis for heat transport and third order analysis for mass flow. For a detailed description of the HRM model, please refer to Reference 1. Some of the key parameters of the L^3C^2 cooler are tabulated in Table 1.

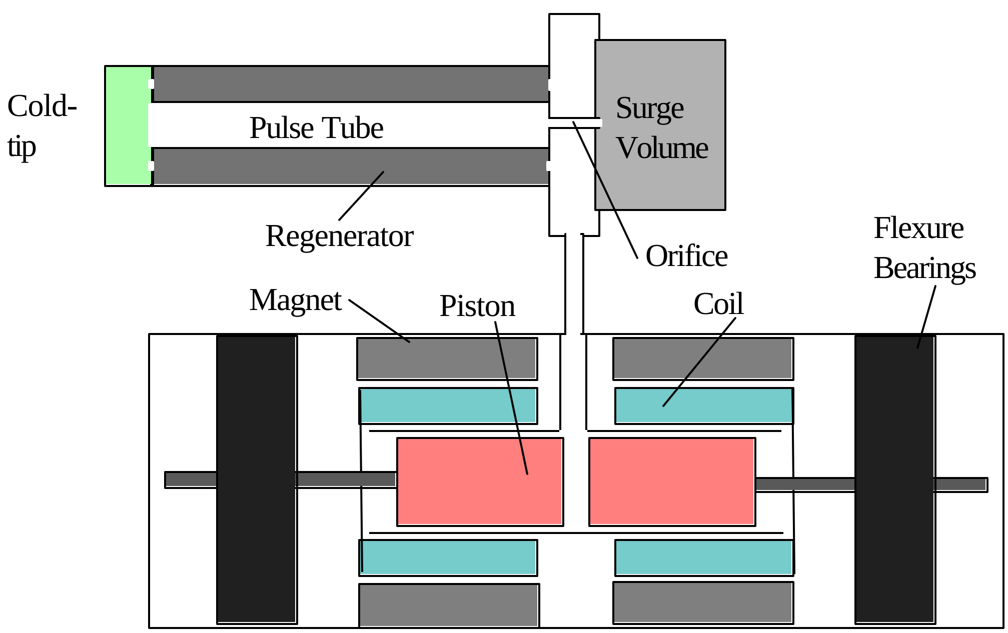

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Figure 1. A schematic diagram of the Dual Use L^3C^2 Cooler.

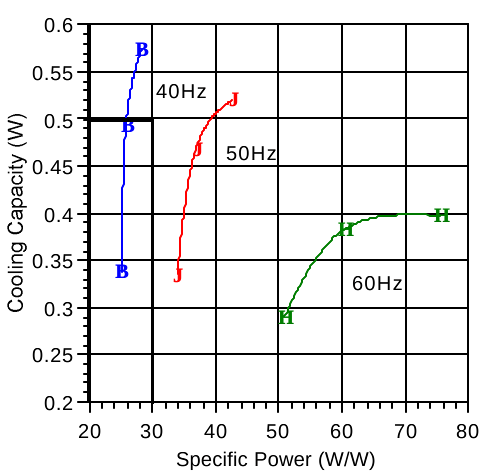
Table 1. Key parameters of the L^3C^2 Cooler.

Compressor Stroke	0.9 cm
Pulse Tube Length	3.58 cm
Pulse Tube Diameter	0.3 cm
Regenerator Length	3.58 cm
Regenerator Diameter	0.5 cm
Orifice Diameter	0.018 cm
Surge Volume	25 cm^3

Figure 2 shows the Cooling Capacity of the cooler as a function of the Specific Power (W/W) for different frequencies. The design point of this cooler is marked by the intersection of 0.5W cooling and 30 W/W specific power. As one can see, the optimum frequency to drive the cooler is between 40 and 50 Hz, agreeing with the operating frequency (at 44.625 Hz) of the TRW's AIRS Pulse Tube Cooler[10-12]. The natural frequency of the BEI compressor is around 60 Hz. To match the desired operating frequency of the compressor to its natural frequency, one can either increase the moving mass of the piston to decrease the natural frequency, or one can use etched-foil regenerators. Experimental data show that due to the less pressure drop of the etched-foil regenerator, one can operate the cooler at a higher frequency.

Figure 3 is a plot of Cooling Capacity versus input power. Unlike Figure 2, the orifice diameter here is 0.018cm. The thermodynamic analysis shows that at 40Hz, the cooler is more efficient with an orifice diameter of 0.018cm, and at 60Hz, the cooler is more efficient with an orifice diameter of 0.016cm.

The effect of the pulse tube / regenerator length on performance is plotted in Figures 4a and 4b. Within the range studied, the model shows a slight increase in the cooling capacity with a shorter regenerator length. The specific power also favors a shorter length. However, the gain in performance is not significant and since the pulse tube is designed to fit inside an existing coldfinger, the length of the existing BEI coldfinger has been chosen.



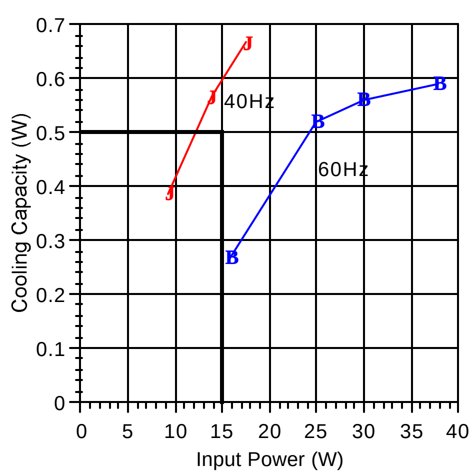


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Figure 2. Refrigeration vs. specific power. **Figure 3.** Refrigeration vs. input power

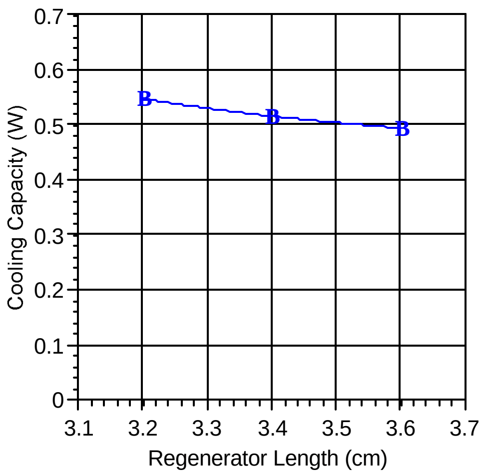

Figure 4a. Cooling capacity versus regenerator length.

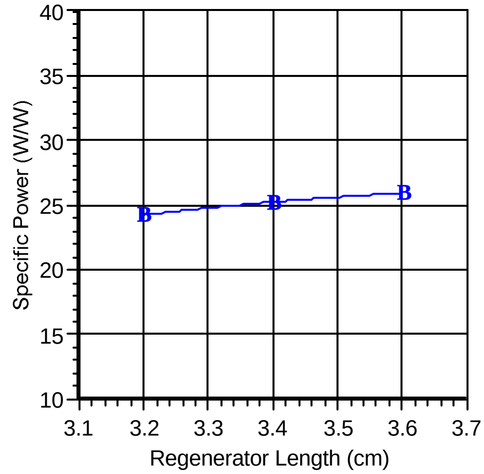

Figure 4b. Specific power versus regenerator length.

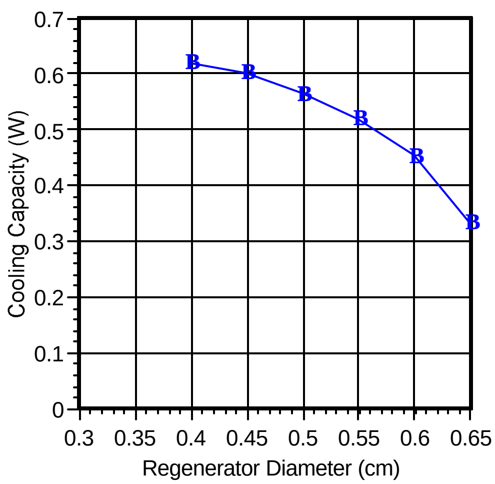

Figure 5a. Cooling capacity versus regenerator diameter.

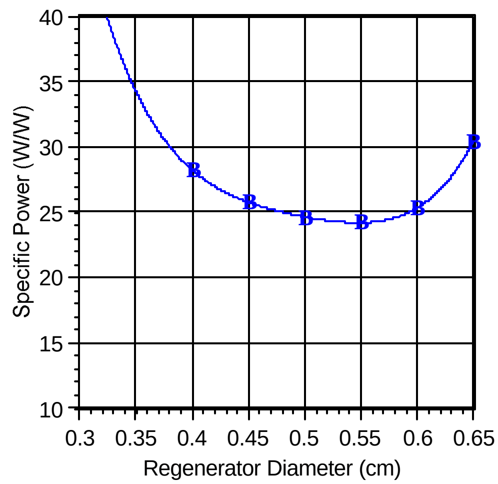

Figure 5b. Specific Power versus regenerator diameter.

The effect of the regenerator diameter on performance is studied in Figures 5a and 5b. While the cooling capacity favors a smaller regenerator, an optimum specific power is found at a regenerator diameter of around 0.5cm. Since the input power poses a bigger concern than the absolute cooling capacity, a regenerator diameter of 0.55cm has been selected.

The cooling capacity and specific power of the L^3C^2 cooler is plotted as a function of the pulse tube diameter in Figures 6a and 6b respectively. In both cases, the optimum performance of the cooler is found at a pulse tube diameter of 0.3cm.

The effect of orifice diameter on performance is depicted in Figures 7a and 7b, with the optimum value at around 0.019cm.

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In order to satisfy the long-life requirement of the cooler, the compressor springs have to be replaced by flexure bearings. A schematic diagram of this compressor can be found in Figure 1.

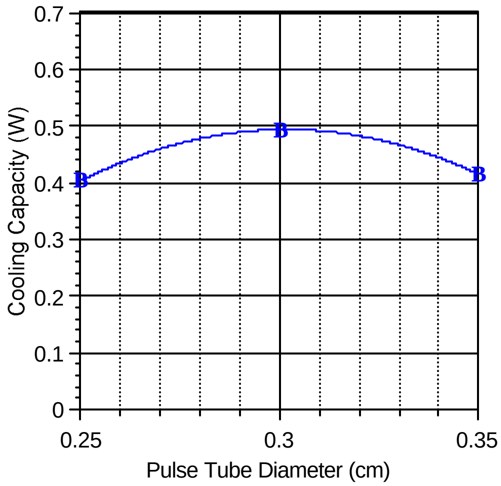

Figure 6a. Cooling capacity versus pulse tube diameter.

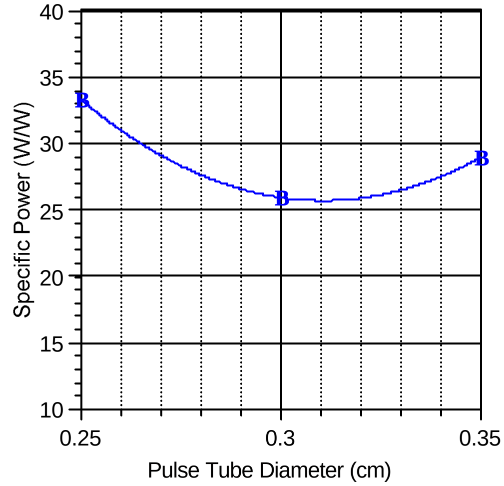

Figure 6b. Specific power versus pulse tube diameter.

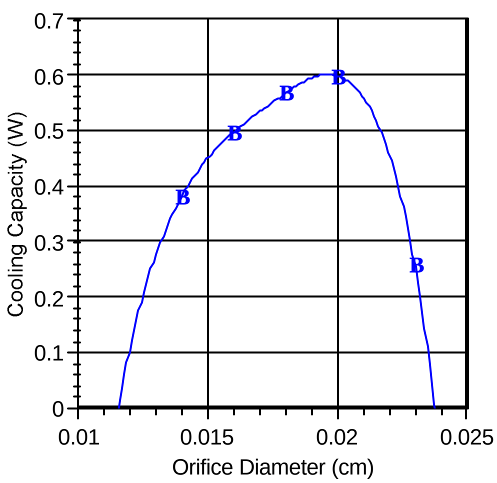

Figure 7a. Cooling capacity versus orifice diameter.

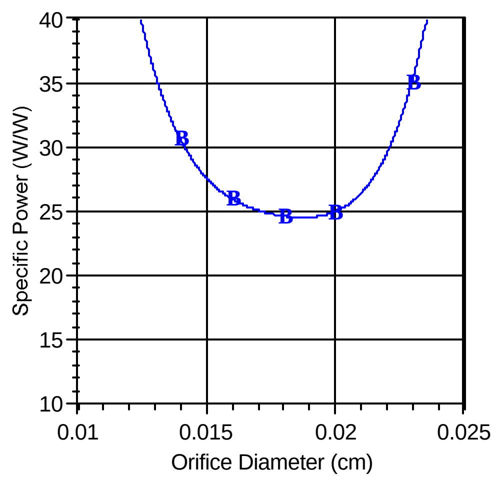

Figure 7b. Specific power versus orifice diameter.

FLEXURE BEARINGS

To allow operation in any gravitational orientation, the non-wearing bearings must provide a high radial stiffness while maintaining a close piston to cylinder concentricity throughout the stroke length. Electro-magnetic bearings, linear flexure bearings, hydrostatic gas bearings and hydrodynamic gas bearings have all been successfully used in this type of application, however, for the sake of simplicity, cost effectiveness, and maximum reliability, only the linear flexure bearing and the hydrostatic gas bearing are practical for the cooler discussed in this paper.

The best designs are the Aerospace and “delta” flexures[13]. These configurations result in the lowest radial noise, the highest radial stiffness to axial stiffness ratio when compared to all the

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other configurations when the characteristics are normalized to the infinite cycle fatigue life limited maximum local stress.

The assembly, alignment, and attachment of the stack of flexure diaphragms and spacers required to create a linear flexure bearing has proven to be feasible but costly. Skilled workers, complex fixturing, and multiple trial and error fit-ups have been required to obtain an acceptable installation. A potential solution to this problem is the use of an integrated flexure bearing cartridge which can be installed in a manner analogous to that used in roller and ball bearing cartridges.

The Peckham version of the linear flexure bearing cartridge is composed of a bonded assembly of diaphragm flexure springs, inner diameter spacers, outer diameter spacers, and a retainer system which maintains the assembly as a single entity with a precise outside diameter, inside diameter and length. The inner and outer diameters are precision ground to the tolerance and concentricity required by the specific design. The ends of the assembly are parallel ground perpendicular to the axis of the ID/OD in order to produce the part in a configuration that can be assembled with the final product without using shims.

A study of the total fabrication / assembly process utilizing the Peckham cartridge verified the potential cost savings of this approach, however, this study also showed that an alternative approach which located the outer fixed rim by the use of three locating pins rather than a precision outside diameter surface reduced the cost of both the cartridge and the assembly housing. Additional finite element analysis showed that the flexure could be improved by shaping the outer edge of the flexure leaf. In addition, the use of the locating pins to position the cartridge eliminated the need for a circular outer rim, thereby reducing the material content of a flexure. Johnson (one of the authors) incorporated all these changes into an alternate flexure bearing cartridge, identified as the ETA flexure bearing.

Figure 8 shows the ETA flexure bearing cartridge. Peckham now manufactures both the Aerospace and the ETA type flexure bearing cartridges. These “Delta” flexure cartridges have other advantageous characteristics: The tangential leaf configuration virtually eliminates radial noise since it is not subjected to the many natural vibration modes of the spiral bladed flexure; the flexure cartridge is easily integrated into a moving sleeve compressor configuration; and the individual cartridges can be electrically insulated so that the flexure can also serve as the electrical power lead for the moving coil.

Hydrostatic gas bearings have the advantage of high radial stiffness, but they have the disadvantage of parasitic high pressure working gas flow rate required to provide this high stiffness. Due to the power limitation of this high efficient L^3C^2 cooler, the use of flexure bearings is favored.

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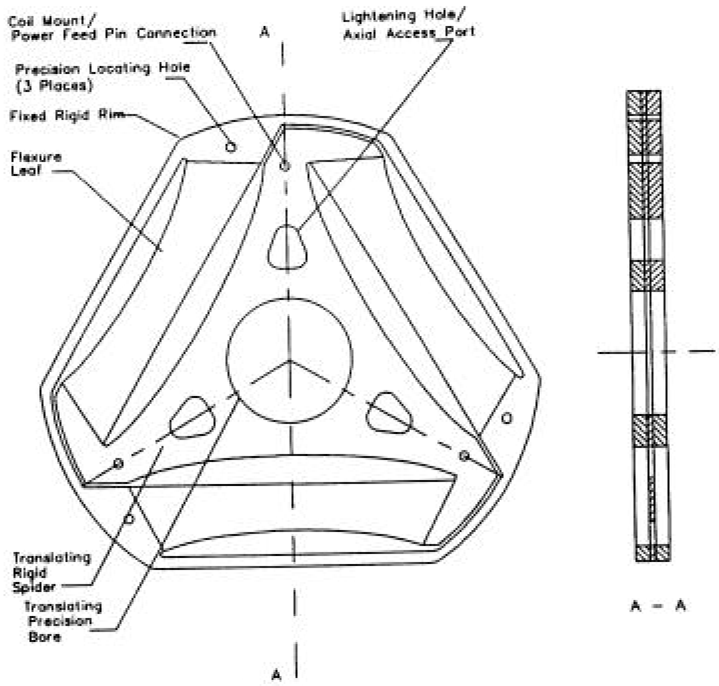

Figure 8. The ETA flexure bearing cartridge.

CONCLUSIONS

The design of a Long-Life Low-Cost Pulse Tube Cooler is discussed in this paper. Using a well-validated computer model, the L^3C^2 cooler was predicted to deliver 0.5W cooling at 80K, with an input power of less than 15W. The predicted frequency agrees with the operating frequency of the TRW AIRS Pulse Tube Cooler. The pulse tube and the regenerator are designed to fit within the design of an existing BEI coldfinger. To increase reliability of the cooler, flexure bearings are to be incorporated into the cooler to extend the life time to beyond 5 years. This cooler will be fabricated and tested in fall of 1997.

REFERENCES

1. D. Kuo, T. Loc, and S.W.K. Yuan, Experimental and Predicted Performance of the BEI Mini-linear Cooler, in Proc. the 9th International Cryocooler Conference, (1997) p. 119.

2. S.W.K. Yuan and R. Radebaugh, A Blind Test on the Pulse Tube Refrigerator Model, in "Advances in Cryogenic Engineering", Vol. 41, (1996) p.1383.

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3. S.W.K. Yuan, Validation of the Pulse Tube Refrigerator Model Against a Lockheed Built Pulse Tube Cooler, in “Cryogenics”, Vol. 36, No.10, (1996) p.871.

4. S.W.K. Yuan, L.G. Naes, and T.C. Nast, Prediction of Natural Frequency of the NASA 80 K Cooler by the Stirling Refrigerator Performance Model, in: “Cryogenics”, Vol. 34, No.5, (1994) p.383.

5. S.W.K. Yuan, I.E. Spradley, and W.G. Foster, Validation of the Stirling Refrigerator Performance Model Against the Oxford Refrigerator, in: “Advances in Cryogenic Engineering”, Vol. 39, (1994) p.1359.

6. S.W.K. Yuan and I.E. Spradley, Validation of the Stirling Refrigerator Performance Model Against the Philips/NASA Magnetic Bearing Refrigerator, in: “Proc. 7th Int. Cryocooler Conf.”, Vol. 1, Phillips Lab, USA (1993) p.280.

7. S.W.K. Yuan, I.E. Spradley, P.M. Yang, and T.C. Nast, Computer Simulation Model for Lucas Stirling Refrigerators, in: “Cryogenics”, Vol. 32, (1992) p.143.

8. S.W.K. Yuan and I.E. Spradley, A Third Order Computer Model for Stirling Refrigerators, in: “Advances in Cryogenic Engineering”, Vol. 37 (1992) p.1055.

9. D.T. Kuo, A.S. Loc, and S.W.K. Yuan, Enhanced Performance of the BEI 0.5 Watt Mini-Linear Stirling Cooler, a parallel paper at Cryogenic Engineering Conference, 1997.

10. C.K. Chan, et. al., Performance of the AIRS Pulse Tube Engineering Model Cooler, in Proc. of the 9th International Cryocooler Conference, (1997) p. 195.

11. R.G. Ross, Jr., and K.E. Green, AIRS Cryocooler System Design and Development, in Proc. of the 9th International Cryocooler Conference, (1997) p. 885.

12. C.K. Chan, et.al., AIRS Pulse Tube Cryocooler System, in Proc. of the 9th International Cryocooler Conference, (1997) p. 895.

13. Electro Thermo Associates, Manhattan Beach, CA, 90266, USA

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