BAE's Life Test Results on Various Linear Coolers and Their Correlation with a First Order Life Estimation Method

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ABSTRACT

Life test results of various models of BAE Stirling coolers are presented in this paper together with a first order life approximation model.

A cryocooler life estimation method based on the Watt-Hour approach has been developed elsewhere[1]. According to this method, the total energy of a cryocooler (i.e., the product of mean input power and total operating time) is conserved. From actual life test data of input power rise as a function of time, the energy of the cooler in Watt-Hour can be calculated by integrating the life test curve. With this knowledge and the specification, one can proceed to estimate life. The biggest disadvantage of this method is that it requires prior knowledge of the life test data before life estimation can be performed. In the present paper, a first order approach is used to estimate the rise in input power as a function of time, which can then be used in life estimation.

INTRODUCTION

BAE Systems has conducted life test on various linear motor coolers, including B512C (Ref. 2), B602C (Ref. 3) and B1000E coolers. Conditions of the life tests are summarized in Table 1.

Table 1. Life test conditions on various coolers.

Cryocooler Model Number	B512C	B602C	B1000E
Heat Load, Q	212 mW	350 mW	3,750 mW
Maximum Input Power, W	20 W	35 W	60 W
Cold Tip Temperature, T_C	78 K	78 K	145 K
Ambient Temperature, T_H	30°C	40°C	40°C
Charge Pressure, P	44.8 bar	31 bar	31 bar
Piston Area, A (arbitrary unit)	1	1.4	5.3

Life test data of three different models of coolers in input power vs. time can be found in Figures 1a, 2a, and 3a. Life test data of cooldown time vs. time are plotted in Figures 1b, 2b, and 3b. And life test data of minimum refrigeration vs. time are presented in Figures 1c, 2c, and 3c respectively.

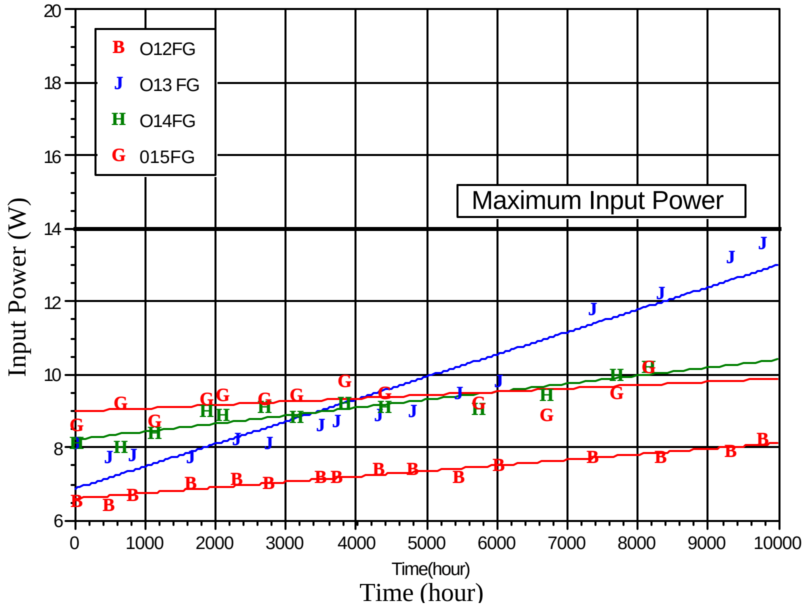


Figure 1a. Input Power of B512C cooler vs. time

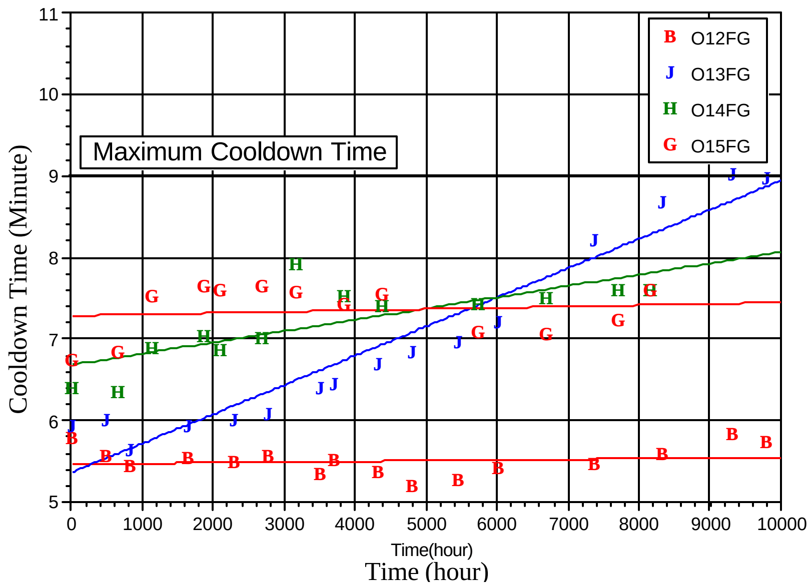
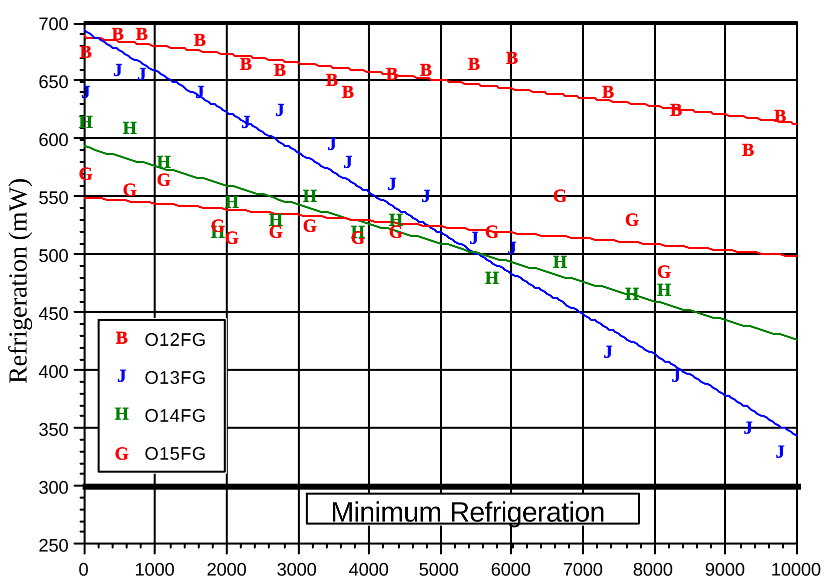
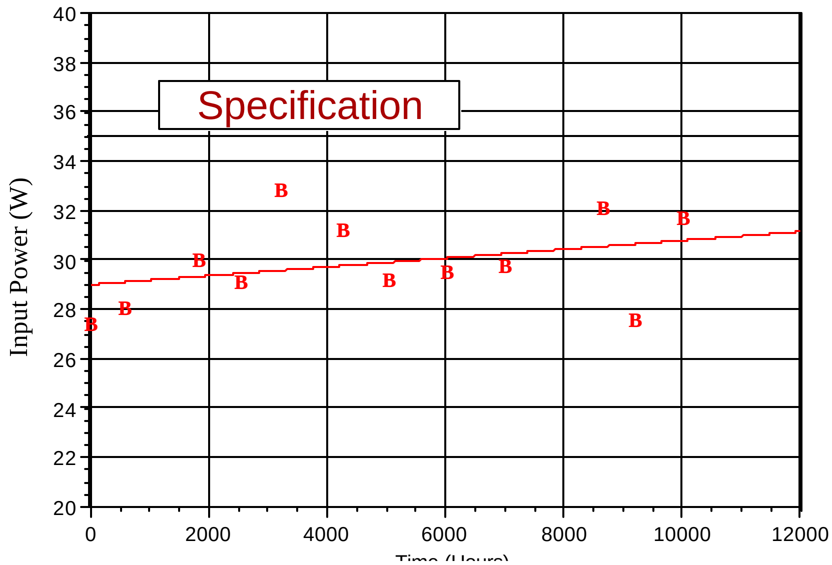


Figure 1b. Cooldown time of the B512C cooler vs. time.



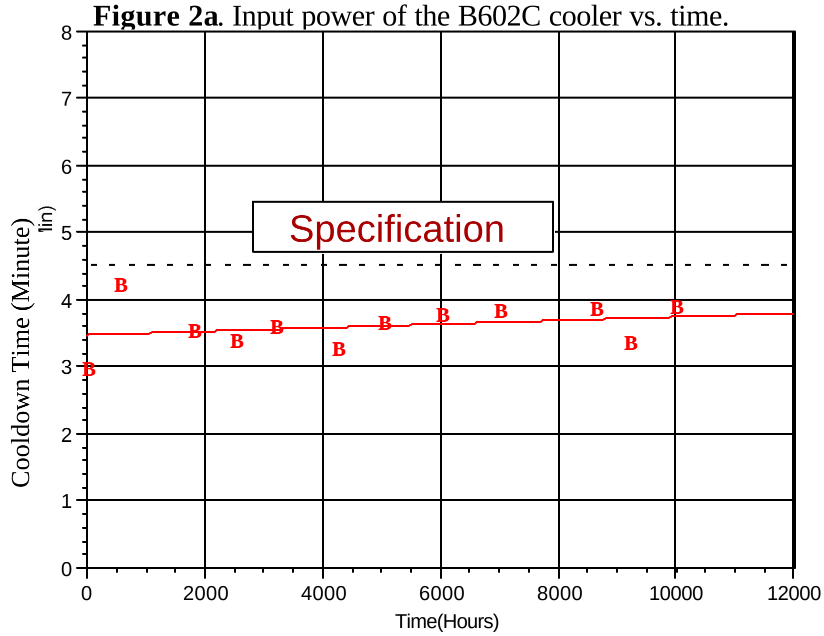
Time (hour)

Figure 1c. Minimum refrigeration of the B512C cooler vs. time.



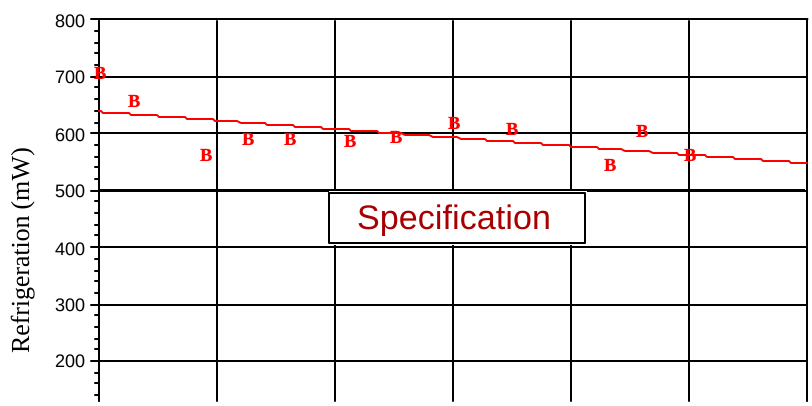
Time (hour)

Figure 2a. Input power of the B602C cooler vs. time.



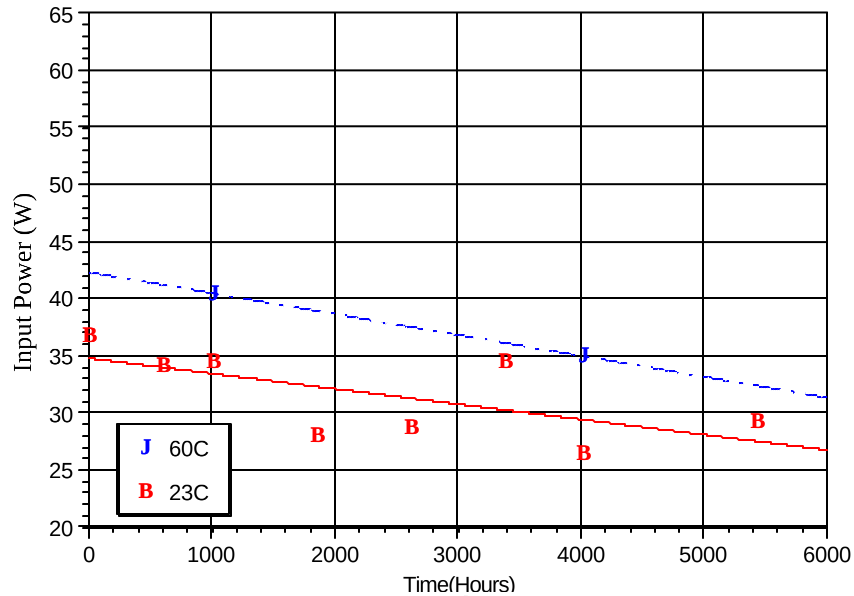
Time (hour)

Figure 2b. Cooldown time of the B602C cooler vs. time.



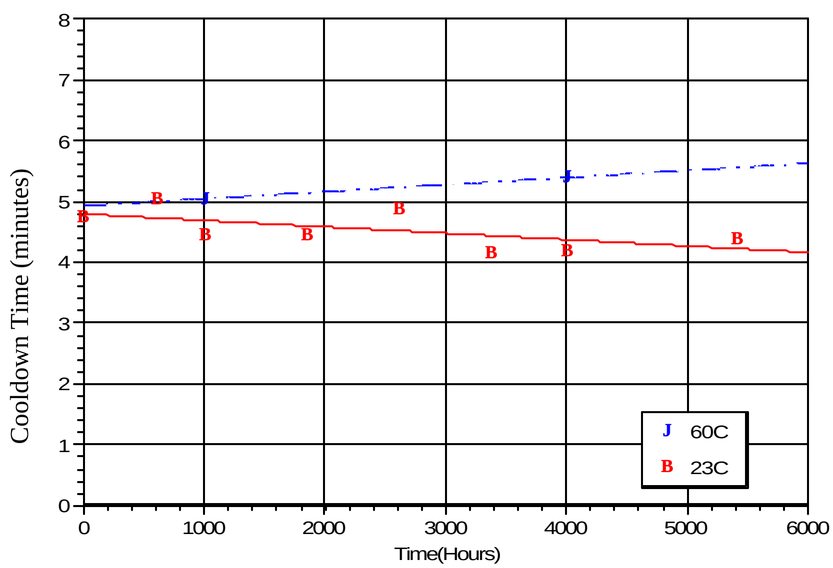
Time (hour)

Figure 2c. Minimum refrigeration of the B602C cooler vs. time.



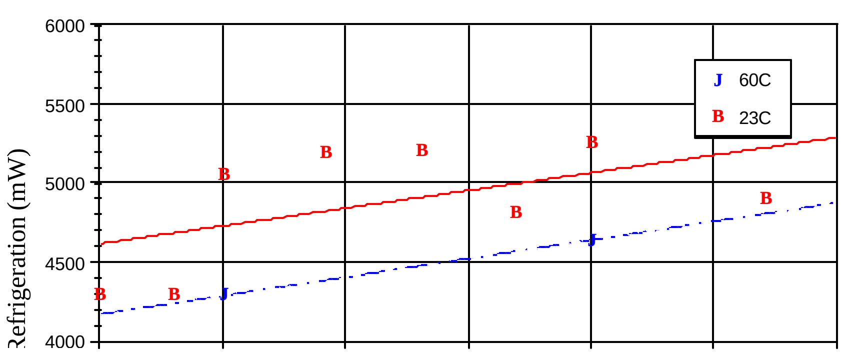
Time (hour)

Figure 3a. Input power of B1000E cooler vs. time.



Time (hour)

Figure 3b. Cooldown time of B1000E cooler vs. time.



Time (hour)

Figure 3c. Minimum refrigeration of B1000E vs. time.

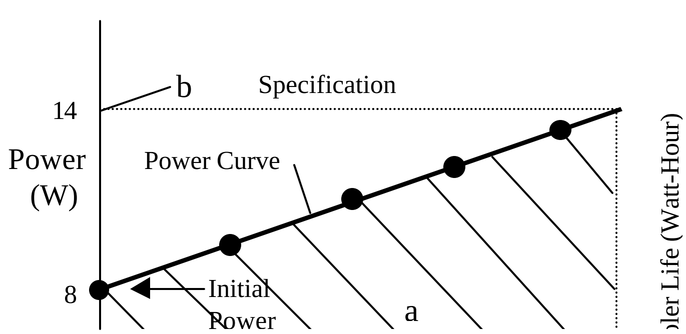
The life test of the BAE B602C (0.6 W linear) cooler was terminated at 10,008 hours when it failed the specification. The failure was caused by particulate contamination which blocked the flow in the regenerator. After installing a new regenerator, the performance of the cooler was restored. This proved that the compressor was not the root cause for failure. The life tests of both the B512C (0.5 W linear) coolers and the B1000E (1 W linear) cooler are still in progress, with the MTTF of the B512C cooler and the B1000E cooler exceeding 9,000 hours and 5,000 hours respectively.

Cooler Life Estimation and Correlation with Experimental Data

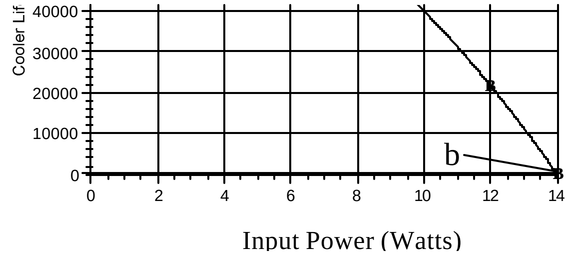
Cooler life estimation using a Watt-Hour approach was evaluated in Reference 1. The method assumes that the total Watt-Hour of a cooler is conserved, i.e., running the cooler at low power will extend its life and vice versa. Under normal conditions, cooler life is a function of compressor piston wear. As the clearance gap grows (which increases the blow-by losses) due to wear, the driver needs to drive the piston harder to make up for the lost performance. This in turn increases the power (see Figure 4a). When the power exceeds the user's specification, the end-of-life of the cooler has been reached. Given the experimental data of the input power increase as a function of time (power curve, Figure 4a), one can then calculate the total Watt-Hour of the cooler by integrating the power curve to calculate the total area underneath it. For the example in Figure 4a, an integration from the initial power of 8 W to the specification of 14 W, gives us the total Watt-Hour of the cooler that is then entered into Figure 4b as data point a. The procedure is repeated for various initial powers to come up with Figure 4b. Of course, if one starts with an initial power of 14 W, the cooler would have essentially no life as indicated in point b of Figure 4b.

A major shortcoming of this method is that it takes extensive life test data to predict life. Moreover, due to the variation in performance from cooler to cooler, data taken from one cooler may not be applicable to others. This means that a large number of coolers need to be tested before the life of an average cooler can be determined.

In this paper, a simple first order model is proposed to estimate the rise in input power as a function of time (power curve). The slope of the power curve (Figure 4a) is assumed to be proportional to the heat load, the ambient temperature, and the charge pressure, and inversely proportional to the cold tip temperature and the bearing area of the piston seal.



(a)



(b)

Figure 4. Watt-Hour life estimation.

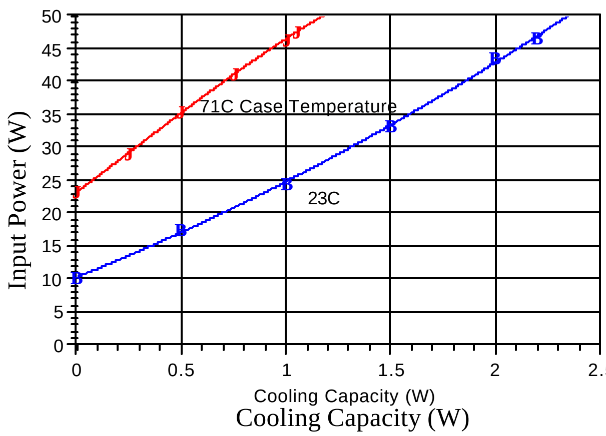


Figure 5. Heat load vs. input power at 78K.

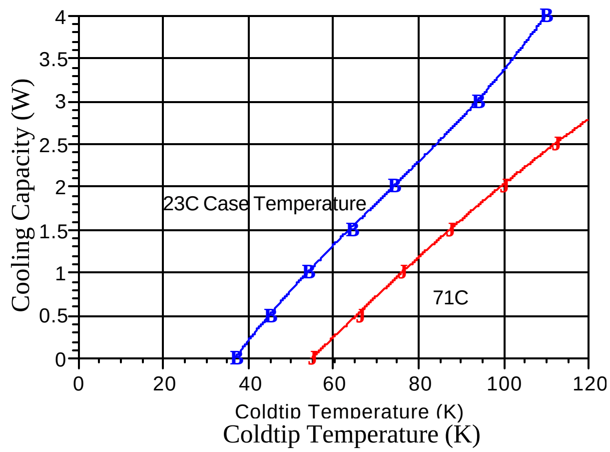


Figure 6. Heat load vs. cold tip temperature.

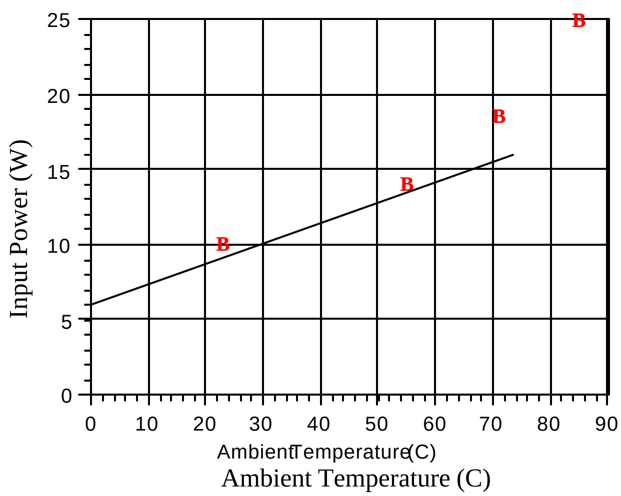


Figure 7. Input power vs. ambient temperature.

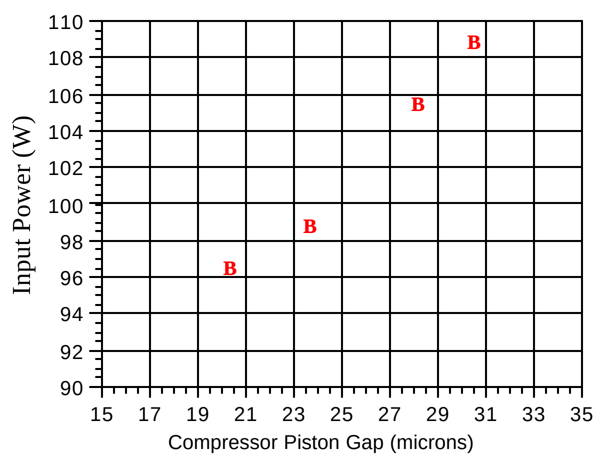


Figure 8. Input power vs. piston wear.

The effect of heat load and cold tip temperature on life can be deduced from Figures 5 and 6. Heat load (cooling capacity) versus input power is plotted in Figure 5, and heat load versus cold tip temperature is plotted in Figure 6, for the B1000E cooler. Heat load is almost a linear function of the input power within the range of interest. Large heat loads require high input powers which reduce the cooler life. The linear dependence of heat load on cold tip temperature (in Figure 6) suggests that the cold tip temperature is also a linear function of life. With the same input power, the heat load a cooler can alleviate is less at low cold tip temperatures. This means that for the same heat load, one has to apply a higher input power at a low cold tip temperature, which shortens the life of the cooler.

In Figure 7, the influence of ambient temperature on input power is depicted. The data were taken on a B512C cooler at various ambient temperatures at 78 K and with 300 mW heat load. The data appear to be quite linear between 0 to 60°C, with a much sharper rise at temperatures above 60°C.

The effect of surface area on life can be obtained from Figure 8, which shows the predicted performance of a cooler (by a second order cooler simulation model) versus compressor piston gap. Since the piston wear is inversely proportional to the piston surface area, and the piston gap is a measure of the piston wear, Figure 8 implies an inverse linear function between cooler life and bearing surface of the piston.

Table 2. Predicted and experimental power increase vs. time.

	B512C	B602C	B1000E
Predicted Slope (W/Hour)	0.00020	0.00022	0.00033
Experimental Slope (W/Hour)	0.00023	0.00020	-0.00175

With the above information, one can come up with a simple first order model, by assuming that the slope of the power curve (Figure 4a) in W/hour is

$$\text{Slope} = \text{Cont}\ P\ Q\ T_H\ /\ A\ T_C \qquad (1)$$

Where P is the charge pressure in bars, Q is the heat load applied to the cooler in watts, T_H is the ambient temperature in °C, A is the piston area (cm^2), and T_C is the cold tip temperature in K. Cont is a constant that equals to 5.475E-5.

The slope of the power curve (Figure 4a) can be calculated by Equation (1) with the parameters listed in Table 1. The predictions are then compared to the life test data of the three coolers in Table 2.

The model gives a good prediction on the slope of the power curve for both the B512C and the B602C coolers despite a wide range of differences in cooler parameters (Table 1). The correlation of the first order model with the life test data of the B1000E cooler is not possible due to a decrease in input power (negative power curve slope) as the cooler wears in during the life test. More run time is needed in order to validate the model. Equation (1) can be applied to other Stirling coolers, for the trends described in Figures 5 to 8 are generic to most coolers. In order to apply Eq. (1), one must have some life test data as depicted in Figure 4a to obtain the constant (Cont) in Eq. (1). With this information, one can proceed to estimate life of different models of coolers of the same design, or coolers of the same model operated at different conditions.

As depicted in Figures 1 to 3, some of the parameters to be monitored during a life test include, input power, cooldown time and minimum refrigeration. Failure in meeting the specification in any of these three criteria constitutes a failure of the cooler. The life estimation discussed in this paper can be applied to all three criteria mentioned above. One simply measures the slopes of the life test data in W/hour (rise in input power vs. time in Figures 1a, 2a and 3a), minutes/hour (increase in cooldown time vs. time in Figures 1b, 2b and 3b) and mW/hour (decrease in minimum refrigeration vs. time in Figures 1c, 2c and 3c). To estimate the life of the same built of cooler under another set of operating conditions, simply apply Eq. (1). The slopes of the life curves are directly proportional to the ambient temperature, heat load, charge pressure, and inversely proportional to piston area and coldtip temperature. For example, if the ambient temperature is doubled, one would expect the slopes to be doubled and life of the cooler halved, and if the heat load is halved, the slopes are halved, and cooler life doubled, etc.

Precautions must be taken in using Eq. (1), not to exceed the range that this simple approach is intended for. For example, a cooler without any heat load applied will not have infinite life or zero slope (for the power curve). Also, the equation is only valid for ambient temperatures above 0 °C. Generally speaking, the room temperature data is a worst case estimation for life at sub-zero (°C) temperatures.

CONCLUSIONS

Life test results of BAE's B512C, B602C and B1000E coolers were presented. The B602C cooler exceeded 10,000 hours of life test, with the life test of both the B512C (> 9,000 hours) and the B1000E (> 5,400 hours) coolers still in progress. A simple first order life test estimation is suggested, which gave good correlation to the life test data of the B512C and the B602C coolers. More data is needed to validate the model against the B1000E cooler. The effect of charge pressure on life should be further studied. The life estimation method proposed in this paper can be used to predict cooler life as limited by the constraints of input power, cooldown time and minimum refrigeration.

REFERENCES

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