CRYOCOOLER LIFE ESTIMATION AND ITS CORRELATION WITH EXPERIMENTAL DATA

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ABSTRACT

While the life of a cryocooler is guaranteed under the manufacturer's specification, the manufacturer is constantly faced with the problem of trying to determine cooler life for customers' specific applications. An attempt has been made to estimate cooler life based on a Watt-Hour approach proposed by Scott Miskimins[1]. In the current paper, the total life of a cooler in Watt-Hour is expressed as a function of initial power and the failure criterion. BEI is currently conducting two life tests on the 0.5 W Stirling cooler (B512), with various heat loads at 78K (at room temperature ambient). Correlation of the experimental life test data with the theory will be discussed in detail, together with life estimate of operating the cooler at conditions other than that of the life tests, namely, high and low ambient temperatures, different heat loads and coldtip temperatures, etc.

INTRODUCTION

Miskimins[1] proposed to estimate cooler life using a watt-hour approach. For a given failure criterion, a cooler has certain life in terms of watt-hours, i.e., the product of input power and cooler life (in hours) is a constant. Therefore, if a cooler operates at low power it's life is extended and vice versa. The theory proposed in this paper differs from that of Reference 1, which assumes a linear correlation between cooler life (in Watt-Hour) and input power.

Figure 1 shows the life test data of BEI's B512C cooler with input power as a function of life. A least squares function is used to fit the data as represented by the solid line. The total life of the cooler in Watt-Hours is represented by the total area under the life test curve (Figure 1). It is BEI's experience in conducting life tests that coolers with same configuration have almost the same slope, when input power is plotted as a function of life. Coolers with better alignment tend to have lower input power, but the slope remains almost the same (Figure 1).

Assuming a failure criterion of 14 W, one can integrate curves (e.g., a, b and c) of same slope from various initial input power to the failure criterion to get the cooler life curve as shown in Figure 2.

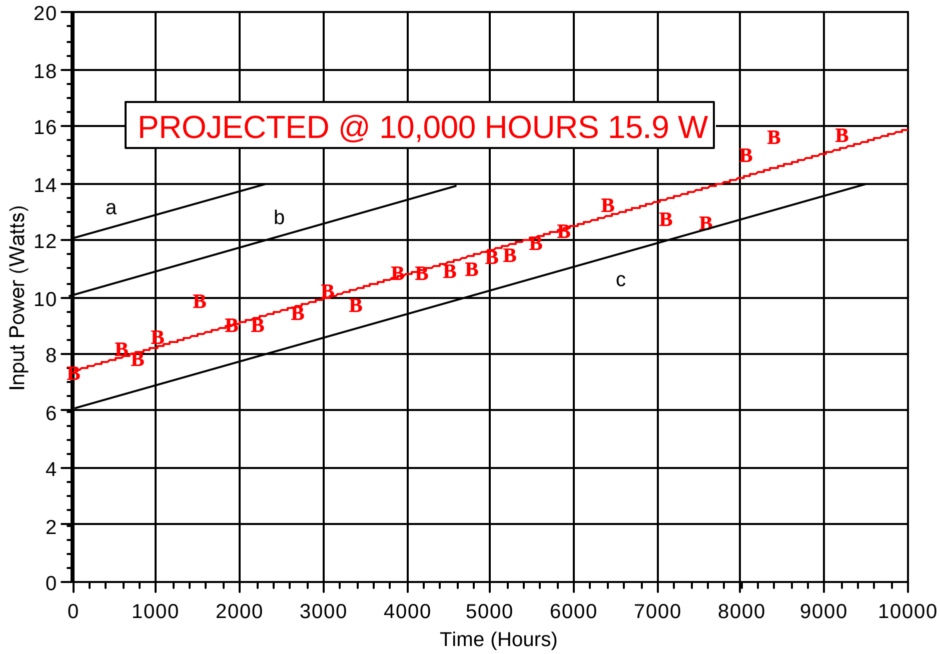

Figure 1. Life test data of BEI's B512C Cooler.

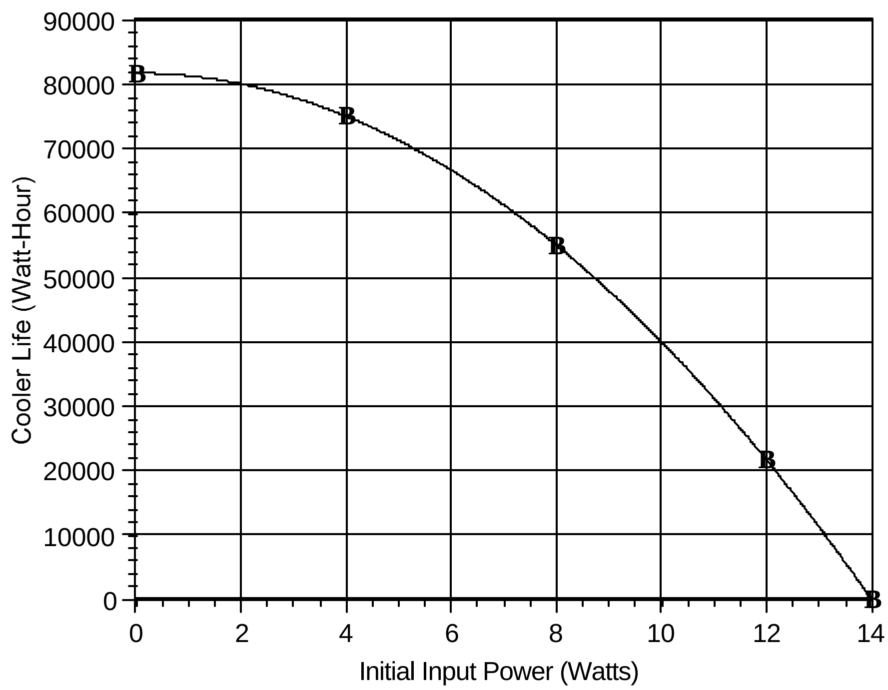

Figure 2. B512C cooler life curve (14 W as failure criterion).

Given Figure 2, one can proceed to estimate cooler life. For example, a cooler with an initial power of 10 W, has an estimated life of about 40000 Watt-Hours. The life of the cooler in time is then 40000W-Hr/10W = 4000 hours. If the initial power of the cooler is 14 W, the cooler has essentially no life.

Cooler life curves like that of Figure 2 can be easily constructed if one knows the slope of the life test data (W/Hour). The total area underneath the life test curve in Figure 1 with initial power (P_i) and failure criterion (P_f) can be written as

$$\text{Cooler Life (W-Hr)} = \text{Area Under Curve} = ((P_f+P_i)/2)*(P_f-P_i)/\text{slope}$$

$$= (P_f^2-P_i^2)/(2*\text{slope}) \quad (1)$$

Note that Figure 2 is not a linear curve as suggested in Reference 1. Miskimins suggested that extrapolation of the linear curve towards low power might not be accurate. Figure 2, which is based on integration of the life test data should provide more accurate prediction of life at low power.

With Figure 2, one can also estimate cooler life at conditions other than that of the life test. The life test data in Figure 1 was taken with a heat load of 150 mW at room temperature ambient. Higher heat load or ambient temperature tends to shorten life and lower heat load or ambient temperature has the opposite effect. Moreover, the life test cooler has a transfer line of one inch in length. Longer transfer line tends to degrade life. If the initial input power of the cooler at conditions other than that of the life test are known, the cooler life at these conditions can be estimated from Figure 2. For example, a cooler with 150 mW load has an initial power of 6.5 W (Figure 3)[5]. From Figure 2, this cooler should have an estimated life of close to 9700 hours (63000W-Hr/6.5W). If the case temperature of this cooler is raised to 71°C, the input power becomes 12W (Figure 3) and the cooler life becomes ~1850 hours (22000W-Hr/12W).

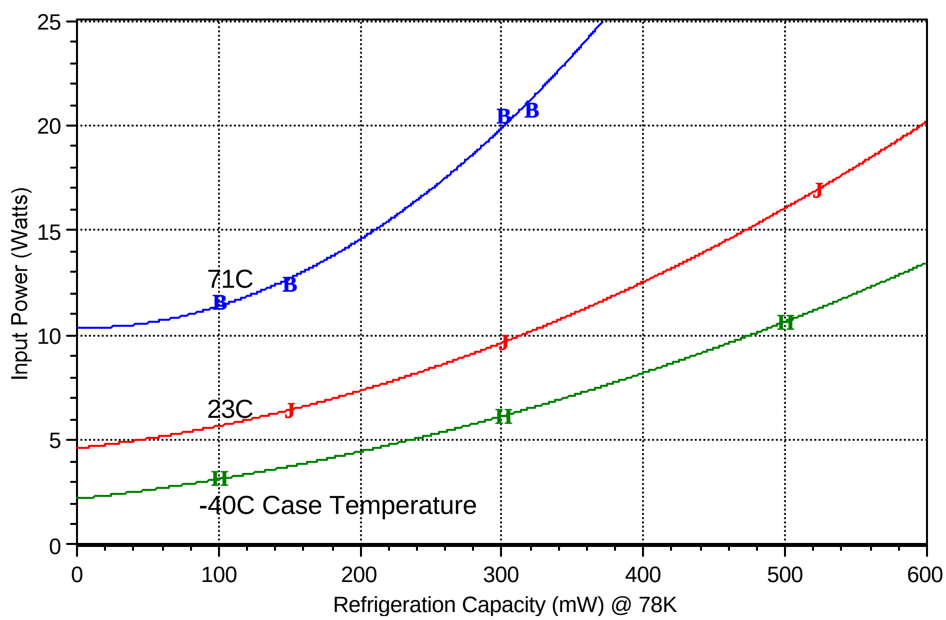

Figure 3. Typical performance of B512C coolers.

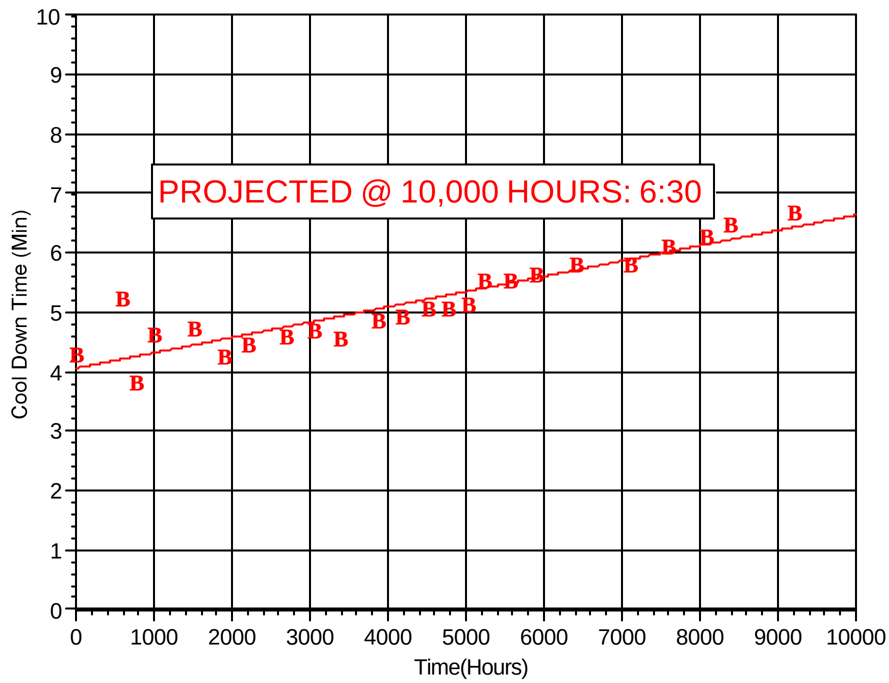

Figure 4. B512C cooler cooldown time vs. life.

By the same token, if the heat load is 300 mW (at 23°C case temperature), the life of the cooler is about 4400 hours (42000W-Hr/9.5W). Note that in the above calculations, a failure criterion of 14W input power was assumed.

Input power is not the only criterion for failure. Other criteria like cooldown time and minimum refrigeration are also important. Figure 4 shows the cool down time as a function of life. Although the life of the B512C cooler is close to 8000 hours (Figure 1), based on the criterion of input power, the life of the cooler is less than 4000 hours (Figure 4) if the criterion on cooldown time is $\leq$ 5 minutes.

Since both the B512C cooler and the B512B cooler use the same compressor (with different design of expander), it is conceivable that the life data collected for the B512C cooler can be applied to the B512B cooler. A separate life test was conducted on the B512B cooler with three coolers running at 212 mW (average value represented by dotted lines in Figures 5 to 7). These three coolers have an average initial input power of 8.5 W. From Figure 2, one can estimate the life of the B512B cooler to be around 6200 hours (53000W-Hr/8.5W). Unfortunately, the actual life test data fell short of the prediction. Further examination of the data showed that besides the difference in the expander design, the charge pressure of the B512B cooler (650 psig) was also much higher than that of the B512C cooler (450 psig). Due to the presence of larger dead volumes inside the B512B expander, a higher charge pressure is needed to prevent the compressor pistons from hitting. It is a known fact that higher charge pressure tends to enhance piston wear and thus shorten cooler life. From this one should note that the theory presented in this paper is only applicable to coolers of same configuration

To meet the 4000-hour life requirement, BEI modified the material of the piston seal from a teflon to a teflon based material with glass. The life test data of coolers made of old and new seal materials are presented in Figures 5 to 7. Coolers with old piston seal material are represented by dotted lines (average of three coolers). Three coolers with the new piston seal material are also included in the figures. Out of the six life test coolers, five of them have heat loads of 212mW applied during the life test. Cooldown tests were performed with no heat load. The remaining unit with the new piston seal material has been tested to a much tougher specification, with 300mW load during life test and 120mW load during cooldown.

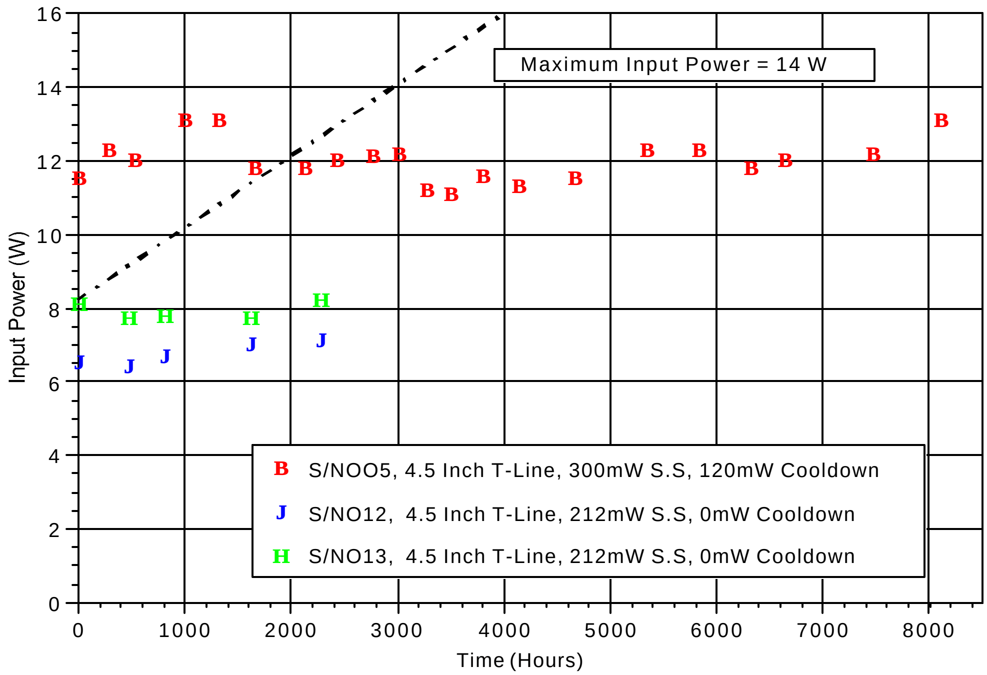

Figure 5. Input power vs. life for B512B cooler.

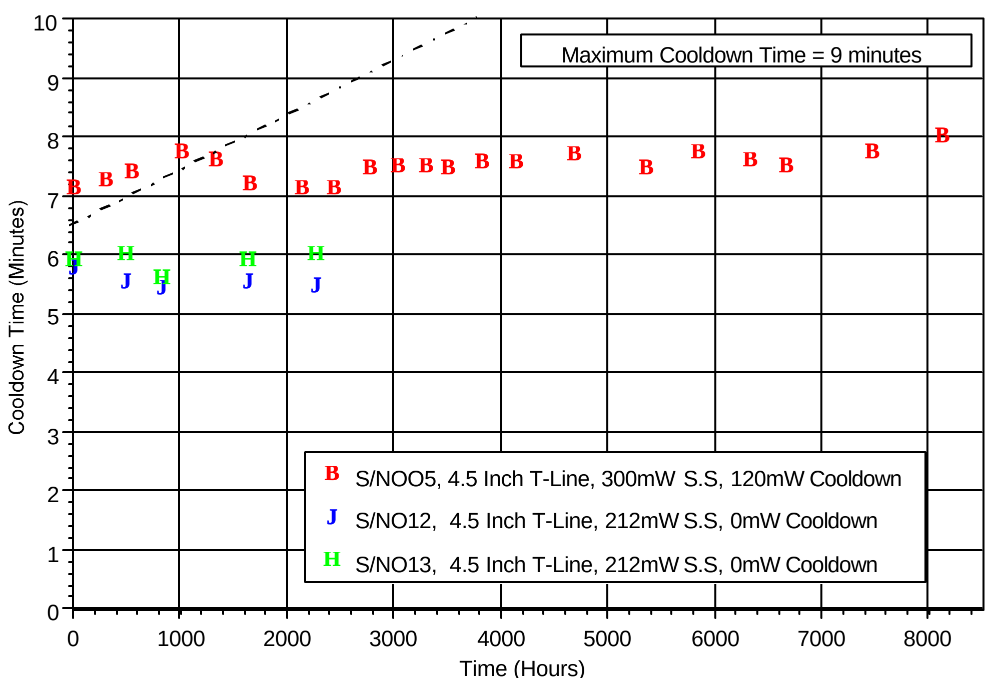

Figure 6. Cooldown time vs. life for B512B cooler.

Figure 5 is a plot of input power as a function of life. Figure 6 shows the cooldown time from ambient to 78K with 11 volt input power. Figure 7 is a plot of minimum refrigeration at 11 volt versus life. As one can see, the slope of the old piston seal material (dotted line) is far steeper than that of the new material, indicating a far shorter life. Due to this finding, BEI has changed the piston seal material in all coolers[2-9] across the board. To date, two of coolers with new piston seal have accumulated more than 2200 hours showing little or no sign of wear. The third unit which has been tested to a tougher specification (300mW) has been running for more than 8000 hours.

Life test data of B602 cooler. Life test data on the B602 cooler is presented in Reference 9. The B602 cooler is a 600 mW cooler. It can provide larger cooling capacity than the B512 cooler, but it also consumes more energy. Figure 8 shows the cooler life (in Watt-Hour) of the B602 cooler as a function of input power for failure criteria of 30W, 32W and 34W, as predicted by Equation 1. At this range, close to the failure criteria, the life curves appear to be a straight line. Currently, the B602 life test unit has more than 7000 hours accumulated, and it's input power is still below 30 W. The cooler's initial input power was 27.4W

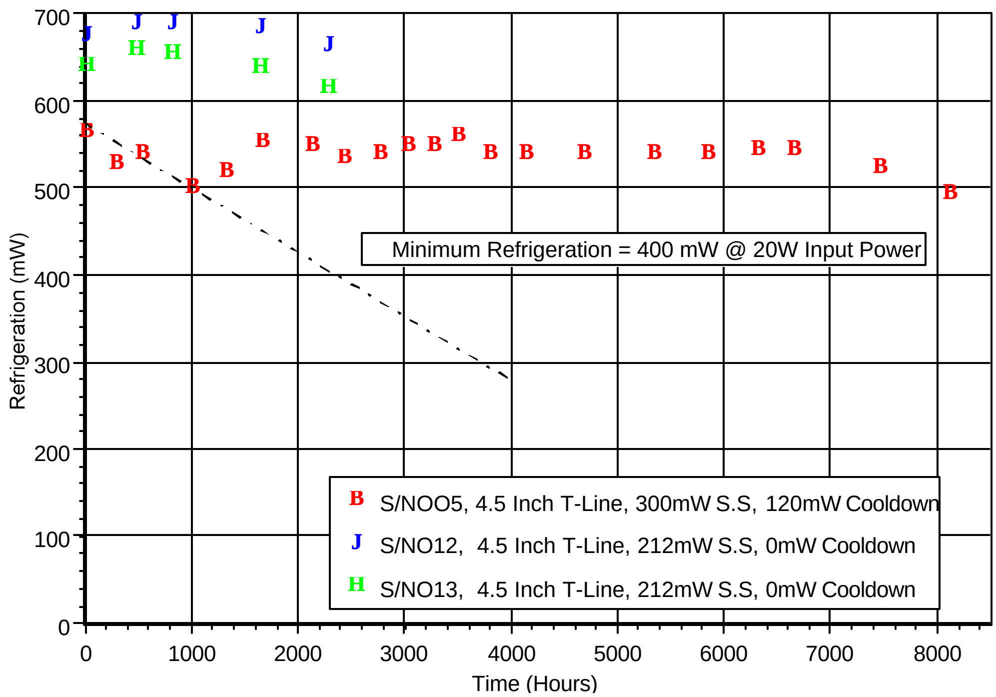

Figure 7. Refrigeration vs. life for B512B cooler.

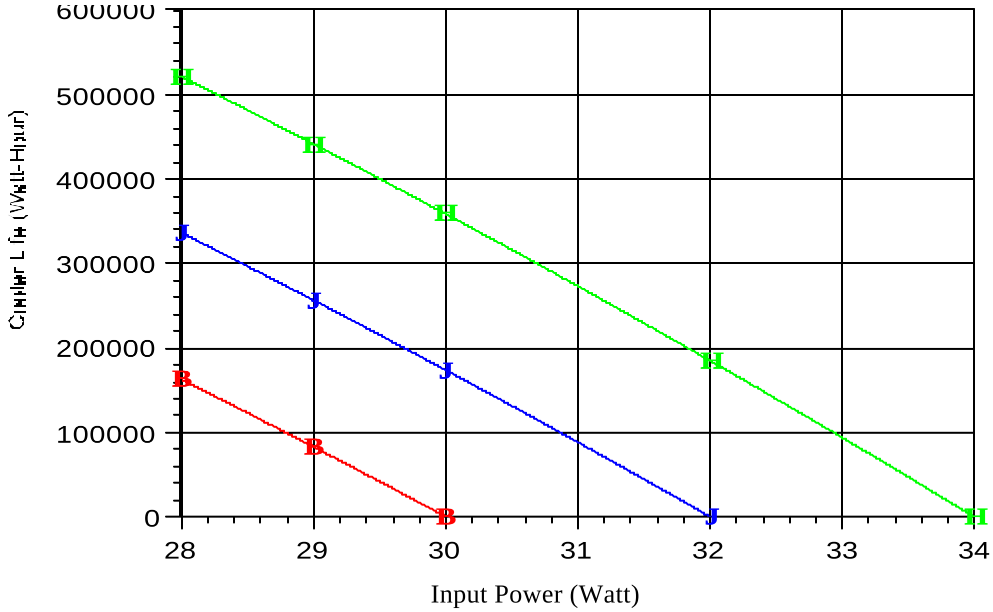

Figure 8. Cooler life curve for BEI's B602C Cooler.

CONCLUSIONS

A watt-hour approach based on integration of the life test data has been suggested to estimate life of cryocoolers. If the life of a cooler under a particular condition is know, the life of the same model of coolers under various conditions can be estimated. Life test data of various models of BEI Cryocoolers have also been presented.

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