Process Model and Capacity Upgrades of The CTI-4000 Liquid Helium Coldbox

Benjamin Hansen[a], Hans Quack[b] and Arkadiy Klebaner[a]

[a]*Fermilab, P.O. Box 500, Batavia, IL 60510 U.S.A.*
[b]*Technische Universitaet Dresden, Dresden, Germany*

Abstract. Fermi National Accelerator Laboratory (FNAL) is in the process of re-commissioning a vintage CTI-4000 liquid helium coldbox, initially supplied by CTI-Cryogenics/Sulzer to Los Alamos in 1979. The coldbox was originally designed as a liquid helium refrigerator with capacity of ~1200 W at nominal 4-K. The process utilized LN_2 precooling, in-series operation of two centrifugal gas bearing turboexpanders and final Joule-Thomson (J-T) expansion. At FNAL, the coldbox will be utilized as a liquefier to support 2-K operations. A process model was developed to aid in the upgrade decisions and used to determine the nominal capacity of the liquefier. Capacity upgrades are achieved by safely utilizing the internal LN2 precooler, the addition of a 3-inch reciprocating wet expansion engine and increasing the overall process pressure by recertifying two limiting pressure vessels to a higher MAWP.

Keywords: Helium, Liquefier, Refrigerator, Coldbox, Wet Engine, Model

INTRODUCTION

The CTI-4000 helium refrigerator was designed and built by CTI/Sulzer for the Los Alamos, Bonneville Power Authority Peak Shaving Project in the mid 1970s. This plant was the first CTI/Sulzer plant utilizing Sulzer gas bearing turbines. Linde Kryotechnik in Pfungen is the successor of the Sulzer/CTI activities and the owner of the original CTI-4000 documentation. The cold box was extensively and successfully operated over the course of 25 years in various mixed modes by Los Alamos and SLAC National Accelerator Laboratories [1-2]. Fermilab acquired the cold box from SLAC in 2011 and is now in the process of re-commissioning it as a helium liquefier. The cold box will be used to help meet the nominal 2-K cryogenic demands of the future Cryomodule Test Facility (CMTF) and/or the Advanced Superconducting Test Accelerator at the New Muon Lab (NML).

The original T-S diagram provided in the CTI-Cryogenics Operator's Manual is redrawn in FIGURE 1b and with a simplified schematic in FIGURE 1a. The refrigerator was originally designed for a flow rate of 140 g/s, a process pressure of 14 bara, and a capacity of ~1200 W at nominal 4-K. The process utilizes 20 g/s of LN2 precooling, the in-series operation of two centrifugal gas bearing turboexpanders and J-T expansion into the two-phase region. A set of parallel adsorber beds are located at suitable temperature levels for the removal of any residual air and neon. At Fermilab, three parallel Mycom screw compressors will be dedicated to the CTI-4000. Each compressor has a nominal output of 60 g/s and can provide a discharge pressure of up to 325 psig. The process flow and pressure is regulated by a dedicated inventory control system and storage tank farm.

INCREASING CAPACITY

As part of the re-commissioning process, various upgrades were identified and analyzed including methods to increase the overall liquefier capacity. Three identified capacity upgrades that have been pursued are:

1. Reutilize liquid nitrogen precooling and increase flow rate as needed
2. Increase the helium process pressure
3. Replace the Joule-Thomson (J-T) expansion into the two-phase region with a more efficient reciprocating expander (wet engine, WE)

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

Utilizing Nitrogen Precooling

The coldbox was reconfigured by SLAC in 2004 to utilize 80 K helium instead of nitrogen in HX1-2 [2]. Historically, these plate-fin heat exchangers have been known to crack and develop nitrogen to helium leaks. The potential failure modes include:

1. A plant/system upset where the nitrogen is frozen by a sudden quench or return of excess cold helium. The mechanical failure then occurs from thermal contraction or sudden flashing and pressure spikes produced upon warm-up.
2. Introducing liquid nitrogen into a warm heat exchanger and the rapid localized cooling and/or pressure spikes when the liquid flashes may cause mechanical failure.

SLAC's work-around introduced a separate helium loop that is cooled externally to ~80 K by a nitrogen bath and then fed into the nitrogen side of HX1-2. It was successful in preventing further heat exchanger failures but is an undesirable solution from an efficiency and nitrogen consumption standpoint. In order to get the maximum refrigeration capacity and reduce nitrogen consumption, controls and hardwire interlocks were developed to safely use liquid nitrogen in HX1-2 as initially intended.

To avoid the first failure mode, the cold helium inlet temperature to HX1-2 will be monitored by hardwired interlocks that activate a bypass system (open VBY, open V46 and close V42) if the temperature approaches the freezing point of nitrogen. For this solution, unused bayonet ports BC-2 and BC-5 were shorted with an insulated U-tube jumper and the existing internal bypass line is utilized. It should also be noted that the CTI-4000 will be primarily used as a liquefier and for cooling low SRF cavities with relatively low stored energy, so the risk of quench and sudden rush of cold helium return gas is small.

To avoid the second failure mode, the plant will undergo a controlled cooldown while maintaining the temperature difference between the HX1-2 cold end streams in the range of 30-50 K. Only the turbines will provide cooling during the first stage. Liquid nitrogen will only be introduced after the temperature of HX1-2 is below 120 K to avoid sudden flashing. The plant will operate for extended periods of time without a shutdown, so the extra time needed to cooldown safely is not an issue. Furthermore, the addition of a wet expander will help cooldown the J-T heat exchanger (HX7) and help save time during the final stage of cooldown.

Increasing Process Pressure

Upon investigating the pressure vessels within the CTI-4000 it was discovered that the MAWP of each heat exchanger was 300 psia, whereas the nitrogen adsorbers (E3 and E4) had an MAWP of 280 psia and therefore dictated the upper limit for normal operating pressure. The adsorber's construction and u-stamped pressure rating was completed in 1975. Since that time, the applicable ASME code has been updated several times. The updated code now allows for maximum allowable stresses based on a factor of 3.5 instead of the older version that used 4.0 [3]. Therefore, by applying the new code the vessels could be rated to a higher MAWP. The adsorbers were subsequently removed from the system and sent out to Ability Cryogenics where they were recertified and stamped to the higher 300 psia MAWP.

Adding a Wet Engine

The original process utilizes the isenthalpic J-T expansion into the 2-phase region. It has been shown previously that replacing the J-T expansion with a reciprocating expansion engine can significantly increase the overall capacity [4]. The reciprocating wet engines (WE) are now readily available from the decommissioned Tevetron Satellite refrigerators. In our case, the addition of a WE is a relatively straight forward upgrade because FNAL has extensive experience in the operation of FNAL-modified Koch Model 1400 wet engines [5]. The addition of a WE required the installation of two new bayonets on each side of the J-T valve. This gives the flexibility of operating the coldbox in J-T or WE modes individually or in a mixed mode. The typical isentropic efficiency of these wet engines is ~75%. At the maximum allowable engine speed the mass flow is ~95 g/s for the 3" piston size. If further capacity is desired the J-T valve could be opened in series.

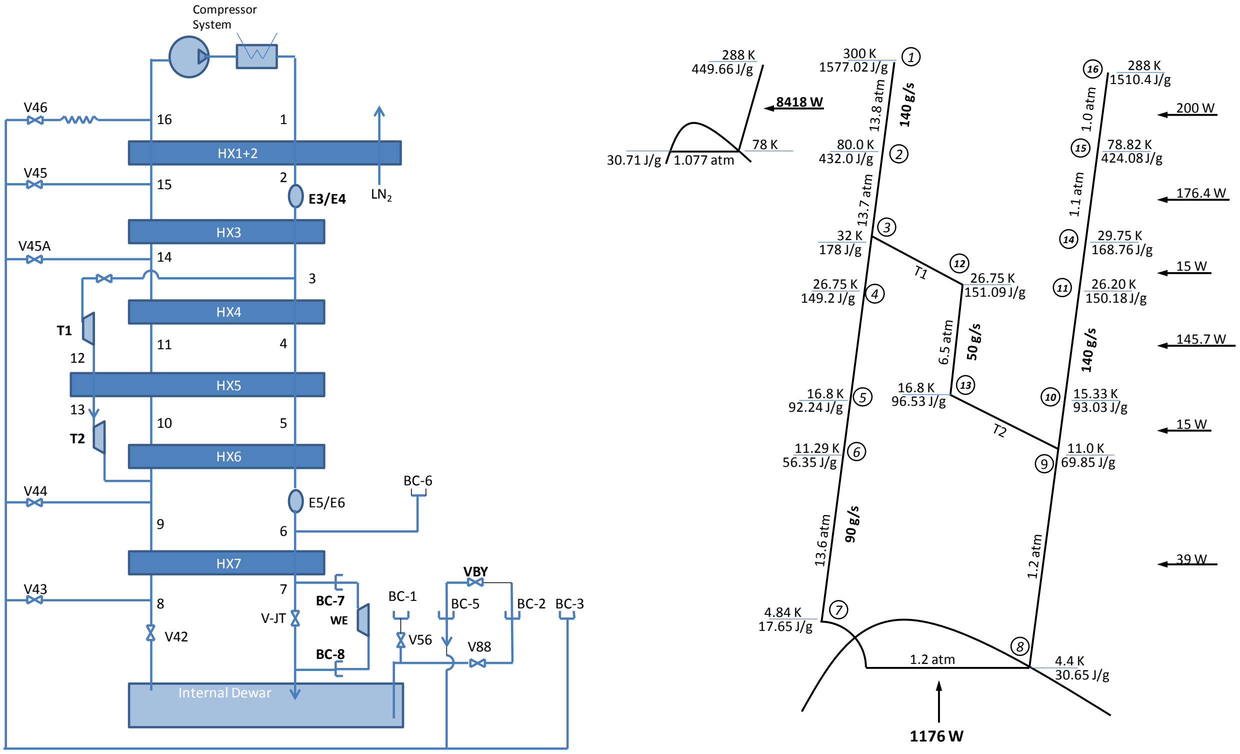

FIGURE 1. (a) Simplified schematic of CTI-4000 coldbox and (b) Original T-S diagram provided with user manual

PROCESS MODEL

A process model was developed to help determine the approximate liquefier capacity of the CTI-4000 after the upgrades of adding a WE and increasing the process pressure. Since very little documentation is available on the detailed design and actual performance of the CTI-4000, the original T-S diagram was used to extract some critical parameters needed to complete a basic process analysis [6]. From the diagram, heat exchanger sizes (Number of Thermal Units, NTU), turbine efficiencies and the turbine size parameters were calculated. The model was then developed by performing a 1st law analysis of the heat exchangers, applying the turbine efficiencies and maintaining an overall mass balance. HX1-2 was broken into its two heat exchangers, one for the nitrogen evaporator and the other for extracting the sensible heat of the vapor, as shown in FIGURE 4. HX5 was also broken up into two separate heat exchangers, one that cools the intermediate turbine flow and the other that cools the HP helium stream.

For each set of different boundary conditions (i.e. process pressure, liquefaction instead of refrigeration, J-T or WE expansion, etc) the following were kept constant: HX NTUs, the turbine size parameters, turbine and WE isentropic efficiencies, heat exchanger static heat leaks and temperature boundary conditions. The pressure drop across components were estimated from the original T-S diagram and kept constant for each analysis. The temperature boundary conditions used for each analysis include: 300 K supply, 80 K HP helium out of HX1-2 and saturated helium temperature at 1.2 bara at the dewar inlet and outlet. The system of equations is written and iteratively solved using Engineering Equation Solver (EES) and a set of reasonable guess values [7]. The helium fluid properties are obtained at each node using HePaK [8]. A diagram window was created within EES to conveniently display the model results on a simplified flow schematic and T-S diagram (See FIGURES 2 and 3).

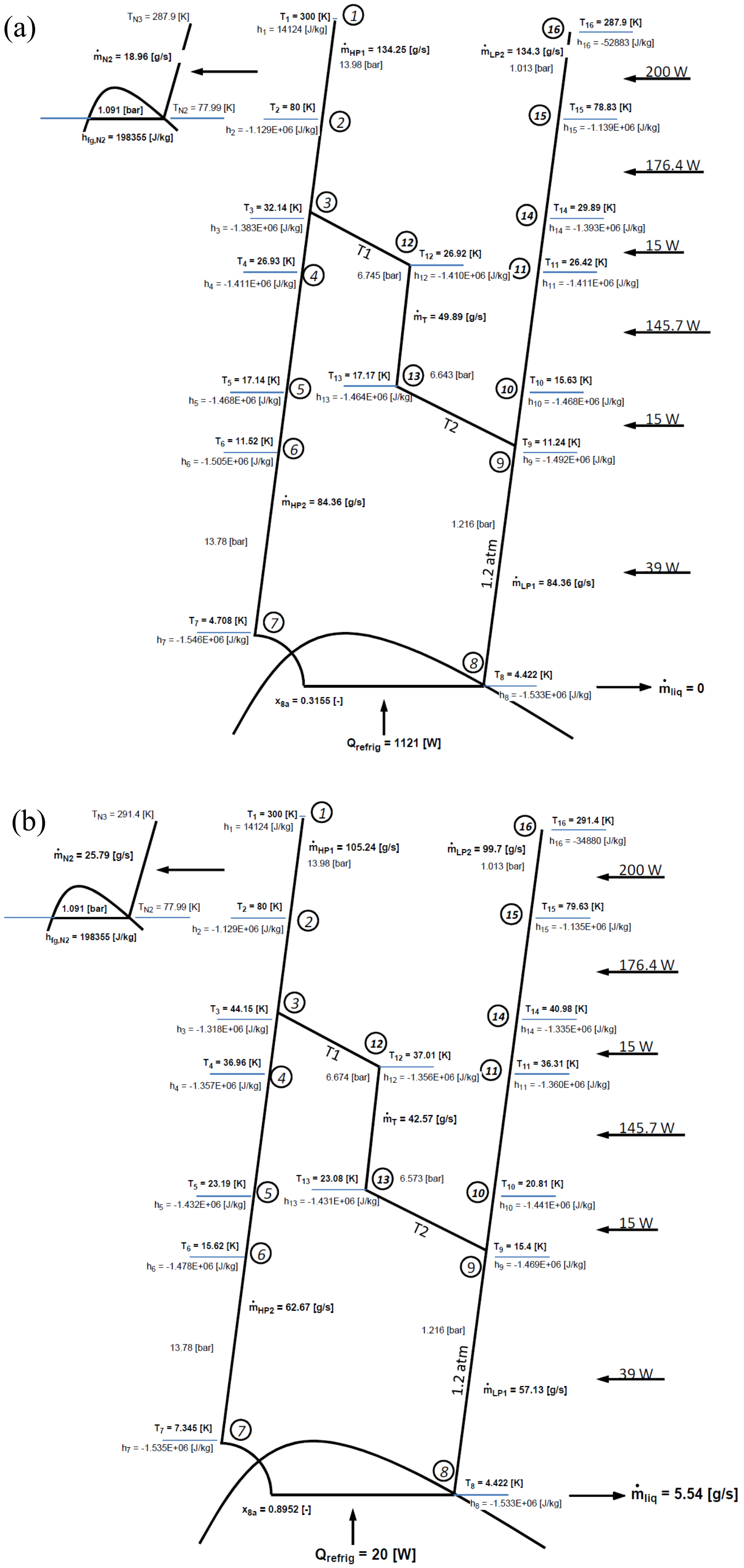

FIGURE 2. Model output for JT-Mode in (a) Refrigeration and (b) Liquefaction at 14 bara

RESULTS

The model was first verified by using the same boundary conditions as the original process diagram, see FIGURE 2a. The small difference between the original process diagram (Fig. 1b) and the model result (Fig. 2a) is due to the updated helium properties when using HEPAK with EES. The heat load to the dewar was specified to 20 W to account for the approximate static heat load. The J-T liquefier results for the original process conditions are presented in FIGURE 2b , with the most important result being a liquefier rate of ~5.5 g/s. Figure 3 shows the model results for the WE mode at original process conditions. The addition of a WE increased the liquefier capacity from 5.5 g/s to 8.57 g/s, representing an increase in capacity of ~50%.

The model was then run consecutively for various refrigeration loads to obtain the liquefaction curves for J-T mode and WE mode at the original process pressure (14 bara), and WE mode at an elevated process pressure (18 bara). The results are presented in FIGURE 4a-b. The change in slope of the liquefaction curve is a result of a temperature pinch occurring at the cold end of HX6. As the amount of liquefaction is increased, the temperature pinch at HX6 outlet continues to narrow until it reaches ~0.2 K. At this point the temperature pinch is fixed and the original NTU constraint for HX6 is removed and allowed to float (see FIGURE 4b). Detailed heat exchanger analysis and modeling are required to more accurately define the temperature pinch and heat exchanger performance.

Our model indicates the addition of a WE with 75% efficiency will increase the refrigeration and liquefier capacities by ~50%. By increasing the process pressure from 14 bar to 18 bar in WE mode, the liquefaction capacity increased by an additional 37% to ~11.75 g/s. Overall, we predict that the liquefier capacity will double by adding a WE and increasing the process pressure.

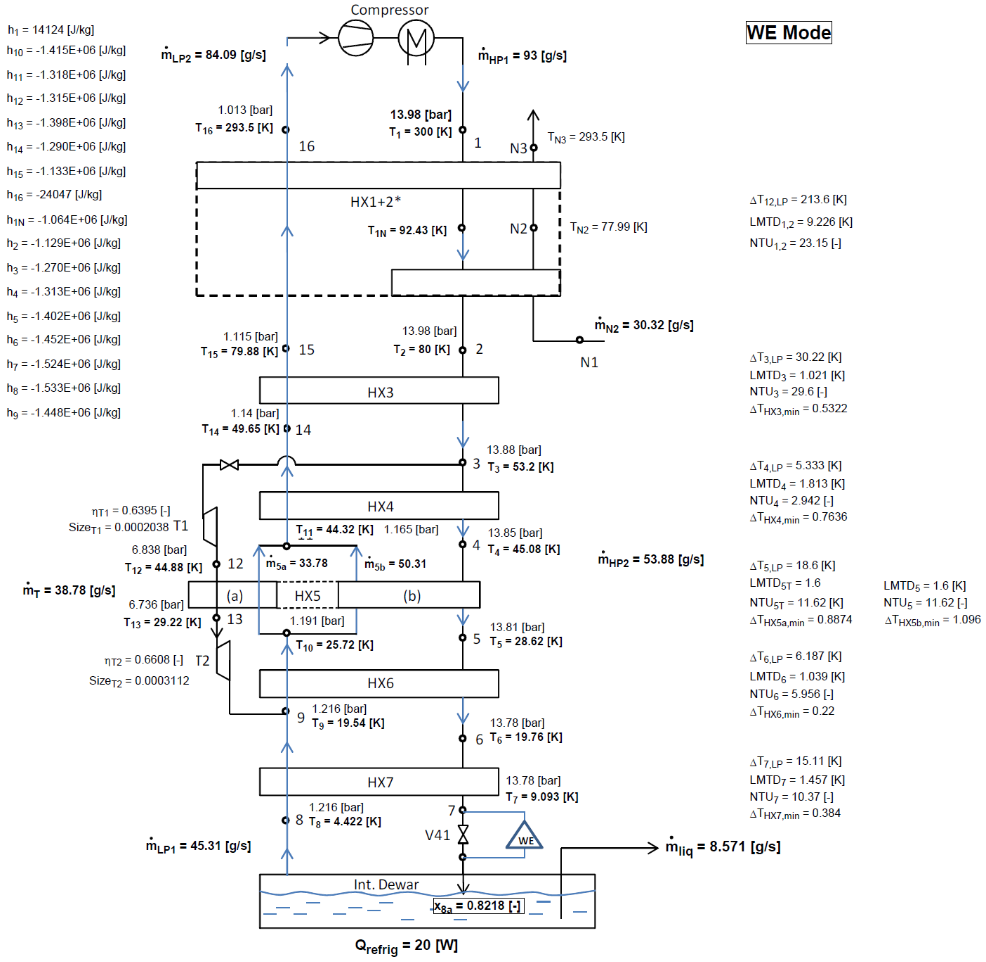

FIGURE 3. Model output for WE mode in graphical form

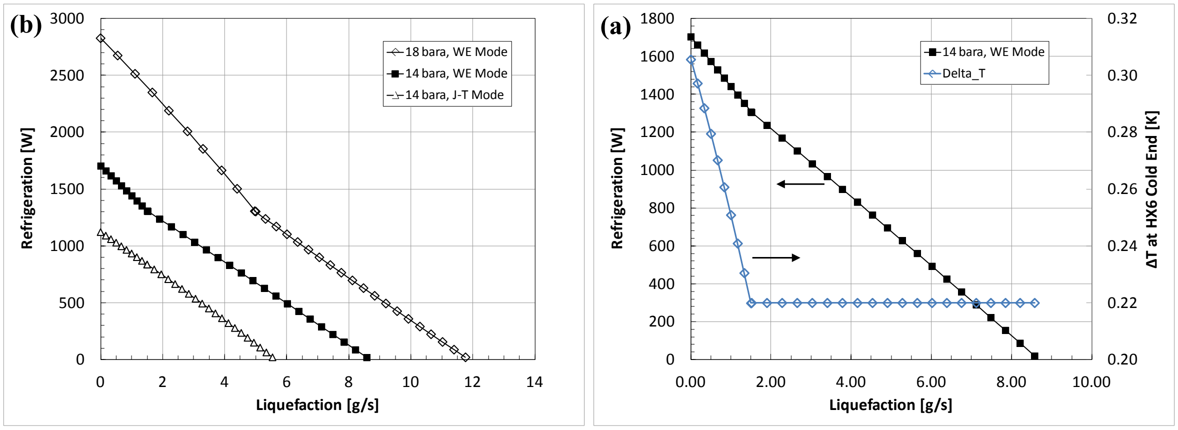

FIGURE 4. (a) Liquefaction curves calculated for various modes and process pressures. (b) Temperature pinch point at HX6 outlet versus liquefaction.

CONCLUSION

The CTI-4000 re-commissioning is currently underway. Capacity upgrades include reutilizing the internal nitrogen precooling safely, increasing process pressure by recertifying two limiting pressure vessels to a higher MAWP, and adding a 3-inch reciprocating wet engine to the final expansion into the two-phase region. The process was modeled in EES by performing a first law analysis with mass balance and taking key parameters from the original T-S diagram. The model predicts the liquifier capacity could more than double with the upgrades, where the capacity increased from 5.5 g/s in J-T mode at 14bara to ~11.75 g/s in WE mode at 18 bara.

ACKNOWLEDGMENTS

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

REFERENCES

1. J. G. Weisend II, R. Boyce, W. Burgess, A. Candia, R. Carr, J. Gao, K. Gustafsson, C. Jones, G. Oxoby, H. Quack, A. Scott and T. Weber, "The Cryogenic System for the SLAC E-158 Experiment" in *Advances in Cryogenic Engineering*, edited by S. Breon et al., AIP Conference Proceedings 613, American Institute of Physics, Melville, NY, 2001, **47A**, pp. 170-179
2. T. B. Weber, A. Candia, G. Howell, M. Racine, and J. G. Weisend II, "Unique Method for Liquid Nitrogen Precooling of a Plate Fin Heat Exchanger in a Helium Refrigeration Cycle" in *Proceedings of 20th International Cryogenic Engineering Conference*, edited by L. Zhang and G. Chen, 2005, pp. 67-70.
3. 2010 ASME BPVC Section VIII Div. 1
4. V. Ganni, R. Moor, P. Winn, "Capacity Upgrade of the Exell Helium Liquefier Plant by the Addition of a Wet Engine" in *Advances in Cryogenic Engineering*, edited by R. W. Fast et al., AIP Conference Proceedings, 1986, **31**, pp. 699-707.
5. T. J. Peterson, "Fermilab's Satellite Refrigerator Expansion Engines" in *Advances in Cryogenic Engineering*, edited by R. W. Fast et al, AIP Conference Proceedings, 1984, **29**, pp. 443-451.
6. *CTI-Cryogenics Operator's Manual* for Model 4000 Helium Refrigerator, Oct. 1976.
7. *Engineering Equation Solver (EES) v8.238, F-Chart Software, 10/8/2008, www.fChart.com*
8. HEPAK, v. 3.4, Horizon Technologies, March 2005, http://www.users.qwest.net/~varp/cryocomp.htm.