



Fermi National Accelerator Laboratory

FERMILAB-Conf-81/68
1650.000

SIMULATION OF THE ENERGY SAVER REFRIGERATION SYSTEM*

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October 1981

*Submitted to the 1981 Cryogenics Engineering Conference,
San Diego, California, August 10-14, 1981

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INTRODUCTION

The helium refrigeration for the Energy Saver is supplied by a Central Helium Liquefier and 24 Satellite Refrigerators installed over a 1-1/4 square mile area.¹ An interactive, software simulator has been developed to calculate the refrigeration available from the cryogenic system over a wide range of operating conditions. The refrigeration system simulator incorporates models of the components which have been developed to quantitatively describe changes in system performance. The simulator output is presented in a real-time display which has been used to search for the optimal operating conditions of the Satellite-Central system, to examine the effect of an extended range of operating parameters and to identify equipment modifications which would improve the system performance.

THE METHOD FOR SIMULATION CALCULATIONS

A cryogenic refrigerator consists of a set of counter-flow heat exchangers, each of which must conserve energy. For a refrigerator containing N heat exchangers, there are N simultaneous equations representing conservation of energy. Since these equations are linear in enthalpy, it is natural to solve the problem by calculating the enthalpy (not the temperature) at each of the process points. This choice of variables avoids any difficulties due to the variation of specific heat with temperature.

The number of process points is $2N$, so N additional equations

are required. The N additional equations are obtained by requiring that the overall heat transfer coefficient times area, UA , of each of the N heat exchangers have the correct value. This means performing N integrations to solve the first-order differential equation for heat transfer for each of the heat exchangers.

In doing the analysis of the refrigerator, the correct UA values are obtained by successively correcting the choice of enthalpies at N process points and performing trial integrations for each of the heat exchangers until the desired UA values are obtained. At each step of this iterative procedure, a matrix of partial derivatives $\partial(UA)_j/\partial H_i$ is calculated by the finite difference method while satisfying the N energy equations. If $\delta(UA)_j$ is the desired adjustment in the UA value for heat exchanger number j , then the first order adjustments are

$$\delta(UA)_j = \sum_i \frac{\partial(UA)_j}{\partial H_i} \delta H_i$$

In order to extract the enthalpy corrections δH_i , the $N \times N$ matrix of partial derivatives is inverted and multiplied times $\delta(UA)_j$. Since the energy conservation equations are used at each iteration, the energy constraints are always satisfied.

A modification of this procedure is required if the capacity rate (specific heat times mass flow) of the minimum stream is so small that the counter-flowing streams approach the same temperature. In this case, the full size of the heat exchanger cannot be utilized.

The helium flow to an expander in the cycle comes from one of the process points mentioned above. The efficiency of the expander is defined as the actual enthalpy decrease produced by the expander divided by the enthalpy decrease which would result from an isentropic expansion of helium at the inlet conditions. The enthalpy at the exit of the expander is calculated by using the specified expander efficiency and pressure ratio. In cycles where the helium discharged from the expander is mixed with another helium stream, the enthalpy of the mixture is calculated using a linear mixing formula. This procedure is used at each iteration of the simulation so that the effect of the expanders is always accurately modeled.

COMPUTER SIMULATION PROGRAMS

Simulation programs have been written for the Central Liquefier and the Satellite Refrigerator. The output of the simulator is displayed on the screen of a graphics terminal. The operator of the simulator enters input at the keyboard of this terminal. A sample of this simulator display is shown in Figure 1. This display was designed to include a flow diagram with numbered process points.

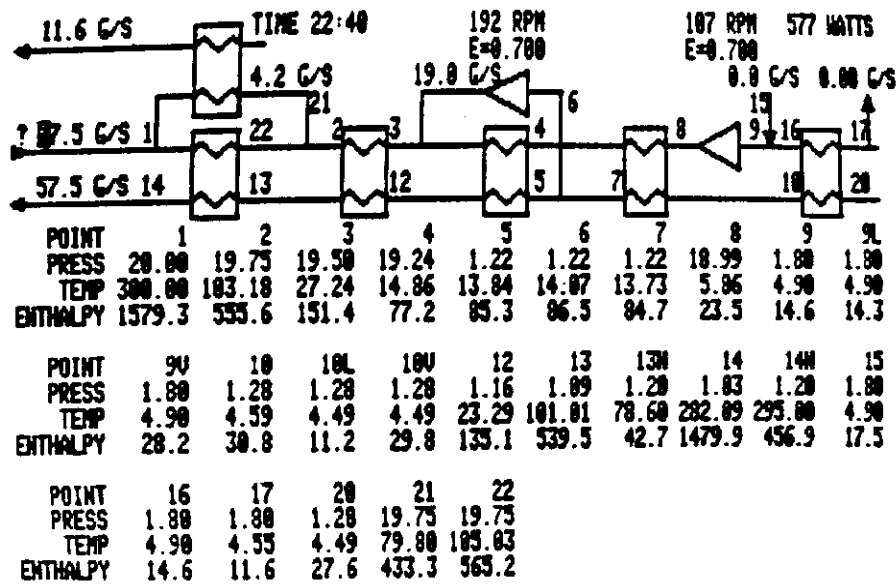


Figure 1. Sample simulator display for the Satellite Refrigerator.

Pressure, temperature and enthalpy for the process points are displayed. The flow at each process point is determined by the operator, who types numbers directly on the display of the flow diagram.

Since the UA values depend on flow, the simulator calculates the effective UA values for the heat exchangers; for finned tubing heat exchangers in the Satellite, $UA \sim f^{0.8}$. Approximately five iterations on the heat balance are required to get acceptable UA values. This takes several seconds on the Cyber 175 computer and the resulting operating conditions are displayed on the operator's terminal immediately afterward.

A COMPARISON WITH CENTRAL LIQUEFIER DATA

The simulation model contains the equations which are fundamental requirements for any thermodynamic system. During testing of the Central Liquefier in April 1981, considerable data were accumulated which could be used as an experimental check of the model. A chi-squared analysis of 25 sets of process data consisting of simultaneous measurements recorded from 16 process points in the Liquefier was used to establish the accuracy of the simulation equations. The data for this analysis were taken while the plant was liquefying 1200 l/hr of helium without nitrogen precooling.

The flow diagram for the Central Liquefier shown in Figure 2 is a sample of the simulator output. The values shown are for full-capacity operation of the Liquefier. The heat exchangers for the

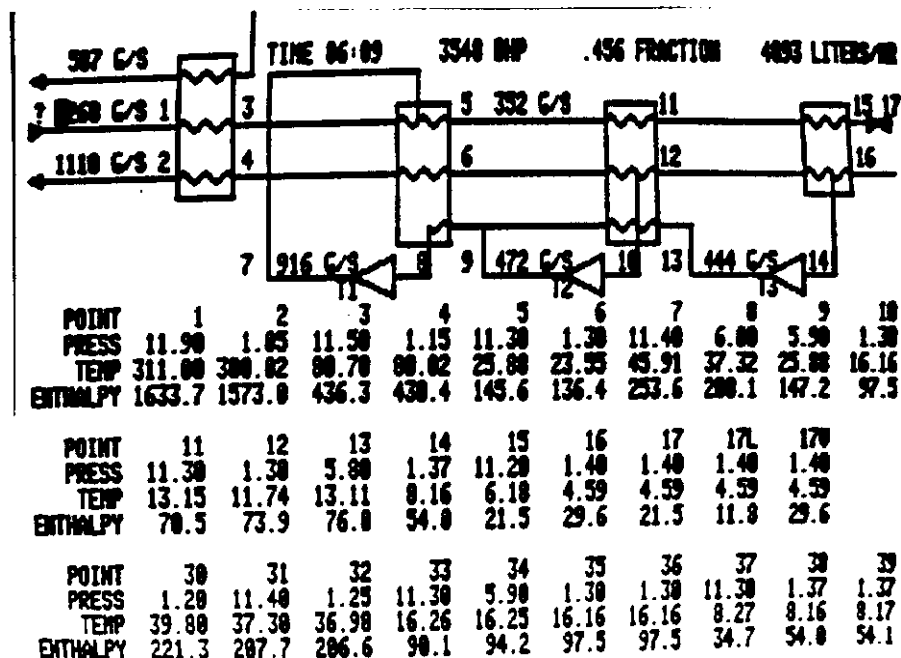


Figure 2. Sample simulator display for the Central Liquefier.

Central Liquefier are grouped into four modules and are of aluminum, finned-plate construction.² Because the process instrumentation is installed externally to these four modules, not all process points are measured. The measurements taken do exceed the minimum number required so that a seven constraint fit to the data is possible. A fit is necessary because the raw data do not conserve energy or helium due to small experimental errors in the measurements. The flow measurements are made with venturis and have an accuracy of $\pm 4\%$ of the compressor discharge flow. The enthalpy measurements were made using strain gauge, pressure transducers and silicon diode temperature transducers so that the enthalpy has an accuracy of $\pm 2\text{J/g}$. With these measurement uncertainties, the data satisfy the seven constraint equations with chi-squared values of 7.0 or lower in all but several instances. The enthalpy measurements at 16 process points and the flow data at 6 points are used in the least-squares fit to the model.

This work verifies that the equations used in the simulator are an accurate description of the Liquefier. Additional data taken while operating over a wide range of compressor flows will be needed to verify the scaling dependence of heat exchanger UA on flow.

The Central Liquefier is supplied with 12 atm helium by two reciprocating compressors with 600 g/s capacity each and by the screw

compressors of the Satellites. If the flow to the plant is increased 40% above its design value of 1268 g/s by using additional compressors, the capacity of the plant could be increased 37% with the present heat exchangers. The simulator has been used to study this upgrade of the Central Liquefier. Three replacement turboexpanders would be required to handle 1282, 660 and 622 g/s of helium flow. If these expanders have efficiencies of 82.5, 82 and 81%, they would operate with exit temperatures of 37.7, 16.4 and 8.2K.

RESULTS FOR THE SATELLITE REFRIGERATOR

During normal accelerator running, the Satellite Refrigerator will be operated without nitrogen precooling and with the higher-temperature expander off. In this mode the heat exchangers of the Satellite Refrigerator are unbalanced by liquid helium flow obtained from the Central Liquefier. If f is the high pressure flow and F is the low pressure flow, the flow imbalance of the Satellite heat exchangers is $\beta = 1 - f/F$. At a flow of 40 g/s, the total available UA of a Satellite is 14,000 W/K. The high pressure stream is expanded from 20 atm to 1.8 atm using the wet engine of the Satellite.

Figure 3 shows the calculated refrigeration available at the magnets using the simulator model for the Satellite Refrigerator. Lines labeled with values of β represent proportional changes in flow. The curvature of these lines is due to the decrease in effectiveness of the heat exchangers as flow is increased.

Operation of the Satellite Refrigerator at the lowest mass flow results in the lowest two-phase temperature at the magnets. The shell-side pressure drop in the model is proportional to $F^{1.8}$. Figure 3 shows dashed isotherms; E-F is 4.4K, G-H is 4.5K and I-J is 4.6K.

There are operating modes when the Satellite Refrigerator must function as a helium liquefier. The model has been used to calculate the reduction in refrigeration which occurs when liquefaction is provided. This effect is shown in Figure 4. During normal, steady-state operation, each Satellite Refrigerator must supply 0.7 g/s of liquid helium on the average to cool the magnet power leads. During cooldown of Energy Saver magnets and quench recovery, the liquefaction requirements are greater. Non-zero liquefaction increases the demand for helium from the Central Liquefier.

SOME APPLICATIONS OF SIMULATION

The simulator can be used to quantitatively study abnormal operating modes of a system of cryogenic hardware and is a powerful tool for predicting the refrigeration margin available from the system when components are operating with reduced performance.

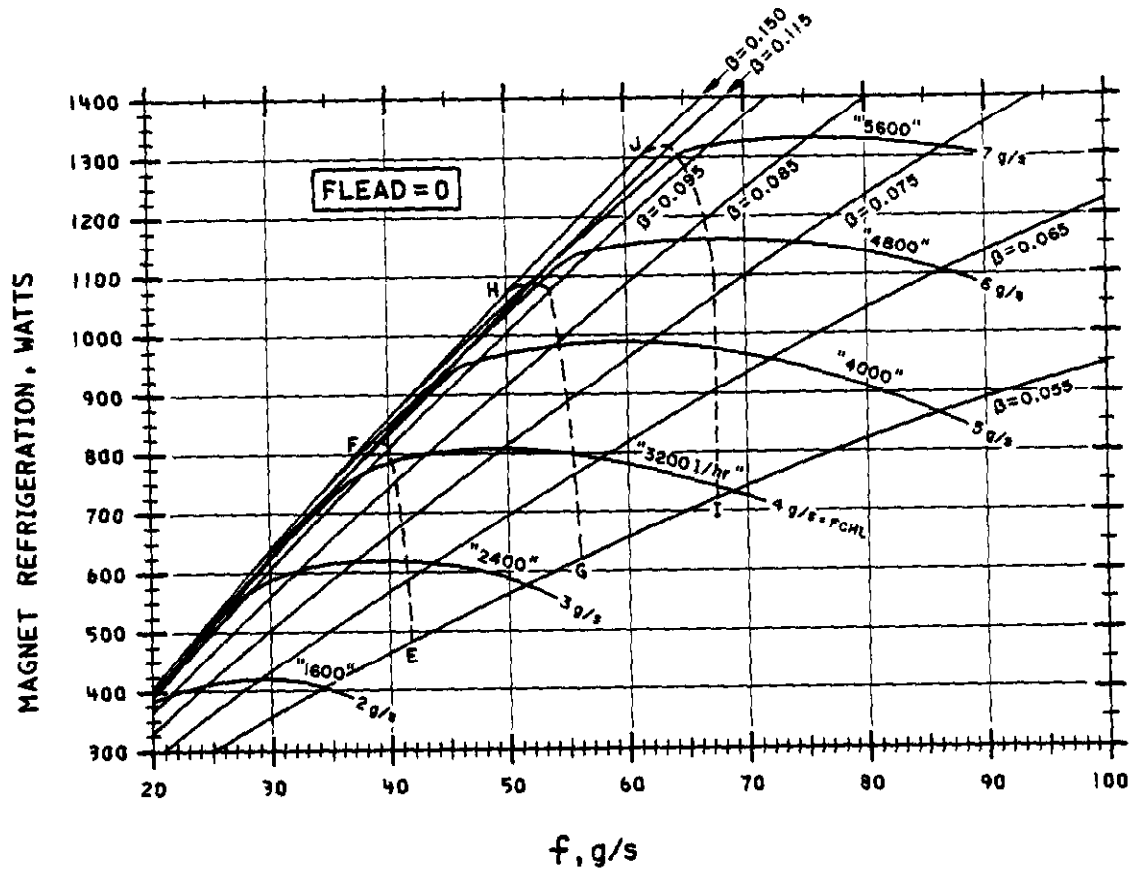


Figure 3. Refrigeration provided by the Satellite Refrigerator as a function of compressor and Central Liquefier flows.

The simulator has been used to make design decisions which will boost the cryogenic performance of the refrigeration system. The output of the simulator serves as a guide to the operator of the cryogenic system. Changes in the operating mode can be tested on the simulator beforehand to determine the magnitude of the effects the operator of the cryogenic system will encounter.

More precise detection of out-of-limits transducer readings is possible when the data are tested against comparable simulation output rather than the minimum and maximum operating extremes. Because the transducers in a cryogenic system supply information redundant to the minimum set required by the simulator, the reading from a failed transducer can be replaced by a number which has been calculated by the simulator.

The simulator can be incorporated in the control system of the cryogenic system. This will allow the controls to anticipate

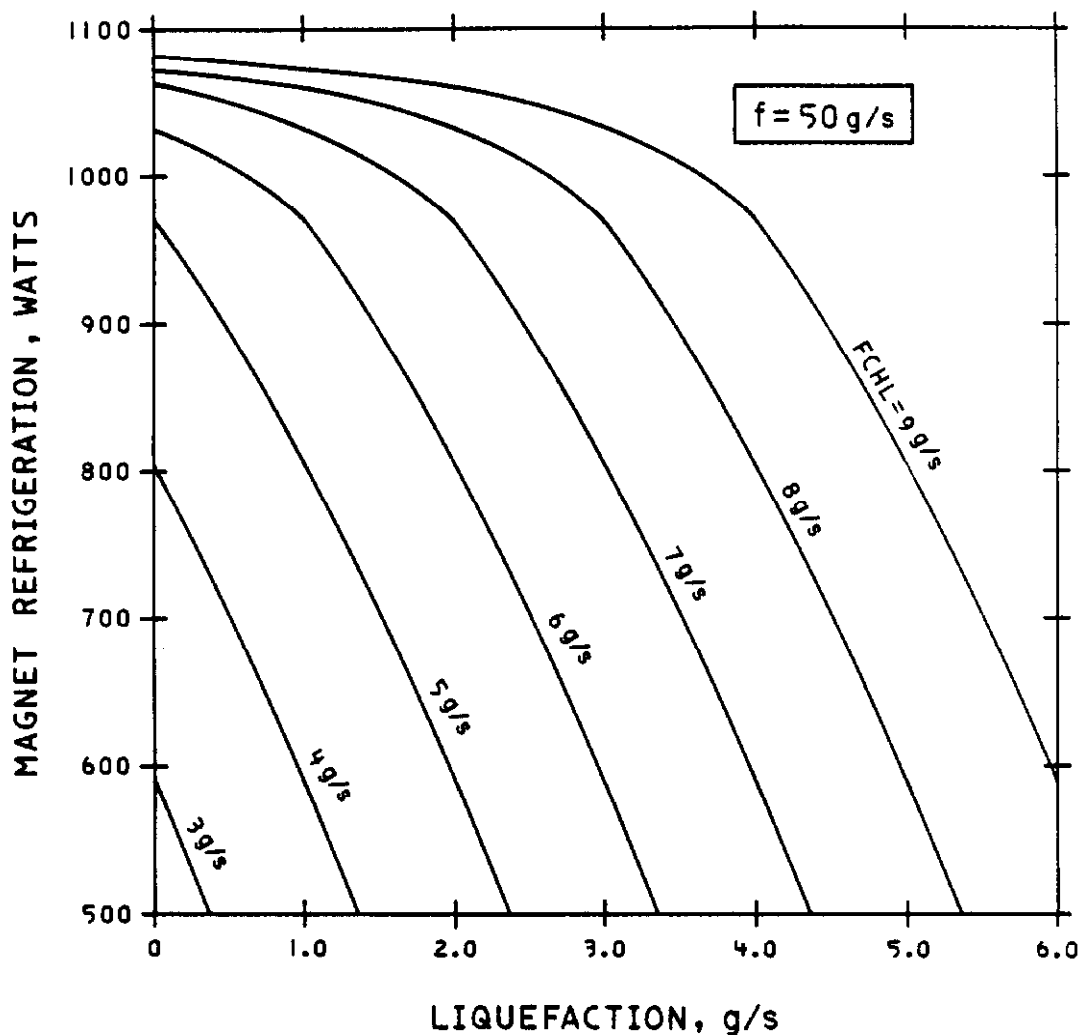


Figure 4. Effect on magnet refrigeration when liquefaction is required.

effects on the system before they become measurable upsets in the process. A feedforward control system requires a model of the process in order to predict the behavior of the cryogenic system. Since the time response of cryogenic systems is very slow, this type of model-driven control system would improve stability of operation.

ACKNOWLEDGEMENTS

The simulators use subroutines written at the Cryogenics Division of the National Bureau of Standards to calculate helium properties, and several subroutines obtained from Brookhaven National Laboratory.³

REFERENCES

1. P.C.VanderArend, Helium Refrigeration System for Fermilab Energy Doubler, in: "Advances in Cryogenic Engineering," Vol. 23, K.D.Timmerhaus, ed., Plenum Press, New York, 420-430 (1977).
2. W.M.Toscano and F.J.Kudirka, Thermodynamic and Mechanical Design of the FNAL Central Helium Liquefier, in: "Advances in Cryogenic Engineering," Vol. 23, K.D.Timmerhaus, ed., Plenum Press, New York, 456-466 (1977).
3. R.King, Determination of the Performance and Cost of the Model 4000 Helium Liquefier, ISABELLE Division Technical Note No. 19, July 23, 1976.