SIMULATING THE TEVATRON LIQUID HELIUM
SATELLITE REFRIGERATORS

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ABSTRACT

A computer program to simulate the Fermilab Tevatron liquid helium satellite refrigeration system has been developed. The simulator program takes advantage of the Macintosh platform upon which it was developed to produce a unique, easy to use Macintosh interface to facilitate ease of cycle design and modification. The user can drag icons representing refrigerator components around on the screen and piece them together to form a variety of liquid helium refrigeration cycle configurations. Extensive use of the icons, windows, and pull–down menus of the Macintosh interface allows the user to easily alter refrigeration component configurations and parameters. Calculation accuracy is retained by using existing helium property subroutines and component models. The user interface, program output, and code details are described. Sample configurations and results are presented.

INTRODUCTION

A computer program to simulate the Fermilab Tevatron liquid helium satellite refrigeration system has been developed. This simulator was intended for the study of a variety of design configurations and operating conditions for the planned low temperature upgrade to our system. The upgrade involves the addition of a cold compressor to the existing liquid helium refrigerator cycle to lower the temperature of the accelerator magnets and allow for higher beam energy.[1,2] The simulator program takes advantage of a unique, easy to use Macintosh interface while retaining the calculation accuracy obtained from existing helium property subroutines and component models.

Earlier work was done to simulate the original Tevatron cryogenic system over a very limited operating range.[3] This new software not only allows the upgraded system to be modeled but also offers other major improvements. Two notable areas of improvement are the heat exchanger model and the ease with which the user can design and modify the system to be simulated. Also, the new version allows for nitrogen precooling and operation of an intermediate temperature expansion engine in the heat exchanger column.

The user first specifies the physical cycle configuration and the details of how each component will operate. Then, each state point for the steady state case may be completely solved for in terms of temperature, pressure, enthalpy, entropy, exergy, percent liquid (for two phase conditions), and mass flow rate. The program obtains the

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Table 1. Available components and inputs

Component	Symbol	Inputs
Expander		exhaust pressure, efficiency
Cold Compressor		exhaust pressure, efficiency
Phase Separator Dewar		two–phase liquid bath pressure, cooling tube outlet Δt, dewar heat leak
JT Throttle Valve		exhaust pressure
Heat Exchanger Column		flow imbalance ratio (shell side mass flow / tube side mass flow), tube side pressure & pressure drop, shell side pressure drop, tube inlet temperature, dry engine mass flow, dry engine efficiency, nitrogen exchanger He flow, heat exchanger algorithm
Liquid Helium Adder (from Central He Liquifier)		liquid reservoir pressure & temperature, percentage of total liquid He addition (if more than one)
Magnet String		magnet heat load, power lead mass flow, single-phase pressure drop, two–phase pressure drop

solution by iteratively performing mass and energy balance calculations. Additionally, the user may choose to run a set of related simulations, in which selected inputs are automatically varied over a user-specified range. The values of other variables (selected by the user) for each simulation in the set are then outputted in a tabular fashion.

To accurately handle helium properties throughout the cycle, the simulator program accesses a customized version of the helium properties program, HePak (by Cryodata, Inc.), which is based on work by Arp and McCarty.[4] Also, to ensure simulation accuracy, special attention was given to the heat exchanger component. A rigorous heat exchanger model must be used to accurately account for the property variations experienced in a cryogenic helium heat exchanger. After a comparison of several simulation methods,[5] it was decided to model the heat exchanger by breaking the column up into an appropriate number of log mean temperature difference steps.

The program's interface, as it takes advantage of the Macintosh platform upon which it was developed, is very simple and easy to use. The user can drag icons representing refrigerator components around on the screen and piece them together to form a variety of cycle configurations. Extensive use of the icons, windows, and pull-down menus of the Macintosh interface allows the user to easily alter the component configurations and parameters, facilitating design optimization and cycle performance studies. The new interface certainly offers an improvement over previous versions, which required the user to modify and recompile the source code to make any changes in the cycle configuration. Also, the ordered structure of file/user inputs are avoided, in that the user can alter the value of any parameter at any time, or even specify a sequence of values through which they can automatically be varied.

USER INTERFACE

The code first requires the user to drag icons representing components onto a window, arranging them together into the desired configuration for the satellite helium refrigeration system. See Table 1 for a listing of the components available (which are accessible within the program via a scrolling palette). An example configuration in a document window is shown in Figure 1. Note that the configuration appears as an "open cycle" with high pressure gas provided to refrigerator and low pressure gas returned. A warm compressor with a user defined efficiency is assumed to be operating between these points although it is not displayed.

By "double-clicking" with the mouse on a component's icon, the user may provide general specifications for the operation of that component. In this manner, each component's parameters may be specified. Table 1 shows the variables that may be input

Table 2. Sample Program Output

Point #	T (K)	P (Atm)	h(J/g)	s (J/g/K)	% Liquid	Flow (g/s)	Exergy (J/g)
0	300.0001	20.0000	1579.7383	25.3640	0.0000	38.7184	1872.3258
1	6.5706	19.0000	26.4982	4.1620	0.0000	38.7184	6679.6819
2	5.0434	2.0000	16.7597	4.8173	96.7051	38.7184	6473.3436
3	3.6621	2.0000	8.0911	2.8953	100.0000	38.7184	7041.2779
4	3.5821	2.0000	7.8291	2.8230	100.0000	38.7184	7062.7193
5	3.5821	2.0000	7.8291	2.8230	100.0000	37.7184	7062.7193
6	3.5621	0.5000	7.8291	3.1321	96.5709	37.7184	6969.9736
7	3.5621	0.5000	23.7364	7.5888	27.5835	37.7184	5648.8702
8	3.5621	0.5000	24.0054	7.6642	26.4168	37.7184	5626.5298
9	3.5621	0.5000	14.5438	5.0134	67.4504	6.8078	6412.3183
10	3.5621	0.5000	22.5588	7.2589	32.6906	44.5262	5746.6718
11	3.5621	0.5000	30.0967	9.3708	0.0000	44.5262	5120.6497
12	5.6905	1.2000	40.2583	10.1262	0.0000	44.5262	4904.1962
13	264.8763	1.0500	1391.1382	30.8364	0.0000	44.5262	42.0105

Nitrogen Exchanger Heat Transfer (kW): 0.0000
Est. Warm Compressor Work (kW): 208.9925
Est. CHL Work (kW): 191.6411
Total Est. Input Work (kW): 400.5581

	Exergy Flow (kW)	% of Input Exergy
Useful Refrigeration:	47.2450	11.7948
Useful Lead Cooling:	7.0627	1.7632
CHL Losses:	159.0621	39.7101
CNL Losses:	0.0000	0.0000
Warm Compr. Losses:	125.4724	31.3244
Satellite Losses:	61.7160	15.4075
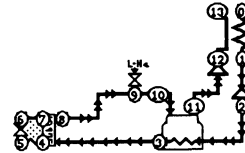
for each component. If no values are entered for a particular component, default settings are used. The general configuration as well as all of the component specifications may be saved and later recalled and modified or printed.

PROGRAM OUTPUT

When an acceptable configuration has been built, the simulation code will calculate each process state point for steady state conditions by performing mass and energy balances. The code assigns each boundary between components a state point number (as well as points within certain components) which can be matched to the tabular output. A second law-exergy analysis is also performed[6]. A sample of the program output is displayed in Table 2. Alternatively, the user can choose to run a sequence of simulations where the values of one or more variables are automatically altered in a user-defined manner. The values of other variables, selected by the user, are
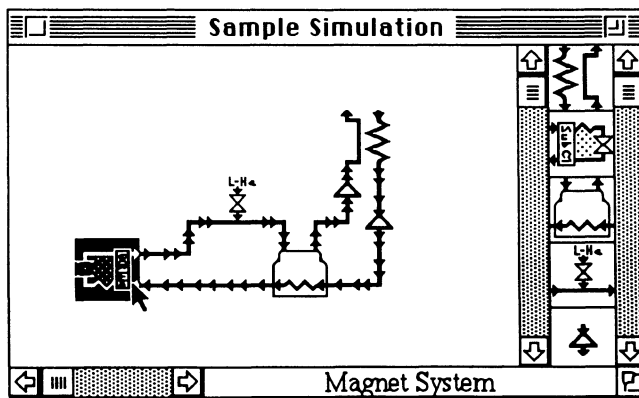

Figure 1. Sample simulation window and configuration

outputted for each run. When solving a simulation cycle, the code repeatedly checks for various error conditions and breaks to inform the user with an appropriate message upon encountering one.

CODE DETAILS

The program, written in Object Pascal, makes extensive use of object-oriented programming, the Macintosh Toolbox, and Symantec's THINK Class Library. The class library provided reusable code modules to aid in handling many complex parts of the program's interface, such as scrollable windows with multiple sub-elements. Also, the OOP paradigm was applied to the problem of describing, modifying, and simulating a general refrigeration cycle. The algorithms could be written, for the most part, in terms of generic, abstract classes that described any possible component. These algorithms were then applied, at run-time, to a variety of subclasses which describe the properties of specific components, such as cold compressors or dewars. In this manner, not only is it possible to simulate a wide variety of configurations, but also the easy extension of the program by the addition or modification of components is facilitated. Since the algorithms are written to apply to any component, to create a new component one must merely define an appropriate subclass which encapsulates the properties specific to that component. The new component will then automatically be managed correctly by all other parts of the program—it will not only be simulated correctly, but in addition it will be seamlessly incorporated into the user interface, allowing it to be positioned and edited just like any other component. Of course, modifications to the actual simulation algorithm itself would require more widespread code changes, but the methods of object-oriented programming serve to minimize the repercussions of any change.

The HePak helium properties code package and also code from previous simulation programs, all written in VAX FORTRAN, were used to perform many of the numerical calculations for the program. In order to properly incorporate the relevant portions of these programs into our simulator, we were required to translate them into Pascal. This was primarily done through the use of a number of macros we wrote for the word processor/editor Nisus (by Nisus Software, Inc.). A few lines of code also required additional translation by hand.

A COMPARISON TO EXPERIMENTAL OBSERVATIONS

Experiments were done to compare simulator predictions with actual refrigerator performance observations. Tests were conducted in one of the satellite refrigerators cooling Tevatron magnets. Temperatures, pressures, and flow rates were measured at various points in the cycle for a variety of cold compressor operating conditions. Observations agreed well with simulator predictions, within measurement uncertainties.

These tests were limited to the cold compressor suction inlet being above atmospheric pressure due to the possibility of contamination in the cryogenic system
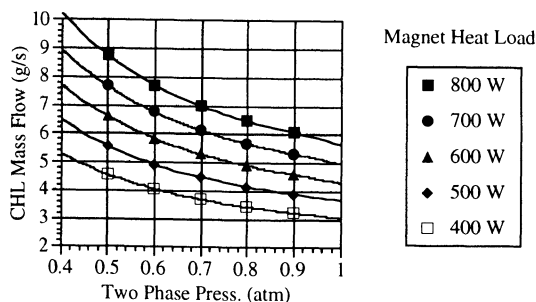

Figure 2. Predicted Central Helium Liquefier Flow Requirements

adversely effecting accelerator operations. However, a case in which the cold compressor was forced to work somewhat hard (by throttling a valve at the heat exchanger low pressure outlet) was studied. In the future, more testing will be done to compare simulator predictions to cases in which sub atmospheric pressures are achieved.

SOME RESULTS

A sample of some results obtained from multiple runs of the program are shown in Figure 2. This plot illustrates the predicted helium flow required from the Central Helium Liquifier (point 9 in Table 2) for various magnet heat loads and sub atmospheric two phase helium pressures. The cycle was chosen to operate with 20% liquid returning from the magnet strings (to provide an adequate quench safety margin). For these results the model assumes that the heat exchanger has no pressure drop, the isentropic efficiencies of the expander and cold compressor are 75% and 60% respectively, CHL flow arrives to the refrigerator at 5K and 3 atm., the dewar aftercools the expander exhaust to 0.1K above the bath temperature, and the cold compressor pumps on saturated vapor. Power leads are taken to need 1 g/s of helium flow. The refrigerator is provided with high pressure helium at 300K and 19 atm. This figure demonstrates the rising demand placed on the CHL plant as magnet load increases and magnet temperature decreases.

CONCLUSIONS

An accurate, versatile, and easy to use simulator program has been developed to predict the performance of the Fermilab Tevatron liquid helium refrigeration cycle. The program has been beneficial in guiding the design and understanding the operation of the upgraded cryogenic system.

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REFERENCES

1. J. C. Theilacker, Current operating experience and upgrade plans of the Tevatron cryogenic system, "Advances in Cryogenic Engineering," Vol. 35B, Plenum Press, New York (1990), p. 917.
2. J. D. Fuerst, Trial operation of cold compressors in the Fermilab satellite refrigerators, "Advances in Cryogenic Engineering," Vol. 35B, Plenum Press, New York (1990), p. 1023.
3. H. R. Barton,Jr., J. E. Nicholls, and G. T. Mulholland, Simulation of the Energy Saver refrigeration system, "Advances in Cryogenic Engineering," Vol. 27 Plenum Press, New York (1982), p. 541.
4. V. D. Arp and R. D. McCarty, "Thermophysical Properties of Helium-4 from 0.8 to 1500 K with Pressures to 2000 MPa," NIST Technical Note 1334, U.S. Dept. of Commerce/National Institute of Standards and Technology, Boulder, Colorado (1989).
5. W. M. Soyars, The applicability of constant property analyses in cryogenic helium heat exchangers, "Advances in Cryogenic Engineering," Vol. 37A, Plenum Press, New York (1991), p. 217.
6. W. M. Soyars, Exergy analysis of Tevatron liquid helium satellite refrigerator upgrade, "Advances in Cryogenic Engineering," Vol. 37A, Plenum Press, New York (1991), p. 661.