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ABSTRACT

The cryogenic system for the Mirror Fusion Test Facility (MFTF) is a 14-kW, 4.35-K helium refrigeration system that proved to be highly successful and cost-effective. We were able to meet all operating objectives, while remaining within a few percent of our initial cost and schedule plans. The management approach used in MFTF allowed us to make decisions quickly and effectively, and it helped keep our costs down. Manpower levels, extent and type of industrial participation, key aspects of subcontractor specifications, and subcontractor interactions are reviewed, as well as highlights of the system tests, operation, and present equipment status. Organizations planning large, high-technology systems may benefit from our experience with the MFTF cryogenic system.

INTRODUCTION

In this paper, we discuss the management approach used to design and operate the cryogenic system for MFTF. Equipment and technical aspects are discussed in Slack et al., and Chronis and Slack.[1,2] In addition to highlighting management and operational aspects of the MFTF Cryogenic system, we discuss system documentation and present equipment status.

MANAGEMENT APPROACH

When the MFTF project was approved in 1982, LLNL decided to subcontract most of the cryogenic system hardware to private enterprise. At that time, the MFTF cryogenic group consisted of two engineers and two mechanical technicians. We wanted to keep the group small to permit rapid decision making and to keep costs low. The group remained this size until near the start of operations. In early 1985, a controls engineer was added to help program the equipment controllers and do controls analysis.

CRYOGENIC SYSTEM SPECIFICATIONS

The cryogenics group wrote a request for proposal (RFP) in 1982. The RFP was primarily a performance specification requiring delivery of hardware, installation, and testing. The RFP stated, for example, that a liquid helium refrigerator of 8 kW plus 30.8 G/s at 4.35 K was required. We also specified those areas where the subcontractor had to interface hardware with other equipment. For example, the subcontractor was assigned required stay in zones within the MFTF building. We also specified helium distribution piping sizes and relief devices where magnet natural convection flows or quench vent pressures were affected. This was necessary since the cryogenic system subcontractor did not have magnet design details. The specification could be termed a hybrid because it required the subcontractor to deliver a certain performance but under the hardware restrictions imposed by LLNL.

In the interest of economy, we tried to minimize the analysis and paperwork required by the subcontractor. We did ask the subcontractor to check the sizing of pipes that provide natural convection flow to the magnets, to provide a backup to calculations done at LLNL. We also required a seismic analysis. In addition, the specification required a 30 to 50% reserve capacity above calculated loads in the cryogenic system. The reserve proved necessary for several reasons. The MFTF plant and capital equipment (PACE) acceptance tests could not have been completed without the reserve, as a result of problems encountered with poor insulating vacuum in the vessel and incomplete flooding of some nitrogen shields. Of course, given more time, these problems would have been corrected.

Three areas were considered important in obtaining the best system at minimum cost. They were to:

- o Write a specification that required minimum changes after the contract was awarded.
- o Encourage effective competitive bidding.
- o Provide maximum cooperation and assistance to the subcontractor throughout the project.

The first item simply required adequate analysis prior to releasing the RFP. In regard to the second item, bidding for the MFTF cryogenic system was limited primarily to Kogh, Inc., and CVI Corp. Both companies were serious enough to establish a true competitive bidding situation. Providing maximum cooperation was made easy by the attitude and diligence with which CVI Corp. took on the job once awarded the contract.

Under the contract, CVI provided the following:

- o An 8-kW plus 30-G/s helium refrigerator,
- o A 400-kW nitrogen subcooler,
- o A 500-kW nitrogen reliquefier,
- o An extensive helium distribution system including 13 supply dewars for magnets and cryopanels and a forced-flow cooling system,
- o A nitrogen distribution system.

Under a previous contract for the first phase of MFTF (MFTF-A), CVI Corp. supplied a 3-kW helium refrigerator, a 100-kW nitrogen subcooler, a distribution system, and parts of a helium recovery system. LLNL supplied high-pressure helium gas storage totaling 343 m^3 at 12 MPa, and a 12-MPa, 600-hp helium recovery compressor. All of these components make up the MFTF cryogenic system.

TRAINING AND OPERATION

System operating instructions and manuals for this complex a system could not be economically or effectively completed before actually running the system. Operational procedures written prior to start-up of an untried, complex system are generally inaccurate and serve only as an outline or overview. Consequently, our RFP required only minimal procedure write-up prior to system operation. Start-up and initial operation--first of system components, then the entire system--were directly controlled by engineers who designed and built the system. The engineers used system drawings, particularly piping and instrumentation drawings, with various check lists. The system had five operator stations over a distance of 200 m, so several people needed to be involved in operating the system. Walkie-talkies provided the most effective communication method during early phases of operation. Modern industrial-grade walkie-talkies operated well, even through the steel building used to house MFTF.

During start-up operations, we found it important to be at the equipment where we could observe sights and sounds that would be unobservable to even the best instrumented remote operator. Sights, sounds, and vibration changes in machinery and piping provided valuable diagnostic tools. We also found that the most effective and safest way to start a new system of this type is to ensure that personnel most involved with designing the system are in operational control. Instant communication must be maintained between operators.

Prior to start-up operations, operators need to be trained so they can become familiar with equipment layouts, location of instrumentation, purpose of the equipment, and operational philosophies. In the interest of economy, the number of technicians associated with the cryogenic group remained at two until just prior to start-up for the PACE acceptance tests. In hindsight, more should have been involved earlier. As a result of our decision, we needed to train 24 new people on the job (6 people for each of 4 shifts), while debugging the new system. During the cryogenic system start-up and PACE acceptance tests, which lasted about 6 months, a few key personnel worked up to 100 h/week, which at times tested the limits of their endurance.

SYSTEM OPERATION AND PROBLEMS

In general, the system performed very well. Preliminary and acceptance tests by CVI Corp. demonstrated performance to specification. Subsequently, the system cooled the 1.05 million kg of magnets in MFTF to 4.5 K as required. It is noteworthy that this was done within a very tight time schedule. The PACE acceptance tests were completed without a full-system test of the cryogenic system. During cooldown and operation of the 22 MFTF magnets, failure of the cryogenics system for more than a few days would have forced us to abort PACE because of schedule and budget constraints and the time required for to recool the system. Consequently, problems were dealt with on-line.[2]

Oil Carry-Over

After a month of operation, the effectiveness of heat exchanger 1 (room temperature to 80 K) in the 8-kW cold box decreased. This change resulted in loss of capacity and in icing of compressor return lines, which forced a shutdown. About 3 L of an odorous oil substance was removed from the heat exchanger. After cleaning and restart, the system operated another month and the problem reoccurred. Analysis of oil from the heat exchanger showed light ends of the compressor oil. Analysis of gas entering the cold box during operation showed an oil content of about 1 ppm, which would result in the 3 L/month carryover of oil actually found in the cold box.

Propylene glycol, the lightest end of the polypropylene glycol oil used in the compressors, has a vapor pressure that would more or less account for 1 ppm carry-over as a vapor. We concluded that the compressor oil either had excessive light ends or the light ends were being generated during operation. In MFTF, the second stage operates at an 8:1 compression ratio, which gives an adiabatic compression temperature of about 690 K. This temperature may be causing the carryover problem. At a 4:1 compression ratio, the adiabatic compressor temperature is about 520 K. Thermal degradation of the compressor oil starts at 480 K. The presence of abundant oil in the compressor reduces temperatures well below adiabatic; however, the evenness of oil distribution and its effect to cool the helium during compression is not well understood. Consequently, we believe compression ratios in the future systems should be limited to 4:1. To solve this problem, we plan to install a freeze-out heat exchanger upstream of the cold box.

SYSTEM DOCUMENTATION

A mixture of published and unpublished data exists relating to the MFTF cryogenic system. Published documents include Slack et al., Chronis and Slack, and Krause and Kozman.[1-3] Additional data include:

- o Complete, well-documented drawings maintained in LLNL central drawing files.
- o A two-volume design data book covering numerous calculations and data accumulated during the design and construction phases of MFTF.
- o A 27-volume operations and maintenance manual compiled by CVI Corp.
- o Disks containing software for equipment programmable controllers.

EQUIPMENT STATUS

Presently, some repairs are needed to return the MFTF cryogenic system to full operational status. Specifically, we need to:

- o Add a freeze-out systems for oil carryover problems,
- o Replace an impeller in the nitrogen reliquefier compressor.
- o Repair an absorber bed in the helium recovery system purifier.

An estimated cost for these repairs as well as other minor repairs would be $100,000 to $200,000. The system can be operated in its present condition but not for extended duration. We plan to operate the system every 6 to 12 months to maintain operational capability while mothballed.

SUMMARY

In designing and developing the cryogenic system for MFTF, our management approach at LLNL allowed us to make decisions quickly and effectively. It also helped keep costs down while allowing us to meet our operating objectives.

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