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Cost Effective Use of Liquid Nitrogen in Cryogenic Wind Tunnels

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FINAL REPORT ON NASA CONTRACT NAS 1-18216

"COST EFFECTIVE USE OF LIQUID NITROGEN IN CRYOGENIC WIND TUNNELS"

PROJECT SUMMARY

This study had two independent objectives. One was to investigate the feasibility of reliquefying a portion of the cold, pressurized exhaust vapor from the tunnel. The second objective was to survey cryogenic equipment and procedures at the Langley 0.3 m tunnel to suggest safer and more efficient use of liquid nitrogen in the facility. Both study objectives were achieved with qualified positive results for the first part and detailed recommendations for the second portion of the work.

Extensive reliquefaction calculations have been made with the aid of a computer program developed for the project. These calculations indicate that liquid yields of from 12 to nearly 20% of flow can be obtained by utilizing low temperature pressure energy in the tunnel exhaust vapor in a simple system consisting of a counterflow heat exchanger and positive displacement wet expander. Technical and economic success of the reliquefaction scheme hinges on the expander. Computer modeling and calculations of a

proprietary rotary positive displacement expander by Milburn Stirling Corporation indicate that high adiabatic efficiency can be obtained. Despite higher than anticipated preliminary cost estimates, use of the Milburn Stirling "Turgine" expander appears economically feasible, and Cryolab recommends a scale model development program.

Upgrade of the 0.3 m wind tunnel cryogenic system is feasible and, overall, economically justified. Aside from the obvious conclusion that the 28,000 gallon liquid nitrogen storage dewars should be refurbished, Cryolab found that the largest liquid nitrogen loss results from the blowdown/repressurization procedure necessary to subcool liquid for pumping. Cryolab recommends the use of a subcooler to reduce these losses. Improved safety and better system control can be realized by locating a cryogenic control panel in the wind tunnel Control Room and installing motor operators on all functioning valves. Cryolab recommends incorporating vacuum-jacketed lines along with the subcooler and remote operated valves to bring the system up to current technology and achieve maximum liquid nitrogen utilization efficiency. The system upgrade recommendations are low-risk because the proposed work is well within the state of the art and cost estimates are reasonably accurate.

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REFERENCES

[1] R.O. Voth and T.R. Strobridge, "Cryogenic Design and Safety Review, NASA-Langley Research Center 0.3 Meter Transonic Cryogenic Tunnel," NBSIR 77-857, April 1977.

[2] R.B. Zwicker, "National Transonic Facility, Facility Description Document, Section C, NTF's Nitrogen System," NASA LRC Report D-17, March 1986.

[3] T.J. Webster, "A Report on Possible Safety Hazards Associated With The Operation of The 0.3 m Transonic Cryogenic Tunnel At The NASA Langley Research Center," NASA Contractor Report 166026, October 1982.

[4] R.F. Barron, "Cryogenic Systems," Oxford University Press, New York (1985).

1. INTRODUCTION

1.1 Background

The 0.3 m transonic cryogenic wind tunnel at NASA Langley Research Center was set up as a temporary demonstration in the early 1970's. The cryogenic facility has been enhanced somewhat over the years as valuable contributions of the tunnel earned permanent status for it. Throughout its history, NASA personnel have been concerned about the safety and efficiency of the facility, and two previous studies [1],[3] have addressed these problems. Cryogenic deficiencies identified in these reports were generally rectified, but no cost-effective method of recovering or reliquefying nitrogen was identified.

In May 1986 Cryolab found that the 28,000 gallon storage dewars were performing poorly, the condition of foam insulated pipe varied from good to fair, the piping itself was routed with excess lengths in order to allow personnel to reach manual valves, and a significant portion of tunnel run preparations required personnel to be in the cryogenic area. No specific hazards or unsafe practices were identified during the study, but it was observed that the blowdown/repressurization procedure to get subcooled liquid for pump inlets caused large quantities of nitrogen vapor to be vented.

1.2 Summary

Cryolab performed the Phase I study in two parts as originally proposed. Technical and, to an extent, economic feasibility of a partial reliquefaction scheme was investigated in Part 1. Results showed that 12 to 19% of tunnel inlet flow could be reliquefied with a simple system which would generate a modest amount of power under normal operating conditions. It was determined that success of this system depended on the efficiency, reliability and cost of an innovative rotary positive displacement expander called a "Turgine" by its developer, Milburn Stirling Corporation. Although the calculated performance of the Turgine supported feasibility of Cryolab's reliquefier scheme, a small-scale development program was suggested because machines of this type had not been used in cryogenic service.

In Part 2, Cryolab made a series of recommendations to improve efficiency, convenience and safety of the cryogenic system for the 0.3 m wind tunnel. Recommended upgrades included refurbishing the dewars, adding a subcooler to reduce liquid nitrogen losses, locating a remote control panel in the wind tunnel Control Room and installing a complete set of motor-operated valves on the system and, finally, converting to vacuum-jacketed piping to further

reduce liquid nitrogen losses and provide a consistent level of technology for the system. Part 2 recommendations were all based on established technology for immediate implementation with little technical or economic risk.

1.3 Accomplishment of Phase I Objectives

1.3.1.1

By means of the computer program, "RECOVERY", the nitrogen cold gas reliquefier was analyzed for a variety of inlet conditions and expander efficiencies and was found to be technically feasible.

1.3.1.2

Studies by Milburn Stirling Corporation indicated no fundamental reason why the Turgine should not be successful as a cryogenic expander.

1.3.1.3

Milburn Stirling prepared a computer program to size and calculate performance of cryogenic Turgines. Summaries of design values for two sizes appear in paragraph 4.2. The larger size would be one of four parallel units for the 0.3 m wind tunnel.

1.3.1.4

A Turgine development and refrigerator test program is mentioned in paragraph 6.0. This program would consist of designing a 1/12 scale refrigerator and 1/3 scale Turgine. The test program would necessarily be done at the 0.3 m wind tunnel facility in order to have a supply of cold nitrogen vapor.

1.3.2.1

Cryolab pesonnel spent most of the week of May 12-16, 1986 at the 0.3 m wind tunnel facility examining the system and observing operations.

1.3.2.2

Schematic of the optimized cryogenic system for the wind tunnel is presented as drawing VJ 10029-2.

1.3.2.3

The schematic of VJ 10029-2 is actually specific for the 0.3 m wind tunnel although it would match any similar system with storage dewars capable of modest pressurization.

1.3.2.4

Specific hardware suggestions for upgrading the 0.3 m wind tunnel cryogenic system are included in the text of the report and are shown on drawings VJ 10029-1, 3 and 4.

1.3.2.5

Cryolab personnel intend to present the results of the study in a one-day trip to NASA Langley to be scheduled in mid-December 1986 or early January 1987.

1.3.2.6

Specific suggestions for upgrading cryogenic hardware for the 0.3 m wind tunnel are included in paragraph 9.0. Estimated costs are developed in paragraph 10.0, and overall conclusions for implementation are given in paragraph 11.0.

1.4 Phase II Recommendations

Phase II work on the two parts of this study should be handled separately. Hardware upgrade for the 0.3 m wind tunnel is a defined project which can be accomplished over a nine- to twelve-month period. Specific follow-on is not likely.

The Part 1 nitrogen reliquefier study better fits the SBIR program. A Phase II program is necessary to establish feasibility of using a Turgine as a cryogenic expander and the practicality of reliquefying a portion of nitrogen flow from a wind tunnel. Potential Phase II opportunities include installing a full-scale nitrogen reliquefier for the 0.3 m wind tunnel and modification of the Turgine for other cryogenic expander applications.

PART I

Nitrogen Reliquefaction

2.0 Background

High consumption of costly* liquid nitrogen in the 0.3 meter Transonic Cryogenic Tunnel leads to consideration of ways to recover nitrogen and its available refrigeration that is presently "wasted" up the vent stack. However, a study [1] conducted for NASA Langley Research Center correctly concluded that reliquefaction and/or recovery of the nitrogen was uneconomical. The primary basis for this conclusion was that the tunnel operates at a high liquid nitrogen consumption rate only a small percentage of the time, implying a disproportionately large recovery system which would mostly sit idle.

Cryolab's approach to nitrogen reliquefaction is to focus on the "free" pressure energy and refrigeration that is

* In a March 1986 Document [2], the cost of liquid nitrogen for the National Transonic Facility is stated at $90/ton or $0.304/gallon. Since liquid to the 0.3 m wind tunnel must be supplied by truck, Cryolab has arbitrarily assigned a higher price of $0.10/litre or $0.3785/gallon.

available and utilize it in a low cost system which recovers only 12 to 20% of the liquid nitrogen consumed. This may seem like a small fraction but, at a consumption rate of 200 gallons per minute, a typical 17% recovery rate recaptures 34 gpm or over 2,000 gallons per hour of liquid nitrogen.

A schematic of Cryolab's system is shown in Figure 1. The four elements of the system are the heat exchanger, wet expansion engine and electric motor/generator, liquid receiver and a pump to move liquid back to storage. Functionally, the heat exchanger receives nitrogen vapor at essentially tunnel temperature and pressure (a little above saturation) and cools it in counterflow with low pressure exhaust gas. Even at quite high inlet temperatures, above 120 K, some condensation takes place in the heat exchanger and the expander inlet is in the wet region. The expander is a special positive displacement machine which expands the wet inlet mix down to near 1 atmosphere with formation of additional liquid. Expander exhaust falls into the liquid receiver which provides a liquid sump and directs unliquefied vapor up into the low pressure side of the heat exhanger. The system is completed by a transfer pump which returns liquid nitrogen to storage or the wind tunnel supply line.

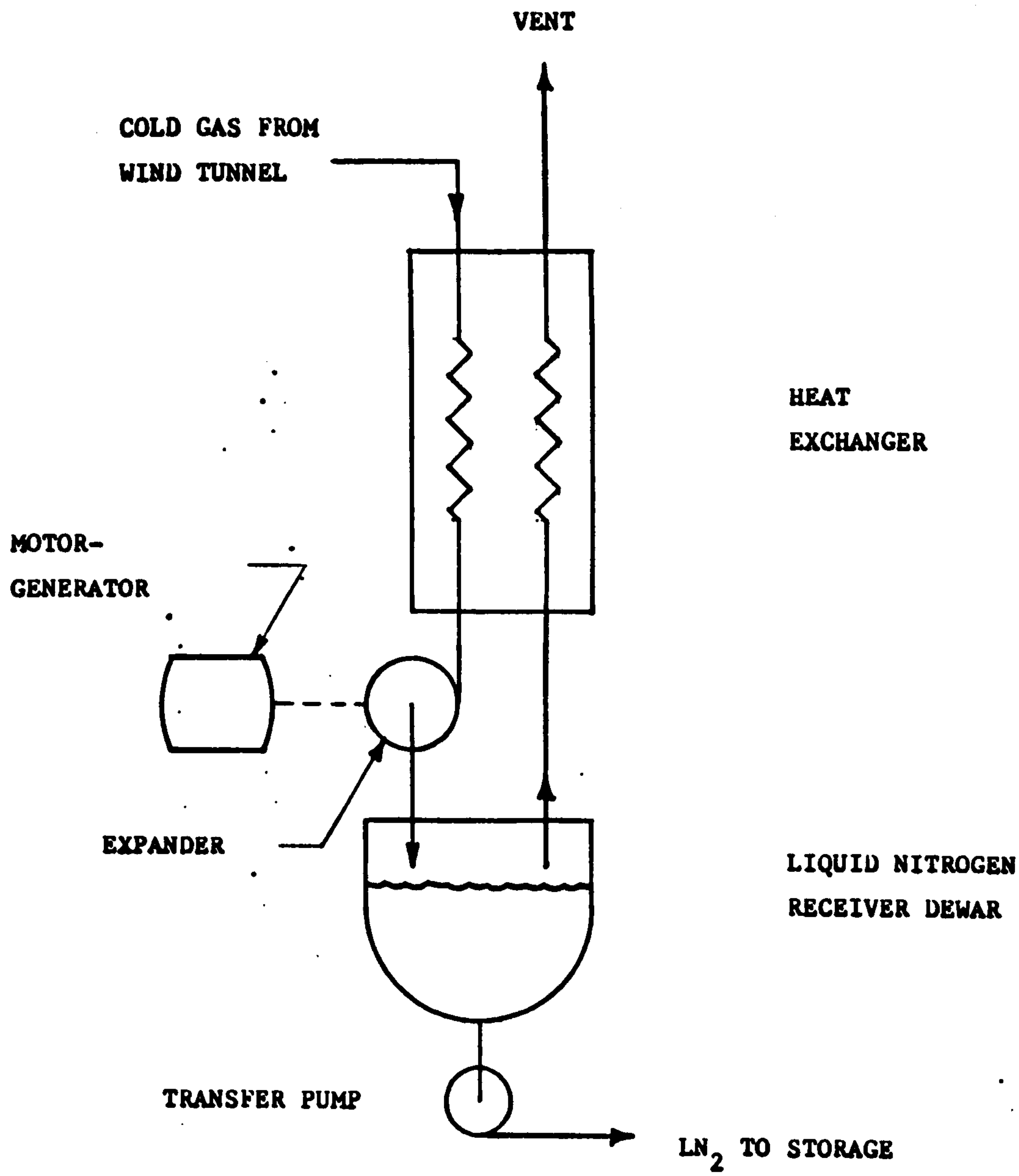


FIG. 1
COLD GAS RELIQUEFIER

3.0 Analysis and Calculations

A thermodynamic schematic of the reliquefaction cycle is shown in Figure 2. Pertinent heat balance equations are given alongside the schematic with terms defined as follows:

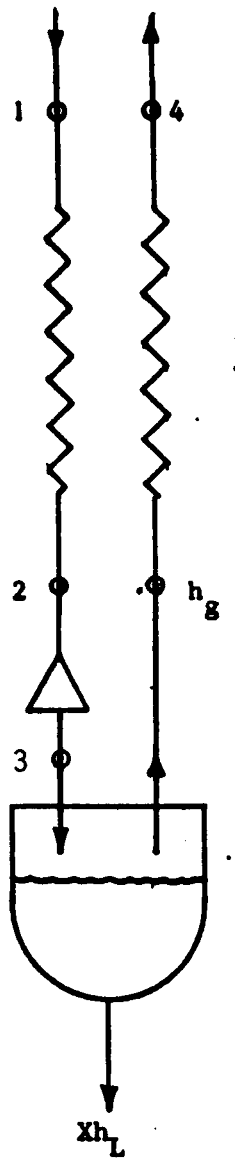
- h[1] = enthalpy of entering nitrogen vapor
- h[2] = enthalpy of wet mixture at expander inlet
- E = isentropic efficiency of the expander
- h[3] = actual enthalpy of expander exhaust
- h[3'] = ideal enthalpy of expander exhaust
- X = fraction of nitrogen flow reliquefied
- h[L] = liquid nitrogen enthalpy
- h[g] = enthalpy of saturated nitrogen vapor
- h[4] = enthalpy of exhaust nitrogen gas
- s[2] = entropy of wet mixture at expander inlet
- s[L] = entropy of liquid nitrogen
- s[g] = entropy of saturated nitrogen vapor

Equation (1) can be solved for x as follows:

$$x = 1 - (h[1] - h[2])/(h[4] - h[g]) \qquad (5)$$

Equations (2), (3) and (4) can also be solved for x:

$$x = (h[2](1-E) + Eh[L] - h[g])/(h[L]-h[g]) - E(s[2] - s[L])/(s[g] - s[L] \qquad (6)$$



$$h_1 - h_2 = (1 - X)(h_4 - h_g) \qquad (1)$$

$$h_3 = h_2 - E(h_2 - h_3') \qquad (2)$$

$$h_3 = Xh_L + (1 - X)h_g \qquad (3)$$

$$h_3' = h_L + \frac{(s_2 - s_L)(h_g - h_L)}{(s_g - s_L)} \qquad (4)$$

FIG. 2

RELIQUEFIER THERMODYNAMIC SCHEMATIC

By substituting a series of related values for h[2] and s[2], x can be iterated until equations (5) and (6) result in the same value.

3.1 Liquid Nitrogen Recovery Calculations

The equations and procedure described above were utilized to calculate a number of points. However, this iterative technique is tedious and time consuming. To ease this problem and provide a convenient check for those less thermodynamically diligent, the Principal Investigator and his associate, Dr. Mostafa K. Abdelsalam of the University of Wisconsin-Madison, prepared a computer program, RECOVERY, which calculates a data point in approximately 10 seconds using a Personal Computer equipped with an 8087 or equivalent math co-processor. RECOVERY, which is written in FORTRAN 77, is particularly convenient because it also incorporates subroutines for the necessary nitrogen thermodynamic data from the National Bureau of Standards'program, MIPROPS.

A copy of RECOVERY on a diskette is furnished to NASA with this report and may be used on an unrestricted basis. The program has been extensively checked against manual calculations and is believed to give liquefier yields accurate to +/- 0.002 except for inlet temperature of

99 K. The program currently has a "bug" for this inlet temperature, and results should be disregarded.

A printout of the format for RECOVERY is included as page 14. As illustrated, a set of calculations is initiated by asking for all of the pertinent data. Then, after the calculation results are printed, the program asks which variable is to be changed. Thus, it is easy to make a series of calculations as a function of one variable. RECOVERY was used to make several sets of calculations for nitrogen reliquefaction. Results of these calculations are plotted in Figures 3, 4, and 5. Figure 3 is most definitive in that it shows reliquefier yields for 75 and 80% expander efficiencies with heat exchanger temperature difference of 2 K for inlet temperatures just above saturation at each pressure. For 80% expander efficiency, the reliquefaction yields range from 12.9% at 4 atm to 19.9% at 8 atm. 75% expander efficiency reduces the yield range to 12.2% to 18.9% for the same spread of inlet conditions.

Figures 4 and 5 zero in on the more practical operating pressure of 6 atm. Figure 4 shows the effect of expander efficiency on yield for varying inlet temperatures and a constant heat exchanger temperature difference of 2 K. Figure 5 illustrates the impact of heat exchanger

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  THIS PROGRAM IS DESIGNED TO RUN IN INTERACTIVE MODE . HOWEVER , IT ALLOWS
THE USER TO KEEP A RECORD OF THE OUTPUT . THIS COULD BE EITHER AN OUTPUT FILE
OR A PRINTED COPY .
  THREE OUTPUT OPTIONS ARE AVAILABLE IN ADDITION TO THE INTERACTIVE MODE :
        1. NO RECORD OF THE OUTPUT
        2. SELECTIVELY RECORD PORTIONS OF THE OUTPUT ( YOU WILL
                        BE PROMPTED FOR A DECISION )
        3. COMPLETE RECORD OF THE OUTPUT (NO PROMPT)

          WHICH OPTION DO YOU PREFER  (1/2/3) ?                 : 1

PLEASE ENTER A TITLE FOR THIS RUN ( ONE LINE )
Demonstration

          INLET PRESSURE (ATM)                                  : 6

          INLET TEMPERATURE (K)                                 : 97

          TEMPERATURE DIFFERENCE BETWEEN NODES 1 AND 4          : 2

          EXPANDER EFFICIENCY (%)                               : 80

          DO YOU WANT TO MAKE CHANGES IN YOUR INPUT (1/0) ?     : 0



Demonstration


        T1           T2           T3           T4
      97.0000      96.5753      77.3627      95.0000

     INLET PRESSURE                P1 =    6.0000  ATM
     OUTLET PRESSURE               P4 =    1.0000  ATM
     QUALITY AT EXPANDER INLET     Y  =   90.7745  %
     NITROGEN YIELD                X  =    0.1692



DO YOU WANT TO CHANGE :
        1) INLET PRESSURE    ,
        2) INLET TEMPERATURE  ,
        3) TEMPERATURE DIFFERENCE BETWEEN NODES 1&4,
        4) EXPANDER EFFICIENCY ,
   OR
        5) RESTART
        6) QUIT

          PLEASE ENTER NUMBER CORRESPONDING TO YOUR CHOICE        :
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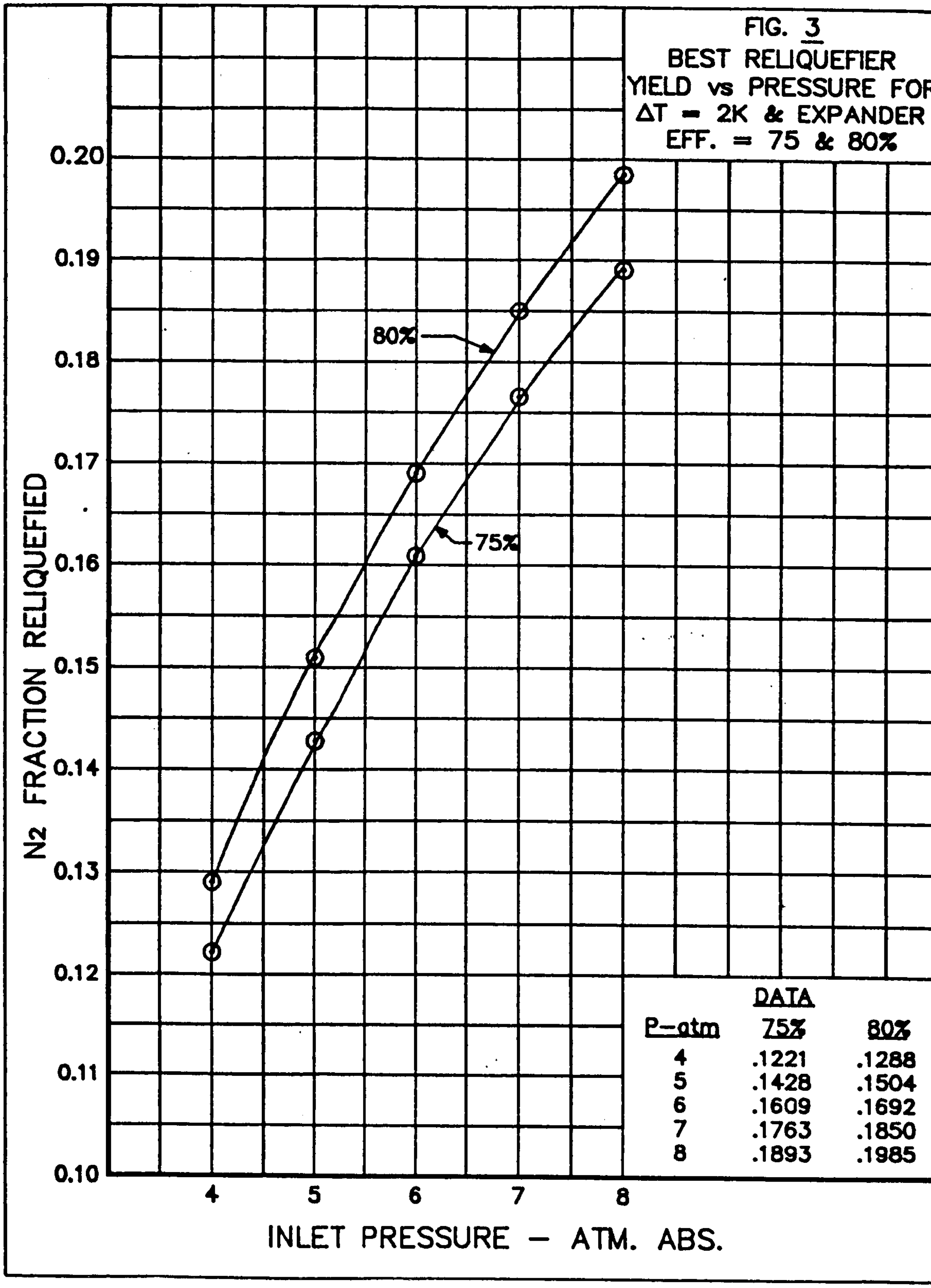
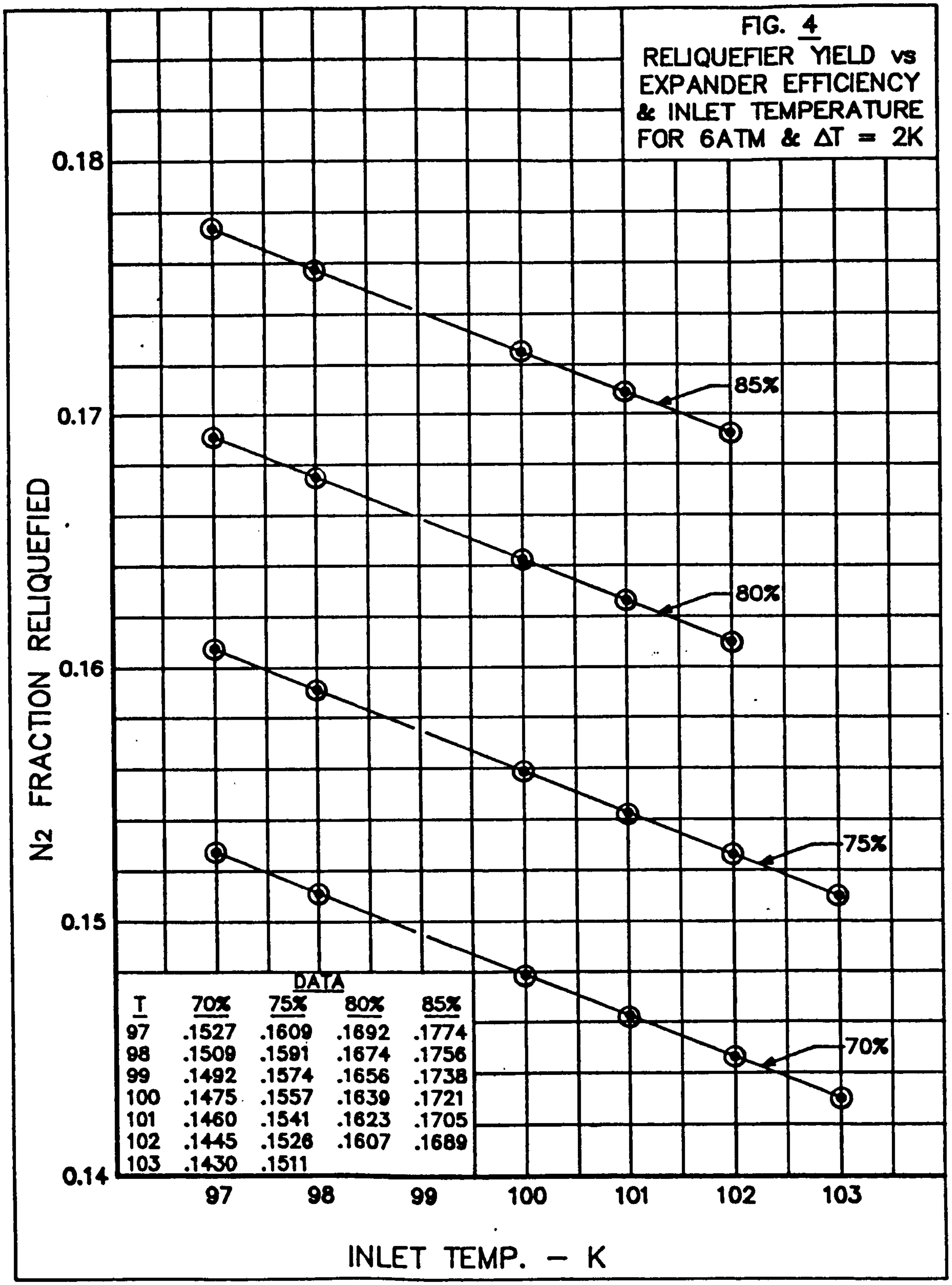


FIG. 3
BEST RELIQUEFIER YIELD vs PRESSURE FOR ΔT = 2K & EXPANDER EFF. = 75 & 80%

DATA

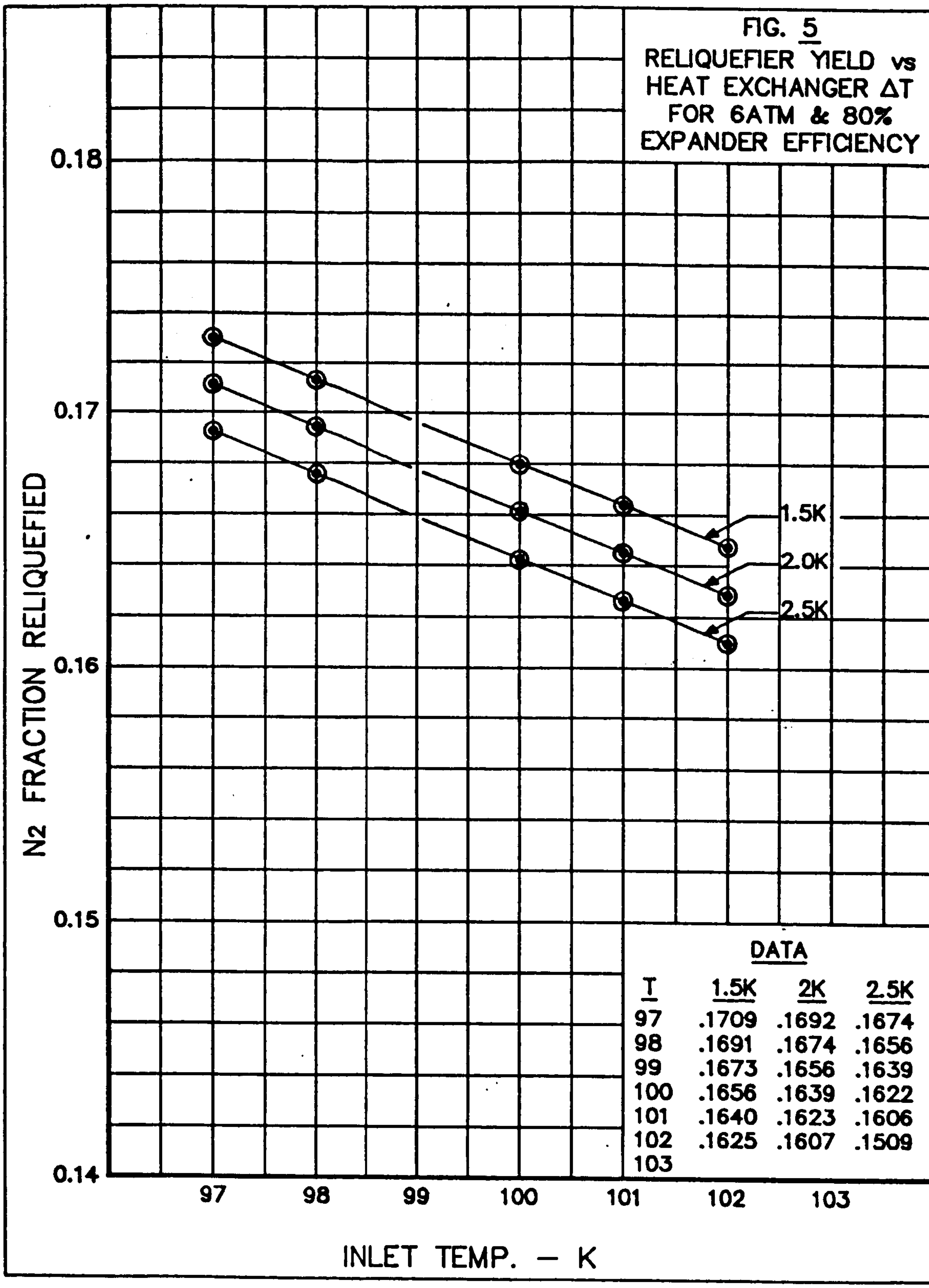
P–atm	75%	80%
4	.1221	.1288
5	.1428	.1504
6	.1609	.1692
7	.1763	.1850
8	.1893	.1985



DATA

T	70%	75%	80%	85%
97	.1527	.1609	.1692	.1774
98	.1509	.1591	.1674	.1756
99	.1492	.1574	.1656	.1738
100	.1475	.1557	.1639	.1721
101	.1460	.1541	.1623	.1705
102	.1445	.1526	.1607	.1689
103	.1430	.1511		

FIG. 4
RELIQUEFIER YIELD vs EXPANDER EFFICIENCY & INLET TEMPERATURE FOR 6ATM & ΔT = 2K



T	1.5K	2K	2.5K
97	.1709	.1692	.1674
98	.1691	.1674	.1656
99	.1673	.1656	.1639
100	.1656	.1639	.1622
101	.1640	.1623	.1606
102	.1625	.1607	.1509
103			

temperature difference when the expander efficiency is held constant at 80%.

Principal conclusions that can be drawn from these calculations include:

* Practical reliquefaction yields of 12 to 18% can be achieved with the system.
* The system is only moderately sensitive to inlet temperature. Data from Figure 5 indicates yield reduction of less than 5% for inlet increase of 5 K.
* Heat exchanger temperature difference decrease of 1 K from 2.5 to 1.5 K improves best performance only 2.1% implying reasonable insensitivity to this variable.
* Liquid yield is almost directly proportional to expander efficiency. Data from Figure 4 at 97 K inlet temperature indicates yield improvement of 16.2% for expander efficiency increasing 15 percentage points (21.4%) from 70 to 85%.

4.0 Reliquefier Components

The following paragraphs include discussion of the physical components of a reliquefier for the 0.3 m wind tunnel. All calculations are based on a liquid nitrogen consumption rate of 200 gallons per minute (12.617 litres/s), which is equivalent to a flow rate of 9.828 kg/s.

4.1 Heat Exchanger

The reliquefier heat exchanger receives nitrogen vapor at tunnel pressure and slightly above saturation temperature and exhausts low pressure gas several degrees colder. On the high pressure side, incoming vapor is cooled to saturation and some condensation takes place. Exit quality is between 91 and 92% vapor for 6 atm operating pressure and 80% expander efficiency with 2 K temperature difference at the top end. (The heat exchanger should be oriented vertically to facilitate draining of condensed liquid.) Low pressure saturated vapor at 78 to 79 K enters the cold end of the heat exchanger and exits to vent from 1.5 to 3 K colder than the inlet stream. Typical service requirements for the heat exchanger are given in Table 1.

Table 1

Reliquefier Heat Exchanger Service

High Pressure	4 - 7 atm abs.
Low pressure	1 - 1.25 atm abs.
Flow	9.83 kg/s
Typical heat load	1.905 E5 j/s
Typical top end temp. diff.	2 K

Typical cold end temp. diff.	18 K
Log mean temp. diff.	7.282 K
Nominal high pressure surface area	30 sq. metres

Likely, the most economical heat exchanger for this service would be a commercial brazed aluminum unit, but vendors have not been contacted. Preliminary design of a Hampson heat exchanger made with copper tubes was done. This design was based on use of 0.635 cm OD x 0.0762 cm wall (1/4 OD x 0.030 in wall) copper tubes 4.572 m long. The heat exchanger requires 1,500 parallel tubes arranged in 20 wraps with 75 tubes per wrap. Overall dimensions of the heat exchanger vacuum jacket are 0.61 m OD x 3.1 m high. Estimated weight of the assembly is 1455 Kg, and its cost will be approximately $50,500.

4.2 Wet Expander

Key to Cryolab's proposed liquid nitrogen recovery system is a wet expander. This machine receives two phase nitrogen from the heat exchanger at nearly tunnel pressure and expands it down to approximately 1 atmosphere. Requirements for the expander are unusual because of the large volume of flow and wet mixture in addition to bearing and seal problems unique to cryogenic applications. The most common solution to large cryogenic expander flows is to use radial inflow turbines, but they are impractical in the wet region because of rapid impeller erosion by liquid droplets. Piston expanders have been developed for wet applications for flows generally smaller than for the 0.3 m wind tunnel (200 gpm consumption in the tunnel at 6 atm results in expander inlet flow of 0.3587 cubic metres at 96.5753 K.). Multi-cylinder piston expanders may be feasible for the nitrogen reliquefier, but their size, cost and only moderate reliability have encouraged Cryolab to seek an alternate machine.

Cryolab's alternate expander is a rotary positive displacement machine named a "Turgine" by its developer, Milburn Stirling Corporation. The Turgine is a rotary nutating machine which may be used as either a compressor or expander (gas motor). A cutaway view of a four element balanced Turgine is shown in Figure 6, and Figure 7 tracks one chamber through an intake/exhaust cycle. The advantages of a Turgine include:

* Large displacement for compact machine size.
* Variable displacement is possible.
* High adiabatic efficiencies have been measured on air motors and are predicted for expander applications.
* Linear seal forces are very low.

Disadvantages include:

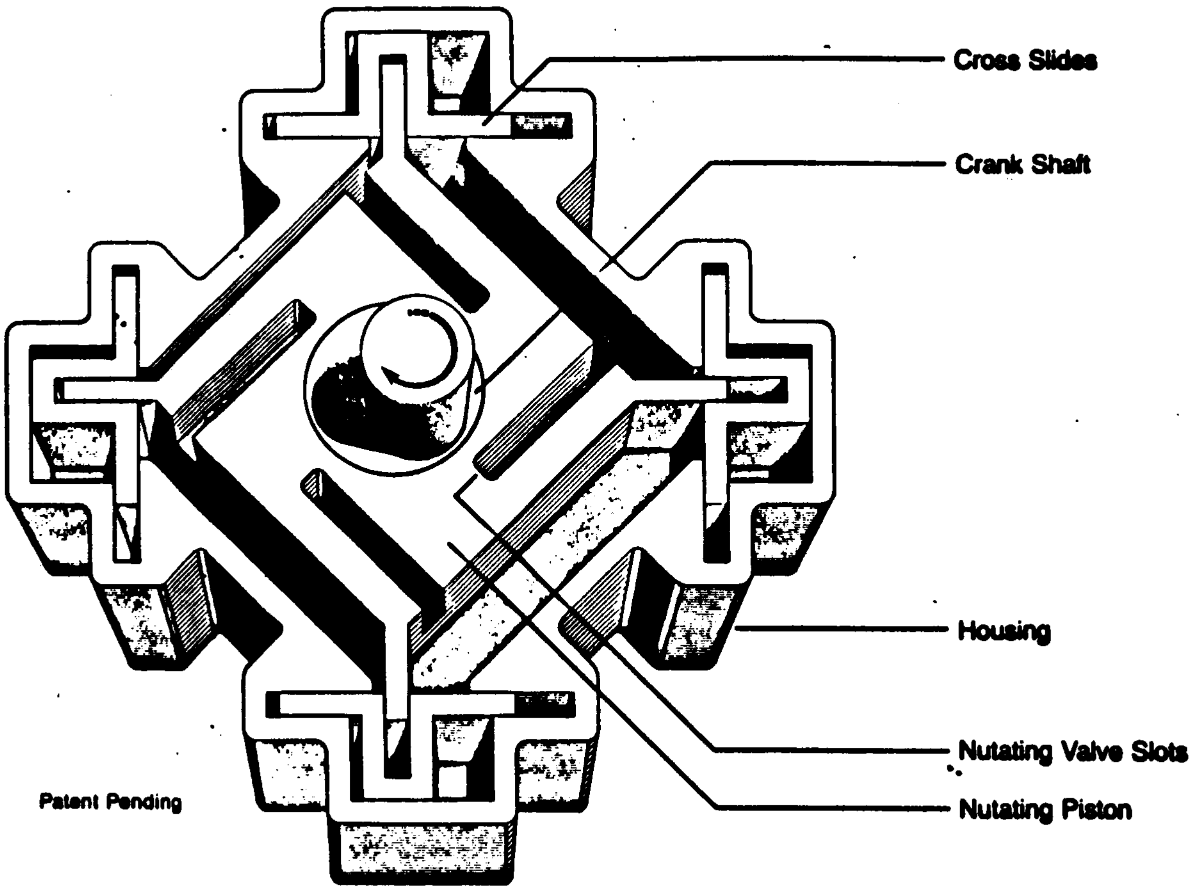


FIG. 6

TURGINE CUTAWAY DIAGRAM

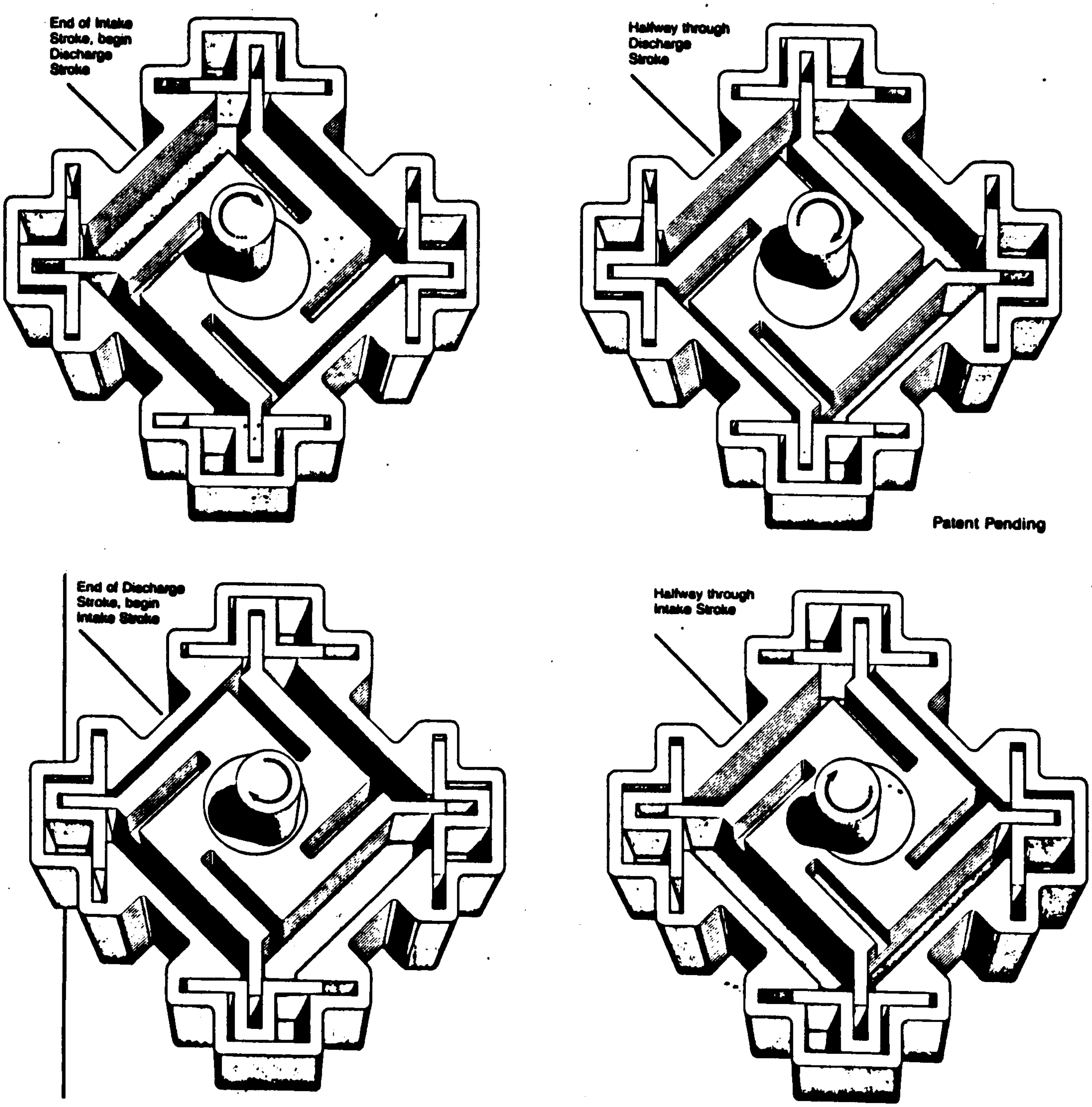


FIG. 7

TURGINE OPERATING CYCLE

* Multiple large sliding surfaces requiring precision machining.

* More parts than a piston expander.

Despite the development that needs to be done, Cryolab has selected a Turgine for the nitrogen reliquefier because of its large displacement, high calculated efficiency and potential for other cryogenic applications.

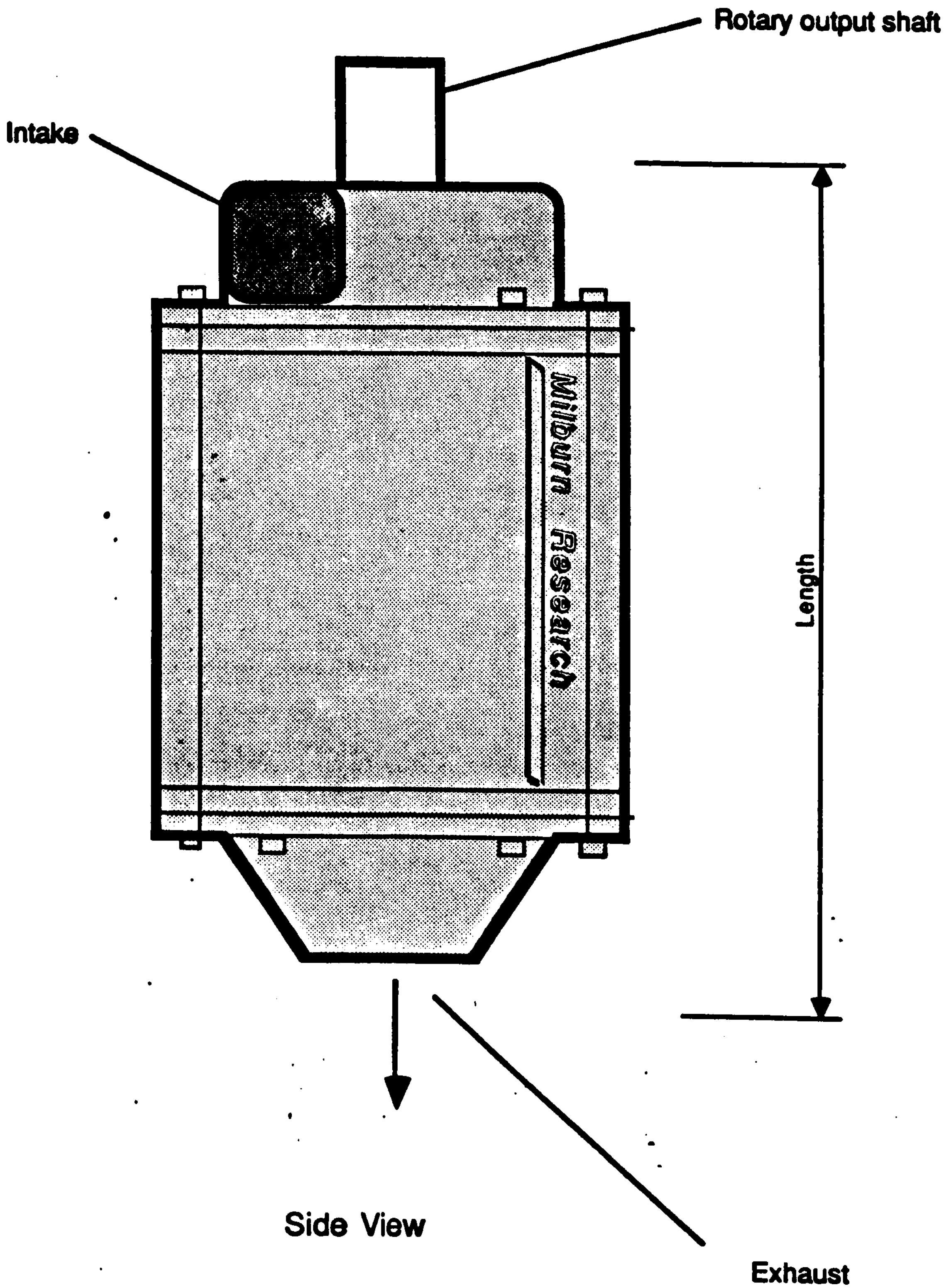
Milburn Stirling has prepared a proprietary computer program to size Turgine expanders and compute their performance. A summary of calculations for non-optimum machines sized for inlet flows of 1.415 and 5.38 cubic metres/min (50 and 190 cfm) is presented in Table 2.

Table 2

Turgine Sizing and Performance Calculations

Item	1.415 m(3)	5.38 m(3)
Inlet pressure - atm	6.0	6.0
Inlet temperature - K	96.6	96.6
Outlet pressure - atm	1.1	1.04
Outlet temperature - K	78.0	77.6
Maximum displacement - m(3)	0.02378	0.09113
Overall width & height - m	0.497	0.856
Overall length - m	0.597	0.825
Seal preload - N/m	4.425	4.425
Speed - rpm	1200	1200
Net power - kw	12.2	51.0
Adiabatic & aero. efficiency - %	85.5	76.8

Proposed X-4 Gas Motor for Nitrogen Expansion for Cryolab



Side View

FIG. 8

TURGINE SIDE VIEW

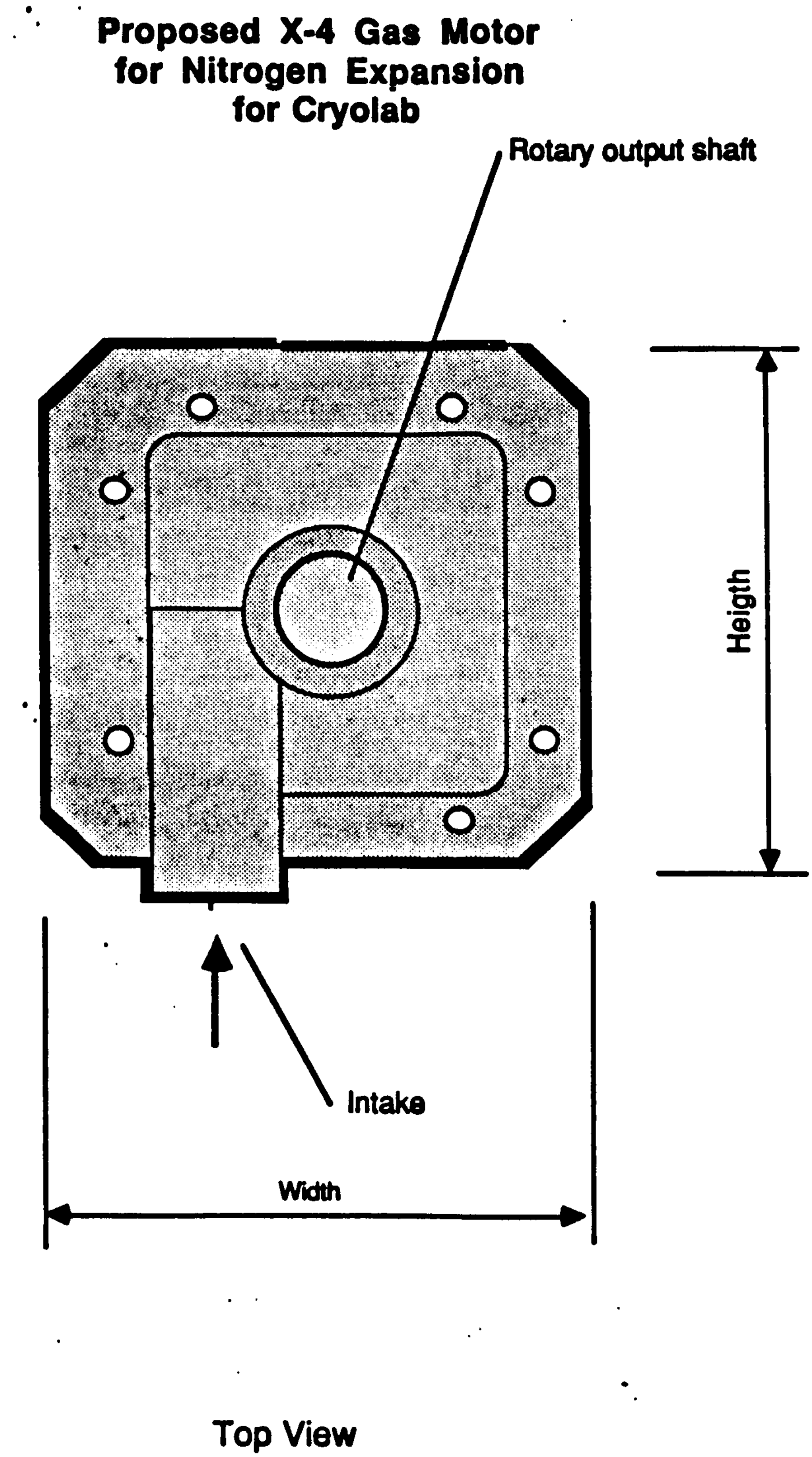


FIG. 9

TURGINE TOP VIEW

Physical sizes listed in Table 2 relate to outline drawings of two views of a Turgine expander shown in Figures 8 and 9. The significance of the two sizes is that the smaller is appropriate for a developmental reliquefier, and the larger handles one-fourth of the calculated flow from the 0.3 m wind tunnel when operated at 6 atm with liquid nitrogen consumption of 200 gpm.

The bottom line in Table 2 indicates an efficiency of 85.5% for the smaller Turgine and 76.8% for the larger. According to Milburn Stirling, the higher efficiency results from a width/length ratio of 0.75 compared to a ratio of 1 for the 5.38 m(3) machine. Higher calculated performance, above 80%, should be obtainable with the larger machine with a similar 0.75 width/length ratio. The important conclusion is that Turgines utilized as Cryogenic expanders predict efficiency values well within the feasibility range of a nitrogen reliquefier.

Cost of a set of four parallel Turgine expanders for 200 gpm flow into the 0.3 m wind tunnel has been estimated by Milburn Stirling. Since no cryogenic Turgines have been built, Milburn Stirling's total estimate of $841,000 for the four machines must be considered quite preliminary.

4.3 Liquid Receiver

At a maximum practical reliquefaction rate of 18%, liquid production would be 136 litres per minute (36 gallons). If the transfer pump is sized for 150 litres per minute, the receiver should have "High" and "Low" settings which allow some over- and under-shoot without creating operating problems. Thus, the receiver dewar is sized at 450 litres by allowing a minute's pumping above the "High" setting, a minute between the settings, and a minute's flow below the "Low" setting. Configuration of the dewar is not critical, but a vertical cylinder with dished heads forms a convenient sump ahead of the transfer pump. The dewar could be a modified commercial 500 litre unit and should be available for about $3,500.

4.4 Transfer Pump

An industrial gas transfer pump will be used to move liquid produced back to storage. The pump will be rated at 50 psig and 150 litres/minute (40 gpm) and will require a 1 1/2 to 3 hp electric drive. An external pump to meet these requirements will cost about $1,500. A more sophisticated submerged pump would have lower heat leak and should be investigated for an actual system.

5.0 Economics of Reliquefaction

Estimated costs of a Turgine-based reliquefier system sized for the 0.3 m wind tunnel are summarized as follows:

Heat exchanger	$ 50,500
Turgine expander - 4 parallel units	841,000
Electric motor/generators for Turgines	12,000
Liquid receiver dewar	3,500
Transfer pump	1,500
System engineering	12,500
Installation	25,000
Total cost	$946,000

Against this total cost, the system should recover about 16.5% of nitrogen consumed in the wind tunnel. At the 200 gpm figure used throughout the study, recovery would approximate 33 gpm, worth $12.49 at $0.3785 per gallon. On an hourly basis, value of recovered liquid nitrogen is about $750. For a rounded up installed cost of $1,000,000, payout would be realized after 1333 hours of operation at the assumed rate. However, any such projection should be treated with caution on two counts.

(1) Cryolab recommends testing a scale model

Turgine-based reliquefier before going ahead with a full-size system for the 0.3 m wind tunnel. Thermodynamic and mechanical performance of a small Turgine could impact the desirability of the whole scheme.

(2) Projected cost of the four Turgines stands out as the major item in a nitrogen reliquefier. Successful work with a scale model Turgine would reduce technical and cost uncertainties permitting more realistic pricing.

6.0 Reliquefier Conclusions and Recommendations

Theoretical feasibility of a nitrogen reliquefier using waste pressure energy from wind tunnel exhaust vapor has been demonstrated. It appears that nitrogen reliquefaction is cost effective if usage is sufficiently great, expander efficiency is about 70%, and costs are less than or a little greater than preliminary estimates.

As noted in Paragraph 4.0, Cryolab believes that conclusions about the Turgine expander are sufficiently qualified that it would be unwise to immediately proceed with a full-scale reliquefier. A 1/12 scale model reliquefier with a single 1/3 scale Turgine expander is recommended. A reliquefier of this size will prove out the system and establish a scaleable design of the Turgine expander permitting valid technical and economic projections.

PART 2

0.3 m Wind Tunnel Cryogenic System

7.0 Existing System

The cryogenic system for the 0.3 m wind tunnel continues to suffer from its start in life some 14 years ago as a "temporary" demonstration. Since then, the tunnel has become established as a valuable research facility, but vestiges of its origin still exist in the cryogenic support system. Upgrades have been made in vent piping, a new fill location and some of the valves have been converted to remote or automatic power operation, but most of the foam-insulated piping layout is below industry standards in terms of loss rates and arrangements.

Specifically, the cryogenic system for the wind tunnel consists of two, 28,000 gallon liquid nitrogen dewars, a free standing heat exchanger for pressurization, 150 and 250 gpm parallel pumps and the aforementioned foam-insulated piping to interconnect the dewars and supply liquid to the tunnel and carry away excess flow to the off-service dewar. NASA drawing LD-740188 (not a part of this study) is a substantially accurate representation of the arrangement. All liquid valves associated with the 28,000 gallon dewars are manual as are the main vent valves.

Thus, setup for operation of the tunnel requires personnel to enter the nitrogen storage area to set valves properly. When the manual valves are set, the tunnel can be operated with power-actuated valves until it is necessary to shut down or to switch from one dewar to the other. Although safety procedures are well worked out [1], [3] and low oxygen sensors are located throughout the facility, the present system does expose personnel to some degree of hazard from low oxygen atmosphere and possible accidental contact with liquid nitrogen or cold vapor in the event of a line or component failure.

8.0 Operating Loss of Existing System

Liquid nitrogen losses fall into three categories: essentially constant losses of the two storage dewars, blowdown-repressurization cycles prior to start of a run, and piping system losses during operation. During its on-site survey, Cryolab measured the loss rates of the two dewars and calculations have been made for the other losses as reported in the following paragraphs.

8.1 28,000 Gallon Dewar Losses

Boiloff tests were made on both tanks "A" and "B" on May 15, 1986. These were fairly low precision measurements utilizing an instantaneous flow meter as compared to a more desirable totalizing meter. No corrections were made for changes in barometric pressure during the brief test periods, and it was not possible to measure dewar vacuums. However, it was noted that Dewar A was being pumped throughout the week of Cryolab's visit to Langley.

Measured loss rates on the two dewars were as follows:

Dewar A	69 gal/day
	0.246%/day loss rate
	487.5 j/s heat leak
Dewar B	128 gal/day
	0.457%/day loss rate
	904.4 j/s heat leak

This data indicates that performance of Dewar A was enhanced by use of the vacuum pump. Boiloff values for both dewars were high compared to a reasonably acceptable loss rate of 0.1% per day which is equivalent to 28 gallons per day. If the vacuum pump was sufficient to improve Dewar A by 59 gallons per day over Dewar B, it would seem prudent to, at a minimum, put pumps on both dewars. At the assumed liquid nitrogen cost of $0.3785 per gallon, the 59 gallons per day saved would have a value of $22.33, not counting fill losses. This would pay for an adequate vacuum pump in four to six months. Of course, the preferred solution is to take the dewars out of service, leak check and repair as necessary, re-insulate and re-evacuate them. This would get the losses on each dewar down into the range of 20 to 30 gallons per day.

8.2 Pressure Cycle Losses

Current procedure is to allow a filled dewar to build pressure until a preset value is reached and then vent periodically under pressure switch control. Prior to a wind tunnel run, the supply dewar is vented down to approximately atmospheric pressure and then repressurized to 30 to 35 psia to provide subcooled liquid (Net Positive Suction Head) to the pumps. This blowdown/repressurization process consumes a great deal of liquid nitrogen.

Using equations developed in Appendix A, a sample calculation was made for a 28,000 gallon dewar initially containing 21,000 gallons of liquid at 50 psia (35 psig) which was vented down to 1 atm and then repressurized to 30 psia using the Saturation Rule [4]. Resultant significant values are as follows:

Initial quantity of liquid & vapor	60,010.6 kg
Liquid & vapor at 1 atm	52,493.2
Blowdown loss	7,517.4 kg
Pressurization liquid loss	224

Net Loss	7,741.4 kg
Net loss percentage	12.9%

As will be shown subsequently, this 2500 gallon loss relatively dwarfs other operating losses and points to the use of a subcooler as described in a following paragraph.

8.3 Piping System Losses

Heat leak of the flow system has been calculated (omitting the two pumps) using optimistic assumptions for insulation effectiveness around valves and riser pipes. The results of these calculations are summarized in Table 3.

Table 3

Piping System Heat Leak and Losses

Item	Unit Heat Leak Watt	No./ Length	Total Heat Leak Watt	Loss gal/hr
Supply line	36.7 w/m	50.3 m	1845.0	10.9
Return line	30.2 w/m	50.3 m	1518.2	9.0
Wet valves	23.5 w	8	187.6	1.1
Vent/relief risers	5.54 w	9	49.8	0.3
Instrument line risers	2.1 w	7	14.6	0.1
Totals			3,615.2	21.4
New Fill Line	32.0 w/m	74.7 m	2,390.8	14.1

8.4 Total Loss in Existing System

Because filling a dewar and blowing it down are batch processes, losses of the existing system are based on filling a dewar from the 10% level up to 28,000 gallons and then making a run at 200 gpm until the level falls to 10%. Data is presented as a series of line items.

(1) Dewar fill: 28,000 - 2800 = 25,200 gallons. Assume fill rate of 200 gpm for 126 minutes or 2.1 hours. Actual filling loss, including valve and coupling, will approximate 16 gal/hr for a total loss of 33.6 gallons. (Actual fill rate would be 200.27 gpm to make up for losses.)

(2) Blowdown/repressurization: loss is approximately 12.9% or (0.129)(28,000) = 3,600 gallons.

(3) Piping System: 21.4 gpn x 25,200/200 x 60 = 45 gallons

(4) Summary:

Fill	34. gallons
Blowdown, etc.	3600.
Piping System	45.
Total	3679. gallons

This does not include continuous dewar losses, pump heat leak, flow work in pipes and higher or lower piping losses as a function of actual flow rate to the tunnel. In any case, it is clear that the dominant loss is the blowdown/repressurizing operation. Even if the pressures are lower than assumed, this loss will approximate 10% of dewar capacity per cycle and represent about 95% of the total liquid nitrogen loss for a tunnel operating cycle from one dewar.

Although there is room for improvement of the hardware, there is more to be gained by a change in procedures. It is recommended that the storage dewars be held at the lowest feasible pressure consistent with purge gas requirements in the tunnel area. (If purge gas is the pacing item, it can be supplied less expensively from a small dewar.) This can significantly reduce blowdown losses and speed transfer from one dewar to the other during sustained operations.

9.0 Recommended System

Cryolab has evaluated the 0.3 m wind tunnel cryogenic system using the following criteria:

- Safety and convenience
- Liquid nitrogen losses
- Economics
- Technical image

Key elements of Cryolab's recommended system are:

* Make entire system operable from a graphic panel in the Control Room.

* Replace foam-insulated piping and valves with a vacuum-jacketed system.

* Replace the blowdown/repressurization procedure with a combination subcooler and vapor/liquid separator to permit continuous operation from either or both supply dewars.

* Refurbishment of both 28,000 gallon supply dewars.

Operation of the cryogenic system from the Control Room adds a measure of safety since pesonnel will not have to enter the liquid nitrogen dewar area for any phase of wind tunnel operations. In addition, at least one less operator will be required, time will be saved and communication improved by centralizing operations where it properly belongs in the Control Room.

Two principal changes are required to bring cryogenic operations into the Control Room: first, all of the functional valves and controllers must be remotely operated and, second, a control panel similar to that shown on Cryolab drawing VJ 10029-4 must be installed in the Control Room with appropriate connections to the cryogenic area. Although the documentation supplied with this report assumes new vacuum-jacketed piping and use of a subcooler, this recommendation for operation from a control panel is independent of other suggested upgrades.

Use of vacuum-jacketed piping is part economics and part aesthetics. Economics show up in lower liquid nitrogen loss rates and lower maintenance costs. Heat leak elements for the vacuum-jacketed system are shown in Table 4 which has the same format as Table 3 for foam-insulated valves and lines.

Table 4

Losses in Vacuum-Jacketed Line System

Item	Unit Heat Leak Watt	No./ Length	Total Heat Leak Watt	Loss gal/hr
Supply line	0.8 w/m	50.3 m	40.2	0.24
Return line	1.1 w/m	50.3	55.3	.33
2 IPS Valve	8.0	7	56.0	.33
3 IPS Valve	20.0	3	60.0	.35
Vent/Relief Risers	1.85	9	16.7	.1
Instrument Line Risers	0.7	7	4.9	.03
Sub-cooler	5.0	1	5.0	.03
	System Totals		238.1	1.41
Fill line	.08	74.7	59.8	0.35

Operating loss in the vacuum-jacketed system is 238 w compared with 3,615 w for the existing system, which saves 21.4 - 1.4 = 20 gallons/hr. of liquid nitrogen. At the assumed rate of $0.3785, this would total $7.57 saved per hour of tunnel operation. Overall economics of the vacuum-jacketed line system are discussed in a following paragraph. No price tag can be put on the aesthetics of a vacuum-jacketed system, but there is no question that this suggested modification would bring the technology level of the cryogenic system up more nearly to that of the wind tunnel itself. Although all details are not included, the revised piping layout shown on Cryolab drawing VJ 10029-3 indicates substantial simplification over the existing layout. Eliminating the necessity to bring valves down so that they can be reached for manual operation is a major factor in simplifying the piping.

Large losses resulting from the current blowdown/repressurization procedure have been quantified in paragraph 7.2. Cryolab's recommended system shown on drawing VJ 10029-2 includes a subcooler and vapor/liquid separator. Details of this device are shown on drawing VJ 10029-1. As a subcooler, a small portion of liquid withdrawn from the supply dewar is directed into the volume surrounding the heat transfer tubes. This liquid is maintained at essentially atmospheric pressure which enables the down-flowing main liquid nitrogen stream to be cooled to about 79 K. The main liquid nitrogen stream enters the top of the subcooler at just below supply dewar pressure. This liquid, along with return liquid from the wind tunnel, passes through the subcooler tubes to pump inlet.

The advantage of the subcooler over the existing system is that only a small portion of dewar contents need be vented down to atmospheric pressure. Thus, the overall venting losses are substantially smaller. For the same initial conditions as discussed in paragraph 8.4, 50 psia saturation, the ratio of subcooler flow to pump inlet flow is 7.8% or 7.24% of the total flow. This compares with 12.9% blowdown/repressurization loss with the existing procedure. 7.24/12.9 = 0.56, making the subcooler loss some 40% less or, for the example of paragraph 8.4, the subcooling loss would drop to about 2,160 gallons for a 1,440 gallon saving per dewar. In round numbers, the subcooler will reduce liquid nitrogen consumption 5% and save about $530 per dewar fill.

Subcooler savings do not include the small contribution due to routing return flow back to the subcooler. In this case, the subcooler first serves as a vapor/liquid separator and then as a subcooler for the remaining liquid. Savings come from the fact that the vapor/liquid return mixture is not vented down to low pressure which preserves a maximum amount of liquid to be recycled. The fact that the tunnel can operate with only one dewar is a convenience because it frees up the second unit to be filled, pressurized or whatever is necessary for almost instantaneous switchover to supply the tunnel operation.

Losses for a dewar operational cycle with the recommended system are calculated to compare with the example of paragraph 7.4.

(1) Dewar fill:

Loss = (2.1 hours)(59.8 + 7 + 0.7) = 141.8 w-hr

= 0.84 gallons

(2) Subcooler:

(0.0724)(25,200 gallons) = 1824.5 gallons

(3) Piping System:

1.41 gal/hr × 25,200/200 × 60 = 2.96 gallons

(4) Summary:

Fill	.84 gallons
Subcooler	1824.5
Piping System	2.96
Total	1828.3 gallons

As in the previous example, this total does not include continuous dewar losses, pump heat leak, flow work in lines and piping cooldown losses. However, on a comparative basis, the recommended system reduces losses about 1851 gallons per dewar most favorably and in excess of 1500 gallons for less optimum conditions, resulting in savings of $568 to $700 per 28,000 gallon cycle.

10.0 Economics of Proposed System

Economic value of the proposed changes are a function of cost, potential savings in liquid nitrogen consumption, wind tunnel usage rate and delivered cost of liquid nitrogen. Assessing the value of labor savings is beyond the scope of this work. Principal assumptions made for economic calculations include tunnel operation at 200 gpm, liquid nitrogen cost of $0.3785 per gallon and 25,200 gallons of liquid nitrogen available from each dewar. Cost estimates used are not firm prices but should be within 10% of Cryolab's subsequent fixed price quotation.

10.1 Cost of Recommended System

Costs summarized are for all of the hardware needed to bring the 0.3 m cryogenic wind tunnel up to the level shown on P and ID drawing VJ 10029-2 for remote operation from the Control Room. Vacuum-jacketed line costs include all attached valves and operators, relief devices and locally mounted instrumentation. The subcooler includes all the controls mounted on it and all of the controls and instrumentation for the system which are to be mounted on the graphic panel shown on drawing VJ 10029-4. Costs do not include on-site installation, but four weeks of field engineering is included as a line item.

Components and Estimated Cost

Principal vacuum-jacketed 3 IPS process lines	$129,166
Auxiliary 1 1/2 IPS lines	29,439
Vacuum-jacketed 1 1/2 IPS fill line	26,879
Sub-total of all vacuum-jacketed lines and attachments	$185,484
Subcooler, attached instruments and controls and Graphic Panel components	80,000
Graphic Panel	4,000
Non-jacketed valves, safety devices and remote instrumentation for dewar vents	8,336
Hardware sub-total	$277,820
System Engineering	12,000
Installation Engineering - 4 weeks on-site in two trips	11,300
Hardware and Engineering	$301,120

These costs do not include minor modifications to existing vent piping manifolds and system installation labor.

10.2 Potential Cost Savings Compared to Investment

Cryolab is not in possession of enough operating data to accurately project a payout for the recommended system based on saving liquid nitrogen. However, two values have been developed which can be used to calculate reasonably accurate payout times: first, the installed cost of Cryolab's recommended system is about $350,000 including an allowance of $50,000 for installation labor and, second, liquid nitrogen saved per 25,200 gallon tankfull should be 1500 gallons or greater (worth $568 at $0.3785 per gallon). With no other consideration, the payout requires 616 tanks of liquid nitrogen, which is the equivalent of 1294 hours of tunnel operation at a consumption rate of 200 gmp. Actual payout can be calculated readily from a projected operating schedule weighted by required tunnel conditions which dictate the rate of liquid nitrogen consumption. For instance, a program of 8 hours per week, 50 weeks per year at 200 gpm would total 400 hours per year leading to payout in 3 1/4 years.

Potential savings from refurbishing the two, 28,000 gallon dewars is fairly clear-cut. Estimated cost of refurbishing each dewar to a loss rate of 28 gallons per day (0.1%/day) is $7500. From an unpumped dewar, this conveniently results in saving 100 gallons per day worth $37.85. Since the dewars are cold continuously, the payout is 198 days. A one year payout requirement would support a refurbishment budget of $13,800 which should considerably exceed commercial cost of doing the work.

11.0 Part 2 Conclusions

The cryogenic system for the 0.3 m wind tunnel can be improved and cost-effective reductions in liquid nitrogen consumption can be realized. Further, operational safety and convenience can be improved significantly. Recommended steps and reasons for them are presented in order of precedence.

(1) Change operating procedures so that liquid in the 28,000 gallon dewars is held at the lowest feasible pressure. This change only involves resetting or replacing the vent pressure switches and, possibly, adding a cut-out switch to the pressure switch circuit. Cost of implementation is negligible, and this change directly impacts blowdown losses which are the largest in the system.

(2) Refurbish the dewars. Cost of implementation is low and payback should be less than one year.

(3) Install a graphic panel in the Control Room and replace remaining manual valves with motor-operated valves to provide safety and convenience of remote operation of the cryogenic system. Payback of this modification is hard

to quantify but, operationally, this is the most significant improvement of the recommendations.

(4) Install a subcooler to replace the present method of subcooling liquid nitrogen supplied to the pumps. Adding the combined subcooler and vapor/liquid separator improves flexibility of operations and results in large liquid nitrogen savings. Payback depends on a number of factors, but liquid nitrogen usage will always be less than with the blowdown/repressurization procedure.

(5) Install vacuum-jacketed pipe and valves. VJ lines by themselves are a slow payback in this facility because there are other, much greater, losses. However, VJ process, auxiliary and fill lines save 33.74 gallons per hour, worth $12.77, over the present installation. More importantly, VJ lines are consistent with the remotely operated state-of-the-art system which Cryolab proposes.

APPENDIX A

Blowdown and Repressurization Losses in a Dewar

Blowdown:

Nomenclature:

M[1] = total initial mass in dewar, kg

M[v] = mass of vapor vented

M[2L] = mass of liquid at blowdown pressure

M[2G] = mass of vapor at blowdown pressure

s[1] = initial unit entropy of dewar contents, j/kg-K

s[v] = average unit entropy of vented vapor

s[2L] = unit entropy of blowdown liquid

s[2G] = unit entropy of blowdown vapor

s[1G] = initial unit entropy of vapor

V = total volume of dewar, cubic metres

S.G. = specific gravity, cubic metres/kg

Equations:

M[1]s[1] = M[v]s[v] + M[2L]s[2L] + M[2G]s[2G] (1)

s[v] = (s[1G] + s[2G])/2 (2)

M[1] = M[v] + M[2L] + M[2G] (3)

V = V[2L] + V[2G] (4)

From which:

M[2L]S.G.[2L] + M[2G]S.G.[2G] = V (5)

$$M[1](s[1]/s[v]-1) =$$

$$M[2L](s[2L]/s[v]-(S.G.[2L]/S.G.[2G])(s[2L]/s[v]-1)-1) +$$

$$V/S.G.[2G](s[2G]/s[v]-1) \qquad (6)$$

Method of solution:

1. Solve (6) for M[2L]
2. Solve (5) for M[2G]
3. Solve (3) for M[v], the vapor vented.

Repressurization:

Nomenclature:

M[G] = mass of liquid vaporized for pressurization, kg.

V[1] = initial vapor volume, cubic metre

V[2] = final vapor volume

D[1] = initial saturated vapor density, kg/cubic metre

D[2] = final saturated vapor density

Equation:

$$M[G] = V[2]D[2] - V[1]D[1] \qquad (7)$$

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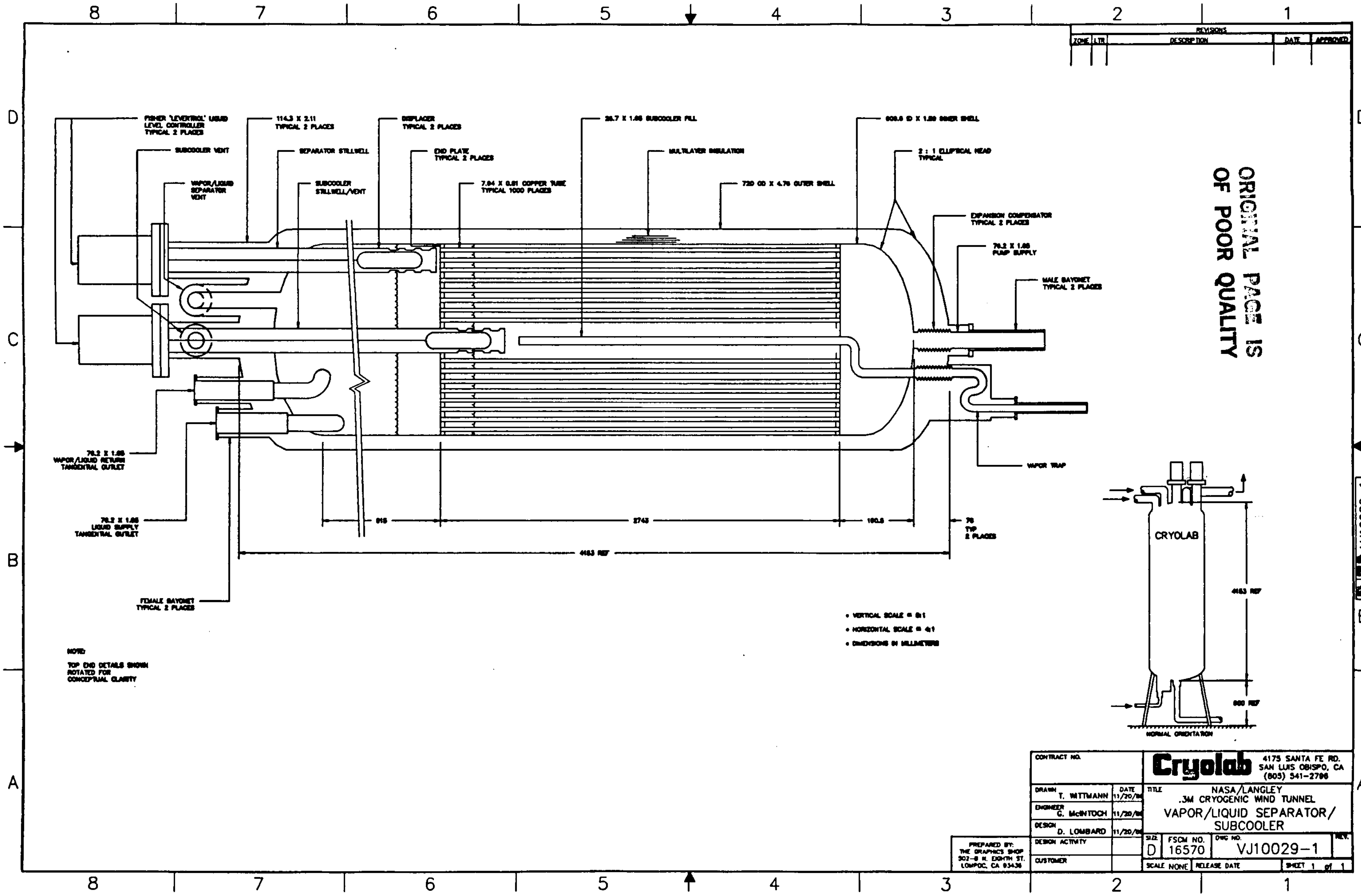

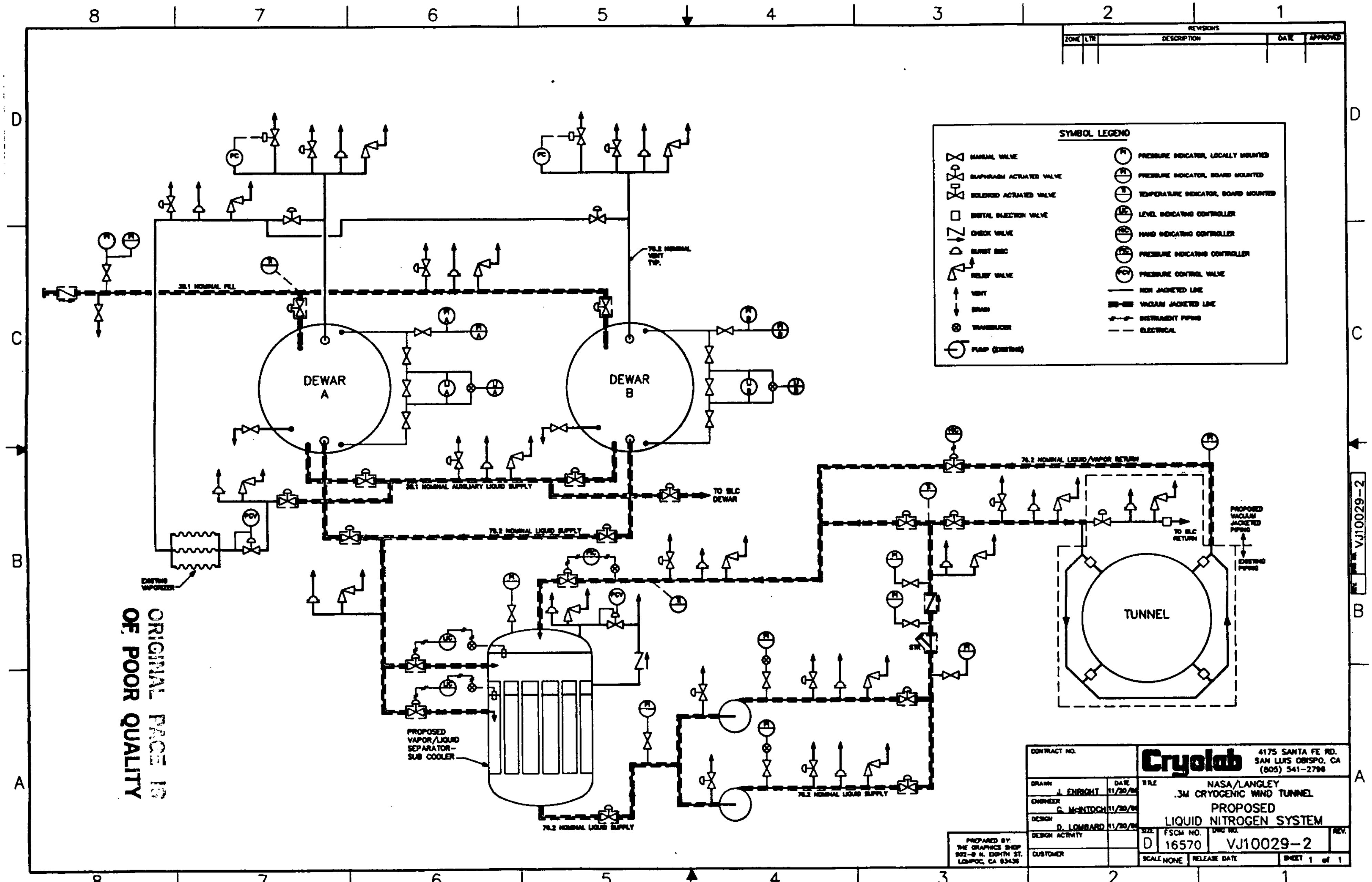
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DIAPHRAGM ACTUATED VALVE
SOLENOID ACTUATED VALVE
DIGITAL INJECTION VALVE
CHECK VALVE
BURST DISC
RELIEF VALVE
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DRAIN
TRANSDUCER
PUMP (EXISTING)
PRESSURE INDICATOR, LOCALLY MOUNTED
PRESSURE INDICATOR, BOARD MOUNTED
TEMPERATURE INDICATOR, BOARD MOUNTED
LEVEL INDICATING CONTROLLER
HAND INDICATING CONTROLLER
PRESSURE INDICATING CONTROLLER
PRESSURE CONTROL VALVE
NON JACKETED LINE
VACUUM JACKETED LINE
INSTRUMENT PIPING
ELECTRICAL
DEWAR A
DEWAR B
TUNNEL
38.1 NOMINAL FILL
76.2 NOMINAL VENT TYP.
38.1 NOMINAL AUXILIARY LIQUID SUPPLY
76.2 NOMINAL LIQUID SUPPLY
76.2 NOMINAL LIQUID/VAPOR RETURN
TO BLC DEWAR
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ENGINEER G. McINTOCH 11/20/86
DESIGN D. LOMBARD 11/20/86
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SAN LUIS OBISPO, CA
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LIQUID NITROGEN SYSTEM
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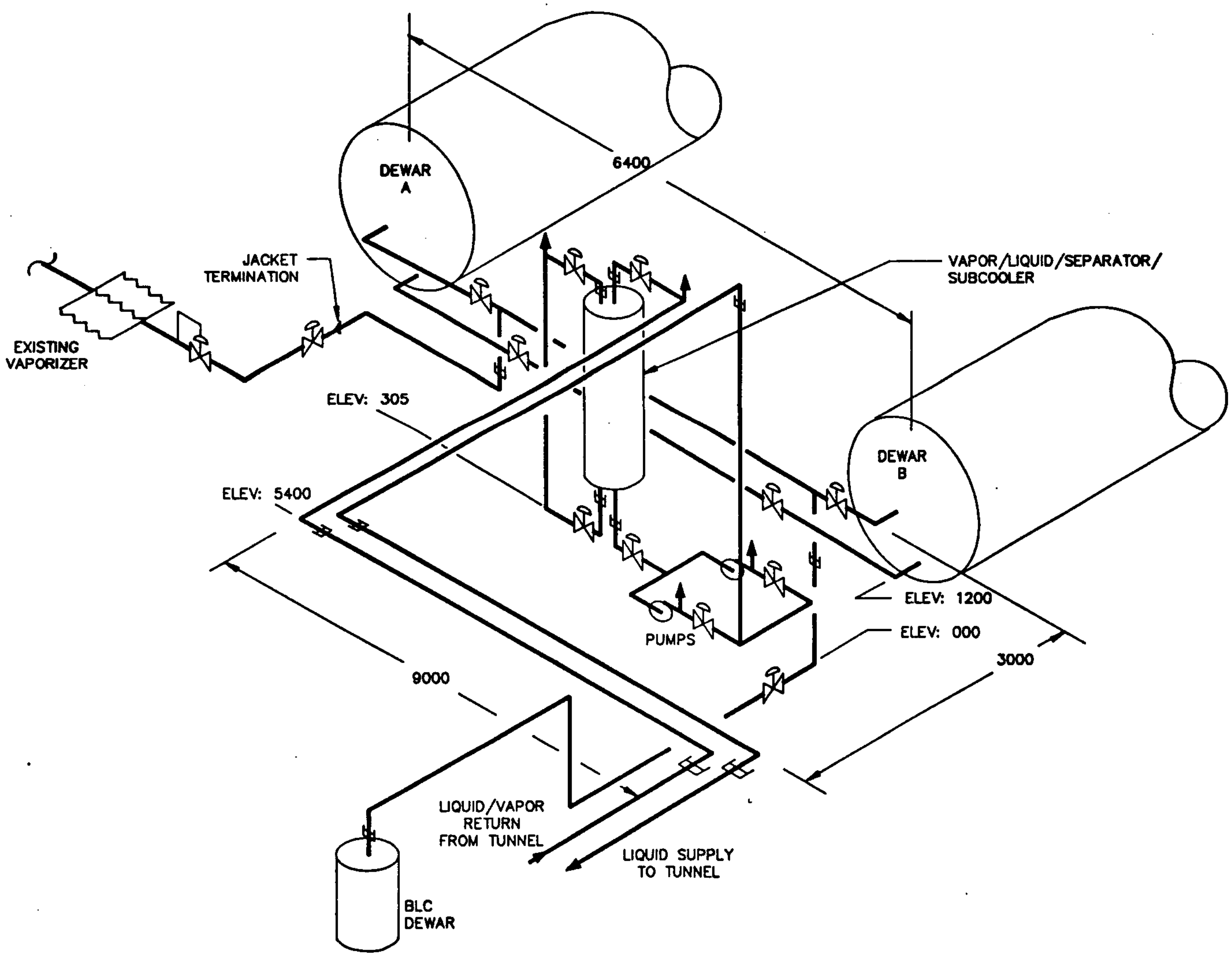

NOTES:

1. PIPING INTO BUILDING & FIELD FABRICATED VENT PIPING IS OMITTED FOR CLARITY.
2. ▲ INDICATES VENT RISER TO INCLUDE REMOTE OPERATED VENT VALVE, RELIEF VALVE & BURST DISC.
3. ALL VALVES SHOWN ARE REMOTE OPERATED ON/OFF VALVES.
4. ╫ INDICATES BAYONET CONNECTION.
5. APPROXIMATE DIMENSIONS IN MILLIMETERS.
6. ELEVATIONS GIVEN ARE ABOVE GROUND LEVEL AND ARE APPROXIMATE.

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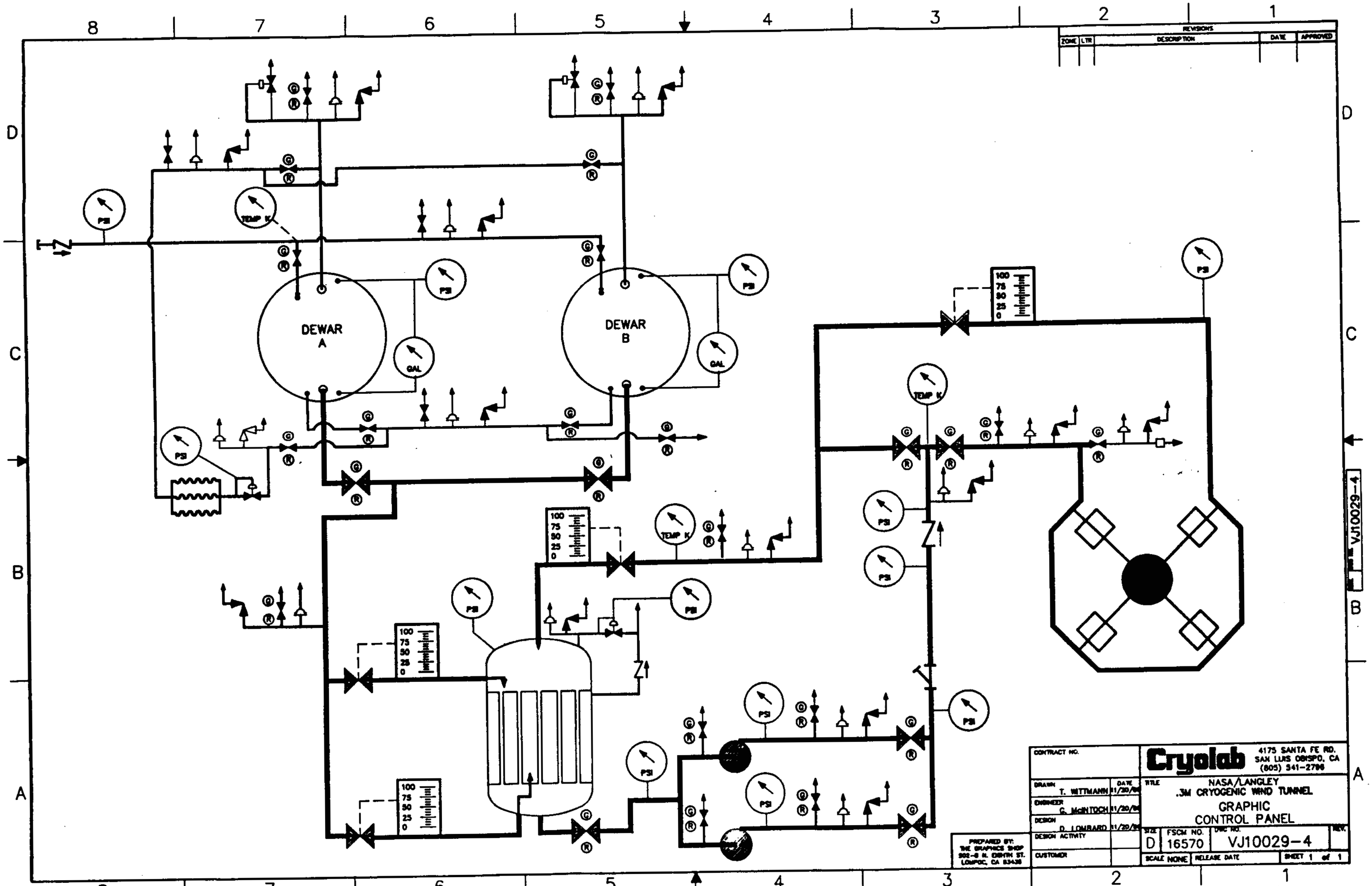

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Langley Technical Monitor: Robert A. Kilgore

16. Abstract

A method of reliquefying from 12 to 19% of the nitrogen exhaust gas from a cryogenic wind tunnel has been developed. Technical feasibility and cost effectiveness of the system depends on performance of an innovative positive displacement expander which requires scale model testing to confirm design studies.

The existing cryogenic system at the 0.3-m transonic cryogenic tunnel has been surveyed and extensive upgrades are proposed. Upgrades are generally cost effective and may be implemented immediately since they are based on established technology.

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