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COST-EFFECTIVE USE OF LIQUID NITROGEN IN CRYOGENIC WIND TUNNELS

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PROJECT OVERVIEW

Cryogenic wind tunnels typically have high liquid nitrogen consumption rates to overcome energy input from circulating fans and heat leak through relatively inefficient thermal insulation. Mass balance in a cryogenic tunnel is maintained by continuous venting of cold nitrogen vapor. No refrigeration is recovered from the vented vapor. Thus, the tunnel heat load is taken primarily by latent heat of vaporization.

The latent heat of vaporization of atmospheric liquid nitrogen is 85 percent of the enthalpy change required to warm the vapor from 77.3 K to 300 K. As a result, in a typical cryogenic wind-tunnel operation, more refrigeration (but not more refrigeration work) is vented than is actually used. This appears to be an obvious application for a reliquefier capable of using refrigeration in the vented vapor. While technically valid, studies have shown that reliquefaction is not economically viable because wind-tunnel-use patterns involve high liquid nitrogen consumption rates during operation followed by lengthy down times. Resultant reliquefier capital costs are disproportionate to refrigeration savings.

The subject reliquefying scheme is an economic compromise between free venting and a reliquefier. In this concept, shown in figure 1, the refrigeration and pressure energy available in the vent vapor is utilized in a system which reliquefies a fraction of the vent flow without power input. An efficient heat exchanger and a wet expander are the only major components. Depending on tunnel operating conditions, this system can reliquefy approximately 20 percent of the vapor flow with an 80 percent efficient expander and nitrogen recovery greater than 15 percent can be achieved for many combinations of tunnel conditions and component efficiency.

A wet expander is the absolutely vital element in the reliquefying system. It must be a positive displacement machine to avoid two-phase flow problems; and efficiency should be at least 70 percent of isentropic to achieve 15 percent recovery at 6 atm, a common tunnel operating pressure. Most of the work reported here deals with adapting William Milburn's nutating expander concept to a low-temperature machine capable of meeting system requirements.

Milburn's prior experience with nutating positive displacement machines involved temperatures near ambient and use of oil lubricated bearings and seals. Adapting this technology to liquid nitrogen temperature requires different materials and a change to dry seals and bearings. Accordingly, early focus of the work was on suitable seal materials and identification of successful cryogenic bearings. The literature survey was followed by design and operation of a seal test device.

Initiation of the seal test work marked the start of experimental problems. Failure of the principal investigator (P.I.) to restrict the scope of the seal tests was mainly responsible. The test device initially designed by Milburn combined seal testing with nutating valve development. This design appeared unworkable at the outset and a complete new design was executed by Cryolab; but it, unfortunately, retained the dual-function concept. Due to a fundamental shaft alignment problem, the seal test device devoured bearings; and much more time was spent modifying and repairing it than accumulating seal wear data. Eventually, some wear data were collected and the Teflon-based Rulon A material top-rated in the literature search was selected for use.

Although seriously delayed by organizational and personnel changes, Milburn produced a credible expander design. The design was reviewed by the P.I. and his associates for Cryolab and was found suitable for fabrication. To keep the work close to Milburn and the P.I., Cryolab elected to have the fabrication done in the Denver area. This was accomplished without significant problems but much more slowly than projected. The machine was assembled, taken apart for cleaning, and reassembled in late September 1989. In order to avoid oil contamination from shop air, the machine was <u>not</u> flow tested prior to shipment to California.

Meanwhile, the P.I.'s base organization, Cryogenic Technical Services, Inc. (CTS), had designed a reliquefaction test system which was fabricated and installed by Cryolab. When the wet expander arrived at Cryolab in early October, it was immediately installed and preliminary test operation was attempted. The machine did not rotate when nitrogen gas was applied. A 1-1/2 horsepower (hp) motoring drive was also unable to cause rotation with or without gas pressure. After several drive and motor iterations, a 15-hp motor did sustain rotation but no net power was produced. To the contrary, when nitrogen inlet pressure was raised to approximately 50 psig, the machine stalled the geared-down drive motor. A high rate of blowby along the crankshaft was also noted.

The serious problems observed prompted the decision to return the wet expander to Colorado for diagnosis and modifications. Disassembly of the machine revealed evidence of minor overheating where the large pressure-loaded Rulon nutating valve plates effectively acted as disc brakes. Calculations by CTS indicated that the combination of area, pressure, and coefficient of friction of Rulon on stainless steel was enough to overcome any possible power developed. It was clear that the nutating valve plates required replacement.

Replacement of the nutating valves was complicated by the fact that budget and time constraints precluded a complete new design. It was essential to retain as much of the machine as possible. Accordingly, CTS designed new cam-operated poppet valves which only required a thicker exhaust static plate and a 1/8-inch-thick shim plate to accommodate the inlet valves. Design and fabrication of the new valve system plus several minor modifications took some 4 months, November 1989 through February 1990. When the modifications were complete, the machine was run on shop air and repeatedly demonstrated its ability to start up and run without any external assistance. Unfortunately, the shop air supply was of limited capacity so that sustained running was not possible; a running time of 1 to 2 minutes depleted the air supply and caused the expander to stop. With this limited success, the expander was partially disassembled, cleaned, reassembled, and returned to Cryolab.

At Cryolab, the expander was again installed in the test stand and the system was set up for operation. To the immense consternation of the P.I. and his Cryolab associates, the modified machine would motor easily with and without nitrogen pressure; but it would not start on its own or maintain rotation without some power from the electric motor. Subsequent trouble shooting entailed removal and disassembly/reassembly of the machine on a 2-day schedule for some 10 days--a daunting effort considering the 1800-lb weight of the expander. Trouble shooting covered a number of minor areas including lapping the inlet valves to improve sealing. It was finally concluded that the exhaust valves were timed to close too soon and the four exhaust cams were milled to hold these valves open longer. With this modification, the machine proved able to start on its own and to generate a very modest amount of net power. (No explanation was ever found for the earlier ability of the machine to run in Denver but not after it was returned to Cryolab.)

The expander ran well enough after the exhaust cams were modified that other problems became noticeable. In particular, poor rotating balance was observed and speed diminished when pressure was increased above about 40 psig. Poor balance was judged a minor, fixable problem and the pressure/performance relationship was deferred in favor of collecting some kind of data. This effort was short lived because the machine seized before it was completely cooled down. The subsequent teardown revealed that one of the main bearings had failed and that the other was in very bad condition. Also, the combination of dynamic operation and vibration had caused two inlet valves and one exhaust valve to fail.

In a final repair effort, bearings with composite ball spacers were obtained and all of the valves were returned to working order. These repairs enabled the machine to start readily and it ran better than previously. In fact, its ability to rev relatively freely accentuated the balance problem, particularly at speeds over 400 rpm. Also, raising the nitrogen gas pressure to 45 psig caused the expander to stall. Despite these problems, instrumentation was set up for a low-pressure run and cooldown was started. Cooldown proceeded at about 300 rpm and 25-to 30-psig inlet pressure. The machine ran acceptably at first but began to lose torque as the 30-minute cooldown period progressed.

Toward the end of this period, the machine stalled intermittently; but it could be restarted and operation continued until a final stall occurred at an inlet temperature of 122 K. After the final stall, the machine could be rotated easily while still cold but it would not restart. A subsequent teardown revealed that the beryllium copper torsion spring on one inlet valve was broken and the linkage on a second inlet valve had shaken apart. Momentary early operation at speeds above 1000 rpm was thought to have contributed to the inlet valve failures. The test program was ended at this point.

The decision to end testing was based on several factors including expiration of the project budget and contract period. Short-term problems included the need to acquire and fabricate a new beryllium copper inlet valve spring and the more complex task of balancing the machine. Poor dynamic reliability of the valves and increase of internal friction, probably due to the cross slides, at higher pressures were more fundamental problems with solutions requiring major redesign and rework. No quick fix of these items was projected.

Overview conclusions include:

A. Initial mechanical design of the wet expander was nonfunctional.

B. Except for problems related to dry bearings, difficulties with the machine were not related to cryogenics.

C. The large size of the prototype machine added to project costs in initial fabrication and was a burden on the development program because the machine was difficult to handle and laborious to work with.

D. As a corollary to item C, chances of success of the modified valves would have greatly improved had it not been necessary to salvage as much as possible from the existing machine.

E. The cross-slide piston seals appear to be nonfunctional. This seems to be the only area requiring fundamental redesign in order to produce a viable nutating wet expander.

F. The bearing problem is solvable. Although not readily available in the required size, ball bearings with Teflon ball separators have performed satisfactorily in cryogenic applications. Diamond coated balls are becoming available and are almost certain to work on cryogenic machines.

G. The subject work did not verify the choice of a nutating expander over a piston machine. The nutating machine is more complex internally than a piston expander but it appears more suitable for high-volume, relatively low-pressure flows typical of cryogenic wind tunnels.

H. The concept of partial reliquefaction of vent nitrogen from wind tunnels is valid. Output of the revised "RECOVERY" program shows that reliquefaction of 15 to 20 percent of the tunnel vent flow is feasible for a wide range of operating conditions.

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1.0 Introduction

In Phase I, a simple cryogenic wind tunnel partial reliquefaction scheme, figure 1, was introduced. Manual and preliminary computer calculations indicated that the proposed system could reliquefy between 15 and 20 percent of wind-tunnel vent flow "free" of power input and with relatively inexpensive equipment. A positive displacement wet expander was identified as the key element in the system. Further, a positive displacement nutating expander developed by Milburn Technologies was proposed for this application because of its high-volume, uniflow characteristics.

The Phase II program was intended to prove out the concept. Milburn's ambient temperature expander design was to be modified for low temperature operation and a prototype reliquefier built to test it. The machine was sized to handle one-fourth of the nominal vent rate from the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) at NASA Langley Research Center. Approximately 40 percent of the project budget was allocated to the design and fabrication of the nutating wet expander. The second major task was to design and fabricate a reliquefier test facility at Cryolab. Using this facility to test the system was the third major task. Cryogenic seal studies and testing and upgrading the "RECOVERY" software program were subsidiary tasks. The technical results of this work and relevant conclusions are presented herein.

2.0 Wet Expander Development

The goal of this major element of the project was to develop a nutating wet expander for nitrogen having a volumetric flow of 0.0236 m^3/s (50 cfm). Nominal design pressure was 6 atm (absolute) with an operating range from 4 to 8 atm. Inlet quality was to range from 90 to nearly 100 percent (all vapor). Minimum acceptable

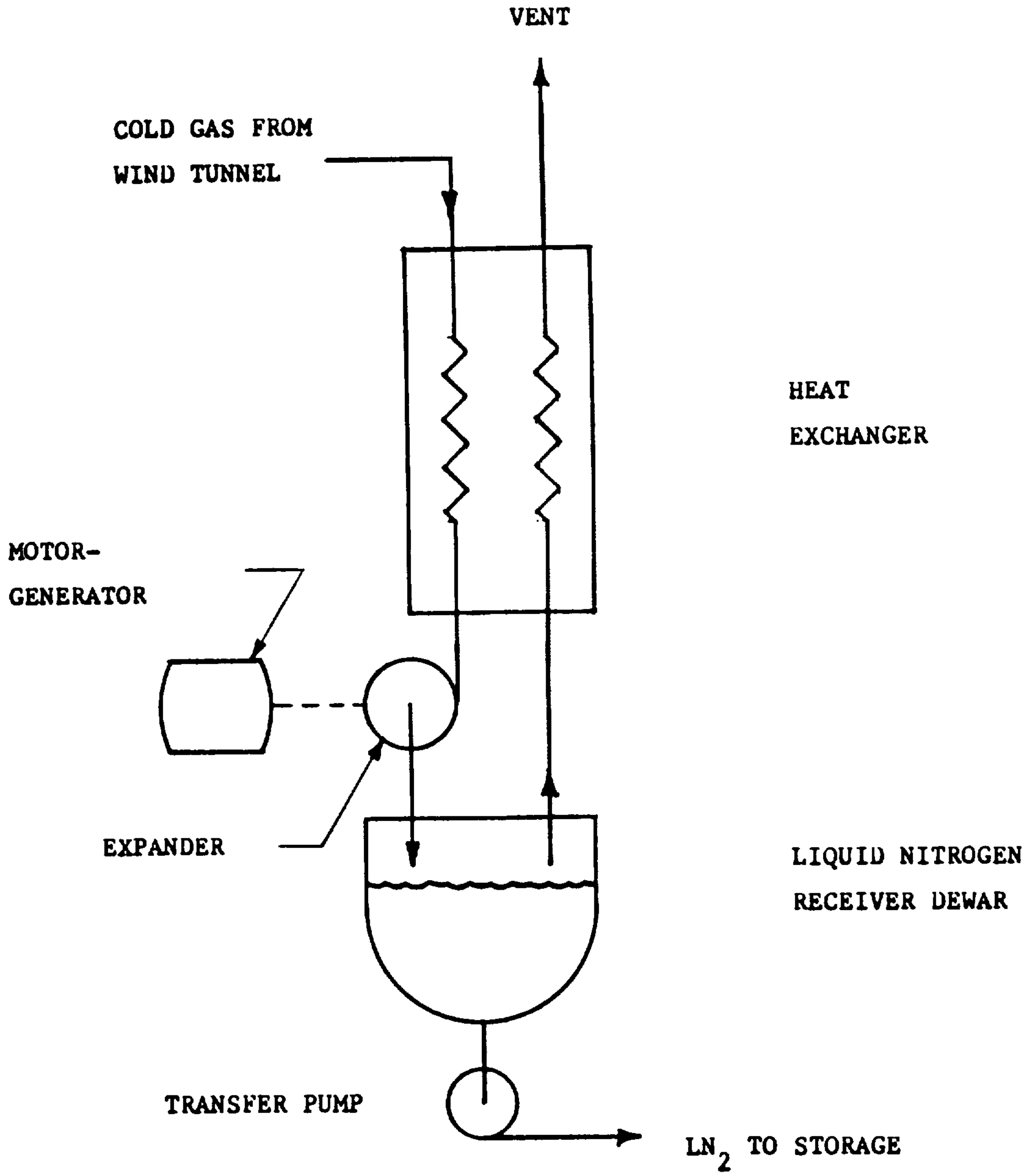


FIG. 1
COLD GAS RELIQUEFIER

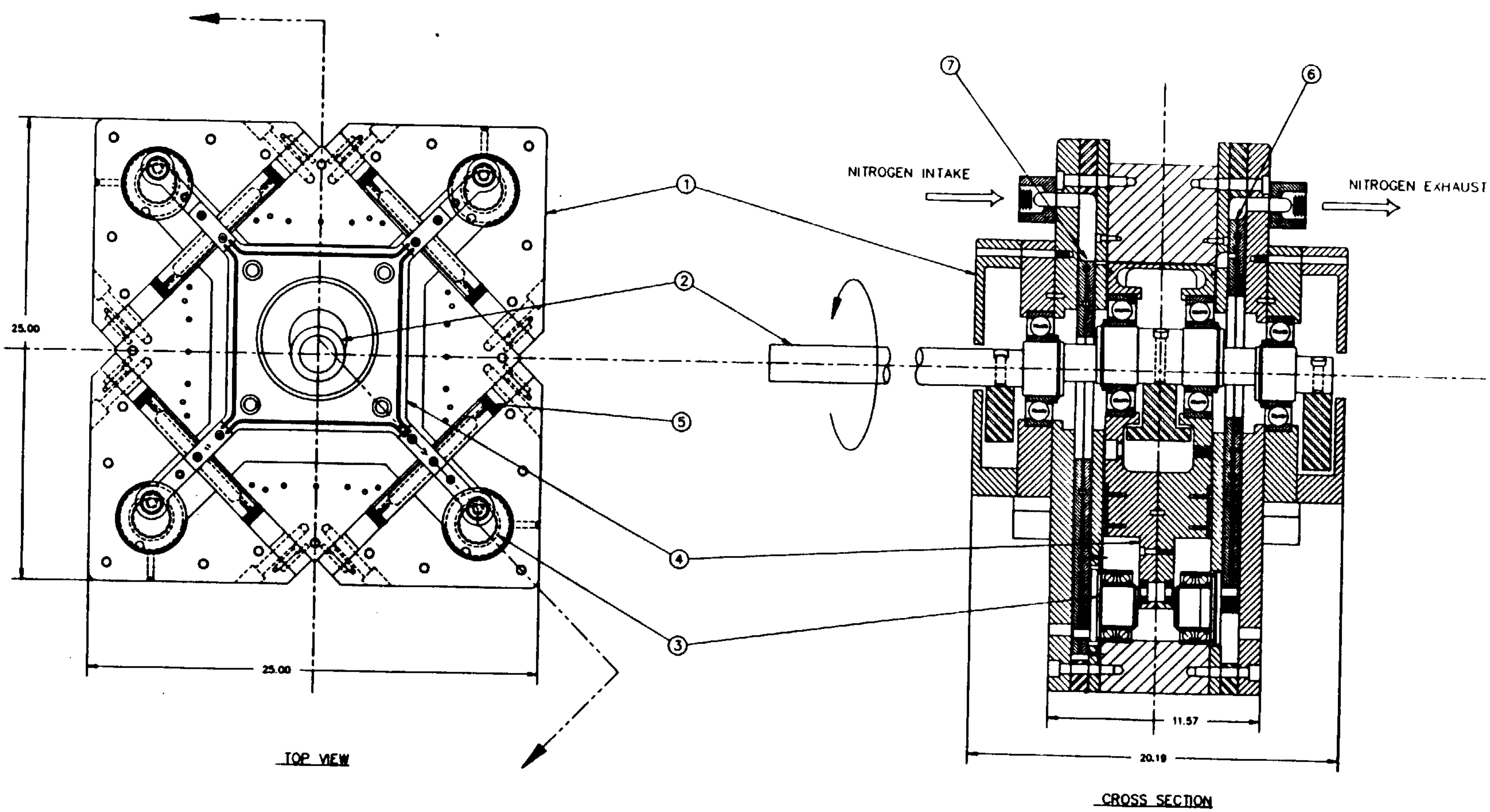
isentropic efficiency was 70 percent and the design goal was 85 percent. The machine was to be operated with a vertical axis so that nitrogen flow would have a straight-through, downward path. Machine speed at rated capacity was 1200 rpm.

2.1 Initial Design

Assembly of Milburn's wet expander is shown on Dwg. MN-001. It is immediately evident that this machine, mostly stainless steel, is a large and heavy assembly. Actual weight is approximately 1830 lb (830 kg). Principal elements of the machine are identified and details are shown in subsequent drawings.

Functioning of the nutating wet expander can be grasped by study of Dwg. MN-001 and supporting photographs. First, note that the case is a bolted assembly of four corner pieces, four internal wedges, and eight rectangular spacer bars. A photograph of these pieces in position for assembly is shown in figure 2. Item 4, the nutating assembly, moves within the case but does not rotate because of the four idler assemblies (item 3). The nutating assembly (piston) is shown in the top dead center (TDC), minimum clearance position relative to the upper volume; the right hand volume is halfway through its exhaust stroke; the left hand volume is halfway through its expansion stroke; and the bottom volume is fully expanded at bottom dead center (BDC). A photograph of the nutator installed in the case, rotated 180°, is shown in figure 4.

Other features to note on Dwg. MN-001 are the eight slide assemblies (item 5) and the nutating valve assemblies (items 6 and 7). The slide assemblies, also shown in figure 4, are pressure loaded to press against the nutator arm extensions to seal the four working volumes from each other. Friction in this mechanism may contribute to stalling of the expander at higher operating pressures. The Rulon nutating valve plates are timed by the location of driving pins on the idler eccentrics. A set of the valve plates in place on the eccentrics is



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6	1		EXHAUST VALVE ASSEMBLY		[illegible]
5	8		SLIDE ASSEMBLY		[illegible]
4	1		NUTATOR ASSEMBLY		[illegible]
3	4		IDLER ASSEMBLY		[illegible]
2	1		CRANK SHAFT ASSEMBLY		[illegible]
1	1		CASE ASSEMBLY		[illegible]

Milburn Labs
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CHECKED		
ENG. MGR.		

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TITLE NITROGEN MOTOR ASSEMBLY

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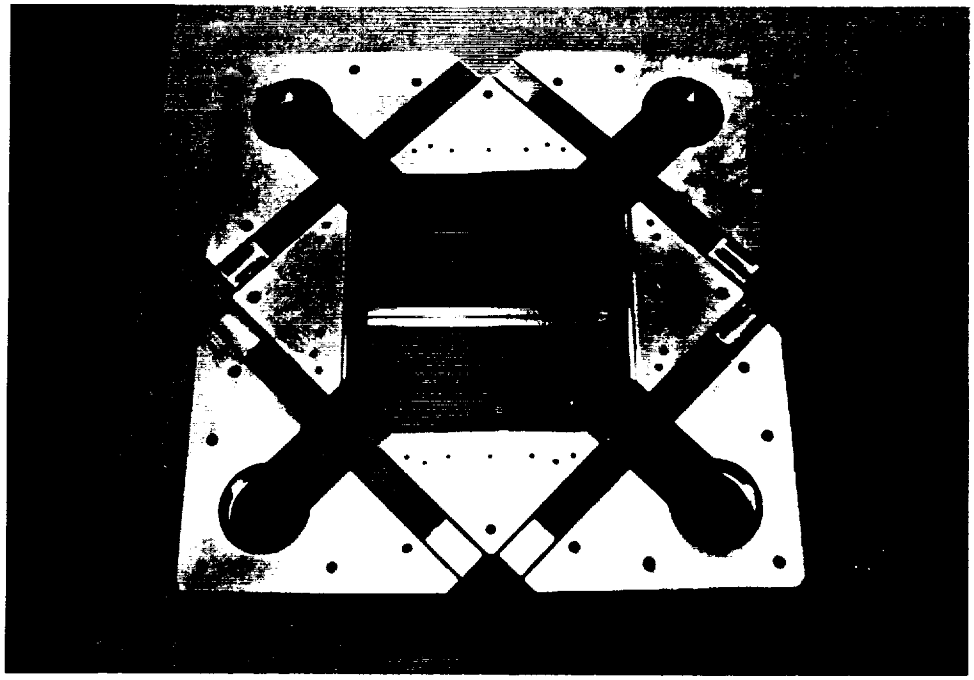

Fig. 2
Nutating Expander Case Assembly

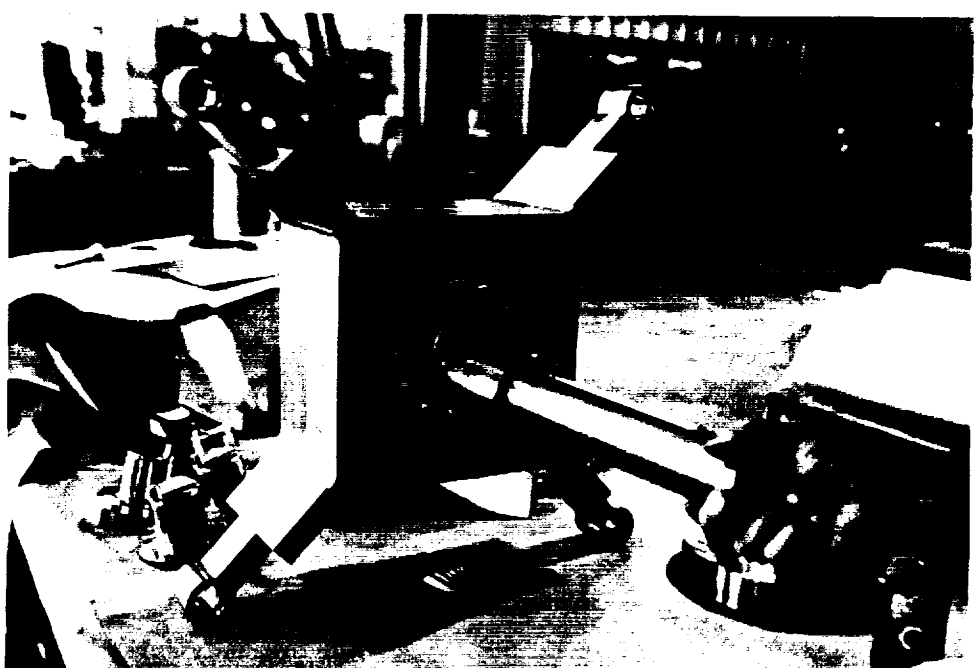

Fig. 3
Nutating Assembly and Crankshaft

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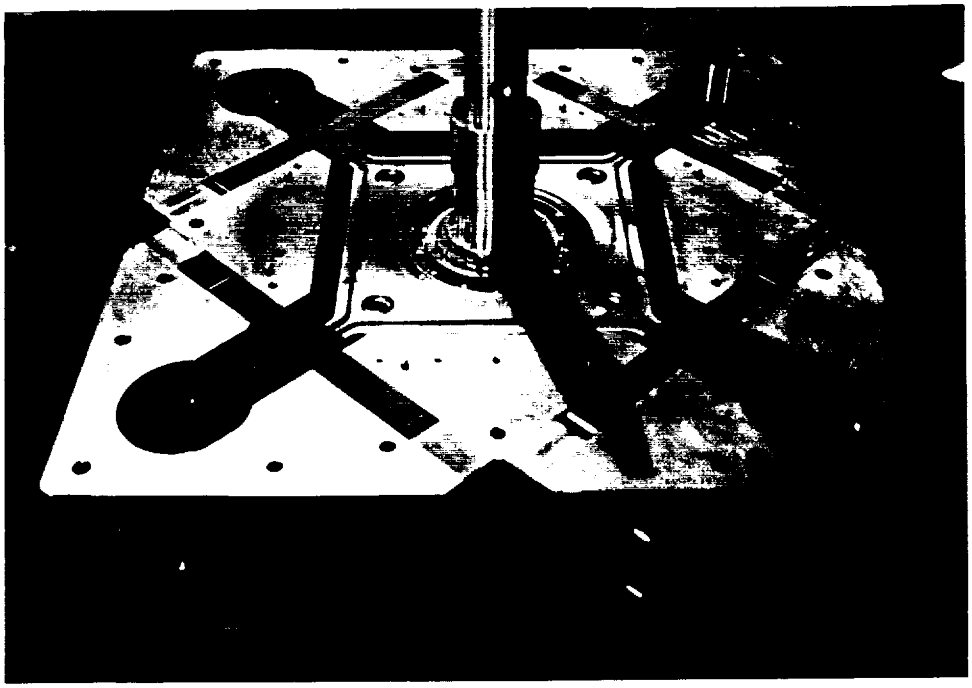


Fig. 4
Nutator Installed in Case

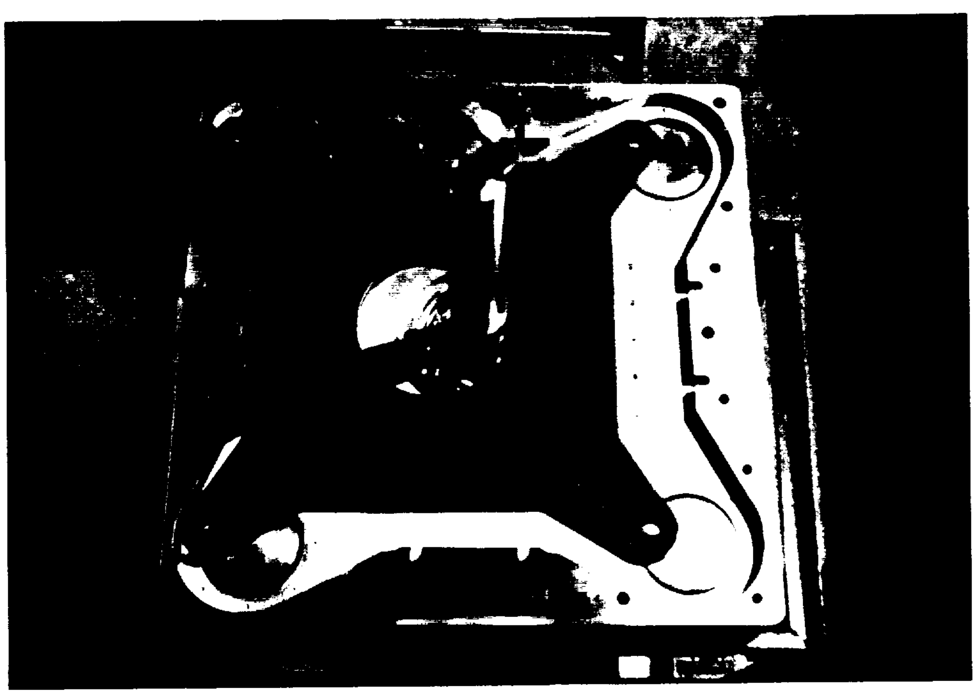


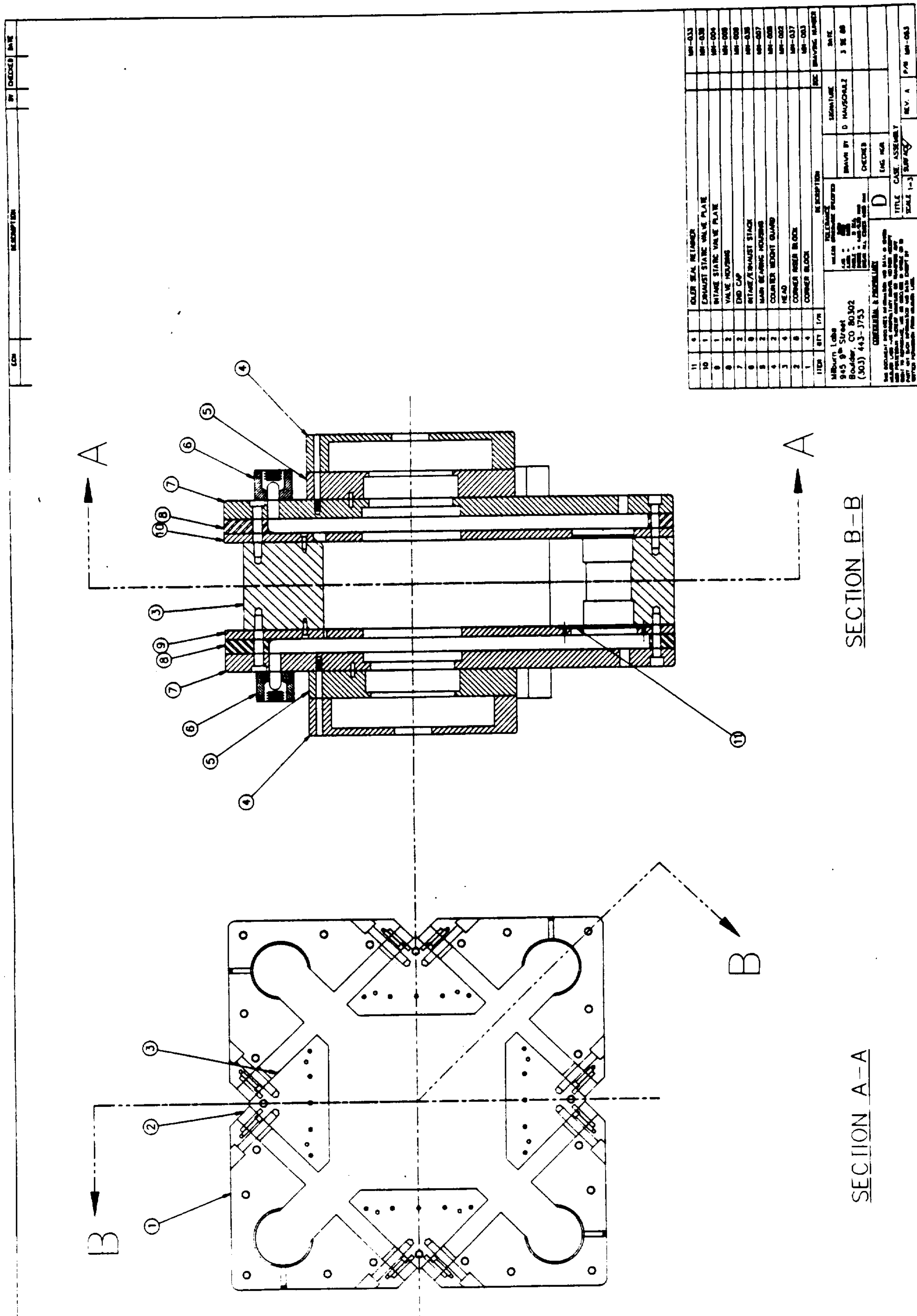
Fig. 5
Rulon Nutating Valve Plates

shown in figure 5. Large differential pressure forces between the nutating valves and static plates produced high frictional forces which were in excess of the torque generated. This resulted in the machine being inoperable. The cross section of Dwg. MN-001 also shows that gas leakage parallel to the Rulon plates found an easy exit in either direction along the unsealed crankshaft.

Other details of the initial design are shown on Dwgs. MN-053, MN-054, and MN-057. Dwg. MN-053 shows the Case Assembly as described above with identification of the major parts. Dwg. MN-054 shows the Nutator Assembly including seal strips and Rulon pads on the extension arms. The Rulon seal strips backed by wave springs appeared to work effectively and showed little evidence of wear throughout the program. Dwg. MN-057, Crankshaft Assembly, shows the crankshaft with bearings and counterweights installed. Because bearings with Teflon ball spacers were not readily available in the required sizes, items 6 and 10 are called out with bronze ball spacers. One of the outboard bearings failed in operation and caused the crankshaft to seize and the other was seriously worn at this point. Figure 6 is a photograph of the worn bearing showing "gold" colored balls coated with bronze particles.

2.2 Performance of Initial Design

As reported in the Overview, the initial design would not run when supplied with nitrogen gas pressure. It could be driven with a 15-hp electric motor but no useful work was generated. A subsequent teardown revealed some discoloration of the nutating valve plates due to friction heating. Calculations confirmed that the product of valve plate area, differential pressure, and coefficient of friction of Rulon on stainless steel produced more braking torque than the machine could generate. This prompted the decision to design an alternate valve system.



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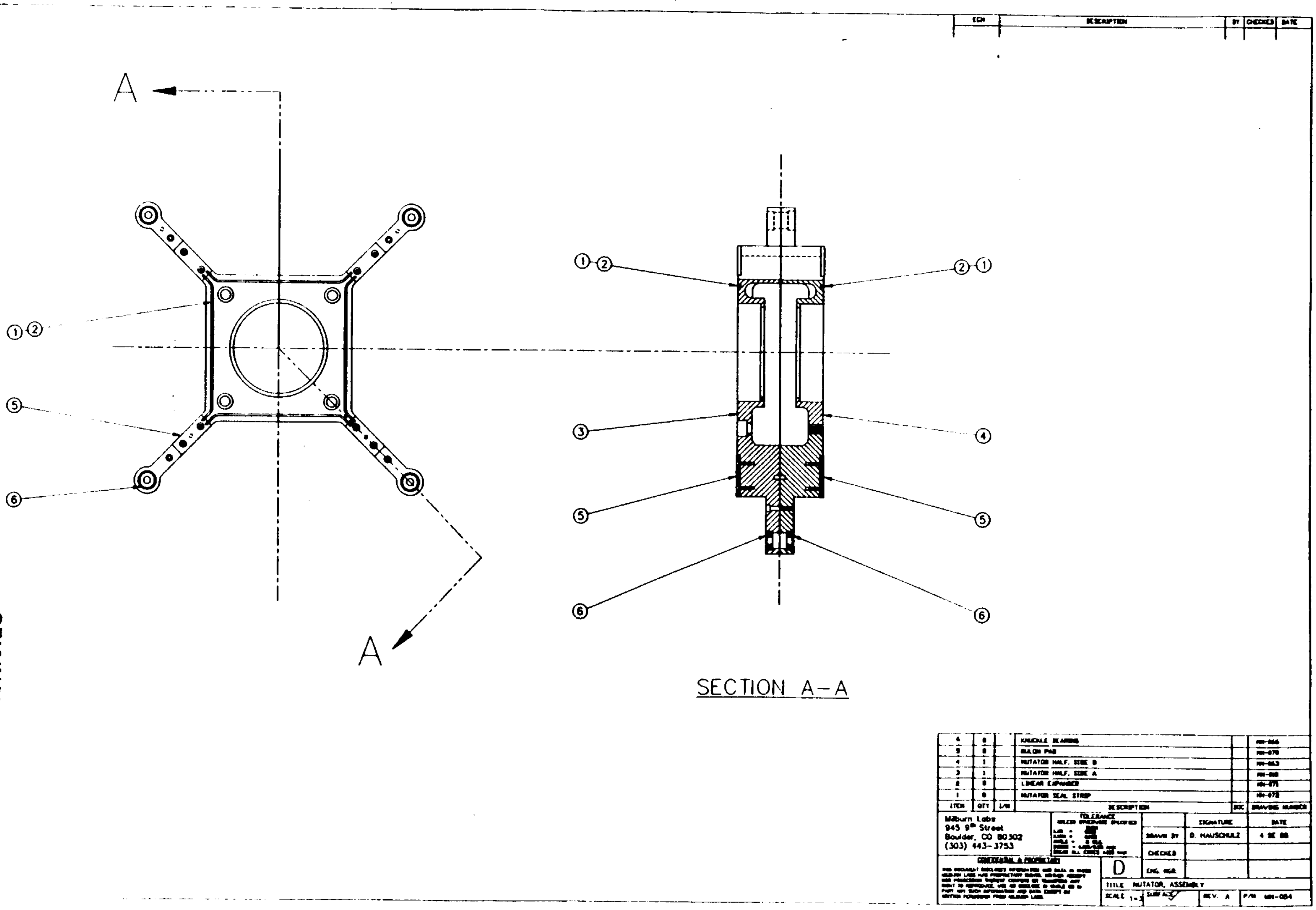
A
A
SECTION A-A
1 2
3
4
5
6
ECN
DESCRIPTION
BY
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DATE
6 KNUCKLE BEARING
5 BULON PAD
4 1 NUTATOR HALF, SIDE B
3 1 NUTATOR HALF, SIDE A
2 LINEAR EXPANDER
1 NUTATOR SEAL STRIP
ITEM QTY U/M DESCRIPTION DOC DRAWING NUMBER
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TOLERANCE
SIGNATURE
DATE
DRAWN BY D. HAUSCHULZ
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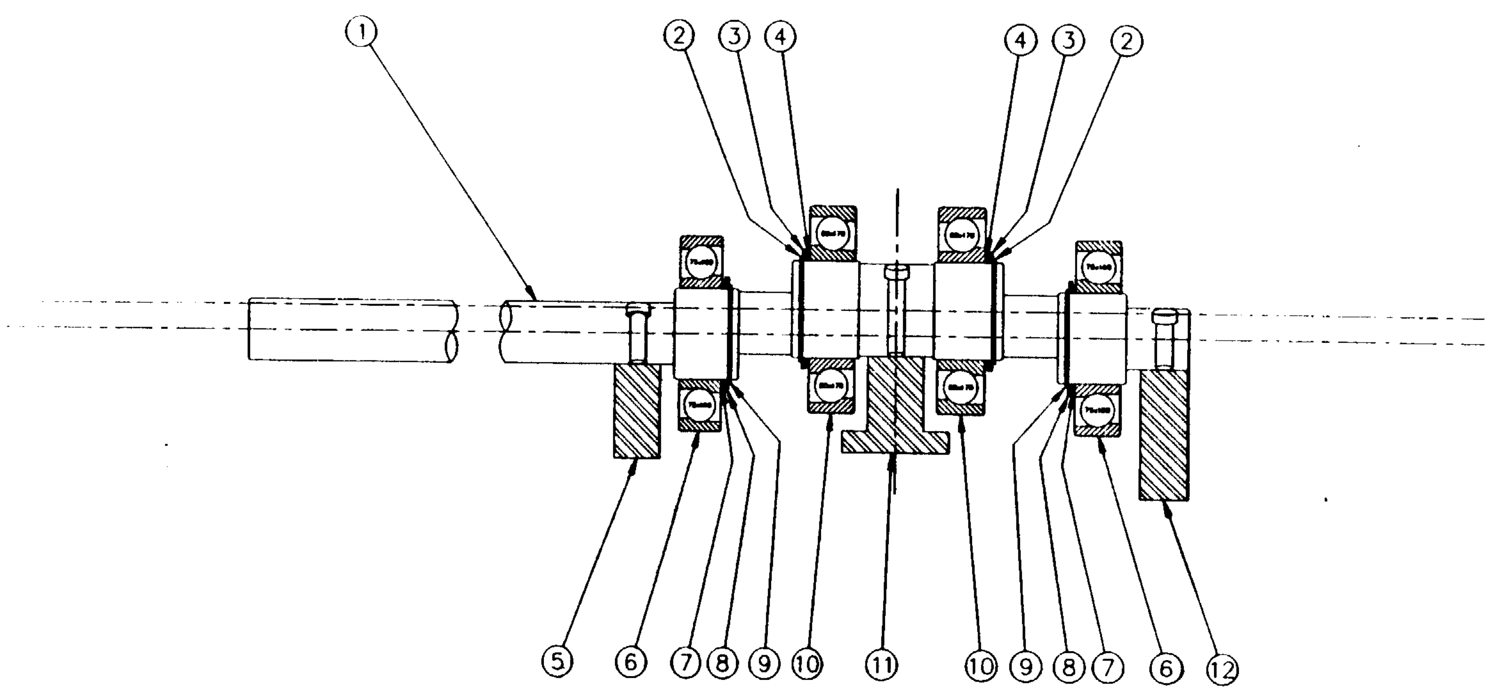
TITLE NUTATOR, ASSEMBLY
SCALE 1-1
SURFACE
REV. A
P/N MN-084



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11	1		INSIDE COUNTER WEIGHT		[illegible]
10	2		MAIN ECCEN BEARING, FAFNIR 7316WN WITH TCGF CYL		[illegible]
9	2		SNAP RING, WALDES TRUARC 5100-283		[illegible]
8	2		WASHER, 75 mm		[illegible]
7	2		WAVE SPRING, SMALLEY SSR-0337-S17		[illegible]
6	2		MAIN BEARING, FAFNIR 7315WN WITH TCGF CYL		[illegible]
5	1		OUTSIDE COUNTER WEIGHT, INTAKE		MH-047
4	2		WAVE SPRING, SMALLEY SSR-0362-S17		[illegible]
3	2		WASHER, 80 mm		[illegible]
2	2		SNAP RING, WALDES TRUARC 5100-315		[illegible]
1	1		CRANK SHAFT		[illegible]

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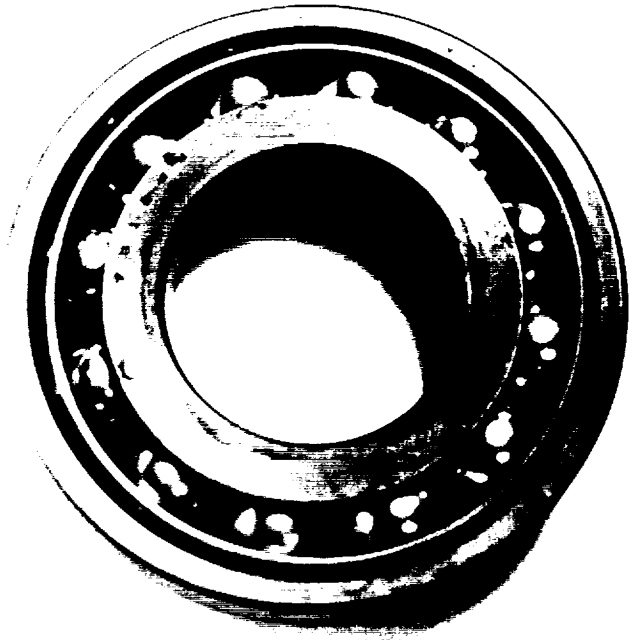

Fig. 6
Worn Main Bearing

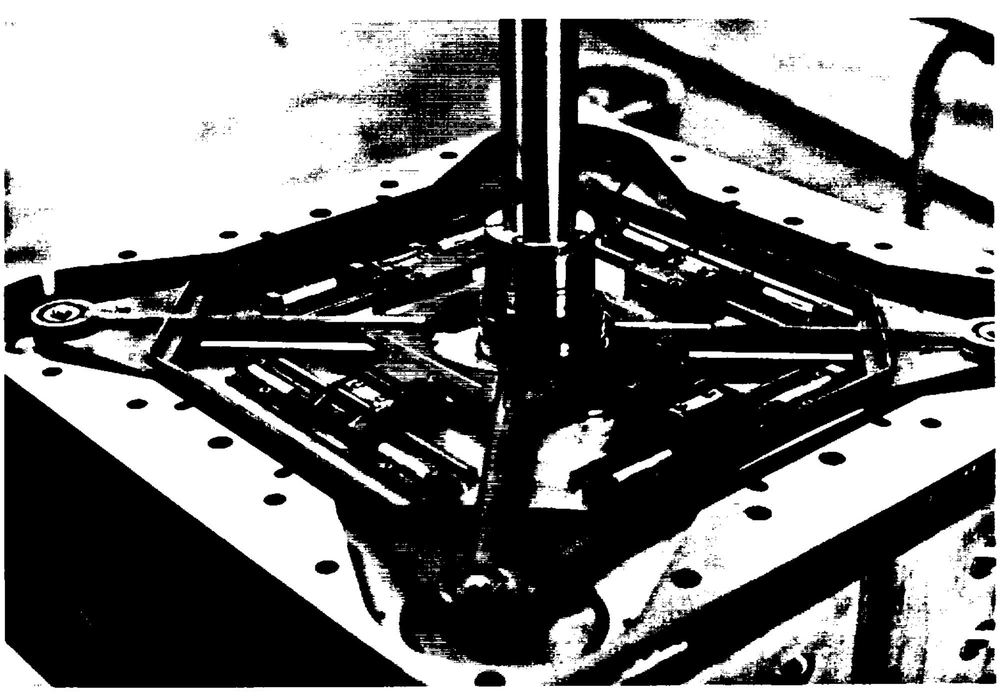

Fig. 7
Inlet Valves and Cam

2.3 Valve Redesign

Redesign goals were to produce valves with minimal drag on the machine, which would utilize all or essentially all of the existing hardware and would have actuators permitting easy timing changes. Low leakage rates and use of gas pressure to augment closing forces were also desired. The need to retain existing hardware ruled out the first-choice arrangement which was to install externally cam-actuated poppet valves. Instead, the redesign was based on internal cams operating off the idler eccentrics with linkage-driven poppet valves. This was not an attractive choice, but it was possible to do with only minor changes in most of the machine.

The redesigned inlet valve system is shown on Dwg. D-1960. It consists of a lightweight stainless steel cam assembly, replaceable cam blocks, and valve linkage assemblies closed by beryllium copper torsion springs. Section Dwg. D-1961 shows additional details of the valve linkage, newly installed sealing plates, and the housing spacer which was required to provide valve linkage clearance. The figure 7 photograph shows the cam and four valves. (KEL-F strips fit into the original valve slots under the brass rods. Beryllium copper torsion springs with tubular Teflon spacers are shown outboard of the valves.)

The revised exhaust valve system is shown on sheets 1 and 2 of Dwg. D-1971. A section view appears on sheet 1 and the cam detail is shown on sheet 2. This arrangement also features replaceable cam blocks and pressure closing poppets. The long, slender poppets for both the inlet and exhaust valves are very poor mechanical and fluid-flow configurations; but they fit existing slots in the static valve plates.

2.4 Performance of Modified Expander

The modified expander was tested on shop air in Colorado before shipment to Cryolab. Within limits of the air supply, the machine

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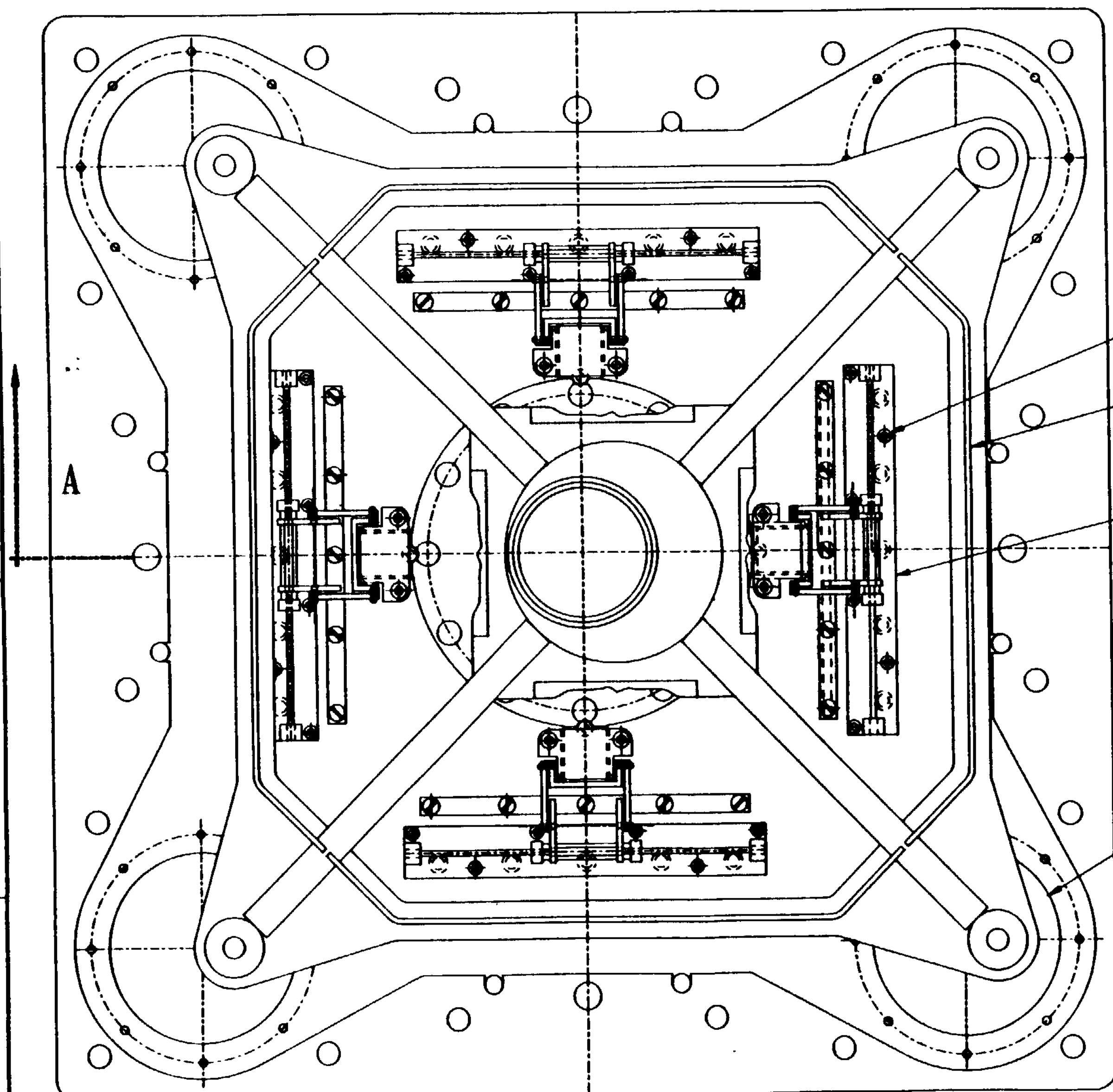


A

NOTE: SEE DRAWING D-1961 FOR SECTION A -- A

ITEM NO.	SIZE	PART NO	QTY	TITLE	MATERIAL SPECIFICATION
4	C	2008	4	IDLER ECCENTRIC, INLET VALVE	
3	D	1982	4	TURBINE INLET VALVE	
2	D	1977	1	TURBINE INLET VALVE CAM	
1		#10 - 24UNC	24	SOCKET HD. CAP SCREW 1/2" LG.	18 - 8 S.STL.

CRYOGENIC TECH. SERVICES, INC.

TURCINE INLET VALVE & CAM

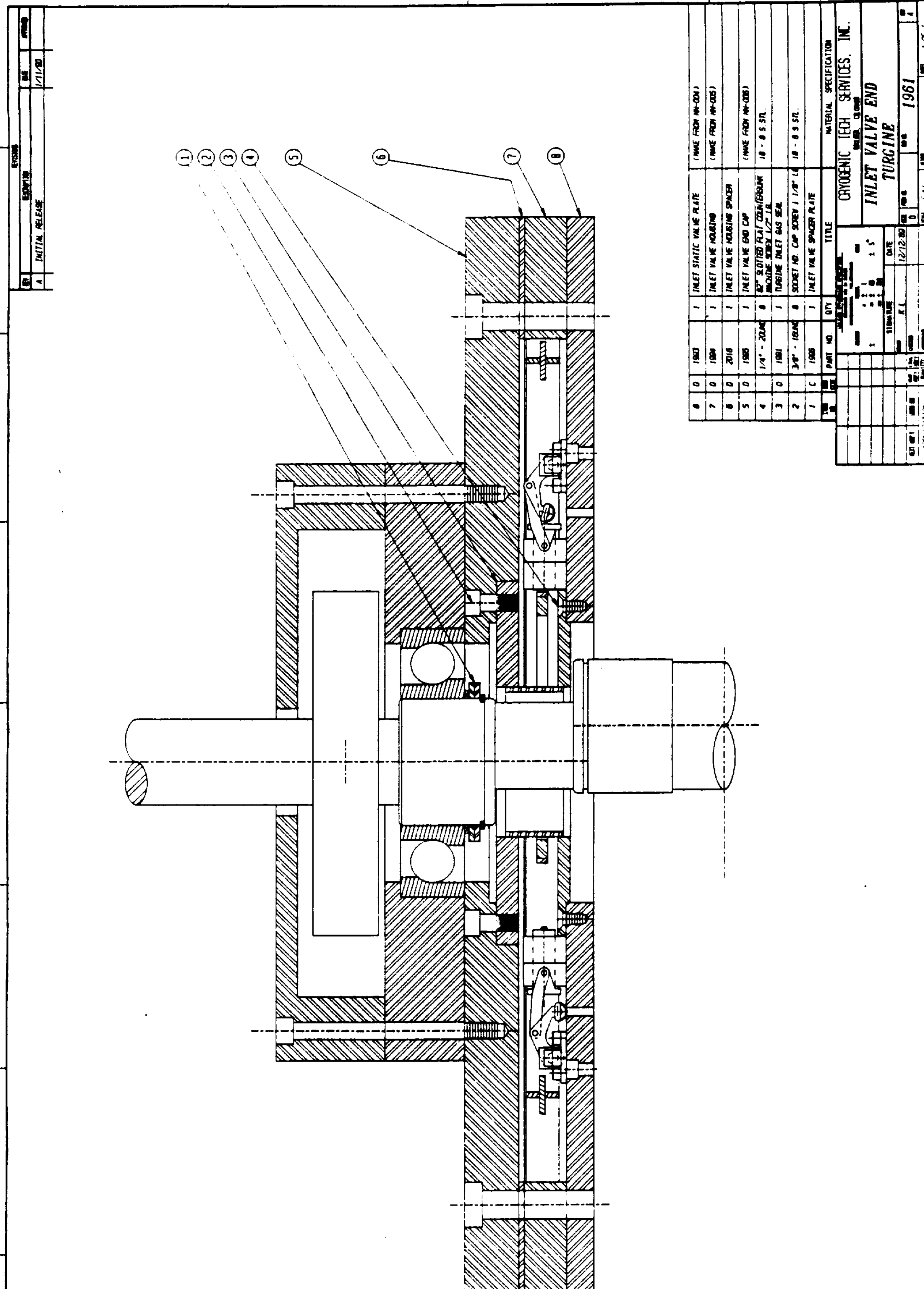
K.L. 12/12/89

1960

SCALE 3/4" = 1"

SHEET 1 OF 1

APPLICATION



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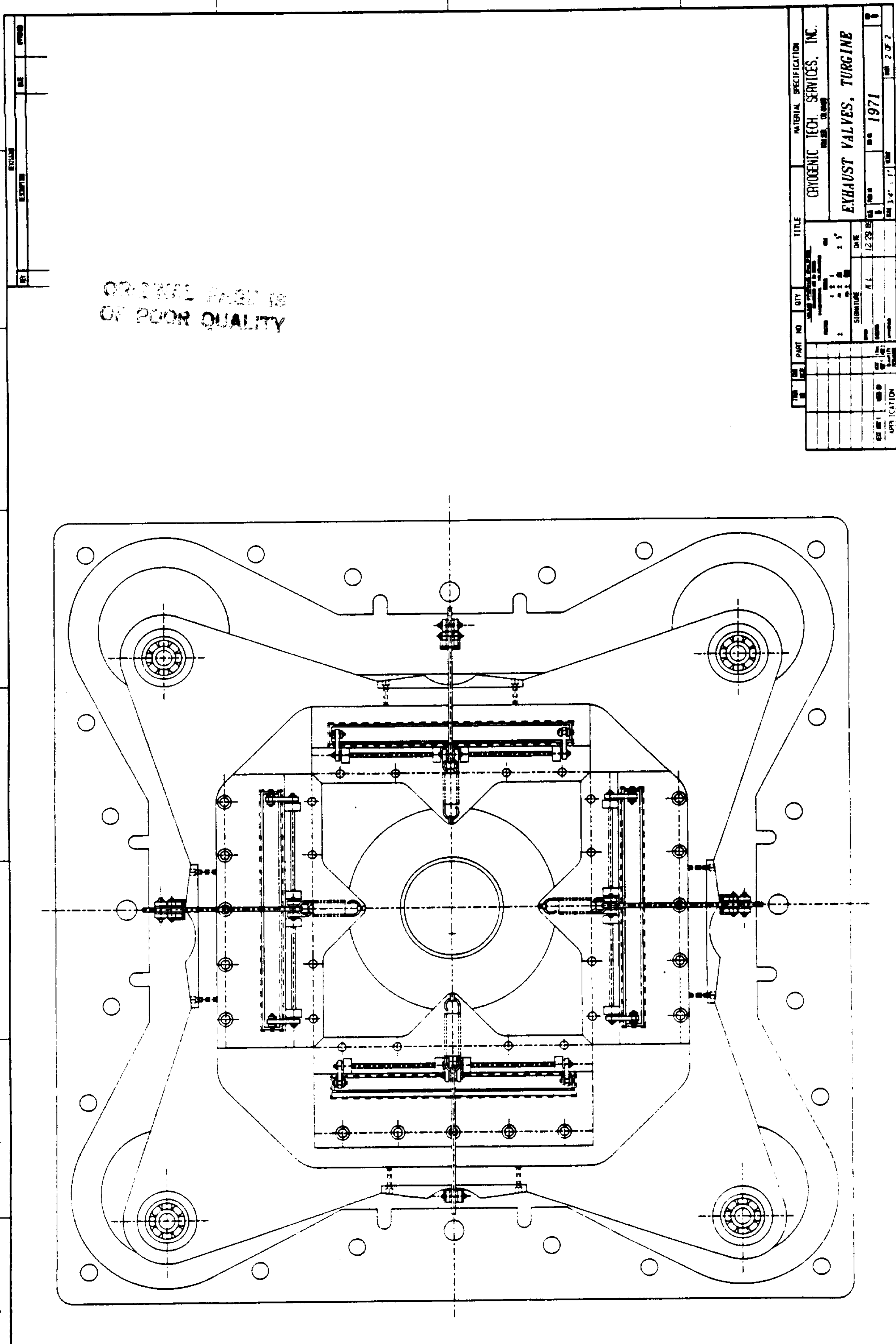
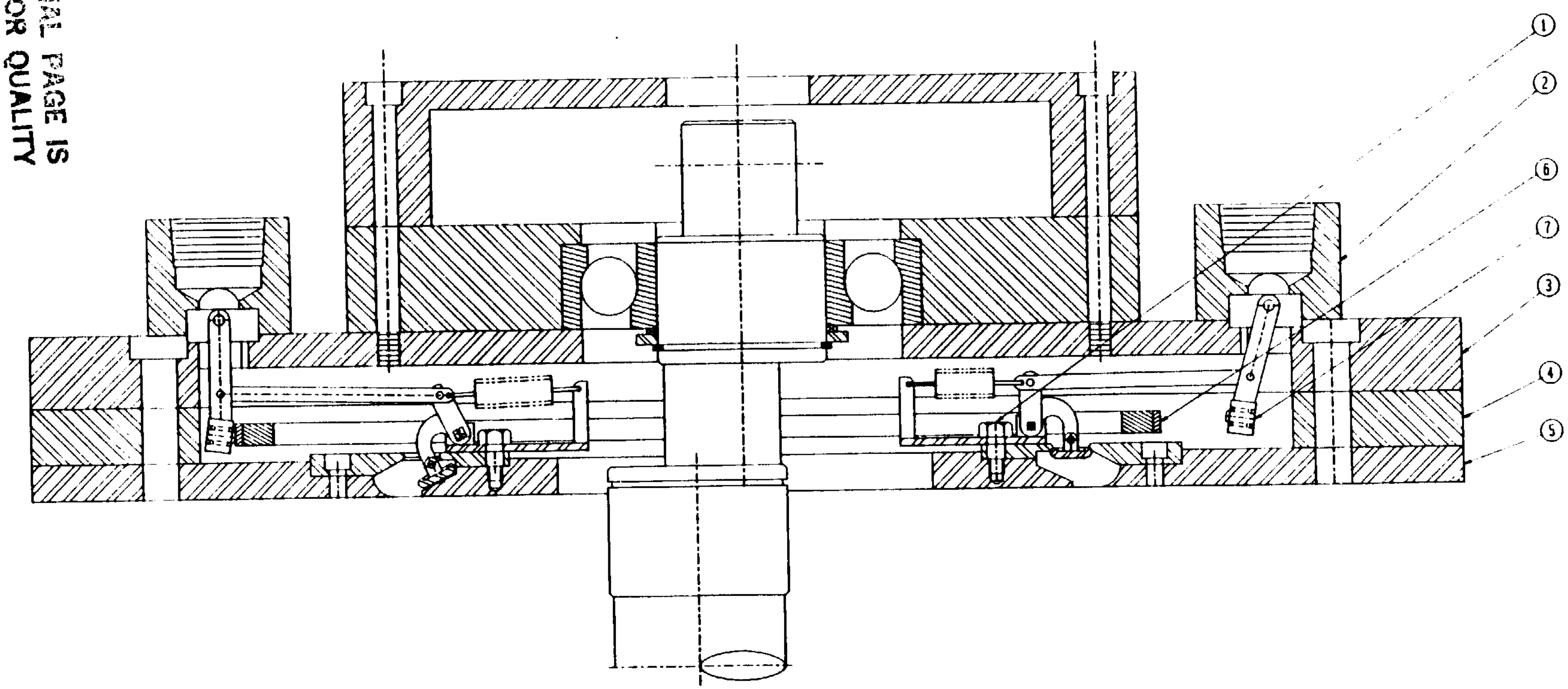

MATERIAL SPECIFICATION
TITLE
CRYOGENIC TECH. SERVICES, INC.
EXHAUST VALVES, TURGINE
1971
2 OF 2
PART NO
QTY
SIGNATURE
DATE
12 29 85
APPLICATION



ITEM NO.	REV	PART NO	QTY	TITLE	MATERIAL SPECIFICATION
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6	0	2011	1	EXHAUST CAM	
5	0	2013	1	EXHAUST STATIC PLATE	MAKE FROM MH-038
4	0	2014	1	EXHAUST VALVE HOUSING	MAKE FROM MH-005
3	0	2015	1	EXHAUST END CAP	MAKE FROM MH-005
2	C	2038	4	EXHAUST STACK	MAKE FROM MH-035
1		1/4" -20UNC	20	HEX HEAD BOLT	18 - 8 S STL

CRYOGENIC TECH. SERVICES, INC.

EXHAUST VALVES, TURGINE

SIGNATURE	DATE	DWG NO.	SCALE	SHEET
K L	12/29/89	1971	FULL	1 OF 2

APPLICATION

started readily and ran until the air pressure fell below about 10 psig. The inlet valves were timed to open at TDC and close at about 50°. Exhaust valves opened at about 175° and were set to close some 30° before TDC. (Early closing of the exhaust valves caused the machine to stop rather abruptly but was not recognized as a problem at the time.)

After the shop air tests, the expander was taken apart, cleaned, reassembled, and shipped to Cryolab. At Cryolab, it was installed in the test system and operation was attempted. Despite previous successful running on shop air, the expander could not be made to run at Cryolab. A series of trouble-shooting disassembly/reassembly cycles ensued with no definitive results. It was finally concluded that the exhaust valves were closing too early, resulting in excess recompression work. The cams were milled to close the exhaust valves 12° to 15° before TDC and the machine ran successfully.

Subsequent operations were marred by valve linkage and torsion-spring problems, excess vibration, and bearing failure. Experience in running the machine suggests that the combination of heavy vibration from poor balancing and dynamic operating conditions was overly severe for the valve linkage as designed. Except on the one occasion when a main bearing failed and seized; every operating stoppage was caused by valve linkages becoming disengaged and/or broken or, twice, when an inlet valve torsion spring broke. These problems, amenable to analysis and developmental testing, were not addressed because of a more fundamental pressure related malfunction.

In the first testing sequence, the expander would only run when driven by a 15-hp motor. Even under these conditions, the machine could be stalled when inlet nitrogen pressure was raised to approximately 50 psi. Since the nutating valves were clearly a contributor to this problem, substitution of cam-actuated valves was projected as a solution. The fact that the machine would run after the valve modification was evidence of improvement. However, it was observed that the expander would only run freely at pressures up to about 30 psig. The machine began to slow down for inlet pressures above 30 psig and it would stall in the range of 40 to 45 psig. This indicated that internal braking forces were rising faster than the torque generated by the machine. Although there was not time for analysis and experimentation, the two suspect sources of friction were the slides which seal against the eccentric arms and, possibly, the axial forces between the nutator and static valve plates.

Reduction of internal friction is key to successful future application of the nutating expander. It will be necessary to reduce sliding friction around the eccentric arms and to assure that nutator seals and tolerances match. Use of thrust bearings on the nutator will help the centering and tolerance problem.

A program to make the existing machine functional would consist of at least the following steps:

a. Balance the machine.
b. Revise the valve linkage for higher speed, dynamic use.
c. Redesign intake valve torsion springs.
d. Optimize valve timing and mill new cams.
e. Install thrust bearings on the nutator.
f. Spring load the sliders and replace sliding with at least one side.
g. Reduce blowby gas leakage paths.

Successful execution of the above tasks will result in a functional expander capable of generating system data. It will not be an optimum machine but should be the basis for design of a second-generation expander suitable for commercial use.

3.0 Seal Development

Conversion of Milburn's lubricated ambient temperature nutating expanders to cryogenic machines required selection and testing of suitable metal and seal combinations. This work was done in two phases as reported in the following paragraphs.

3.1 Seal Literature Survey

The following notes were made from a review of literature and manufacturers' publications which relate to the design of dynamic seals and bearings for dry cryogenic service.

3.1.1 Wear Factor, k

The wear factor, k, is useful in calculating the rate of wear for a seal or bearing.

$$r = kPVT$$

where:

r = wear, inches
P = pressure, psi
V = velocity, ft/min
T = time, hours

Units for k are in^3-min/lb-ft-hr. Values of k were found in the literature for several materials as follow:

Note: Subscripts refer to references listed at the end of the report.

Material	k
60% Bronze, $Teflon_2$	5.6×10^{-10}
15% Glass, 5% MOS_2, $Teflon_3$	9×10^{-10}
25% Glass, $Teflon_4$	10×10^{-10}
Rulon "A"$_1$	2.5×10^{-10}
Vespel SP-211_5	28×10^{-10}

3.1.2 Surface Finish

The mating surface finish recommended for filled Teflon piston rings in dry service is 16 microinch (ref. 2). This is in good agreement with reference 4 which shows 8-12 microinch as being the optimum surface, although this will vary with the materials used. Soft materials such as aluminum and brass are not recommended for rubbing surfaces.

3.1.3 Seal Loading

Reference 2 is a design manual for filled Teflon piston rings. In the sample calculation, they used an expander ring which preloaded the seal surface to 5 psi. This is close to the 6-1/4 psi calculated from Milburn data of 0.080-inch-wide ring loaded 0.5 lb per inch. For calculating wear on the ring, reference 2 uses a loading pressure which is a function of the gas pressure difference across the ring.

3.1.4 Critical PV

For each material there is a critical PV above which seal performance deteriorates rapidly. Each stepwise increase in PV is accompanied by an increase in temperature; the breakdown occurs at the softening temperature of the plastic material. For cryogenic service, higher critical PV values can be expected; but no test data are given in the literature. PV ratings are usually given for 0.005 inch of wear in 1,000 hours of operation.

3.1.5 Coefficient of Friction

Some typical values for dynamic coefficient of friction are listed. These can vary with pressure, velocity, mating material hardness, and surface finish and could also be a function of temperature.

Material	Dynamic Coefficient of Friction	PV for 0.005 Inch Wear Per 1,000 Hrs.	Ref. No.
Rulon "A"	0.12 - 0.19	20,000	(1)
Vespel SP-211	0.12 - 0.24	1,800	(5)
25% Glass-Teflon	0.15 - 0.25	5,000	(1)(3)
60% Bronze-Teflon	0.14	9,000	(1)(3)
15% Glass, 5% MOS_2-Teflon	0.14	5,500	(3)
15% Graphite-Teflon	0.12	1,400	(3)
Porous Bronze, Lubricated*	0.03 - 0.10	5,000 - 50,000	(1)

*For comparison

3.1.6 Conclusions

All materials mentioned have potential for our seal test program. In addition, we could consider graphite filled Teflon and glass and graphite filled Teflon. Overall, Rulon "A" appears to have the best combination of wear rate, PV rating, and low coefficient of friction. Results could be different for low-temperature, liquid nitrogen lubricated operation. Finally, it was suggested that dense felt might be used for seals but no data on the material was found in the literature.

There is some indication that the metal wearing surface takes on a film of Teflon which serves to reduce subsequent seal wear. This shows up in the form of rapid initial seal wear followed by uniform wear. In comparing the wear rate of different materials, the first material tested would provide this film and suffer a higher overall wear rate than the material tests that follow. One researcher started each test with new metal to overcome this problem.

3.1.7 Recommended Materials

The following seal materials are recommended for testing in the cryogenic test fixture:

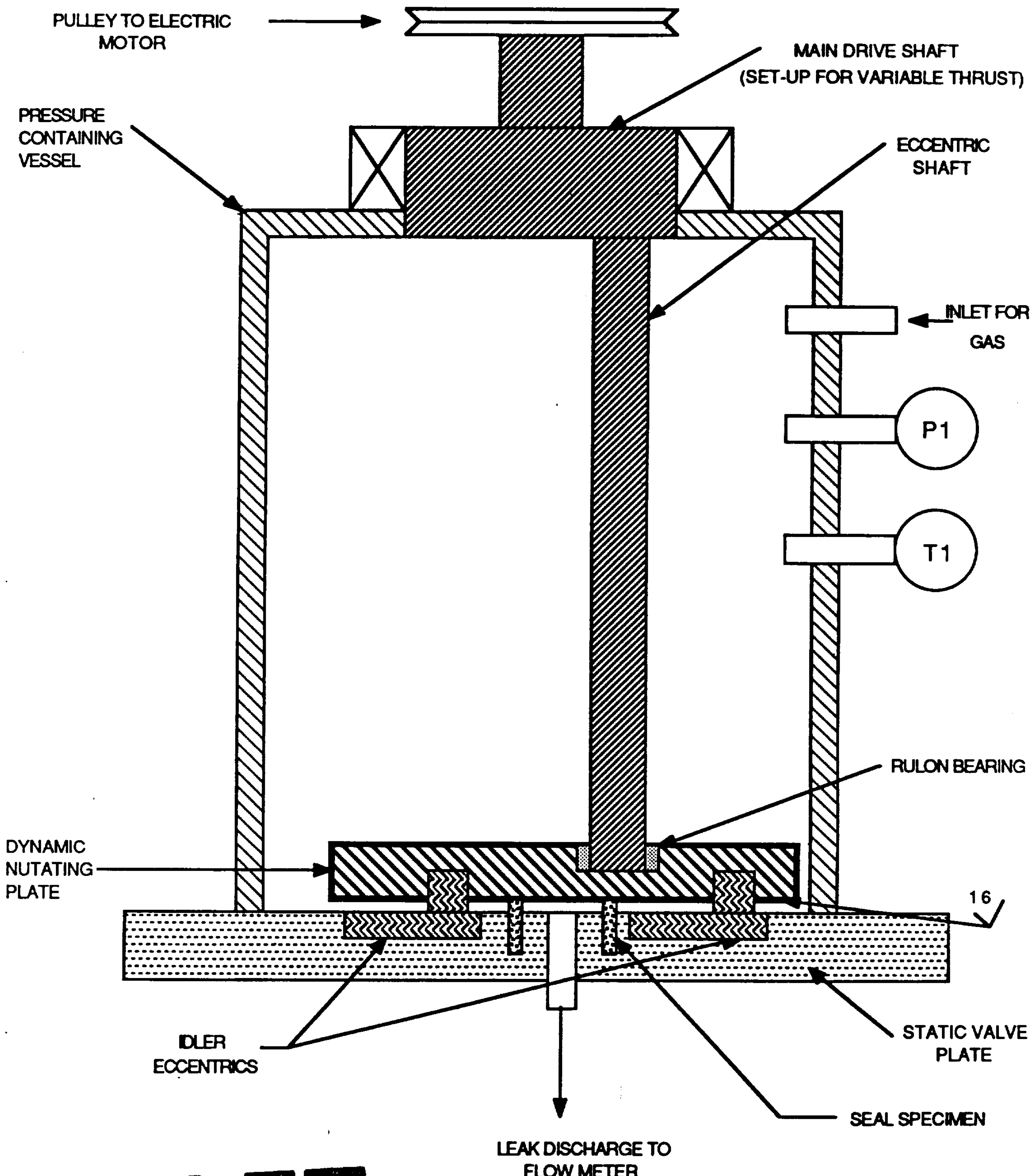
(1) Rulon "A"
(2) 60 percent Bronze-Teflon
(3) 15 percent Glass, 5 percent MOS_2, Teflon

Each material is to be tested for wear in 1,000 hours of operation and for gas leakage rate continuously throughout each test.

3.2 Seal Test Program

The seal test was intended to generate relatively long duration seal wear data on several candidate seal materials. The initial-seal-test concept sketch prepared by Milburn is included as figure 10. This simple apparatus was to be partially submerged in liquid nitrogen and pressurized with helium gas. A cylindrical seal specimen was to be exposed to nutating action from a thrust-loaded plate in an arrangement which could run continuously. Wear data were to be taken periodically and leakage rate measured with a totalizing gas meter.

Unfortunately, the simple system of figure 10 became far more complex as actually designed. When reviewed by the P.I., it was found to be unsuitable for cryogenic testing; and a revised apparatus was designed. This design retained cryogenic bearings and a continuous supply of low-pressure helium. When built and put into service by Cryolab, the seal tester had almost continuous problems with bearings in the nutating mechanism; and gaseous helium consumption was excessive. It was later learned that the twin-shaft nutating mechanism imposed very high loads on the cryogenic bearings which prompted their repeated, short-lived failures. To conserve helium, the test seal materials were allowed to run completely dry. Although adjacent to liquid nitrogen, the uncooled, unlubricated seals generated substantial heat which



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SEAL TEST SETUP

FIG. 10

accelerated wear. The only useful quantitative data confirmed that seal wear rates on a clean, smooth stainless-steel surface were initially quite high but fell rapidly to wear rates somewhat higher than predicted by the literature survey. After some 6 months of intermittent testing and apparatus repair, Rulon "A" was chosen as the seal material for the wet expander. This appears to have been a good choice although a lower coefficient of friction would have been helpful.

4.0 System Optimization

System optimization is a misnomer because all of the characteristics which improve reliquefaction yield are monotonic. Therefore, the highest rate of reliquefaction is achieved with the smallest heat exchanger ΔT, highest expander isentropic efficiency, highest tunnel operating pressure, and lowest tunnel temperature consistent with the tunnel pressure. What can be illustrated is the impact of these variables in a less than optimum combination.

Despite the very simple reliquefaction cycle shown in figure 1, calculation of performance is tedious because liquid yield of a wet expander must be solved by iteration. This is an obvious application for a computer, but Phase I software developed by Dr. Mostafa Abdelsalam of the University of Wisconsin was not entirely satisfactory because of a discontinuity at 99 K and inconsistencies above about 120 K. Therefore, the optimization task for Phase II involved improving the software and using it to calculate a broad envelope of possible operating conditions.

4.1 "RECOVERY" Software

Dr. Abdelsalam again worked on this software. He made minor changes in the computational software and made the program easier to use. His major contribution was to open up the NBS nitrogen properties program, MIPROPS, and smooth the underlying data. When this was done, the discontinuity and scatter disappeared. The revised and upgraded

"RECOVERY" program was used to calculate nitrogen reliquefier yields for 4, 5, 6, 7, and 8 atmospheres for heat exchanger inlet temperature differences of 1.5, 2, and 2.5 K and wet expander efficiencies of 65, 70, 75, and 80 percent. Tabulated results of those calculations are printed out in Appendix A.

4.2 Potential Reliquefier Performance

Calculated data are extracted from Appendix A to illustrate typical performance of a nitrogen reliquefier. Figure 11 shows the performance impact of wet expander efficiency on liquefier yield. Figure 12 illustrates reliquefier yield at 6 atm as a function of heat exchanger inlet temperature difference.

Conclusions to be drawn from figures 11 and 13 are quite straight forward. From figure 11, it is clear that raising tunnel pressure from 4 to 8 atm increases reliquefier yield by about 50 percent. Improving expander efficiency from 75 to 80 percent has almost a linear 5 percent improvement in yield. Figure 12 shows that the yield/expander efficiency relationship stays almost constant for a range of inlet temperature. Finally, figure 13 heat exchanger temperature difference is not very important with only an average 1 percent impact for 0.5 K change. Overall, we conclude that inlet pressure has the greatest impact on reliquefier yield; performance improves almost linearly with wet expander efficiency; and heat exchanger temperature difference, the easiest factor to improve, has only a minor influence. On a cost/benefit basis, more money is justified if the thermal performance is at least linear with expenditures. It is not justified when performance per dollar starts to flatten out.

5.0 Prototype Reliquefier

The test system installation is shown schematically on Dwg. D-1642. The system is designed to supply the expander heat exchanger inlet with an adequate flow of nitrogen gas at a controlled temperature and

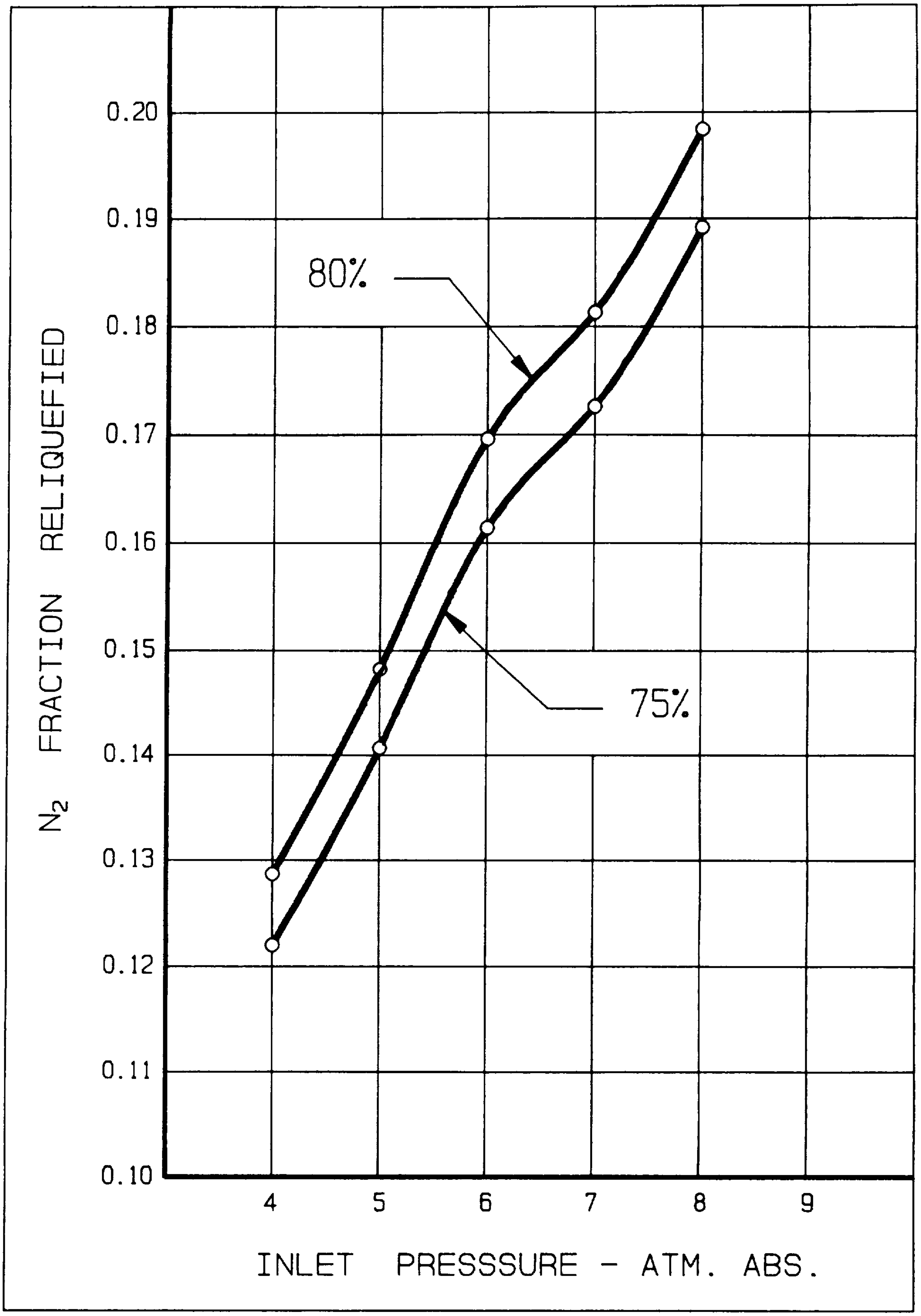


FIG. 11.

BEST RELIQUEFIER YIELD vs PRESSURE

FOR $\triangle T$ = 1.5 K & EXPANDER EFF. = 75 & 80%

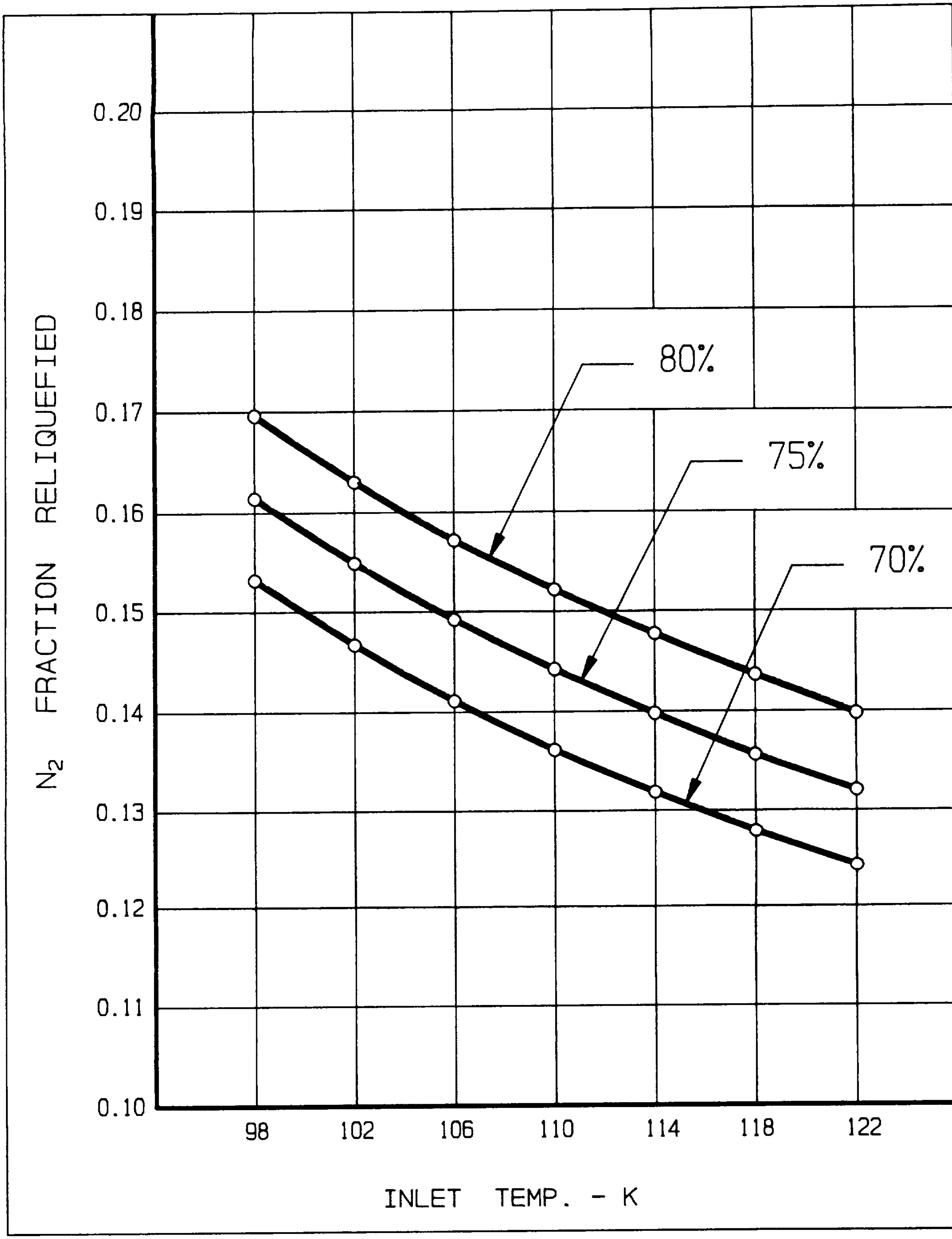


FIG. 12.

RELIQUEFIER YIELD vs EXPANDER EFF. & INLET TEMP. FOR 6 ATM & $\triangle T = 1.5$ K

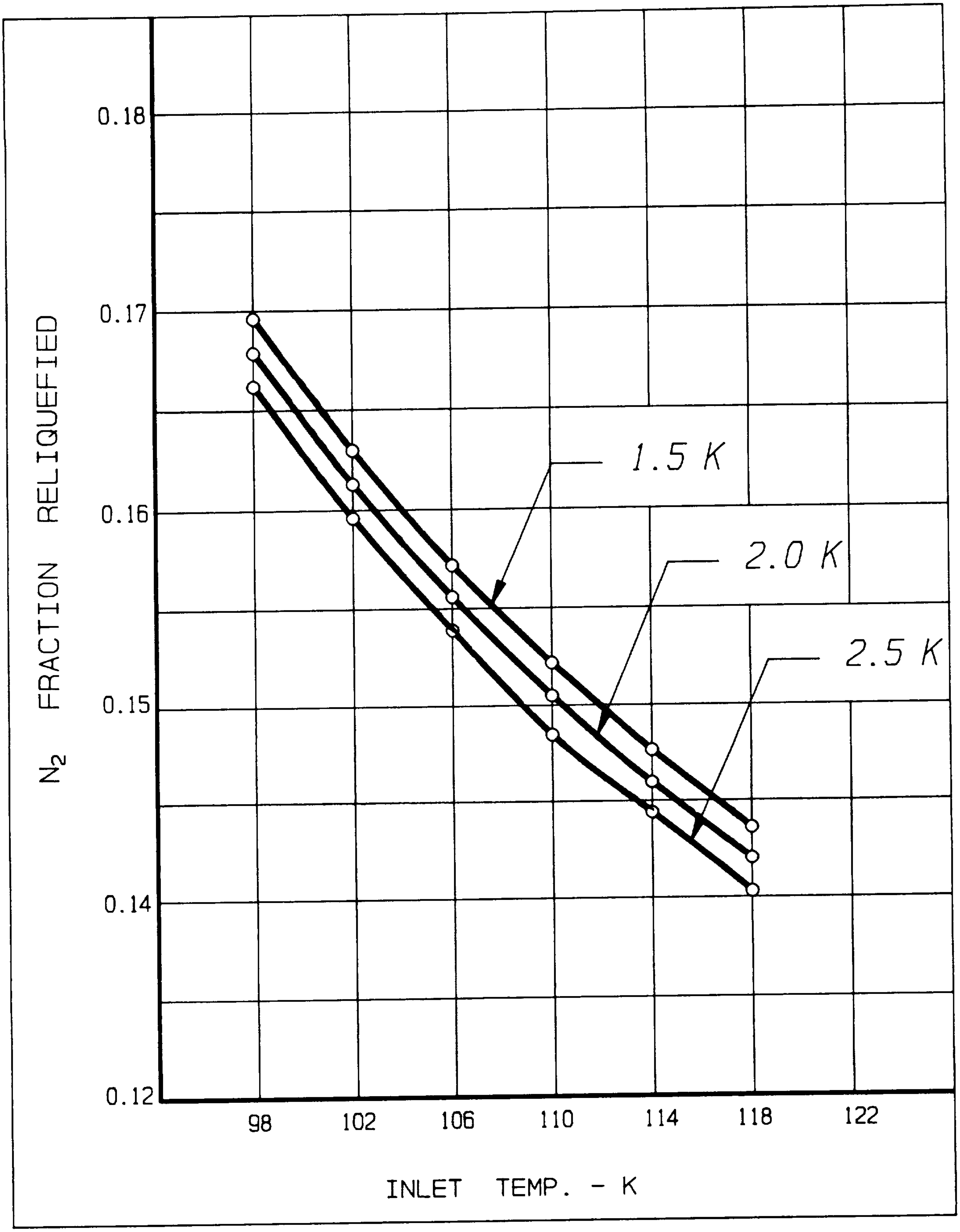
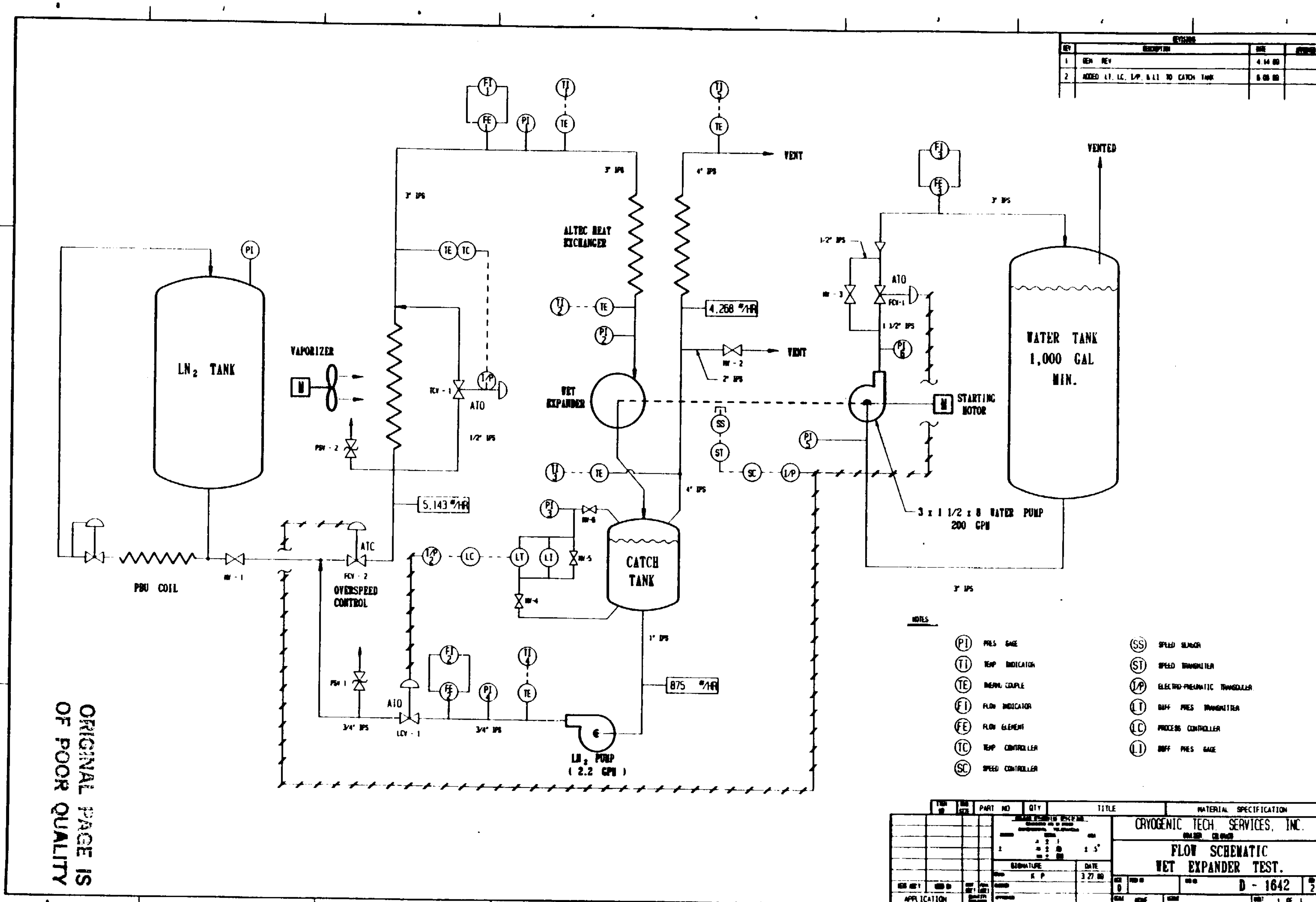


FIG. 13.

RELIQUEFIER YIELD vs HEAT EXCHANGER $\triangle$T FOR 6 ATM & 80% EXPANDER EFFICIENCY



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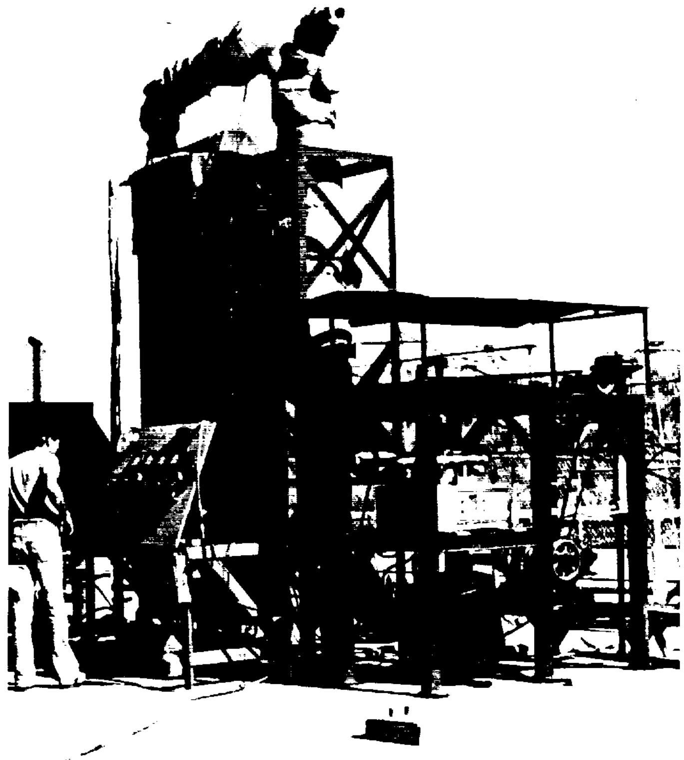

Fig. 8
Reliquefier Test Installation

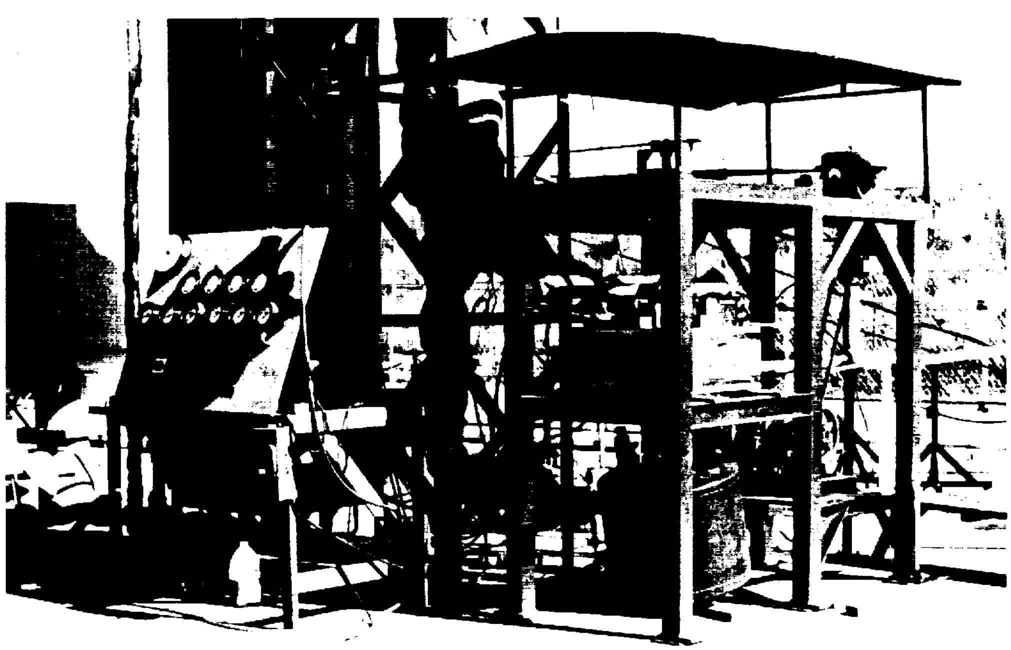

Fig. 9
Reliquefier Closeup

pressure, to provide for the collection and measurement of the liquid nitrogen produced, and to provide a variable load at the expander shaft to absorb the work generated by the expansion process while controlling the rotational speed of the expander. The reliquefier system installed at Cryolab is shown in figures 8 and 9. In figure 8, the nitrogen supply dewar is in the left background, the enclosed ambient vaporizer is next, and the insulated brazed aluminum heat exchanger stands in the right-hand high frame. Figure 9 shows the wet expander prior to insulation and attachment of the catch tank with the instrumentation and control panel in the left foreground.

5.1 Heat Exchanger

The heat exchanger provides for the recovery of some of the refrigeration available in the expander exhaust, thereby improving the efficiency of the system by recooling the inlet gas to the expander below the temperature at which gas is supplied to the system.

A plate-fin brazed aluminum heat exchanger was selected for this application. The principal advantages of the plate-fin design are high thermal efficiency combined with low pressure drop and reasonable cost.

5.2 Loading Device

A water pump was selected to absorb the work generated by the wet expander. The pump is installed in a flow loop with a water storage tank of sufficient volume to permit test runs of several hours without overheating and incorporating a control valve to provide for varying the load on the expander as well as controlling the rotational speed of the expander. This pump will absorb 10 hp at minimum flow of 30 gpm up to 20-hp at 200 gpm at an expander speed of 1200 rpm.

5.3 Controls and Instrumentation

Dwg. D-1642 shows the instrumentation and control loops used in the test system. The control panel is shown in figure 9.

5.3.1 Gas Supply System

A liquid nitrogen tank and vaporizer are installed to provide the large quantities of gas required at controlled temperature and pressure. The pressure is controlled by the automatic control valve on the pressure building circuit of the liquid nitrogen tank. The set point of this valve can be adjusted to provide a wide range of pressures for the various test conditions expected. The temperature of the gas supplied to the expander heat exchanger inlet is controlled by a liquid nitrogen valve (TCV-1) which bypasses the oversized vaporizer to automatically control the gas temperature to a preset value.

Downstream of the vaporizer are instruments for measuring the flow (FI-1), pressure (PI-1), and temperature (TI-1) of the gas supplied to the wet expander heat exchanger.

5.3.2 Liquid Nitrogen Production Measurement

Exhaust from the wet expander is discharged into the catch tank which also serves as a phase separator. Vapor from the separation is vented through the wet expander heat exchanger while the liquid phase is retained in the catch tank. A differential pressure-type liquid level gauge is provided on the catch tank so the rate of liquid production can be measured by using a stopwatch while observing changes in liquid level with the liquid withdrawal line closed.

A small liquid nitrogen pump is provided to empty the catch tank and recycle it to the supply system. A flowmeter (FI-2), pressure gauge (PI-2), and temperature indicator (TI-4) provide an additional method of measuring the liquid production rate by metering flow in the nitrogen pump discharge line.

5.3.3 Speed Control

The rotational speed of the wet expander is limited to 1200 rpm by the speed control system. A magnetic pickup (SS) senses shaft speed by the electrical pulses generated as shaft gear teeth pass by the pickup. Pulses are fed into a signal conditioner (ST) which provides a standard input signal to the speed controller (SC). Output from the speed controller is converted to a pneumatic signal by converter (I/P) for controlling valves FCV-1 and FCV-2 in sequence. FCV-1 provides normal speed control while FCV-2 operates to shut off flow of gas to the wet expander in the event of overspeed beyond the maximum design rotational speed.

6.0 Conclusions, Costs and Recommendations

Poor performance of the wet expander and a lack of data to evaluate reduces part of this section to projections. However, our extensive hands-on experience with the machine provides a perspective not originally anticipated.

6.1 Conclusions

Work was ended because both time and the budget had expired. Although substantially improved from its original design, the wet expander was not sufficiently developed to be considered functional. Making the existing expander work entails the tasks of balancing the machine and upgrading the valve linkages plus the major tasks of installing thrust bearings and reducing internal friction. Accomplishing these tasks would result in a functional but not optimized machine.

New thinking is required to optimize the nutating expander. The valve cams must be moved outside the main enclosure to permit direct, linear valve motion. Bearings suitable for cryogenic service must be used and provision must be made for axial alignment. Internal friction must be significantly reduced, particularly in the area of the eccentric arms and cross slides. With these nontrivial modifications, it is believed that the nutating expander is capable of performance superior to that of a well-developed reciprocating expander.

6.2 Technical Feasibility

Work in refining the "RECOVERY" software clearly identifies the feasibility of reliquefying from about 12 to nearly 20 percent of the vent flow from a cryogenic wind tunnel. Of the two major components, the brazed aluminum cryogenic heat exchanger can be bought off the shelf. Thus, technical feasibility depends almost solely on availability of an efficient positive displacement wet expander. Existing reciprocating expander designs should be capable of wet performance in the 70 to 75 percent efficiency range with special attention to valves. Interest in the nutating expander stems from its straight through, down flow path with its potential for isentropic efficiency of 80 percent or greater. Nitrogen reliquefaction is feasible with either type of positive displacement expander; it is potentially improved with a nutating expander.

6.3 Wet Expander Costs

In round numbers, material and labor cost of the initial nutating expander was \$100,000. It is a typically expensive prototype. Redesign with an eye to value engineering is projected to reduce this cost by about one-third for a single unit. Anticipated technical design changes will not increase the cost of the expanders. Projected costs of four parallel units as might be required for the 0.3-m TCT at Langley are \$50,000 each for a total of \$200,000. The cost scaling factor for these machines will be 0.7. Thus, in principle, a single machine to replace four units would have a cost as follows:

$$\text{Cost} = (\text{unit cost})(\text{size ratio})^{0.7}$$

or

$$\text{Cost} = (\$66{,}667)(4)^{0.7} = \$175{,}935$$

A problem with this analysis is that there may be a convenient size limitation for nutating expanders. It may be more comfortable to utilize multiple smaller units which are easier to manufacture and service.

6.4 Wind Tunnel Reliquefier Costs

A brief study of wind-tunnel reliquefier costs was made. Results of this work are reported in the following paragraphs.

6.4.1 Capital Costs

Projected cost of a nitrogen reliquefier for the Langley 0.3-m TCT is estimated as follows:

Expanders	$200,000
Brazed aluminum heat exchanger	30,000
Insulating enclosures	50,000
Liquid catch tank	15,000
Instruments and controls	12,000
System structure	15,000
Inter-connecting piping	15,000
Power absorber/speed control	20,000
Engineering & project management	50,000
Total	$407,000

This does not include installation at NASA Langley.

6.4.2 Operating Costs and Payback

Tunnel operating personnel will be able to start and stop the reliquefier which is otherwise able to run unattended. Therefore, the basic financial consideration is payback. Base this on tunnel operation at 6 atm with a 75-percent-efficient expander and 1.5 K heat exchanger temperature difference for a reliquefaction yield of 16.14 percent. Reduce the yield to 15 percent to allow for cooldown and warmup losses. For a system flow of 2.6 kg/s, the liquid recovery rate would be 0.39 kg/s or 0.1275 gal/s. At $1/gal, liquid recovered is valued at $459/hr. Projected payout for the equipment on this basis is 886.7 hours of tunnel operation. Payout based on 1,000 hours of tunnel operation is valid for preliminary planning purposes.

6.5 Recommendations

Recommendations for future work include:

A. Make minor and major modifications to the existing expander and prove it out mechanically by operation on dry, ambient air.

B. Install the modified machine in the flow system at Cryolab and accumulate cryogenic operating experience and performance data.

C. Design, fabricate, and test a totally new, smaller (one-fourth of the present machine) cryogenic nutating expander.

D. Design a nitrogen recovery system sized for the Langley 0.3-m TCT.

APPENDIX A

Nitrogen Reliquefier Performance Calculations

This appendix consists of tabular results of thermodynamic nitrogen reliquefier calculations performed using the revised "RECOVERY" software as referenced in Section 4.1. The three calculation sets included are based on inlet-outlet gas temperature differences of 1.5, 2, and 2.5 K. Each calculation set covers a pressure range from 4 to 8 atm absolute, inlet temperatures from 94 to 142 K with 4 K increments, and isentropic expander efficiences of 65, 70, 75, and 80 percent.

Delta T = 1.5 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.50	10.86	93.49
4.0	98.00	91.41	77.36	77.36	96.50	10.41	94.05
4.0	102.00	91.41	77.36	77.36	100.50	10.03	94.53
4.0	106.00	91.41	77.36	77.36	104.50	9.68	94.96
4.0	110.00	91.41	77.36	77.36	108.50	9.38	95.34
4.0	114.00	91.41	77.36	77.36	112.50	9.10	95.68
4.0	118.00	91.41	77.36	77.36	116.50	8.84	96.00
4.0	122.00	91.41	77.36	77.36	120.50	8.61	96.29
4.0	126.00	91.41	77.36	77.36	124.50	8.40	96.56
4.0	130.00	91.41	77.36	77.36	128.50	8.20	96.80
4.0	134.00	91.41	77.36	77.36	132.50	8.01	97.04
4.0	138.00	91.41	77.36	77.36	136.50	7.83	97.26
4.0	142.00	91.41	77.36	77.36	140.50	7.67	97.46
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.50	12.57	92.27
5.0	102.00	94.18	77.36	77.36	100.50	12.06	92.93
5.0	106.00	94.18	77.36	77.36	104.50	11.61	93.51
5.0	110.00	94.18	77.36	77.36	108.50	11.22	94.02
5.0	114.00	94.18	77.36	77.36	112.50	10.87	94.48
5.0	118.00	94.18	77.36	77.36	116.50	10.55	94.90
5.0	122.00	94.18	77.36	77.36	120.50	10.26	95.28
5.0	126.00	94.18	77.36	77.36	124.50	9.99	95.63
5.0	130.00	94.18	77.36	77.36	128.50	9.74	95.95
5.0	134.00	94.18	77.36	77.36	132.50	9.51	96.25
5.0	138.00	94.18	77.36	77.36	136.50	9.29	96.53
5.0	142.00	94.18	77.36	77.36	140.50	9.09	96.80
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.50	14.50	90.49
6.0	102.00	96.58	77.36	77.36	100.50	13.86	91.36
6.0	106.00	96.58	77.36	77.36	104.50	13.31	92.12
6.0	110.00	96.58	77.36	77.36	108.50	12.83	92.77
6.0	114.00	96.58	77.36	77.36	112.50	12.40	93.35
6.0	118.00	96.58	77.36	77.36	116.50	12.01	93.88
6.0	122.00	96.58	77.36	77.36	120.50	11.66	94.35
6.0	126.00	96.58	77.36	77.36	124.50	11.35	94.78
6.0	130.00	96.58	77.36	77.36	128.50	11.05	95.18
6.0	134.00	96.58	77.36	77.36	132.50	10.78	95.55
6.0	138.00	96.58	77.36	77.36	136.50	10.53	95.90
6.0	142.00	96.58	77.36	77.36	140.50	10.29	96.22

Delta T = 1.5 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.50	15.52	89.79
7.0	106.00	98.69	77.36	77.36	104.50	14.85	90.74
7.0	110.00	98.69	77.36	77.36	108.50	14.28	91.55
7.0	114.00	98.69	77.36	77.36	112.50	13.77	92.27
7.0	118.00	98.69	77.36	77.36	116.50	13.32	92.90
7.0	122.00	98.69	77.36	77.36	120.50	12.91	93.48
7.0	126.00	98.69	77.36	77.36	124.50	12.55	94.00
7.0	130.00	98.69	77.36	77.36	128.50	12.21	94.47
7.0	134.00	98.69	77.36	77.36	132.50	11.90	94.92
7.0	138.00	98.69	77.36	77.36	136.50	11.61	95.32
7.0	142.00	98.69	77.36	77.36	140.50	11.34	95.71
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.50	17.10	88.15
8.0	106.00	100.60	77.36	77.36	104.50	16.30	89.34
8.0	110.00	100.60	77.36	77.36	108.50	15.62	90.33
8.0	114.00	100.60	77.36	77.36	112.50	15.03	91.19
8.0	118.00	100.60	77.36	77.36	116.50	14.52	91.95
8.0	122.00	100.60	77.36	77.36	120.50	14.05	92.64
8.0	126.00	100.60	77.36	77.36	124.50	13.63	93.25
8.0	130.00	100.60	77.36	77.36	128.50	13.25	93.81
8.0	134.00	100.60	77.36	77.36	132.50	12.90	94.32
8.0	138.00	100.60	77.36	77.36	136.50	12.58	94.80
8.0	142.00	100.60	77.36	77.36	140.50	12.28	95.24

Delta T - 1.5 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.50	11.53	93.55
4.0	98.00	91.41	77.36	77.36	96.50	11.07	94.12
4.0	102.00	91.41	77.36	77.36	100.50	10.68	94.62
4.0	106.00	91.41	77.36	77.36	104.50	10.32	95.07
4.0	110.00	91.41	77.36	77.36	108.50	10.01	95.46
4.0	114.00	91.41	77.36	77.36	112.50	9.72	95.82
4.0	118.00	91.41	77.36	77.36	116.50	9.46	96.15
4.0	122.00	91.41	77.36	77.36	120.50	9.22	96.45
4.0	126.00	91.41	77.36	77.36	124.50	9.00	96.73
4.0	130.00	91.41	77.36	77.36	128.50	8.79	96.99
4.0	134.00	91.41	77.36	77.36	132.50	8.60	97.23
4.0	138.00	91.41	77.36	77.36	136.50	8.41	97.46
4.0	142.00	91.41	77.36	77.36	140.50	8.24	97.68
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.50	13.32	92.36
5.0	102.00	94.18	77.36	77.36	100.50	12.80	93.03
5.0	106.00	94.18	77.36	77.36	104.50	12.34	93.64
5.0	110.00	94.18	77.36	77.36	108.50	11.95	94.16
5.0	114.00	94.18	77.36	77.36	112.50	11.58	94.64
5.0	118.00	94.18	77.36	77.36	116.50	11.26	95.07
5.0	122.00	94.18	77.36	77.36	120.50	10.96	95.47
5.0	126.00	94.18	77.36	77.36	124.50	10.68	95.83
5.0	130.00	94.18	77.36	77.36	128.50	10.42	96.17
5.0	134.00	94.18	77.36	77.36	132.50	10.18	96.48
5.0	138.00	94.18	77.36	77.36	136.50	9.96	96.78
5.0	142.00	94.18	77.36	77.36	140.50	9.75	97.06
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.50	15.32	90.59
6.0	102.00	96.58	77.36	77.36	100.50	14.67	91.48
6.0	106.00	96.58	77.36	77.36	104.50	14.11	92.26
6.0	110.00	96.58	77.36	77.36	108.50	13.62	92.93
6.0	114.00	96.58	77.36	77.36	112.50	13.19	93.53
6.0	118.00	96.58	77.36	77.36	116.50	12.79	94.07
6.0	122.00	96.58	77.36	77.36	120.50	12.43	94.56
6.0	126.00	96.58	77.36	77.36	124.50	12.11	95.01
6.0	130.00	96.58	77.36	77.36	128.50	11.81	95.43
6.0	134.00	96.58	77.36	77.36	132.50	11.53	95.82
6.0	138.00	96.58	77.36	77.36	136.50	11.26	96.18
6.0	142.00	96.58	77.36	77.36	140.50	11.02	96.51

Delta T - 1.5 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.50	16.39	89.92
7.0	106.00	98.69	77.36	77.36	104.50	15.71	90.89
7.0	110.00	98.69	77.36	77.36	108.50	15.13	91.72
7.0	114.00	98.69	77.36	77.36	112.50	14.61	92.46
7.0	118.00	98.69	77.36	77.36	116.50	14.16	93.12
7.0	122.00	98.69	77.36	77.36	120.50	13.74	93.71
7.0	126.00	98.69	77.36	77.36	124.50	13.37	94.25
7.0	130.00	98.69	77.36	77.36	128.50	13.02	94.75
7.0	134.00	98.69	77.36	77.36	132.50	12.70	95.21
7.0	138.00	98.69	77.36	77.36	136.50	12.40	95.63
7.0	142.00	98.69	77.36	77.36	140.50	12.12	96.03
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.50	18.01	88.30
8.0	106.00	100.60	77.36	77.36	104.50	17.20	89.50
8.0	110.00	100.60	77.36	77.36	108.50	16.52	90.52
8.0	114.00	100.60	77.36	77.36	112.50	15.93	91.40
8.0	118.00	100.60	77.36	77.36	116.50	15.40	92.19
8.0	122.00	100.60	77.36	77.36	120.50	14.93	92.89
8.0	126.00	100.60	77.36	77.36	124.50	14.50	93.52
8.0	130.00	100.60	77.36	77.36	128.50	14.11	94.10
8.0	134.00	100.60	77.36	77.36	132.50	13.75	94.64
8.0	138.00	100.60	77.36	77.36	136.50	13.42	95.13
8.0	142.00	100.60	77.36	77.36	140.50	13.11	95.60

Delta T = 1.5 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.50	12.20	93.61
4.0	98.00	91.41	77.36	77.36	96.50	11.73	94.20
4.0	102.00	91.41	77.36	77.36	100.50	11.33	94.71
4.0	106.00	91.41	77.36	77.36	104.50	10.97	95.17
4.0	110.00	91.41	77.36	77.36	108.50	10.65	95.58
4.0	114.00	91.41	77.36	77.36	112.50	10.35	95.95
4.0	118.00	91.41	77.36	77.36	116.50	10.08	96.29
4.0	122.00	91.41	77.36	77.36	120.50	9.83	96.61
4.0	126.00	91.41	77.36	77.36	124.50	9.60	96.90
4.0	130.00	91.41	77.36	77.36	128.50	9.39	97.17
4.0	134.00	91.41	77.36	77.36	132.50	9.18	97.43
4.0	138.00	91.41	77.36	77.36	136.50	8.99	97.67
4.0	142.00	91.41	77.36	77.36	140.50	8.81	97.90
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.50	14.07	92.45
5.0	102.00	94.18	77.36	77.36	100.50	13.55	93.14
5.0	106.00	94.18	77.36	77.36	104.50	13.08	93.76
5.0	110.00	94.18	77.36	77.36	108.50	12.67	94.30
5.0	114.00	94.18	77.36	77.36	112.50	12.30	94.80
5.0	118.00	94.18	77.36	77.36	116.50	11.97	95.25
5.0	122.00	94.18	77.36	77.36	120.50	11.66	95.66
5.0	126.00	94.18	77.36	77.36	124.50	11.37	96.04
5.0	130.00	94.18	77.36	77.36	128.50	11.11	96.39
5.0	134.00	94.18	77.36	77.36	132.50	10.86	96.72
5.0	138.00	94.18	77.36	77.36	136.50	10.63	97.03
5.0	142.00	94.18	77.36	77.36	140.50	10.41	97.32
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.50	16.14	90.70
6.0	102.00	96.58	77.36	77.36	100.50	15.49	91.61
6.0	106.00	96.58	77.36	77.36	104.50	14.92	92.40
6.0	110.00	96.58	77.36	77.36	108.50	14.42	93.09
6.0	114.00	96.58	77.36	77.36	112.50	13.98	93.71
6.0	118.00	96.58	77.36	77.36	116.50	13.57	94.27
6.0	122.00	96.58	77.36	77.36	120.50	13.21	94.78
6.0	126.00	96.58	77.36	77.36	124.50	12.87	95.25
6.0	130.00	96.58	77.36	77.36	128.50	12.56	95.68
6.0	134.00	96.58	77.36	77.36	132.50	12.27	96.08
6.0	138.00	96.58	77.36	77.36	136.50	12.00	96.46
6.0	142.00	96.58	77.36	77.36	140.50	11.75	96.81

Delta T = 1.5 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.50	17.26	90.05
7.0	106.00	98.69	77.36	77.36	104.50	16.57	91.05
7.0	110.00	98.69	77.36	77.36	108.50	15.98	91.90
7.0	114.00	98.69	77.36	77.36	112.50	15.46	92.66
7.0	118.00	98.69	77.36	77.36	116.50	15.00	93.34
7.0	122.00	98.69	77.36	77.36	120.50	14.57	93.95
7.0	126.00	98.69	77.36	77.36	124.50	14.19	94.51
7.0	130.00	98.69	77.36	77.36	128.50	13.84	95.02
7.0	134.00	98.69	77.36	77.36	132.50	13.51	95.50
7.0	138.00	98.69	77.36	77.36	136.50	13.20	95.94
7.0	142.00	98.69	77.36	77.36	140.50	12.91	96.36
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.50	18.92	88.44
8.0	106.00	100.60	77.36	77.36	104.50	18.11	89.67
8.0	110.00	100.60	77.36	77.36	108.50	17.42	90.71
8.0	114.00	100.60	77.36	77.36	112.50	16.82	91.62
8.0	118.00	100.60	77.36	77.36	116.50	16.29	92.42
8.0	122.00	100.60	77.36	77.36	120.50	15.81	93.15
8.0	126.00	100.60	77.36	77.36	124.50	15.37	93.80
8.0	130.00	100.60	77.36	77.36	128.50	14.98	94.40
8.0	134.00	100.60	77.36	77.36	132.50	14.61	94.96
8.0	138.00	100.60	77.36	77.36	136.50	14.27	95.47
8.0	142.00	100.60	77.36	77.36	140.50	13.95	95.95

Delta T = 1.5 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.50	12.87	93.67
4.0	98.00	91.41	77.36	77.36	96.50	12.39	94.28
4.0	102.00	91.41	77.36	77.36	100.50	11.98	94.80
4.0	106.00	91.41	77.36	77.36	104.50	11.61	95.28
4.0	110.00	91.41	77.36	77.36	108.50	11.28	95.70
4.0	114.00	91.41	77.36	77.36	112.50	10.98	96.09
4.0	118.00	91.41	77.36	77.36	116.50	10.70	96.44
4.0	122.00	91.41	77.36	77.36	120.50	10.45	96.77
4.0	126.00	91.41	77.36	77.36	124.50	10.21	97.07
4.0	130.00	91.41	77.36	77.36	128.50	9.98	97.36
4.0	134.00	91.41	77.36	77.36	132.50	9.77	97.62
4.0	138.00	91.41	77.36	77.36	136.50	9.58	97.88
4.0	142.00	91.41	77.36	77.36	140.50	9.39	98.12
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.50	14.82	92.54
5.0	102.00	94.18	77.36	77.36	100.50	14.29	93.25
5.0	106.00	94.18	77.36	77.36	104.50	13.82	93.89
5.0	110.00	94.18	77.36	77.36	108.50	13.40	94.45
5.0	114.00	94.18	77.36	77.36	112.50	13.02	94.96
5.0	118.00	94.18	77.36	77.36	116.50	12.68	95.42
5.0	122.00	94.18	77.36	77.36	120.50	12.36	95.85
5.0	126.00	94.18	77.36	77.36	124.50	12.07	96.24
5.0	130.00	94.18	77.36	77.36	128.50	11.80	96.61
5.0	134.00	94.18	77.36	77.36	132.50	11.54	96.95
5.0	138.00	94.18	77.36	77.36	136.50	11.30	97.27
5.0	142.00	94.18	77.36	77.36	140.50	11.08	97.58
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.50	16.96	90.80
6.0	102.00	96.58	77.36	77.36	100.50	16.30	91.73
6.0	106.00	96.58	77.36	77.36	104.50	15.72	92.54
6.0	110.00	96.58	77.36	77.36	108.50	15.22	93.25
6.0	114.00	96.58	77.36	77.36	112.50	14.77	93.89
6.0	118.00	96.58	77.36	77.36	116.50	14.36	94.47
6.0	122.00	96.58	77.36	77.36	120.50	13.98	94.99
6.0	126.00	96.58	77.36	77.36	124.50	13.64	95.48
6.0	130.00	96.58	77.36	77.36	128.50	13.32	95.93
6.0	134.00	96.58	77.36	77.36	132.50	13.03	96.34
6.0	138.00	96.58	77.36	77.36	136.50	12.75	96.74
6.0	142.00	96.58	77.36	77.36	140.50	12.49	97.10

Delta T = 1.5 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.50	18.13	90.19
7.0	106.00	98.69	77.36	77.36	104.50	17.44	91.20
7.0	110.00	98.69	77.36	77.36	108.50	16.84	92.08
7.0	114.00	98.69	77.36	77.36	112.50	16.31	92.86
7.0	118.00	98.69	77.36	77.36	116.50	15.84	93.55
7.0	122.00	98.69	77.36	77.36	120.50	15.41	94.19
7.0	126.00	98.69	77.36	77.36	124.50	15.02	94.76
7.0	130.00	98.69	77.36	77.36	128.50	14.65	95.30
7.0	134.00	98.69	77.36	77.36	132.50	14.32	95.79
7.0	138.00	98.69	77.36	77.36	136.50	14.00	96.25
7.0	142.00	98.69	77.36	77.36	140.50	13.71	96.69
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.50	19.84	88.59
8.0	106.00	100.60	77.36	77.36	104.50	19.02	89.84
8.0	110.00	100.60	77.36	77.36	108.50	18.33	90.90
8.0	114.00	100.60	77.36	77.36	112.50	17.72	91.83
8.0	118.00	100.60	77.36	77.36	116.50	17.18	92.66
8.0	122.00	100.60	77.36	77.36	120.50	16.69	93.40
8.0	126.00	100.60	77.36	77.36	124.50	16.25	94.08
8.0	130.00	100.60	77.36	77.36	128.50	15.84	94.70
8.0	134.00	100.60	77.36	77.36	132.50	15.47	95.28
8.0	138.00	100.60	77.36	77.36	136.50	15.12	95.81
8.0	142.00	100.60	77.36	77.36	140.50	14.79	96.31

Delta T = 2 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.00	10.66	93.74
4.0	98.00	91.41	77.36	77.36	96.00	10.22	94.29
4.0	102.00	91.41	77.36	77.36	100.00	9.83	94.77
4.0	106.00	91.41	77.36	77.36	104.00	9.49	95.20
4.0	110.00	91.41	77.36	77.36	108.00	9.19	95.57
4.0	114.00	91.41	77.36	77.36	112.00	8.91	95.92
4.0	118.00	91.41	77.36	77.36	116.00	8.66	96.23
4.0	122.00	91.41	77.36	77.36	120.00	8.43	96.51
4.0	126.00	91.41	77.36	77.36	124.00	8.22	96.78
4.0	130.00	91.41	77.36	77.36	128.00	8.02	97.02
4.0	134.00	91.41	77.36	77.36	132.00	7.84	97.25
4.0	138.00	91.41	77.36	77.36	136.00	7.66	97.47
4.0	142.00	91.41	77.36	77.36	140.00	7.50	97.67
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.00	12.38	92.51
5.0	102.00	94.18	77.36	77.36	100.00	11.87	93.17
5.0	106.00	94.18	77.36	77.36	104.00	11.43	93.75
5.0	110.00	94.18	77.36	77.36	108.00	11.04	94.26
5.0	114.00	94.18	77.36	77.36	112.00	10.69	94.72
5.0	118.00	94.18	77.36	77.36	116.00	10.37	95.13
5.0	122.00	94.18	77.36	77.36	120.00	10.08	95.51
5.0	126.00	94.18	77.36	77.36	124.00	9.82	95.85
5.0	130.00	94.18	77.36	77.36	128.00	9.57	96.17
5.0	134.00	94.18	77.36	77.36	132.00	9.34	96.47
5.0	138.00	94.18	77.36	77.36	136.00	9.13	96.75
5.0	142.00	94.18	77.36	77.36	140.00	8.93	97.01
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.00	14.32	90.74
6.0	102.00	96.58	77.36	77.36	100.00	13.68	91.61
6.0	106.00	96.58	77.36	77.36	104.00	13.13	92.36
6.0	110.00	96.58	77.36	77.36	108.00	12.65	93.01
6.0	114.00	96.58	77.36	77.36	112.00	12.22	93.59
6.0	118.00	96.58	77.36	77.36	116.00	11.84	94.11
6.0	122.00	96.58	77.36	77.36	120.00	11.49	94.58
6.0	126.00	96.58	77.36	77.36	124.00	11.18	95.01
6.0	130.00	96.58	77.36	77.36	128.00	10.89	95.41
6.0	134.00	96.58	77.36	77.36	132.00	10.62	95.78
6.0	138.00	96.58	77.36	77.36	136.00	10.37	96.12
6.0	142.00	96.58	77.36	77.36	140.00	10.13	96.44

Delta T = 2 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.00	15.35	90.04
7.0	106.00	98.69	77.36	77.36	104.00	14.68	90.98
7.0	110.00	98.69	77.36	77.36	108.00	14.11	91.79
7.0	114.00	98.69	77.36	77.36	112.00	13.60	92.51
7.0	118.00	98.69	77.36	77.36	116.00	13.15	93.14
7.0	122.00	98.69	77.36	77.36	120.00	12.75	93.71
7.0	126.00	98.69	77.36	77.36	124.00	12.38	94.23
7.0	130.00	98.69	77.36	77.36	128.00	12.05	94.70
7.0	134.00	98.69	77.36	77.36	132.00	11.74	95.14
7.0	138.00	98.69	77.36	77.36	136.00	11.45	95.55
7.0	142.00	98.69	77.36	77.36	140.00	11.18	95.93
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.00	16.93	88.41
8.0	106.00	100.60	77.36	77.36	104.00	16.13	89.58
8.0	110.00	100.60	77.36	77.36	108.00	15.46	90.57
8.0	114.00	100.60	77.36	77.36	112.00	14.87	91.44
8.0	118.00	100.60	77.36	77.36	116.00	14.35	92.20
8.0	122.00	100.60	77.36	77.36	120.00	13.89	92.87
8.0	126.00	100.60	77.36	77.36	124.00	13.47	93.48
8.0	130.00	100.60	77.36	77.36	128.00	13.10	94.04
8.0	134.00	100.60	77.36	77.36	132.00	12.75	94.55
8.0	138.00	100.60	77.36	77.36	136.00	12.42	95.03
8.0	142.00	100.60	77.36	77.36	140.00	12.12	95.47

Delta T = 2 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.00	11.33	93.80
4.0	98.00	91.41	77.36	77.36	96.00	10.88	94.37
4.0	102.00	91.41	77.36	77.36	100.00	10.49	94.86
4.0	106.00	91.41	77.36	77.36	104.00	10.13	95.30
4.0	110.00	91.41	77.36	77.36	108.00	9.82	95.69
4.0	114.00	91.41	77.36	77.36	112.00	9.54	96.05
4.0	118.00	91.41	77.36	77.36	116.00	9.28	96.37
4.0	122.00	91.41	77.36	77.36	120.00	9.04	96.67
4.0	126.00	91.41	77.36	77.36	124.00	8.82	96.95
4.0	130.00	91.41	77.36	77.36	128.00	8.62	97.21
4.0	134.00	91.41	77.36	77.36	132.00	8.42	97.45
4.0	138.00	91.41	77.36	77.36	136.00	8.24	97.67
4.0	142.00	91.41	77.36	77.36	140.00	8.07	97.89
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.00	13.13	92.60
5.0	102.00	94.18	77.36	77.36	100.00	12.62	93.28
5.0	106.00	94.18	77.36	77.36	104.00	12.16	93.88
5.0	110.00	94.18	77.36	77.36	108.00	11.77	94.40
5.0	114.00	94.18	77.36	77.36	112.00	11.41	94.87
5.0	118.00	94.18	77.36	77.36	116.00	11.08	95.30
5.0	122.00	94.18	77.36	77.36	120.00	10.78	95.69
5.0	126.00	94.18	77.36	77.36	124.00	10.51	96.06
5.0	130.00	94.18	77.36	77.36	128.00	10.26	96.39
5.0	134.00	94.18	77.36	77.36	132.00	10.02	96.70
5.0	138.00	94.18	77.36	77.36	136.00	9.80	96.99
5.0	142.00	94.18	77.36	77.36	140.00	9.59	97.27
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.00	15.14	90.84
6.0	102.00	96.58	77.36	77.36	100.00	14.49	91.73
6.0	106.00	96.58	77.36	77.36	104.00	13.93	92.50
6.0	110.00	96.58	77.36	77.36	108.00	13.45	93.17
6.0	114.00	96.58	77.36	77.36	112.00	13.01	93.77
6.0	118.00	96.58	77.36	77.36	116.00	12.62	94.31
6.0	122.00	96.58	77.36	77.36	120.00	12.27	94.80
6.0	126.00	96.58	77.36	77.36	124.00	11.94	95.24
6.0	130.00	96.58	77.36	77.36	128.00	11.64	95.65
6.0	134.00	96.58	77.36	77.36	132.00	11.37	96.04
6.0	138.00	96.58	77.36	77.36	136.00	11.11	96.39
6.0	142.00	96.58	77.36	77.36	140.00	10.86	96.73

Delta T = 2 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.00	16.22	90.17
7.0	106.00	98.69	77.36	77.36	104.00	15.54	91.14
7.0	110.00	98.69	77.36	77.36	108.00	14.96	91.97
7.0	114.00	98.69	77.36	77.36	112.00	14.45	92.70
7.0	118.00	98.69	77.36	77.36	116.00	13.99	93.35
7.0	122.00	98.69	77.36	77.36	120.00	13.58	93.95
7.0	126.00	98.69	77.36	77.36	124.00	13.21	94.48
7.0	130.00	98.69	77.36	77.36	128.00	12.86	94.97
7.0	134.00	98.69	77.36	77.36	132.00	12.54	95.43
7.0	138.00	98.69	77.36	77.36	136.00	12.25	95.85
7.0	142.00	98.69	77.36	77.36	140.00	11.97	96.25
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.00	17.84	88.55
8.0	106.00	100.60	77.36	77.36	104.00	17.04	89.75
8.0	110.00	100.60	77.36	77.36	108.00	16.36	90.76
8.0	114.00	100.60	77.36	77.36	112.00	15.76	91.65
8.0	118.00	100.60	77.36	77.36	116.00	15.24	92.43
8.0	122.00	100.60	77.36	77.36	120.00	14.77	93.13
8.0	126.00	100.60	77.36	77.36	124.00	14.34	93.76
8.0	130.00	100.60	77.36	77.36	128.00	13.96	94.34
8.0	134.00	100.60	77.36	77.36	132.00	13.60	94.87
8.0	138.00	100.60	77.36	77.36	136.00	13.27	95.36
8.0	142.00	100.60	77.36	77.36	140.00	12.96	95.82

Delta T = 2 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.00	12.00	93.86
4.0	98.00	91.41	77.36	77.36	96.00	11.54	94.44
4.0	102.00	91.41	77.36	77.36	100.00	11.14	94.95
4.0	106.00	91.41	77.36	77.36	104.00	10.78	95.41
4.0	110.00	91.41	77.36	77.36	108.00	10.46	95.81
4.0	114.00	91.41	77.36	77.36	112.00	10.17	96.18
4.0	118.00	91.41	77.36	77.36	116.00	9.90	96.52
4.0	122.00	91.41	77.36	77.36	120.00	9.66	96.83
4.0	126.00	91.41	77.36	77.36	124.00	9.43	97.12
4.0	130.00	91.41	77.36	77.36	128.00	9.22	97.39
4.0	134.00	91.41	77.36	77.36	132.00	9.01	97.64
4.0	138.00	91.41	77.36	77.36	136.00	8.83	97.88
4.0	142.00	91.41	77.36	77.36	140.00	8.65	98.11
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	96.00	13.89	92.69
5.0	102.00	94.18	77.36	77.36	100.00	13.36	93.39
5.0	106.00	94.18	77.36	77.36	104.00	12.90	94.00
5.0	110.00	94.18	77.36	77.36	108.00	12.50	94.54
5.0	114.00	94.18	77.36	77.36	112.00	12.13	95.03
5.0	118.00	94.18	77.36	77.36	116.00	11.79	95.48
5.0	122.00	94.18	77.36	77.36	120.00	11.49	95.88
5.0	126.00	94.18	77.36	77.36	124.00	11.21	96.26
5.0	130.00	94.18	77.36	77.36	128.00	10.94	96.61
5.0	134.00	94.18	77.36	77.36	132.00	10.70	96.93
5.0	138.00	94.18	77.36	77.36	136.00	10.47	97.24
5.0	142.00	94.18	77.36	77.36	140.00	10.25	97.53
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	96.00	15.97	90.94
6.0	102.00	96.58	77.36	77.36	100.00	15.31	91.85
6.0	106.00	96.58	77.36	77.36	104.00	14.74	92.64
6.0	110.00	96.58	77.36	77.36	108.00	14.25	93.33
6.0	114.00	96.58	77.36	77.36	112.00	13.81	93.95
6.0	118.00	96.58	77.36	77.36	116.00	13.41	94.50
6.0	122.00	96.58	77.36	77.36	120.00	13.04	95.01
6.0	126.00	96.58	77.36	77.36	124.00	12.71	95.47
6.0	130.00	96.58	77.36	77.36	128.00	12.40	95.90
6.0	134.00	96.58	77.36	77.36	132.00	12.12	96.30
6.0	138.00	96.58	77.36	77.36	136.00	11.85	96.67
6.0	142.00	96.58	77.36	77.36	140.00	11.60	97.02

Delta T = 2 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.00	17.09	90.30
7.0	106.00	98.69	77.36	77.36	104.00	16.41	91.29
7.0	110.00	98.69	77.36	77.36	108.00	15.82	92.14
7.0	114.00	98.69	77.36	77.36	112.00	15.30	92.90
7.0	118.00	98.69	77.36	77.36	116.00	14.83	93.57
7.0	122.00	98.69	77.36	77.36	120.00	14.41	94.18
7.0	126.00	98.69	77.36	77.36	124.00	14.03	94.74
7.0	130.00	98.69	77.36	77.36	128.00	13.68	95.25
7.0	134.00	98.69	77.36	77.36	132.00	13.35	95.72
7.0	138.00	98.69	77.36	77.36	136.00	13.05	96.16
7.0	142.00	98.69	77.36	77.36	140.00	12.76	96.58
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.00	18.76	88.69
8.0	106.00	100.60	77.36	77.36	104.00	17.95	89.91
8.0	110.00	100.60	77.36	77.36	108.00	17.26	90.95
8.0	114.00	100.60	77.36	77.36	112.00	16.66	91.86
8.0	118.00	100.60	77.36	77.36	116.00	16.13	92.66
8.0	122.00	100.60	77.36	77.36	120.00	15.65	93.38
8.0	126.00	100.60	77.36	77.36	124.00	15.22	94.03
8.0	130.00	100.60	77.36	77.36	128.00	14.82	94.63
8.0	134.00	100.60	77.36	77.36	132.00	14.46	95.18
8.0	138.00	100.60	77.36	77.36	136.00	14.12	95.70
8.0	142.00	100.60	77.36	77.36	140.00	13.80	96.17

Delta T = 2.0 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	92.00	12.67	93.92
4.0	98.00	91.41	77.36	77.36	96.00	12.21	94.52
4.0	102.00	91.41	77.36	77.36	100.00	11.80	95.04
4.0	106.00	91.41	77.36	77.36	104.00	11.43	95.51
4.0	110.00	91.41	77.36	77.36	108.00	11.10	95.93
4.0	114.00	91.41	77.36	77.36	112.00	10.80	96.31
4.0	118.00	91.41	77.36	77.36	116.00	10.52	96.67
4.0	122.00	91.41	77.36	77.36	120.00	10.27	96.99
4.0	126.00	91.41	77.36	77.36	124.00	10.04	97.29
4.0	130.00	91.41	77.36	77.36	128.00	9.81	97.57
4.0	134.00	91.41	77.36	77.36	132.00	9.61	97.84
4.0	138.00	91.41	77.36	77.36	136.00	9.41	98.09
4.0	142.00	91.41	77.36	77.36	140.00	9.23	98.32
5.0	94.00	***** SECOND LAW VIOLATION *****					
5.0	98.00	94.18	77.36	77.36	96.00	14.64	92.78
5.0	102.00	94.18	77.36	77.36	100.00	14.11	93.49
5.0	106.00	94.18	77.36	77.36	104.00	13.64	94.12
5.0	110.00	94.18	77.36	77.36	108.00	13.23	94.68
5.0	114.00	94.18	77.36	77.36	112.00	12.85	95.19
5.0	118.00	94.18	77.36	77.36	116.00	12.51	95.65
5.0	122.00	94.18	77.36	77.36	120.00	12.20	96.07
5.0	126.00	94.18	77.36	77.36	124.00	11.91	96.46
5.0	130.00	94.18	77.36	77.36	128.00	11.64	96.82
5.0	134.00	94.18	77.36	77.36	132.00	11.38	97.16
5.0	138.00	94.18	77.36	77.36	136.00	11.14	97.48
5.0	142.00	94.18	77.36	77.36	140.00	10.92	97.79
6.0	94.00	***** SECOND LAW VIOLATION *****					
6.0	98.00	96.58	77.36	77.36	96.00	16.79	91.04
6.0	102.00	96.58	77.36	77.36	100.00	16.13	91.97
6.0	106.00	96.58	77.36	77.36	104.00	15.56	92.78
6.0	110.00	96.58	77.36	77.36	108.00	15.05	93.49
6.0	114.00	96.58	77.36	77.36	112.00	14.60	94.12
6.0	118.00	96.58	77.36	77.36	116.00	14.20	94.70
6.0	122.00	96.58	77.36	77.36	120.00	13.82	95.22
6.0	126.00	96.58	77.36	77.36	124.00	13.48	95.70
6.0	130.00	96.58	77.36	77.36	128.00	13.17	96.15
6.0	134.00	96.58	77.36	77.36	132.00	12.87	96.56
6.0	138.00	96.58	77.36	77.36	136.00	12.60	96.95
6.0	142.00	96.58	77.36	77.36	140.00	12.34	97.32

Delta T = 2.0 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	100.00	17.96	90.43
7.0	106.00	98.69	77.36	77.36	104.00	17.27	91.44
7.0	110.00	98.69	77.36	77.36	108.00	16.68	92.32
7.0	114.00	98.69	77.36	77.36	112.00	16.15	93.09
7.0	118.00	98.69	77.36	77.36	116.00	15.68	93.79
7.0	122.00	98.69	77.36	77.36	120.00	15.25	94.42
7.0	126.00	98.69	77.36	77.36	124.00	14.86	94.99
7.0	130.00	98.69	77.36	77.36	128.00	14.50	95.52
7.0	134.00	98.69	77.36	77.36	132.00	14.17	96.01
7.0	138.00	98.69	77.36	77.36	136.00	13.85	96.47
7.0	142.00	98.69	77.36	77.36	140.00	13.56	96.90
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	100.00	19.68	88.83
8.0	106.00	100.60	77.36	77.36	104.00	18.86	90.08
8.0	110.00	100.60	77.36	77.36	108.00	18.17	91.14
8.0	114.00	100.60	77.36	77.36	112.00	17.56	92.07
8.0	118.00	100.60	77.36	77.36	116.00	17.02	92.90
8.0	122.00	100.60	77.36	77.36	120.00	16.54	93.64
8.0	126.00	100.60	77.36	77.36	124.00	16.10	94.31
8.0	130.00	100.60	77.36	77.36	128.00	15.70	94.93
8.0	134.00	100.60	77.36	77.36	132.00	15.32	95.50
8.0	138.00	100.60	77.36	77.36	136.00	14.97	96.03
8.0	142.00	100.60	77.36	77.36	140.00	14.65	96.53

Delta T = 2.5 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	91.50	10.46	93.99
4.0	98.00	91.41	77.36	77.36	95.50	10.02	94.54
4.0	102.00	91.41	77.36	77.36	99.50	9.63	95.02
4.0	106.00	91.41	77.36	77.36	103.50	9.30	95.43
4.0	110.00	91.41	77.36	77.36	107.50	8.95	95.87
4.0	114.00	91.41	77.36	77.36	111.50	8.72	96.15
4.0	118.00	91.41	77.36	77.36	115.50	8.48	96.46
4.0	122.00	91.41	77.36	77.36	119.50	8.25	96.74
4.0	126.00	91.41	77.36	77.36	123.50	8.04	97.00
4.0	130.00	91.41	77.36	77.36	127.50	7.84	97.24
4.0	134.00	91.41	77.36	77.36	131.50	7.66	97.47
4.0	138.00	91.41	77.36	77.36	135.50	7.49	97.68
4.0	142.00	91.41	77.36	77.36	139.50	7.33	97.88
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	95.50	12.19	92.76
5.0	102.00	94.18	77.36	77.36	99.50	11.68	93.42
5.0	106.00	94.18	77.36	77.36	103.50	11.24	93.99
5.0	110.00	94.18	77.36	77.36	107.50	10.81	94.56
5.0	114.00	94.18	77.36	77.36	111.50	10.51	94.95
5.0	118.00	94.18	77.36	77.36	115.50	10.19	95.36
5.0	122.00	94.18	77.36	77.36	119.50	9.91	95.74
5.0	126.00	94.18	77.36	77.36	123.50	9.64	96.08
5.0	130.00	94.18	77.36	77.36	127.50	9.40	96.40
5.0	134.00	94.18	77.36	77.36	131.50	9.17	96.69
5.0	138.00	94.18	77.36	77.36	135.50	8.96	96.97
5.0	142.00	94.18	77.36	77.36	139.50	8.76	97.23
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	95.50	14.13	90.99
6.0	102.00	96.58	77.36	77.36	99.50	13.50	91.86
6.0	106.00	96.58	77.36	77.36	103.50	12.95	92.60
6.0	110.00	96.58	77.36	77.36	107.50	12.43	93.31
6.0	114.00	96.58	77.36	77.36	111.50	12.05	93.83
6.0	118.00	96.58	77.36	77.36	115.50	11.67	94.35
6.0	122.00	96.58	77.36	77.36	119.50	11.32	94.82
6.0	126.00	96.58	77.36	77.36	123.50	11.01	95.24
6.0	130.00	96.58	77.36	77.36	127.50	10.72	95.63
6.0	134.00	96.58	77.36	77.36	131.50	10.45	96.00
6.0	138.00	96.58	77.36	77.36	135.50	10.20	96.34
6.0	142.00	96.58	77.36	77.36	139.50	9.97	96.66

Delta T = 2.5 K, n = 65 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	99.50	15.17	90.29
7.0	106.00	98.69	77.36	77.36	103.50	14.50	91.23
7.0	110.00	98.69	77.36	77.36	107.50	13.89	92.10
7.0	114.00	98.69	77.36	77.36	111.50	13.43	92.75
7.0	118.00	98.69	77.36	77.36	115.50	12.98	93.38
7.0	122.00	98.69	77.36	77.36	119.50	12.58	93.95
7.0	126.00	98.69	77.36	77.36	123.50	12.22	94.46
7.0	130.00	98.69	77.36	77.36	127.50	11.89	94.93
7.0	134.00	98.69	77.36	77.36	131.50	11.58	95.37
7.0	138.00	98.69	77.36	77.36	135.50	11.29	95.77
7.0	142.00	98.69	77.36	77.36	139.50	11.03	96.15
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	99.50	16.76	88.66
8.0	106.00	100.60	77.36	77.36	103.50	15.96	89.83
8.0	110.00	100.60	77.36	77.36	107.50	15.25	90.88
8.0	114.00	100.60	77.36	77.36	111.50	14.70	91.68
8.0	118.00	100.60	77.36	77.36	115.50	14.19	92.44
8.0	122.00	100.60	77.36	77.36	119.50	13.73	93.11
8.0	126.00	100.60	77.36	77.36	123.50	13.31	93.72
8.0	130.00	100.60	77.36	77.36	127.50	12.94	94.28
8.0	134.00	100.60	77.36	77.36	131.50	12.59	94.78
8.0	138.00	100.60	77.36	77.36	135.50	12.27	95.26
8.0	142.00	100.60	77.36	77.36	139.50	11.97	95.69

Delta T = 2.5 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	91.50	11.13	94.05
4.0	98.00	91.41	77.36	77.36	95.50	10.68	94.61
4.0	102.00	91.41	77.36	77.36	99.50	10.29	95.10
4.0	106.00	91.41	77.36	77.36	103.50	9.95	95.54
4.0	110.00	91.41	77.36	77.36	107.50	9.59	95.98
4.0	114.00	91.41	77.36	77.36	111.50	9.35	96.28
4.0	118.00	91.41	77.36	77.36	115.50	9.10	96.60
4.0	122.00	91.41	77.36	77.36	119.50	8.86	96.90
4.0	126.00	91.41	77.36	77.36	123.50	8.65	97.17
4.0	130.00	91.41	77.36	77.36	127.50	8.44	97.42
4.0	134.00	91.41	77.36	77.36	131.50	8.25	97.66
4.0	138.00	91.41	77.36	77.36	135.50	8.07	97.89
4.0	142.00	91.41	77.36	77.36	139.50	7.91	98.10
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	95.50	12.94	92.85
5.0	102.00	94.18	77.36	77.36	99.50	12.43	93.53
5.0	106.00	94.18	77.36	77.36	103.50	11.98	94.11
5.0	110.00	94.18	77.36	77.36	107.50	11.54	94.69
5.0	114.00	94.18	77.36	77.36	111.50	11.23	95.11
5.0	118.00	94.18	77.36	77.36	115.50	10.91	95.53
5.0	122.00	94.18	77.36	77.36	119.50	10.61	95.92
5.0	126.00	94.18	77.36	77.36	123.50	10.34	96.28
5.0	130.00	94.18	77.36	77.36	127.50	10.09	96.61
5.0	134.00	94.18	77.36	77.36	131.50	9.85	96.92
5.0	138.00	94.18	77.36	77.36	135.50	9.63	97.21
5.0	142.00	94.18	77.36	77.36	139.50	9.43	97.48
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	95.50	14.96	91.09
6.0	102.00	96.58	77.36	77.36	99.50	14.31	91.98
6.0	106.00	96.58	77.36	77.36	103.50	13.76	92.74
6.0	110.00	96.58	77.36	77.36	107.50	13.23	93.47
6.0	114.00	96.58	77.36	77.36	111.50	12.84	94.01
6.0	118.00	96.58	77.36	77.36	115.50	12.45	94.54
6.0	122.00	96.58	77.36	77.36	119.50	12.10	95.03
6.0	126.00	96.58	77.36	77.36	123.50	11.78	95.47
6.0	130.00	96.58	77.36	77.36	127.50	11.48	95.88
6.0	134.00	96.58	77.36	77.36	131.50	11.20	96.26
6.0	138.00	96.58	77.36	77.36	135.50	10.95	96.61
6.0	142.00	96.58	77.36	77.36	139.50	10.70	96.95

Delta T = 2.5 K, n = 70 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW VIOLATION	*****			
7.0	98.00	*****	SECOND LAW VIOLATION	*****			
7.0	102.00	98.69	77.36	77.36	99.50	16.04	90.42
7.0	106.00	98.69	77.36	77.36	103.50	15.37	91.38
7.0	110.00	98.69	77.36	77.36	107.50	14.75	92.27
7.0	114.00	98.69	77.36	77.36	111.50	14.28	92.94
7.0	118.00	98.69	77.36	77.36	115.50	13.83	93.59
7.0	122.00	98.69	77.36	77.36	119.50	13.42	94.18
7.0	126.00	98.69	77.36	77.36	123.50	13.04	94.71
7.0	130.00	98.69	77.36	77.36	127.50	12.70	95.20
7.0	134.00	98.69	77.36	77.36	131.50	12.39	95.66
7.0	138.00	98.69	77.36	77.36	135.50	12.09	96.08
7.0	142.00	98.69	77.36	77.36	139.50	11.82	96.47
8.0	94.00	*****	SECOND LAW VIOLATION	*****			
8.0	98.00	*****	SECOND LAW VIOLATION	*****			
8.0	102.00	100.60	77.36	77.36	99.50	17.68	88.80
8.0	106.00	100.60	77.36	77.36	103.50	16.87	89.99
8.0	110.00	100.60	77.36	77.36	107.50	16.15	91.07
8.0	114.00	100.60	77.36	77.36	111.50	15.60	91.89
8.0	118.00	100.60	77.36	77.36	115.50	15.08	92.67
8.0	122.00	100.60	77.36	77.36	119.50	14.61	93.36
8.0	126.00	100.60	77.36	77.36	123.50	14.19	93.99
8.0	130.00	100.60	77.36	77.36	127.50	13.80	94.57
8.0	134.00	100.60	77.36	77.36	131.50	13.45	95.10
8.0	138.00	100.60	77.36	77.36	135.50	13.12	95.59
8.0	142.00	100.60	77.36	77.36	139.50	12.81	96.04

Delta T = 2.5 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	91.50	11.80	94.11
4.0	98.00	91.41	77.36	77.36	95.50	11.35	94.69
4.0	102.00	91.41	77.36	77.36	99.50	10.95	95.19
4.0	106.00	91.41	77.36	77.36	103.50	10.60	95.64
4.0	110.00	91.41	77.36	77.36	107.50	10.23	96.10
4.0	114.00	91.41	77.36	77.36	111.50	9.99	96.41
4.0	118.00	91.41	77.36	77.36	115.50	9.72	96.75
4.0	122.00	91.41	77.36	77.36	119.50	9.48	97.05
4.0	126.00	91.41	77.36	77.36	123.50	9.25	97.34
4.0	130.00	91.41	77.36	77.36	127.50	9.04	97.61
4.0	134.00	91.41	77.36	77.36	131.50	8.85	97.86
4.0	138.00	91.41	77.36	77.36	135.50	8.66	98.09
4.0	142.00	91.41	77.36	77.36	139.50	8.48	98.31
5.0	94.00	*****	SECOND LAW	VIOLATION	*****		
5.0	98.00	94.18	77.36	77.36	95.50	13.70	92.94
5.0	102.00	94.18	77.36	77.36	99.50	13.18	93.63
5.0	106.00	94.18	77.36	77.36	103.50	12.73	94.24
5.0	110.00	94.18	77.36	77.36	107.50	12.28	94.83
5.0	114.00	94.18	77.36	77.36	111.50	11.95	95.26
5.0	118.00	94.18	77.36	77.36	115.50	11.62	95.70
5.0	122.00	94.18	77.36	77.36	119.50	11.32	96.11
5.0	126.00	94.18	77.36	77.36	123.50	11.04	96.48
5.0	130.00	94.18	77.36	77.36	127.50	10.78	96.83
5.0	134.00	94.18	77.36	77.36	131.50	10.54	97.15
5.0	138.00	94.18	77.36	77.36	135.50	10.31	97.45
5.0	142.00	94.18	77.36	77.36	139.50	10.09	97.74
6.0	94.00	*****	SECOND LAW	VIOLATION	*****		
6.0	98.00	96.58	77.36	77.36	95.50	15.79	91.19
6.0	102.00	96.58	77.36	77.36	99.50	15.13	92.10
6.0	106.00	96.58	77.36	77.36	103.50	14.57	92.88
6.0	110.00	96.58	77.36	77.36	107.50	14.04	93.62
6.0	114.00	96.58	77.36	77.36	111.50	13.64	94.18
6.0	118.00	96.58	77.36	77.36	115.50	13.24	94.73
6.0	122.00	96.58	77.36	77.36	119.50	12.88	95.24
6.0	126.00	96.58	77.36	77.36	123.50	12.55	95.70
6.0	130.00	96.58	77.36	77.36	127.50	12.24	96.12
6.0	134.00	96.58	77.36	77.36	131.50	11.96	96.52
6.0	138.00	96.58	77.36	77.36	135.50	11.69	96.89
6.0	142.00	96.58	77.36	77.36	139.50	11.44	97.24

Delta T = 2.5 K, n = 75 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW VIOLATION		*****		
7.0	98.00	*****	SECOND LAW VIOLATION		*****		
7.0	102.00	98.69	77.36	77.36	99.50	16.92	90.55
7.0	106.00	98.69	77.36	77.36	103.50	16.24	91.53
7.0	110.00	98.69	77.36	77.36	107.50	15.61	92.44
7.0	114.00	98.69	77.36	77.36	111.50	15.13	93.13
7.0	118.00	98.69	77.36	77.36	115.50	14.67	93.81
7.0	122.00	98.69	77.36	77.36	119.50	14.25	94.41
7.0	126.00	98.69	77.36	77.36	123.50	13.87	94.97
7.0	130.00	98.69	77.36	77.36	127.50	13.52	95.47
7.0	134.00	98.69	77.36	77.36	131.50	13.20	95.94
7.0	138.00	98.69	77.36	77.36	135.50	12.90	96.38
7.0	142.00	98.69	77.36	77.36	139.50	12.61	96.79
8.0	94.00	*****	SECOND LAW VIOLATION		*****		
8.0	98.00	*****	SECOND LAW VIOLATION		*****		
8.0	102.00	100.60	77.36	77.36	99.50	18.59	88.94
8.0	106.00	100.60	77.36	77.36	103.50	17.79	90.16
8.0	110.00	100.60	77.36	77.36	107.50	17.06	91.25
8.0	114.00	100.60	77.36	77.36	111.50	16.50	92.10
8.0	118.00	100.60	77.36	77.36	115.50	15.97	92.90
8.0	122.00	100.60	77.36	77.36	119.50	15.50	93.62
8.0	126.00	100.60	77.36	77.36	123.50	15.07	94.27
8.0	130.00	100.60	77.36	77.36	127.50	14.67	94.86
8.0	134.00	100.60	77.36	77.36	131.50	14.31	95.41
8.0	138.00	100.60	77.36	77.36	135.50	13.97	95.92
8.0	142.00	100.60	77.36	77.36	139.50	13.66	96.40

Delta T = 2.5 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
4.0	94.00	91.41	77.36	77.36	91.50	12.48	94.17
4.0	98.00	91.41	77.36	77.36	95.50	12.01	94.76
4.0	102.00	91.41	77.36	77.36	99.50	11.61	95.28
4.0	106.00	91.41	77.36	77.36	103.50	11.25	95.75
4.0	110.00	91.41	77.36	77.36	107.50	10.88	96.22
4.0	114.00	91.41	77.36	77.36	111.50	10.62	96.54
4.0	118.00	91.41	77.36	77.36	115.50	10.35	96.89
4.0	122.00	91.41	77.36	77.36	119.50	10.10	97.21
4.0	126.00	91.41	77.36	77.36	123.50	9.86	97.51
4.0	130.00	91.41	77.36	77.36	127.50	9.65	97.79
4.0	134.00	91.41	77.36	77.36	131.50	9.44	98.05
4.0	138.00	91.41	77.36	77.36	135.50	9.25	98.30
4.0	142.00	91.41	77.36	77.36	139.50	9.06	98.53
5.0	94.00	***** SECOND LAW VIOLATION *****					
5.0	98.00	94.18	77.36	77.36	95.50	14.46	93.02
5.0	102.00	94.18	77.36	77.36	99.50	13.93	93.74
5.0	106.00	94.18	77.36	77.36	103.50	13.47	94.36
5.0	110.00	94.18	77.36	77.36	107.50	13.01	94.97
5.0	114.00	94.18	77.36	77.36	111.50	12.68	95.42
5.0	118.00	94.18	77.36	77.36	115.50	12.34	95.88
5.0	122.00	94.18	77.36	77.36	119.50	12.03	96.30
5.0	126.00	94.18	77.36	77.36	123.50	11.74	96.68
5.0	130.00	94.18	77.36	77.36	127.50	11.47	97.04
5.0	134.00	94.18	77.36	77.36	131.50	11.22	97.38
5.0	138.00	94.18	77.36	77.36	135.50	10.99	97.70
5.0	142.00	94.18	77.36	77.36	139.50	10.76	98.00
6.0	94.00	***** SECOND LAW VIOLATION *****					
6.0	98.00	96.58	77.36	77.36	95.50	16.62	91.29
6.0	102.00	96.58	77.36	77.36	99.50	15.96	92.22
6.0	106.00	96.58	77.36	77.36	103.50	15.39	93.02
6.0	110.00	96.58	77.36	77.36	107.50	14.85	93.78
6.0	114.00	96.58	77.36	77.36	111.50	14.44	94.36
6.0	118.00	96.58	77.36	77.36	115.50	14.03	94.93
6.0	122.00	96.58	77.36	77.36	119.50	13.66	95.45
6.0	126.00	96.58	77.36	77.36	123.50	13.32	95.93
6.0	130.00	96.58	77.36	77.36	127.50	13.01	96.37
6.0	134.00	96.58	77.36	77.36	131.50	12.72	96.78
6.0	138.00	96.58	77.36	77.36	135.50	12.44	97.17
6.0	142.00	96.58	77.36	77.36	139.50	12.18	97.53

Delta T = 2.5 K, n = 80 %

P1 ATM	T1 K	T2 K	T3 K	T4 K	T5 K	YIELD %	QUALITY %
7.0	94.00	*****	SECOND LAW	VIOLATION	*****		
7.0	98.00	*****	SECOND LAW	VIOLATION	*****		
7.0	102.00	98.69	77.36	77.36	99.50	17.79	90.68
7.0	106.00	98.69	77.36	77.36	103.50	17.11	91.68
7.0	110.00	98.69	77.36	77.36	107.50	16.48	92.61
7.0	114.00	98.69	77.36	77.36	111.50	15.99	93.33
7.0	118.00	98.69	77.36	77.36	115.50	15.52	94.02
7.0	122.00	98.69	77.36	77.36	119.50	15.10	94.65
7.0	126.00	98.69	77.36	77.36	123.50	14.71	95.22
7.0	130.00	98.69	77.36	77.36	127.50	14.35	95.74
7.0	134.00	98.69	77.36	77.36	131.50	14.02	96.23
7.0	138.00	98.69	77.36	77.36	135.50	13.70	96.69
7.0	142.00	98.69	77.36	77.36	139.50	13.41	97.12
8.0	94.00	*****	SECOND LAW	VIOLATION	*****		
8.0	98.00	*****	SECOND LAW	VIOLATION	*****		
8.0	102.00	100.60	77.36	77.36	99.50	19.51	89.08
8.0	106.00	100.60	77.36	77.36	103.50	18.70	90.32
8.0	110.00	100.60	77.36	77.36	107.50	17.97	91.44
8.0	114.00	100.60	77.36	77.36	111.50	17.41	92.31
8.0	118.00	100.60	77.36	77.36	115.50	16.87	93.13
8.0	122.00	100.60	77.36	77.36	119.50	16.39	93.87
8.0	126.00	100.60	77.36	77.36	123.50	15.95	94.54
8.0	130.00	100.60	77.36	77.36	127.50	15.55	95.16
8.0	134.00	100.60	77.36	77.36	131.50	15.17	95.73
8.0	138.00	100.60	77.36	77.36	135.50	14.83	96.26
8.0	142.00	100.60	77.36	77.36	139.50	14.51	96.75

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16. Abstract

Cryogenic seal tests were performed and Rulon "A" was selected for the subject nutating positive displacement expander. A four-chamber expander was designed and fabricated. A nitrogen reliquefier flow system was also designed and constructed for testing the cold expander. Initial tests were unsatisfactory because of high internal friction attributed to nutating Rulon inlet and outlet valve plates. Replacement of the nutating valves with cam-actuated poppet valves improved performance. However, no net nitrogen reliquefaction was achieved due to high internal friction.

Computer software was developed for accurate calculation of nitrogen reliquefaction from a system such as that proposed. These calculations indicated that practical reliquefaction rates of 15 to 19 percent could be obtained. Due to mechanical problems, the nutating expander did not demonstrate its feasibility nor that of the system. It was concluded that redesign and testing of a smaller nutating expander was required to prove concept feasibility.

17. Key Words (Suggested by Author(s))

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