Title
COMPRESSOR PERFORMANCE

Authors
Hoyer, Egon
Byrns, Roscoe.

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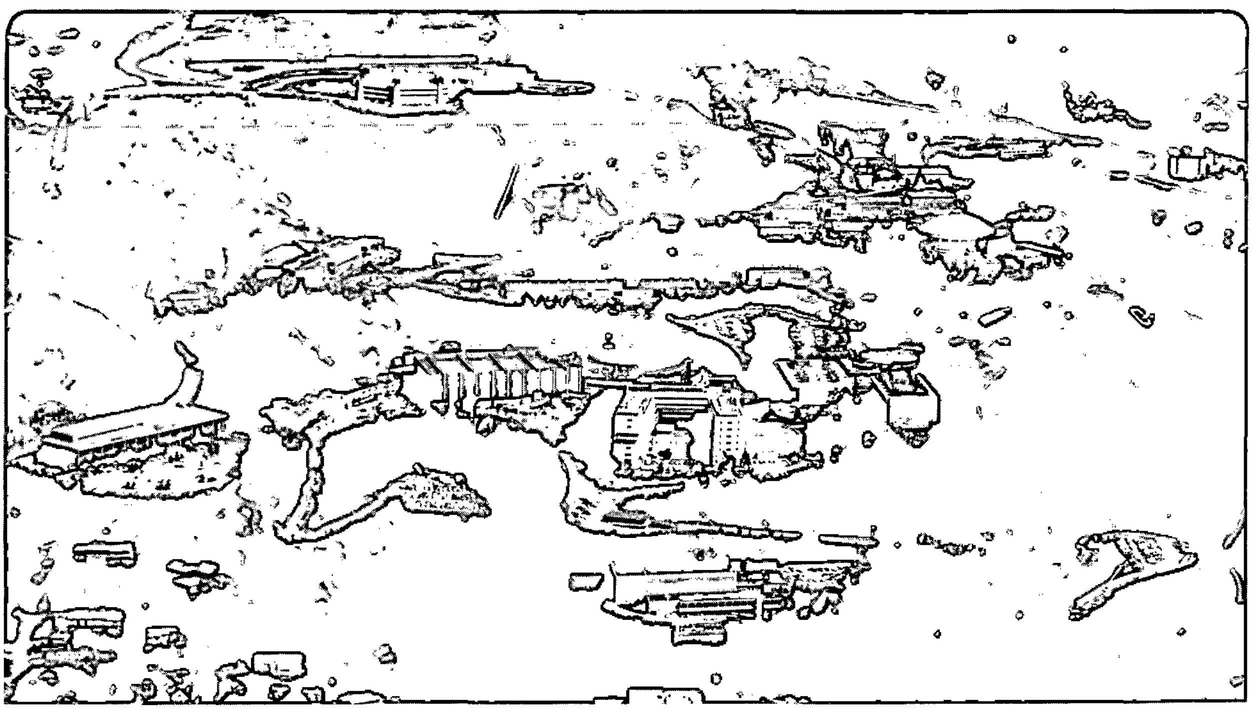
UNIVERSITY OF CALIFORNIA

Engineering & Technical Services Division



DISCLAIMER

LAWRENCE BERKELEY LABORATORY - UNIVERSITY OF CALIFORNIA ENGINEERING NOTE		CODE ES0510	SERIAL M5129	PAGE 1 OF 9
AUTHOR E. Hoyer/R. Byrns	DEPARTMENT Mechanical	LOCATION Berkeley	DATE JULY 1977 Thru Feb 78	

PROGRAM — PROJECT — JOB

ESCAR

Refrigeration Plant

TITLE

Compressor Performance

Table of Contents

Preamble

This note contains measured operating data and efficiency factors for the ESCAR 1500 watt helium refrigeration compressors. Efficiencies are about as predicted, 75-85% volumetric and 65-75% isentropic.

The first stage machine is a Sullair oil-injected screw compressor, C25LB-704-2.6-200 HP; motor service factor 1.15 = 230 HP (172 kw). Second stage is C25LA-704-3.7-800 HP; service factor 1.15 = 930 HP (686 kw). Displacement is 1710 CFM at 3550 RPM for both. Operation of first stage is 1 to 3 atm at 113 gms/sec and second stage is 3 to 18 atm at 250 gms/sec (helium gas). Reference: LBL Specification M480. Total installed horsepower is thus 230 + 930 = 1160 HP (with added potential of about 90 HP for interstage cooler).

Most of the data was taken operating on Capella D oil. We are now using UCON-LB-165X, a synthetic polyalkyl glycol. Heat transfer and output seem better, with less foaming. We believe separation is also improved. The machines were delivered in September, 1976, and presently, have over 400 clock hours of operation. Oil content in the process stream past the aftercooler (at the first coalescer) is 30 PPM_w.

At BNL, J. Bamberger in late 1976 purchased a C20LA-704-4.8-400 HP (881 CFM Displacement) operating on helium gas (1-15 atm) with UCON-170. This first machine now has over 4000 hours of operating time. They optioned for two more C20LA's and are now installing them. Presently they don't use any charcoal on clean-up, only through (3) Balston coalescers in series. They have redesigned and rebuilt the compressor control with solid state, claiming more reliability (lightening/voltage dips and interlock read outs) and less cost. Mass flow is about half capacity, 27 gms/sec, the most that their CTi-2000 refrigerator will take (≈ 200 watts). The single compressor has replaced 7 smaller units.

Input power here at LBL was measured with calibrated on-line wattmeters. We can actually get more input than rated because the voltage runs as high as 490 V reducing current draw and resistance heating. Mass flow was measured with orifice plates past the aftercoolers, together with temperature and pressure. Orifice plates and data are described in Engineering Note M5015A. We now have enlarged the orifice plate on the first stage machine to reduce the pressure drop. Pressure and temperature gauges were pre-calibrated.

Sample efficiency calculations are given. Isentropic is based on discharge pressure at the compressor. There is pressure drop through the bulk oil separator, and aftercoolers and this must be allowed for in plant design. This pressure drop could (or should?) be included in efficiency, as well as cooling water pump power, but was not done in this case. The efficiency does include the compressor electric drive motor losses.

Reference: Thermodynamic Performance of Oil-Floded Helium Screw Compressors
W. M. Toscano and L. C. Hoagland
Helix Corporation, Waltham, Massachusetts
ASME Paper No. 76-WA/PID-15

Sample Calculations 1st stage compressor at 36.8 psia out with 113.3 gm/sec and 144 kw input power

SUCTION @ 0.6 psia

one atm = 14.3 psia

Volumetric Efficiency, η_{vol}

$$\eta_{vol} = \frac{\dot{m}}{\rho_{inlet} V_{displ.}} = \frac{113.3 \text{ gm/sec}}{\left(\frac{14.9}{14.7}\right) 1.72\times10^{4} \frac{gm}{cm^3}\left(1710 \frac{ft^3}{min}\right)} \quad \frac{60 \text{ sec/min}}{1728 \frac{in^3}{ft^3}\underbrace{(2.54 cm)^3}_{16.39}}$$

at 284°K

ρ_{inlet} = density is function(t, p)

$$\boxed{\eta_{vol} = 80.5\%}$$

Quicker Conversion Factors

100 gm/sec = 1235 SCFM @ 284°K, 14.7 psia
= 1275 " @ 293°K "

$$\eta_{vol} = \frac{113.3 \text{ g/s} \quad 12.50}{(14.9/14.7) \quad 1710} = \boxed{\eta_{vol} = 81.8\%}$$

Compression Ratio, R_c $\quad R_c = \left(\frac{36.8}{14.9}\right) = 2.47$

Isentropic Effic, η_s (includes motor eff.)

$$\eta_s = \frac{\dot{m}\,\gamma\, R\, T_{inlet}}{\gamma-1\,(W_{act})}\left[\left(\frac{P_{in}}{P_{out}}\right)^{1-\frac{1}{\gamma}} - 1\right] \qquad \left(\frac{\gamma-1}{\gamma} = \frac{5/3-3/3}{5/3} = 2/5 = 0.4\right)$$

$$\eta_s = \frac{(113.3 \text{ gm/sec})(2.5)\left(20.50 \frac{cm^3\text{-}atm}{gm\ °K}\right)(284°K)\left[R_c^{0.4}-1\right]\left(\frac{1033 \text{ gm}}{cm^2\text{-}atm} \cdot \frac{watt.sec}{1.02\times10^4 \text{ gm cm}}\right)}{144\times10^3 \text{ watt}}$$

$$\boxed{\eta_s = 50.5\%}$$

Recap - Isentrop Eff, η_s

$$\eta_s = \frac{\dot{m}\frac{\gamma}{\gamma-1} R\, T_{in}\left[R_c^{\frac{\gamma-1}{\gamma}} - 1\right]}{W_{actual}}$$

$$= \dot{m}(\text{gm/sec})(2.5)\ 20.5\left(\frac{cm^3\text{-}atm}{gm\ °K}\right)(T_{in})\left(R_c^{0.4}-1\right)\left(\frac{1033 \text{ gm}}{cm^3\text{-}atm} \frac{watt\ sec}{1.02\times10^4 \text{ gm cm}}\right)$$

$$\doteq \frac{\dot{m}(\text{gm/sec})\, T_{in}(°K)\,(5.194\times10^{-3})\,(R_c^{0.4}-1)}{W_{act}\ (kW)}$$

$$\eta_s = \frac{\dot{m}(\text{gm/sec})\ 1.488\ (R_c^{0.4}-1)}{W_{act}\ (kW)} \quad \text{when } T_{in} = 284°K.$$

LAWRENCE RADIATION LABORATORY - UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

CODE	SERIAL	PAGE
ES0510	M5129	

AUTHOR: EGON HOYER | DEPARTMENT: MECH. ENGINEERING | LOCATION: BERKELEY | DATE: 7/27/77

PROGRAM — PROJECT — JOB: ESCAR - REFRIG SYSTEM

COMPRESSOR DEVELOPMENT

TITLE: DATA FOR 1ST STAGE COMPRESSOR elev 700 ft

SULLAIR C25 LB-704-2.6-200HP atm = 14.3 psi

DATE			7/26/77	7/26/77	3/14	3/18	3/18	3/15	3/15	3/2	3/10	3/1[illegible]
CAPACITY CONTROL SETTING			MAX	MAX	max	MAX	MAX	max	MAX	max	max	m[illegible]
SUCTION PRESSURE		(PSIG)	.54	.54	1.6	0.6	0.6	0.6	0.6	3.0	0.6	1.4
	✓	(ATM)	1.01	1.01		1.04	1.04	1.04	1.04			
COMPRESSOR OUTPUT PRES.		(PSIG)	35.5	30.0	44.0	36.5	33.0	30.0	25.5	35		
		(ATM)	3.39	3.01		3.55	3.31	3.10	2.78			
COMPRESSION RATIO			3.36	2.99	3.64	3.42	3.31	2.98	2.68	2.85	2.88	2.7
OUTPUT PRESSURE		(PSIG)	27.5	22.6	36.0	29.0	25.0	22.0	17.0	26.4		
	✓	(PSIA)	41.8	36.9	50.3	43.3	39.3	36.3	31.3	40.7	35.3	35.[illegible]
OUTPUT TEMP		(°C)	19.8	19.8		12	11.5	11.0	11.0	10.8		
	✓	(°K)	292.8	292.8		285	284.5	284	284	283.8		
ORIFICE PLATE DIFF. PRES		("H_2O)	7.6	8.2		6.6	7.2	7.9	9.0	28.5		
THRU PUT		(GM/SEC)	117.5	114.6	118	113.1	112.5	113.3	112.1	131.9	113	12[illegible]
MOTOR POWER		(KW)	146.8	134.4	182.4	157.2	151.2	144.0	132.0	158.4	144	146.[illegible]
OIL COOLER		(KW)										
AFTER COOLER		(KW)	32.6	28.7								
OIL TEMP		(°F)	108.0	107.5	113	112.6	112.8	112.8	112	112.6	110	111
BULK OIL SEP TEMP		(°F)	167	170	178	180	183	187	190.5	187	181.4	183
ADIABATIC EFF		(%)										
ISOTHERMAL EFF		(%)	75.6	71.2	65.0	68.1	68.5	64.6	61.5	65.0	62.0	64.[illegible]
OIL			UCON LB-165X	UCON LB-165X	Capella D	CAPELLA D	CAPELLA D	Capella D	Capella D	Capella D	Capella D	
VOLUMETRIC EFF. / η_{vol} %			86	83.9	79.8	81.5	81.3	81.3	80.8	81.8	81.5	86.[illegible]

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ENGINEERING NOTE

CODE	SERIAL	PAGE
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AUTHOR	DEPARTMENT	LOCATION	DATE
Hoyer / Byron	Mech	Berk	

SECOND STAGE

Sullair Screw Compressor Helium Gas, Capella D Oil 5-17-77

C25LA-704-3.7-800 atm = 14.3 psig

Suction Pressure = 22.5 PSIG (2.57 ATM) Maximum Capacity Control

Comp. Output Pres. PSIG (ATM)	Comp. Ratio R_C	Output Pres. PSIG (PSIA)	Output Temp. ^oC (^oK)	Orifice Plate ΔP in. H_2O (PSI)	Power kw (HP)	Thruput (gm/sec)	Volumetric Eff. (%)	Isentropic Eff. (%)
202 (15.13)	5.88	194 (208.3)	11.8 (284.8)	22.0 (.7944)	557 (746)	264.7	75.1 (76.2)	73.2 73.8
220 (16.38)	6.37	208 (222.3)	14.9 (287.9)	20.8 (.7511)	594 (796)	264.5	75.0 77.3	72.7
240 (17.78)	6.91	230 (244.3)	12.4 (285.4)	18.4 (.6644)	624 (836)	262.0	74.3 76.5	72.9
263 (19.39)	7.54	252 (266.3)	13 (286)	16.8 (.6067)	660 (885)	261.2	74.1 76.2	73.2
278 (20.44)	7.94	267 (281.3)	13.9 (286.9)	16.0 (.5778)	677 (907)	261.6	74.2 76.4	74.2

5-18-77

Suction Pressure 22.5 PSIG = (2.57 ATM) 80% Capacity Control

Comp. Output Pres. PSIG (ATM)	Comp. Ratio R_C	Output Pres. PSIG (PSIA)	Output Temp. ^oC (^oK)	Orifice Plate ΔP in. H_2O (PSI)	Power kw (HP)	Thruput (gm/sec)	Volumetric Eff. (%)	Isentropic Eff. (%)
200 (14.99)	5.70	192 (206.3)	11.3 (284.3)	8.4 (.3033)	388 (520)	163.1		62.8
220 (16.38)	6.37	210 (224.3)	11.6 (284.6)	7.9 (.2853)	412 (552)	164.9		59.8
240 (17.78)	6.91	231 (245.3)	12.0 (285)	7.4 (.2672)	438 (587)	166.8		
260 (19.18)	7.46	252 (266.3)	12.8 (285.8)	6.8 (.2456)	468 (627)	166.4		
279 (20.51)	7.98	272 (286.3)	13.0 (286.0)	6.6 (.2383)	492 (660)	169.9		
299 (21.91)	8.53	294 (308.3)	13.5 (286.5)	5.7 (.2058)	516 (692)	163.7		64.3

SECOND STAGE

Sullair Screw Compressor Helium Gas, Capella D Oil 5-18-77

C25LA-704-3.7-800

Suction Pressure = 0 - 0.5 PSIG Maximum Capacity Control

Comp. Output Pres. PSIG (ATM)	Comp. Ratio R_c	Output Pres. PSIG (PSIA)	Output Temp. ^oC (^oK)	Orifice Plate ΔP in. H_2O (PSI)	Power kw (HP)	Thruput (gm/sec)	Volumetric Eff. (%)	Isentropic Eff. (%)
300 (21.98)	21.98	294 (308.3)	13 (286)	2.3 (.0831)	588 (788)	104.1	78.2	64.3
278 (20.44)	20.44	273 (287.3)	12.9 (285.9)	2.6 (.0939)	552 (740)	106.9	79.2	67.4
260 (19.18)	19.18	252 (266.3)	14.6 (287.6)	2.9 (.1047)	528 (708)	108.3	79.2	69.0
240 (17.78)	17.78	232 (246.3)	14.6 (287.6)	3.3 (.1192)	506 (679)	111.1	80.8	70.6
220 (16.38)	16.38	210 (224.3)	14.6 (287.6)	3.5 (.1764)	480 (643)	109.2	80.	69.8
200 (14.99)	14.99	193 (207.3)	14.8 (287.8)	3.7 (.1336)	450 (611)	107.9	79.3	69.6

5-20-77

Suction Pressure = 28.5 PSIG (3 ATM) Maximum Capacity Control

Comp. Output Pres. PSIG (ATM)	Comp. Ratio R_c	Output Pres. PSIG (PSIA)	Output Temp. ^oC (^oK)	Orifice Plate ΔP in. H_2O (PSI)	Power kw (HP)	Thruput (gm/sec)	Volumetric Eff. (%)	Isentropic Eff. (%)
203 (217.3)	5.06	190 (204.3)	15.5 (288.5)	29.5 (1.0653)	586 (785)	301	75.6	69.8
220 (234.3)	5.46	206 (220.3)	16 (289.0)	27.2 (.9822)	612 (820)	300.4	75.4	71.0
241 (255.3)	5.95	228 (242.3)	16.9 (289.9)	25.0 (.9028)	648 (869)	301.6	75.8	72.0

Overall Heat Balance $Kw_{in} = Kw_{out}$

Run 5/25/77

$P_{Suction}$ = 30 PSIG + 14.3

= 44.3 PSIA = 3.0 ATM

$P_{Discharge}$ = 258 PSIG + 14.3

= 272.3 PSIA = 18.5 ATM

$T_{Out} = 14.8^{o}C = 287.8^{o}K$

P_{Out} = 250 PSI = 264.3 PSIA

ΔP = 11" = .3972 PSI

$\dot{m}$ = 210.0 gm/sec

$P = (.41) \dfrac{1200\ kw}{.746\ \frac{kw}{HP}} = 660\ HP\ (\underline{492\ kw})$

$T_{Oil} = 119^{o}F$ $T_{BOS} = 177^{o}F$

$T_{H_2O\ inlet} = 13.8^{o}C\ (56.8^{o}F)$

Oil Cooler

$\Delta T = 18.2 - 13.8 = 4.4^{o}C$

G(12 PSI) = 270 GPM

$P_{OC} = \dfrac{270\ GPM}{3.8\ \frac{GPM\ ^{o}C}{kw}} 4.4^{o}C = \underline{313\ kw}$

Aftercooler

$P_{AC} = \dfrac{155\ GPM}{3.8\ \frac{GPM\ ^{o}C}{kw}} 1.7^{o}C = \underline{69\ kw}$

Heat Balance

$492\ kw_{in} \simeq 313\ kw + 69\ kw$ plus losses

Run 5/26/77

$P_{Suction}$ = 30 PSIG + 14.3

= 44.3 PSI = 3.0 ATM

$P_{Discharge}$ = 257 + 14.3

= 271.3 PSI = 18.46 ATM

$T_{Out} = 16.2^{o}C = 289.2^{o}K$

P_{Out} = 250 PSI = 264.3 PSIA

ΔP = 11.5" = .4153 PSI

$\dot{m}$ = 214.2 gm/sec

$P = (.42)(1200) = \underline{504\ kw}\ (676\ HP)$

$T_{Oil} = 123^{o}F$ $T_{H_2O\ inlet} = 15^{o}C$

$T_{BOS} = 178^{o}F$

Oil Cooler

$\Delta T = 25.8 - 15 = 10.8^{o}C$

ΔP = 3 PSI = 134 GPM

$P_{OC} = \dfrac{134\ GPM}{3.86\ \frac{GPM\ ^{o}C}{kw}} 10.8^{o}C = \underline{381\ kw}$

Aftercooler

$P_{AC} = \dfrac{103\ GPM}{3.8\ \frac{GPM\ ^{o}C}{kw}} 2.5^{o}C = \underline{68\ kw}$

Heat Balance

$504\ kw_{in} \simeq 381\ kw + 68\ kw$ plus losses

AUTHOR: Hoyer Byrns | DEPARTMENT: Mech | LOCATION: Berk | DATE: Jan 25, 1978

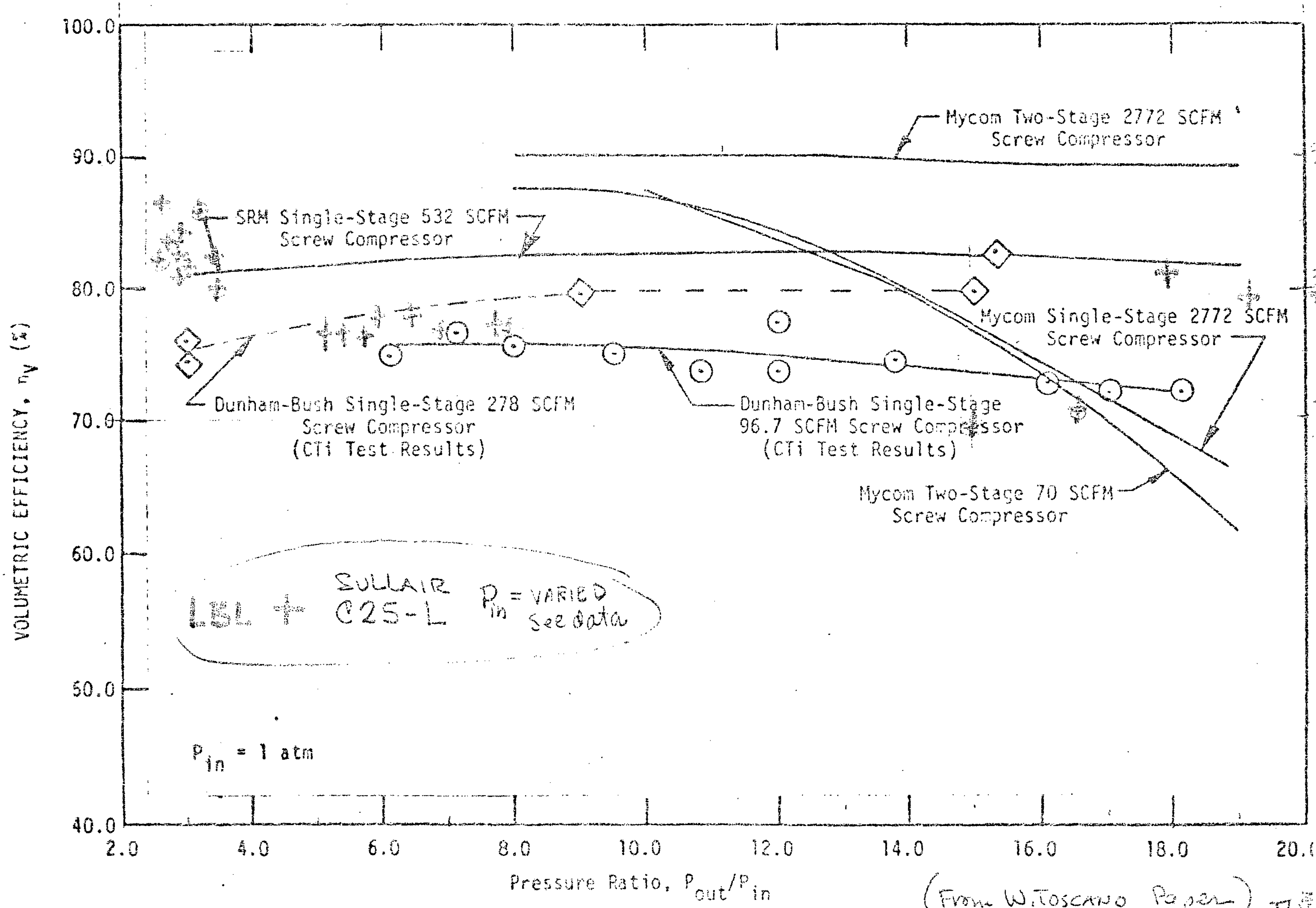
as of: Jan 25, 1978 — 408 hrs on comp #1, 439 " " " #2 — K-1 - 128 hrs (T1), K-3 - 153 hrs (T2)

OIL - UCON LB-165X

Compressor	#1	#2	#1	#2	#1	#2	#1	#2	#1	#2	#1	#2
Date	Jan 25-78		1-24		1-24		1-23		1-23		1-24	
Time	0015		21:40		23:30		21:30 - 22:00		24:10/04:30		18:30	
ORIFICE (PSIG / INCH)	11"	30"	5"	11.5"	5"	11.7	17.5" / 18.0"	13.5" / 13"	15.3" / 17"	14.5" / 15.3"	4.5"	10"
Suct press	4	30 psia	(19.5 psia) 5.2	30	(19.5 psia) 5.2	26	5 / 6	20 / 19	16	18 / 16		
Discharge psig	31.5	210	30	205	26	163	20 / 19	200 / 165	14.8 / 16	143 / 137	33	210
	$R_c = (2.5) = R_c = 5.06$						$R_c = 1.78$	6.25	1.46	$R_c = 5.36$		
Temp °C	14°	2.34 / R 5.59	11.5°		11°		15°		13°c	14°	11°c	
% Capacity	max	max	75%	75%	75	75	max	~95%	max	max	75	75
Motor power watts	190 w	670 w	135	420	125	385	175 / 170	525 / 500	153 / 160	405 / 400	125	430
Refer @ 4.5K load-watts	1010 W (NO LN)		600 W		600 W		310 W on XE-2; 630 W on XSFR LINE; ~200 W on mag. cryo; Σ 1140				~750 W	
No. of turbines	one	Turb. 1	two	T-1 T-2	two	T-1 T-2	two	T1 T2			T1 / T2	
mass flow g/s	145	315	97	195	94	177	150	208	~140 est / 145	184 / 186	95	185
$\eta_{volumetric}$	84.8	76.4					83.4	~71%	80.5	68		
$\eta_{isentropic}$	50.2%	64%					33.5%	65%	22.4	65.6%		

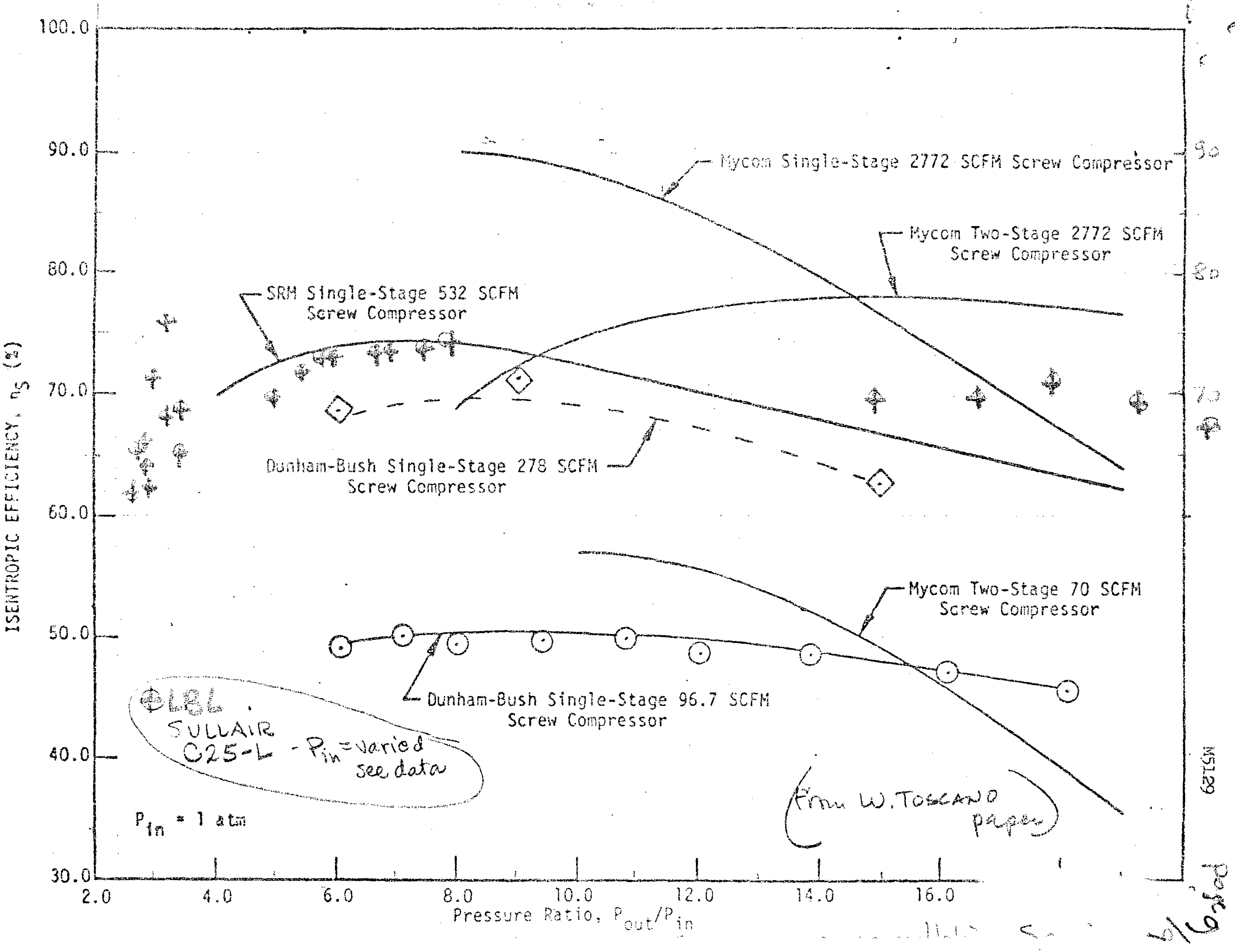
64% ← THIS DATA BASED ON P(disch) AT AFTERCOOLER - ORIFICE PLATE

(67.2) - on compress. discharge



(From W. Toscano Paper)

FIGURE 4 VOLUMETRIC EFFICIENCY OF VARIOUS SCREW COMPRESSORS FOR HELIUM SERVICE



100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
ISENTROPIC EFFICIENCY, η_S (%)
Mycom Single-Stage 2772 SCFM Screw Compressor
Mycom Two-Stage 2772 SCFM Screw Compressor
SRM Single-Stage 532 SCFM Screw Compressor
Dunham-Bush Single-Stage 278 SCFM Screw Compressor
Mycom Two-Stage 70 SCFM Screw Compressor
Dunham-Bush Single-Stage 96.7 SCFM Screw Compressor
LBL SULLAIR C25-L - P_{in} = varied see data
P_{in} = 1 atm
From W. TOSCANO paper
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Pressure Ratio, P_{out}/P_{in}
M5129

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720