Introduction to Cryogenic Engineering

J. G. Weisend II

CERN

February 2001

Objective:

The purpose of this class is to provide an introduction to the basic principles and problems of Cryogenic Engineering.

The class is not sufficient to make anyone an expert in cryogenics, but should provide:

- **A foundation for future learning**
- **An appreciation of the role that cryogenics may play in your own specialty.**

Most examples will be taken from high energy physics

Outline

Lecture #	Subject
1	Introduction & Properties of Cryogenic Fluids
2	Cryogenic Properties of Materials & Refrigeration (Part I)
3	Refrigeration (Part II) & He II Properties
4	Aspects & Examples of Cryostat Design
5	Instrumentation and Safety Issues

What is Cryogenics?

Cryogenics is the science and technology associated with processes occurring below about 120 K. In particular, this includes refrigeration, liquefaction, storage and transport of cryogenic fluids, cryostat design and the study of phenomena that occur at these temperatures.

The Kelvin Temperature Scale

K = °C + 273 (Note it's K not °K)

Room temperature ~	**300 K**
LN_2	**77 K**
LH_2	**20 K**
LHe	**4.2 K**

Examples of Cryogenic Systems in High Energy Physics:

1) **Superconducting Accelerator Magnets**

   4.5 K: Tevatron (Fermilab),
   HERA (DESY), RHIC (BNL)
   2 K: LHC (CERN)

2) **Large Detector Magnets**
   (superconducting solenoids at ~ 4.2 K)

   CMS (LHC- CERN)
   ATLAS (LHC – CERN)
   BaBar (SLAC)
   Zeus (DESY)
   D0 (Fermilab)

3) Liquid Argon Calorimeters (87 K)

H1 (DESY)
ATLAS (LHC – CERN)

4) Superconducting RF Cavities

4.5 K: LEP (CERN)
2 K: CEBAF, TESLA (DESY)

5) Fixed Targets

E158 (SLAC) – 47 l LH_2 target (20 K)
E159 (SLAC) – Solid NH_3 at 200 mK

Properties of Cryogenic Fluids

- **Vary greatly with temperature and pressure**
- **Typical Properties:**

  Density

  Specific Heat

  Enthalpy (h (J / kg)): $h = u – Pv$

  Entropy (s (J / Kg K)): In a reversible process: $ds = dQ/T$

  Thermal Conductivity

- **Definitions:**

  Supercritical Fluid: a fluid that may no longer be thought or as a liquid or a gas but only as a fluid. Such a fluid is either above its Critical Temperature or Critical Pressure or both. The accuracy of calculated thermodynamic values becomes relatively inaccurate around the critical point

  Triple point: The point in thermodynamic space in which the solid, liquid and vapor phases of a substance coexist.

- **Thermodynamic properties and processes are frequently displayed on a temperature – entropy (TS) diagram**

- **Law of Corresponding States**

  With the exception of helium and hydrogen, the properties of cryogenic fluids can be scaled from one fluid to another with a fair accuracy provided the properties have been normalized (typically by the critical properties of the fluid).

Hydrogen

- **Exists in two molecular spin states:**
  orthohydrogen – spins parallel
  parahydrogen – spins antiparallel

- **At 300 K**

  75% ortho and 25 % para

- **At cryogenic temperatures, parahydrogen is the lowest energy state**

- **Conversion from ortho to para is slow and exothermic**

- **H_2 liquifiers typically include a catalyst (e.g. nickel silicate) to speed up conversion**

- **Thermodynamic properties of ortho and para hydrogen are significantly different**

- **Equations of State**

  - **allow calculation of all thermodynamic state properties**

  - **In theory, are based on the interactions of a molecule with its neighbors**

  - **In reality, are highly empirical**

  - **A simple example is the ideal gas law :**

    $$A(r, T) = RT(\log r - a \log T + S_0)$$

    a = 3/2 for a monatomic gas, 5/2 for a diatomic etc.

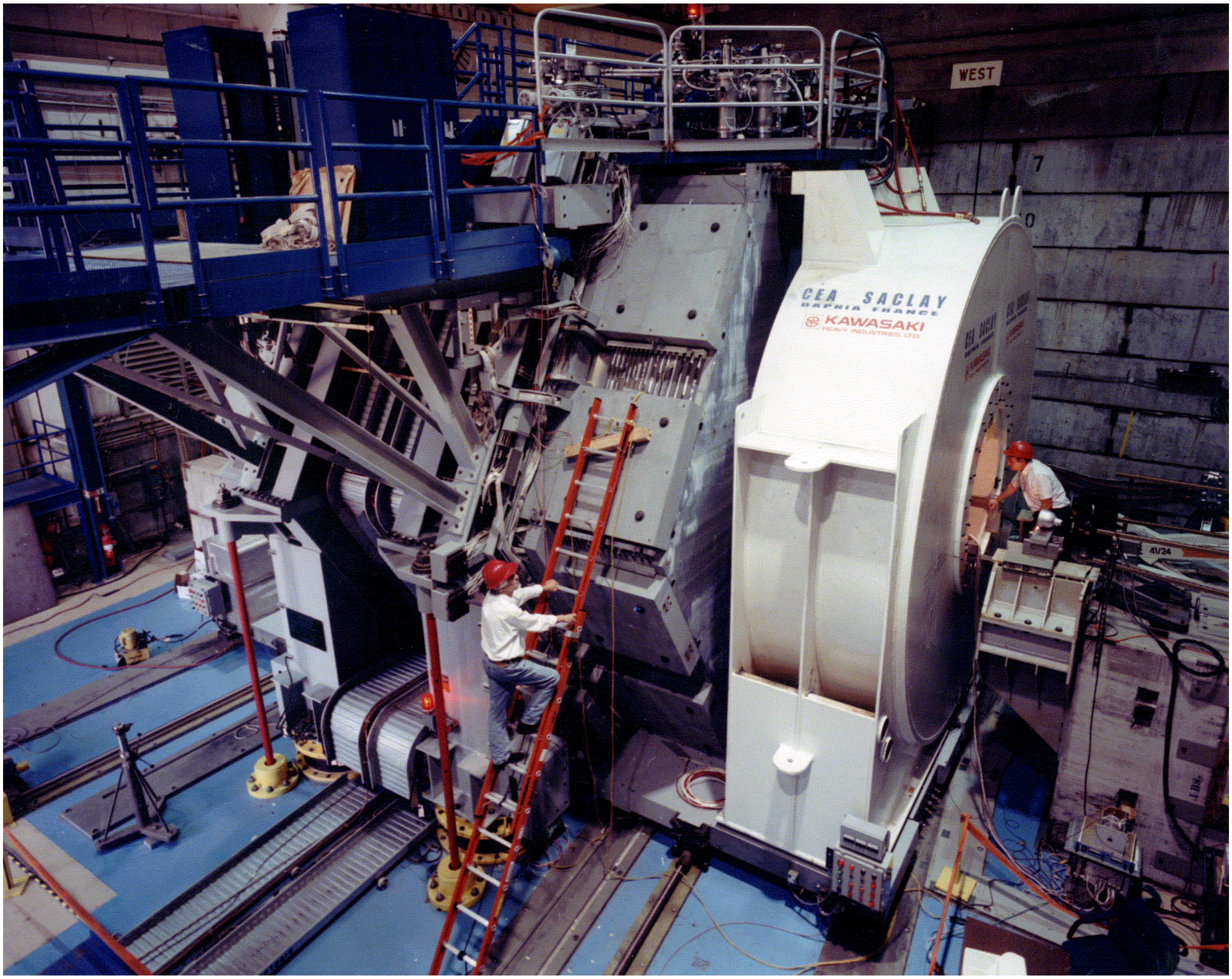
  - **Best calculated via computer codes**

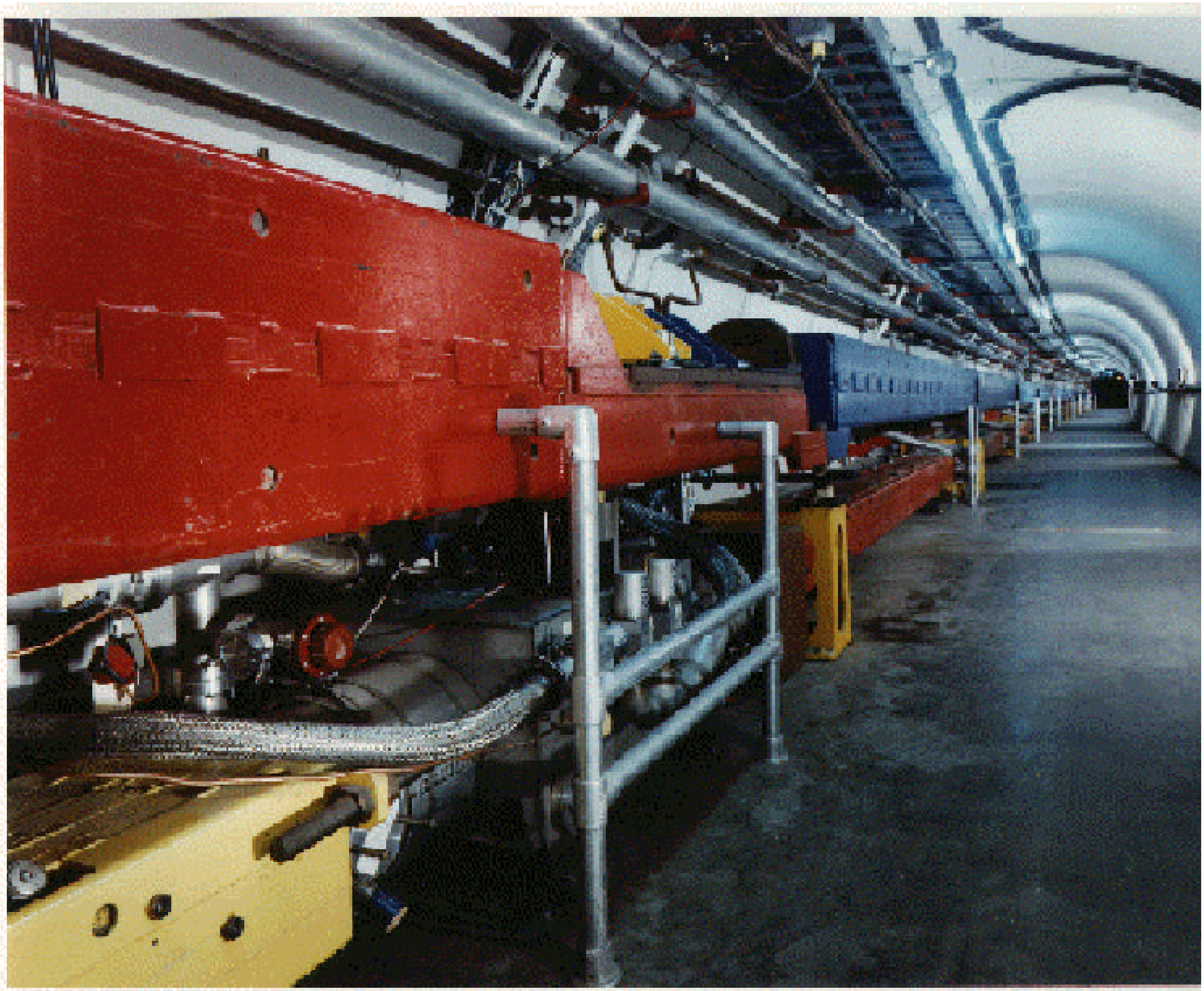
Fluid Property Computer Codes

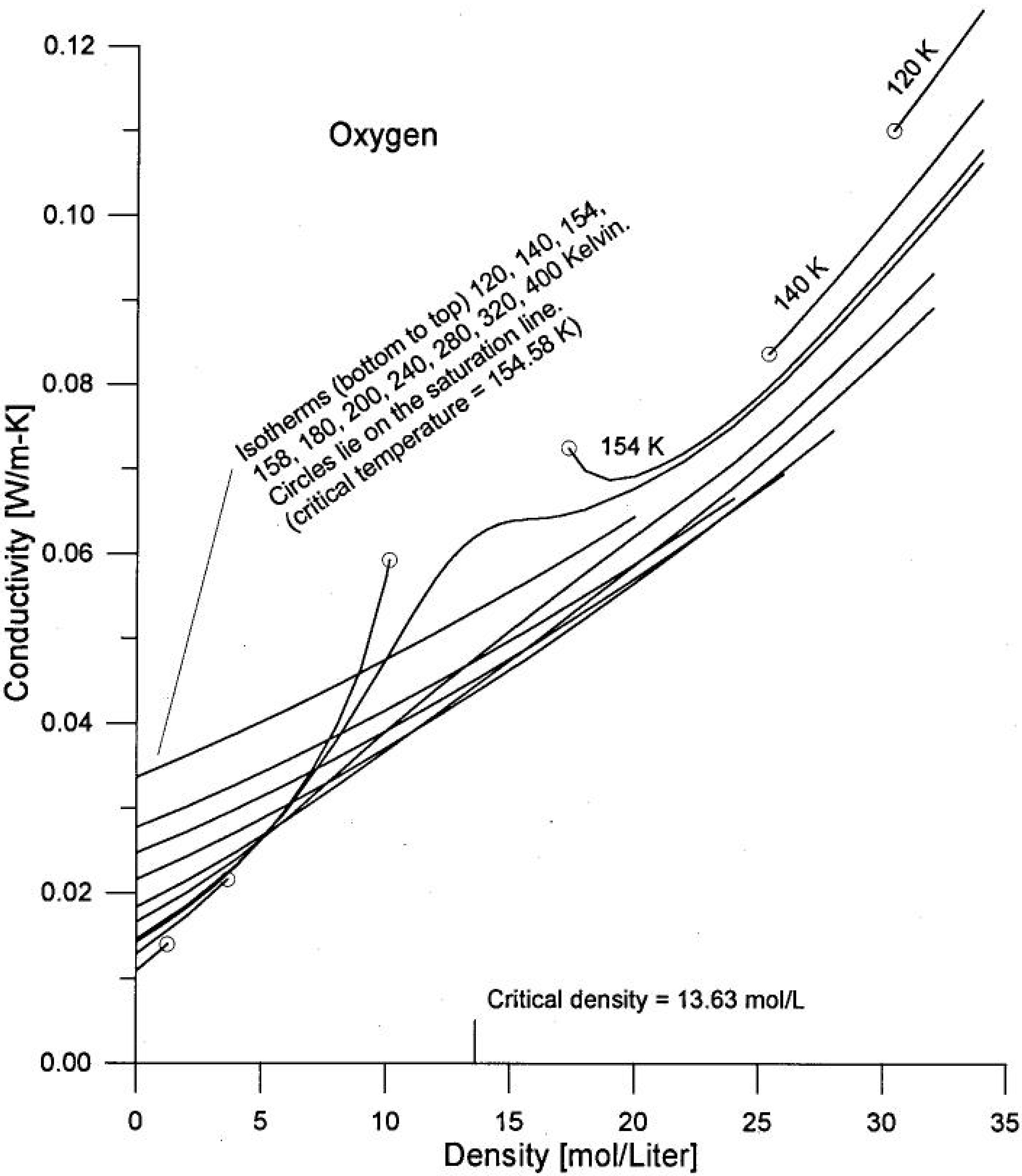
- **ALL PROPS**
University of Idaho

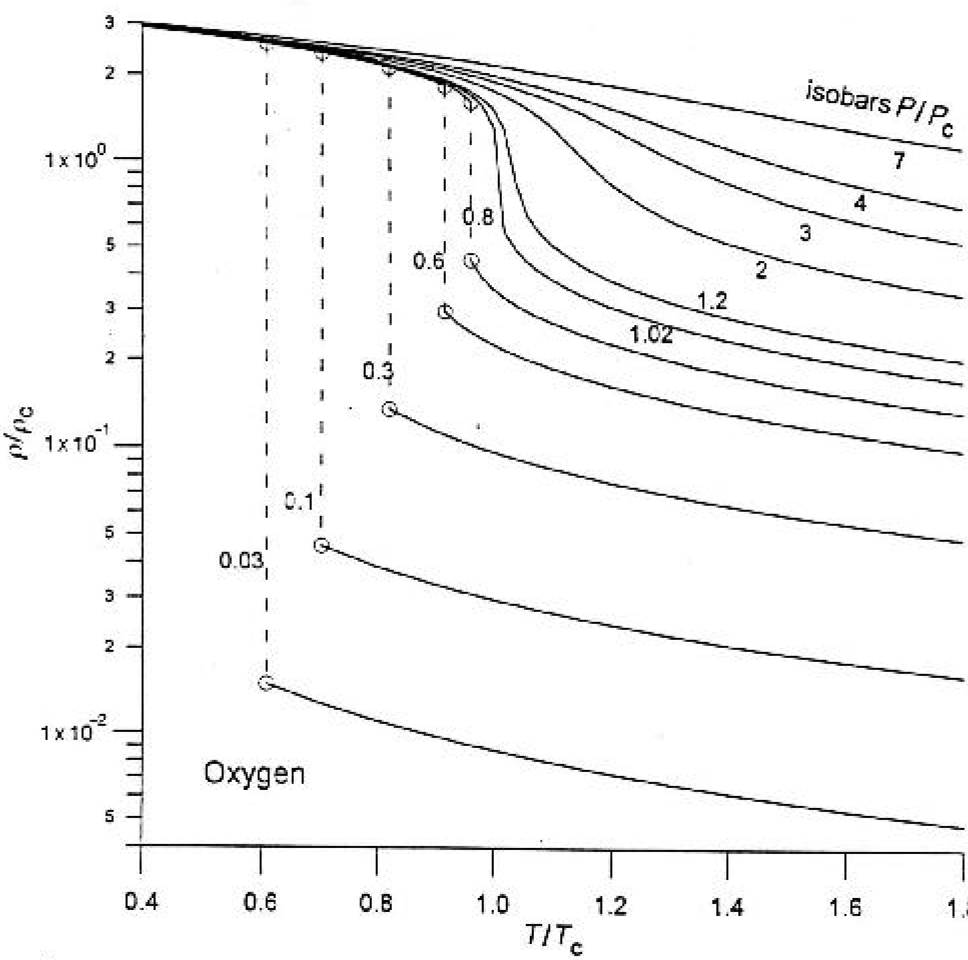
- **NIST - 12**
National Institute for Standards & Technology

- **GASPAK & HEPAK**
Cryodata

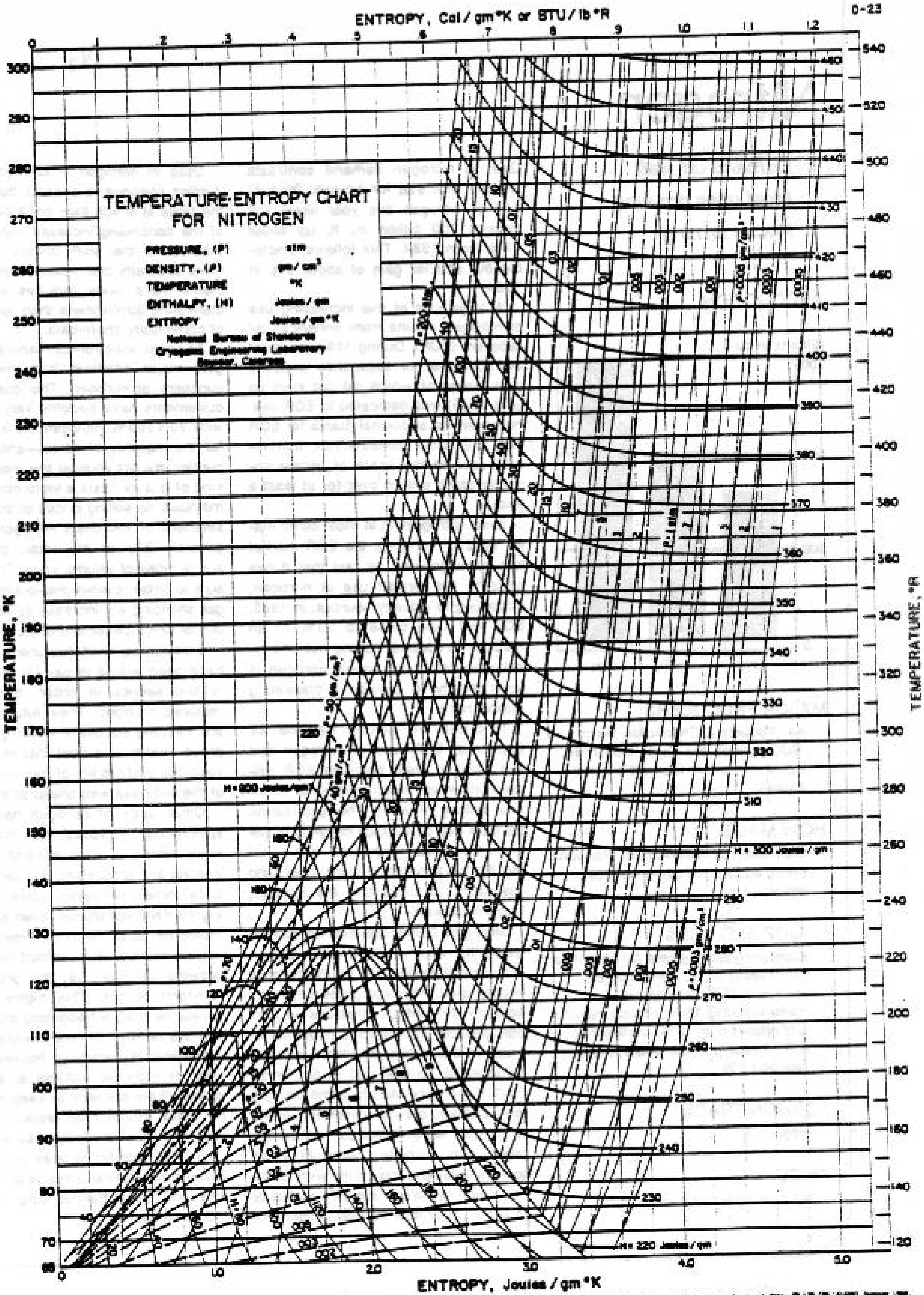

WEST
CEA SACLAY
DAPNIA FRANCE
KAWASAKI
HEAVY INDUSTRIES, LTD.



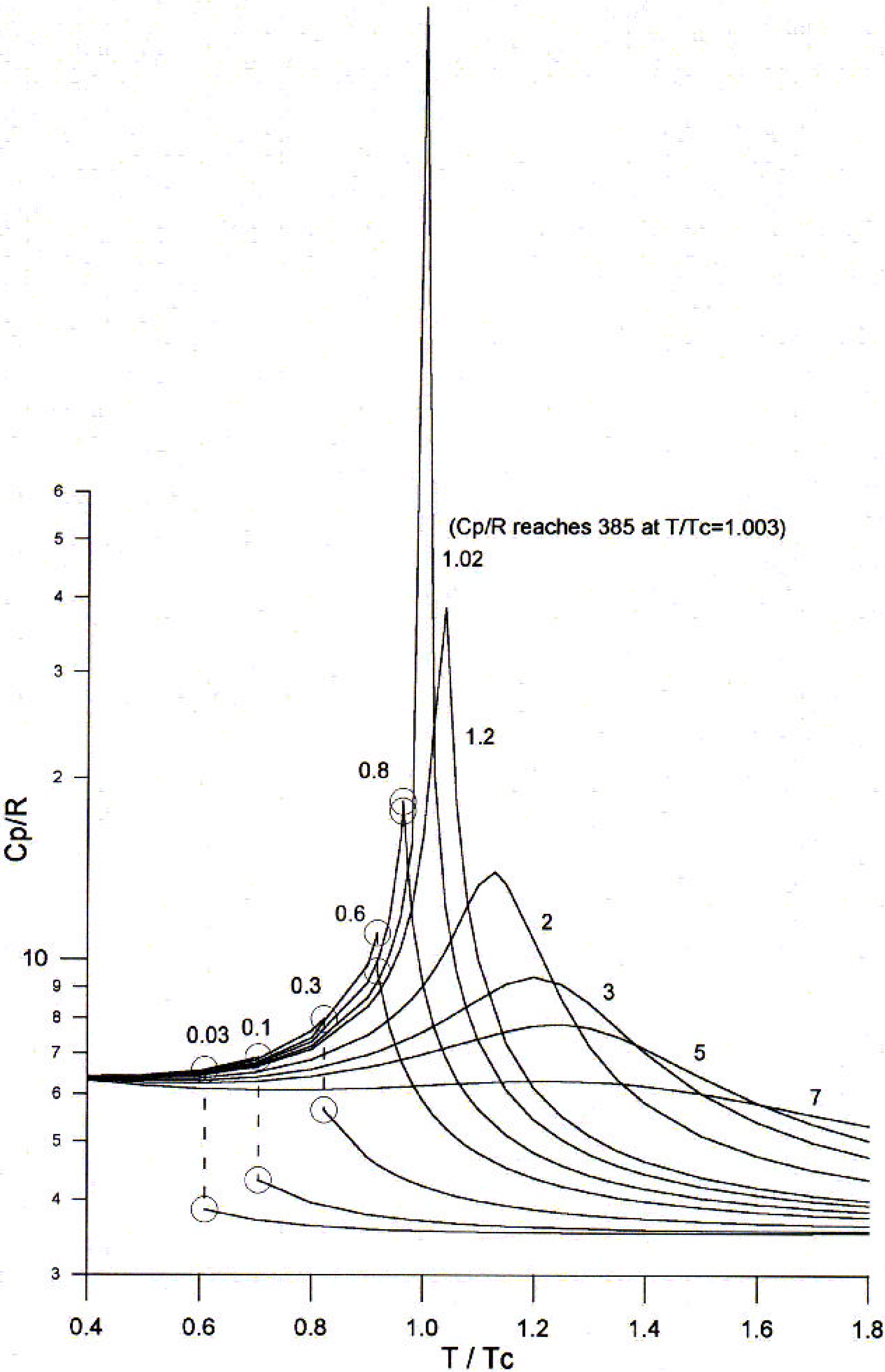

Oxygen
Isotherms (bottom to top) 120, 140, 154, 158, 180, 200, 240, 280, 320, 400 Kelvin.
Circles lie on the saturation line.
(critical temperature = 154.58 K)
120 K
140 K
154 K
Critical density = 13.63 mol/L
Conductivity [W/m-K]
Density [mol/Liter]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0
5
10
15
20
25
30
35



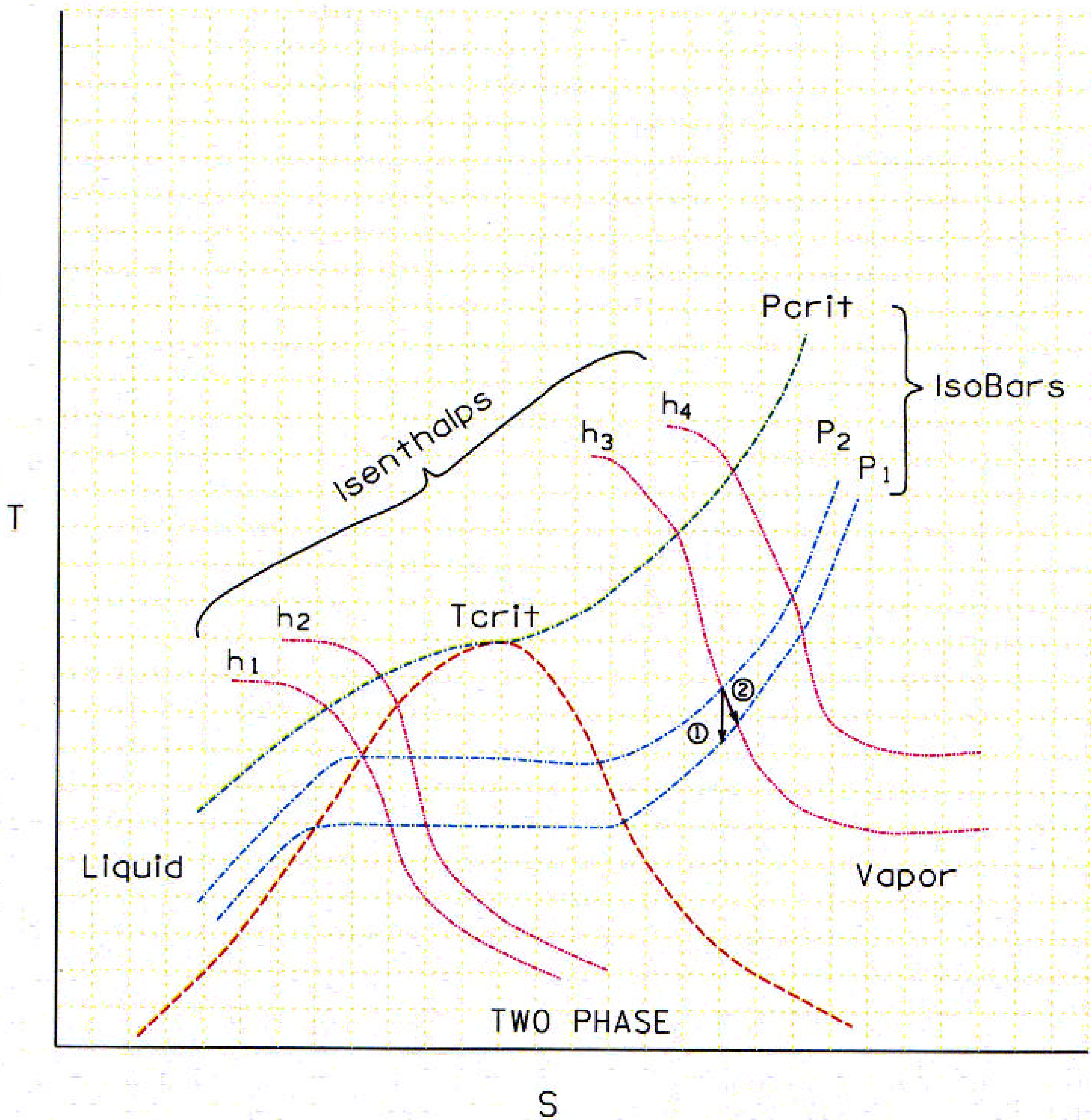
isobars P/P_c
7
4
3
2
1.2
1.02
0.8
0.6
0.3
0.1
0.03
Oxygen
ρ/ρ_c
3
2
1×10^0
5
3
2
1×10^{-1}
5
3
2
1×10^{-2}
5
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
T/T_c


ENTROPY, Cal / gm °K or BTU / lb °R
TEMPERATURE-ENTROPY CHART
FOR NITROGEN
PRESSURE, (P) atm
DENSITY, (ρ) gm / cm³
TEMPERATURE °K
ENTHALPY, (H) Joules / gm
ENTROPY Joules / gm °K
National Bureau of Standards
Cryogenic Engineering Laboratory
Boulder, Colorado
TEMPERATURE, °K
TEMPERATURE, °R
ENTROPY, Joules / gm °K
H = 200 Joules / gm
H = 300 Joules / gm
H = 220 Joules / gm
P = 200 atm
P = 1 atm
ρ = 0.0003 gm / cm³
ρ = 30 gm / cm³

B-37872



(Cp/R reaches 385 at T/Tc=1.003)
1.02
1.2
0.8
0.6
2
0.3
3
0.03
0.1
5
7
Cp/R
6
5
4
3
2
10
9
8
7
6
5
4
3
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
T / Tc



SCHEMATIC T-S DIAGRAM

① Isentropic Expansion
② Isenthalpic Expansion