CRYOGENIC PROPULSION SYSTEM

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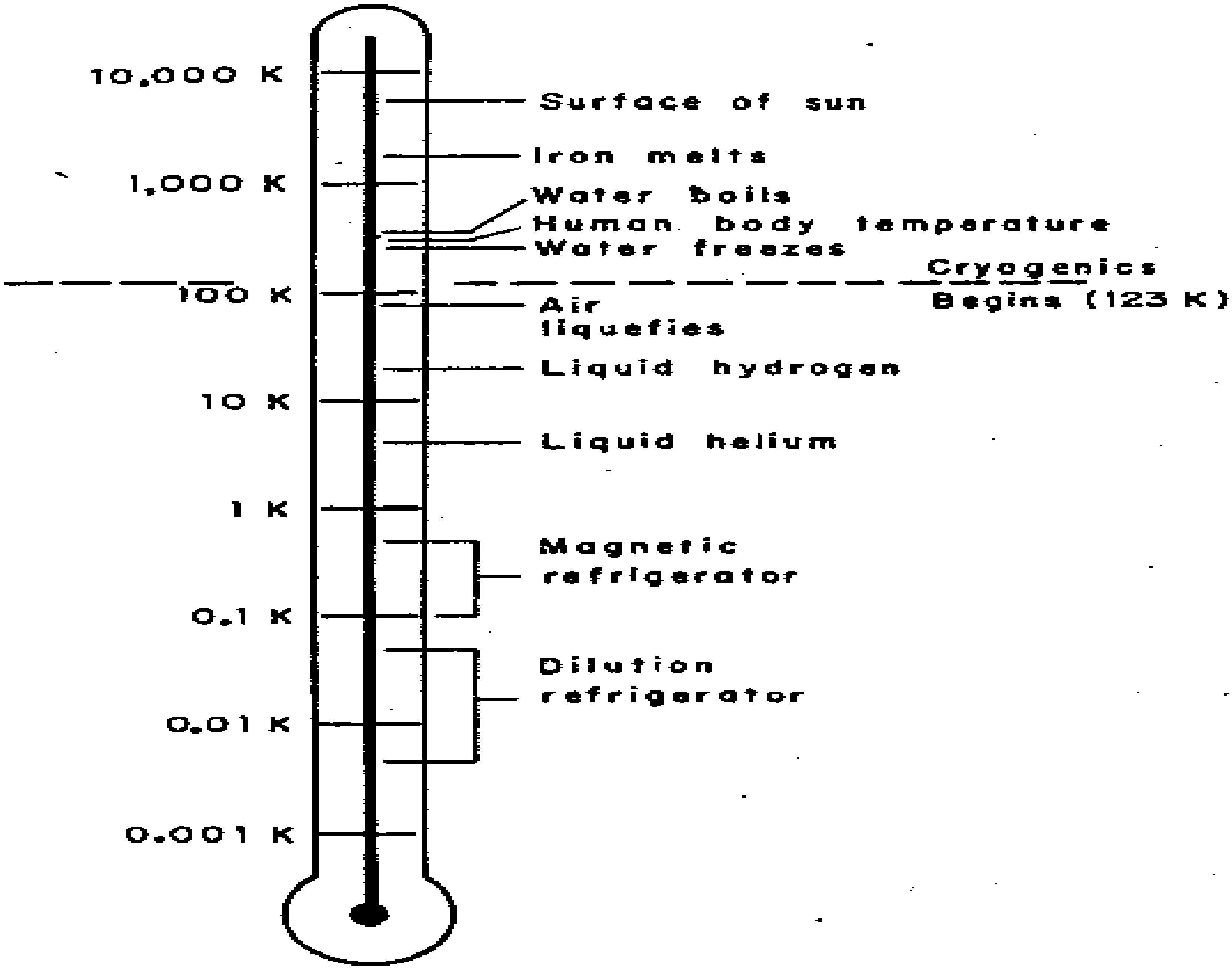

10,000 K
1,000 K
100 K
10 K
1 K
0.1 K
0.01 K
0.001 K
Surface of sun
Iron melts
Water boils
Human body temperature
Water freezes
Cryogenics Begins (123 K)
Air liquefies
Liquid hydrogen
Liquid helium
Magnetic refrigerator
Dilution refrigerator

I INTRODUCTION

- ‘Cryogenics’ means production of icy cold
- The field of cryogenics involves temperatures below 123 K or –150 deg. C.
- This is logical dividing line because the normal boiling points of the so called permanent gases such as Helium, Hydrogen, Neon, Nitrogen, Oxygen and air lie below 123 K.
- The Freon refrigerants, Hydrogen Sulphide, Ammonia and other conventional refrigerants all boil at temp. above –150 deg. C.

- In 1726, Jonathan Swift wrote in Gulliver's Travels while describing Gulliver’s account of his trip to the mythical Academy of Lagado, about some people condensing air into dry tangible substance.
- Swift envisioned air liquefaction 150 years ahead of the accomplishment of the feat.

WHY CRYOGENIC PROPULSION ?

1. Very High Specific Impulse.

   (due to low molecular weight combustion products resulting in high exhaust gas velocities).
2. Lower cost of propellants
3. Non – toxic/harmless exhaust gases
4. Non corrosive Propellants
5. Low attenuation effect of exhaust gases on RF signal

Disadvantages.

1. Insulated tanks are required.
2. Handling of continuously evaporating vapours
3. Low Density of Hydrogen resulting in bulky tanks

Typical mixture ratio (O/F)	-	5:1
Corresponding volume ratio	-	1:3

II CRYOGENIC TECHNOLOGY EVENTS

Year	Event
1877:	Cailletet (French) and Pictet (Swiss) liquified Oxygen.
1883:	Liquification of nitrogen & oxygen in Cracow, Poland
1892:	James Dewar developed vacuum insulated vessel for cryofluid storage.
1895:	Linde granted patent for air liquification
1908:	Liquification of Helium
1912-1922:	Production plants for liquification of air, natural gas, argon, neon, helium.

Year	**Event**
1926:	Dr. Robert Goddard test fired the first Cryogenic (LOX-Gasoline) rocket
1933:	Magnetic cooling used to attain below 1K.
1942:	Dr. Walter Dornberger test fired V2 rocket (LOX – Ethyl Alcohol) system.
1957:	LOX-RP1 propelled Atlas test fired.
1961:	Saturn-V launch vehicle flight.

III DESIGN IMPLEMENTS

- Difficult to storage & handling of low temperature fluids vapourizing constantly.
- Maximum experimentation and testing must be planned with simulated fluids.
- This necessitates well refined modelling with respect to physical characteristic of fluid behaviour for scalability and applicability
- Therefore extensive data base and theoretical formulations including empirical are to be developed.
- Very good understanding and application of thermodynamics, heat transfer and two phase flow behaviour are required.
- Handling of two phase flow in theory and pratice will decide the success of the designs

- Very high quality of cleanliness in the tanks, engines, pumps, pipelines and all cavities is inherent part of system requirement
- Any contamination like ingress of ambient air, micro level leak within the system can develop into solid crystals in cryo fluids endangering flow, blockage of valves etc.
- Continuous preservation of subassemblies & system is to be planned & implemented.
- Propellant storage in tanks as well as their flow characteristics in flight is a real challenge to engineering design.

IV THRUST CHAMBER & COMBUSTION DEVICES

- Most of the storable propellants are hypergolic in nature and ignite on their mixing inside thrust chamber. Cryogenic propellants obviously need ignition devices to initiate combustion.
- Low temperature propellant flow from tanks to engine requires certain cooling of lines as well as warming/heating. For these events to take place as per design in flight, careful calculation and their validation in simulation & ground testing are required.
- Application of relevant Dimensionless numbers are very useful tools in solving many of these problems.

V PROPELLANT TANKS & FEED SYSTEMS

- Liquid Hydrogen has low density and higher mixture ratio with liquid oxygen and therefore a large volume fuel tank. This leads to a taller tank and taller vehicle structure. The tank design although is based on pressure vessel standards, flight loads on the tank structure & the design optimization is important.
- The propellant tanks in cryogenic temperature undergo shrinkage axially as well as radially. The preservation pressure inside the tank causes dilation. The design of tanks should take care of these aspects.

- When turbo pumps are used in feed systems hydrogen characteristics require a very high pump speed for injecting the fuel at a specified pressures. The rotating parts of the pumps, their seals are to be designed to take care of contraction due to low temperature as well as friction free high speed rotation.
- Thermal management of cryo propellants from tanks to engine inlet is a complex process covering thermal insulation, aerodynamic heating, heat-in-leak, pressurization & venting aspects and propellant mass budgetting to achieve the mission.

VI CONTROL SYSTEM & VALVES

The special requirement of control system & valves for cryogenics is that the design of the system should take care of the following:

- Contraction due to low temperature
- Very high level of cleanliness
- Design of orifices considering two phase flow
- Purge requirements for trapped vapour.

VII MATERIALS

- In general, all the materials exhibit improved properties at cryogenic temperature and therefore materials selection is not an issue.
- At lower temperature due to decreased thermal vibration of the alloy element atoms, a larger applied stress is required to tear dislocation from their ambience of alloying atoms. Therefore, for most engineering materials yield strength would increase at lower temperature.
- This is applicable for fatigue strength also

- The impact strength is largely determined by the lattice structure. The FCC lattice has more slip planes available for plastic deformation than BCC lattice. In addition, inerstitial impurity atoms retard slipping in FCC. Therefore, FCC materials are preferred than BCC for cryogenics for their impact strength.
- Materials with 5% elongation exhibit ductility at lower temperature.
- At lower temperature interatomic & intermolecular forces increase due to lower vibration. So elastic moduli tend to improve.
- It has been experimentally proven that Poisson's ratio for isotropic materials does not change appreciably with temperature reduction.

VIII ORTHO & PARA HYDROGEN

Hyrogen exists in 2 different molecular forms

i) Ortho Hydrogen: 2 protons in the molecules spin in same direction

ii) Para Hydrogen: 2 protons in the molecules spin in opposite direction.

- The mixture of these two forms at high temperatures is called normal hydrogen which is mixture of 75% ortho & 25% para.
- The equilibrium composition is a function of temperature.
- At normal boiling point (20.3 K) the equilibrium hydrogen is 99.8% para hydrogen.

- On cooling to normal boiling point, ortho H2 decreases from 75% to 0.2% slowly
- When H2 is liquified the liquid has practically the room temperature composition of 75% ortho which on strorage over a period of time tend to attain equilibrium of 99.8% para.
- The change over involves heat of conversion which results in high boil off (1% per hr.) of the LH2. Therefore a catalyst is used to speed up the conversion during liquifaction process so that the energy is removed prior to storage of liquid in the container.

IX PROPELLANTS SERVICING

Filling of the fuel tanks, oxidizer tanks and charging of gas bottles is one of the key operations during the final count-down preparation of the rocket for the launch. At the end of this operation only it is a true rocket.

These operations are carried out very close to launch based on controlled processes & procedures. These operations are validated well in advance by using simulated flight hardware, first by using water and then real propellants. The total operations done remotely by automated control system is fully validated including software well ahead of launch in order to ensure, a reliable & safe launch.

X Performance Data for LOX-Kerosene Booster Engines

Engine	F-1	RD- 171	RD - 180
Rocket	Saturn-5	Zenith / Energia	
Thrust SL kN	6770	7259	3826
Thrust Vac. kN	7776	7904	4152
Mix. Ratio	2.27	2.60	2.72
Chamber Pressure MPa	6.77	24.50	25.66
Isp – SL (s)	265	309	310
Isp – Vac (s)	304	337	338
Exp. Ratio	16	37	37
Throttle %)	100\	50-100	47-100
Cycle	GG	SC	SC
Burn Time (s)	165	150	250

Performance Data for LH2-LOX Booster Engines

Engine	LE-7	RD-120	SSME	VULCAIN	J-2	J-2S
Rocket	H-II		SS	Ariane-5	Saturn	Saturn
Thrust kN (Vac)	1080	1860	2090	1145	1020	1180
Mix Ratio	6.0	6.0	6.0	5.3	5.5	5.5
Cham. Press. MPa	12.7	20.6	20.7	11.0	5.2	8.3
Isp-Vac s	446	455.5	453.5	430.6	425	436
Cycle	SC	SC	SC	GG	GG	Tap-off
Exp. Ratio	52	85.7	77.5	45	27.5	40
Throttle %	-	25-106	65-109	-	-	17-100

THANK YOU