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LIQUID AIR CYCLE ENGINES

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BASIC LACE

In the late 50's and early 60's Marquardt Company engineers devised a unique propulsion system referred to as LACE - Liquid Air Cycle Engine. (Figure 1). The cycle was predicated on improving the ISP above that of a rocket and be used for reusable space vehicle. You could envision this as an airbreathing rocket. The principle of operation is straight forward. Liquid hydrogen is pumped and is circulated through the condenser and through the precooler and is then used to cool combustion chamber prior to being injected into the combustion chamber. Air enters through the precooler and processed to saturated conditions at the condenser face. The air is condensed to a liquid and pumped into the combustion chamber. The hydrogen air combust at high pressure and exit through a nozzle to provide thrust. The Basic LACE requires an equivalence ratio of 7 to 8 and results in a specific impulse of about 1000 seconds. The Isp is low even though the air is free because of constraints of the heat exchangers and the liquid hydrogen heat capacity.

IMPROVED LACE

Operating the cycle near stoichiometric would lead to large improvements in the specific impulse. System mission requirements consisting of broad Mach number and altitude operability presented design challenges for the propulsion engineers. A single cycle is incapable of meeting these requirements. The Basic Lace was then expanded upon and advanced Liquid Air Cycles were defined. The evolution of Advanced Combined engine cycles is shown in Figure 2.

Modification to the Basic Lace Cycle are shown in Figure 3. These concepts were evaluated in 1966 for NASA. In a study of Composite Propulsion Systems for Advanced Launch Vehicle Application. Each concept was a step toward improving the specific impulse over a wide operating range, thrust to weight ratio and compact installation. A cryojet engine, one of those shown on the previous chart was a viable advanced thermodynamic cycle that offered high specific impulse, high thrust to weight ratios and an increased Mach number capability and increased complexity. Figure 4 shows two variations of the cryojet. The cryojets operational equivalence ratio varies from 1.5 to 1.0 for Mach number operation from 0 to 4. Specific impulses vary from 3,000 to 4,000 seconds and can have high thrust to weight ratios because of the very small relative size of the turbomachinery required in the liquid jet. An example of the speed range and specific impulse for the cryojet operation is shown in Figure 5 and Figure 5 also shows relationship with other propulsion phases that comprise a multi-mode engine. The cryojet makes use of many key technologies to improve cycle performance.

Key Technologies

1. Heat exchanger design and fabrication techniques
2. Liquid Hydrogen handling to achieve greatest heat sink capacities,
3. Air decontamination to prevent heat exchanger fouling

Heat Exchanger Design Heat exchanger designs have progressed a long way since the LACE concept originated. Heat exchanger matrices originally evaluated were tube bundles, plate and fin, and finned tube bundles. Heat exchangers were designed, fabricated and tested. Performance of various matrices were defined analytically and experimentally. Bare tube matrices were found to provide advantages for performance, weight and compact volume. System tests also provided insight to design. For precoolers, vertical bare tubes are preferred especially in the aft portion of the unit. Under some conditions the condensing front moves into the precooler and with bare tubes the liquid can run off the tubes. Fin tubes trapped the condensed liquid and freezing occurred. Bare tubes are also preferred in the condenser and tubes oriented in a vertical direction provides better condensing coefficient characteristics. At low condensing pressures tubes in the vertical position allows liquid to run down the tubes and wash off slush as freezing conditions are approached. Figure 6 presents a concept for fabrication that has advantages for fabrication, leak checking and assembly and provides a light weight configuration. Tube rows are fabricated then assembled to form a unit.

Today design concepts are continuing to be formulated that will considerably improve fabrication techniques and improve performance. Analytical results indicate that the volume of some units could be reduced by 50 percent with a significant weight reduction. Many materials are also being evaluated to reduce weight such as aluminum, thin wall stainless steel, beryllium.

Liquid Hydrogen Handling. The efficient operation of the heat exchanger system requires achieving the greatest heat sink capacities. The use of catalysts to speed conversion of para hydrogen to ortho hydrogen is required. The heat of conversion can be used to augment the amount of liquid air produced with smaller heat exchanger units. The metal ruthenium deposited on aluminum oxide has proven to be an efficient catalyst for the conversion process. The catalyst could be contained in a bed or within the tubes and manifolds of the heat exchanger. The problem is to get sufficient surface area for the conversion. Between 5 and 7 lbs of catalyst is required per lb per second of hydrogen flow rate for a 90% conversion. Catalyst evaluations were done in the 60's and are continuing today. Figure 7 shows the effects of conversion. Subcooled and Slush Hydrogen provides a significant improvement in the system performance if the engine can be operated at equivalence ratios near 1.0. By recirculating the excess hydrogen back into a subcooled or slush hydrogen tank this can improve the Isp of the propulsion system. Slush hydrogen has two advantages. The higher density of the solid can increase the tank capacity or reduce volume of the tank and increase the low temperature heat sink. The slush provides 15 to 18 percent increase in the density and about a 20 increase in the low temperature heat sink. By the use of slush hydrogen in the tank we can also increase our hydrogen equivalence ratio from a 7.3 to 12.1 in the heat exchangers and reduce the volume in the condenser by as much as 15 percent and in the precooler by as much as 50 percent for a significant volume and weight reduction. Figure 8 shows effects of recycling and slush hydrogen. Another method of improving refrigerant effect of hydrogen as a coolant is hydrogen turbine expanders. Expanding the hydrogen reduces the temperature and can be useful in a cascading condenser system as in the liquid cryojet. An example of the use of turbine expanders is shown in figure 9. A problem associated with the LACE types propulsion systems is heat exchanger fouling due to water vapor in the atmosphere. This problem usually occurs at low altitudes, 0 to about 20,000 ft. These altitude conditions have a specific humidity range from 0.03 lbs of water per lb of air down to 0.001. As moisture is ingested into the heat exchangers, ice forms on the tubes causing an increase in pressure drop and a decrease in heat transfer. The ice can continue to build up until flow cannot be maintained. Considerable progress has been made to alleviate the affects of water vapor. Some of the alleviation techniques investigated are shown below:

1. Tube Coatings
2. Surface Finishes
3. Ultrasonic Tube Vibrations
4. Airstream Vibrations
5. Pulsed Coolant Flow
6. Thermal Pressure Tube Distortions
7. Rotary Heat Exchangers
8. Snow Formation
9. Cyclic De-icing
10. Liquid Air Injection
11. Ice Collection
12. Glycol Injection
13. Liquid Condensation with Glycol

Glycol Injection was demonstrated as the most feasible for preventing icing on heat exchangers. Air pressure drop across the heat exchangers and heat transfer coefficient were selected as parameters to show effectiveness of decontamination. Figure 10 shows effects of water vapor on heat exchanger pressure drop. This was caused by water vapor freezing on the tubes. Also shown on figure are results with the prevention system of spraying glycol into the airstream to mix with the water vapor and reduce freezing point. The water vapor glycol mixture was then removed by a separator prior to going into the system precooler. This system was demonstrated in the 1960's. A requirement to fly the propulsion system on hot day atmospheric conditions with specific humidities up to 0.030 lbs of water vapor to lbs of air required a modification to the glycol injection system. This system reduced the air specific humidity to 0.001 lbs/lb consistent with previous system tests. The system has demonstrated capability to prevent heat exchanger fouling for air specific humidities up to 0.043 lbs H_2/lb air with water injections up to 0.2 pps to simulate rain storms and ingested runway water. Cyclic glycol injection has been demonstrated as a technique to reduce glycol consumption and weight volume.

This brief report of the LACE (Liquid Air Cycle Engine) has defined LACE engines with the technologies existing. Technology needs to be extended in areas of design and fabrication of heat exchangers to improve reliability with weight and volume reductions. Catalysts need to improve so that conversation can be achieved with lower quantities and lower volumes. Packaging studies need to be investigated both analytically and experimentally. Recycling with slush hydrogen needs further evaluation with experimental testing.

BASIC LACE (LIQUID AIR CYCLE ENGINE) SCHEMATIC

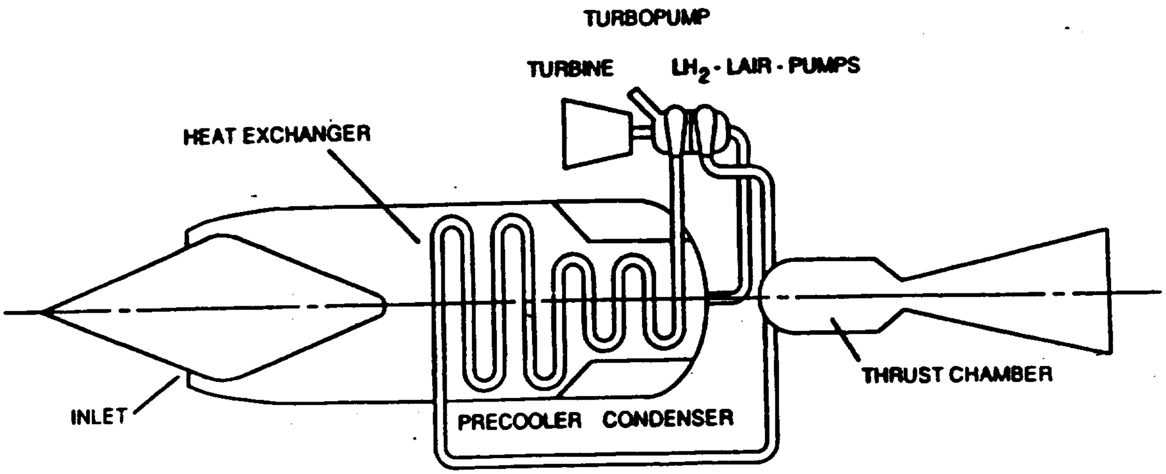


Figure 1

EVOLUTION OF ADVANCED PROPULSION SYSTEMS

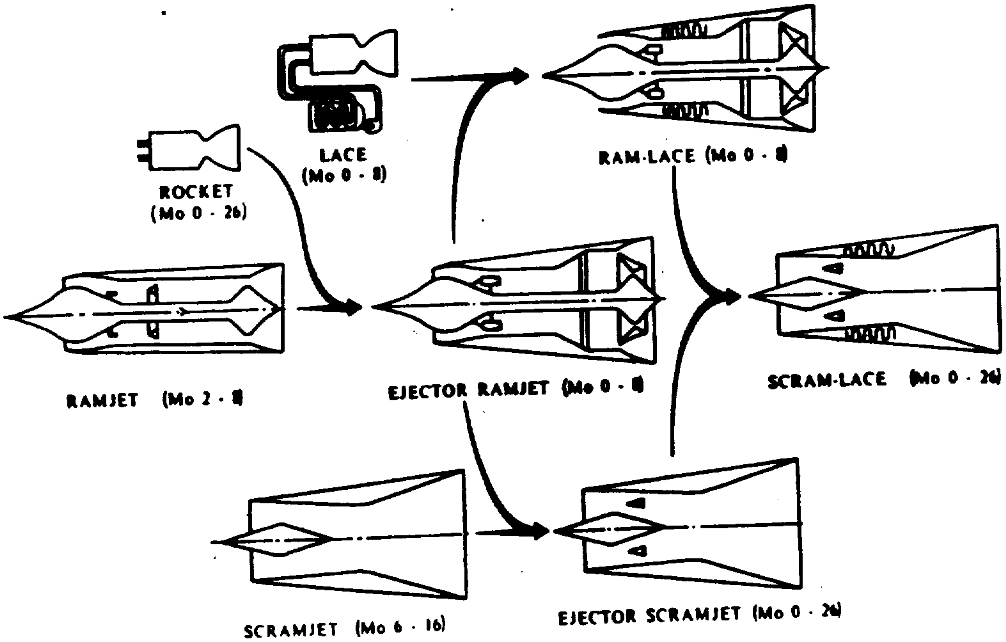


Figure 2

ADVANCED LIQUID AIR CYCLE ENGINES

CRYO JETS

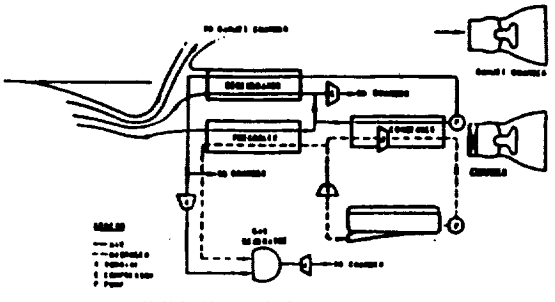


FIGURE 2. SCHEMATIC OF THE [illegible] PROPULSION SYSTEM

LIQUIDIFICATION OF AIR

OPERATIONAL EQUIVALENCE RATIO = 1.5 TO1.0

MACH 0 -4

SPECIFIC IMPULSE 3000 - 4000 SECONDS

HIGH THRUST TO WEIGHT RATION

SMALL RELATIVE SIZE OF TURBOMACHINERY

CONDENSER - CASCADING SYSTEM WITH
EXPANSION TURBINE TO REDUCE
TEMPERATURE OF H_2

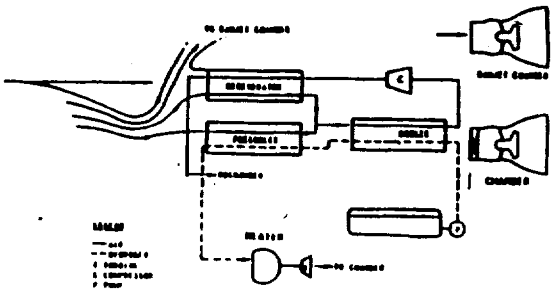


FIGURE 3. SCHEMATIC OF THE [illegible] PROPULSION SYSTEM

ELIMINATED LIQUIFICATION OF AIR

SINGLE FLOW PATH

CYCLE LIMITED TO RELATIVELY LOW CHAMBER PRESSURES

SPECIFIC IMPULSE 3000 - 4000 SECONDS

LOWER THRUST TO WEIGHT RATIO THAN LIQUID.

Figure 4

LACE CYCLES EVALUATED FOR ADVANCED VEHICLE APPLICATIONS 1966

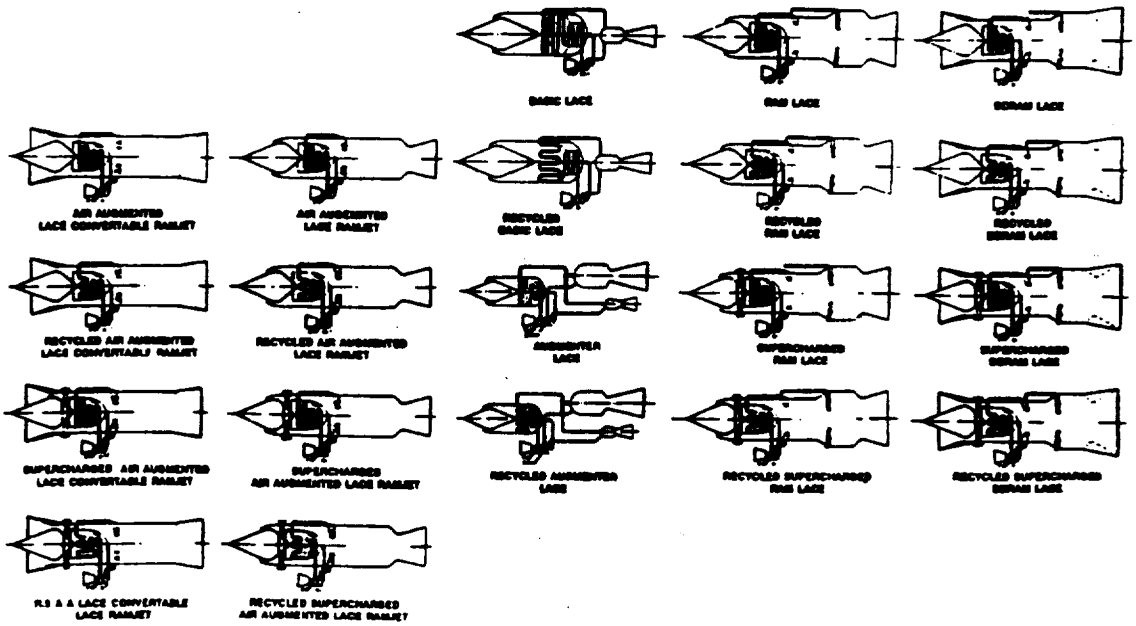


Figure 5

SPECIFIC IMPULSE VERSUS VELOCITY

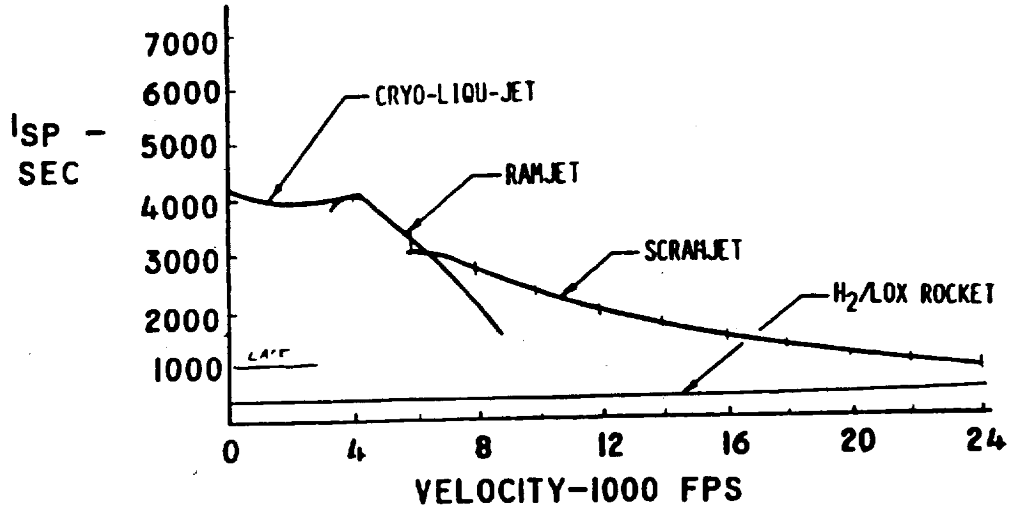
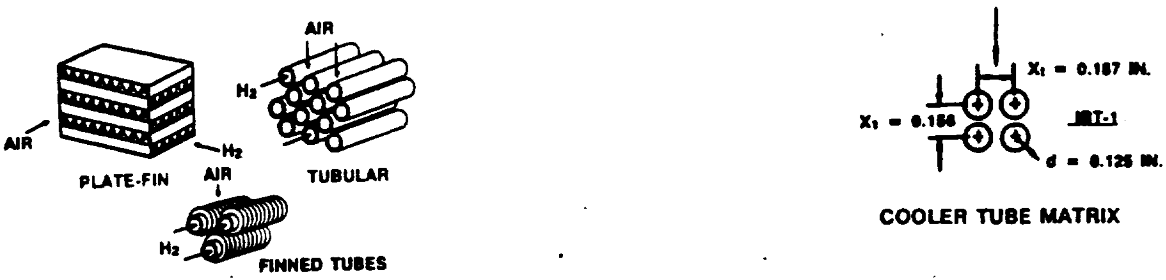
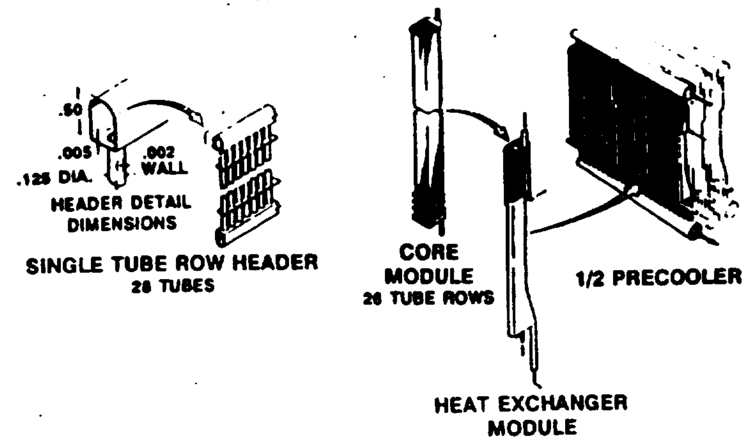


Figure 5

KEY TECHNOLOGIES
HEAT EXCHANGER DESIGN & FABRICATION





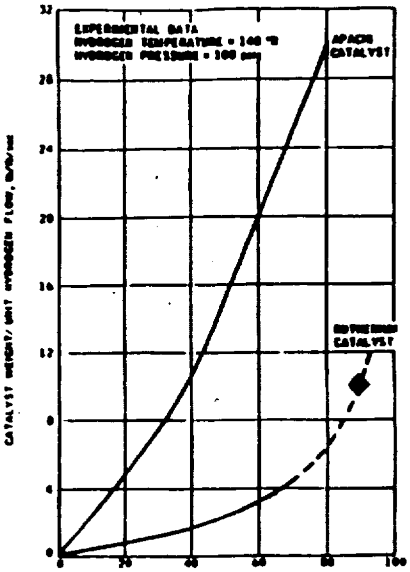
CONTINUING TODAY

MATRIX EVALUATION
FABRICATION TECHNIQUES
MATERIALS EVALUATION

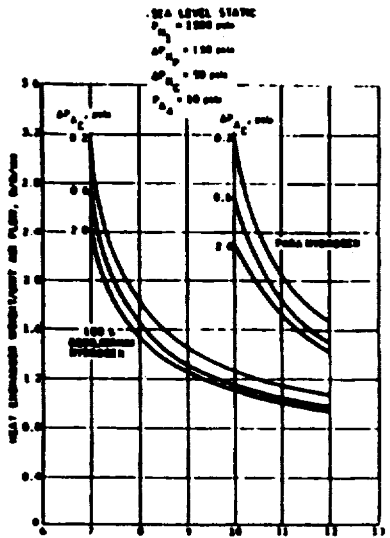
Figure 6

KEY TECHNOLOGIES
LIQUID HYDROGEN HANDLING

PARA/ORTHO CONVERSION



CATALYST WEIGHT

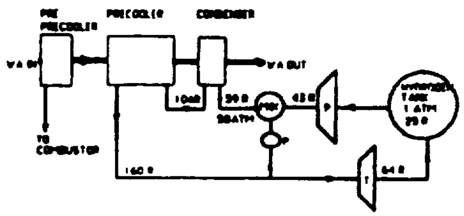


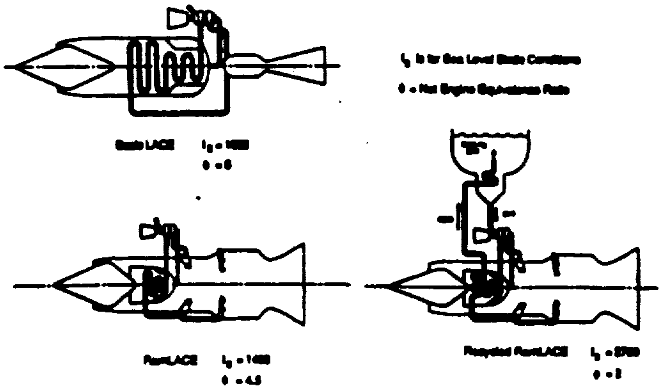
TOTAL HEAT EXCHANGER CORE WEIGHT
EFFECT OF EQUIVALENCE RATIO

Figure 7

KEY TECHNOLOGIES
SLUSH HYDROGEN

SLUSH HYDROGEN SCHEMATIC





LACE/RamLACE "Cycle Leaning-out" Trends

ADVANTAGES OF SLUSH HYDROGEN

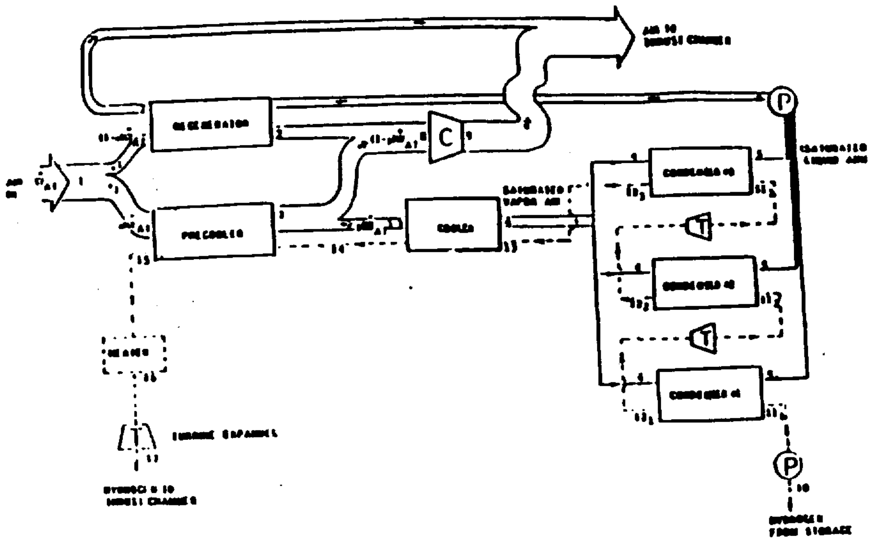
HYDROGEN TANK CAPACITY GREATER DUE TO HIGHER DENSITY OF THE SOLID--- 16 PERCENT--- APPROXIMATELY THE SAME AMOUNT OF LIQUID IN THE TANK AFTER AS IF ORIGINALLY LOADED WITH JUST LIQUID

HEAT EXCHANGER SIZE AND WEIGHT 15-50 PERCENT LOWER

	PARA/ORTHO	PARA/SLUSH
	CONDENSER	
HYDROGEN EQUIV RATIO φ	7.3	12.1
VOLUME (IN)^3	4420	3700
PERCENT REDUCTION		15
	PRECOOLER	
HYDROGEN EQUIV RATIO φ	7.3	12.1
VOLUME (IN)^3	10384	[illegible]
PERCENT REDUCTION		53
ENGINE OPERATING φ	4.5	1.0

Figure 8

KEY TECHNOLOGIES
TURBO MACHINERY



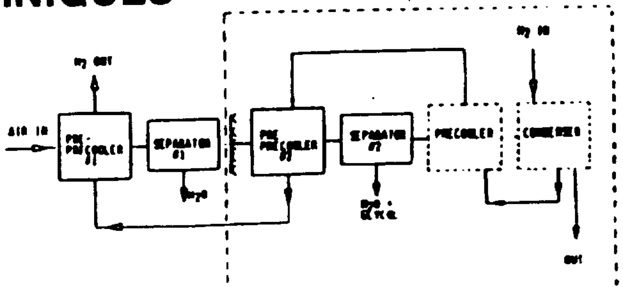
4. SCHEMATIC OF THE CYRO-LIQU-JET CYCLE

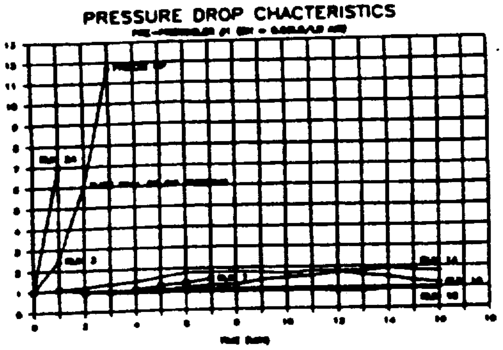
Figure 9

SUCCESSFUL CONTAMINATION ALLEVIATION TECHNIQUES

ALLEVIATION TECHNIQUES INVESTIGATED

1 TUBE COATINGS
2 SURFACE FINISHES
3 ULTRASONIC TUBE VIBRATIONS
4 AIRSTREAM VIBRATIONS
5 PULSED COOLANT FLOW
6 THERMAL/PRESSURE TUBE DISTORTIONS
7 ROTARY HEAT EXCHANGERS WITH SUBLIMATION
8 SNOW FORMATION
9 CYCLIC DE-ICING
10 LIQUID AIR INJECTION
11 ICE COLLECTION
12 GLYCOL INJECTION
13 LIQUID CONDENSATION WITH GLYCOL





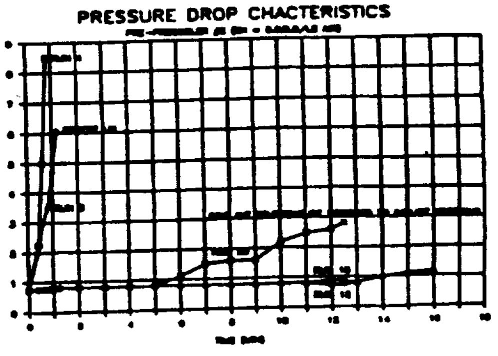


Figure 10