Two types of LACE, or liquid air cycle engines, were discussed in the paper "Liquid Air Cycle Engines for High-speed Aircraft" by R. A. Jeffs and A. B. P. Beeton of the National Gas Turbine Establishment, at the British Interplanetary Society's symposium on aerospace vehicles in London last month. Extracts from the paper are given in this article.

The use of liquid hydrogen as a fuel for airbreathing propulsion systems has been discussed for many years; for most applications in the past its high caloric value per pound and the simplicity of the combustion system required to realize this have been outweighed by its very low density and low temperature, the problems brought by the tankage insulation and bulk. However, with flight speeds moving into the region where vehicle cooling becomes a major issue, it has become fashionable to reconsider the use of liquid hydrogen, this time with more emphasis on its extra value as a heat sink both for the engine and the airframe.

A few years ago, it was observed in America that the cooling capacity of liquid hydrogen could be used in a somewhat unconventional fashion—the name of Marquardt being associated with the work. Air is taken into the engine system from the atmosphere in the usual way. Instead of being directly burned with the hydrogen fuel, the air is liquefied by heat exchange with the liquid hydrogen. We now have the possibility of a family of engines, known as LACE or liquid air cycle engines, in which liquid air and the now hot and gaseous hydrogen can be used for propulsion or control purposes in a variety of ways.

The system known as straight LACE is illustrated in Fig 1. Both the air and the hydrogen are pumped up to a high pressure in the liquid phase; the liquid air and the gaseous hydrogen from the heat exchanger are burned in a rocket chamber and expanded in a normal propelling nozzle. It will be seen later that heat-exchanger limitations always cause this system to run with a hydrogen/air ratio much richer than stoichiometric with a consequent penalty in performance. Nevertheless, it should result in a fuel specific impulse in the region of 600 to 1,000sec in the flight Mach number range from 4 to 8; this is a useful improvement over a hydrogen/oxygen rocket giving 400 to 450, but compares badly with figures of 2,000 to 4,000 which a ramjet should achieve.

Illustrated in Fig 2 is the air-scooping system, perhaps better called the "oxygen condensation" version, which incorporates a separator after the air liquefer and is used in conjunction with a considerably larger hydrogen-burning ramjet as the main propulsion engine. The liquid oxygen from the separator is stored for later use in a rocket engine. The liquid nitrogen is available for cooling duties, probably as illustrated for precooling the LACE air, before being fed back into the main ramjet combustion chamber. This chamber can now continue to work at chemically correct mixture with only slightly reduced performance, and does not therefore waste hydrogen in the same way that the "straight LACE" system has to because of its necessarily over-rich mixture.

The most obvious application for this system is in multi-stage space vehicle launchers; the take-off and early stages of the acceleration would be carried out with the oxygen tanks of the upper stage rockets either empty or perhaps filled with hydrogen. At speeds around \( M = 5 \) to 7 the scoop system would be used to fill these tanks with oxygen.

**Performance and Applications of Straight LACE**

The performance of the simple liquid air cycle engine has been worked out for the two fuel/air ratios, \( \alpha = 0.15 \) and 0.20, expanding between a chamber pressure of 20 atm down to ambient static. The calculated gross engine thrusts are, of course, debited with the drag of the intake air in order to arrive at the net thrust. For comparison, the performance of a hydrogen/oxygen rocket has been evaluated over the same pressure range, assuming equilibrium expansion and no losses.

Fig 4 plots the net thrust per unit fuel consumption for both the pure rocket and liquid air cycles as a function of flight Mach number and e.a.s. It will be recalled from the curves of Fig 3 that in the case of the liquid air cycle the weakest possible fuel/air ratio looks like falling between the two values 0.15 and 0.20, with the speed range \( M = 6 \) to 7 offering the best chance of achieving the lower figure. Fig 4 now indicates that at these speeds a performance of about 900sec may be possible with the liquid air cycle engine, compared with a possible 450sec with the pure rocket. It is also worth noting that, at lower Mach numbers, where it is the intake pressure level rather than the intake temperature that limits the fuel/air ratio, the deterioration in thrust parameter brought about by the necessity for richening up \( \alpha \) is just about compensated by the upward slope of the curves of \( \alpha \) in this region. This means that the liquid air cycle engine should in fact maintain its superiority over the rocket down to \( M = 4 \) at least.

The price to be paid for this possible doubling of the thrust performance lies chiefly in the weight of the heat exchanger. It is not possible to estimate this weight with the same degree of confidence that can be applied to the performance calculations, but the