SUSTAINABLE LUNAR IN-SITU RESOURCE UTILISATION = LONG-TERM PLANNING. A. A. Ellery[1], [1] Department of Mechanical & Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON. K1S 5B6; aellery@mae.carleton.ca.

Introduction: Sustainability will be an essential component of lunar in-situ resource utilization (ISRU) on the Moon if we are not bring all our bad habits with us from Earth, yet few proposals consider sustainability systematically. The spirit of sustainability is to ensure that future generations are not faced with a barren wasteland as a result of desolation by our wanton practices. Implicit in this definition is the need to plan our ISRU practices over the long-term to ensure: (a) we do not consume scarce resources; (b) we employ renewable technologies as far as is feasible; (c) we adopt processes that do not yield toxic material; (d) we minimize waste through recycling loops. To observe this, we need to design a long-term approach to lunar ISRU that adopts the philosophy of indigenous peoples – exploit that which is abundant and waste nothing. As a corollary to this, we cannot simply transport terrestrial technology *in toto* to the Moon – terrestrial technology is dependent on a global infrastructure that founds it. For example, a smart phone comprises some 50 different materials, not including the processing reagents. We must live off the land as much as possible to minimize our reliance on an Earth-based supply chain. To that end, we have constructed a lunar industrial ecology.

Lunar Demandite: The first step in defining our lunar ecology is to determine our needs. We assume that there is no human presence on the lunar surface though we do not disbar it. Most ISRU proposals are focused on the supply of consumables such as water, oxygen and liquid hydrogen/oxygen propellant/oxidizer. We discount this for 4 reasons (though oxygen is a byproduct of our lunar ecology): (i) current environment control and life support systems (ECLSS) are highly efficient in recovering and recycling oxygen and water so only leakage resupply rather than primary resupply is necessary; (ii) liquid hydrogen/oxygen require long-term cryogenic storage (liquid hydrogen requires temperatures below 20 K) which will be challenging; (iii) hydrogen is a scarce resource except in difficult-to-access permanently-shaded craters at the poles; (iv) propellant/oxidizer consumption can be replaced with abundant and renewable solar-electric power for rover surface sorties and electromagnetic launchers for transport to lunar orbit.

Rather than focusing on building specific products from lunar material, we have adopted to build the *means of production*. In essence, we are attempting to build a universal construction mechanism from lunar resources which will enable us to build a wide suite of products. Specifically, we wish exploit lunar resources to build mining machines, unit chemical processors, manufacturing machines and assembly machines. The common factor is that they are all robotic machines. This is corroborated by John von Neumann's universal constructor concept which comprised of a computer controlling an abstract robotic machine. Any kinematic machine may be characterized as a specific configuration of actuators. Hence, we have selected two key components to be manufactured from lunar material – electric motors for robotic actuation and vacuum tubes (rather than solid-state manufacturing) as the key component in computing machines (in this case, based on analogue neural network architectures rather than CPU-based architectures). They also provide the basis for electrical energy generation (thermionic conversion of Fresnel lens-based thermal energy) and storage (motorized flywheels).

Lunar Ecology: We have built a lunar ecology that processes lunar minerals and volatiles into materials to construct our electric motors and vacuum tubes. We require NaCl imported from Earth as a recycled reagent (it is not consumed). We also assume that meteoritic material is available from which a variety of alloying metals can be extracted via the Mond process. Volatiles of interest include hydrogen (from water), carbon compounds and small amounts of nitrogen which can be extracted thermally and fractionally condensed. The carbon provides the basis for silicone plastic manufacture. The lunar minerals that we process to extract metals include ilmenite (Fe and Ti), anorthite (Al), orthoclase and pyroxene. With mineral preprocessing, the Metalysis FFC process can reduce metal oxides into pure metal as a solid-state sintered cathode suitable for 3D printing processes. Its $CaCl_2$ electrolyte is manufactured as a byproduct of metal extraction.

3D Printing: We have adopted 3D printing as our universal manufacturing technique. We have demonstrated 3D printing of an electric motor except its wire coils but the latter is in process. We have 3D printed testpieces of almost all the materials required to construct a vacuum tube (specifically, a magnetron). We are constructing a custom 3D printer to print metal and silicone plastic simultaneously. Once complete, we shall then proceed to lunar analogue material.

Conclusion: We are in the process of demonstrating that key components to a lunar industrial ecology can be constructed from lunar-like material. The lunar ecology is essential if ISRU is to be sustainable.