PHASE EQUILIBRIUM EXPERIMENTS ON POTENTIAL LUNAR CORE COMPOSITIONS: EXTENSION OF CURRENT KNOWLEDGE TO MULTI-COMPONENT (Fe-Ni-Si-S-C) SYSTEMS. K. Righter[1], K. Pando[2], L. Danielson[2], [1]Mailcode KT, NASA Johnson Space Center, 2101 NASA Pkwy., Houston, TX 77058 (kevin.righter-1@nasa.gov); [2]Jacobs JETS, NASA Johnson Space Center, 2101 NASA Pkwy., Houston, TX 77058.

Introduction: Numerous geophysical and geochemical studies have suggested the existence of a small metallic lunar core (e.g., [1-5]), but the composition of that core is not known. Knowledge of the composition can have a large impact on the thermal evolution of the core, its possible early dynamo creation, and its overall size and fraction of solid and liquid. Thermal models predict that the current temperature at the core-mantle boundary of the Moon is near 1650 K [6]. Re-evaluation of Apollo seismic data [7] has highlighted the need for new data in a broader range of bulk core compositions in the PT range of the lunar core. Geochemical measurements have suggested a more volatile-rich Moon than previously thought [8]. And GRAIL mission data may allow much better constraints on the physical nature of the lunar core [9]. All of these factors have led us to determine new phase equilibria experimental studies in the Fe-Ni-S-C-Si system in the relevant PT range of the lunar core that will help constrain the composition of Moon's core.

Previous work: Studies of the lunar core suffer from several different data gaps. First, there is a lack of information at the pressure conditions of the lunar core (~ 4.5 GPa). The detailed study of the Fe-S-Si system [10] showed that the solid phase at 10 GPa and 1700 K is Fe_2Si, and also that there is a two liquid field at < 15 GPa (Figure 1). A more recent study of the Fe-S-Si system concentrated on temperatures too high for the lunar core - > 1900 K [11]. The topology down to the lower pressures and temperatures of the lunar core is important to discover because it may reveal a possible solid inner core candidate as well as the existence of two metallic liquids at conditions relevant to the Moon's interior.

Second, there is detailed information only about simple systems such as Fe-S or Fe-C ([12-18]; Figure 2), but not a comprehensive understanding for additional and multiple elements such as Fe-Ni-S-C-Si. For example, studies of the Fe-S-C system have shown that Fe_3C and liquid are stable phases at 4.5 GPa and 1630 K, but the detailed phase equilibria might change with addition of Ni or Si, or lower amounts of C and S. For example, addition of Ni to the Fe-S system is known to lower the liquidus by as much as 100 K ([19,20]). Also, there may be two liquids at conditions of the lunar core, because the transition from one to two liquids takes place between the pressures of 2 and 6 GPa (Figure 2). This lack of information has resulted in uncertainties in basic characteristics of the lunar core such as

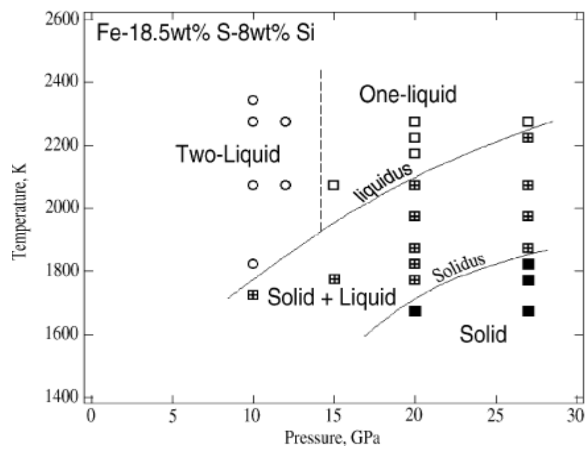

Figure 1: The Fe-S-Si phase diagram [10] showing a two metallic liquid region < 15 GPa, and a "liquid + Fe_2Si" region <1800 K and 10 GPa.

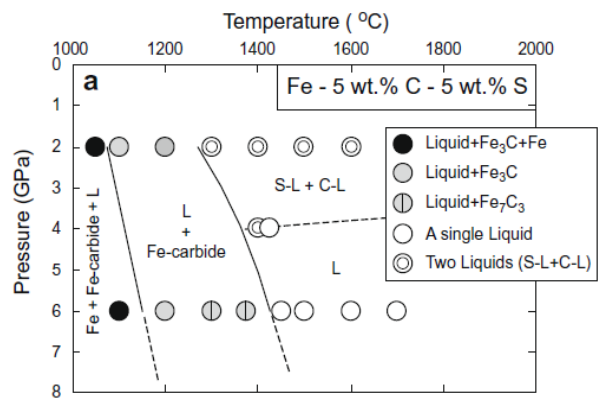

Figure 2: A portion of the Fe-S-C system [14] showing a two metallic liquid field at 4 GPa and less, and also a "liquid + Fe_3C" field at conditions of the Moon's core.

whether there is liquid immiscibility (two liquids) at these conditions, what is the melting temperature of the core, and how do recent studies indicating a molten outer core relate to the phase equilibria and to the size of the solid core? Is the solid core a metallic alloy or could it be a phase such as Fe_3C or Fe_2Si ?

In order to gain a full and relevant understanding of the phase equilibria in the lunar core, we have carried out experiments on one of several bulk compositions relevant to the lunar core.

Experimental approach: The first composition is Ni- and Si-bearing and is: Fe 59% (Fe + Fe-S), S 6% (from Fe-S), Ni 20%, Si 15%. This composition was studied between 1 to 4 GPa and between 1200 and 1800 K. These experiments were carried out in two capsule types: a) graphite capsules, where the graphite dissolves a small amount of C into the Fe-Ni-S-Si metallic starting liquid; and b) MgO capsules where carbon contents may be controlled by adding an amount lower than that of graphite saturation. In this way it is possible to control C contents in the metal between 0 and ~ 5 wt. %. Experiments at 1 and 3 GPa were carried out in a piston cylinder apparatus using 10 and 13 mm $BaCO_3$ cell assemblies and graphite heaters [21,22]. Experiments at higher pressures were carried out in an 880 ton multi-anvil press using WC cubes with 8 mm truncations (14/8 COMPRES assembly) [23]. Experimental charges were then analyzed with scanning electron microscopy (SEM) and electron microprobe analysis (EMPA) to determine the phase equilibria and compositions.

Table 1: Experimental conditions for core experiments (all graphite capsules)

run	Temperature (°C)	Pressure (GPa)	phases
LC1-12	1200	1	2 liq
LC1-13	1300	1	2 liq
LC1-14	1400	1	2 liq
LC1-15	1500	1	2 liq
LC1-16	1600	1	2 liq
LC3-12	1200	3	sol + 2 liq
LC3-13	1300	3	2 liq
LC3-14	1400	3	2 liq
LC3-15	1500	3	2 liq
LC3-16	1600	3	2 liq
BJJB-237	1300	5	2 liq
BJJB-234	1650	5	2 liq

Preliminary results: The composition studied has an extensive phase field consisting of two liquids – a Si-bearing FeNi liquid and an S-bearing FeNi liquid. Only in the two lowest temperature experiments at 3 GPa is there a solid phase present (Table 1). It thus appears, for this particular composition, that at the PT conditions close to the lunar core (4.5 GPa and 1630 K), there would be two liquids present.

Future work: We will select several additional compositions for study including those with less Si, and more S. With the phase equilibria information for additional compositions, we will be able to evaluate whether there is a two liquid field (immiscibility) near the conditions of the lunar core, address the question of the melting point of the lunar core, and finally identify potential candidates for the solid inner core, whether it is Fe alloy, Fe_3C, Fe_2Si, or a different compound that might include Ni and S. In addition, these results will have an influence on interpretation of volatile siderophile element partitioning between solid metal, liquid metal and liquid silicate. This class of elements includes As, Sb and Cu, all of which are strongly dependent upon S- and Si-content of the metallic liquids [24]. The nature of the light element in the lunar core is debated [7,25], but includes S and Si, and thus the volatile siderophile elements will provide additional constraints on the composition and size of the core [24].

References: [1] Dickey, J.O. et al. (1994) *Science* 265, 482-490; [2] Khan, A. and Mosegaard, K. (2001) *GRL* 28, 1791-1794; [3] Wieczorek, M.A., et al. (2006) In (B.L. Jolliff, Wieczorek, M.A., Chearer, C.K., and C.R. Neal, eds.) *Rev. Mineral. Geochem.* 60, 221-364; [4] Hood, L.L., et al. (1999) *GRL* 26, 232-236; [5] Righter, K. (2002) *Icarus 158*, 1-13; [6] Spohn, T., et al. (2001) *Icarus* 149, 54–65; [7] Weber, R.C., et al. (2011) *Science* 331, 309-312; [8] Saal, A.E. et al., (2008) *Nature* 454, 192-195; [9] Zuber, M.T., et al. (2011) *42nd LPSC*, # 1967; [10] Sanloup, C. and Fei, Y. (2004) *PEPI* 147, 57-65; [11] Morard, G. and Katsura, T. (2010) *GCA* 76, 3659–3667; [12] Fei, Y., et al. (1997) *Science* 275, 1621-1623; [13] Buono, A. and Walker, D. (2011) *GCA* 75, 2072-2087; [14] Dasgupta, R., et al. (2009) *GCA* 73, 6678-6691; [15] Chabot, N.L. et al., (2008) *GCA* 72, 4146–4158; [16] Chen B., et al. (2008) *High Pressure Res.* 28, 315-326; [17] Chen B., et al. (2008) *GRL* 35, L07201; [18] Morard, G., et al. (2007) *EPSL* 263, 128-139; [19] Pike, W.A., et al. (1999) *30th LPSC*, #1489; [20] Stewart, A.J. et al. (2007) *Science* 316, 1323-1326; [21] Righter et al. (2011) *Amer. Mineral.*96, 1278–1290; [22] Filiberto, J. et al. (2008) *MaPS* 43, 1137–1146; [23] Leinenweber, K. D., et al. (2012). *Amer. Mineral.* 97, 353-368; [24] Righter et al., (2014) *45th LPSC* abstract, this volume; [25] Armytage, R.M.G. et al. (2012) *GCA* 77, 504-514.