

## High-temperature electrical and thermal properties of Burdett, Dalhart, Faucet and Wellman ordinary chondrites\*

Meteorites are fragments of rocks which originated from outer planetary bodies and fell on the surface of the earth. Meteorites can be divided into two major types, primitive and differentiated. Differentiated meteorites are igneous rocks that were crystallized from magmas generated at the interiors of their parent bodies. On the other hand, the primitive ones have not experienced the melting in their parent bodies, thus their bulk compositions, except for volatiles, are considered to represent those of the solar nebula where and when the meteorites formed. Since the majority of primitive meteorites have chondrules, they are commonly called chondrites. Chondritic meteorites are the oldest and most primitive rocks in the solar system. The primary divisions of chondrite classification are the carbonaceous, ordinary, and enstatite classes<sup>1</sup>. The ordinary chondrites are so-called because they are vastly more abundant on the earth than all other types of meteorites. The ordinary chondrites are divided into three groups, viz. H-type which have high total Fe-contents, L-type having low total Fe-contents, and LL-having very low metallic Fe relative to the total Fe, as well as low total Fe-contents. Earlier studies on the ordinary chondrite were focused on chemical composition of major minerals, petrology, and metamorphic episodes<sup>1-5</sup>. The chemical distinction among the H-, L-, LL-group chondrites depends on the distribution of iron between metal and silicates. It has been established that there is no or very little compositional overlap among these H, L, and LL chondrites<sup>3</sup>. The metallic minerals in chondrites behave like good electrical conductors, while silicates as insulating material. High-temperature electrical properties measurements are proven to be very useful in understanding metal-silicate fractionation<sup>6</sup>, which will be useful in obtaining information about a wide variety of solar system processes. We have chosen four meteorites that are classified as H-type ordinary chondrites for the present study.

The meteorite samples are mostly brittle in nature. Therefore discs could not

be made by the usual coring technique. To avoid any risk in making the discs from the meteorite samples, the samples are first moulded in plaster of Paris. After three days of solidification the discs were made by the usual coring technique. To avoid any reaction with ordinary water, distilled water is used for coring the meteorite samples. The measurements have been carried out after drying the meteorite discs at 313 K for more than 48 h.

Thermal conductivity has been measured by modified divided bar apparatus using a special technique<sup>7</sup>. Density of all meteorite samples is determined by conventional technique using Archimedean principle. Specific heat of meteorites has been determined by using conventional technique. Thermal diffusivity of all the meteorite samples has been estimated by using the relationship  $\kappa = k/\rho C$  as the parameters thermal conductivity ( $k$ ), density ( $\rho$ ) and specific heat ( $C$ ) have already been determined. The thermal inertia ( $\gamma$ ) has been estimated for all meteorite, lunar and rock samples by using the relationship  $\gamma^{-1} = (K\rho C)^{1/2}$  where  $k$ ,  $\rho$  and  $C$  are thermal conductivity, density and specific heat of the sample respectively. For all these measurements quartz was used as standard for which thermo-physical properties are well known<sup>8</sup>.

DC electrical conductivity measurements were made at room pressure by adopting the conventional four leads method. A constant current source (Keithley 263), 6½ digits digital multimeter (HP-3455) and a digital electrometer (Keithley 614) were used as measuring

units. The values of electrical resistivity of ordinary chondrites were too high to measure at room temperature (more than input impedance of the electrometer  $10^{13}$  ohms). So the measurements were started at 723 K. The upper limit of furnace was 1300 K. The temperature was measured with Pt-10/Rh-Pt thermocouple with an accuracy of 0.2%. The furnace was maintained at inert atmosphere.

The composition of the four chondrites is listed in Table 1. The samples contain mainly olivine, low Ca-ortho-pyroxene, albite-rich feldspar and minor amount of triolite, chromite and merrillite. The olivines of the chondrites have a composition of forsterite 88–82 mol% and fayalite 12–18 mol%. It is well established that the fayalite content of the H-group chondrite varies from 16 to 20 mol%<sup>1</sup>. The overall composition has been found to be consistent with the standard mean values of established ordinary chondrites<sup>3</sup>.

Thermo-physical properties of meteorites are very useful as they are essential in delineating the nature of thermal metamorphism seen in meteorite samples and the processes that may be responsible for it. However, there may be both random and systematic variations of the thermo-physical properties of chondrites, depending upon the degree of chemical differentiation, crystal or particle size, anisotropy, cooling history in igneous rock and metamorphic history in rocks, etc. Though there are some calculations on the temperature dependence of specific heat of chondrites available in the literature<sup>2-5,9,10</sup>, there are no previous reports

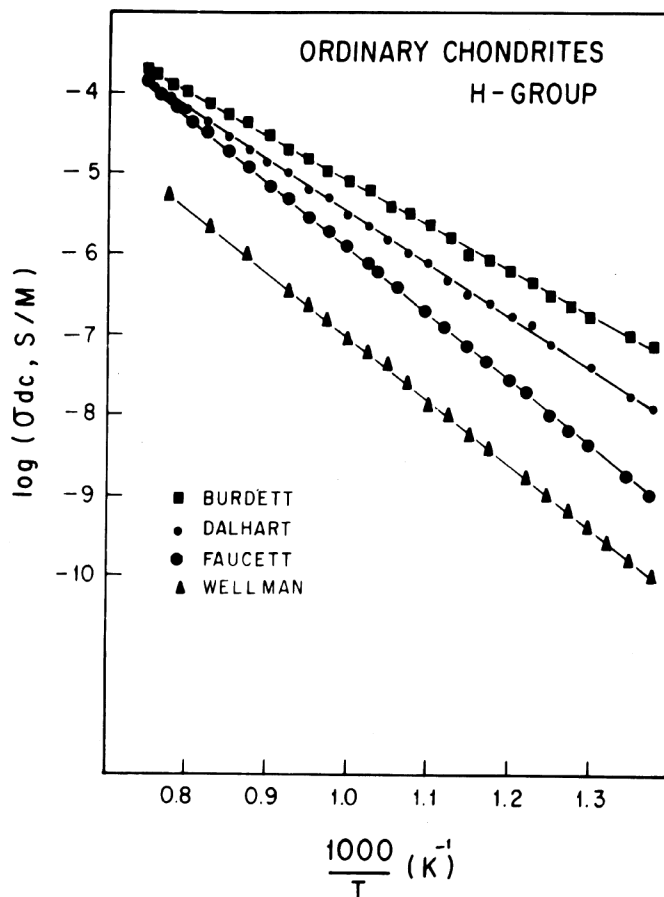
**Table 1.** Chemical composition of the chondrites

Samples Elements (in wt%)	Burdett	Dalhart	Faucett	Wellmann
Si	26.87	26.98	27.02	27.10
Ti	0.05	0.04	0.05	0.06
Al	1.92	1.97	1.20	1.25
Cr	0.20	0.28	0.29	0.40
Fe	42.8	42.0	42.3	39.0
Mn	0.35	0.32	0.30	0.25
Mg	23.35	23.90	23.95	25.20
Ca	1.63	1.58	1.57	1.62
Na	0.82	0.85	0.88	0.85
K	0.10	0.09	0.10	0.08
Ni	2.58	2.50	2.55	2.70

\*This article is dedicated to S. Ramaseshan.

**Table 2.** Thermo-physical properties of four ordinary chondrites at room at ambient temperature and pressure

Sample no.	Density (g/cc) $\rho$	Specific heat (kJ kg <sup>-1</sup> K <sup>-1</sup> ) $C_p$	Thermal conductivity (W m <sup>-1</sup> K <sup>-1</sup> ) $k$	Thermal diffusivity (in 10 <sup>-7</sup> m <sup>2</sup> s <sup>-1</sup> ) $\kappa$	Thermal inertia (in 10 <sup>-4</sup> m <sup>2</sup> KW <sup>-1</sup> s <sup>-1/2</sup> ) $\gamma$
Burdett H29-33	3.55	0.55	3.20	16.59	4.02
Wellman H39-242	3.65	0.76	5.72	24.46	2.32
Faucett-419	3.52	0.80	3.56	8.29	3.55
Dalhart	3.34	0.76	3.96	11.79	3.66

**Figure 1.** Arrhenius plot of the temperature dependence of the dc electrical conductivity of four different ordinary chondrites.

on thermal properties on the studied sample. Earlier studies were based on the theoretical calculations based on the weighted average of the specific heat capacities of the constituent minerals. The calculated specific heat at constant temperature ( $C_v$ ) of H-chondrites increases from 0.65 kJ/kg/K at 300 K to 875 kJ/kg/K at 1050 K, where there is a phase transition with a sudden drop in specific heat capacity from 875 to 810 kJ/kg/K (ref. 10). Such a transition would cer-

tainly show a distinct behaviour in the temperature dependence of the electrical resistivity. But we do not see any such transition at 1050 K in the studied samples (Figure 1). Moreover the values of the specific heat measured in the present study represent the specific heat at constant pressure ( $C_p$ ), which is more than the calculated value at room temperature. Room temperature specific heat of the Burdett sample (0.55 kJ/kg/K) is found to be lower than the value of other studied

samples. At present we do not understand the reason for this observation. Our results show that thermal conductivity ( $k$ ) varies from 3.20 to 5.72 Wm<sup>-1</sup> K<sup>-1</sup>, specific heat ( $C_p$ ) from 0.55 to 0.80 kJ Kg<sup>-1</sup> K<sup>-1</sup>, and density varies from 3.34 to 3.65. These values are found to be similar to the values measured for forsterite-rich mantle-derived dunite samples<sup>11</sup> for which the thermal conductivity varies from 3.53 to 5.14 Wm<sup>-1</sup> K<sup>-1</sup> and specific heat varies from 0.59 to 0.80 kJ kg<sup>-1</sup> K<sup>-1</sup>. However, the values of thermal diffusivity ( $\kappa$ ) of the chondrites are found to vary from 8.29 to 24.96 × 10<sup>-7</sup> m<sup>2</sup> s<sup>-1</sup>. Whereas for mantle-derived dunite sample it varies only in the narrow range from 7.16 to 8.48 m<sup>2</sup> s<sup>-1</sup>. As the thermal inertia is an important parameter, for determining the rate of cooling of the surface, we have calculated the thermal inertia of the ordinary chondrites. The values of thermal inertia ( $\gamma$ ) of the chondrites were found to be in the range 2.32 to 4.02 × 10<sup>-4</sup> m<sup>2</sup> K W<sup>-1</sup> s<sup>-1/2</sup>. The results on thermo-physical properties at NTP reveal that high thermal conductivity, and thermal diffusivity of Wellman H39-242 meteorite as compared to other meteorites (Table 2) could be due to the presence of carlsbergite CrN as minor accessory mineral in Wellman, which is known to have more thermal conductivity and is electrically more insulating. We did not observe the presence of carlsbergite in the other samples of the studied ordinary chondrites. This is supported by the electrical resistivity measurements of the ordinary chondrites (Figure 1). It has been observed that shock-induced melt veins occur in many ordinary chondrites, which affect the physical properties of some of the ordinary chondrites. For example, the shocked veins of H-6 chondrite (Yamato 75267) contains high-pressure mineral phases like ringwoodite, majorite-pyrope garnet, hollandite as accessory minerals in veins,

**Table 3.** Electrical conductivity and activation energy of ordinary chondrite

Samples	Conductivity at 723 K (S/m)	Conductivity at 1333 K (S/m)	Activation energy (eV)
Burdett	$7.08 \times 10^{-8}$	$1.99 \times 10^{-4}$	1.086
Dalhart	$1.25 \times 10^{-8}$	$1.25 \times 10^{-4}$	1.27
Faucett	$1.02 \times 10^{-9}$	$1.58 \times 10^{-4}$	1.65
Wellmann	$1.08 \times 10^{-10}$	$5.01 \times 10^{-6}$	1.57

which affect the thermal properties of the ordinary chondrites<sup>12</sup>.

Figure 1 shows the temperature dependence of the electrical conductivity of four ordinary chondrites as a function of temperature (723 to 1333 K). At room temperature the values of the conductivity are too low and could not be measured with the existing measuring instruments. The upper limit of the temperature of the present investigation was limited to 1333 K, due to an instrumental problem. The contact was made only by applying the stress on the platinum electrical leads. The temperature dependence of the dc conductivity shows the Arrhenius behaviour with single activation energy over the temperature range of the investigations (723 to 1333 K). The activation energy was calculated for all the chondrite and the values are listed in Table 3. The values of activation energy for electronic conduction are found to vary from 1.086 eV for Burdett sample to 1.65 eV for Faucett sample. It is interesting to note that the value of the zero pressure activation energy of the studied ordinary chondrites is found to be in very close

agreement with that of San Carlos olivine 1.5 eV, indicating the olivine-rich nature of the ordinary chondrite, which is consistent with the chemical composition study. The single activation energy of all the samples reveals that there is no change of conductivity mechanism in the temperature range of investigations (723 to 1333 K) and also the absence of any hydrous or other volatile components in these ordinary chondrite samples.

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## A novel ( $8\pi + 8\pi$ ) cycloaddition of benzocondensed iminoketenes

Both concerted and nonconcerted cycloaddition reactions of various orders involving reactive intermediates such as ketenes are well known<sup>1–4</sup>. However, *in situ* generation of a diene or dienophile is of comparatively recent interest<sup>5–10</sup>. It is interesting to note that sulphinamide anhydride will also generate *in situ* diene, which on Diels–Alder reaction should yield various types of heterocycles<sup>11</sup>.

Although orbital symmetry-controlled ( $8\pi + 8\pi$ ) cycloadditions are forbidden, few examples of this type were reported in the literature<sup>12,13</sup>. When anthranilic

acid is treated with thionyl chloride, the corresponding sulphinamide anhydride is formed. Sulphinamide anhydride **1** gradually decomposes to iminoketene **2**, which is already reported in the literature<sup>14–17</sup>. It has been found that in the absence of dienophile, sulphinamide anhydride decomposes to iminoketene **2**, which then undergoes ( $8\pi + 8\pi$ ) cycloaddition forming dibenzo-[c,g]-[1,5]diazocene-1,5-dione **3** (Scheme 1).

Compound **3** is unknown and identified by spectroscopic data and alternate method of synthesis<sup>18</sup>. It seems that the

reaction is a nonconcerted one, as the intermediate **2** dimerizes to form **3**. An analogous compound isatoic anhydride **4**, gave the same dimer **3** under microwave conditions<sup>18</sup> (Scheme 2).

Sulphinamide anhydride (667.8 mg, 3.64 mmol) in dry benzene (20 ml) was left overnight. Excess solvent was removed by vacuum distillation and the residue was dissolved in  $\text{CHCl}_3$  (20 ml) which was washed with 10%  $\text{NaHCO}_3$  ( $3 \times 10$  ml), water ( $3 \times 10$  ml), dried over anhydrous  $\text{MgSO}_4$  and chromatographed over silica gel (60–120 mesh) using