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LUNAR SAMPLE ANALYSIS PROGRAM

Investigation of the Maximum Magnetic Field Ever Present on the Moon

Technical Progress Report for Apollo 11 Lunar Samples
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Evidence for an Ancient Lunar Magnetic Field

by

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ABSTRACT

Magnetic studies of samples 12002 and 12022 have shown that these samples contain a weak remanent magnetic moment. Progressive thermal demagnetization experiments suggest that these moments are stable and were not acquired as a result of exposure to the earth's magnetic field. The primary carrier of remanence is native iron. In addition, two spinel phases (chromite and ulvospinel) and troilite are also present in these samples. Progressive thermal demagnetization experiments, in which the samples were cooled in the presence of a known field, suggest that the remanent magnetization of these rocks was acquired on the Moon in the presence of an applied field of up to 5000 gammas, provided that the initial magnetization was acquired by an ordinary partial thermoremanent process. This would imply that the Moon had a weak magnetic field 3.5 to 4.0 aeons ago and suggests that small conducting fluid core may have been present at that time.

Alternatively, the remanence could have been acquired in a much lower field as a result of the introduction of crystalline defects during thermal cycling or radiation exposure and thus the progressive thermal demagnetization experiments would imply an erroneously high estimate of the intensity of the paleofield.

INTRODUCTION

The magnetic studies on Apollo 11 samples showed that lunar materials are capable of possessing an apparently stable remanent magnetization and that this magnetization was acquired by the samples in the lunar environment. The magnetic studies on the Apollo 11 material also indicate that the magnetization was acquired in a field of in excess of 1500 γ (Helsley, 1970). Similar studies on Apollo 12 materials are reported below.

The two rocks studied in this investigation are 12002 and 12022. These rocks are olivine microgabbros and rock 12002 is conspicuously vesicular. Petrographic observations of these samples suggest a near surface, probably extrusive, origin. The potentially magnetic phases present in each sample (in order of decreasing abundance) are a zoned spinel (ülvospinel cores and chromite rims), troilite and native iron. Of these only the native iron and the troilite are potentially magnetic above room temperature.

THERMOMAGNETIC ANALYSIS

Thermomagnetic analyses were made on thirty to eighty milligram fragments. The samples were crushed and sealed in evacuated quartz capillaries (pressure <0.01 mm of Hg) and heated in a magnetic force balance to temperatures of up to 850°C in a field of about 3 koe. The heating and cooling rates varied from 5° to 20°C per minute. The results of these experiments are shown in Figure 1. Both rocks show a progressive decrease in intensity that can be attributed to the changing susceptibility of the iron bearing paramagnetic minerals in the sample. At temperatures in excess of 500°C the magnetization begins to drop steadily towards a Curie point near 770°C indicating the presence of native iron as the dominant magnetic phase. Upon cooling, the curve is not reproduced and Curie points near 600°C and 120°C are indicated. This behavior is reproduced upon recycling as is shown in the lower part of Figure 1. These curves are remarkably similar to those observed in iron bearing meteorites (Stacey et al, 1961, Lovering and Parry, 1962). The Curie points observed suggest that the iron alloy (Kamacite) has more than 7% nickel (Lovering and Parry, 1962, Table 3) and that a small amount of taenite may also be present (Curie point near 120°C). No other Curie points are present in the initial run. The curve observed on reheating of sample 12002 suggests that some chemical change has taken place since the heating curve upon recycling begins to decrease rapidly near 600°C rather than near 700°C as in the initial run.

The thermomagnetic observations support the polished thin section observations in which iron, troilite, chromite ülvospinel and ilmenite were observed and suggest that the dominant carrier of the remanence observed in these rocks should be the iron alloy.

X-ray microprobe analysis of the opaque oxides in Sample 12002 indicate that nickel is present in the iron in quantities up to at least 20 percent. Iron grains internal to the ulvospinel and chromites are the highest in nickel while those in contact with silicate minerals, i.e. those formed later, have nickel contents near 5 percent.

NATURAL REMANENT MAGNETIZATION

Initial measurements of the natural remanent magnetization (NRM) of samples 12002 and 12022 yielded specific intensities of 0.153×10^{-5} and 0.208×10^{-4} emu per gram respectively. Each sample initially was stored in a field free region for several days with repeat observations being made each day. The observed intensity and direction changed progressively during these tests suggesting that the samples had acquired a small moment since return to the earth. Alternating field demagnetization was not done since the mineralogy observed in polished thin sections was similar to that for Apollo 11 samples which were shown to have remanent coercivities near 50 oersted and it was deemed advisable to concentrate on making a paleointensity determination rather than determine a coercivity spectrum.

Both samples were subjected to progressive thermal demagnetization experiments in 50°C steps. The furnace used was a conventional non-inductively wound furnace operated in a region where the ambient field was maintained at 0 ± 10 gammas. Sample 12002 was heated in a sealed evacuated tube (pressure <0.01 mm of Hg) while sample 12022 was heated in a vacuum furnace in which the pressure was maintained at <0.01 mm of Hg during the entire run. In the sealed tube technique the thermocouple was outside the sample container while the vacuum furnace had an internal platinum thermocouple mounted about 2 mm from the sample. The results of these demagnetization experiments are shown in Figure 2. After demagnetization at each step above 100°, each sample was reheated to the same temperature and allowed to cool for 50 or 100°C in the presence of a known field of 1000 to 10000 γ depending upon the particular run.
Thus the sample was allowed to acquire a partial thermal

remanence so that paleointensity determinations by the double heating method of Thellier and Thellier (1959) could be calculated. For sample 12002 these measurements were carried out in the temperature range 20°C to 150°C and the results are shown in Figure 3. At temperatures above 200°C the sample did not demagnetize systematically and thus these observations cannot be used for paleointensity determinations. Between 20°C and 150°C the ratio of the field lost to that gained in 10000 gammas is 0.45. As is described below, the lunar surface temperature cycle is in this same range, consequently the significance of the 4500 gamma paleointensity determination from this sample is in doubt.

Sample 12022 demagnetized systematically, i.e. the intensity decreased smoothly and the direction of magnetization was constant, up to 308°C. However, after the partial thermal demagnetization run at 308°C, the magnetization acquired during the PTRM experiment apparently was not completely removed. Upon heating to 350°C, the PTRM acquired at 308°C apparently remained, i.e. the component in the direction of the applied field remained unchanged. Since it is unlikely that the magnetization acquired in cooling from 308°C to 200°C should remain unchanged, even after heating to 350°C, it must be assumed that the magnetization of the sample has more than one component. In this particular case, one would surmise that the sample has a magnetic moment acquired below 300°C that is dominant at temperatures below 300°C and that a weaker component acquired above 300°C is also present. Studies on the high temperature portion of the magnetization have as yet not been completed. The average of the eight independent paleointensity determinations for 12022 was 4800 gammas with the total range being 2800 to 10060 gammas.

PALEOINTENSITIES AND THE ORIGIN OF THE MAGNETIZATION

If one assumes that the observations made at temperatures below 300°C are valid indicationsof the field present at the time of origin of the rock, then one is led to the estimates of field intensity given in Table 1. Of the four rocks studied so far, 10022, 10069, 12002, and 12022, an estimate between 1000 and 5000 gammas seems to be indicated. This compares with the present lunar field of 38 gammas (Dyal et al, 1970) and suggests that the lunar field may have had a much larger value early in the Moon's history (Helsley, 1970). This field could be of internal lunar origin or could have been acquired while the Moon was in close proximity to the Earth. The fact that fields of reasonable size (>1000 gammas) are indicated for rocks of two distinctly different ages suggest that the observed paleofield was of internal origin since the moon would not be expected to be able to remain close to the earth (inside its magnetic field) for a period of 300 to 400 million years as is indicated by the age differences (Cliff, et al, 1971).

During the course of the experiments made on 12022 corrections were made for the time the sample was kept at elevated temperatures according to the formula given by Stacey (1963),

$$\frac{T_1}{T_2} = \frac{\ln (3C\tau_2)}{\ln (3C\tau_1)}$$

where T is temperature in °K, τ is the time in question and C is a constant with a value of 10^{10}. Thus an experimental run of ten minutes duration at 300°C is equivalent to two weeks at a temperature of 120°C. Although the theory pertains strictly to a single magnetic phase with a single relaxation time, these calculations agreed qualitatively with the observations in that repeat runs at the same temperature produced a continued slow decrease in observed intensity. However, this theory, when applied to lunar rocks, suggests that there should be no change in the intensity below 300°C for all components with this stability range should have been removed during the 120+°C temperatures of the lunar day. Moreover, it would suggest that only the magnetization remaining above 525°C has a certain meaning in terms of paleointensity for it would be the only magnetization that could survive a billion years at 120°C. However, this conclusion involves a very large extrapolation that may not be valid since, as mentioned above, the theory upon which it is based pertains only to single domain, single relaxation time material. Moreover, the demagnetizing effects produced by repeated heating to a low temperature (120°C) may not be comparable to a long single heating to the same temperature.

The significant changes of magnetization observed at temperatures below 300°C, particularly for sample 12002, require the conclusion that Stacey's calculations are not entirely applicable to lunar material since no changes would have been observed if the theory were entirely correct. Since most of the iron is multidomain (the critical radius for single domain behavior is very small for iron; 20Å Chikazumi, 1964; 70Å Kittel, 1949; 160Å Néel, 1947), the magnetization observed at temperatures below 300° could be due to domain wall pinning on dislocations resulting from stresses induced during rapid heating and cooling in the lunar surface environment. This pinning could enhance, or make more stable, any isothermal remanence acquired during an isolated magnetic event that occurred at some time since the original cooling of the rock. Thus, the samples could perhaps acquire their remanence as the result of thermal cycling in a weak field provided that a momentary stronger field had once been present. Such a field may have been caused by a meteorite impact or as a result of a strong solar flare (Sonnet, et al, 1970).

In all the samples studied so far the anomalous behavior observed at temperatures below 450°C could be attributed to the removal of the defects, produced during thermal cycling on the moon, by laboratory heating to temperatures higher than those experienced on the lunar surface. Butler and Cox (1971) have recently confirmed that radiation induced damage can affect the magnetic properties of iron. In their experiment, changes in coercivity were produced as the result of irradiation of pure iron samples in a high neutron flux. Thus, they propose that the stable remanence observed in lunar samples is induced by the defects produced during cosmic ray bombardment in a weak field.

In view of the fact that most of the stable remanence in lunar rock is only stable at low temperatures and that potential mechanisms exist for producing apparently stable remanence at low temperatures in the presence of a weak field or momentary strong field, the estimates of the paleointensity given in Table I should be used with caution until observations of stable remanence at higher temperatures are made to confirm, or refute, their validity.

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Table 1.

INTENSITY ESTIMATES FOR ANCIENT LUNAR MAGENTIC FIELD

SAMPLE	ESTIMATED FIELD (GAMMAS)
10022	1500
10069	1000 TO 170000
12002	4500
12022	4800
PRESENT (A-12)	30 TO 50
EARTH	24000 TO 70000

Figure Captions

Figure 1. Thermomagnetic analysis curves of samples 12002 and 12022. The temperatures recorded for 12002 are approximately 50°C too high as a result of unfavorable sample geometry.

Figure 2. Thermal stability of NRM of 12002 and 12022. Closed dots - observations before PTRM experiment (see text); open dots after PTRM experiment; T,N,E,U indicate total moment, north component, east component, and upwards component respectively.

Figure 3. Relation between field lost (NRM) to field gained (TRM) for sample 12002

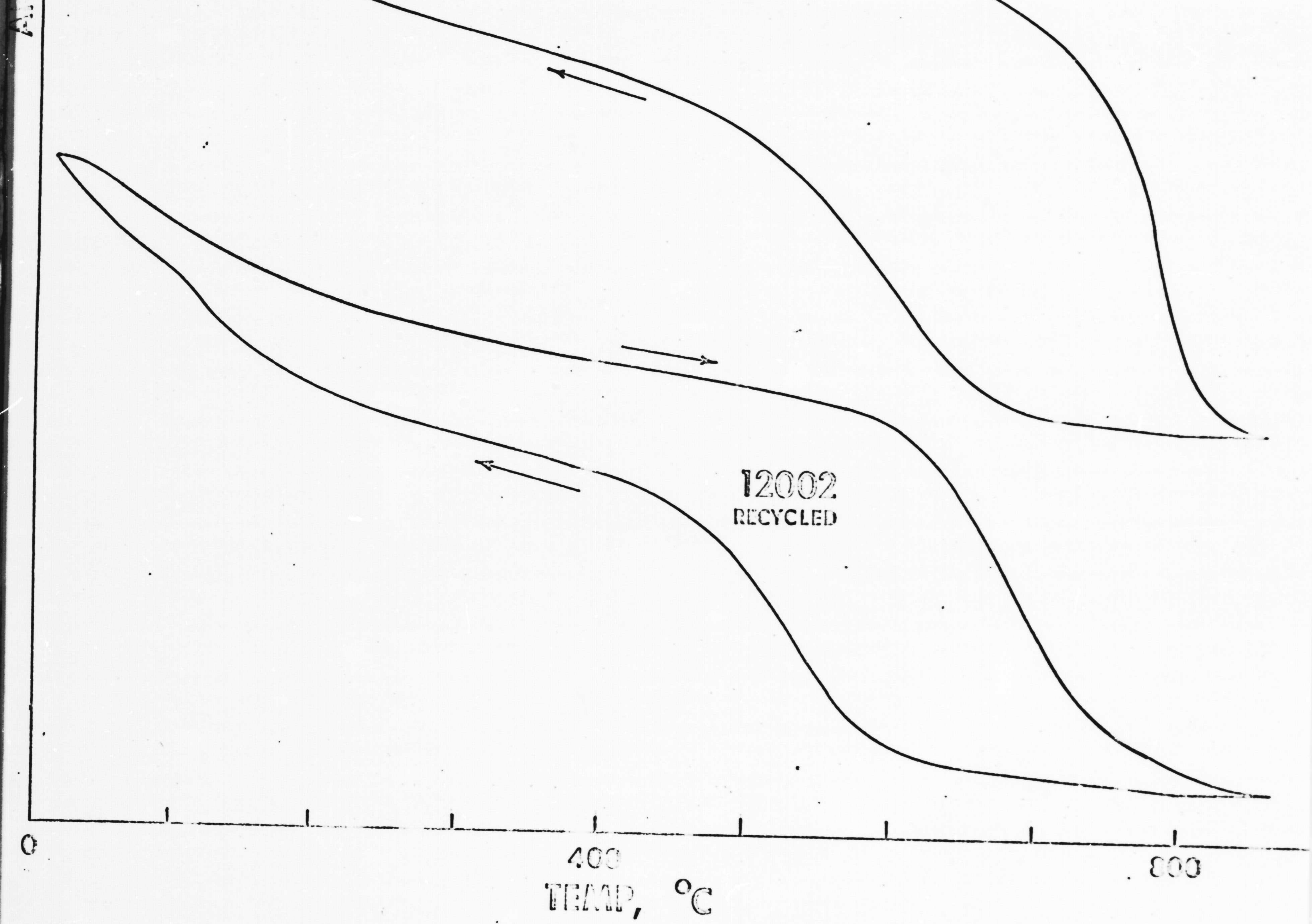


Figure 1.

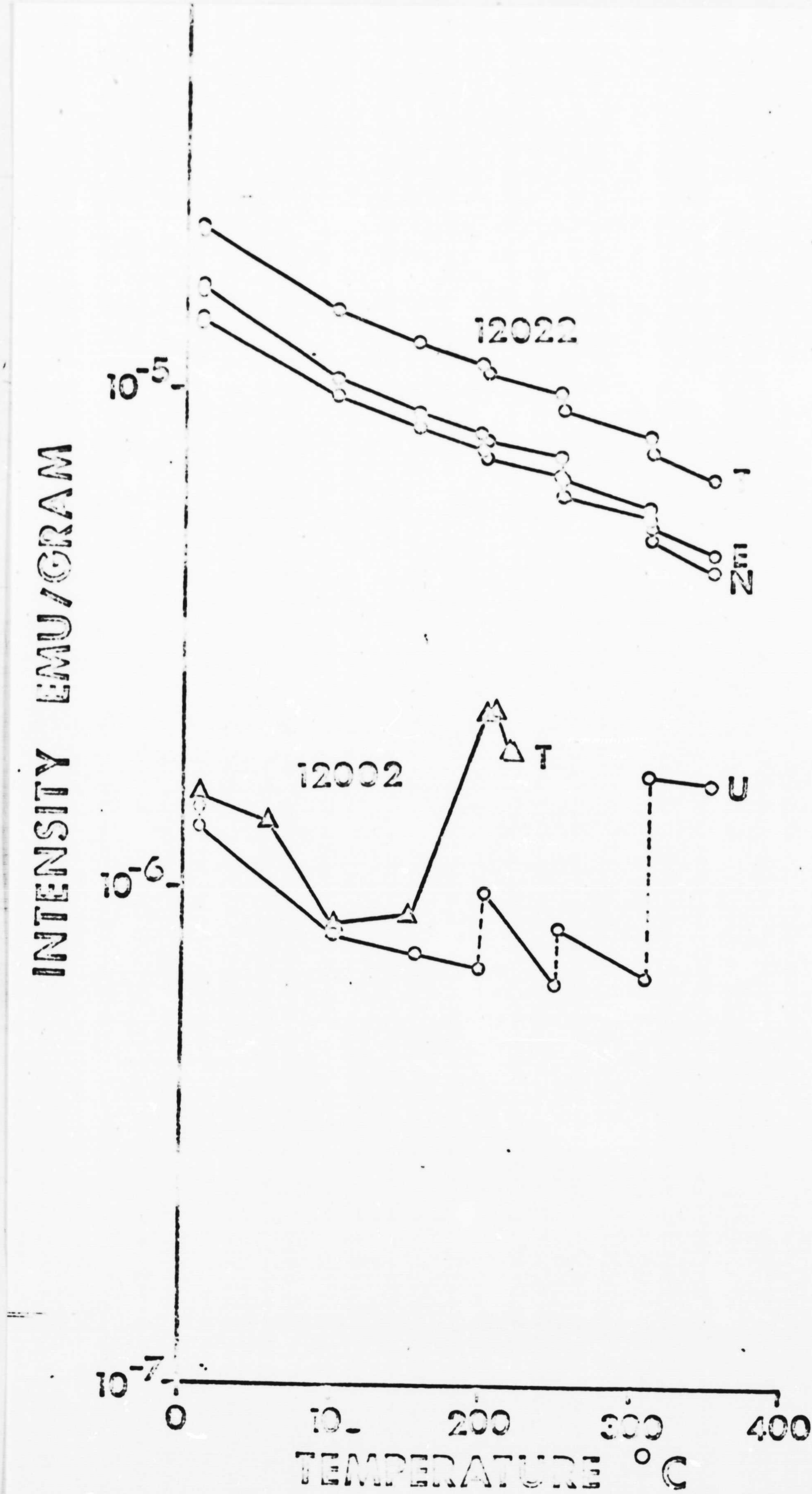
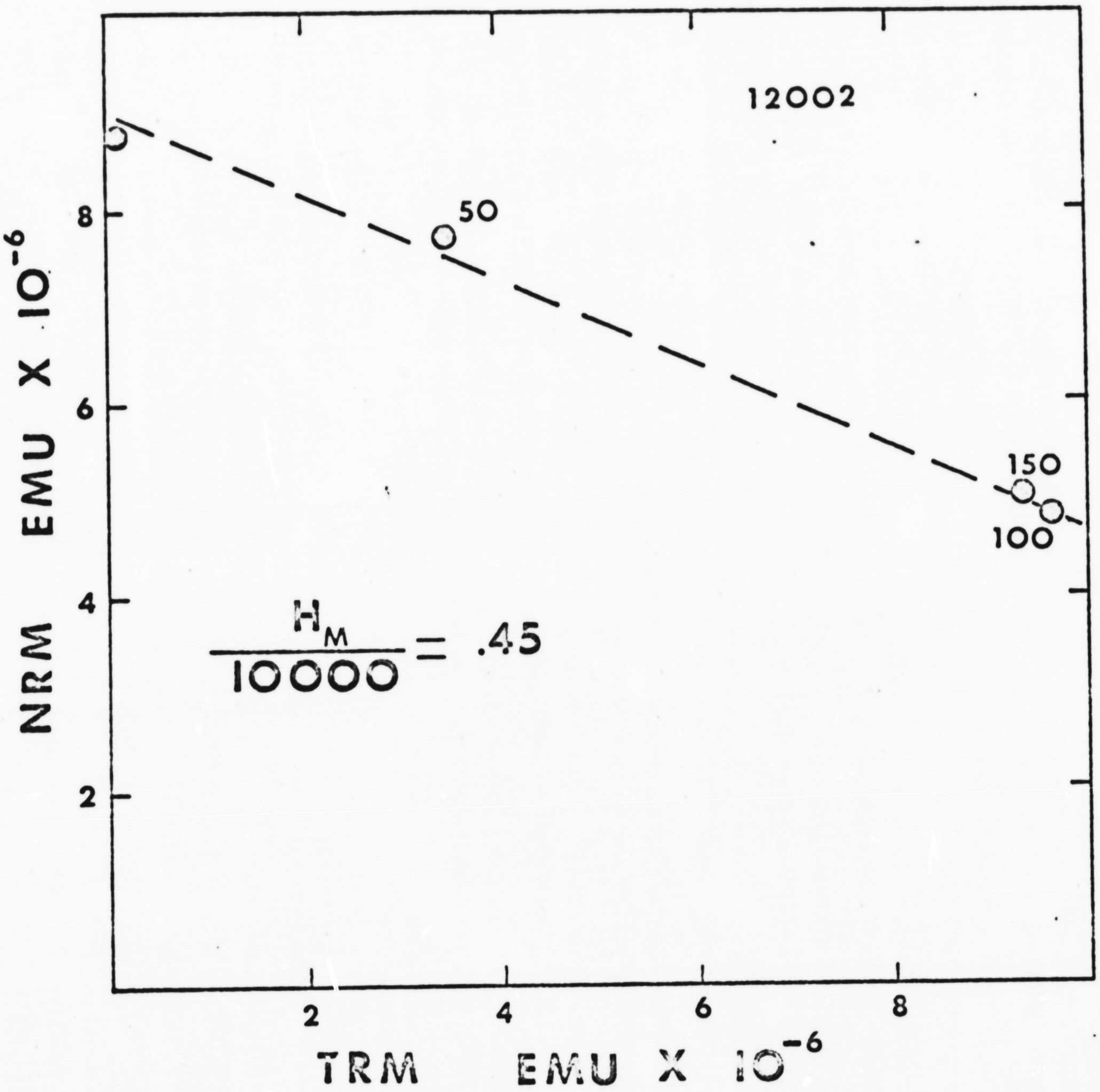

INTENSITY EMU/GRAM
10-5
10-6
10-7
12022
J
E
N
12002
T
U
0
100
200
300
400
TEMPERATURE °C

Figure 2.



12002
50
150
100
$\frac{H_M}{10000} = .45$
NRM EMU X 10^{-6}
2
4
6
8
TRM EMU X 10^{-6}
2
4
6
8

Figure 3.