# ENGINEERING PROPERTIES OF FROZEN ORES FROM LABRADOR

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by

Sun-Meng Yap

A Thesis for the Degree of Master of Engineering

Department of Mining Engineering & Applied Geophysics

## ABSTRACT

This thesis presents the results of a laboratory investigation of some of the engineering properties of five types of frozen geological materials from the Timmins Mine area, Labrador.

Five types of tests (resistivity, thermal conductivity, compressive strength, shearing strength and the sonic wave velocities) were performed on a total of 201 specimens which were prepared from 16 large samples supplied by the Iron Ore Company of Canada. The properties were determined for temperatures between 28°F and 36°F.

Previous studies have been reviewed and the facilities and experimental procedures used have been described in detail.

The appendices include the test data obtained by the writer.

# ENGINEERING PROPERTIES OF FROZEN ORES

# FROM LABRADOR

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Sun-Meng Yap, B.Sc. (Mining)

A Thesis submitted to the Faculty of Graduate Studies
and Research in partial fulfillment of the requirements
for the degree of Master of Engineering

Department of Mining Engineering
& Applied Geophysics
McGill University
Montreal, Quebec

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## SYMBOLS EMPLOYED

| | | |
|---|---|---|
| $A_a$ | = | Exposed surface area of copper disc A ($cm^2$) |
| $A_b$ | = | Exposed surface area of copper disc B ($cm^2$) |
| $A_c$ | = | Exposed surface area of copper disc C ($cm^2$) |
| $A_s$ | = | Exposed surface area of specimen ($cm^2$) |
| d | = | Thickness of specimen disc (cm) |
| e | = | Heat emitted from exposed surface (x $10^{-3}$ calorie/sec.$cm^2$ C°) |
| f | = | Resonant frequency (c.p.s.) |
| H | = | Height of specimen (in.) |
| K | = | Thermal conductivity (x $10^{-3}$ calorie/sec.cm.C°) |
| L | = | Length of specimen (in.) |
| r | = | Radius of specimen disc (cm.) |
| $T_A$ | = | Temperature of copper disc A (°C) |
| $T_B$ | = | Temperature of copper disc B (°C) |
| $T_C$ | = | Temperature of copper disc C (°C) |
| V | = | Velocity of sonic wave (ft/sec) |
| W | = | Water content (%) |

## SPECIMEN NOTATION EMPLOYED

| | |
|---|---|
| M I F | Middle Iron Formation |
| L I F | Lower Iron Formation |
| R C H | Ruth Chert |
| J S P | Jaspillite |
| Q T Z | Quartzite |

# I. INTRODUCTION

## 1.1 General

The purpose of this research was to study and to examine the engineering properties of frozen geological materials from the Timmins Mine area near Schefferville, Quebec. It has been found that much of the ore deposit at this mine is perennially frozen (permafrost).

The existence of widespread occurrences of permafrost in the area was unknown before 1954. Small areas of frozen ore were found in two of the Gagnon mine pits in 1955, however, and these caused some difficulties in handling the ores (Ives, 1963; Bird, 1964; Lang, 1966).

Trenching operations in the same year at the Ferriman ore bodies revealed the presence of frozen ores with high water contents. During the extraction of these, blasting and drilling problems, which increased the cost of open-pit mining operations, were encountered.

At present, a considerable amount of the known reserves in the vicinity of Schefferville are found in permafrost regions. This indicates that blasting and drilling practices and the mining methods used may require modifications in the future.

Drilling in frozen ground results in the generation of heat, and this can cause melting of the sides of a borehole. The caving which follows, as the result of melting, complicates the correct placing of explosives. As a consequence, blasting patterns are influenced and poor fragmentation results (Ives, 1963; Lang, 1966).

Blasting problems will probably increase in proportion to the content of frozen water in the ore. When water content exceeds about

10% the segregation of ice as lenses (from 1/4 to 2 inches thick), pipes and disseminated ice crystals occurs. This may result in the absorption of a large part of the energy released by blasting. An increased consumption of explosives and incomplete and unsatisfactory rupture of the pit face would result.

Successive blasts under such circumstances have been found to produce uneven and incomplete breaking at the toe of the bench and on the pit floor. As the slope of the floor becomes progressively higher, production becomes more difficult and may become impossible to continue. A typical blast in frozen ore resulted in the production of large blocks, many of which could not be handled by shovels or removed (Ives, 1963; Lang, 1966).

It was suggested that these problems could be solved by using secondary blasting (Ives, 1963; Lang, 1966). This required more explosives and increased the cost of mining. Large blocks of frozen ore were also broken by mechanical percussion. In some cases natural thawing, which converted the frozen boulders of ore into unfrozen masses of "soil", was used to achieve a solution (Ives, 1963; Lang, 1966).

About half of Canada is within permafrost "zones", as shown in Figure 1. The future development of the mining industry and of mineral resources in the north will be affected by the conditions caused by permafrost. Although the occurrence of permafrost in northern latitudes has been known since 1642 (Tsytovich, 1963), it has only received serious attention during the past twenty years. At present, our knowledge of the properties of permafrost is very incomplete. This is particularly true of the properties of frozen ores from mining districts.

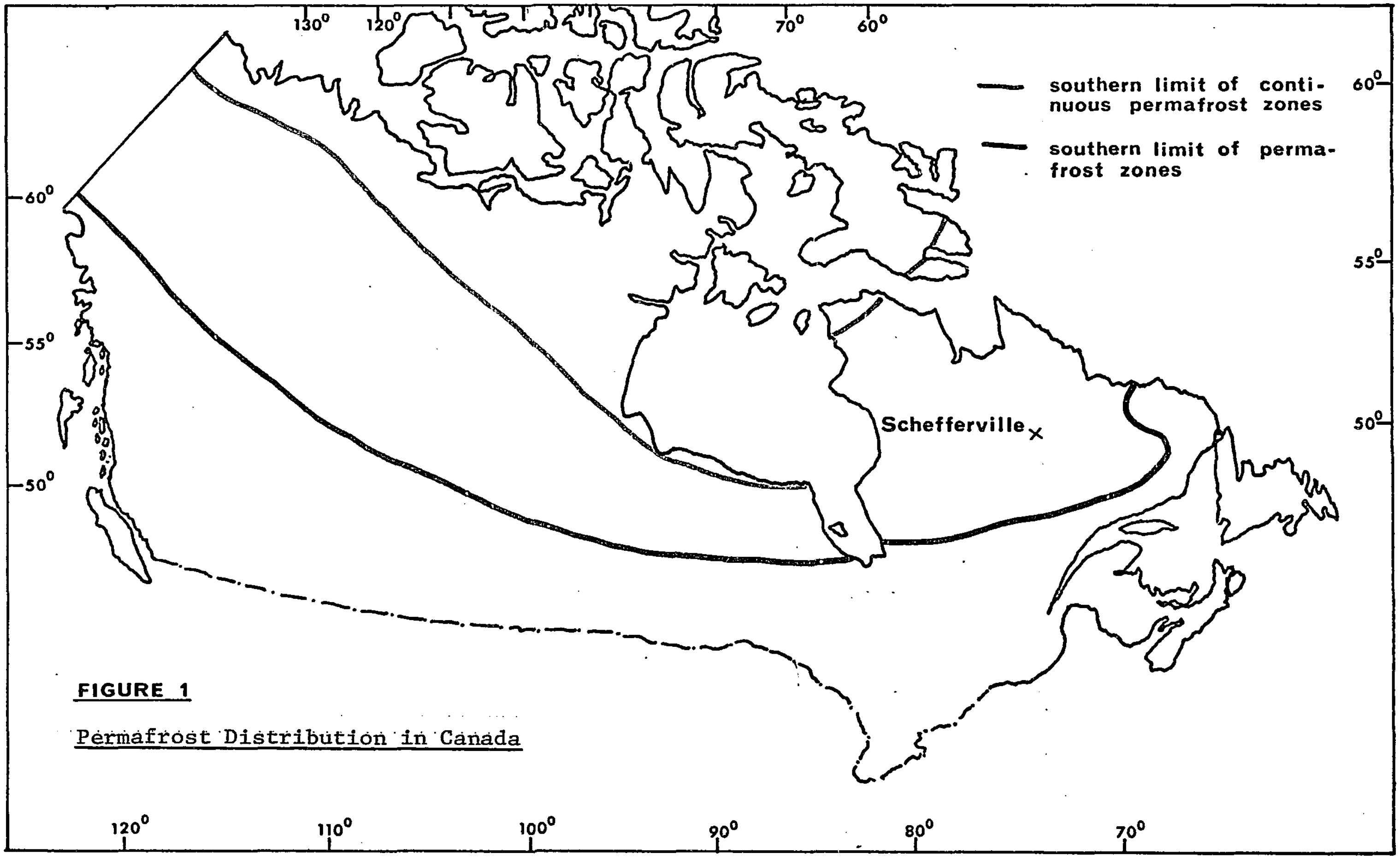



**FIGURE 1**

Permafrost Distribution in Canada

Mining practices must be modified in order to be suited to the significant changes in the properties of the ores which result from thawing. As temperature is increased the stability of slopes in frozen materials will be greatly affected by changing thermal and strength conditions. Bakakin (1959) has stated, as the result of his experience in Russia, that it is from 10 to 15 times more difficult to mine frozen surface deposits than it is to extract ores from thawed ground. The difficulties are associated with the mechanical properties, the compositions, the water contents and the temperatures of the materials. Because of these factors, such operations are much more expensive than those conducted under normal conditions.

Since it is reasonable to assume that the properties of a frozen ore will change appreciably during thawing, the writer has investigated some of the changes which took place as temperatures were increased to exceed the freezing point. The approach used may have been original since natural samples of frozen ores, shipped under controlled conditions, were tested.

The present investigation is a starting point for future research. In this study some of the properties of five types of frozen geological materials were determined. These were: the strengths in compression and in shear; thermal conductivities; resistivities; and the velocities of sonic waves. Measurements of these for each of the rock types at several temperatures between 28° and 36°F were made.

It is hoped that these values will aid in the design of pit slopes and that some application to improved fragmentation may be found. The reduction of mining costs is an objective at any mining operation and perhaps the results presented herein will be useful to that end. At some later stage an attempt to correlate the experimental data with in-situ results should be made. A successful study in this regard would result in more reliable techniques of interpretation in the field.

## 1.2 A Review of Previous Work

At the beginning of this thesis it was noted that there appeared to be little information concerning the properties of rocks or ores in the frozen state. The Russians have made the greatest contribution in terms of the number of research projects and in publications on permafrost (Black, 1954). Unfortunately, most of the references from the Russian literature which have been translated have described research with frozen soils ("frozen dispersed rock") rather than with rocks of the type which are studied in the field of rock mechanics. These latter materials are referred to in some Russian papers as "frozen bedrock" (Mellor, 1970).

A great many studies have been made concerning the properties of frozen soils, and of ice and snow, in connection with problems related to construction in the north. To the writer's knowledge, the engineering properties of frozen ores and the relationships between them and the development of open-pit mines in the north, have not yet been studied.

In the previous investigations to which the writer refers, artificially manufactured samples were tested. Mantis (1951) reported some of the properties of ice and snow. He mentioned that many investigators had conducted the experiments and that his work was an effort to collect the data available. Khomichevskaya (1940) measured the compressive strengths of samples of a frozen artificial silt loam, some frozen soils, and ice. Brodskaia (1962) presented strength values of frozen soils which resulted from tests performed in the temperature range of -0.3°C to -20°C. Mellor and Smith (1966) carried out a series of compression tests in which artificial samples of snow and ice were tested at temperatures in the range of 0°C to -50°C. William and Becich (1968) studied the direct shear properties of a frozen saturated Ottawa sand. Strength tests on three kinds of rocks in the temperature range of 23°C to -195°C were performed by Mellor (1971), who observed that the strengths of the rocks varied significantly according to the environmental conditions. MacFarlane (1970) carried out a series of unconfined compression tests on frozen samples of peat with very high water contents. The temperatures at which the tests were performed were -9.5°C and -15.5°C. As a result of this study he concluded that the ultimate compressive strengths of the frozen samples were of the order of 350 to 400 times as great as those of the unfrozen samples. He also indicated that many variables were involved in the strength properties of ice and frozen soils and that, because of the elements of doubt which were involved, the results might best be used for rough comparisons.

Penner (1970) measured the thermal conductivities of two kinds of frozen soils over a temperature range which extended from 0°C to -22°C. The transient heat flow method which was used was not successful in the region between 0°C and -2°C. Scott (1964) studied the values of thermal conductivities of frozen soils which might be used in computations and gave particular attention to the values for temperatures near 0°C. Mellor (1971) has stated that the thermal conductivities of rocks at temperatures below the freezing point has not yet been studied.

According to Scott (1969), very little work has been done on the electrical properties of frozen soils and frozen rocks. Scott has made a brief mention of the resistivity values for a few frozen and unfrozen geological materials. Joesting (1945) gave some typical resistivity values for thawed and frozen ground from results which were obtained in Alaska. Barnes (1963) noted the contrast in resistivity values between those for frozen and unfrozen rocks and stressed that small variations in temperature, lithology and vegetation could cause large variations in resistivity. Parkhomenko (1967), a Russian scientist, published a book in which he described the electrical resistivities of rocks and in which he presented data for various rock types and ores. He revealed that the studies of rock resistivities at very low temperatures had been undertaken by a relatively small group of investigators in Russia. Unfortunately, the references which he cited were (in Russian) not available to this writer. For the experiments reported in this thesis the writer has used a method, described by Doborzyński (1971), for measuring the resistivities of rocks. A detailed description of the technique will be found in another section of this thesis.

The properties of rocks, as related to the passage of seismic waves through frozen materials, have not yet been extensively studied. Several investigators have measured the elastic properties of ice, snow, and frozen soils (Northwood, 1947; Smith, 1965; Kaplar, 1967) using laboratory techniques. Pihläinen (1963) reported some field data concerning the velocities of longitudinal waves in permafrost areas. He compared the velocities in thawed and frozen organic materials and established the fact that these are different. A summary of the data for compressional (longitudinal) wave velocities obtained in permafrost regions during a 25 year period was compiled by Barnes (1963), who suggested that seismic velocity surveys could be used to delineate permafrost bodies. This would be made possible by the large differences in velocities between those noted for frozen and unfrozen grounds. Timur (1968) studied the velocities of compressional sonic waves in various consolidated, porous rocks at test temperatures which were varied from 26°C to -36°C. He pointed out that the wave velocity in a rock with a very low moisture content was almost independent of temperature. There was, however, a significant increase in wave velocity when a water-saturated rock was frozen.

In conclusion, the writer believes that information relating to the engineering properties of frozen ores and rocks is very limited. Very few studies have been done which relate to the physical properties of natural permafrost.

# II. GEOLOGY OF THE TIMMINS MINE AREA

## 2.1 Location and Climate

The area in which the Timmins Mine has been developed is situated near Schefferville, Quebec, about 700 miles northeast of Montreal. (Figure 2).

The mine area is accessible by road and rail from Schefferville. Transportation facilities in the region have been developed by the Iron Ore Company of Canada and by the Quebec North Shore and Labrador Railway Company (which is a subsidiary).

The climate in this area, which is located within the southern boundary of the discontinuous permafrost belt, is described as sub-arctic. The mean annual air temperature at Schefferville is 24°F (Ives, 1963). The entire region is abnormally cold in terms of latitude. This is due to its high elevation, the persistent coolness of nearby seas, the high proportion of bare rock and, particularly, its exposure to radiative cooling (Mayer, 1966).

## 2.2 General Geology

The iron ore deposits of the Quebec-Labrador region occur in a long and narrow band which extends in a southeasterly direction from the western shore of Ungava Bay to the 50th parallel of latitude. It is commonly known as the "Labrador Trough" (Figure 2). This trough consists of a 700-mile long geosynclinal segment of a sedimentary basin which is composed of tightly folded and faulted proterozoic sediments, volcanics and intrusives. It is approximately 55 miles wide in the Schefferville region (Schwellnus, 1957).

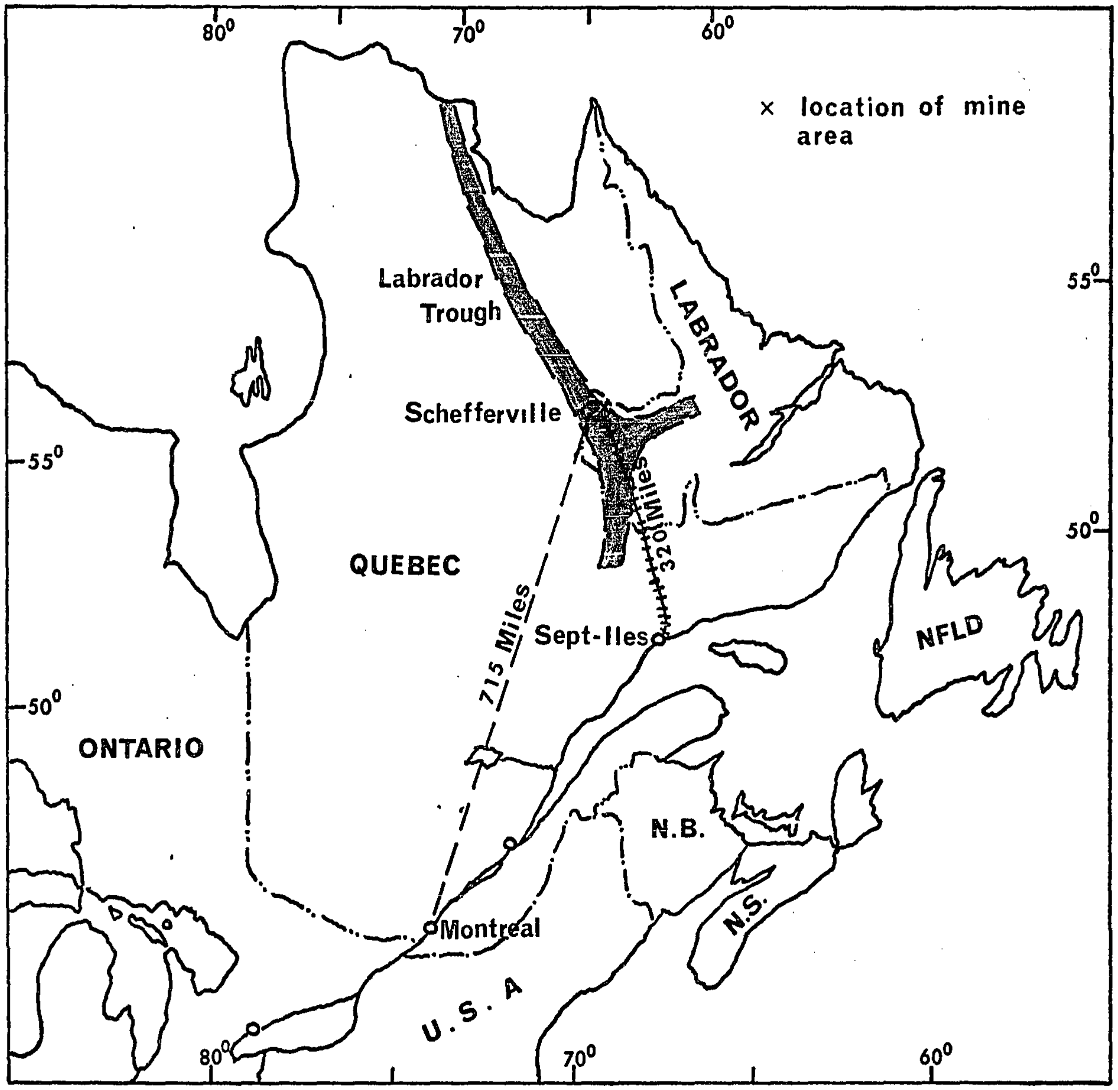



**FIGURE 2**

Location of the Timmins Mine Area

Rocks surrounding the trough consist of a complex of gneisses which have been subsequently intruded by granitic and other intermediate to alkaline intrusives. The sedimentary and metasedimentary rocks of the Trough consist of conglomerates, breccias, quartzites, shales and slates, dolomite and iron formation (I.O.C. Geological Report, 1971).

The rocks of the Trough in the area near Schefferville are grouped together as the Kaniapiskau system, which is divided into four groups based on the lithology, rock associations, distribution and structure. These are: the Doublet-Laporte, Murdoch, Howse and Knob Lake groups. The iron ore deposits (Sokoman Iron Formation) of the region are associated with the latter group (Schwellnus, 1957; Seguin, 1963; I.O.C. Geological Report, 1971).

The Knob Lake group has been further sub-divided (by Dufresne, 1952) into three series: the Point, Ferriman and Hamilton River, as shown in Table 1.

In this study, all of the frozen materials obtained from the Timmins Mine area were associated with three formations:

| | | |
|---|---|---|
| | Sokoman formation: | MIF, LIF and JSP |
| Ferriman Series: | Ruth formation: | Ruth chert |
| | Wishart formation: | Quartzite. |

## 2.3 Description of the Frozen Samples

### 2.3.1 General

Five types of frozen geological materials were chosen by the Iron Ore Company of Canada for the study. These were:

(a) Middle (Metallic) Iron Formation;

(b) Lower Iron Formation;

(c) Ruth chert;

TABLE 1

FORMATIONS OF THE KANIAPISKAU SYSTEM

(KNOB LAKE GROUP)

| SERIES | FORMATION | ROCK TYPE |
|---|---|---|
| Point | Menihek | Calcareous and Carbonaceous Shales |
| | Unconformity? | |
| Ferriman | Sokoman (500'-800') | Cherty and cherty iron bearing sediments |
| | Ruth (0 - 100') | Ferruginous Shales |
| | Wishart (150'-200') | Felspathic Quartzite and some chert at the top |
| Hamilton River | Fleming (0 - 400') | Chert Breccia |
| | Denault (0 - 400') | Dolomite |
| | Attikamagen (1000') | Carbonaceous and Calcareous Shales |
| | Unconformity | |
| | Basement complex of Granites and Gneisses | |

(after Schwellnus, 1957)

(d) Jaspillite;

(e) Quartzite.

Samples sufficiently large to be useful for testing were selected after blasting of the working face at the Timmins Mine. Each sample chosen was placed in a plastic bag in order to prevent the sublimation of contained ice. Four or five of these samples (depending on size) were then inserted into an insulated ice chest with approximate internal dimensions of 22" x 11" x 11" (Figure 3). Additional protection was achieved by surrounding the samples with ice packs and foam. A small thermometer was placed in each ice chest. This enabled the writer to assess if the samples were damaged by thawing during shipment. As a final precaution, tape and rope were used to secure the lids of the chests.

The ice chests were then shipped by air freight from Schefferville to Dorval airport, Montreal. They were received by the writer as quickly as possible and transported immediately to the cold room laboratory. This involved a drive of approximately fifty miles.

For all of the shipments, the thermometers in the ice chests indicated temperatures in the range of 28° to 30°F. It was assumed, therefore, that no damage to the frozen samples had taken place during shipment.

The ice packs and foam were then removed from the chests and the chests allowed to remain open until the samples had become acclimatized to the controlled conditions in the cold room (28°F). Samples were then prepared to the dimensions required for testing.

The Iron Ore Company of Canada provided a total of 16 large samples. From these, the writer selected, depending on shape, those which would be the most suitable for the tests to be performed. Additional details are given in the sections of this thesis in which the test results are presented.

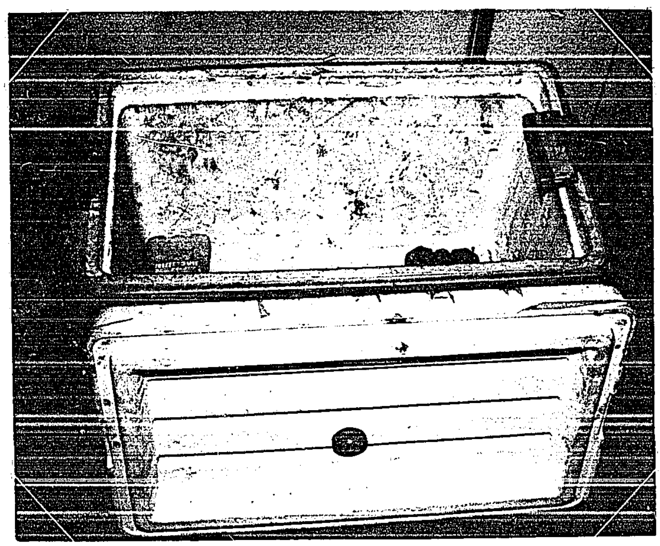


Figure 3

Insulated Ice Chest

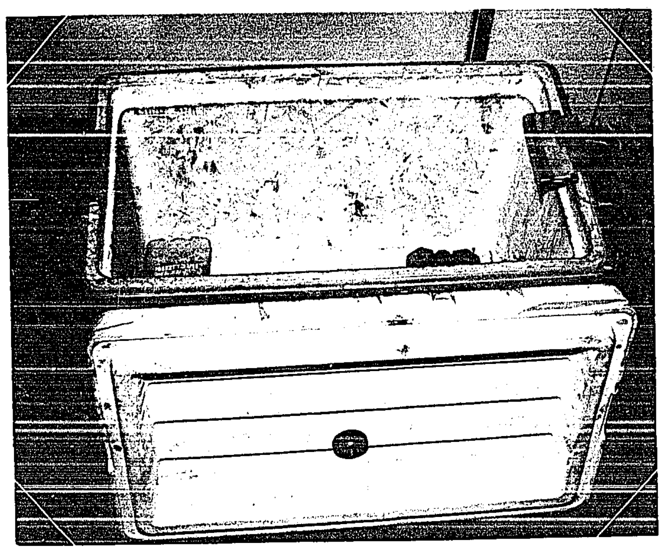


Figure 3

Insulated Ice Chest

### 2.3.2 M.I.F. (Metallic) (Middle Iron Formation)

This is a silica-iron oxide ore, which was readily recognized by the metallic lustre caused by the high original iron content, primarily in the form of blue hematite (Figure 4). The colour varied from a dull purplish-red to a bluish-black. The reddish colour was characteristic of decomposed chert while the bluish-black was characteristic of hematite and magnetite.

This type of ore was porous and had a medium-grained sandy appearance at temperatures above the freezing point. The rock grains were bonded together by interstitialed ice particles which could not be seen without magnification. Small lenses of ice on the surface of the material were observed.

### 2.3.3 L.I.F. (Lower Iron Formation)

The yellow Lower Iron Formation (which exhibited a wide range of colour variations - yellow, yellowish-green, brownish-yellow to reddish-orange) was composed mainly of blue hematite, yellow chert and some goetite and magnetite. As indicated by the variations in colour, there was a strong variability in the composition of the material (Figure 5).

### 2.3.4 Ruth Chert (Ruth Formation)

The Ruth Formation varied in colour from a dark grey to a brownish black. It consisted of bands of white chert with thin red argillaceous bands and blue hematite. Occasional bands of red chert were a characteristic of the formation. (Figure 5).

The rock was distinctly ferruginous and contained iron oxides, iron silicates and a variable, but substantial, percentage of organic carbon (I.O.C. Geological Report, 1971).

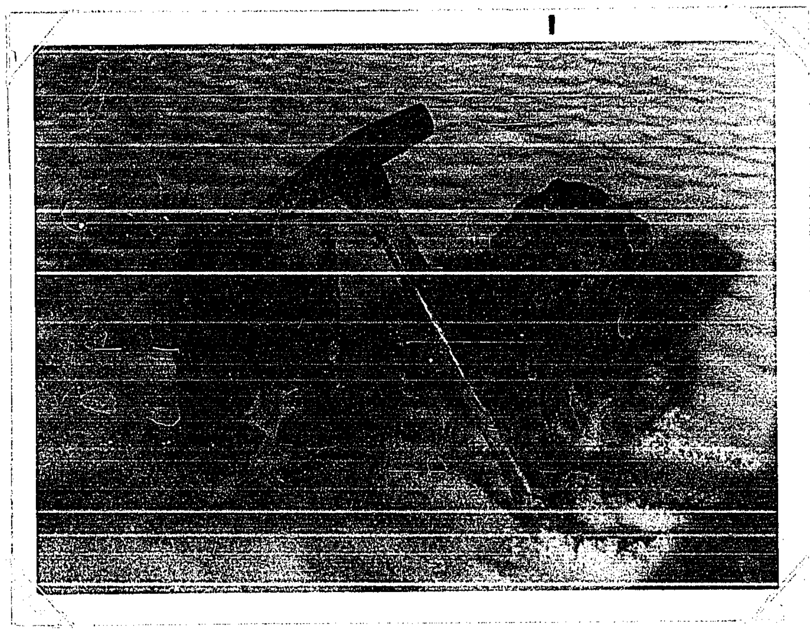


Figure 4

Samples of Middle Iron Formation

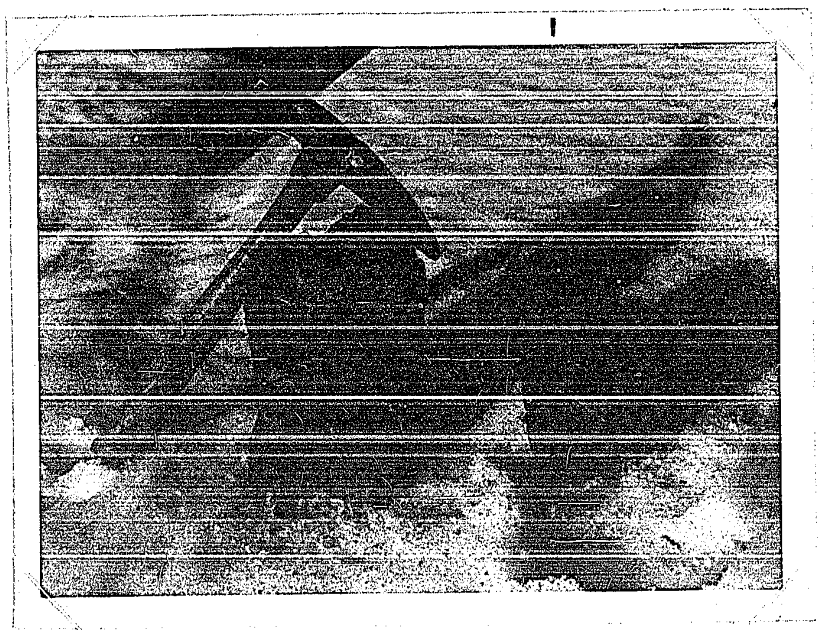


Figure 5

Samples of Lower Iron Formation (left)
and Ruth Chert (right)

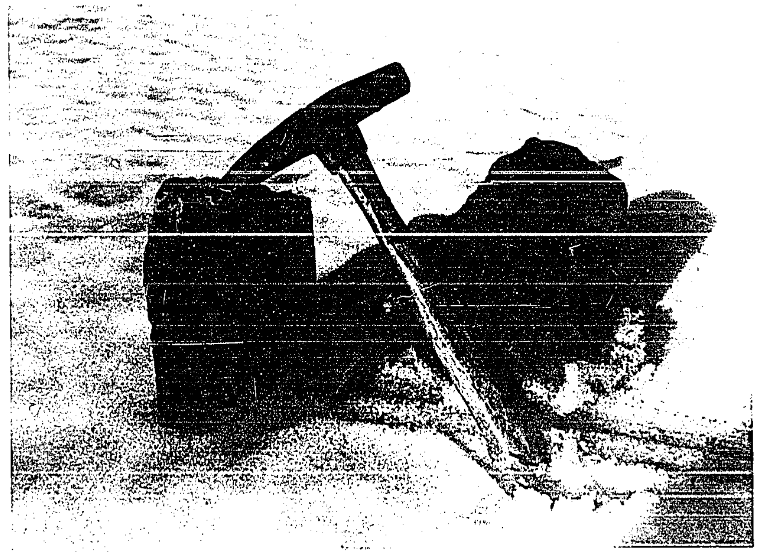


Figure 4

Samples of Middle Iron Formation

Figure 5

Samples of Lower Iron Formation (left)
and Ruth Chert (right)

### 2.3.5 Jaspilite

This was a fairly hard rock, which consisted of alternating jasper, chert and blue hematite bands (Figure 6). Due to leaching, it was less consolidated than the Ruth Chert. The rock contained inclusions of blue hematite embedded in the matrix. It was a vari-coloured ore and, as in the case for L.I.F., exhibited wide variations in composition. The writer was advised that, while there are variations on a small scale, the rock unit as a whole is relatively uniform (F. H. Nicholson, personal communication).

### 2.3.6 Quartzite (Wishart Formation)

The Wishart Formation quartzite was a light brownish-orange, hard and medium- to coarse-grained orthoquartzite (Figure 7). It was composed of rounded pure quartz grains cemented by variable proportions of pink to purple feldspar grains and chert.

Figure 6

Sample of Jaspillite

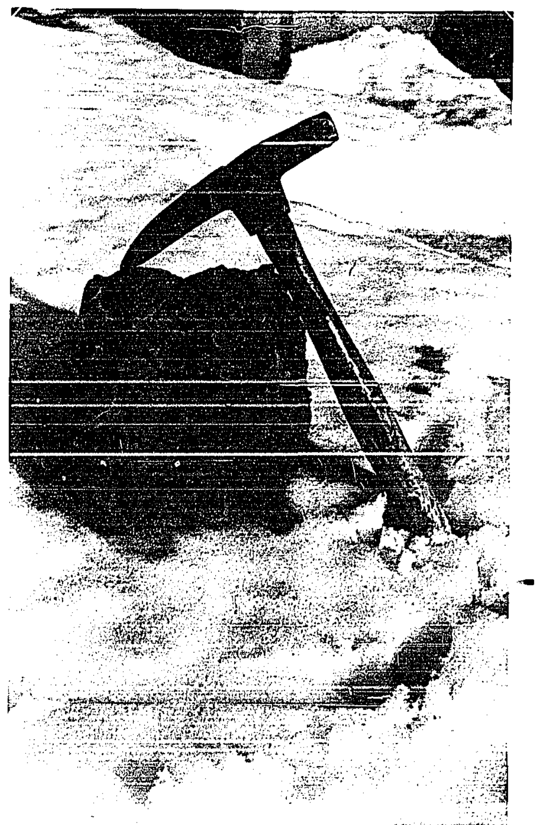


Figure 6

Sample of Jaspillite

Figure 7

Sample of Quartzite

Figure 7

Sample of Quartzite

# III. DESCRIPTION OF THE COLD ROOM AND APPARATUS

## 3.1 The Cold Room

The cold room laboratory,which was completed in August 1969 and which has been in operation since May 1971, is located at the Institute for Mineral Industry Research at Mont St-Hilaire, about 26 miles from Montreal, Quebec.

The laboratory, as shown in Figure 8, consists of a main cold room in which the experiments were carried out, an ante-room which contained storage space and a freezer, and a refrigeration plant. The layout of the cold room laboratory is shown in Figure 9.

The main cold room, which is essentially a walk-in refrigerator, has internal dimensions of 10' 8" x 10' x 9' high. The interior is finished with eight separate panels, made of zinc coated steel sheets with white baked enamel surfaces. The three exterior walls are insulated with eight inches of Urethane. The fourth wall, which is an interior wall separating the working area from the refrigeration unit, is insulated with four inches of Urethane. The floor of the room is composed of five layers of materials. In order, from top to bottom, these are: 3/4 inch layer of plywood; 1/4 inch steel plate; 18 gauge galvanized sheet metal; 8 inches of Urethane insulation; and 18 gauge galvanized sheet metal. Illumination is provided by two vapor-proof interior light fixtures.

The ante-room, with internal dimensions of 6' 5" x 7' 9" x 9' high, provides access to the main room. It is insulated with three inches of Urethane.

The compressors located outside of the cold room furnish Freon R-12 refrigerant to an evaporator installed in a small compartment behind

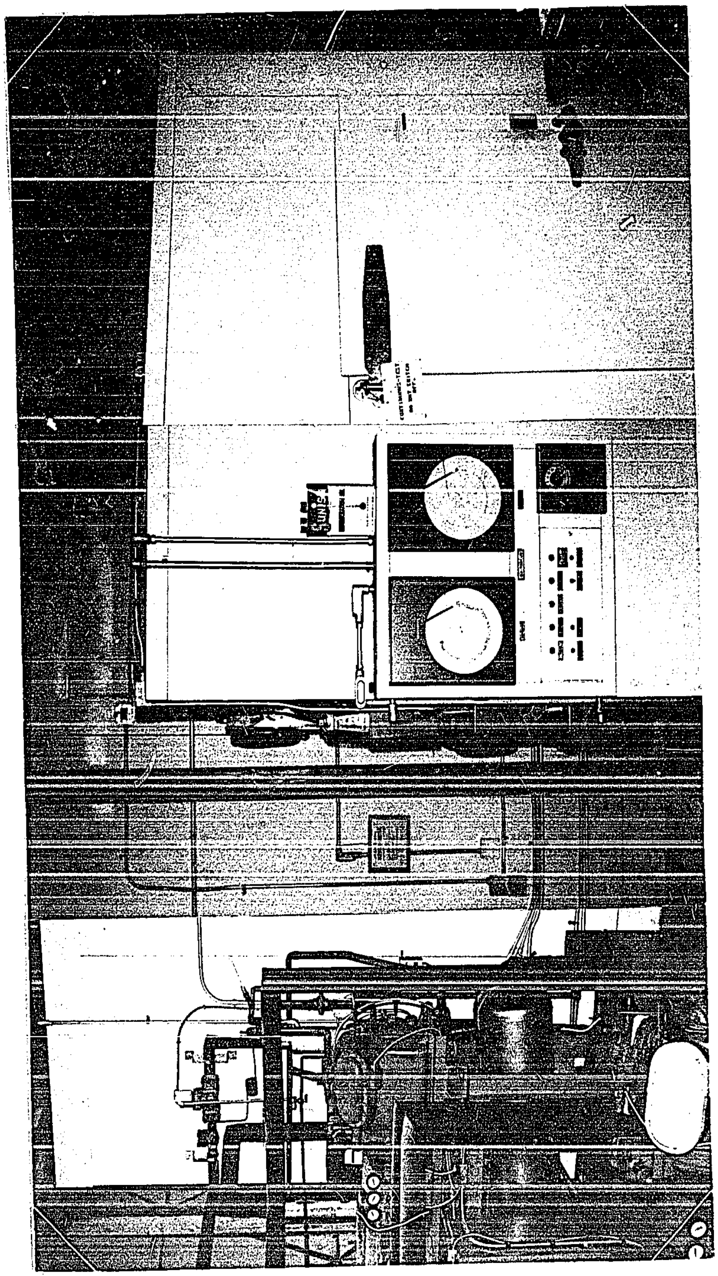


Figure 8

General View of the Cold Room Laboratory

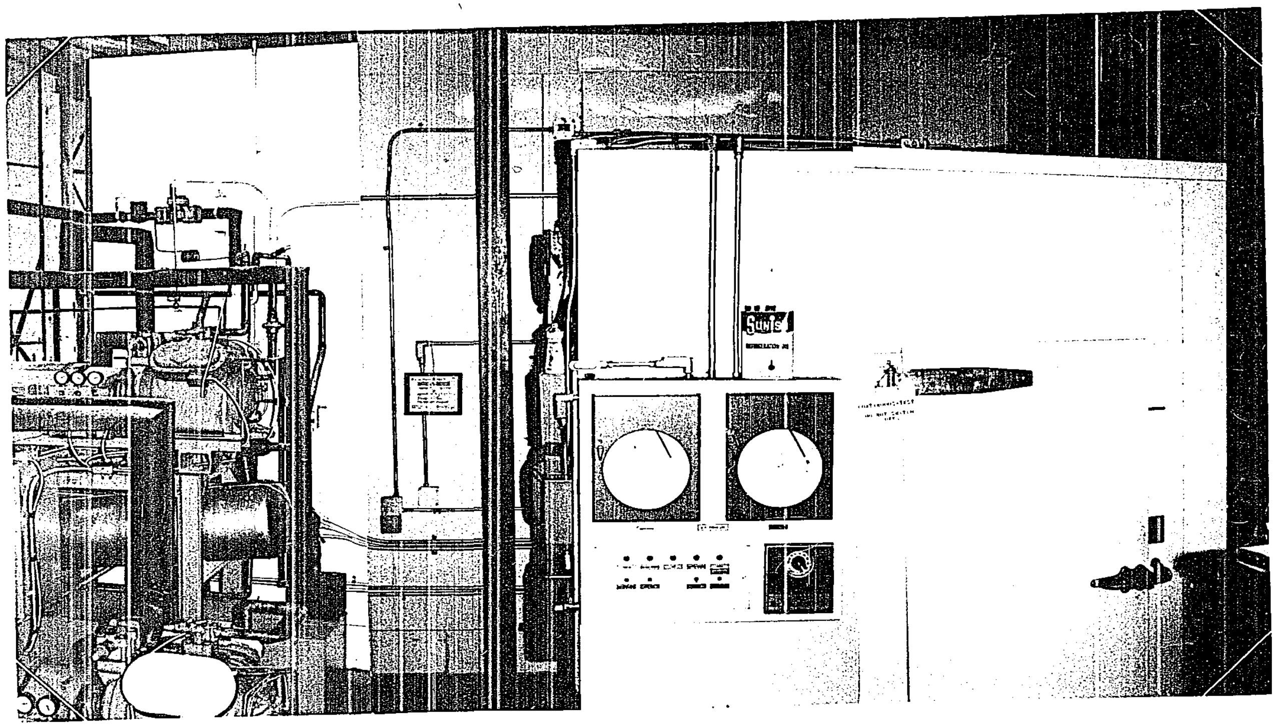


Figure 8

General View of the Cold Room Laboratory

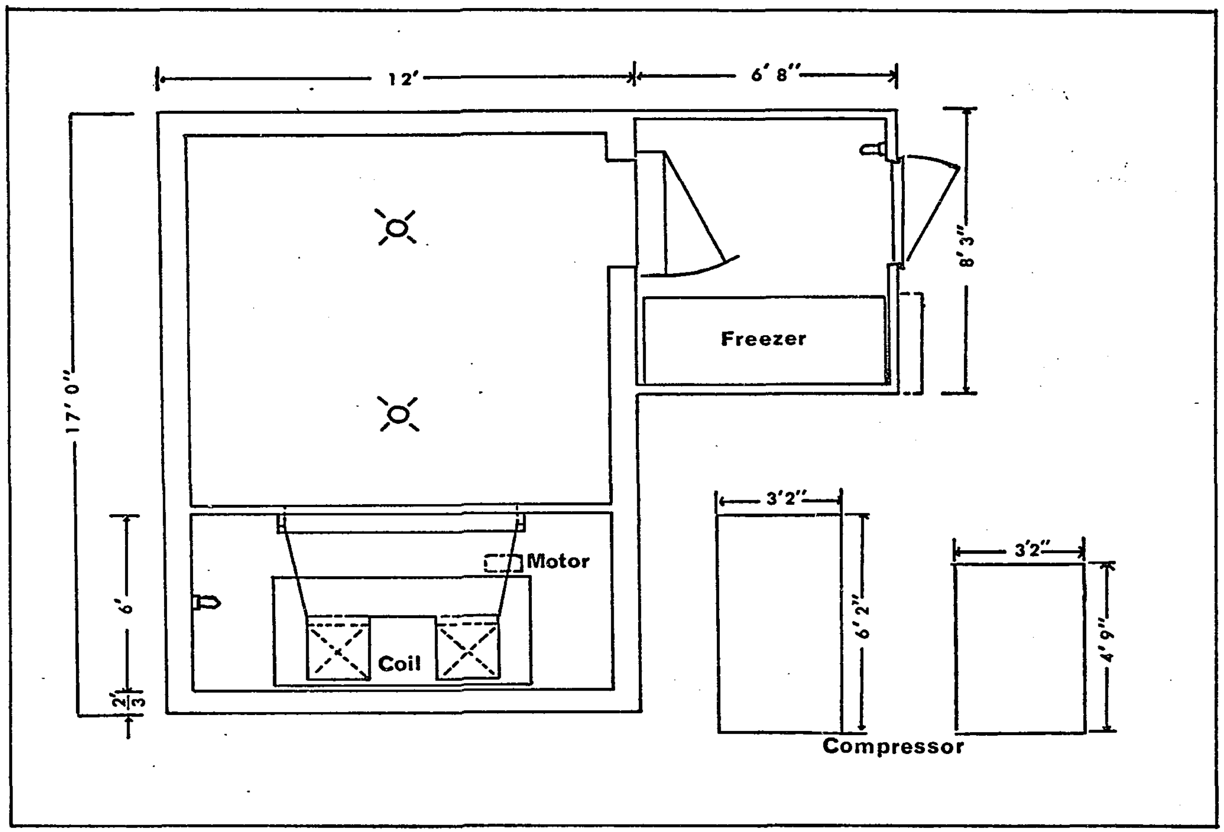



**FIGURE 9**

Lay-out of the Cold Room Laboratory

the interior wall of the cold room. The exterior walls of this compartment are insulated to the same specifications as the testing area. The evaporator acts as a cooling system and supplies cooled air through the perforated ceiling of the test area. Air is circulated in a closed circuit using fans and ducting.

Control of room temperature is achieved with a Minneapolis-Honeywell resistance thermometer controller with a range from -150°F to +300°F. In practice, temperature is controlled within the range of -50°F to +40°F (with an accuracy of ±1°F). Two Servoline recorders are used to record the temperature and humidity in the chamber.

## 3.2 Apparatus

### 3.2.1 Resistivity Tests

The apparatus employed consisted of a hand-operated hydraulic press (capacity - 6000 lbs), two malleable lead plates (which acted as conductive material) and a sensitive Universal resistance bridge with a range of from 0.01 Ω to 10.45 MΩ. The apparatus is shown in Figure 10.

The softness of the lead plates was such that, under load, these deformed to conform with any irregularities on the surfaces of the specimens. The lead plates with the specimen between were restrained by 1/4" thickness plexi-glass sheets mounted on wooden blocks. The plexi-glass acted as an insulator and prevented interference due to other conductive materials.

### 3.2.2 Thermal Conductivity Tests

The apparatus used is shown in Figure 11. It consisted of three copper discs held by a wooden frame. These discs separated the specimen and the heating coil from the frame. The temperature of each disc was measured with a thermometer with a range from -5°C to 105°C in 0.1°C divisions. A controllable voltage source provided a constant voltage of 6 volts. Current was adjusted using a variable resistance with a capacity of 20 Ω. A voltmeter and an ammeter completed the equipment required.

### 3.2.3 Compression Tests

A 200,000 lb. capacity hydraulic compression machine, equipped with a load cell to permit accurate determinations of applied loads, was used for most of the tests at 28° and 31°F (see Figure 12).

A smaller compression machine, used for determining the unconfined compressive strength of soils, was used for the uniaxial compression tests carried out at 33° and 36°F (see Figure 13). This testing machine was equipped with an electric drive which could be adjusted to provide a constant strain rate.

### 3.2.4 Shear Tests

The apparatus used for shear testing was a standard testing machine of the type normally used to determine the shear strength of soils. The machine was driven electrically and, similar to the compression machine, could be adjusted to produce a constant rate of shearing stress. Force was detected by a calibrated proving ring (Figure 14).

The rate of stress required was achieved by adjusting a variable-speed drive connected to a motor and to the shearing box.

### 3.2.5 Sonic Tests

The testing apparatus is shown in Figure 16. It consisted of a sonometer, a driver and a pick-up assembly. A diagram of the circuitry is shown in Figure 17.

The driving circuit included a variable oscillator which provided the range of audio frequencies required to perform the sonic test and an amplifier which supplied power to energize the driving transducer. The electrical output of the amplifier was converted to mechanical vibration by the driver. The vibrations transmitted by the driver to the specimen were of the same frequency as the oscillator output.

The pick-up circuit was made up of a pick-up assembly, an amplifier, an oscilloscope and an ammeter. The sound vibrations transmitted through the specimen were detected by a needle in the pick-up assembly.

The needle was in contact with the specimen. The ammeter and the oscilloscope were used to determine the resonant frequency and the mode of resonance of the specimen.

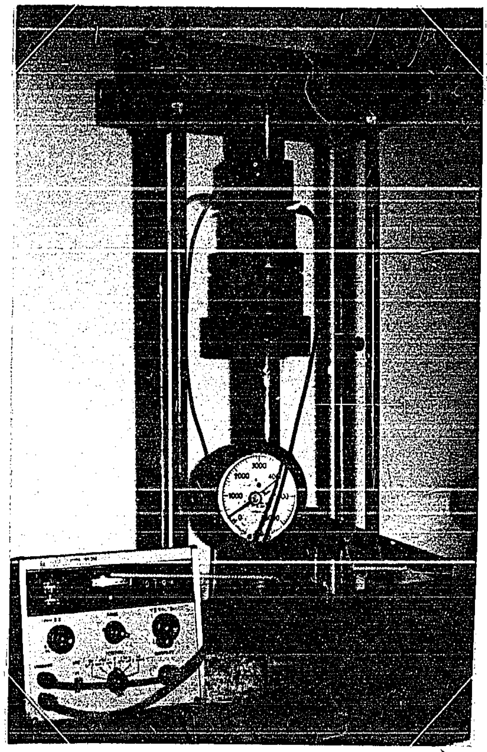


Figure 10

Apparatus for the Resistivity Tests

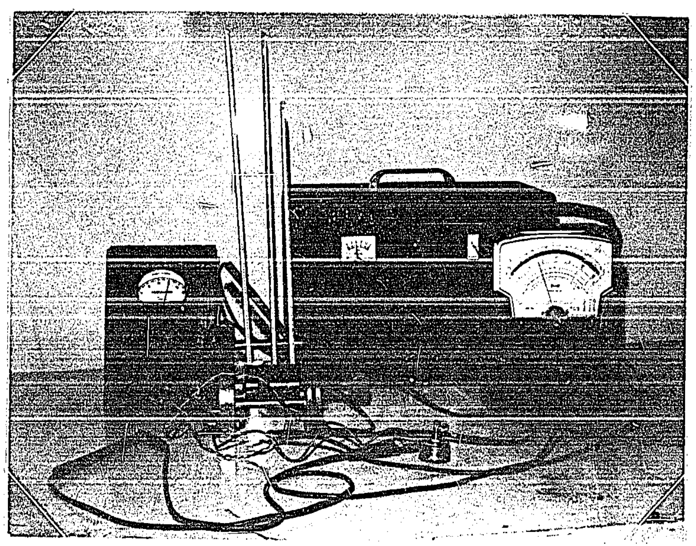


Figure 11

Apparatus for the Thermal Conductivity Tests

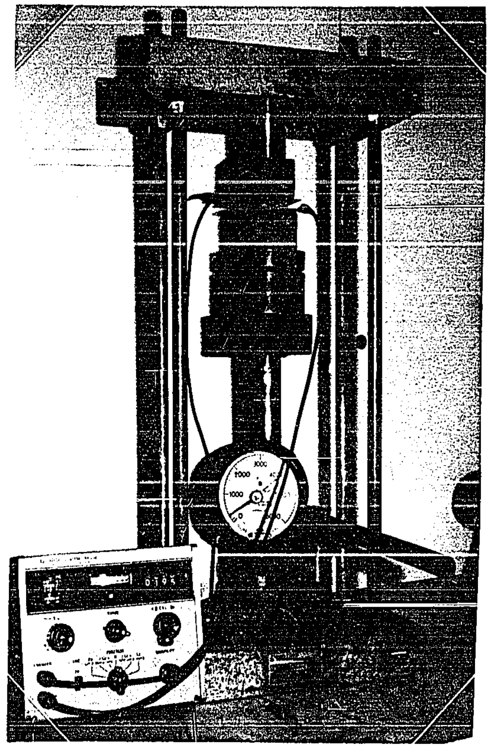


Figure 10

Apparatus for the Resistivity Tests

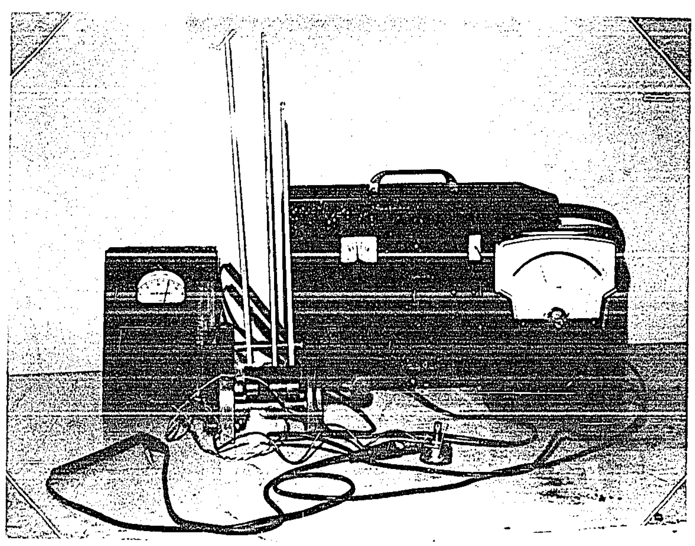


Figure 11

Apparatus for the Thermal Conductivity Tests

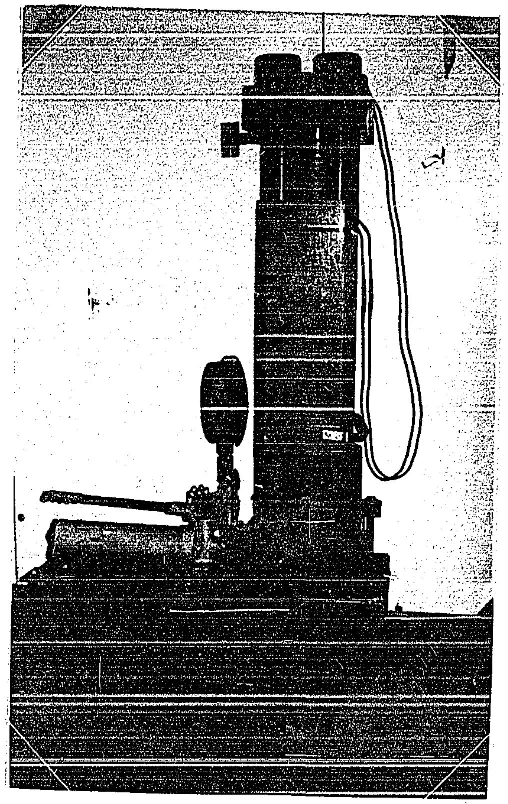


Figure 12

Hydraulic Compression Machine

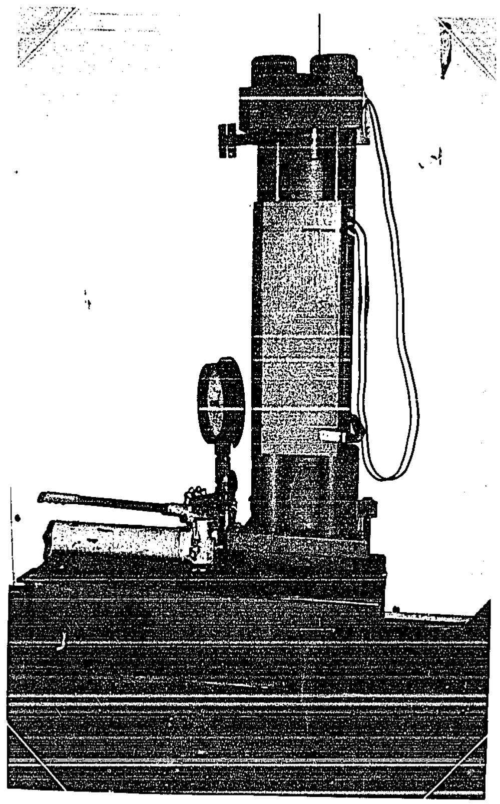


Figure 12

Hydraulic Compression Machine

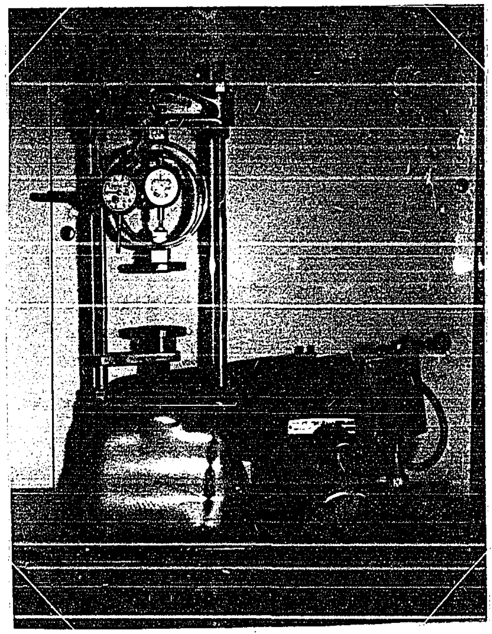


Figure 13

Soiltest Uniaxial Unconfined Compression Machine

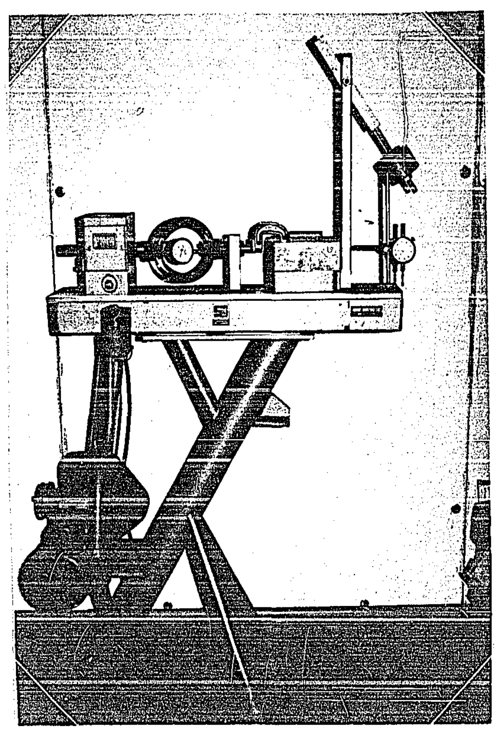


Figure 14

Direct Shear Testing Machine

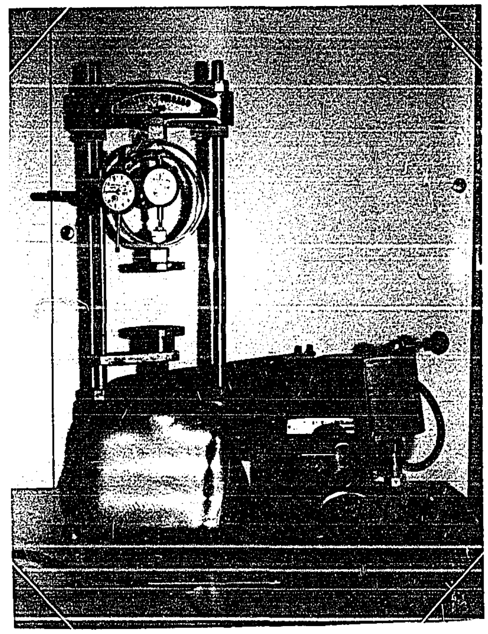


Figure 13

Soiltest Uniaxial Unconfined Compression Machine

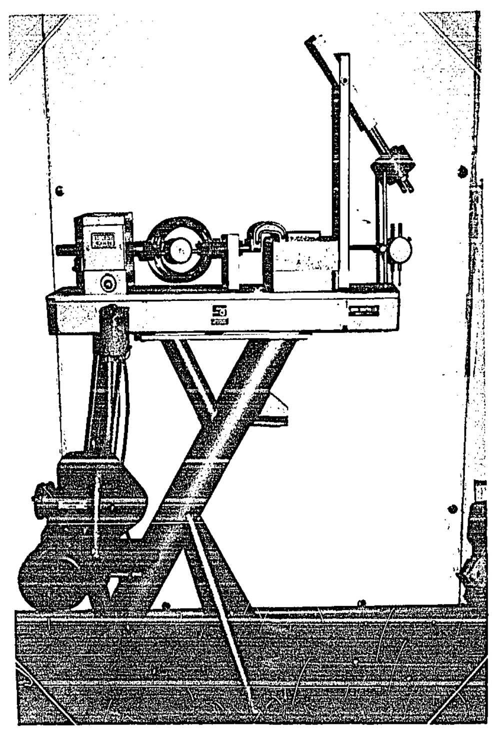


Figure 14

Direct Shear Testing Machine

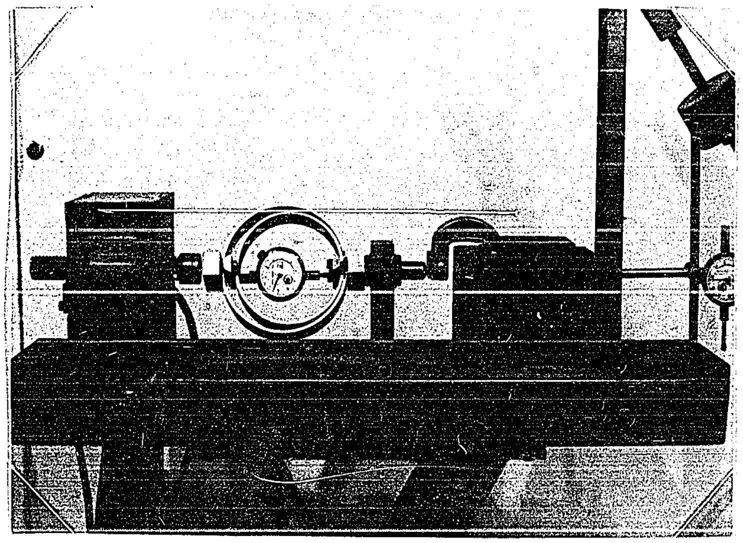


Figure 15

Close-up of Shear Testing Machine

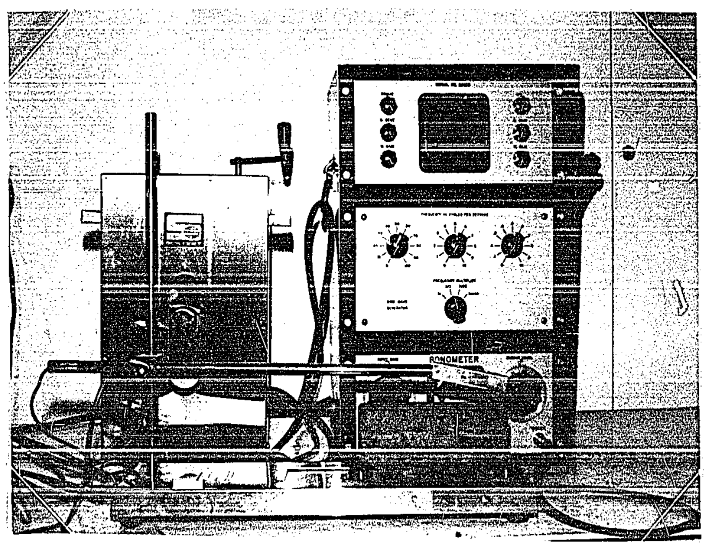


Figure 16

Apparatus for the Sonic Tests

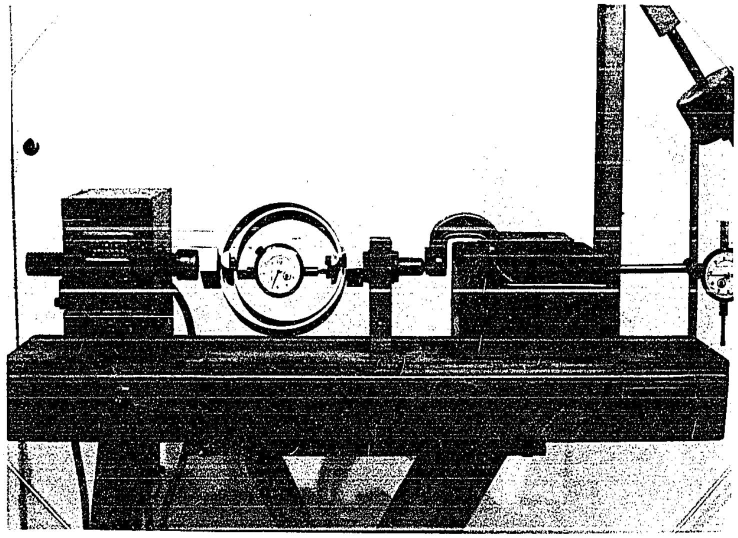


Figure 15

Close-up of Shear Testing Machine

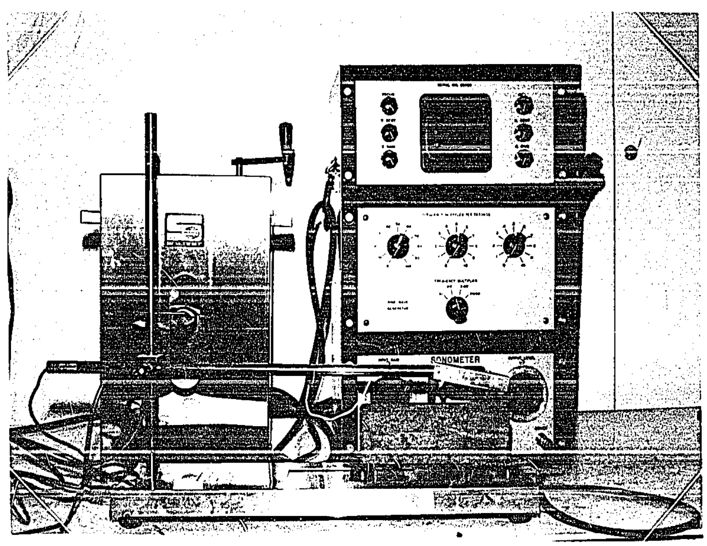


Figure 16

Apparatus for the Sonic Tests

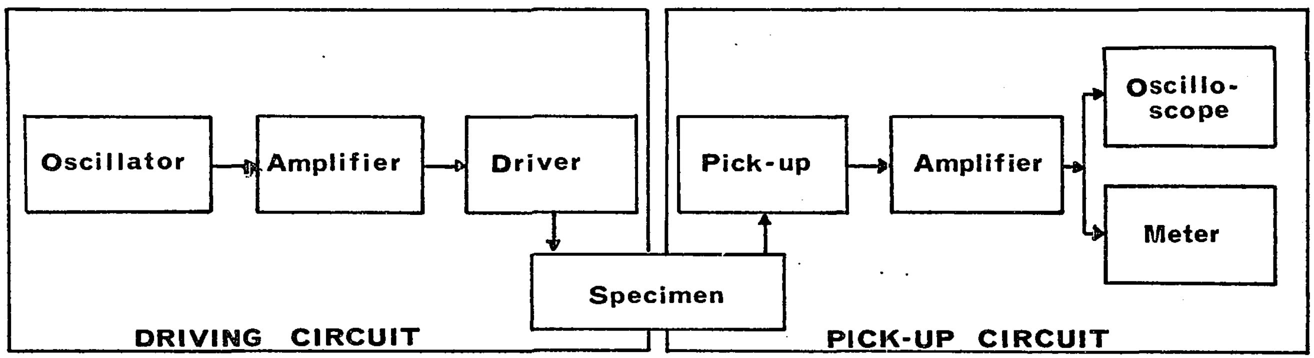



**FIGURE 17**

Circuit Diagram - Sonic Apparatus

# IV. SELECTION AND PREPARATION OF THE SPECIMENS

## 4.1 General

All the specimens used in the experiments were cut with a tile saw at 28°F. Felker abrasive blades with low temperature air as a coolant were used. The cutting machine with a blade and the dust cover in place is shown in Figure 18.

Extreme care must be taken when cutting samples to prevent disturbances of the natural structures and water contents. This is especially critical when the water content exceeds 10%. The Middle Iron Formation samples tested in this study presented the most difficulties in this regard.

After the rock samples were cut to the different shapes and dimensions which were required for the various tests, they were stored under controlled conditions at 28°F in a small freezer near the cold room. The first group of specimens, which was to be tested at 28°F, however, was stored in the cold room since an adjustment to a different temperature was not required and since the specimens were to be tested immediately. All the specimens in storage, including those to be tested at the earliest moment, were covered with plastic bags to prevent the sublimation of ice and water during the conditioning process. As mentioned, the first tests were conducted at 28°F. After these were completed, the temperature in the cold room was raised to 30°F and a new series of specimens taken from the small freezer which was used for storage. These specimens were kept in the plastic bags until they had been conditioned at 30°F for two days. Specimens for subsequent testing at 31°, 32°, 33° and 36°F were handled and conditioned using the same procedures.


Figure 18

Felker Tile Saw with Abrasive Blade and Dust Cover

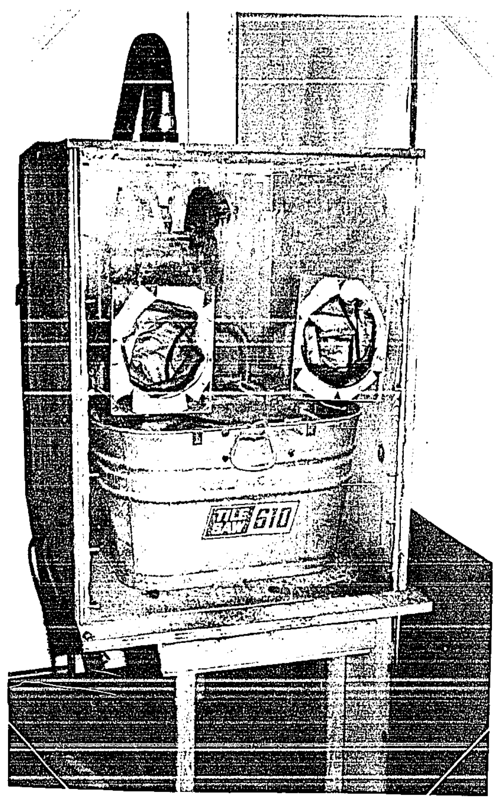



Figure 18

Felker Tile Saw with Abrasive Blade and Dust Cover

## 4.2 Resistivity Tests

The specimens to be tested were cut to the shape of a wafer about 1 cm. in thickness. The end surfaces were in the shape of a square, with the length of each side being about 4.5 cm. As a first step, the sample from the mine was cut vertically to produce a rectangular block for which the cross-sectional dimensions were about 5 cm. The vertical cuts were normal to the bedding planes. The height of the rectangular block produced depended on the height of the raw sample obtained from the field. This block was then cut into slices parallel to the bedding planes. Each slice was about 1.5 cm thick. Slices with ice lenses were discarded (only specimens in the M.I.F. group had noticeable ice lenses). Finally, all specimens were trimmed to the required final dimensions. Care was taken to ensure that the faces of the specimens were as flat and as parallel to each other as possible. Had this not been done, the results would have been influenced by poor contacts between the specimens and the lead plates. After trimming, the specimens were either stored or conditioned in the cold room.

The dimensions of the specimens were measured to an accuracy of 1/100 of an inch, using a vernier caliper. All specimens were classified according to the Iron Ore Company's criteria for ore identification.

## 4.3 Thermal Conductivity Tests

Specimens to be tested by this electrical method should be prepared to the shape of thin discs having the same diameters as those of the copper discs which act as heat conductors. It was difficult to achieve this in practice, however, since the frozen materials failed when attempts were made to cut cylindrically-shaped specimens by coring.

The initial steps in the preparation of specimens were similar to those used for preparing specimens for the resistivity test. The writer attempted to trim the specimens into the shape of discs by making successive cuts on the edges of the slices of frozen materials. A template with the same diameter as that required for the finished specimens was made from a piece of rock core. Using this as a guide, the slices of frozen material were trimmed to the same dimensions. In the writer's opinion, satisfactory nearly-circular specimens were obtained. The average diameter and thickness of the discs prepared in this way were 4.12 cm. and 1 cm., respectively.

The diameter and the thickness of the specimens were measured within an accuracy of 1/100 of an inch.

### 4.4 Compression Tests

The specimens for static compression testing were prepared to a length/width ratio of approximately 2.2-2.4 : 1. The specimens were square in cross-section and of rectangular shape. As mentioned, cylindrical specimens could not be prepared by coring. The end surfaces of specimens were not machined due to the lack of suitable grinding equipment. In order to avoid eccentric loading, which would result in erroneous data, the end surfaces of the specimens were cut and trimmed to be as parallel as possible. Specimens which were seen to contain ice lenses and inclusions of ice and rock on the surfaces were discarded.

After preparation, the length and cross-sectional dimensions of specimens were measured within an accuracy of 1/1000 of an inch, using a vernier caliper.

## 4.5 Shear Tests

All of the specimens to be tested in direct shear were cut to cubical shape, with dimensions of approximately 1" x 1" x 1". Specimens of this size were tested at temperatures of 28° and 31°F. Specimens tested at 33° and 36°F were cut to dimensions of 2" x 2" x 2". It was necessary for the writer to prepare smaller specimens for the tests conducted at lower temperatures since the capacity of the testing machine was insufficient to allow testing of 2 inch cubes at 28° and 31°F. Quartzite was an exception and all specimens were cut to the shape of 1 inch cubes. The specimens were cut with two opposite faces parallel to observed bedding planes. After specimens had been cut, the dimensions were measured within an accuracy of 1/100 of an inch.

## 4.6 Sonic Tests

Specimens were prepared in the shape of rectangles, with a length/width ratio of approximately 4.5 : 1. The lengths of specimens cut varied from 5.985" to 7.580", however, due to the dimensions and shapes of the ore samples supplied.

The surfaces and ends of the specimens were made smooth by careful trimming with an abrasive blade. Care was taken to ensure that the ends were perpendicular to the longitudinal axis.

After each specimen had been cut, the length and cross-sectional dimensions were measured within an accuracy of 1/1000 of an inch. The weight was determined within an accuracy of 1/10 of a gram. (This value was required for the purposes of calculating density).

# V. TESTING PROCEDURE

## 5.1 Resistivity Test

After the preparation and conditioning of a specimen, it was mounted in the testing frame using the arrangement of lead plates and wooden blocks previously mentioned. Pressure was applied in increments of 500 lbs up to a maximum of 5000 lbs. The resistance of the specimen was measured at each of the loads applied.

The tests were performed at temperatures of 28°, 30°, 31°, 32°, 33° and 36°F. The specimens tested at 33° and 36°F, being unfrozen, were more difficult to mount due to their softness.

After the specimen had been placed in the frame, a small amount of pressure (i.e. 50 lbs) was applied in order to tighten the specimen assembly.

The source of voltage at the universal bridge was connected to the lead plates. The resistance of the specimen was measured by balancing the bridge. In order to avoid polarization of the lead plates as the result of an unvarying testing procedure, the voltage was reversed after each reading. The readings were recorded and averaged at specified intervals.

After the completion of each test, the lead plates were cleaned with sandpaper and rock grains left from the previous specimen removed. The plates were brushed to eliminate polarization.

## 5.2 Thermal Conductivity Test

The specimen and the components of the apparatus were placed in the wooden frame in the following order (see Figure 11): copper disc, specimen, copper disc, heating coil, copper disc. After having arranged the discs so that the thermometers could be inserted, the clamp on the frame was tightened. The thermometers were inserted into each of the three copper discs (Figure 11).

The terminals on the apparatus were connected in parallel with a voltmeter and in series with a controllable voltage source, a variable resistance and an ammeter.

After all connections had been made, the current was allowed to flow until a steady state condition was attained. The readings on the voltmeter, ammeter and thermometers were noted.

## 5.3 Compression Test

### 5.3.1 Testing Procedure at 28°F and 31°F

The testing procedures used at temperatures of 28° and 31°F were as follows:

(a) The specimen was placed in the compression machine and aligned and centred between the platens. In the arrangement used by the writer, the upper platen was fixed to a load cell which was used to monitor load. The lower platen was spherically seated in order to reduce the effects of eccentricities.

(b) A small initial load was applied slowly in order to permit adjustment of the spherically-seated bearing block. A uniform distribution of load was achieved in this way.

(c) A dial indicator, magnetically attached to one of the columns of the testing machine, was used to measure the longitudinal deformation of the specimen.

(d) Compressive load was applied hydraulically at a rate of about 100 psi per second up to the failure of the specimen. Since pressure was applied with a hand-operated pump, some variation in this rate was expected. Every effort was made, however, to achieve a constant rate of loading.

(e) The load applied to the specimens was obtained from a calibrated load cell.

5.3.2 Testing Procedure at 33°F and 36°F

The testing procedures used at 33°F and 36°F were as follows:

The specimens were placed in a standard testing machine which is usually used to determine the unconfined compressive strength of soils. The specimens were in contact with 3-inch diameter steel platens. As a first step, a small load was applied to obtain the best contact between the end surfaces of the specimen and the platens. Compressive load was applied gradually and at a constant rate. Tests were carried out at a strain rate of $3 \times 10^{-4}$ inches per second.

Loads were indicated on a double proving ring assembly with a capacity of 500 lbs and a sensitivity of 0.1 lbs. Readings on the dial were converted into the load applied through a calibration curve supplied by the manufacturer of the testing machine.

Measurements of the longitudinal deformation were read from a dial indicator reading to an accuracy of 0.001" and with a range of up to 1.000". The compressive load applied and the longitudinal strain resulting were recorded at specified intervals.

5.4 Shear Test

Specimens were placed inside the shear box which, as shown in Figure 15, consisted of two parts. Half of the specimen was in contact with each part of the shearing box.

Shearing force was applied by an electric motor drive which caused movement of the upper part of the shearing box at a constant rate.

The shearing force was indicated by a proving ring.

Failure of the specimens was accompanied by a sudden drop in the magnitude of the applied force.

5.5 Sonic Test

5.5.1 General

The transverse and longitudinal resonant frequencies of each specimen were determined using the apparatus described previously. A driver and a pick-up were placed in contact with a specimen which was then driven with sound vibrations of a known frequency. The frequency of induced vibration was varied until a resonant condition was achieved and shown by the indicating devices on the instrument. The resonant frequency was then converted to sonic velocity.

The transverse and longitudinal vibrations measured are dependent on the relative positions of the driver and the pick-up (see Figures 19 and 20).

5.5.2 Determination of Transverse Frequency

The testing procedures are summarized as follows.

(a) The sonometer was turned on and allowed to warm up for at least five minutes before the test.

(b) The supports were adjusted so that they were separated by a distance equal to one-half of the length of the specimen to be tested. The specimen was then placed on the supports so that it was centred. Each support was located at a distance equal to one quarter of the length of the specimen from each end of the specimen. (See Figure 19).

(c) A locking device on the rear of the driver was loosened and the crank rotated until the driver probe was in contact with the centre of the surface of the specimen. A slight amount of pressure was applied.

(d) The needle of the pick-up was placed as close to one end of the specimen as was possible. The needle of the pick-up was parallel to the axis of the specimen.

(e) The initial frequency applied was the lowest that could be generated by the equipment. The level of output was increased as much as possible but only to the point at which a chattering sound indicated that too much power was being applied to the specimen. The input gain control was increased at this point until a small deflection on the ammeter dial was observed.

(f) The frequency of vibration induced in the specimen was varied until a circular pattern was seen on the screen of the oscilloscope. The frequency was then carefully adjusted until a maximum deflection was indicated by the ammeter.

(g) The pick-up was then moved along the length of the specimen to locate the two null points and the three peaks which were sought (see Figure 19). At these two null points, the deflections noted were either zero or very small and a horizontal line was observed on the screen of the oscilloscope. At the three peaks, the deflections were maximum and circular figures were observed on the screen of the oscilloscope. When two null points and three peak positions had been determined it became possible to obtain the fundamental resonant frequency of the specimen.

### 5.5.3 Determination of Longitudinal Frequency

The arrangement used to determine a specimen's longitudinal resonant frequency is shown by Figure 20. The specimen was supported at the centre of its length by a special stand lined with sponge rubber. The driver probe was placed in contact with the centre of the end surface of the specimen and the needle of the pick-up at the other end. The needle of the pick-up was perpendicular to the axis of the specimen. The testing procedure is the same as described previously for the determination of the fundamental transverse resonant frequency with the following exceptions:

(a) the position of the driver and the pick-up;

(b) only a single null point at the mid-point of the specimen's length and two peaks at the ends were sought (Figure 20).

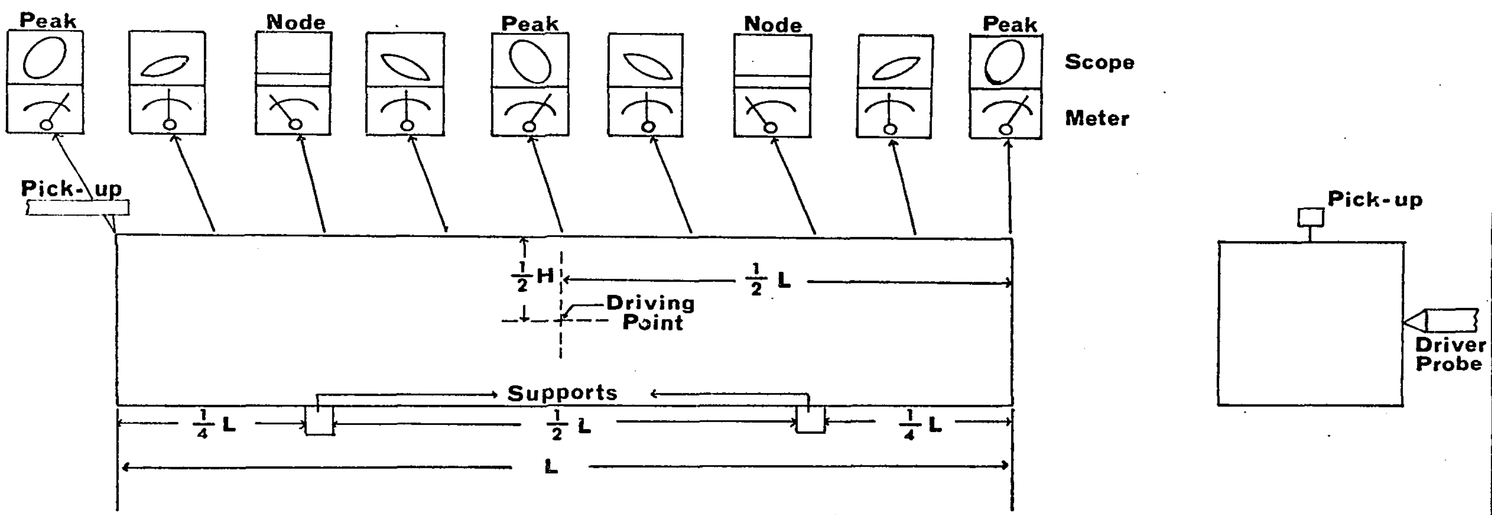



**FIGURE 19**

Set-up of Apparatus for Determination of Fundamental Transverse Resonance

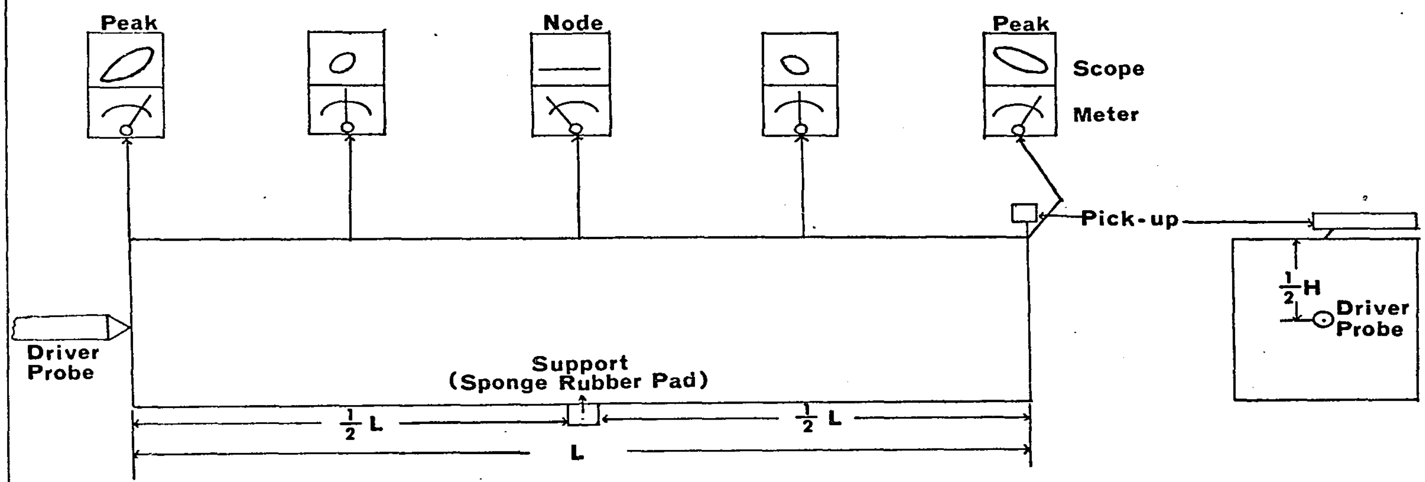



**FIGURE 20**

Set-up of Apparatus for Determination of Fundamental Longitudinal Resonance

# VI. EXPERIMENTAL RESULTS

## 6.1. Resistivity Tests

Sixty specimens from the ten samples selected were tested at temperatures in the range of 28°F to 36°F (six specimens were cut from each sample). The summaries of the resistivity values of these samples are given in Tables 11 through 20 in Appendix A.

Most of the tests show a great variation in resistivities between the frozen and unfrozen states. In particular, this condition is severe for samples of MIF and JSP.

The resistivity values of each sample were plotted as a function of temperature and load (Figures 21 to 30).

## 6.2 Thermal Conductivity Tests

Fifty-four specimens from the eleven samples selected were tested in the temperature range of 28°F to 33°F. The tests showed that there were substantial decreases in the values of thermal conductivity as the temperature was increased. Samples of MIF were an exception since abrupt decreases were noted when the temperature was increased from 31°F to 33°F. The results are summarized in Table 2 and the detailed data are shown in Tables 21 to 25 in Appendix B.

The thermal conductivities of these samples were plotted as functions of temperature (Figures 31 and 32).

## 6.3 Compression Tests

Forty specimens from the ten frozen samples selected for compression tests were tested at four temperatures: 28°F, 31°F, 33°F and 36°F.

A summary of the test results is given in Table 3. Details of the results are tabulated in Tables 4 through 7 and the test data are given in Tables 26 to 49 in Appendix C.

Figures 33 through 36 show the variation of uniaxial compressive strengths as a function of temperature. In all the cases there was a decrease in strength with increasing temperature. These decreases were most marked for samples which had high water contents and high porosities. One significant feature of some of the plots is an abrupt decrease in strength as temperature is raised from 31°F to 33°F.

## 6.4 Shear Tests

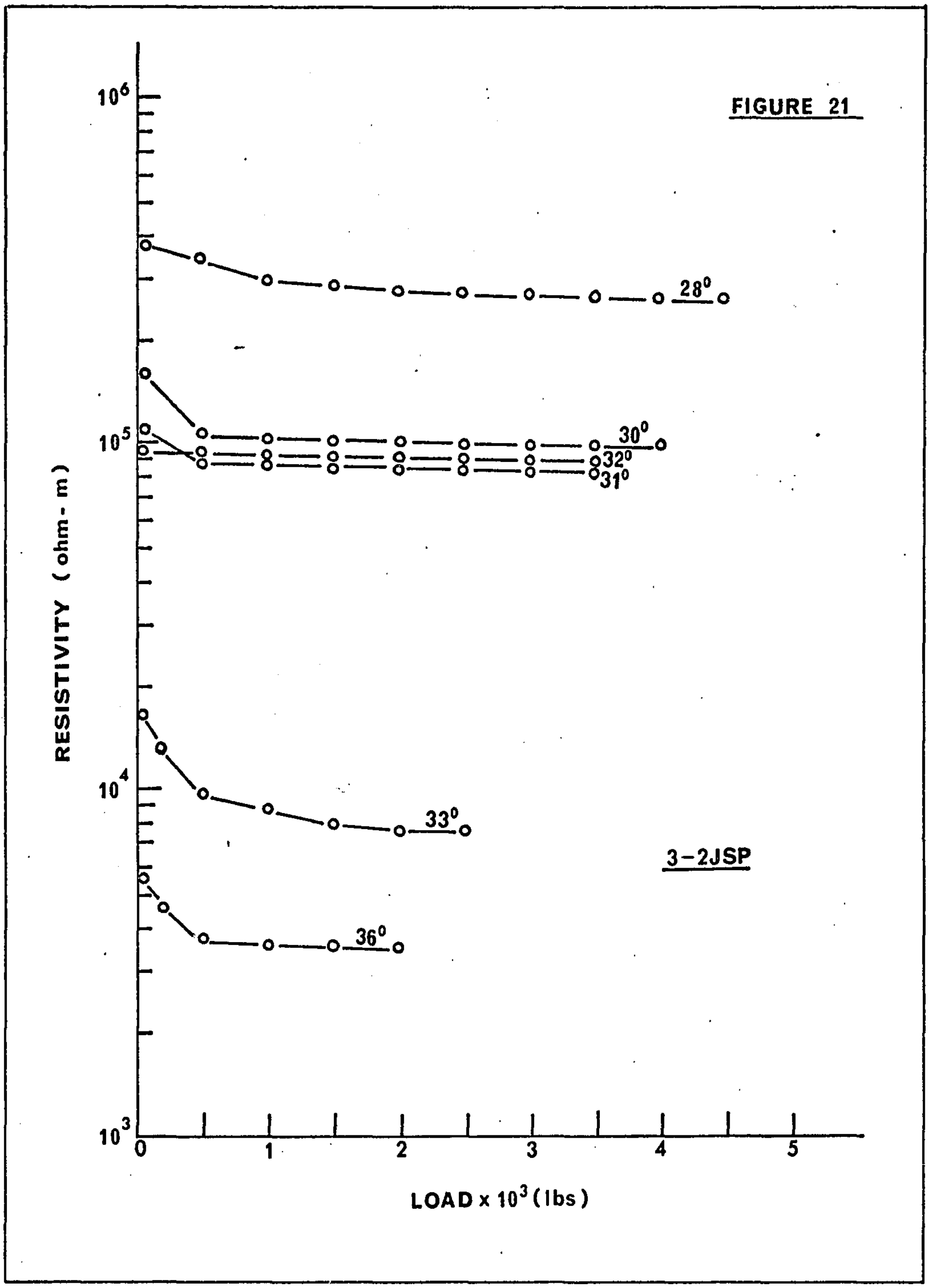
Forty specimens from the ten samples selected were tested at temperatures of 28°F, 31°F, 33°F and 36°F (four specimens, one for each temperature condition, were cut from each sample). Table 8 is a summary of the shearing strengths obtained at the different temperatures. The tests showed great differences in strength values between the frozen and thawed states. The Quartzite samples, which had low water contents, were an exception and appeared to be only slightly affected by temperature.

The detailed data are presented in Tables 50 to 53 in Appendix D. The values of the shearing strengths of these samples are plotted as a function of temperature in Figures 37 to 40.

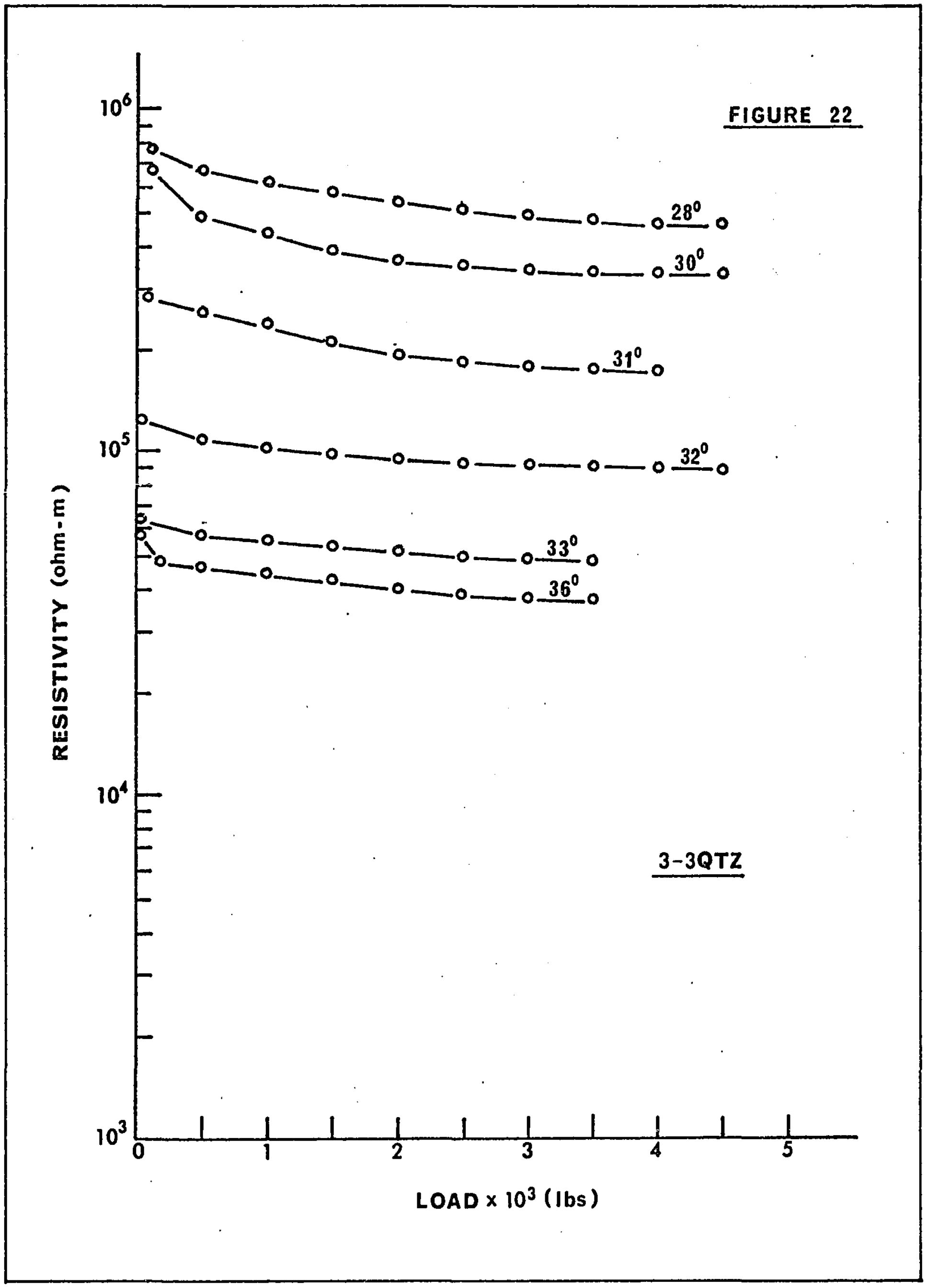
## 6.5 Sonic Tests

The test results for the seven samples tested at different temperatures are presented in Tables 54 through 59 in Appendix E. Summaries are given in Tables 9 and 10. The values of the velocities of the transverse and longitudinal sonic waves through samples were plotted as functions of temperature in Figures 41 and 42, respectively. The test temperatures ranged from 28°F to 32°F for all of the samples tested, with the exception of Quartzite for which the values were determined over a wider range (28°F to 36°F).

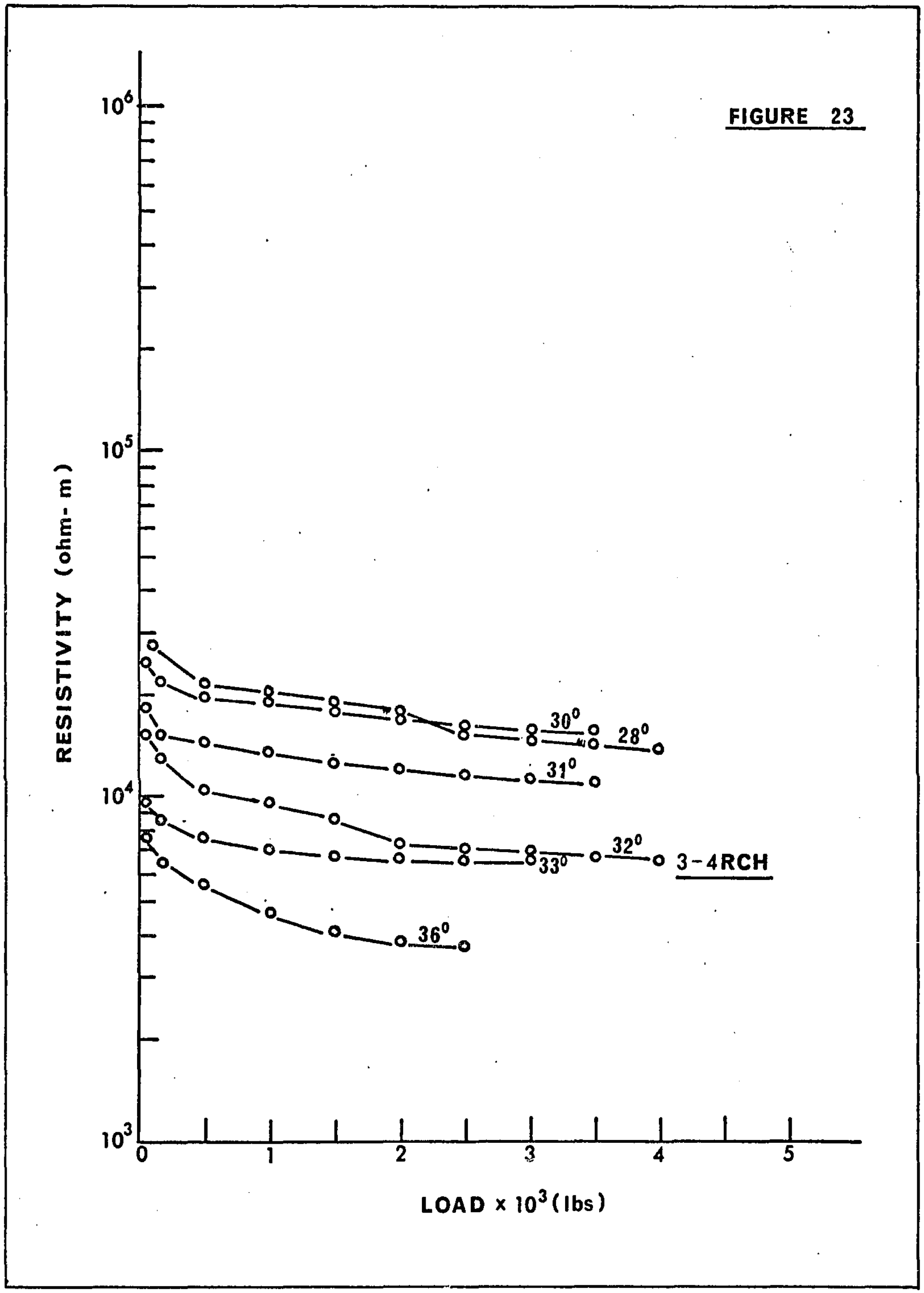
The frozen geological materials tested contained irregular ice particles, grains and stratified ice lenses. For this reason one cannot describe these as having been isotropic, elastic and homogeneous materials. In most of the tests reported herein, the numerical values of the velocities were only slightly changed within the temperature range of 28°F to 32°F. Once again, the sample of Quartzite was an exception. The values determined for Quartzite appeared to be nearly constant for the range of 28°F to 36°F.



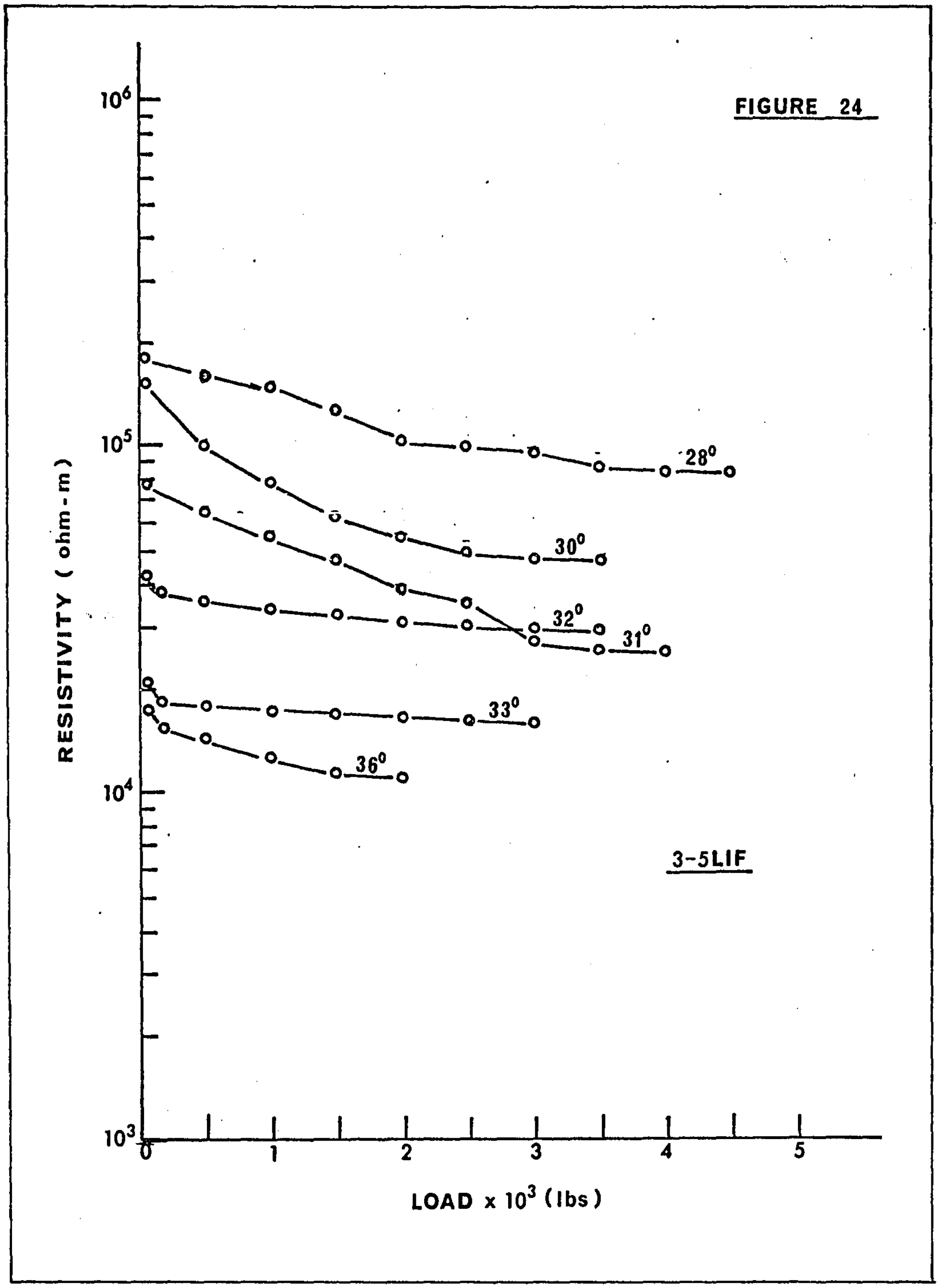

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



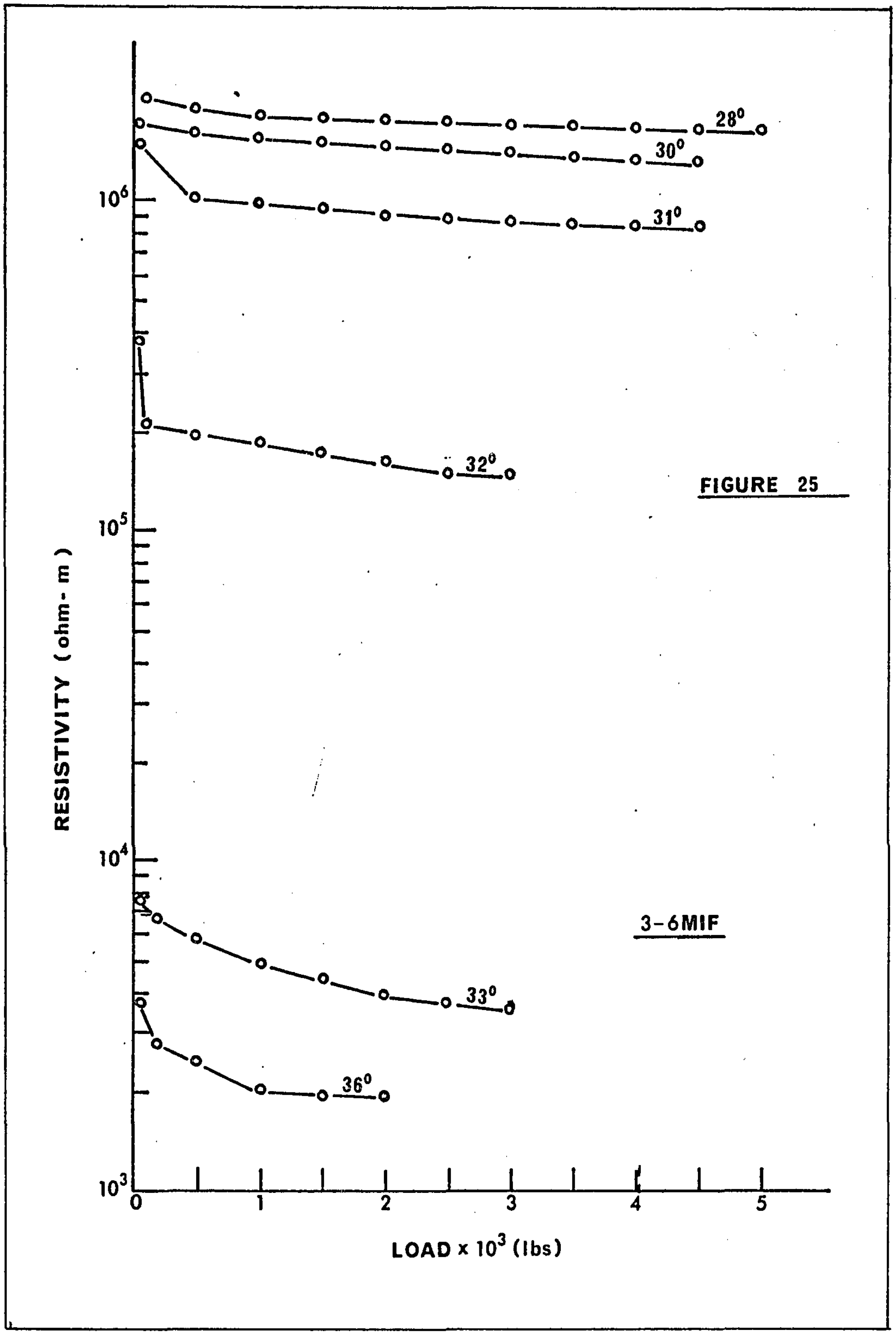

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



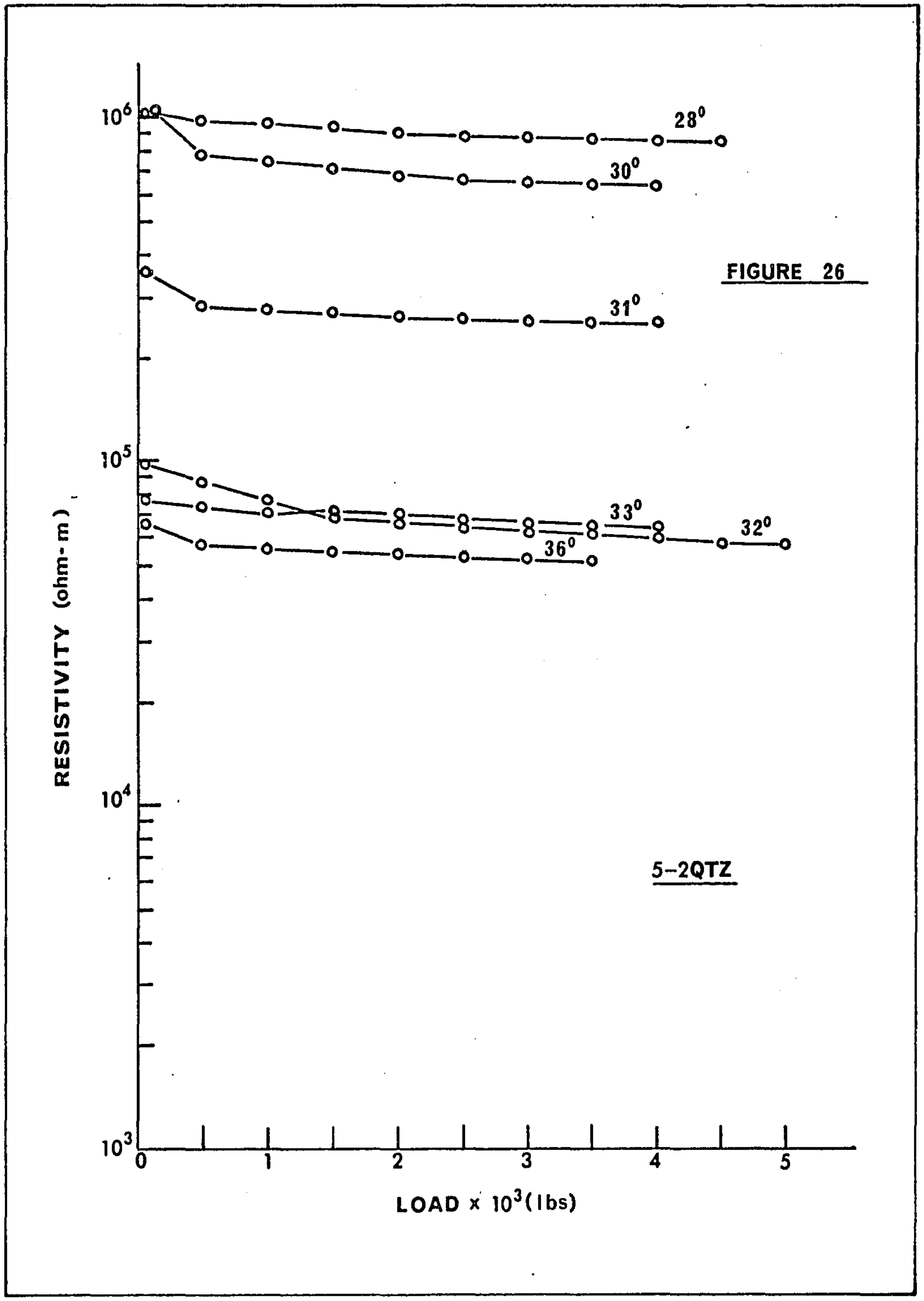

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



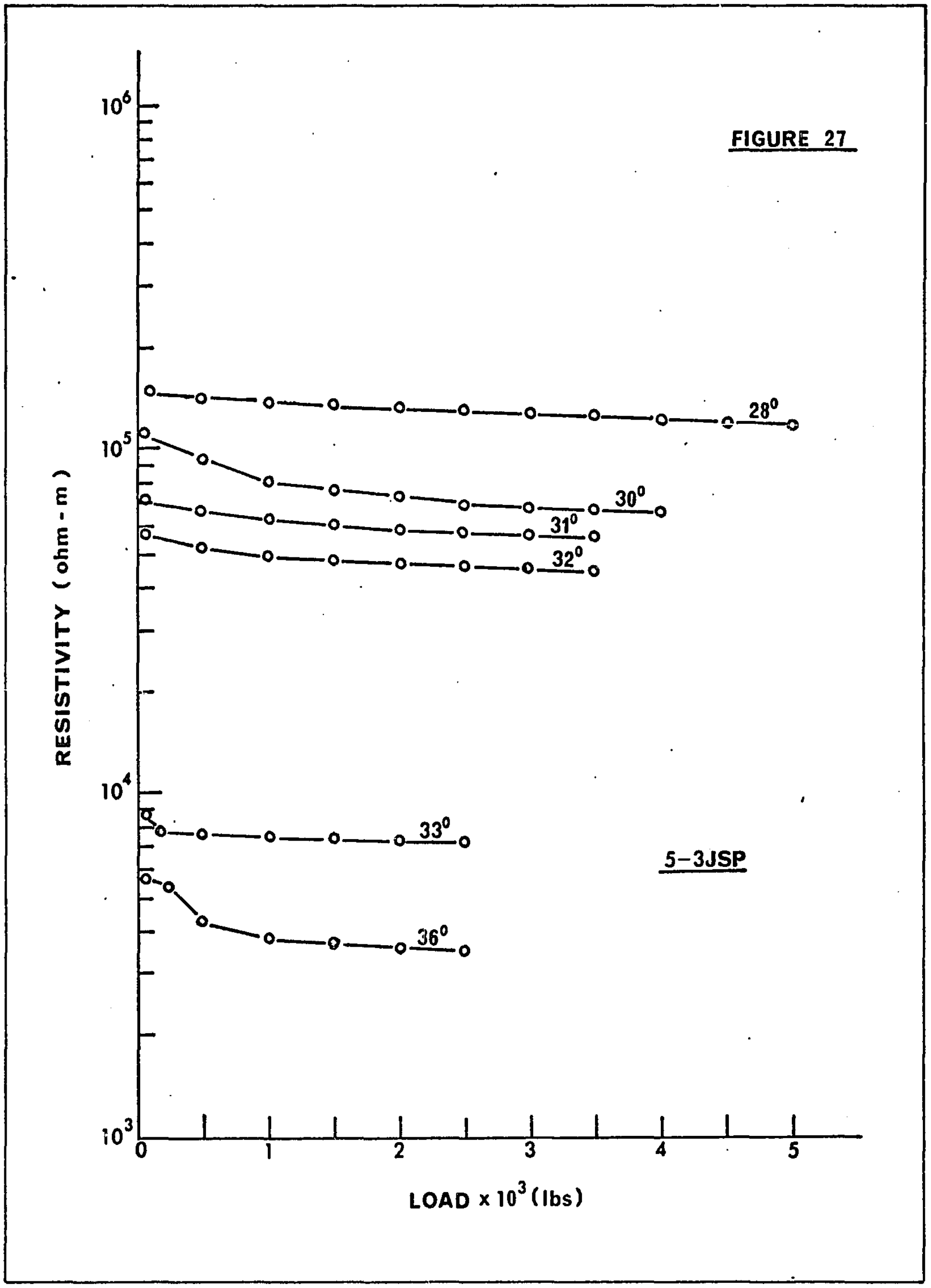

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



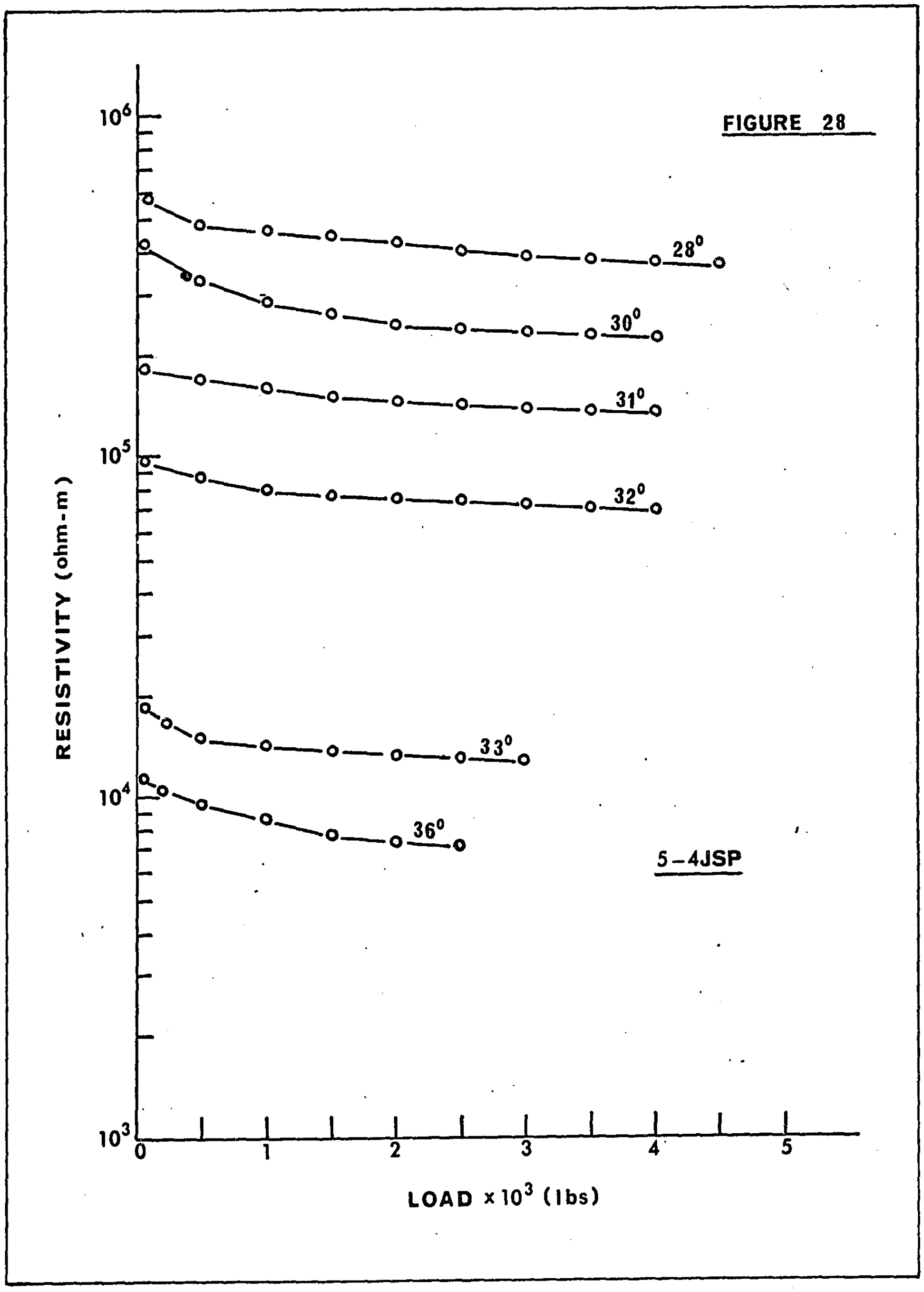

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



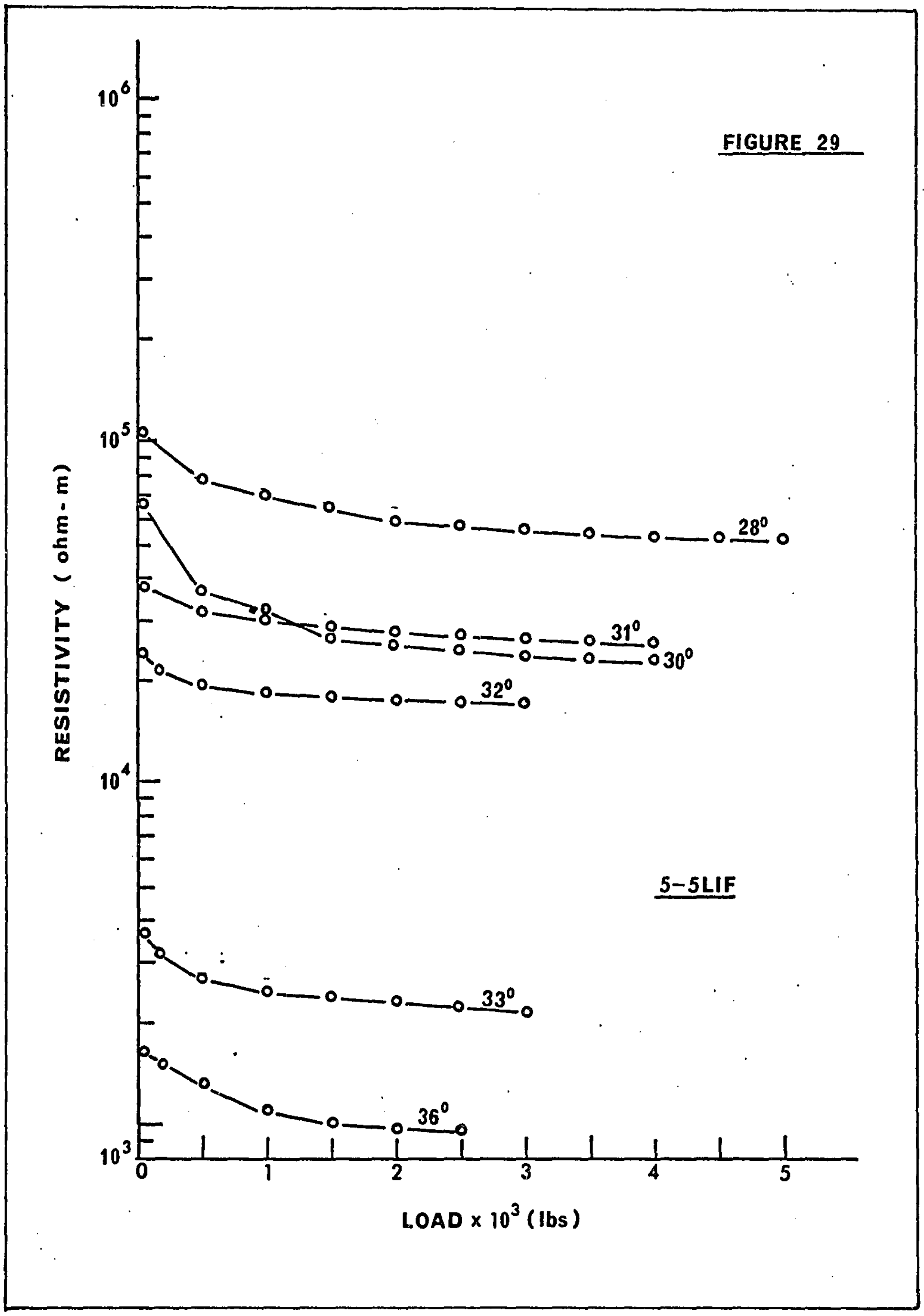

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES



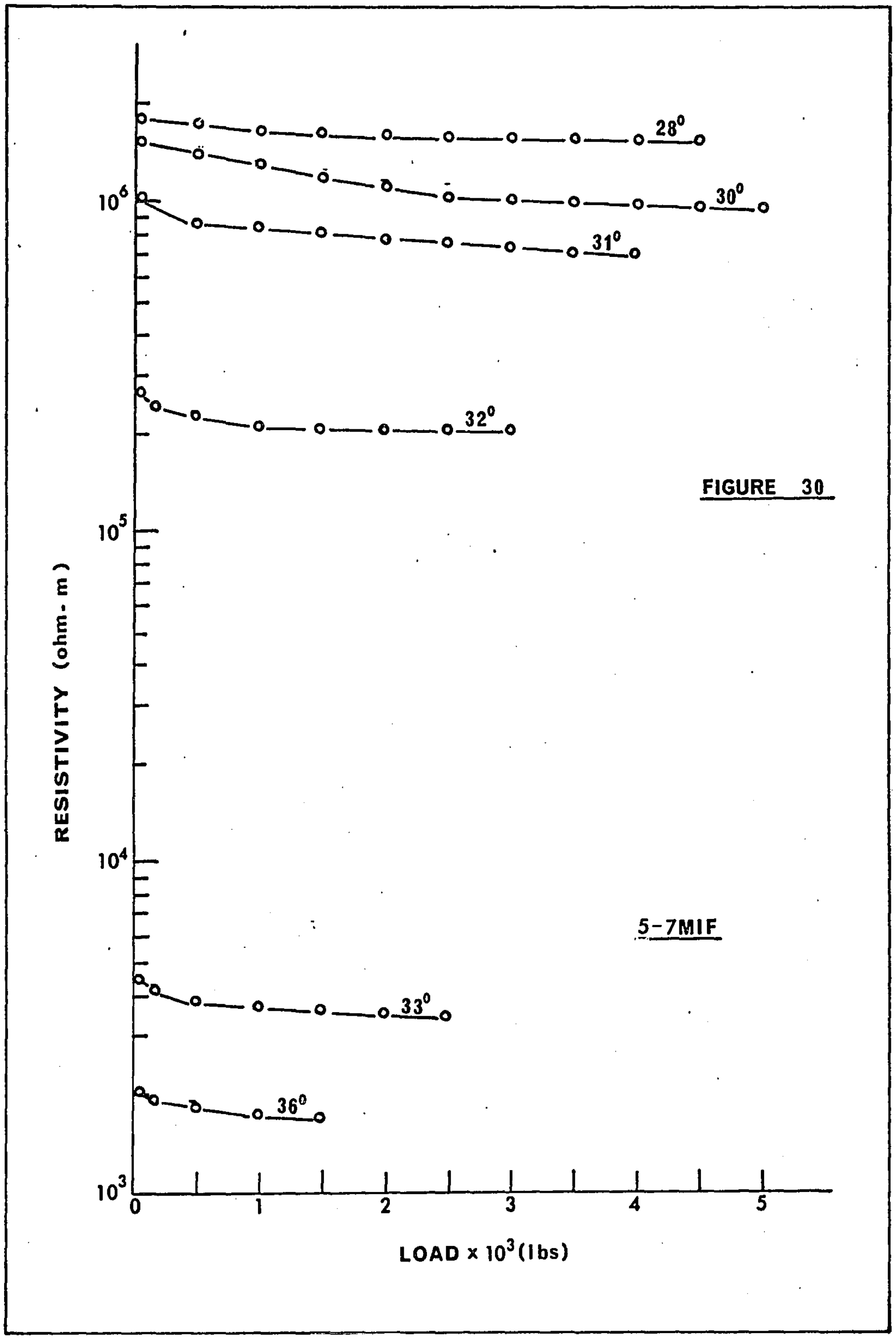

GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES




GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES




GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES

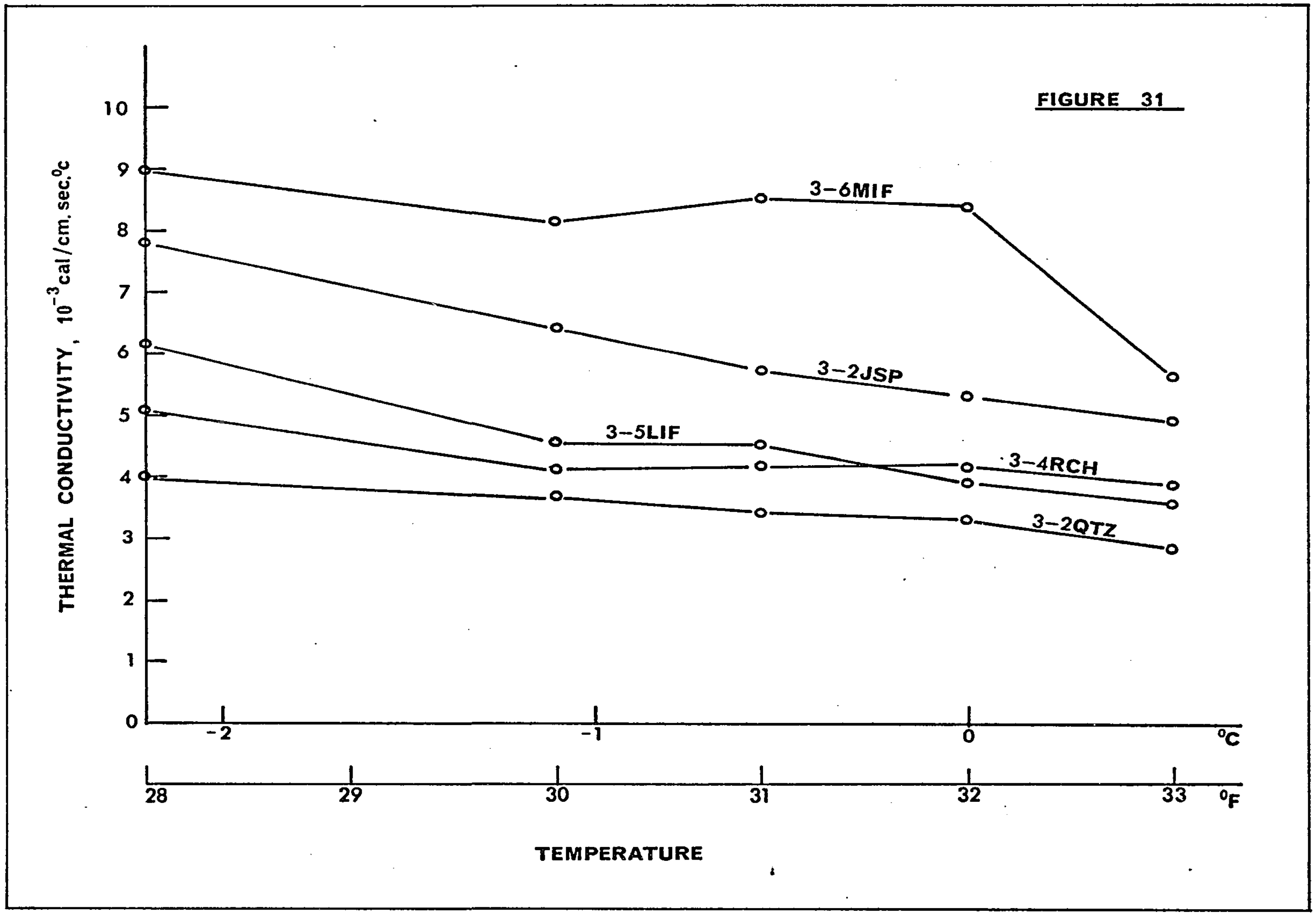



GRAPH OF RESISTIVITY VS. LOADS VS. TEMPERATURES

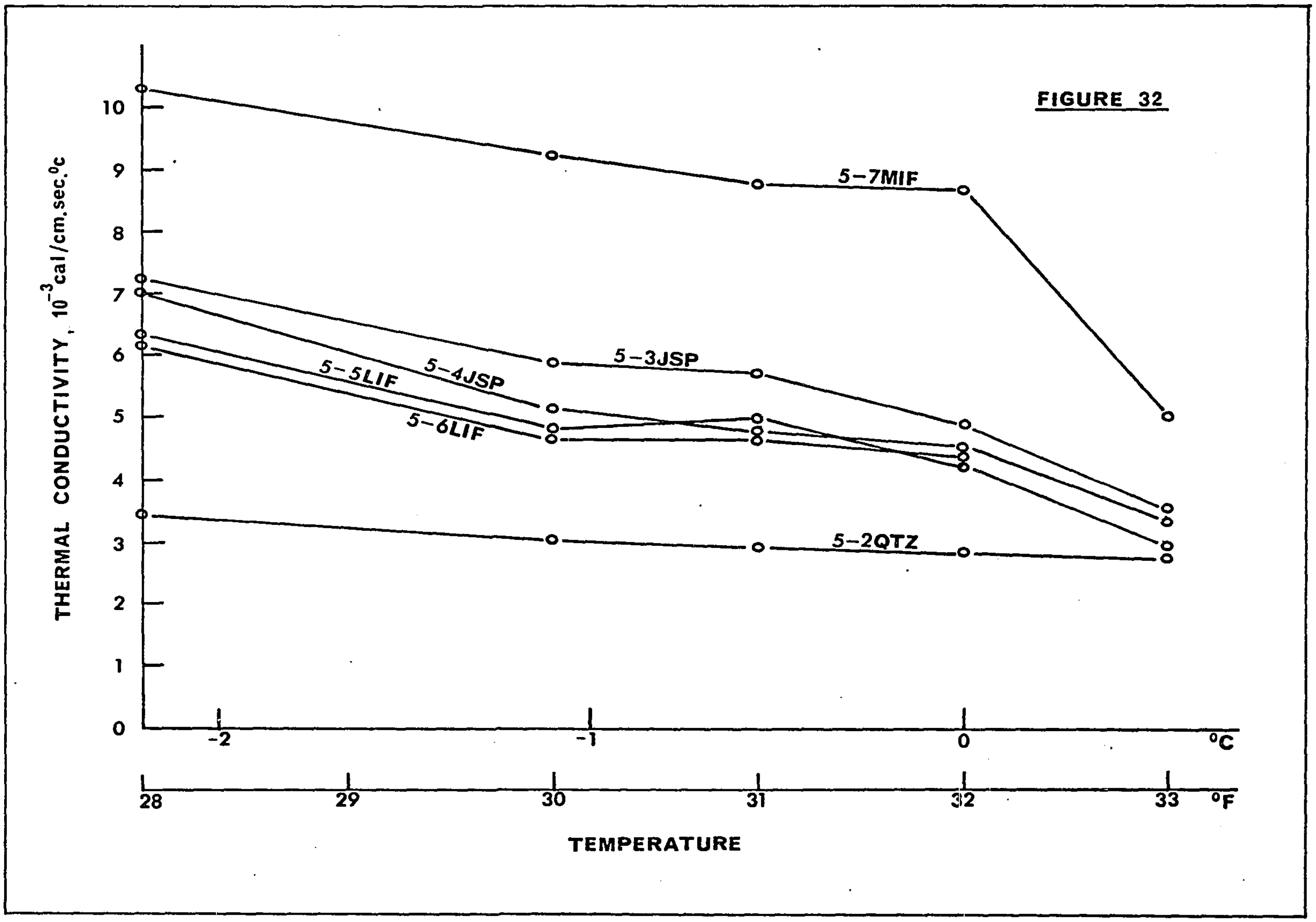
TABLE 2

SUMMARY OF THERMAL CONDUCTIVITY RESULTS

| SAMPLE NUMBER | THERMAL CONDUCTIVITIES AT VARIOUS TEMPERATURES FOR THE SAMPLES LISTED ($x10^{-3}$ cal/sec. cm. C°) | | | | |
|---|---|---|---|---|---|
| | 28°F | 30°F | 31°F | 32°F | 33°F |
| 3-2 JSP | 7.840 | 6.484 | 5.751 | 5.336 | 4.932 |
| 3-3 QTZ | 4.088 | 3.720 | 3.463 | 3.346 | 2.847 |
| 3-4 RCH | 5.167 | 4.137 | 4.185 | 4.102 | 3.938 |
| 3-5 LIF | 6.167 | 4.660 | 4.649 | 3.969 | 3.600 |
| 3-6 MIF | 9.000 | 8.174 | 8.561 | 8.341 | 5.689 |
| 5-2 QTZ | 3.459 | 3.048 | 2.991 | 2.823 | 2.770 |
| 5-3 JSP | 7.272 | 5.908 | 5.730 | 4.937 | 3.501 |
| 5-4 JSP | 7.069 | 5.138 | 4.822 | 4.522 | 3.350 |
| 5-5 LIF | 6.312 | 4.883 | 4.960 | 4.309 | 2.954 |
| 5-6 LIF | 6.279 | 4.776 | 4.821 | 4.410 | - |
| 5-7 MIF | 10.328 | 9.264 | 8.792 | 8.675 | 5.012 |




GRAPH OF THERMAL CONDUCTIVITY VS. TEMPERATURES




GRAPH OF THERMAL CONDUCTIVITY VS. TEMPERATURE

TABLE 3

SUMMARY OF UNIAXIAL COMPRESSION TEST RESULTS

| SAMPLE NO. | UNIAXIAL COMPRESSIVE STRENGTHS AT VARIOUS TEMPERATURES FOR THE SAMPLES LISTED (psi) | | | |
|---|---|---|---|---|
| | 28°F | 31°F | 33°F | 36°F |
| 3-2 SJP | 2300 | 1462 | 32.0 | 19.2 |
| 3-3 QTZ | 4600 | 3471 | 1778 | 1200 |
| 3-4 RCH | 980 | 634 | 69.7 | 42.8 |
| 3-5 LIF | 825 | 596 | 58.5 | 31.4 |
| 3-6 MIF | 1398 | 884 | 32.9 | 11.9 |
| 5-2 QTZ | 8500 | 6400 | 5500 | 4850 |
| 5-3 SJP | 2100 | 1536 | 52.1 | 28.4 |
| 5-5 LIF | 780 | 531 | 67.0 | 43.6 |
| 5-4 SJP | 2600 | 1402 | 44.9 | 20.8 |
| 5-7 MIF | 1240 | 738 | 38.8 | 10.0 |

## TABLE 4

## DETAILS OF UNIAXIAL COMPRESSION TESTS

T Room = 28°F

| SPECIMEN NUMBER | LENGTH (in.) | AREA (in.$^2$) | LOAD AT FAILURE (lbs) | COMPRESSIVE STRENGTH (psi) | MODULUS OF DEFORMATION x $10^3$ psi | REMARKS |
|---|---|---|---|---|---|---|
| 3-2JSP - $C_1$ | 2.580 | 1.282 | 2,950 | 2,300 | 95.6 | Splitting Fracture |
| 3-3QTZ - $C_1$ | 2.588 | 1.304 | 6,000 | 4,600 | 190.0 | Splitting Fracture |
| 3-4RCH - $C_1$ | 2.663 | 1.345 | 1,320 | 980 | 31.4 | Distorted |
| 3-5LIF - $C_1$ | 2.650 | 1.334 | 1,100 | 825 | 27.8 | Shear Fracture |
| 3-6MIF - $C_1$ | 2.585 | 1.288 | 1,800 | 1,398 | 43.2 | Shear Fracture |
| 5-2QTZ - $C_1$ | 2.592 | 1.290 | 11,000 | 8,500 | 1000.0 | Splitting Fracture |
| 5-3JSP - $C_1$ | 2.596 | 1.283 | 2,700 | 2,100 | 77.7 | Splitting Fracture |
| 5-5LIF - $C_1$ | 2.597 | 1.278 | 1,000 | 780 | 30.0 | Shear Fracture |
| 5-4JSP - $C_1$ | 2.688 | 1.305 | 3,400 | 2,600 | 80.5 | Splitting Fracture |
| 5-7MIF - $C_1$ | 2.574 | 1.290 | 1,600 | 1,240 | 48.8 | Shear Fracture |

## TABLE 5

## DETAILS OF UNIAXIAL COMPRESSION TESTS

T Room = 31°F

| SPECIMEN NUMBER | LENGTH (in.) | AREA (in.$^2$) | LOAD AT FAILURE (lbs) | COMPRESSIVE STRENGTH (psi) | MODULUS OF DEFORMATION x $10^3$ psi | REMARKS |
|---|---|---|---|---|---|---|
| 3-2JSP - $C_2$ | 2.608 | 1.265 | 1,850 | 1,462 | 67.80 | Splitting Fracture |
| 3-3QTZ - $C_2$ | 2.598 | 1.311 | 4,550 | 3,471 | 140.00 | Splitting Fracture |
| 3-4RCH - $C_2$ | 2.614 | 1.320 | 850 | 634 | 22.60 | Distorted |
| 3-5LIF - $C_2$ | 2.628 | 1.259 | 750 | 596 | 25.80 | Shear Fracture |
| 3-6MIF - $C_2$ | 2.625 | 1.245 | 1,100 | 884 | 30.20 | Shear Fracture |
| 5-2QTZ - $C_2$ | 2.618 | 1.280 | 8,200 | 6,400 | 480.00 | Splitting Fracture |
| 5-3JSP - $C_2$ | 2.612 | 1.302 | 2,000 | 1,536 | 68.90 | Splitting Fracture |
| 5-5LIF - $C_2$ | 2.604 | 1.271 | 675 | 531 | 23.60 | Shear Fracture |
| 5-4JSP - $C_2$ | 2,604 | 1.284 | 1,800 | 1,402 | 60.50 | Splitting Fracture |
| 5-7MIF - $C_2$ | 2.586 | 1.322 | 975 | 738 | 30.81 | Shear Fracture |

## TABLE 6

## DETAILS OF UNIAXIAL COMPRESSION TESTS

T Room = 33°F

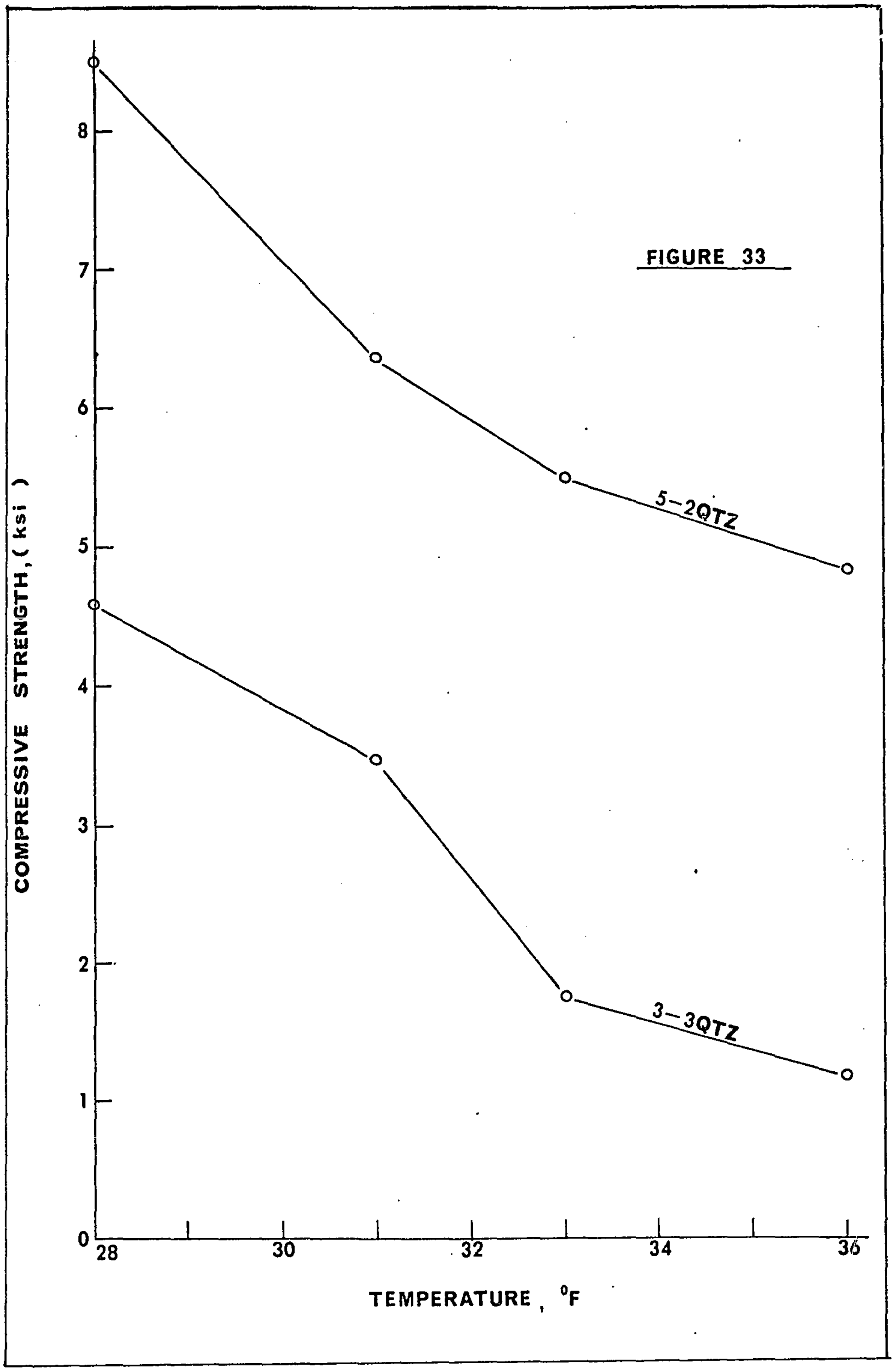
| SPECIMEN NUMBER | LENGTH (in.) | AREA (in.$^2$) | LOAD AT FAILURE (lbs) | COMPRESSIVE STRENGTH (psi) | MODULUS OF DEFORMATION x $10^3$ psi | REMARKS |
|---|---|---|---|---|---|---|
| 3-2JSP - $C_3$ | 2.652 | 1.312 | 42 | 32.0 | 1.86 | Shear Fracture |
| 3-3QTZ - $C_3$ | 2.617 | 1.322 | 2,350 | 1,778 | 108.0 | Splitting Fracture |
| 3-4RCH - $C_3$ | 2.633 | 1.320 | 92 | 69.7 | 2.09 | Distorted |
| 3-5LIF - $C_3$ | 2.596 | 1.299 | 76 | 58.5 | 2.28 | Shear Fracture |
| 3-6MIF - $C_3$ | 2.644 | 1.339 | 44 | 32.7 | 1.82 | Shear Fracture |
| 5-2QTZ - $C_3$ | 2.604 | 1.298 | 7,150 | 5,500 | 390.0 | Splitting Fracture |
| 5-3JSP - $C_3$ | 2.597 | 1.306 | 68 | 52.1 | 2.88 | Shear Fracture |
| 5-5LIF - $C_3$ | 2.605 | 1.328 | 89 | 67.0 | 1.86 | Shear Fracture |
| 5-4JSP - $C_3$ | 2.621 | 1.334 | 60 | 44.9 | 2.48 | Shear Fracture |
| 5-7MIF - $C_3$ | 2.601 | 1.339 | 52 | 38.8 | 2.74 | Shear Fracture |

TABLE 7

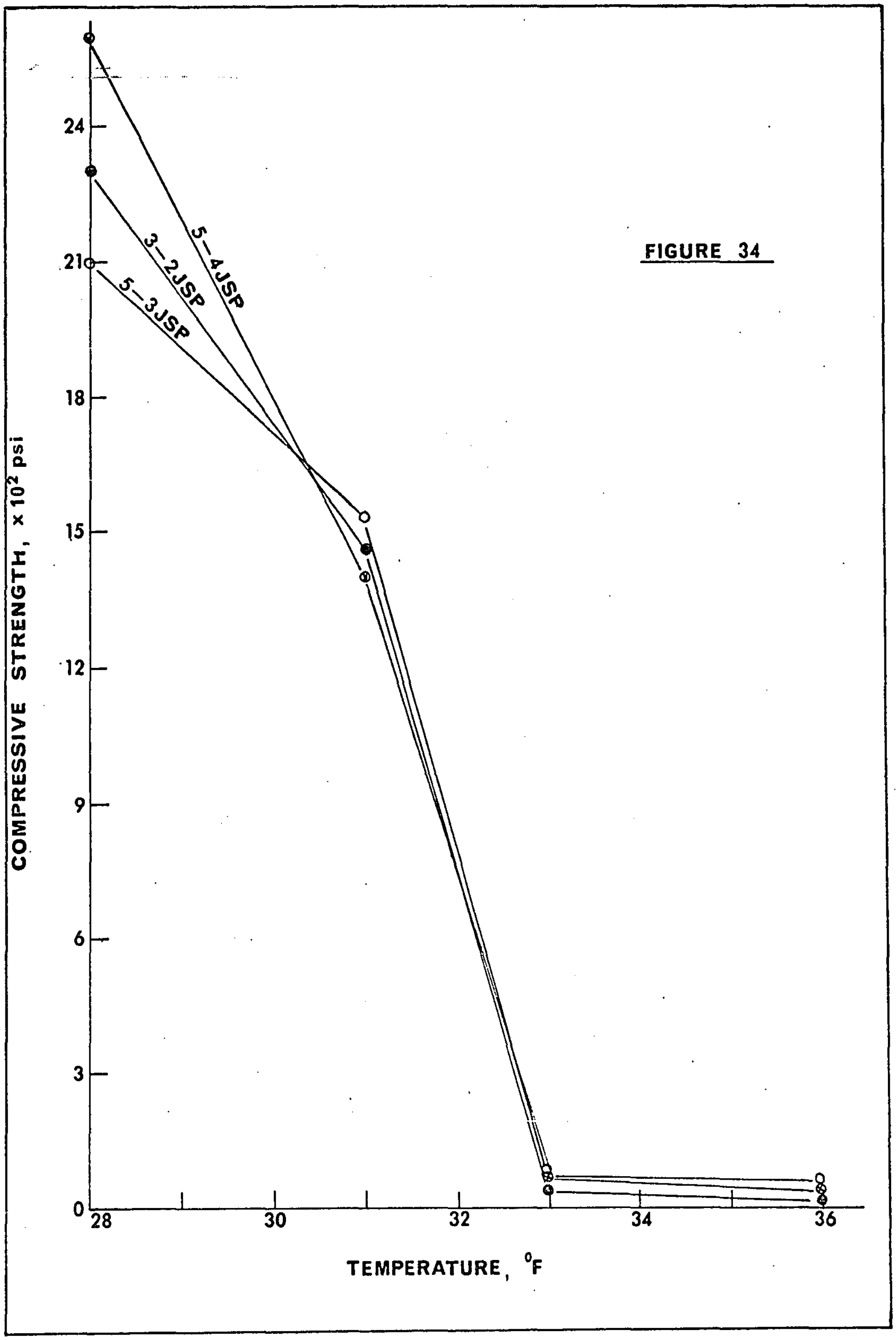
DETAILS OF UNIAXIAL COMPRESSION TESTS

T Room = 36°F

| SPECIMEN NUMBER | LENGTH (in.) | AREA (in.$^2$) | LOAD AT FAILURE (lbs) | COMPRESSIVE STRENGTH (psi) | MODULUS OF DEFORMATION x $10^3$ psi | REMARKS |
|---|---|---|---|---|---|---|
| 3-2JSP - $C_4$ | 2.600 | 1.303 | 25.0 | 19.2 | 0.88 | Shear Fracture |
| 3-3QTZ - $C_4$ | 2.602 | 1.292 | 1,550 | 1,200 | 93.0 | Splitting Fracture |
| 3-4RCH - $C_4$ | 2.586 | 1.311 | 56.1 | 42.8 | 1.01 | Distorted |
| 3-5LIF - $C_4$ | 2.510 | 1.212 | 38.1 | 31.4 | 1.57 | Shear Fracture |
| 3-6MIF - $C_4$ | 2.666 | 1.430 | 17.0 | 11.9 | 0.51 | Shear Fracture |
| 5-2QTZ - $C_4$ | 2.610 | 1.308 | 6,350 | 4,850 | 240.0 | Splitting Fracture |
| 5-3JSP - $C_4$ | 2.600 | 1.305 | 37.0 | 28.4 | 0.95 | Shear Fracture |
| 5-5LIF - $C_4$ | 2.607 | 1.304 | 57.7 | 43.6 | 0.65 | Shear Fracture |
| 5-4JSP - $C_4$ | 2.624 | 1.408 | 29.3 | 20.8 | 0.78 | Shear Fracture |
| 5-7MIF - $C_4$ | 2.595 | 1.301 | 13.0 | 10.0 | 0.38 | Shear Fracture |




GRAPH OF COMPRESSIVE STRENGTH VS. TEMPERATURES

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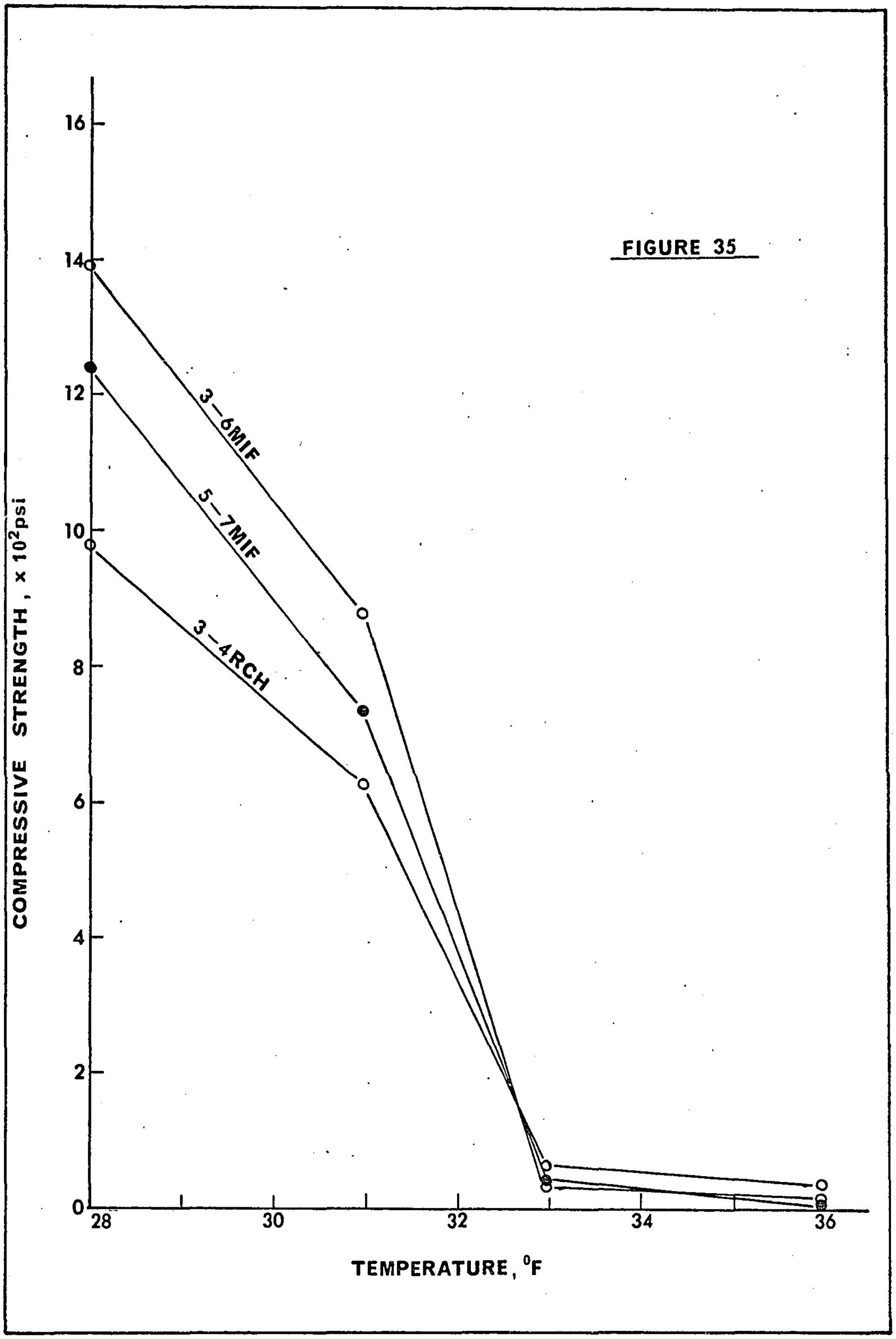
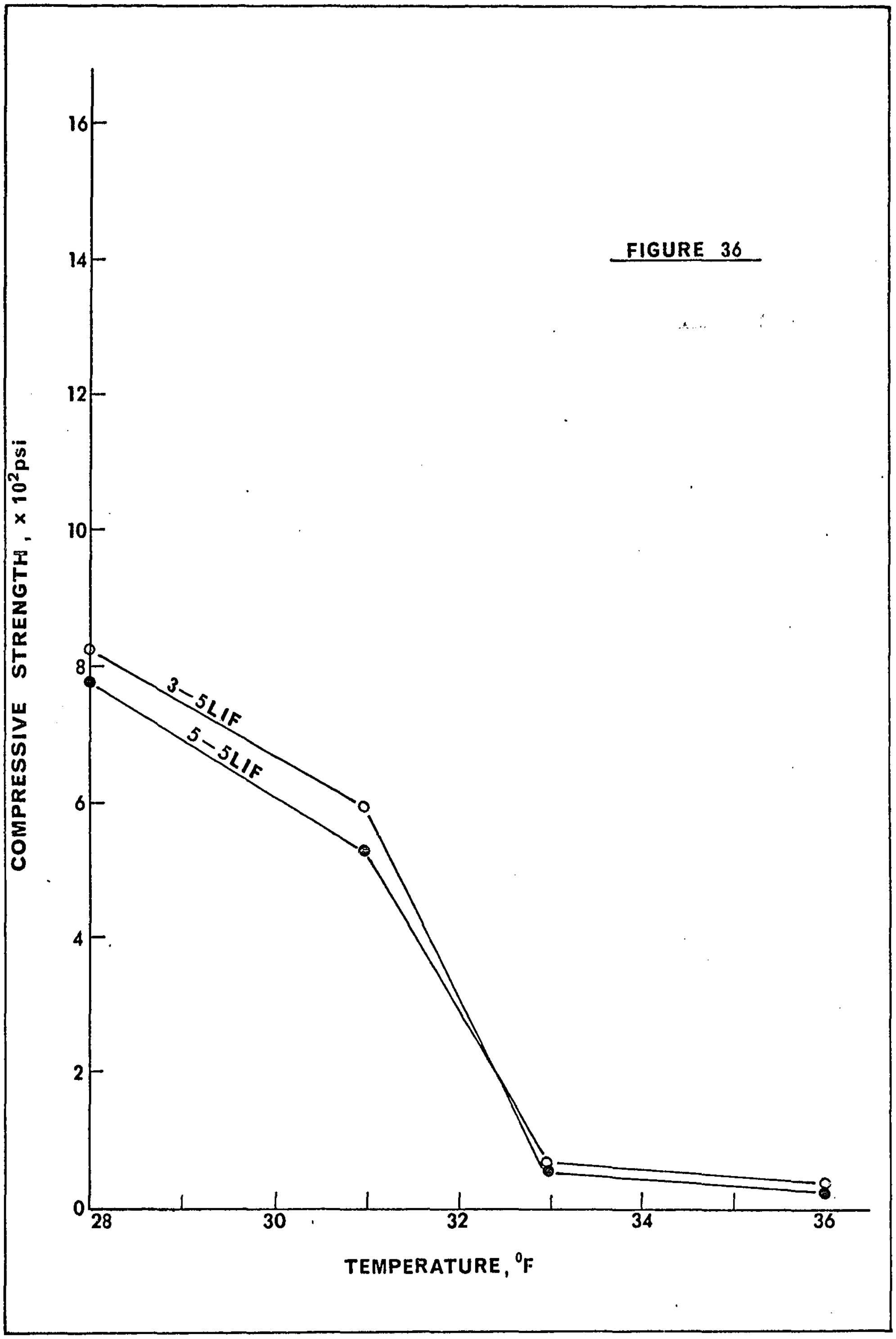



GRAPH OF COMPRESSIVE STRENGTH VS. TEMPERATURES

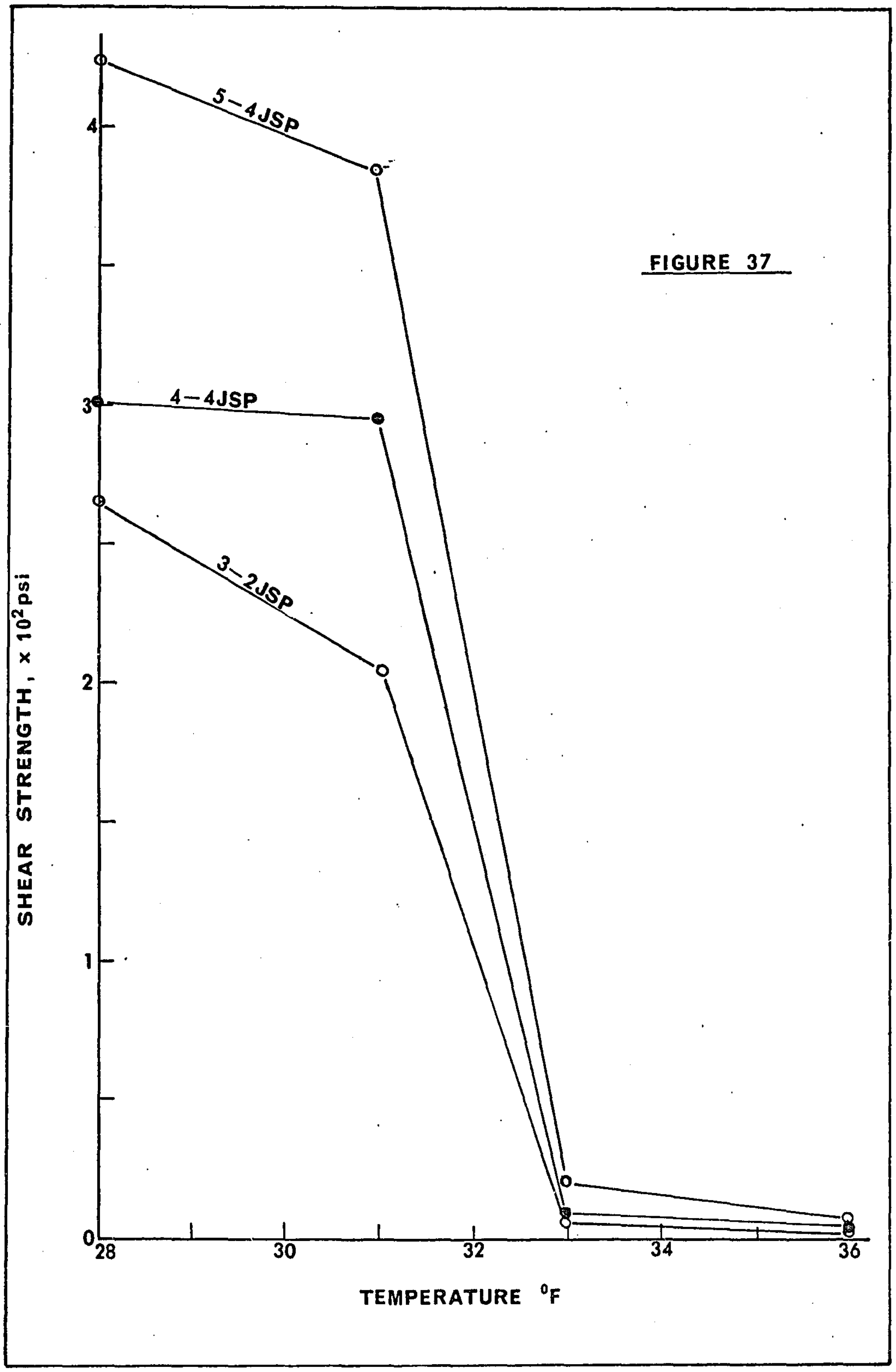



GRAPH OF COMPRESSIVE STRENGTH VS. TEMPERATURES

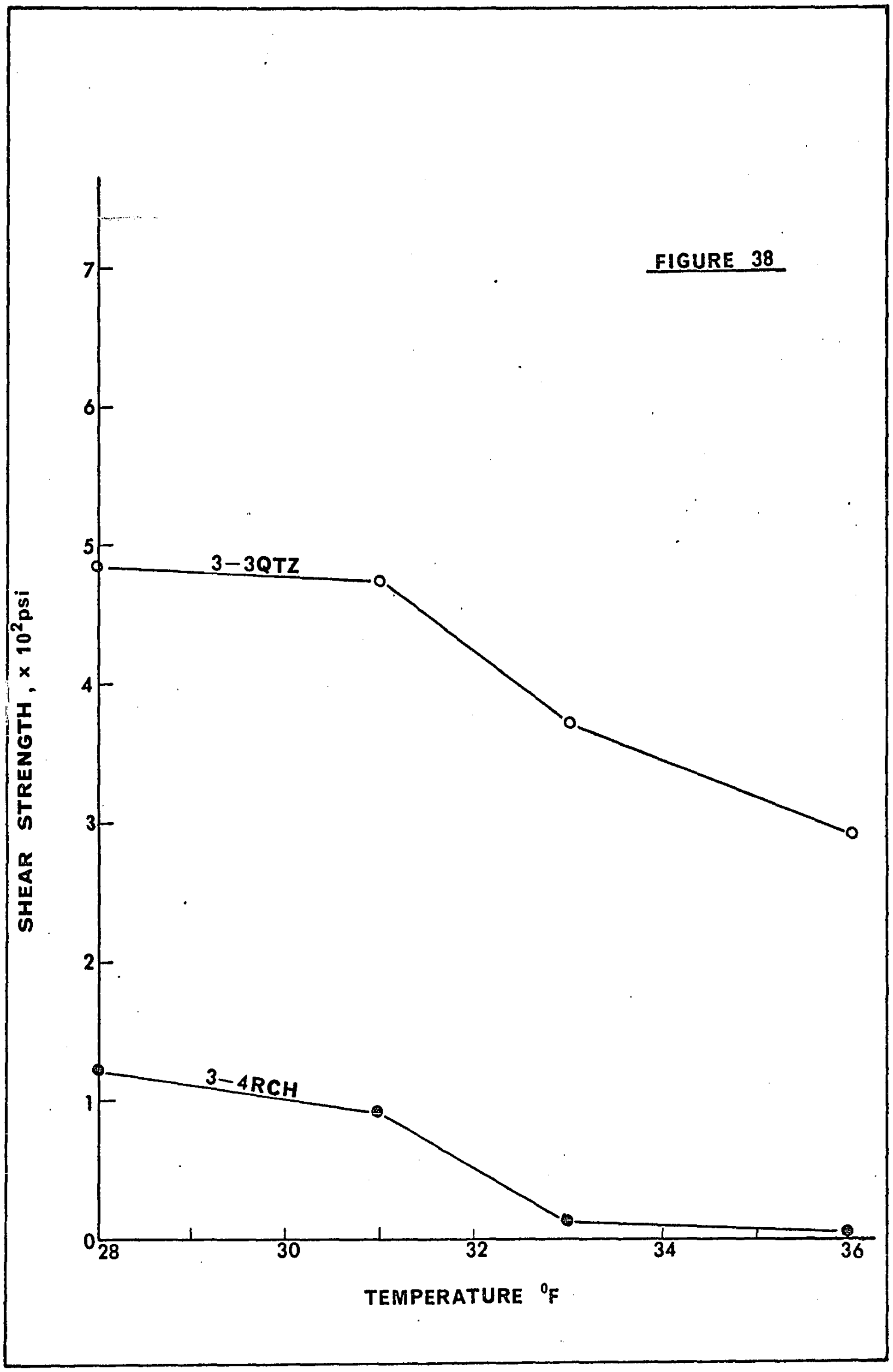
TABLE 8

SUMMARY OF SHEAR TEST RESULTS

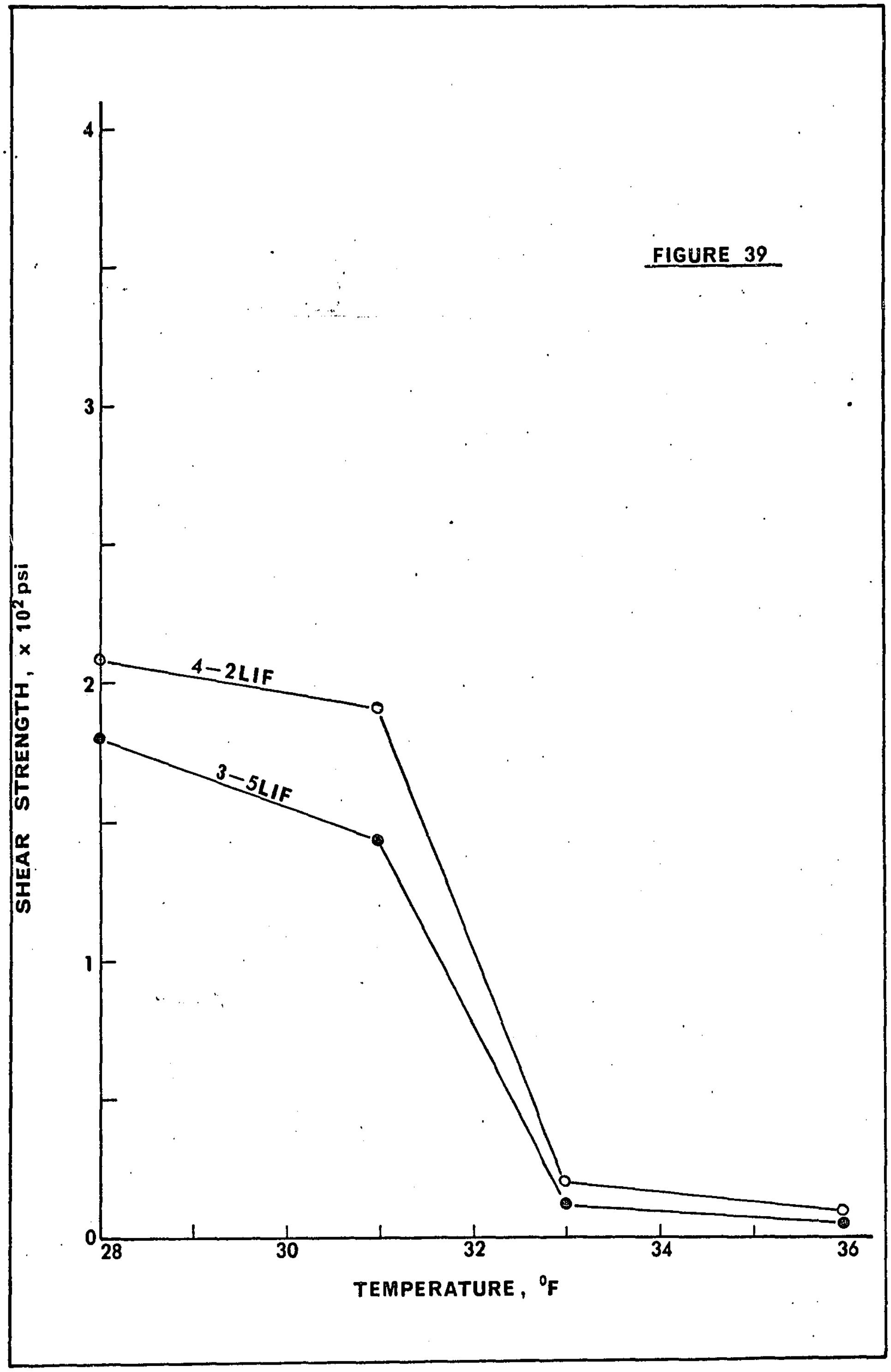
| SAMPLE NUMBER | SHEAR STRENGTHS AT VARIOUS TEMPERATURES FOR THE SAMPLES LISTED (psi) | | | |
|---|---|---|---|---|
| | 28°F | 31°F | 33°F | 36°F |
| 3-2 JSP | 266.7 | 209.5 | 5.6 | 3.42 |
| 3-3 QTZ | 485.9 | 478.9 | 376.8 | 295.0 |
| 3-4 RCH | 122.1 | 90.5 | 12.2 | 4.16 |
| 3-5 LIF | 182.7 | 144.2 | 10.8 | 3.78 |
| 3-6 MIF | 380.9 | 243.8 | 6.59 | 2.19 |
| 4-1 MIF | 338.1 | 269.2 | 7.31 | 2.44 |
| 4-2 LIF | 209.6 | 192.3 | 18.62 | 6.86 |
| 4-4 JSP | 307.7 | 295.2 | 9.31 | 4.88 |
| 5-4 JSP | 420.9 | 385.7 | 20.4 | 5.61 |
| 5-7 MIF | 350.4 | 270.3 | 5.37 | 1.46 |



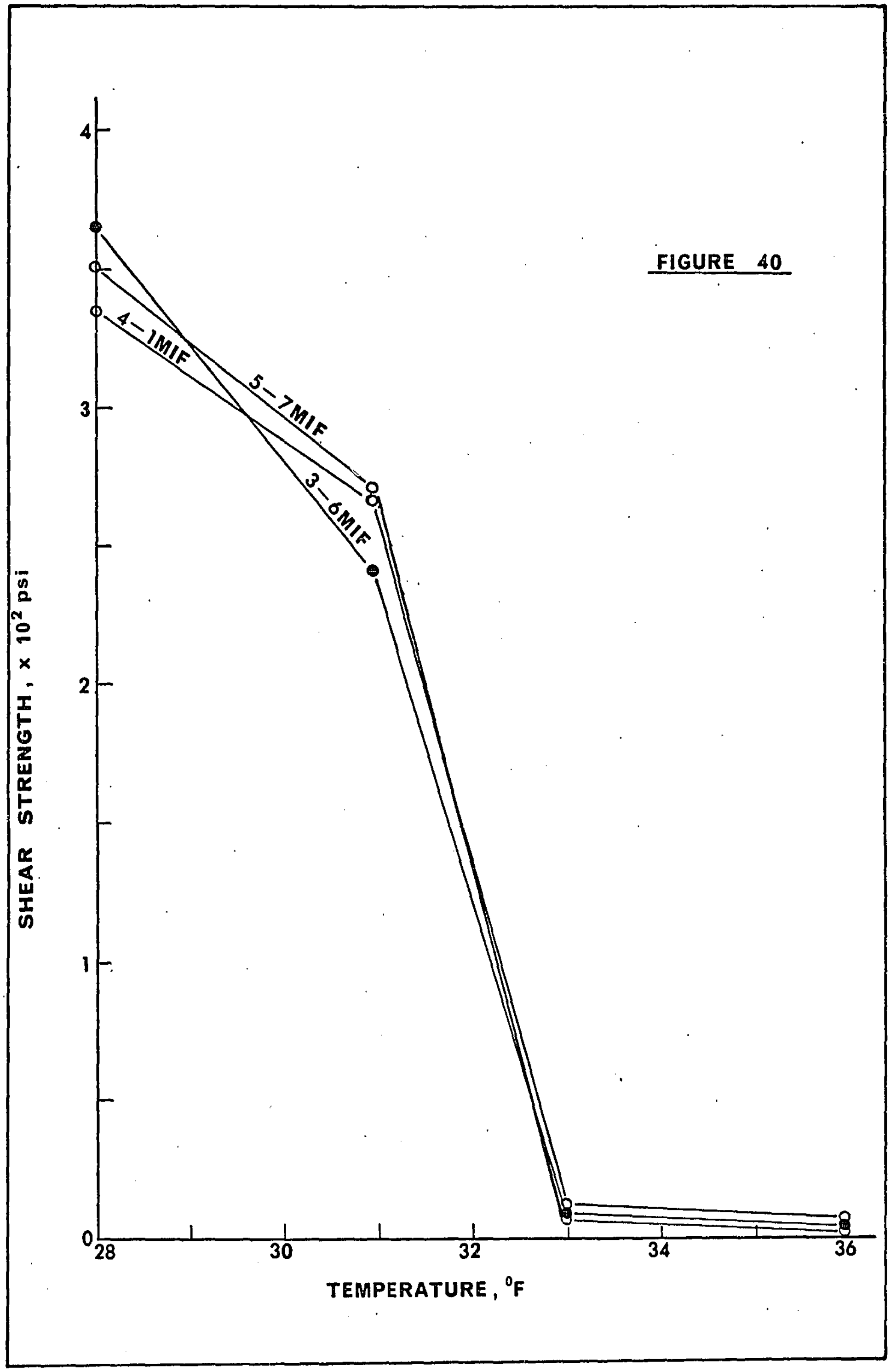

GRAPH OF SHEAR STRENGTH VS. TEMPERATURES




GRAPH OF SHEAR STRENGTH VS. TEMPERATURES




GRAPH OF SHEAR STRENGTH VS. TEMPERATURES




GRAPH OF SHEAR STRENGTH VS. TEMPERATURES

TABLE 9

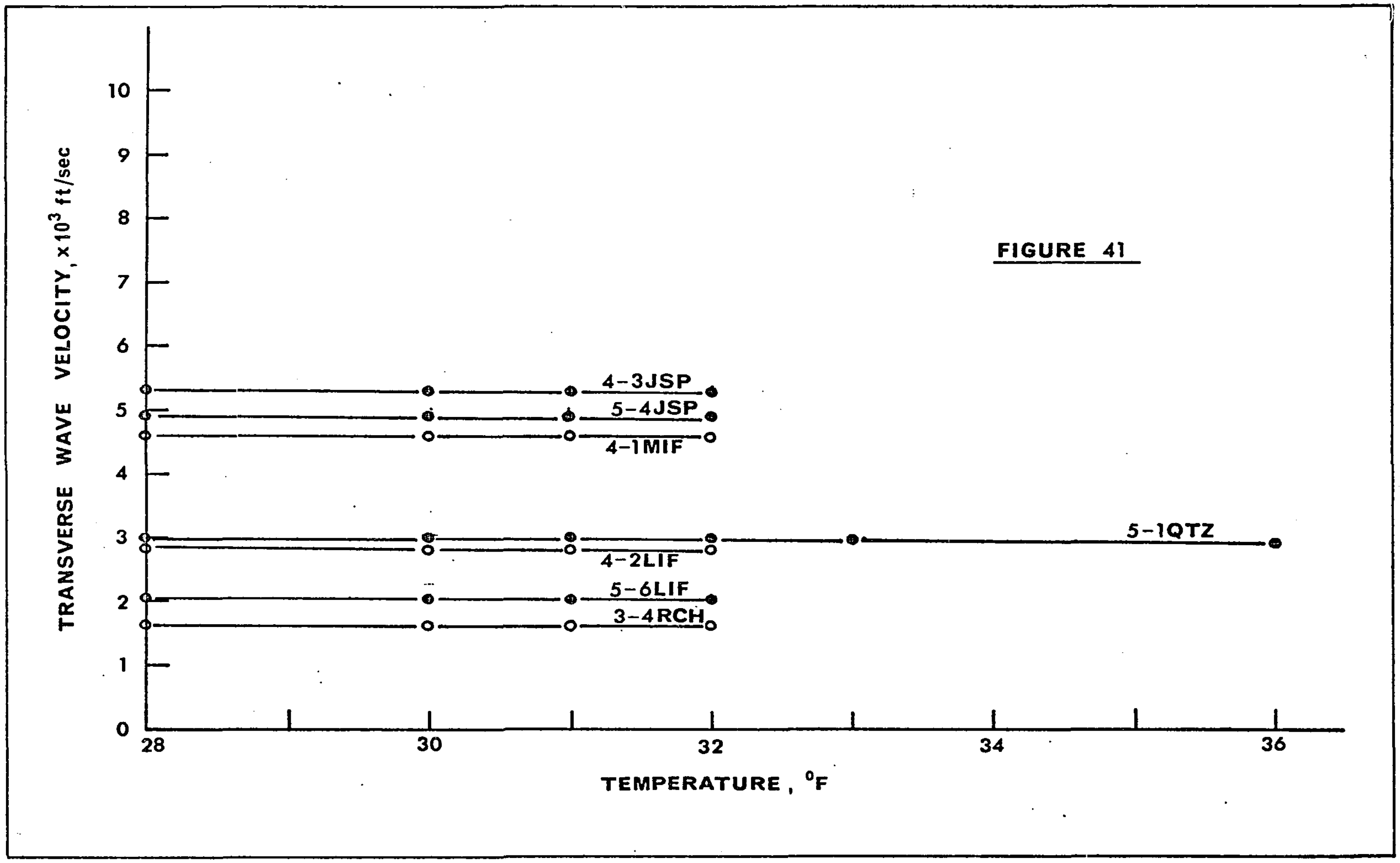
SUMMARY OF SONIC TEST RESULTS

| SAMPLE NUMBER | VELOCITIES OF TRANSVERSE SONIC WAVES THROUGH SAMPLES AT VARIOUS TEMPERATURES LISTED (ft/sec) | | | | | |
|---|---|---|---|---|---|---|
| | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 3 - 4 RCH | 1642 | 1630 | 1627 | 1623 | - | - |
| 4 - 1 MIF | 4660 | 4647 | 4643 | 4630 | - | - |
| 4 - 2 LIF | 2855 | 2836 | 2831 | 2827 | - | - |
| 4 - 3 JSP | 5362 | 5350 | 5343 | 5337 | - | - |
| 5 - 1 QTZ | 3011 | 3004 | 3002 | 3001 | 2993 | 2985 |
| 5 - 4 JSP | 5002 | 4965 | 4955 | 4947 | - | - |
| 5 - 6 LIF | 2072 | 2056 | 2050 | 2041 | - | - |

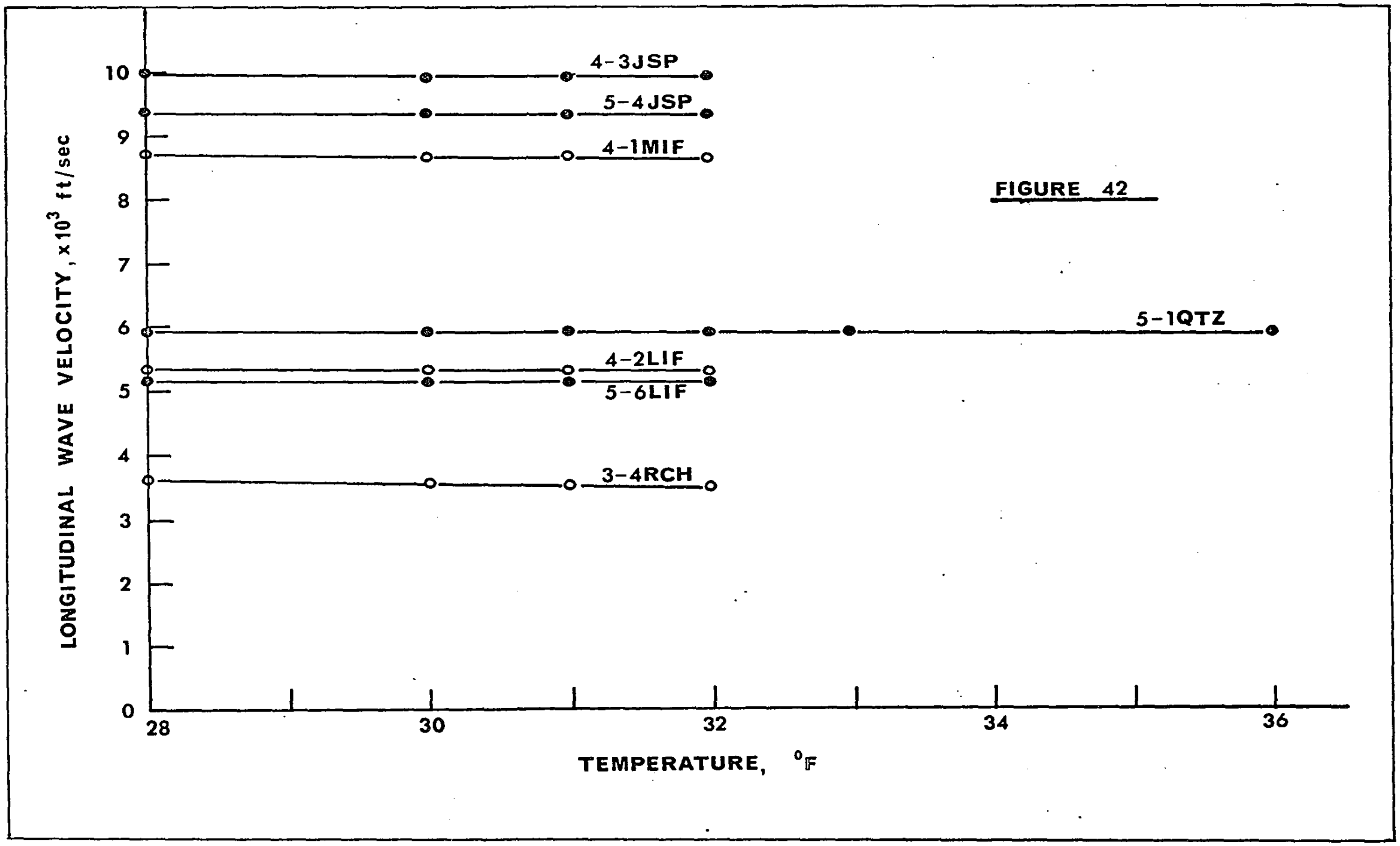
TABLE 10

SUMMARY OF SONIC TEST RESULTS

| SAMPLE NUMBER | VELOCITIES OF LONGITUDINAL SONIC WAVES THROUGH SAMPLES AT VARIOUS TEMPERATURES LISTED (ft/sec) | | | | | |
|---|---|---|---|---|---|---|
| | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 3 - 4 RCH | 3648 | 3609 | 3605 | 3599 | - | - |
| 4 - 1 MIF | 8750 | 8700 | 8691 | 8679 | - | - |
| 4 - 2 LIF | 5334 | 5312 | 5305 | 5301 | - | - |
| 4 - 3 JSP | 10000 | 9980 | 9977 | 9970 | - | - |
| 5 - 1 QTZ | 5952 | 5952 | 5952 | 5952 | 5941 | 5930 |
| 5 - 4 JSP | 9457 | 9398 | 9385 | 9378 | - | - |
| 5 - 6 LIF | 5268 | 5246 | 5237 | 5227 | - | - |




GRAPH OF TRANSVERSE WAVE VELOCITY VS. TEMPERATURES




GRAPH OF LONGITUDINAL WAVE VELOCITY VS. TEMPERATURES

# VII. DISCUSSION OF RESULTS

## 7.1 General

The frozen ores tested in the experiments can be described as granular materials. The grains were of single minerals, organic particles, small fragments of rocks or polycrystalline aggregates. The cementing materials included ice crystals or grains, ferruginuous, calcareous and siliceous minerals and other substances.

Since these frozen ores were observed to be heterogeneous, anisotropic and inelastic materials, the writer believes that all the data from five different tests have been influenced by temperature, testing conditions and the structure of the materials.

Each type of test was carried out on the basis of one specimen of each rock type at a specified temperature. The high transportation cost plus the difficulties in obtaining, preparing and cutting specimens did not make it possible for the writer to test samples in the quantities required for statistical treatment of the data.

All the data obtained from the experiments are believed to be valid but must be associated with the testing conditions. These conditions have been found to exert an important influence on the results obtained. For this reason, the results of the tests should not be regarded as being absolute values of the engineering properties of the frozen materials. More extensive testing, using improved methods, will be necessary before the properties of a type of frozen rock can be given with a high degree of confidence. The influences of testing conditions must be studied and, at the same time, statistical analyses of test results must be made.

These initial results, however, do permit one to obtain an appreciation of the properties of some frozen materials. The differences in the properties which have been obtained at different temperatures may prove to be useful in future attempts to delineate permafrost bodies.

7.2 Compression Tests

Factors affecting the values of uniaxial compressive strength of the frozen geological materials tested are as follows.

7.2.1 Temperature and Water Content

As shown by Figures 34 to 36, it is clear that the uniaxial compressive strengths of the four different types of ores (JSP, LIF, MIF and RCH) were greatly reduced when the temperature was increased from 31° to 33°F. The compressive strength of QTZ specimens, however, appears to have been only slightly affected by temperature (Figure 33). The writer suggests that this may be due to the low water content of QTZ (less than 6%).

Temperature is probably a very important variable when the water content of frozen ores exceeds 10%, The compressive strength properties of frozen ores which are affected by temperature probably depends on the amount of water contained. Water content may be related to the number of ice-cementational bonds, Below freezing, these bonds in the ore bind the individual particles of minerals, organic materials, small fragments of rocks, or poly-crystalline aggregates together to produce material of considerable strength, When thawing takes place, however, the interstitial ice crystals or grains no longer remain frozen in the ore, The phase change from ice to water and simultaneous evaporation of water or sublimation of ice cause the destruction of the ice cementational bonds. This converts the solid frozen ore to a soft unfrozen material with very little cohesive strength. The ratio between the strengths of frozen and unfrozen ore may be as great as 100.

The unconfined uniaxial compressive strength of a specimen of frozen MIF (as shown in Table 3) was 1240 psi at 28°F. This was reduced to 10.0 psi when the temperature was increased to 36°F. For other frozen samples in which the water contents were higher, the effects of temperature were even more severe. One series of specimens, namely RCH, produced results which were not consistent with these trends. Even though the water content of RCH was higher than that of MIF, the uniaxial compressive strength was found to be less influenced by temperature (Figure 35). It is probable that the results have been influenced by composition, texture, porosity and the directional properties of the material. The experimental technique may also have been a factor.

The differences between the strength values of QTZ at 28° and 31°F, as shown in Figure 33, may not be due to temperature, but rather may be due to the lithological characteristics of the material and experimental techniques. The ratios between the strengths at 28° and 36°F are only about 2 and 4 respectively, for the specimens of QTZ tested (Table 3).

All the results for temperatures within the range of 28° to 31°F show decreasing values for strength as the temperature was increased. An abrupt decrease in strength was apparent when the temperature was increased from 31° to 33°F.

#### 7.2.2 The Size and Shape of Specimens

The compressive strength and modulus of deformation of frozen samples are also affected by the size and shape of the specimens. It has been shown by several authors (Tucker, 1945; Udd, 1960; Yu, 1964; Coates, 1970) that an increase in strength corresponds to a decrease in the ratio between length to width or diameter.

Long columns may fail by buckling or by lateral bending rather than by direct compression; thus, a low apparent compressive strength results. Specimens are considered to be long when the ratio between length and diameter exceeds 4. Short columns, with a length/diameter ratio of less than 2, are unsatisfactory due to a distortion of the stress field along the axis of the specimen. This is caused by forces acting at the interface between the specimen and the loading platens.

The writer adopted a ratio between length and width of 2.2-2.4 : 1 for the frozen samples tested in compression. This was in accordance with established procedures and provided a satisfactory compromise between the effects of bending and end conditions. All specimens of the same type of ore were prepared to the same length/width ratio so that the results could be compared.

The effects of the shape of the cross-section of test specimens on experimental results is not established with certainty. One may suspect that edge effects might influence the strength values determined. Butkovich (1958) performed a series of unconfined compression tests on ice samples and reported that the strengths obtained from cylindrical specimens with machined ends were greater than those obtained from samples which had been rough-cut to a shape with a square cross-section.

The writer attempted to produce samples of cylindrical shape but was unable to devise a method by which the specimens could be machined in the time allowed. Specimens of square cross-section were tested and, while the results may have been influenced by the shape chosen, the writer suggests that this shape be the most practical in view of the difficulties which were encountered.

7.2.3 Rate of Loading

The influence of the loading rate on compressive strength is well known (Obert & Duvall, 1967; Hendron, Jr., 1968). In general, the uniaxial compressive strength indicated increases as the rate at which load is applied to specimens is increased. The effect of the rate of loading has been studied by several investigators (Evans, 1958; Wuerker, 1959; Hendron Jr., 1968). A standard rate of 100 psi per second was recommended by the American Society for Testing and Materials and has been used for many years. This rate is considered to be a reasonable compromise between rapid loading and the time which could be required if specimens were loaded at lesser rates.

The loading rate used for the tests described in this thesis, for specimens tested at 28° and 31°F, was in accordance with the A.S.T.M. recommendation.

All of the specimens tested at ambient temperatures of 28° and 31°F failed within 3 minutes. The specimens of LIF and RCH, which were much weaker, withstood the application of load for approximately 10 seconds. Knowing that these samples would be very weak when tested at above-freezing conditions, the writer assumed that a rate of 100 psi per second could be too rapid for the tests in compression at 33° and 36°F. Consequently, much lower rates of $3 \times 10^{-4}$ inches per second were used.

7.2.4 Conditions at End Surfaces of Specimens

The end conditions of specimens have a great influence on the strength and modulus of deformation of frozen geological materials. The end surfaces should be as flat and parallel to each other as is possible and normal to the axis of the specimen.

It has been found by a number of investigators (Obert & Duvall, 1967; Hendron, Jr., 1968; Coates, 1970) that specimens lacking flatness and parallelism of the end surfaces usually fail at loads which are much lower than those which would be supported by specimens with well-prepared end surfaces.

As mentioned in Chapter IV, it was not possible for the writer to prepare the specimens used in the compression tests to the accuracies associated with machined specimens. Several attempts were made but these inevitably resulted in the destruction of the samples. Every attempt was made to cut the specimens accurately and to ensure that the ends were flat and parallel. After cutting, the faces of specimens were trimmed using the abrasive blade. Flatness and parallelism were measured with a vernier caliper. In most cases, the ends were found to be flat and within 0.01 inches of parallelism.

In the writer's opinion, there is no doubt that improvements to the preparation techniques can be made. This, however, will require time. For the present it is suggested that any further refinements will result in increases in the strength properties indicated. The values given in this thesis are probably lower than those which would have resulted from testing of more accurate specimens. It is believed, however, that since specimens were prepared to an accuracy of 0.01 inch that further increases in accuracy will result in small changes to the strength values reported.

### 7.2.5 Failure Patterns

The modes of failure in the uniaxial compression test can be classified into three types: splitting, shear and distortion.

The fracture planes observed during the testing of QTZ specimens were approximately parallel to the direction of loading. These fractures were classified as "splitting failures". The failure of QTZ specimen in compression at 28°F was quite violent. Fragments of the specimens were widely scattered around the testing machine.

Specimens of JSP tested at 28° and 31°F split axially. Those tested at 33° and 36°F failed by shear.

Specimens of LIF and MIF failed in shear. The specimens tested at 28° and 31°F failed on a plane inclined at an angle of about 45° to the direction of loading.

The RCH specimens appeared to have a composition and texture similar to that of peat or clay. These appeared to be dense and compact. It is significant that all of the RCH specimens tested at the different temperatures failed by distortion under applied stress.

7.2.6 Modulus of Deformation

The moduli of deformation of the frozen samples were obtained from the ratio of stress (in. - psi) to the corresponding increment of longitudinal strain (in micro-inches per inch). Modulus of deformation is given by the following formula:

$$E = \frac{\Delta s}{\Delta \varepsilon_{\ell}}$$

where: $E$ = modulus of deformation;

$\Delta s$ = incremental stress;

$\Delta \varepsilon_{\ell}$ = incremental longitudinal strain.

The results, showing the calculated moduli of deformation of ten frozen samples at different temperatures, are tabulated in Tables 4 to 7. The value of the modulus of deformation calculated from any test is greatly affected by the end conditions of the specimens and other factors such as the L/w ratio, the size and shape of the specimen, the rate of loading, inclusions of ice and mineral and the type of platens used to apply load.

## 7.3 Resistivity Tests

The results of the tests for the ten frozen samples which were tested at various temperatures are tabulated in Tables 11 to 20. The values show consistent decreases in resistivity as both temperature and load are increased. All of the data obtained are strongly dependent upon the interstitial fluids (ice, water and air), porosity, permeability, grain size, composition and texture of the materials.

As illustrated by Figures 21, 25, 27, 28 and 30, there were large differences between the resistivities of frozen and unfrozen samples of MIF and JSP. Samples of these materials were porous and had high water contents. The values obtained for the two different phases differed by as much as nearly three orders of magnitude, even though the temperature differences were only 1°F (i.e. 32° and 33°F). The results are in agreement with Barnes (1963) who stressed that small variations in the temperature of frozen materials could cause large variations in resistivity. The high values determined for the samples of MIF and JSP might have been caused by large volumes of pore spaces or voids filled with ice grains or particles below the freezing point. This would have prevented ionic conduction between the ore particles. When the melting of pore ice takes place, however, conducting paths in the specimen are established. This can be an explanation for the rapid decreases in the resistivities of samples of MIF and JSP (as indicated in Figures 21, 25, 27, 28 and 30).

The variations in the resistivities of QTZ specimens, as a function of temperature, were not as great as those for the samples of MIF, JSP and LIF (Figures 22 and 26). The values for the resistivity of 3-3 QTZ and 5-2 QTZ specimens at 28°F were about $6 \times 10^5$ and $9 \times 10^5$ Ω-m respectively. These were reduced to $4 \times 10^4$ and $6 \times 10^4$ Ω-m when the temperature was raised to 36°F. The ratios between these values are 15, and the writer notes that these are many times lower than the ratio between the values for frozen and unfrozen samples of MIF and JSP.

The low values and the slight variations for the resistivities of specimens of RCH were probably due to the texture, composition, porosity or other lithological factors of the material.

The resistivities of all of the frozen samples were found to decrease slowly when the temperature was raised from 28° to 32°F. This may have been due to the gradual conversions of ice to water as the temperature was increased.

A decrease in resistivity as load was increased was noted in all the tests. The application of load has the effect of lowering the resistance of a specimen through closure of the voids or pore spaces. This condition could be utilized in simulating the variations in resistivities of frozen ores with depth. For such an approach, the specimens tested would have to be prepared to very precise specifications so that complete contact could be obtained when load would be applied.

The writer prepared the end faces of the specimens which were to be tested to an accuracy of 0.01 inches of parallelism. From the results in Tables 11 to 20 in Appendix A, it can be seen that the resistivity values for the majority of the specimens decreased very slowly when the load applied exceeded 500 lbs. This was due to there having been proper contacts between the specimens and the lead plates. In addition, further compaction of the specimens would result in decreasing values.

## 7.4 Thermal Conductivity Tests

It is known that the thermal conductivity of ice is 4 times as much as that of water (Penner, 1970). As a result, the overall thermal conductivity of frozen ores with high water contents should decrease as temperature is increased. This effect is due to the process of the liquefaction of ice to water which takes place during melting.

As shown in Figures 31 and 32, the thermal conductivities of the five types of frozen geological materials were only slightly influenced by temperature in the range of 28° to 32°F. Conductivity values decreased when the temperature was increased from 32° to 33°F. In particular, the decrease was especially severe for samples of MIF, which were porous and had a high water content. QTZ specimens, on the other hand, due to low porosity and low water content, displayed only a slight decrease.

The thermal conductivity of the frozen materials should increase as the water content is increased. As shown in Table 2, the conductivity values for 3-3 QTZ were higher than those for 5-2 QTZ. The reverse is true, however, for samples of 3-6 MIF and 5-7 MIF. The writer assumes that the causes are either experimental errors or some other effects.

As mentioned earlier, the frozen ores were not homogeneous. Consequently, the values of thermal conductivity should exhibit a scattering of results. Knowing that, and also that a low number of specimens were tested, the variations observed are not surprising. The writer recommends that further testing should involve specimens in numbers sufficient for techniques of statistical analysis to be applied. In addition, other factors which may have influenced the results are: -

(a) Incomplete contact between the specimens and the copper discs. Flatness and parallelism of the ends of specimens is essential.

(b) Irregularities at the edges of the specimens.

(c) The small interval (1°F) between the testing temperatures.

The writer adopted an electrical conduction method (one-dimensional heat flow) for determining the thermal conductivities of frozen ores reported in the present study. The general theory of the method and a sample calculation of thermal conductivity are described in Appendix H. The apparatus chosen for the tests is commonly used in physics laboratories for measurements of the thermal conductivity of metals or of solid materials. The reasons for utilizing such an apparatus were due to the low cost, the short time required for measurements (readings could be accomplished within 10 minutes) and the ease of operation.

Reasonably reliable measurements, however, were only possible in the region between 28°F and 33°F. The writer attempted to carry out tests at 36°F but was not successful since the specimen discs were too soft to be placed in the apparatus.

It should be noted that the shape, the size and the geometric arrangement of the various constituents of the material (ice, water and ore grains) affect the values of thermal conductivity.

7.5 Shear Tests

From Table 8 and Figures 37 to 40, it can be seen that shear strengths of the samples decreased severely when the temperature was increased from 31° to 33°F. In particular, very sharp decreases in the shearing strengths were observed for the samples of MIF and JSP, both of which were very porous and had high water contents. The shearing strength of QTZ, on the other hand, was an exception since small variations were noted. These were probably associated with the low water content and the strong structure of the material.

Temperature is perhaps the most important variable as regards the shearing strengths of frozen ores for which the water content exceeds 10%. As indicated in Tables 8, the shearing strength values of 3-6 MIF, 4-1 MIF and 5-7 MIF at 28°F were 380.9, 338.1, 350.4 psi, respectively. These were reduced to only 2.19, 2.44 and 1.46 psi respectively when the temperature was increased to 36°F. The average ratio between the strengths of frozen and unfrozen ores was as great as nearly 180. For QTZ specimens, on the other hand, which had water contents of less than 6%, the ratio between the shearing strengths at 28°F and 36°F was only 1.6.

The writer adopted a method of "rapid shear testing" for determining the shearing strengths of the materials considered in the present study. Tests were conducted without any normal load being applied to the specimens. Loading rates of 285.7 - 294.4 psi per minute and 24.4 psi per minute were employed for the freezing temperatures (28°F, 31°F) and melting temperatures (33° and 36°F), respectively. Failures of the frozen specimens usually occurred within two minutes of the commencement of the test. Failures of the specimens tested at melting temperatures occurred within a few seconds.

## 7.6 Sonic Tests

The data which have been used to plot figures 41 and 42 indicate that the sonic wave velocities in frozen ores are only very slightly higher at 28°F than at 32°F. This may be due to the fact that the interstitial fluids remain stable in that temperature range. The velocities of the longitudinal and transverse waves in a QTZ sample are approximately constant in the 28° to 32°F temperature range. Slight variations occur at temperatures of 33° and 36°F. This is in agreement with Timur (1968) who pointed out that the wave velocity in a rock with a very low water content was almost independent of temperature.

The values of the velocities determined for any sample may be affected by the sensitivity of the apparatus, or by the evaporation of water, or the sublimation of ice during the time in which samples are conditioned.

The method and the apparatus used proved to be unsuccessful when temperature exceeded 33°F and when water content exceeded 10% (MIF, LIF, JSP and RCH). Samples tested under these conditions inevitably split when they were placed on the supports of the apparatus prior to testing.

Several investigators (Barnes, 1963; Pihlainen, 1963; Timur, 1968) have found that the velocities of sonic waves in frozen materials are significantly higher than the velocities in unfrozen materials. In theory, this should have been observed.

The values obtained in a sonic test are influenced by porosity, density, grain size, the distribution of ice and the lithology of the material.

As mentioned earlier, the frozen ores tested in the experiments were found to be inhomogeneous and inelastic. Therefore absolutely true values cannot be expected to result from the calculations performed (in which the resonant frequencies of the samples tested are used with the simplified formula $V = 2fL$). The formula is based on assumption of isotropy, elasticity and homogeneity.

# VIII. CONCLUSION AND RECOMMENDATIONS

Several conclusions may be drawn from the experiments which were carried out by the writer. These are based on the limited data which has been presented in the thesis and the writer strongly suggests that more extensive tests will be required to add further accuracy and a high degree of confidence to the test results. The writer hopes that the present study will form the basis for future research on the physical properties of frozen geological materials. If research is continued, improved experimental methods and apparatus will be required.

It is the writer's impression that many aspects of the chemistry and physics of the ice-water-mineral interfaces in frozen geological substances have not yet been fully investigated. Although it is possible to obtain quantitative values for some of the engineering properties of frozen materials, it is not yet possible for one to describe completely the factors and mechanisms involved.

During the preparation of samples, for example, cutting results in the generation of heat which causes melting of the sides and the surfaces of the samples. Since this is unavoidable, the only practical solution is cutting at slow speed and with care. The writer suggests that the mechanics of the cutting and drilling of frozen soils and rocks, with particular reference to mining, are important areas for future research.

The behaviour of frozen geological materials is not yet understood. Many more studies will be required before the influences of environmental conditions on the strength and deformational characteristics are known to any great extent. The results obtained from the present study, however, do provide some quantitative values for the strength and certain other properties of frozen materials from one location. With further research, which is required to add precision to the results, the data should be useful in connection with the design of slopes and open pits in frozen materials. In particular, data for thermal conductivities and the strength properties should be useful in that regard. Data resulting from sonic and resistivity tests should be useful when applied to the mapping of frozen layers or bodies at a particular site. On the basis of this study, it can be concluded that:

(1) The resistivities, thermal conductivities, uniaxial compressive and shearing strengths of the five frozen materials tested decreased as the temperature was increased. Similarly, the velocities of longitudinal and transverse sonic waves through the materials also decreased during thawing. An increase in the test temperature from 28° to 32°F resulted in gradual decrease in the values for all of these properties. A further increase in the test temperature to 33°F, however, resulted in abrupt and severe decreases. These decreases were especially pronounced for the frozen materials which had high water contents and high porosities. When the test temperatures were raised from 33°F to 36°F continuing decreases in resistivities, uniaxial compressive and shearing strengths were noted. These decreases, though, were not as severe as those measured when the temperatures were increased from 32°F to 33°F.

(2) Of the materials tested, the properties of QTZ were the least affected by changes in temperature. The resistivity, thermal

conductivity, uniaxial compressive and shearing strengths of QTZ and the velocities of longitudinal and transverse sonic waves through a sample of QTZ were only slightly changed as temperature was increased.

(3) The water content, the structure of frozen materials and the environmental temperature conditions have a marked effect on the engineering properties of the materials. Changes in the values for these properties are probably associated with the freezing and thawing of interstitial fluids (ice, water, air or gas) contained in the pores of the materials.

(4) It was not possible for the writer to achieve correlations between the data for the various properties. The number of tests performed was limited and the use of such techniques requires that specimens be tested in numbers that are sufficient for the utilization of methods of statistical analysis.

(5) The uniaxial compression test is at present quite satisfactory as a means of determining the compressive strength of a sample of frozen rock or soil. The resistivity and sonic methods proved to be reliable and efficient. Some improvement, however, can be made to the procedures used for specimen preparation. The procedures which the writer followed were time-consuming.

(6) Since all of the frozen samples tested were heterogeneous, inelastic, and anisotropic, the result of a single test cannot be considered as a fixed value for design purposes. Further testing, in order to define the ranges in the values which may be encountered, is required.

## RECOMMENDATIONS

(1) More extensive tests should be conducted to provide sufficient data for the applications of methods of statistical analysis. Attempts should be made to correlate the data for various properties of frozen geological materials. This will make it possible for one to compare the properties of various types of frozen materials and will, therefore, be of value for purposes of design.

(2) Tests should be performed through a wider range of temperatures in order to extend our knowledge of the effects of temperature.

(3) A knowledge of the characteristics of ice (crystallography, structure, texture and grain size) in frozen materials, and the effects of the orientations of bedding planes, the influences of conditioning and thawing periods, and the effects of cutting and sample preparation will be required.

(4) When using the cutting machine that was available, the writer found that he encountered great difficulty in handling and cutting large samples (with height and width exceeding 6 inches). A larger saw will be required for future research.

(5) The method and the apparatus used for measuring the thermal conductivities of the frozen materials was unsuccessful for those tests carried out when the temperature exceeded 33°F. The writer recommends that an attempt be made to achieve the necessary modifications to the equipment. More reliable data will be of value in connection with studies of the rates and depths of thawing that will occur when surfaces of frozen rocks are exposed at a particular pit.

(6) Further experimental and analytical studies should be conducted so that the effects of the following factors may be determined: the influence of moisture (water) migration; variations in conductivities with depth and water content; and specimen preparation techniques.

(7) The tests performed in the future should include tri-axial compression testing. Such tests would add much to our knowledge of the mechanisms of deformation and failure which take place in frozen geological materials.

(8) Shear tests and compression tests performed at melting temperatures and at various rates of loading should be undertaken. At the same time, the deformational characteristics of samples tested in shear should be determined. Normal loads should be applied to specimens tested in shear so that the effects of normal loading may be established.

(9) A modification to the sonic apparatus, which would permit the investigator to measure the velocities of the longitudinal and transverse sonic waves through frozen materials subjected to various pressures, would be very desirable.

(10) Correlations between the data obtained and field data should be undertaken, so that the value of laboratory data may be established.

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# A P P E N D I X   A

## SUMMARY OF RESISTIVITY TEST RESULTS

TABLE 11

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 3-2 JSP

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | 382,880 | 157,820 | 113,140 | 97,500 | 15,740 | 5,690 |
| 200 | - | - | - | 96,060 | 12,470 | 4,313 |
| 500 | 325,550 | 110,690 | 88,710 | 93,570 | 9,734 | 3,605 |
| 1000 | 298,940 | 107,060 | 87,310 | 91,090 | 8,421 | 3,442 |
| 1500 | 282,550 | 103,860 | 85,900 | 89,230 | 8,067 | 3,381 |
| 2000 | 270,270 | 102,180 | 84,700 | 87,980 | 7,775 | 3,300 |
| 2500 | 266,170 | 101,090 | 84,300 | 86,540 | 7,754 | - |
| 3000 | 262,080 | 100,660 | 84,110 | 85,710 | - | - |
| 3500 | 260,030 | 100,240 | 84,110 | 85,500 | - | - |
| 4000 | 257,980 | 100,020 | - | - | - | - |
| 4500 | 257,980 | - | - | - | - | - |

TABLE 12

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 3-3 QTZ

| LOAD | RESISVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | - | - | 124,210 | 62,570 | 59,000 |
| 100 | 770,130 | 687,420 | 278,480 | - | - | - |
| 200 | - | - | - | - | - | 49,680 |
| 500 | 658,340 | 476,060 | 242,880 | 117,180 | 56,370 | 46,990 |
| 1000 | 610,720 | 430,920 | 230,320 | 105,580 | 54,050 | 45,130 |
| 1500 | 573,460 | 385,770 | 203,100 | 95,230 | 52,690 | 43,060 |
| 2000 | 527,910 | 369,360 | 194,730 | 93,160 | 51,910 | 40,370 |
| 2500 | 511,350 | 359,100 | 186,350 | 92,540 | 51,330 | 39,540 |
| 3000 | 496,860 | 352,940 | 182,170 | 92,330 | 50,950 | 39,130 |
| 3500 | 488,580 | 350,890 | 177,980 | 92,130 | 50,950 | 38,900 |
| 4000 | 484,440 | 348,840 | 177,980 | 92,130 | - | - |
| 4500 | 484,440 | 348,840 | - | - | - | - |

TABLE 13

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 3-4 RCH

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN ($\Omega$-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | 23,530 | 17,320 | 14,780 | 9,688 | 7,494 |
| 100 | 26,580 | - | - | - | - | - |
| 200 | - | 21,640 | 14,700 | 12,500 | 8,446 | 6,306 |
| 500 | 21,460 | 19,720 | 14,040 | 10,910 | 7,266 | 5,508 |
| 1000 | 20,350 | 19,130 | 13,160 | 9,440 | 7,038 | 4,545 |
| 1500 | 18,550 | 17,690 | 12,530 | 8,467 | 6,810 | 4,054 |
| 2000 | 16,660 | 16,650 | 12,110 | 7,826 | 6,727 | 3,910 |
| 2500 | 15,570 | 15,930 | 11,870 | 7,349 | 6,686 | 3,849 |
| 3000 | 14,570 | 15,690 | 11,810 | 7,060 | 6,686 | - |
| 3500 | 14,510 | 15,690 | 11,790 | 6,873 | - | - |
| 4000 | 14,490 | - | - | 6,853 | - | - |

TABLE 14

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 3-5 LIF

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | 164,020 | 137,210 | 79,700 | 41,530 | 20,790 | 15,650 |
| 200 | - | - | - | 38,380 | 17,710 | 14,460 |
| 500 | 145,800 | 99,790 | 62,920 | 34,400 | 17,130 | 13,460 |
| 1000 | 135,670 | 79,000 | 54,530 | 32,720 | 16,740 | 12,490 |
| 1500 | 123,520 | 62,370 | 48,240 | 31,880 | 16,350 | 11,740 |
| 2000 | 109,350 | 54,050 | 41,950 | 31,250 | 16,170 | 11,700 |
| 2500 | 101,250 | 49,890 | 35,650 | 30,830 | 16,090 | - |
| 3000 | 95,170 | 47,810 | 27,260 | 30,620 | 16,070 | - |
| 3500 | 89,100 | 47,810 | 25,170 | 30,620 | - | - |
| 4000 | 85,050 | - | 25,170 | - | - | - |
| 4500 | 85,050 | - | - | - | - | - |

TABLE 15

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 3-6 MIF

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | 1,593,600 | 1,372,440 | 369,780 | 7,451 | 3,533 |
| 100 | 2,010,640 | - | - | 211,020 | - | - |
| 200 | - | - | - | - | 6,635 | 2,670 |
| 500 | 1,742,420 | 1,490,400 | 1,027,370 | 198,960 | 5,693 | 2,389 |
| 1000 | 1,699,420 | 1,453,950 | 970,510 | 180,870 | 4,981 | 2,108 |
| 1500 | 1,678,950 | 1,397,250 | 945,020 | 168,810 | 4,312 | 1,987 |
| 2000 | 1,666,660 | 1,377,000 | 909,740 | 156,750 | 3,851 | 1,987 |
| 2500 | 1,652,330 | 1,360,800 | 898,000 | 146,700 | 3,746 | - |
| 3000 | 1,640,050 | 1,342,580 | 884,250 | 146,700 | 3,726 | - |
| 3500 | 1,633,900 | 1,324,350 | 878,370 | - | - | - |
| 4000 | 1,625,710 | 1,318,280 | 874,450 | - | - | - |
| 4500 | 1,621,620 | 1,316,250 | 872,480 | - | - | - |
| 5000 | 1,621,620 | - | - | - | - | - |

TABLE 16

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 5-2 QTZ

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | - | 358,300 | 99,130 | 75,050 | 62,640 |
| 100 | 1,062,650 | 1,080,090 | - | - | - | - |
| 500 | 993,040 | 789,060 | 283,460 | 83,890 | 71,590 | 57,760 |
| 1000 | 952,080 | 737,820 | 267,260 | 74,250 | 70,580 | 55,320 |
| 1500 | 921,380 | 711,180 | 257,140 | 69,810 | 69,760 | 54,100 |
| 2000 | 904,990 | 678,380 | 249,040 | 66,730 | 69,360 | 53,080 |
| 2500 | 892,710 | 670,180 | 240,950 | 64,990 | 68,950 | 52,480 |
| 3000 | 884,520 | 664,030 | 236,890 | 63,060 | 68,540 | 52,070 |
| 3500 | 882,470 | 659,940 | 234,870 | 61,520 | 68,140 | 52,070 |
| 4000 | 880,420 | 659,940 | 234,870 | 60,170 | 68,140 | - |
| 4500 | 880,420 | - | - | 59,400 | - | - |
| 5000 | - | - | - | 59,200 | - | - |

## TABLE 17

## SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

## FOR SAMPLE 5-3 JSP

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | 117,450 | 70,190 | 56,060 | 8,654 | 5,864 |
| 100 | 139,770 | - | - | - | - | - |
| 200 | - | - | - | - | 7,888 | 5,327 |
| 500 | 134,770 | 92,140 | 64,500 | 51,840 | 7,743 | 4,254 |
| 1000 | 131,960 | 80,190 | 61,340 | 49,540 | 7,660 | 3,717 |
| 1500 | 129,760 | 74,930 | 60,290 | 48,000 | 7,577 | 3,638 |
| 2000 | 127,760 | 72,490 | 59,020 | 46,850 | 7,536 | 3,579 |
| 2500 | 126,150 | 70,690 | 58,390 | 45,890 | 7,494 | 3,539 |
| 3000 | 124,750 | 69,860 | 57,760 | 45,310 | - | - |
| 3500 | 123,750 | 69,460 | 57,760 | 45,120 | - | - |
| 4000 | 122,950 | 69,460 | - | - | - | - |
| 4500 | 122,550 | - | - | - | - | - |
| 5000 | 122,350 | - | - | - | - | - |

TABLE 18

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 5-4 JSP

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | 413,600 | 181,750 | 98,400 | 17,360 | 11,710 |
| 100 | 583,200 | - | - | - | - | - |
| 200 | - | - | - | - | 15,250 | 10,580 |
| 500 | 496,120 | 325,600 | 164,570 | 86,700 | 14,350 | 9,346 |
| 1000 | 457,650 | 282,600 | 154,630 | 80,970 | 13,760 | 8,494 |
| 1500 | 431,320 | 255,900 | 148,630 | 76,710 | 13,430 | 7,825 |
| 2000 | 419,180 | 245,700 | 142,830 | 73,870 | 13,270 | 7,420 |
| 2500 | 407,020 | 239,600 | 140,760 | 72,660 | 13,140 | 7,135 |
| 3000 | 400,950 | 233,400 | 139,750 | 71,840 | 13,100 | - |
| 3500 | 396,900 | 229,300 | 139,100 | 71,640 | - | - |
| 4000 | 394,870 | 229,300 | 138,890 | 71,640 | - | - |
| 4500 | 394,870 | - | - | - | - | - |

## TABLE 19

## SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

## FOR SAMPLE 5-5'LIF

| LOAD lbs. | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | 102,660 | 64,980 | 37,940 | 22,880 | 3,481 | 1,556 |
| 200 | - | - | - | 21,460 | 3,150 | 1,392 |
| 500 | 78,570 | 35,920 | 31,970 | 19,230 | 2,775 | 1,249 |
| 1000 | 70,060 | 30,230 | 30,050 | 18,020 | 2,467 | 1,126 |
| 1500 | 63,380 | 26,890 | 28,560 | 17,010 | 2,378 | 1,024 |
| 2000 | 59,740 | 25,710 | 27,280 | 16,400 | 2,313 | 962 |
| 2500 | 57,920 | 24,540 | 26,850 | 16,200 | 2,203 | 961 |
| 3000 | 56,290 | 23,950 | 26,000 | 16,200 | 2,158 | - |
| 3500 | 54,880 | 23,750 | 25,570 | - | - | - |
| 4000 | 54,470 | 23,750 | 25,360 | - | - | - |
| 4500 | 53,860 | - | - | - | - | - |
| 5000 | 53,660 | - | - | - | - | - |

TABLE 20

SUMMARY OF RESISTIVITY - LOAD - TEMPERATURE DATA

FOR SAMPLE 5-7 MIF

| LOAD | RESISTIVITY VALUES FOR THE TEMPERATURES AND LOADS SHOWN (Ω-m) | | | | | |
|---|---|---|---|---|---|---|
| lbs. | 28°F | 30°F | 31°F | 32°F | 33°F | 36°F |
| 50 | - | 1,447,570 | 1,020,200 | 243,650 | 4,300 | 2,082 |
| 100 | 1,660,340 | - | - | - | - | - |
| 200 | - | - | - | 229,320 | 4,110 | 1,943 |
| 500 | 1,614,800 | 1,319,250 | 853,600 | 221,130 | 3,940 | 1,784 |
| 1000 | 1,579,600 | 1,261,100 | 841,000 | 214,990 | 3,815 | 1,665 |
| 1500 | 1,560,970 | 1,192,950 | 803,100 | 210,890 | 3,709 | 1,626 |
| 2000 | 1,552,680 | 1,134,800 | 771,490 | 204,750 | 3,625 | - |
| 2500 | 1,546,470 | 1,078,660 | 733,540 | 202,700 | 3,541 | - |
| 3000 | 1,540,260 | 1,050,590 | 714,580 | 200,650 | - | - |
| 3500 | 1,536,120 | 1,036,550 | 708,250 | - | - | - |
| 4000 | 1,534,050 | 1,028,530 | 706,150 | - | - | - |
| 4500 | 1,531,980 | 1,024,520 | - | - | - | - |
| 5000 | - | 1,024,520 | - | - | - | - |

# A P P E N D I X B

## DETAILS OF THERMAL CONDUCTIVITY TEST

TABLE 21

DETAILS OF THERMAL CONDUCTIVITY TEST

T Room = -2.2°C (28°F)

| SPECIMEN NUMBER | RADIUS r (cm) | THICKNESS d (cm) | $A_s$ ($cm^2$) | $T_a$ (C°) | $T_b$ (C°) | $T_c$ (C°) | HEAT EMITTED (e) $x10^{-3}$cal/sec.$cm^2$C° | K $x10^{-3}$cal/sec.cm.C° |
|---|---|---|---|---|---|---|---|---|
| 3-2JSP - $T_1$ | 2.06 | 1.02 | 13.20 | 2.2 | 4.6 | 5.0 | 2.816 | 7.840 |
| 3-3QTZ - $T_1$ | 2.05 | 1.02 | 13.14 | 1.2 | 4.4 | 5.2 | 3.148 | 4.088 |
| 3-4RCH - $T_1$ | 2.06 | 1.03 | 13.33 | 2.0 | 5.2 | 5.8 | 2.579 | 5.167 |
| 3-5LIF - $T_1$ | 2.06 | 1.03 | 13.33 | 2.0 | 4.8 | 5.4 | 2.739 | 6.167 |
| 3-6MIF - $T_1$ | 2.06 | 1.02 | 13.20 | 2.4 | 4.6 | 5.0 | 2.756 | 9.000 |
| 5-2QTZ - $T_1$ | 2.05 | 1.02 | 13.14 | 1.4 | 5.2 | 6.0 | 2.701 | 3.459 |
| 5-3JSP - $T_1$ | 2.06 | 1.03 | 13.33 | 2.0 | 4.4 | 5.4 | 2.812 | 7.272 |
| 5-4JSP - $T_1$ | 2.06 | 1.02 | 13.20 | 2.2 | 4.8 | 5.2 | 2.730 | 7.069 |
| 5-5LIF - $T_1$ | 2.06 | 1.02 | 13.20 | 2.2 | 5.0 | 5.6 | 2.605 | 6.312 |
| 5-6LIF - $T_1$ | 2.06 | 1.03 | 13.33 | 2.2 | 5.0 | 5.8 | 2.560 | 6.279 |
| 5-7MIF - $T_1$ | 2.06 | 1.00 | 12.94 | 2.5 | 4.4 | 5.2 | 2.723 | 10.328 |

VOLTAGE = 6V

CURRENT = 0.650 AMP.

$A_a$ = 29.5 $cm^2$ = $A_c$

$A_b$ = 16.1 $cm^2$

TABLE 22

DETAILS OF THERMAL CONDUCTIVITY TEST

T Room = -1.1°C (30°F)

| SPECIMEN NUMBER | RADIUS r (cm) | THICKNESS d (cm) | $A_s$ ($cm^2$) | $T_a$ (C°) | $T_b$ (C°) | $T_c$ (C°) | HEAT EMITTED (e) $x10^{-3}$ $cal/sec.cm^2C°$ | K $x10^{-3}$ cal/sec.cm.C° |
|---|---|---|---|---|---|---|---|---|
| 3-2JSP - $T_2$ | 2.05 | 1.04 | 13.40 | 3.1 | 6.2 | 6.6 | 2.081 | 6.484 |
| 3-3QTZ - $T_2$ | 2.06 | 1.02 | 13.20 | 1.9 | 5.8 | 6.8 | 2.328 | 3.720 |
| 3-4RCH - $T_2$ | 2.06 | 1.02 | 13.20 | 3.0 | 7.2 | 7.8 | 1.859 | 4.137 |
| 3-5LIF - $T_2$ | 2.05 | 1.01 | 13.01 | 3.1 | 7.0 | 7.4 | 1.911 | 4.660 |
| 3-6MIF - $T_2$ | 2.06 | 1.00 | 12.94 | 3.0 | 5.4 | 6.2 | 2.261 | 8.174 |
| 5-2QTZ - $T_2$ | 2.05 | 1.03 | 13.27 | 1.8 | 6.4 | 7.0 | 2.237 | 3.048 |
| 5-3JSP - $T_2$ | 2.06 | 1.03 | 13.33 | 3.6 | 7.0 | 7.4 | 1.837 | 5.908 |
| 5-4JSP - $T_2$ | 2.06 | 1.01 | 13.07 | 3.0 | 6.6 | 6.8 | 2.037 | 5.138 |
| 5-5LIF - $T_2$ | 2.06 | 1.02 | 13.20 | 3.2 | 7.0 | 7.4 | 1.894 | 4.883 |
| 5-6LIF - $T_2$ | 2.05 | 1.02 | 13.14 | 3.2 | 7.0 | 8.0 | 1.826 | 4.766 |
| 5-7MIF - $T_2$ | 2.06 | 1.00 | 12.94 | 3.4 | 5.6 | 6.8 | 2.074 | 9.264 |

VOLTAGE = 6V

CURRENT = 0.650 AMP.

$A_a$ = 29.5 $cm^2$ = $A_c$

$A_b$ = 16.1 $cm^2$

<u>TABLE 23</u>

<u>DETAILS OF THERMAL CONDUCTIVITY TEST</u>

T Room = -0.55°C (31°F)

| SPECIMEN NUMBER | RADIUS r (cm) | THICKNESS d (cm) | $A_s$ ($cm^2$) | $T_a$ (C°) | $T_b$ (C°) | $T_c$ (C°) | HEAT EMITTED (e) $\times 10^{-3}$ cal/sec.$cm^2$C° | K $\times 10^{-3}$ cal/sec.cm.C° |
|---|---|---|---|---|---|---|---|---|
| 3-2JSP - $T_3$ | 2.06 | 1.00 | 12.94 | 3.3 | 6.6 | 7.1 | 1.955 | 5.751 |
| 3-3QTZ - $T_3$ | 2.05 | 1.04 | 13.40 | 2.0 | 6.3 | 7.2 | 2.178 | 3.463 |
| 3-4RCH - $T_3$ | 2.06 | 1.03 | 13.33 | 3.2 | 7.4 | 8.4 | 1.754 | 4.185 |
| 3-5LIF - $T_3$ | 2.05 | 1.01 | 13.01 | 3.4 | 7.4 | 7.8 | 1.795 | 4.649 |
| 3-6MIF - $T_3$ | 2.06 | 1.01 | 13.07 | 3.4 | 5.8 | 6.6 | 2.080 | 8.561 |
| 5-2QTZ - $T_3$ | 2.06 | 1.00 | 12.94 | 1.8 | 6.2 | 7.3 | 2.221 | 2.991 |
| 5-3JSP - $T_3$ | 2.05 | 1.02 | 13.14 | 3.4 | 6.8 | 7.4 | 1.885 | 5.730 |
| 5-4JSP - $T_3$ | 2.05 | 1.02 | 13.14 | 3.0 | 6.8 | 7.2 | 1.965 | 4.822 |
| 5-5LIF - $T_3$ | 2.04 | 1.00 | 12.82 | 3.4 | 7.2 | 7.6 | 1.835 | 4.960 |
| 5-6LIF - $T_3$ | 2.06 | 1.03 | 13.33 | 3.2 | 7.0 | 7.8 | 1.847 | 4.821 |
| 5-7MIF - $T_3$ | 2.06 | 1.01 | 13.07 | 3.4 | 5.8 | 6.2 | 2.136 | 8.792 |

VOLTAGE = 6V

CURRENT = 0.650 AMP.

$A_a$ = 29.5 $cm^2$ = $A_c$

$A_b$ = 16.1 $cm^2$

## TABLE 24

## DETAILS OF THERMAL CONDUCTIVITY TEST

T Room = 0°C (32°F)

| SPECIMEN NUMBER | RADIUS r (cm) | THICKNESS d (cm) | $A_s$ ($cm^2$) | $T_a$ (C°) | $T_b$ (C°) | $T_c$ (C°) | HEAT EMITTED (e) $x10^{-3}$ cal/sec.$cm^2$C° | K $x10^{-3}$ cal/sec.cm.C° |
|---|---|---|---|---|---|---|---|---|
| 3-2JSP - $T_4$ | 2.06 | 1.04 | 13.46 | 3.0 | 6.5 | 7.2 | 1.987 | 5.336 |
| 3-3QTZ - $T_4$ | 2.05 | 1.04 | 13.40 | 1.8 | 6.0 | 7.2 | 2.252 | 3.346 |
| 3-4RCH - $T_4$ | 2.07 | 1.01 | 13.14 | 3.2 | 7.4 | 8.2 | 1.777 | 4.102 |
| 3-5LIF - $T_4$ | 2.05 | 1.03 | 13.27 | 3.0 | 7.4 | 8.0 | 1.820 | 3.969 |
| 3-6MIF - $T_4$ | 2.06 | 1.01 | 13.07 | 3.4 | 5.8 | 7.0 | 2.027 | 8.341 |
| 5-2QTZ - $T_4$ | 2.07 | 1.03 | 13.40 | 1.8 | 6.6 | 7.2 | 2.180 | 2.823 |
| 5-3JSP - $T_4$ | 2.05 | 1.03 | 13.27 | 3.0 | 6.8 | 7.0 | 1.987 | 4.937 |
| 5-4JSP - $T_4$ | 2.07 | 1.00 | 13.01 | 2.8 | 6.6 | 7.0 | 2.044 | 4.522 |
| 5-5LIF - $T_4$ | 2.06 | 1.02 | 13.20 | 3.0 | 7.0 | 8.0 | 1.854 | 4.309 |
| 5-6LIF - $T_4$ | 2.06 | 1.02 | 13.20 | 3.2 | 7.2 | 8.4 | 1.769 | 4.410 |
| 5-7MIF - $T_4$ | 2.06 | 1.01 | 13.07 | 3.4 | 5.8 | 6.4 | 2.108 | 8.675 |

VOLTAGE = 6V

CURRENT = 0.650 AMP.

$A_a$ = 29.5 $cm^2$ = $A_c$

$A_b$ = 16.1 $cm^2$

TABLE 25

DETAILS OF THERMAL CONDUCTIVITY TEST

T Room = +0.55°C (33°F)

| SPECIMEN NUMBER | RADIUS r (cm) | THICKNESS d (cm) | $A_s$ ($cm^2$) | $T_a$ (C°) | $T_b$ (C°) | $T_c$ (C°) | HEAT EMITTED (e) $\times 10^{-3}$ cal/sec.$cm^2$C° | K $\times 10^{-3}$ cal/sec.cm.C° |
|---|---|---|---|---|---|---|---|---|
| 3-2JSP - $T_5$ | 2.06 | 1.01 | 13.07 | 3.3 | 7.0 | 7.8 | 1.839 | 4.932 |
| 3-3QTZ - $T_5$ | 2.06 | 1.02 | 13.20 | 2.1 | 7.0 | 8.0 | 1.982 | 2.847 |
| 3-4RCH - $T_5$ | 2.06 | 1.03 | 13.33 | 3.2 | 7.6 | 8.6 | 1.720 | 3.938 |
| 3-5LIF - $T_5$ | 2.05 | 1.01 | 13.02 | 3.2 | 7.9 | 8.7 | 1.695 | 3.600 |
| 3-6MIF - $T_5$ | 2.07 | 1.03 | 13.40 | 3.6 | 7.0 | 7.9 | 1.784 | 5.689 |
| 5-2QTZ - $T_5$ | 2.06 | 1.00 | 12.94 | 1.9 | 6.8 | 7.6 | 2.083 | 2.770 |
| 5-3JSP - $T_5$ | 2.05 | 1.01 | 13.01 | 3.2 | 8.0 | 8.8 | 1.679 | 3.501 |
| 5-4JSP - $T_5$ | 2.05 | 1.01 | 13.01 | 3.2 | 8.2 | 8.8 | 1.666 | 3.350 |
| 5-5LIF - $T_5$ | 2.06 | 1.02 | 13.20 | 3.0 | 8.4 | 9.0 | 1.653 | 2.954 |
| 5-7MIF - $T_5$ | 2.07 | 1.03 | 13.40 | 3.0 | 6.6 | 7.4 | 1.955 | 5.012 |

VOLTAGE = 6V

CURRENT = 0.650 AMP.

$A_a = 29.5\ cm^2 = A_c$

$A_b = 16.1\ cm^2$

# APPENDIX C

## UNIAXIAL COMPRESSION TEST DATA

TABLE 26

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-3QTZ - $C_1$

L = 2.588 in. A = 1.304 $in^2$ $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E $x\ 10^6$ psi |
|---|---|---|---|---|
| 383.4 | 1159 | 383.4 | 1159 | 0.33 |
| 786.8 | 3091 | 383.4 | 1932 | 0.20 |
| 1150.2 | 5023 | 383.4 | 1932 | 0.20 |
| 1533.6 | 6955 | 383.4 | 1932 | 0.20 |
| 1917.0 | 8887 | 383.4 | 1932 | 0.20 |
| 2300.4 | 11205 | 383.4 | 2318 | 0.17 |
| 2683.8 | 13523 | 383.4 | 2318 | 0.17 |
| 3067.2 | 15455 | 383.4 | 1932 | 0.20 |
| 3450.6 | 17387 | 383.4 | 1932 | 0.20 |
| 3834.0 | 19705 | 383.4 | 2318 | 0.17 |
| 4217.4 | 22409 | 383.4 | 2704 | 0.14 |
| | | | Mean | 0.19 |

Specimen failed at 4600 psi

TABLE 27

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-3QTZ - $C_2$

L = 2.598 in. A = 1.311 $in^2$ $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^6$ psi |
|---|---|---|---|---|
| 381.4 | 1925 | 381.4 | 1925 | 0.20 |
| 762.8 | 4234 | 381.4 | 2309 | 0.14 |
| 1144.2 | 7313 | 381.4 | 3079 | 0.12 |
| 1535.6 | 9622 | 381.4 | 2309 | 0.14 |
| 1907.0 | 11931 | 381.4 | 2309 | 0.14 |
| 2288.4 | 14626 | 381.4 | 2695 | 0.16 |
| 2669.8 | 16935 | 381.4 | 2309 | 0.14 |
| 3051.2 | 20014 | 381.4 | 3079 | 0.12 |
| 3432.6 | 23478 | 381.4 | 3464 | 0.11 |
| | | | Mean | 0.14 |

Specimen failed at 3471.0 psi

TABLE 28

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-3QTZ - $C_3$

L = 2.617 in. A = 1.322 $in^2$ $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E x $10^6$ psi |
|---|---|---|---|---|
| 189.1 | 1146 | 189.1 | 1146 | 0.17 |
| 378.2 | 2674 | 189.1 | 1528 | 0.12 |
| 567.3 | 4393 | 189.1 | 1719 | 0.11 |
| 756.4 | 6112 | 189.1 | 1719 | 0.11 |
| 945.5 | 8405 | 189.1 | 2293 | 0.08 |
| 1134.6 | 10698 | 189.1 | 2293 | 0.08 |
| 1323.7 | 12991 | 189.1 | 2293 | 0.08 |
| 1512.8 | 14519 | 189.1 | 1528 | 0.12 |
| 1701.9 | 16430 | 189.1 | 1911 | 0.10 |
| | | | Mean | 0.108 |

Specimen failed at 1778 psi

TABLE 29

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-3QTZ - $C_4$

L = 2.602 in. A = 1.292 $in^2$ $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 154.7 | 1537 | 154.7 | 1537 | 100.6 |
| 309.4 | 3074 | 154.7 | 1537 | 100.6 |
| 464.1 | 4803 | 154.7 | 1729 | 89.4 |
| 618.8 | 6340 | 154.7 | 1537 | 100.6 |
| 773.5 | 8069 | 154.7 | 1729 | 89.4 |
| 928.2 | 9798 | 154.7 | 1729 | 89.4 |
| 1082.9 | 11719 | 154.7 | 1921 | 80.5 |
| | | | Mean | 93.0 |

Specimen failed at 1200 psi

TABLE 30

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-4RCH - $C_1$

L = 2.663 in. A = 1.345 $in^2$ $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 74.3 | 1877 | 74.3 | 1877 | 39.5 |
| 148.6 | 3942 | 74.3 | 2065 | 35.9 |
| 222.9 | 5819 | 74.3 | 1877 | 39.5 |
| 297.2 | 7884 | 74.3 | 2065 | 35.9 |
| 371.5 | 10162 | 74.3 | 2278 | 32.6 |
| 445.8 | 12602 | 74.3 | 2440 | 30.4 |
| 520.1 | 15042 | 74.3 | 2440 | 30.4 |
| 594.4 | 17670 | 74.3 | 2628 | 28.2 |
| 668.7 | 20110 | 74.3 | 2440 | 30.4 |
| 743.0 | 22738 | 74.3 | 2628 | 28.2 |
| 817.3 | 25554 | 74.3 | 2816 | 27.9 |
| 891.1 | 28558 | 74.3 | 3004 | 24.7 |
| 965.9 | 31562 | 74.3 | 3004 | 24.7 |
| | | | Mean | 31.4 |

Specimen failed at 980 psi

TABLE 31

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-4RCH - $C_2$

L = 2.614 in.  A = 1.320 $in^2$  $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 75.8 | 2678 | 75.8 | 2678 | 28.3 |
| 151.6 | 5738 | 75.8 | 3060 | 24.8 |
| 227.4 | 8798 | 75.8 | 3060 | 24.8 |
| 303.2 | 11858 | 75.8 | 3060 | 24.8 |
| 379.0 | 15301 | 75.8 | 3443 | 22.0 |
| 454.8 | 19126 | 75.8 | 3825 | 19.8 |
| 530.6 | 23334 | 75.8 | 4208 | 18.0 |
| 606.4 | 27542 | 75.8 | 4208 | 18.0 |
| | | | Mean | 22.6 |

Specimen failed at 634 psi

TABLE 32

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-4RCH - $C_3$

L = 2.633 in.  A = 1.320 $in^2$  $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 7.58 | 2278 | 7.58 | 2278 | 3.34 |
| 15.16 | 5936 | 7.58 | 3658 | 2.07 |
| 22.74 | 9354 | 7.58 | 3418 | 2.22 |
| 30.32 | 13012 | 7.58 | 3658 | 2.07 |
| 37.90 | 16810 | 7.58 | 3798 | 2.00 |
| 45.48 | 20608 | 7.58 | 3798 | 2.00 |
| 53.06 | 24266 | 7.58 | 3658 | 2.07 |
| 60.64 | 28823 | 7.58 | 4557 | 1.66 |
| 68.22 | 34140 | 7.58 | 5317 | 1.42 |
| | | | Mean | 2.09 |

Specimen failed at 69.7 psi

TABLE 33

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-4RCH - $C_4$

L = 2.586 in.   A = 1.311 $in^2$   $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 3.81 | 3093 | 3.81 | 3093 | 1.23 |
| 7.62 | 6573 | 3.81 | 3480 | 1.09 |
| 11.43 | 10053 | 3.81 | 3480 | 1.09 |
| 15.24 | 13533 | 3.81 | 3480 | 1.09 |
| 19.05 | 17399 | 3.81 | 3866 | 0.99 |
| 22.86 | 21265 | 3.81 | 3866 | 0.99 |
| 26.67 | 24745 | 3.81 | 3480 | 1.09 |
| 30.48 | 28998 | 3.81 | 4253 | 0.90 |
| 34.29 | 32854 | 3.81 | 3866 | 0.99 |
| 38.10 | 37504 | 3.81 | 4640 | 0.82 |
| 41.91 | 42144 | 3.81 | 4640 | 0.82 |
| | | | Mean | 1.01 |

Specimen failed at 42.8 psi

TABLE 34

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-5LIF - $C_1$

L = 2.650 in.   A = 1.334 $in^2$   $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 75.0 | 2264 | 75.0 | 2264 | 33.13 |
| 150.0 | 4151 | 75.0 | 1887 | 39.75 |
| 225.0 | 6038 | 75.0 | 1887 | 39.75 |
| 300.0 | 7925 | 75.0 | 1887 | 39.75 |
| 375.0 | 10189 | 75.0 | 2264 | 33.13 |
| 450.0 | 12453 | 75.0 | 2264 | 33.13 |
| 525.0 | 15849 | 75.0 | 3396 | 22.09 |
| 600.0 | 20000 | 75.0 | 4151 | 18.07 |
| 675.0 | 24528 | 75.0 | 4528 | 16.56 |
| 750.0 | 29434 | 75.0 | 4906 | 15.29 |
| 825.0 | 34340 | 75.0 | 4906 | 15.29 |
| | | | Mean | 27.81 |

Specimen failed at 825 psi

## TABLE 35

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 3-5LIF - $C_2$

L = 2.628 in.   A = 1.259 $in^2$   $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 79.4 | 2283 | 79.4 | 2283 | 34.8 |
| 158.8 | 5327 | 79.4 | 3044 | 26.1 |
| 238.2 | 8371 | 79.4 | 3044 | 26.1 |
| 317.6 | 11035 | 79.4 | 2664 | 29.8 |
| 397.0 | 14079 | 79.4 | 3044 | 26.1 |
| 476.4 | 18265 | 79.4 | 4186 | 18.9 |
| 555.8 | 22451 | 79.4 | 4186 | 18.9 |
| | | | Mean | 25.8 |

Specimen failed at 596.1 psi

TABLE 36

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-5LIF - $C_3$

L = 2.596 in.   A = 1.299 $in^2$   $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $\times 10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $\times 10^{-6}$(in/in) | (5) From (3) & (4) E $\times 10^3$ psi |
|---|---|---|---|---|
| 7.70 | 2696 | 7.70 | 2696 | 2.86 |
| 15.40 | 5778 | 7.70 | 3082 | 2.50 |
| 23.10 | 9281 | 7.70 | 3503 | 2.20 |
| 30.80 | 12363 | 7.70 | 3082 | 2.50 |
| 38.50 | 15866 | 7.70 | 3503 | 2.20 |
| 46.20 | 19718 | 7.70 | 3852 | 2.00 |
| 53.90 | 24340 | 7.70 | 4622 | 1.67 |
| | | | Mean | 2.28 |

Specimen failed at 58.50 psi

TABLE 37

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-5LIF - $C_4$

L = 2.510 in. A = 1.212 $in^2$ $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 4.13 | 2988 | 4.13 | 2988 | 1.38 |
| 8.25 | 5976 | 4.13 | 2988 | 1.38 |
| 12.38 | 7968 | 4.13 | 1992 | 2.07 |
| 16.50 | 10359 | 4.13 | 2391 | 1.73 |
| 20.63 | 13545 | 4.13 | 3186 | 1.30 |
| 24.76 | 16335 | 4.13 | 2528 | 1.63 |
| 28.89 | 19124 | 4.13 | 2789 | 1.48 |
| | | | Mean | 1.57 |

Specimen failed at 31.4 psi

TABLE 38

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-6MIF - $C_1$

L = 2.585 in. A = 1.288 $in^2$ $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E $x\ 10^3$ psi |
|---|---|---|---|---|
| 77.6 | 1161 | 77.6 | 1161 | 66.8 |
| 155.2 | 2321 | 77.6 | 1160 | 66.8 |
| 232.8 | 3482 | 77.6 | 1161 | 66.8 |
| 310.4 | 4643 | 77.6 | 1161 | 66.8 |
| 388.0 | 6190 | 77.6 | 1547 | 50.2 |
| 465.6 | 7350 | 77.6 | 1160 | 66.8 |
| 543.2 | 8511 | 77.6 | 1161 | 66.8 |
| 620.8 | 9671 | 77.6 | 1160 | 66.8 |
| 698.4 | 11605 | 77.6 | 1934 | 40.1 |
| 776.0 | 14313 | 77.6 | 2708 | 28.7 |
| 853.6 | 16634 | 77.6 | 2321 | 33.4 |
| 931.2 | 19342 | 77.6 | 2708 | 28.7 |
| 1008.8 | 22437 | 77.6 | 3095 | 25.1 |
| 1086.4 | 26306 | 77.6 | 3869 | 20.1 |
| 1164.0 | 30561 | 77.6 | 4255 | 18.2 |
| 1211.6 | 37137 | 77.6 | 6576 | 11.8 |
| 1319.2 | 44874 | 77.6 | 7737 | 10.0 |
| | | | Mean | 43.2 |

Specimen Failed at 1397.5 psi

TABLE 39

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-6MIF - $C_2$

L = 2.625 in  A = 1.245 $in^2$  $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 80.3 | 1905 | 80.3 | 1905 | 42.2 |
| 160.6 | 4572 | 80.3 | 2667 | 30.1 |
| 240.9 | 7239 | 80.3 | 2667 | 30.1 |
| 321.2 | 9906 | 80.3 | 2667 | 30.1 |
| 401.5 | 12573 | 80.3 | 2667 | 30.1 |
| 481.8 | 14859 | 80.3 | 2286 | 35.1 |
| 562.1 | 17526 | 80.3 | 2667 | 30.1 |
| 642.4 | 20193 | 80.3 | 2667 | 30.1 |
| 722.7 | 23622 | 80.3 | 3429 | 23.4 |
| 803.0 | 27432 | 80.3 | 3810 | 21.1 |
| | | | Mean | 30.2 |

Specimen failed at 884 psi

TABLE 40

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-6MIF - $C_3$

L = 2.644 in    A = 1.339 $in^2$    $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 3.73 | 1890 | 3.73 | 1890 | 1.97 |
| 7.46 | 3401 | 3.73 | 1511 | 2.47 |
| 11.19 | 5291 | 3.73 | 1890 | 1.97 |
| 14.92 | 7560 | 3.73 | 2269 | 1.64 |
| 18.65 | 9829 | 3.73 | 2269 | 1.64 |
| 22.38 | 11719 | 3.73 | 1890 | 1.97 |
| 26.11 | 13988 | 3.73 | 2269 | 1.64 |
| 29.84 | 17013 | 3.73 | 3025 | 1.23 |
| | | | Mean | 1.82 |

Specimen failed at 32.7 psi

TABLE 41

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 3-6MIF - $C_4$

L = 2.666 in. A = 1.430 $in^2$ $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 1.40 | 1500 | 1.40 | 1500 | 0.93 |
| 2.80 | 4501 | 1.40 | 3001 | 0.47 |
| 4.20 | 6001 | 1.40 | 1500 | 0.93 |
| 5.60 | 9377 | 1.40 | 3376 | 0.42 |
| 7.00 | 13128 | 1.40 | 3751 | 0.37 |
| 8.40 | 16879 | 1.40 | 3751 | 0.37 |
| 9.80 | 21380 | 1.40 | 4501 | 0.31 |
| 11.20 | 26257 | 1.40 | 4877 | 0.29 |
| | | | Mean | 0.51 |

Specimen failed at 11.90 psi

TABLE 42

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 5-4JSP - $C_1$

L = 2.688 in. A = 1.305 $in^2$ $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 306.5 | 3720 | 306.5 | 3720 | 82.3 |
| 613.0 | 7440 | 306.5 | 3720 | 82.3 |
| 919.5 | 10788 | 306.5 | 3348 | 91.5 |
| 1226.0 | 14508 | 306.5 | 3720 | 82.3 |
| 1532.5 | 17856 | 306.5 | 3348 | 91.5 |
| 1839.0 | 21948 | 306.5 | 4092 | 74.9 |
| 2145.5 | 26412 | 306.5 | 4464 | 68.6 |
| 2452.0 | 30876 | 306.5 | 4464 | 68.6 |
| | | | Mean | 80.5 |

Specimen failed at 2600 psi

## TABLE 43

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 5-4JSP - $C_2$

L = 2.604 in.   A = 1.284 $in^2$   $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$ (in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 155.8 | 2304 | 155.8 | 2304 | 67.6 |
| 311.6 | 4224 | 155.8 | 1920 | 81.1 |
| 467.4 | 6528 | 155.8 | 2304 | 67.6 |
| 623.2 | 8832 | 155.8 | 2304 | 67.6 |
| 779.0 | 11904 | 155.8 | 3072 | 50.7 |
| 934.8 | 14592 | 155.8 | 2688 | 58.0 |
| 1090.6 | 17664 | 155.8 | 3072 | 50.7 |
| 1246.4 | 21504 | 155.8 | 3840 | 40.5 |
| | | | Mean | 60.5 |

Specimen failed at 1402.2 psi

TABLE 44

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 5-4JSP - $C_3$

L = 2.621 in. A = 1.334 $in^2$ $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$ (in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-3}$ (in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 3.75 | 1526 | 3.75 | 1526 | 2.46 |
| 7.50 | 2671 | 3.75 | 1145 | 3.28 |
| 11.25 | 4579 | 3.75 | 1908 | 1.97 |
| 15.00 | 6105 | 3.75 | 1526 | 2.46 |
| 18.75 | 7631 | 3.75 | 1526 | 2.46 |
| 22.50 | 9539 | 3.75 | 1908 | 1.97 |
| 26.25 | 10684 | 3.75 | 1145 | 3.28 |
| 30.00 | 12210 | 3.75 | 1526 | 2.46 |
| 33.75 | 13355 | 3.75 | 1145 | 3.28 |
| 37.50 | 15263 | 3.75 | 1908 | 1.97 |
| 41.25 | 17552 | 3.75 | 2289 | 1.64 |
| | | | Mean | 2.48 |

Specimen failed at 44.9 psi

TABLE 45

UNIAXIAL COMPRESSION TEST DATA

FOR SPECIMEN 5-4JSP - $C_4$

L = 2.624 in. A = 1.408 $in^2$ $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 1.42 | 1524 | 1.42 | 1524 | 0.93 |
| 2.84 | 3238 | 1.42 | 1714 | 0.83 |
| 4.26 | 4952 | 1.42 | 1714 | 0.83 |
| 5.68 | 6476 | 1.42 | 1524 | 0.93 |
| 7.10 | 8190 | 1.42 | 1714 | 0.83 |
| 8.52 | 10095 | 1.42 | 1905 | 0.75 |
| 9.94 | 11809 | 1.42 | 1714 | 0.83 |
| 11.36 | 13714 | 1.42 | 1905 | 0.75 |
| 12.78 | 15428 | 1.42 | 1714 | 0.83 |
| 14.20 | 17524 | 1.42 | 2096 | 0.68 |
| 15.62 | 19429 | 1.42 | 1905 | 0.75 |
| 17.04 | 21525 | 1.42 | 2096 | 0.68 |
| 18.46 | 23621 | 1.42 | 2096 | 0.68 |
| 19.88 | 26098 | 1.42 | 2477 | 0.57 |
| | | | Mean | 0.78 |

Specimen failed at 20.8 psi

## TABLE 46

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 5-5LIF - $C_1$

L = 2.597 in. A = 1.278 in.$^2$ $T_{room}$ = 28°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 78.2 | 2310 | 78.2 | 2310 | 33.9 |
| 156.4 | 4812 | 78.2 | 2502 | 31.3 |
| 234.6 | 7314 | 78.2 | 2502 | 31.3 |
| 312.8 | 9624 | 78.2 | 2310 | 33.9 |
| 391.0 | 12126 | 78.2 | 2502 | 31.3 |
| 469.2 | 14628 | 78.2 | 2502 | 31.3 |
| 547.4 | 17515 | 78.2 | 2887 | 27.1 |
| 625.6 | 20402 | 78.2 | 2887 | 27.1 |
| 703.8 | 23482 | 78.2 | 3080 | 25.4 |
| | | | Mean | 30.0 |

Specimen failed at 780 psi

## TABLE 47

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 5-5LIF - $C_2$

L = 2.604 in.  A = 1.271 $in.^2$  $T_{room}$ = 31°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 78.7 | 2688 | 78.7 | 2688 | 29.3 |
| 157.4 | 5760 | 78.7 | 3072 | 25.6 |
| 236.1 | 9216 | 78.7 | 3456 | 22.8 |
| 314.8 | 12672 | 78.7 | 3456 | 22.8 |
| 393.5 | 16512 | 78.7 | 3840 | 20.5 |
| 472.2 | 20352 | 78.7 | 3840 | 20.5 |
| | | | Mean | 23.6 |

Specimen failed at 531 psi

## TABLE 48

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 5-5LIF - $C_3$

L = 2.605 in.   A = 1.328 in.$^2$   $T_{room}$ = 33°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $x10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $x10^{-6}$(in/in) | (5) From (3) & (4) E x $10^3$ psi |
|---|---|---|---|---|
| 7.53 | 3838 | 7.53 | 3838 | 1.96 |
| 15.06 | 7293 | 7.53 | 3455 | 2.18 |
| 22.59 | 11131 | 7.53 | 3838 | 1.96 |
| 30.12 | 15353 | 7.53 | 4222 | 1.78 |
| 37.65 | 19191 | 7.53 | 3838 | 1.96 |
| 45.18 | 23413 | 7.53 | 4222 | 1.78 |
| 52.71 | 28019 | 7.53 | 4606 | 1.63 |
| 60.24 | 32625 | 7.53 | 4606 | 1.63 |
| | | | Mean | 1.86 |

Specimen failed at 67.0 psi

## TABLE 49

## UNIAXIAL COMPRESSION TEST DATA

## FOR SPECIMEN 5-5LIF - $C_4$

L = 2.607 in. A = 1304 in.$^2$ $T_{room}$ = 36°F

| (1) TOTAL STRESS (psi) | (2) TOTAL LONG. STRAIN $\times 10^{-6}$(in/in) | (3) INCREMENTAL STRESS (psi) | (4) INCREMENTAL LONG. STRAIN $\times 10^{-6}$(in/in) | (5) From (3) & (4) E $\times 10^3$ psi |
|---|---|---|---|---|
| 3.83 | 4986 | 3.83 | 4986 | 0.77 |
| 7.66 | 10356 | 3.83 | 5370 | 0.71 |
| 11.49 | 15336 | 3.83 | 4986 | 0.77 |
| 15.32 | 21089 | 3.83 | 5753 | 0.67 |
| 19.15 | 27226 | 3.83 | 6137 | 0.62 |
| 22.98 | 33363 | 3.83 | 6137 | 0.62 |
| 26.81 | 39883 | 3.83 | 6520 | 0.59 |
| 30.64 | 46403 | 3.83 | 6520 | 0.59 |
| 34.47 | 52540 | 3.83 | 6137 | 0.62 |
| 38.30 | 59060 | 3.83 | 6520 | 0.59 |
| 42.13 | 65580 | 3.83 | 6520 | 0.59 |
| | | | Mean | 0.65 |

Specimen failed at 43.6 psi

# A P P E N D I X   D

## SHEAR TEST DATA

## TABLE 50

## SHEAR TEST DATA

T Room = 28°F

| SPECIMEN NUMBER | DIMENSIONS (in. x in. x in.) | LOAD (lbs) | STRENGTH (psi) | RATE OF LOADING (psi/min) |
|---|---|---|---|---|
| 3-2JSP $SH_1$ | 1.0 x 1.0 x 1.05 | 280 | 266.7 | 285.7 |
| 3-3QTZ $SH_1$ | 0.98 x 0.98 x 1.05 | 500 | 485.9 | 291.5 |
| 3-4RCH $SH_1$ | 1.0 x 1.0 x 1.04 | 127 | 122.1 | 288.5 |
| 3-5LIF $SH_1$ | 1.0 x 0.99 x 1.04 | 190 | 182.7 | 288.5 |
| 3-6MIF $SH_1$ | 1.0 x 1.0 x 1.05 | 400 | 380.9 | 285.7 |
| 4-1MIF $SH_1$ | 1.0 x 1.0 x 1.05 | 355 | 338.1 | 285.7 |
| 4-2LIF $SH_1$ | 1.0 x 1.0 x 1.04 | 218 | 209.6 | 288.5 |
| 4-4JSP $SH_1$ | 1.0 x 1.0 x 1.04 | 320 | 307.7 | 288.5 |
| 5-4JSP $SH_1$ | 1.0 x 0.99 x 1.05 | 442 | 420.9 | 285.7 |
| 5-7MIF $SH_1$ | 1.0 x 1.0 x 1.05 | 368 | 350.4 | 285.7 |

TABLE 51

SHEAR TEST DATA

T Room = 31°F

| SPECIMEN NUMBER | DIMENSIONS (in. x in. x in.) | LOAD (lbs) | STRENGTH (psi) | RATE OF LOADING (psi/min) |
|---|---|---|---|---|
| 3-2JSP $SH_2$ | 1.0 x 1.0 x 1.05 | 220 | 209.5 | 285.7 |
| 3-3QTZ $SH_2$ | 0.98 x 0.99 x 1.04 | 488 | 478.9 | 294.4 |
| 3-4RCH $SH_2$ | 1.0 x 0.99 x 1.05 | 95 | 90.5 | 285.7 |
| 3-5LIF $SH_2$ | 1.0 x 0.98 x 1.04 | 150 | 144.2 | 288.5 |
| 3-6MIF $SH_2$ | 1.0 x 1.0 x 1.05 | 256 | 243.8 | 285.7 |
| 4-1MIF $SH_2$ | 1.0 x 1.0 x 1.04 | 286 | 269.2 | 288.5 |
| 4-2LIF $SH_2$ | 1.0 x 1.0 x 1.04 | 200 | 192.3 | 288.5 |
| 4-4JSP $SH_2$ | 1.0 x 0.99 x 1.05 | 310 | 295.2 | 285.7 |
| 5-4JSP $SH_2$ | 1.0 x 1.0 x 1.05 | 405 | 385.71 | 285.7 |
| 5-7MIF $SH_2$ | 1.0 x 1.0 x 1.04 | 281 | 270.3 | 288.5 |

TABLE 52

SHEAR TEST DATA

T Room = 33°F

| SPECIMEN NUMBER | DIMENSIONS (in. x in. x in.) | LOAD (lbs) | STRENGTH (psi) | RATE OF LOADING (psi/min) |
|---|---|---|---|---|
| 3-2JSP $SH_3$ | 2.0 x 1.98 x 2.05 | 23 | 5.60 | 24.4 |
| 3-3QTZ $SH_3$ | 0.98 x 0.99 x 1.04 | 384 | 376.8 | 294.4 |
| 3-4RCH $SH_3$ | 2.0 x 2.0 x 2.05 | 50 | 12.2 | 24.4 |
| 3-5LIF $SH_3$ | 2.0 x 1.99 x 2.04 | 44 | 10.8 | 24.4 |
| 3-6MIF $SH_3$ | 2.0 x 1.99 x 2.05 | 27 | 6.59 | 24.4 |
| 4-1MIF $SH_3$ | 2.0 x 1.98 x 2.05 | 30 | 7.31 | 24.4 |
| 4-2LIF $SH_3$ | 1.99 x 2.0 x 2.05 | 76 | 18.62 | 24.4 |
| 4-4JSP $SH_3$ | 2.0 x 2.0 x 2.04 | 38 | 9.31 | 24.4 |
| 5-4JSP $SH_3$ | 2.0 x 2.0 x 2.04 | 83.2 | 20.4 | 24.4 |
| 5-7MIF $SH_3$ | 2.0 x 1.99 x 2.05 | 22 | 5.37 | 24.4 |

TABLE 53

SHEAR TEST DATA

T Room = 36°F

| SPECIMEN NUMBER | DIMENSIONS (in. x in. x in.) | LOAD (lbs) | STRENGTH (psi) | RATE OF LOADING (psi/min) |
|---|---|---|---|---|
| 3-2JSP $SH_4$ | 2.0 x 1.98 x 2.04 | 14 | 3.42 | 24.4 |
| 3-3QTZ $SH_4$ | 1.0 x 1.0 x 1.04 | 306.8 | 295.0 | 288.5 |
| 3-4RCH $SH_4$ | 2.0 x 2.0 x 2.04 | 17 | 4.16 | 24.4 |
| 3-5LIF $SH_4$ | 2.0 x 1.99 x 2.04 | 15.4 | 3.78 | 24.4 |
| 3-6MIF $SH_4$ | 2.0 x 2.0 x 2.05 | 9 | 2.19 | 24.4 |
| 4-1MIF $SH_4$ | 2.0 x 2.0 x 2.05 | 10 | 2.44 | 24.4 |
| 4-2LIF $SH_4$ | 2.0 x 2.0 x 2.04 | 28 | 6.86 | 24.4 |
| 4-4JSP $SH_4$ | 2.0 x 1.98 x 2.05 | 20 | 4.88 | 24.4 |
| 5-4JSP $SH_4$ | 2.0 x 1.99 x 2.05 | 23 | 5.61 | 24.4 |
| 5-7MIF $SH_4$ | 2.0 x 2.0 x 2.05 | 6 | 1.46 | 24.4 |

# A P P E N D I X  E

## SONIC TEST DATA

## TABLE 54

## SONIC TEST DATA

T Room = 28°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY ($lbs/in^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 3-4RCH - $S_1$ | 5.985 | 0.1012 | 3657 | 1648 | 3648 | 1642 |
| 4-1MIF - $S_1$ | 7.135 | 0.1170 | 7357 | 3918 | 8750 | 4660 |
| 4-2LIF - $S_1$ | 6.584 | 0.1150 | 4861 | 2601 | 5334 | 2855 |
| 4-3JSP - $S_1$ | 7.580 | 0.1162 | 7915 | 4244 | 10000 | 5362 |
| 5-1QTZ - $S_1$ | 7.125 | 0.0850 | 5012 | 2535 | 5952 | 3011 |
| 5-4JSP - $S_1$ | 6.976 | 0.1168 | 8134 | 4302 | 9457 | 5002 |
| 5-6LIF - $S_1$ | 7.512 | 0.1132 | 4208 | 1655 | 5268 | 2072 |

TABLE 55

SONIC TEST DATA

T Room = 30°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY (lbs/in$^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 3-4RCH - $S_2$ | 5.985 | 0.1012 | 3618 | 1634 | 3609 | 1630 |
| 4-1MIF - $S_2$ | 7.135 | 0.1170 | 7315 | 3908 | 8700 | 4647 |
| 4-2LIF - $S_2$ | 6.584 | 0.1150 | 4840 | 2585 | 5312 | 2836 |
| 4-3JSP - $S_2$ | 7.580 | 0.1162 | 7900 | 4235 | 9980 | 5350 |
| 5-1QTZ - $S_2$ | 7.125 | 0.0850 | 5012 | 2530 | 5952 | 3004 |
| 5-4JSP - $S_2$ | 6.976 | 0.1168 | 8082 | 4270 | 9398 | 4965 |
| 5-6LIF - $S_2$ | 7.512 | 0.1132 | 4190 | 1642 | 5246 | 2056 |

TABLE 56

SONIC TEST DATA

T Room = 31°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY ($lb/in^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 3-4RCH - $S_3$ | 5.985 | 0.1012 | 3614 | 1631 | 3605 | 1627 |
| 4-1MIF - $S_3$ | 7.135 | 0.1170 | 7308 | 3904 | 8691 | 4643 |
| 4-2LIF - $S_3$ | 6.584 | 0.1150 | 4835 | 2580 | 5305 | 2831 |
| 4-3JSP - $S_3$ | 7.580 | 0.1162 | 7897 | 4229 | 9977 | 5343 |
| 5-1QTZ - $S_3$ | 7.125 | 0.0850 | 5012 | 2528 | 5952 | 3002 |
| 5-4JSP - $S_3$ | 6.976 | 0.1168 | 8072 | 4262 | 9385 | 4955 |
| 5-6LIF - $S_3$ | 7.512 | 0.1132 | 4183 | 1637 | 5237 | 2050 |

TABLE 57

SONIC TEST DATA

T Room = 32°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY ($lb/in^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 3-4RCH - $S_4$ | 5.985 | 0.1012 | 3608 | 1627 | 3599 | 1623 |
| 4-1MIF - $S_4$ | 7.135 | 0.1170 | 7298 | 3893 | 8679 | 4630 |
| 4-2LIF - $S_4$ | 6.584 | 0.1150 | 4831 | 2576 | 5301 | 2827 |
| 4-3JSP - $S_4$ | 7.580 | 0.1162 | 7892 | 4224 | 9970 | 5337 |
| 5-1QTZ - $S_4$ | 7.125 | 0.0850 | 5012 | 2527 | 5952 | 3001 |
| 5-4JSP - $S_4$ | 6.976 | 0.1168 | 8066 | 4255 | 9378 | 4947 |
| 5-6LIF - $S_4$ | 7.512 | 0.1132 | 4175 | 1630 | 5227 | 2041 |

## TABLE 58

### SONIC TEST DATA

T Room = 33°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY ($lb/in^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 5-1QTZ - $S_5$ | 7.125 | 0.0850 | 5003 | 2520 | 5941 | 2993 |

## TABLE 59

### SONIC TEST DATA

T Room = 36°F

| SPECIMEN NUMBER | LENGTH (in.) | DENSITY ($lb/in^3$) | LONGITUDINAL FREQUENCY (c.p.s.) | TRANSVERSE FREQUENCY (c.p.s.) | LONGITUDINAL WAVE VELOCITY (ft/sec) | TRANSVERSE WAVE VELOCITY (ft/sec) |
|---|---|---|---|---|---|---|
| 5-1QTZ - $S_6$ | 7.125 | 0.0850 | 4994 | 2514 | 5930 | 2985 |

# APPENDIX F

## DETERMINATION OF WATER CONTENT AND DATA

## DETERMINATION OF WATER CONTENT

The water content, w, of the frozen sample is defined as the ratio (%) of the weight of water to the weight of dry rock grains in the mass, or the equation:

$$w = \frac{w_1 - w_2}{w_2 - w_f} \qquad \text{(Eq. 1)}$$

where: $w_1$ = weight of moist sample plus aluminum foil;

$w_2$ = weight of oven-dry sample plus aluminum foil;

$w_f$ = weight of aluminum foil.

Small pieces, weighing about 100 to 200 grams, obtained from the rough sample, were used for the determination of the water content. At least two small pieces were taken from each sample so that an average value could be calculated.

The small piece of material was wrapped with aluminum foil and weighed immediately. After it had been weighed, it was placed in an oven (at 110°C). The aluminum foil was opened during the 24 hour period of drying. The oven-dried piece was then removed from the oven and re-weighed.

The water content of the sample may be calculated from equation (1).

TABLE 60

WATER CONTENTS OF FROZEN SAMPLES

| SAMPLE NUMBER | % | SAMPLE NUMBER | % | SAMPLE NUMBER | % |
|---|---|---|---|---|---|
| 3-2 JSP | 13.9 | 4-1 MIF | 10.8 | 5-1 QTZ | 3.9 |
| 3-3 QTZ | 5.8 | 4-2 LIF | 6.0 | 5-2 QTZ | 3.5 |
| 3-4 RCH | 12.4 | 4-3 JSP | 11.9 | 5-3 JSP | 10.5 |
| 3-5 LIF | 9.8 | 4-4 JSP | 11.6 | 5-4 JSP | 10.2 |
| 3-6 MIF | 13.0 | | | 5-5 LIF | 11.2 |
| | | | | 5-6 LIF | 11.7 |
| | | | | 5-7 MIF | 12.9 |

# A P P E N D I X G

## GRAIN ANALYSES

TABLE 61

GRAIN ANALYSES FOR SAMPLE 3-2 JSP

Weight of Foil = 4.2 g.

Weight of Foil + Dry Rock = 362.9 g. Weight of Dry Rock = 358.7 g.

| SIEVE NUMBER | MESH | SIEVE OPENING (in.) | WEIGHT OF SIEVE (g.) | WT. SIEVE + DRY ROCK (g.) | WEIGHT RETAINED (g.) | % RETAINED | CUMULATIVE % RETAINED | FINER % |
|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 0.0234 | 408.9 | 425.4 | 16.5 | 4.6 | 4.6 | 95.4 |
| 70 | 65 | 0.0083 | 363.2 | 374.6 | 11.3 | 3.1 | 7.7 | 92.3 |
| 100 | 100 | 0.0059 | 354.7 | 383.7 | 29.0 | 8.1 | 15.8 | 84.2 |
| 140 | 150 | 0.0041 | 391.3 | 414.0 | 22.7 | 6.3 | 22.1 | 77.9 |
| 200 | 200 | 0.0029 | 338.6 | 393.7 | 55.1 | 15.4 | 37.5 | 62.5 |
| 325 | 325 | 0.0017 | 334.5 | 415.2 | 80.7 | 22.5 | 60.0 | 40.0 |
| pan | - | - | 377.2 | 520.4 | 143.2 | 40.0 | 100.0 | - |

TABLE 62

GRAIN ANALYSES FOR SAMPLE 3-3 QTZ

WEight of Foil = 4.5 g.

Weight of Foil + Dry Rock = 372.1 g. Weight of Dry Rock = 367.6 g.

| SIEVE NUMBER | MESH | SIEVE OPENING (in.) | WEIGHT OF SIEVE (g.) | WT. SIEVE + DRY ROCK (g.) | WEIGHT RETAINED (g.) | % RETAINED | CUMULATIVE % RETAINED | FINER % |
|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 0.0234 | 408.9 | 517.6 | 108.7 | 29.5 | 29.5 | 70.5 |
| 70 | 65 | 0.0083 | 363.2 | 546.4 | 183.2 | 50.0 | 79.5 | 20.5 |
| 100 | 100 | 0.0059 | 354.7 | 374.0 | 19.3 | 5.3 | 84.8 | 15.2 |
| 140 | 150 | 0.0041 | 391.3 | 402.7 | 11.4 | 3.1 | 87.9 | 12.1 |
| 200 | 200 | 0.0029 | 338.6 | 345.7 | 7.1 | 1.9 | 89.8 | 10.2 |
| 325 | 325 | 0.0017 | 334.5 | 346.2 | 11.7 | 3.2 | 93.0 | 7.0 |
| pan | - | - | 377.2 | 403.2 | 26.0 | 7.0 | 100.0 | - |

TABLE 63

GRAIN ANALYSES FOR SAMPLE 3-4 RCH

Weight of Foil = 5 g.

Weight of Foil + Dry Rock = 362.5 g.

Weight of Dry Rock = 357.5 g.

| SIEVE NUMBER | MESH | SIEVE OPENING (in.) | WEIGHT OF SIEVE (g.) | WT. SIEVE + DRY ROCK (g.) | WEIGHT RETAINED (g.) | % RETAINED | CUMULATIVE % RETAINED | FINER % |
|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 0.0234 | 408.9 | 434.9 | 26.0 | 7.3 | 7.3 | 92.7 |
| 70 | 65 | 0.0083 | 363.2 | 411.4 | 48.2 | 13.4 | 20.7 | 79.3 |
| 100 | 100 | 0.0059 | 354.7 | 376.2 | 21.5 | 6.0 | 26.7 | 73.3 |
| 140 | 150 | 0.0041 | 391.3 | 417.7 | 26.4 | 7.4 | 34.1 | 65.9 |
| 200 | 200 | 0.0029 | 338.6 | 361.3 | 22.7 | 6.4 | 40.5 | 59.5 |
| 325 | 325 | 0.0017 | 334.5 | 431.7 | 97.2 | 27.2 | 67.7 | 32.3 |
| pan | - | - | 377.2 | 492.3 | 115.1 | 32.3 | 100.0 | - |

TABLE 64

GRAIN ANALYSES FOR SAMPLE 3-5 LIF

Weight of Foil = 5.1 g.

Weight of Foil + Dry Rock = 431.3 g. Weight of Dry Rock = 426.2 g.

| SIEVE NUMBER | MESH | SIEVE OPENING (in.) | WEIGHT OF SIEVE (g.) | WT. SIEVE + DRY ROCK (g.) | WEIGHT RETAINED (g.) | % RETAINED | CUMULATIVE % RETAINED | FINER % |
|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 0.0234 | 408.9 | 703.2 | 294.3 | 69.0 | 69.0 | 31.0 |
| 70 | 65 | 0.0083 | 363.2 | 435.7 | 69.5 | 16.3 | 85.3 | 14.7 |
| 100 | 100 | 0.0059 | 354.7 | 368.7 | 14.0 | 3.3 | 88.6 | 11.4 |
| 140 | 150 | 0.0041 | 391.3 | 402.7 | 11.4 | 2.7 | 91.3 | 8.7 |
| 200 | 200 | 0.0029 | 338.6 | 345.8 | 7.2 | 1.7 | 93.0 | 7.0 |
| 325 | 325 | 0.0017 | 334.5 | 351.9 | 17.4 | 4.1 | 97.1 | 2.9 |
| pan | - | - | 377.2 | 389.4 | 12.2 | 2.9 | 100.00 | - |

TABLE 65

GRAIN ANALYSES FOR SAMPLE 3-6 MIF

Weight of Foil = 5.3 g.

Weight of Foil + Dry Rock = 478.3 g. Weight of Dry Rock = 473 g.

| SIEVE NUMBER | MESH | SIEVE OPENING (in.) | WEIGHT OF SIEVE (g.) | WT. SIEVE + DRY ROCK (g.) | WEIGHT RETAINED (g.) | % RETAINED | CUMULATIVE % RETAINED | FINER % |
|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 0.0234 | 408.9 | 529.0 | 120.1 | 25.4 | 25.4 | 74.6 |
| 70 | 65 | 0.0083 | 363.2 | 533.2 | 170.0 | 36.0 | 61.4 | 38.6 |
| 100 | 100 | 0.0059 | 354.7 | 393.9 | 39.2 | 8.3 | 69.7 | 30.3 |
| 140 | 150 | 0.0041 | 391.3 | 422.5 | 31.2 | 6.6 | 76.3 | 23.7 |
| 200 | 200 | 0.0029 | 338.6 | 356.6 | 18.0 | 3.8 | 80.1 | 19.9 |
| 325 | 325 | 0.0017 | 334.5 | 355.3 | 20.8 | 4.4 | 84.5 | 15.5 |
| pan | - | - | 377.2 | 450.6 | 73.4 | 15.5 | 100.0 | - |

# APPENDIX H

## GENERAL THEORY WHICH APPLIES TO THE METHOD USED AND CALCULATIONS OF THERMAL CONDUCTIVITY

## GENERAL THEORY WHICH APPLIES TO THE METHOD USED AND CALCULATIONS OF THERMAL CONDUCTIVITY

Referring to Figure 11, the reader will note that the three principal components (disc, disc, and disc, from left to right) are shown as A, B and C, respectively. This notation will be used in the discussion which follows.

At a steady state, the temperature of A, B and C are $T_A$, $T_B$ and $T_C$° above the ambient temperature, and e calories/sec.cm$^2$C° (assumed to be the same for A, B, C and the specimen) are emitted from the exposed surfaces. Next, if we assume that the temperature of the specimen is equal to the mean temperature of A and B, the total heat emitted per second is given by:

$$H = e A_a T_A + e A_s \frac{T_A + T_B}{2} + e T_B A_b + e A_c T_c \text{ calories} \quad (1)$$

In this equation, where $A_a$, $A_b$, $A_c$ and $A_s$ are the exposed surface areas of A, B, C and the specimen (s), respectively, the areas $A_a$ and $A_c$ include the areas of the flat end surfaces.

This quantity of heat, H, is completely supplied by the heating element:

$$H = \frac{VI}{J} \text{ calories} \quad (2)$$

where: V = the potential difference across the element (in volts);

I = the current flowing (in amps);

J = the mechanical equivalent of heat (in joules per calories) (4.18)

From (1) and (2):

$$e = \frac{VI}{J\left(A_a T_A + A_s \frac{T_A + T_B}{2} + A_b T_B + A_c T_c\right)} \quad \text{calories/sec.cm}^2\text{C}^\circ \qquad (3)$$

The heat flowing through s is given by:

$$h = K\pi r^2 \frac{T_B - T_A}{d} \quad \text{calories/sec.;} \qquad (4)$$

where: K = thermal conductivity;

r = radius of the specimen;

d = thickness of the specimen.

Now, all of the heat entering the specimen (s) from B does not pass into A, since some is emitted from the curved surface of s. The heat flowing through s is taken, therefore, as the mean of the heat entering s from B and that leaving s for A. The heat enetering s from B is that which is emitted by s and A together, that is:

$$H_{Bs} = e A_s \frac{T_A + T_B}{2} + e A_a T_A \quad \text{calories/sec.} \qquad (5)$$

The heat leaving s for A is taht which is emitted by A alone; that is:

$$H_{sA} = e A_a T_A \text{ calories/sec.} \qquad (6)$$

Taking the mean of these quantities gives:

$$H_s = \frac{1}{2} e \left(A_s \frac{T_A + T_B}{2} + 2 A_a T_A\right) \text{ calories/sec.} \qquad (7)$$

Therefore, from (4) and (7):

$$K\pi r^2 \frac{T_B - T_A}{d} = \frac{1}{2} e \left(A_s \frac{T_A + T_B}{2} + 2A_a T_A\right)$$

or

$$K = e \frac{d}{2\pi r^2 (T_B - T_A)} \left(A_s \frac{T_A + T_B}{2} + 2 A_a T_A\right) \text{ calories/sec.cm.C°} \quad (8)$$

The value of K may be calculated from equations (3) and (8).