EXPERIMENTAL OBSERVATIONS OF ROCK FAILURE DUE TO

LASER RADIATION

BY

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ABSTRACT

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Submitted to the Department Civil Engineering on January 20th 1969
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This thesis is an experimental investigation of the thermal
and mechanical response of rock materials to laser radiation.
Specifically, the following three topics have been studied in detail:
1. Temperature measurements made on thin discs subjected to laser
radiation.
2. Strain measurements made on thin discs subjected to laser
radiation.
3. Observation and evaluation of cracking and spalling phenomena
in constrained and unconstrained thin discs respectively, when
subjected to laser radiation.

In conjunction with the experimental work done herein, use was
made of a heat flow analysis and a stress analysis program developed
in Reference [23]. It was possible to theoretically predict the
thermal and mechanical response of a rock specimen to laser radiation
and then compare it with the experimental observations.

Thesis supervisor: Dr. Fred Moavenzadeh
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Mr. Charles Nelson\(^3\) is acknowledged for making his finite element heat and stress analysis programs available to me. In addition, he provided many valuable ideas for experimental research. Mr. J.T. King\(^4\) is also thanked very warmly, for without his help most of the experimental work would not have been made possible. Finally, I wish to convey my appreciation to Mr. Terryl Schein\(^5\) who so kindly permitted me to use his laser laboratory facilities.

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INTRODUCTION

In recent years, problems associated with transportation in large urban areas have become very severe due to the acute limitation of ground space in highly populated or industrialized areas. For this reason, the development and use of underground space has become very important.

In the present state of the art, hard rock tunnelling is a very expensive process due to the fact that tunnelling machines must be built extremely rugged and powerful in order to overcome the high strength of intact hard rock. There has therefore been a considerable amount of interest in assisting the progress of hard rock tunnelling machines by developing techniques to weaken the rock before it is mechanically impinged upon. If significant advances could be made with respect to weakening of rocks then a field application of the laboratory methods would greatly improve the capability of hard rock tunnelling machines.

The mode of rock weakening that this thesis is primarily concerned with is that due to heat. Interest in the topic of thermal response of rock was generated by observations of such dramatic weakening phenomena resulting from flame jet drilling (1) which is currently used in the field to a small extent. For the purpose of conducting an analysis of thermal interaction mechanisms in rocks, it was necessary to choose an appropriate source of heat energy. The continuous \( \text{CO}_2 - \text{N}_2 - \text{He} \) gas laser was found to be most suitable for this purpose owing to the following desirable characteristics:
1. The laser is an accurate and consistent source of heat energy, in that its power level is easily controllable and the geometry of the output beam may be adjusted to any suitable configuration and maintained that way.

2. The transfer of energy from the source to the recipient material is effected without transfer of mass.

3. The infra-red radiation emitted by a laser is well absorbed by rocks such as marble and granite.

Although the high powered gas laser with its present physical characteristics (such as delicacy of components and large overall size) and level of efficiency could not possibly be used for thermal weakening of rock in the field, it is conceivable that with improved technology it could be made small, rugged and efficient, thus enabling field applications. A forecasting study conducted by the U.S. Army Office of Research and Development (1) has predicted that such field endeavours will become technically feasible in 15-20 years time.

This thesis reviews the present state of knowledge regarding the interaction of laser radiation with solid materials such as rocks. It also presents experimental techniques used to cause various modes of failure in rock specimens by laser irradiation. The thermal and mechanical response of laser irradiated specimens are observed and these phenomena are compared with the analytical data for the temperature and stress distributions in such specimens.
This review of literature attempts to outline the present state of knowledge regarding the interaction of laser radiation with solid opaque materials. First, the laser and the properties of laser radiation are described. Secondly, the various phenomena that occur when laser radiation strikes the surface of a material are described. Then the physical and chemical effects arising from this interaction are covered. Finally the various possible damage mechanisms in rocks due to laser radiation are outlined.

The Laser – Its Generation and Properties

The term "laser" is an acronym for "light amplification by stimulated emission of radiation". Basically, a laser is a device that converts different forms of energy into a concentrated beam of coherent electromagnetic radiation.

Depending on the temperature of a given material, its atoms may occupy any one of many discrete quantum levels of internal energy. If the system is in thermal equilibrium, most of the atoms will occupy the lowest possible energy levels, where they are referred to as being in the "ground state". They can be excited to higher energy levels by absorbing energy from some external source. Atoms that are in an excited state may relax to a lower energy state by releasing some of the energy that has been absorbed in order to attain the excited state. Energy releases that take place in this fashion form the basis for the development of lasers [2,10].
Figure 1a. Schematic Diagram of $\text{CO}_2$-$\text{N}_2$-He Flowing Gas Laser [22]
Figure 1b. Photograph of 10 meter long, 2 inch diameter gas laser tube [3]

Figure 2. Vibrational Energy Level Diagram For CO₂ and N₂ [3]
In order to generate this process, the following basic laser components are necessary: an active laser material, an optically resonant cavity, and a means whereby external energy can excite the laser material. When sufficient energy is absorbed by the material, its energy characteristics change and it becomes an emitter of coherent electromagnetic radiation, characteristic of lasers. In gas lasers, where the output can be continuous, the discharge is made directly in the laser material.

The particular laser used in this study is a one-kilowatt continuous gas laser developed by the Raytheon Research Laboratory. It uses a combination of carbon dioxide, nitrogen and helium, operates continuously and emits infra-red radiation of 10.6 micron wavelength by effecting a discharge through the gas mixture [3].

Figure 1 illustrates the basic mode of operation of a high powered continuous gas laser. Figure 2 shows the molecular and atomic interactions that take place in the gas mixture in order to produce laser radiation.

**Interaction of Laser Radiation with Materials**

In general, electromagnetic radiation interacts with a system of bound and free charges which are capable of oscillating at a natural frequency equal to that of the impressed wave [4]. A metal contains bound and free charges whereas a dielectric can be considered as containing only bound charges. If the interacting electric field component varies with a frequency corresponding to a natural frequency of the charged particle, then it will reradiate an electromagnetic wave of the same frequency (as in reflection).
Figure 3. Schematic Model for Laser Interaction With an Opaque Material
The thermal effects involved in the interaction of any laser beam with a material are the same as those of any electromagnetic radiation where the energy is concentrated in a narrow frequency range.

The following model attempts to place in perspective the various phenomena that occur when a concentrated beam of laser radiation strikes the surface of an opaque material [Figure 3]. It must be noted, however, that the effects of melting and vaporization need not occur if the intensity of the beam is low enough.

The laser radiation energy that interacts with a material is consumed in various ways. The relative magnitude of these different ways of energy consumption depends strongly upon the thermal and optical properties of the material being exposed, as well as the characteristics of the radiation.

The total incident laser energy is equal to the sum of the reflected energy, the absorbed energy, the reemitted energy and the transmitted energy. A further elucidation of these four terms is in order at this point:

a) **Reflection and Subsequent Loss of Energy**: This phenomenon is especially marked in the case of metals since they contain charged particles that are able to oscillate in phase with the incident radiation and hence reradiate a certain portion of the energy. The reflected radiation may possibly reinteract with material that has been vaporized due to absorption effects.
The reflection coefficient is the ratio of the reflected intensity to the incident intensity at an interface. This coefficient is dependent upon the properties of the material, the incident angle, the wavelength of the incident beam and the surface finish. When there is absorption of the incident radiation, the reflection coefficient also becomes dependent upon the refractive index and the extinction coefficient (a measure of how fast energy is absorbed in the material) [6]. In metals where there is a high density of free electrons on the surface to absorb energy, the extinction is high. For a metal such as aluminum, the combination of high index of refraction and high extinction coefficient makes it almost totally reflecting at 10.6μ, which is the common wavelength of CO₂ laser radiation.

Dielectrics also exhibit metallic-like reflection at frequencies where there is appreciable surface absorption. These frequencies will coincide with the frequencies of bound electron vibrations [4].

b) Absorption: The ultimate absorption is the conversion of the incident radiation into kinetic energy of electrons in the absorbing medium. The absorbed energy is then reradiated, conducted away, transported away via vapor or mass ejection, or contained in the beam impingement area in the form of a higher energy state material.

The absorption coefficient is a basic material constant. Since absorption of electromagnetic energy is a transfer of energy to electrons in the material, the accessibility of the electrons
to the incident radiation determines the material absorption characteristics. Materials with electrons free to oscillate or which have allowable vibrational frequencies coincident with the particular wavelength of the radiation will show absorption. At 10.6μ, most non-metallic materials show appreciable absorption. Rock and ceramic type materials, for example, are almost perfect absorbers, and hardly reflect any radiant energy at all.

c) **Transmittance:** The unreflected incident radiation which is not absorbed will be transmitted. Since the absorption is a function of the distance travelled, the transmittance will depend on the material thickness. The transmission path can be affected by the scattering and reflection centers within the material. In an opaque material very little energy is transmitted [6].

d) **Emissivity:** Once a material absorbs energy and heats up, then some of this energy will be reradiated by the hot body. The radiant intensity compared with that of a black body radiator describes the emissivity of the material. Most materials radiate somewhat short of black body conditions, with metals the closest approximations. Like absorption, emissivity is a function of allowable electron energy states [8].

**Physical and Chemical Effects**

The following is an outline of the various responses of a material to a heat energy stimulus:
a) **Direct Heating Effect Caused by Absorption of Radiation:**

With the use of high powered continuous lasers, the small area of material that is exposed to radiation will be subject to an intense heating which will cause it to melt and vaporize. If the intensity becomes too high and the beam extremely local, then three effects are apparent:

(i) Practically all the material that is exposed to the radiation is expelled due to vaporization or mass ejection, while the remainder is left relatively unheated [5]. This point will be discussed in more detail under "Phase Changes" and "Thermal Effects of Extremely High Powered Pulsed Lasers."

(ii) When a large amount of energy is absorbed in a very short time (i.e. short compared to the elastic relaxation time constant of the material) it is possible for internal explosions to develop that cause catastrophic failure of the specimen. Essentially, this failure is due to the inability of the material to respond elastically to the heat stimulus in such a short period of time [9].

(iii) If the material that is being irradiated contains an impurity that is more readily vaporizable than the actual material, then this substance may rapidly vaporize, causing large internal pressures (owing to the volume confinement). If these pressures are large enough, they may rupture the parent material. A classic example of this type of effect is the phenomenon of laser paper cutting. Typically, paper contains about 5-10% of water by weight. If a high powered laser beam is focused down to a very narrow spot (of the order of a few thousandths of an inch in diameter), then
the moisture content in a small local area will be instantaneously vaporized. The sudden pressure exerted by this vapor is sufficient to explode the paper fibers apart. Thus a cut can be achieved without any traces of burning or charring.

b) **Phase changes**: Some of the absorbed energy results in phase changes in the interacting material. This is of considerable importance in the application of lasers to working with metals, for example welding and annealing operations [11]. Sufficient heating of most materials causes melting, and the energy input necessary for this can be calculated from the specific heat and heat of solidification which are properties of the given material. Additional energy input causes vaporization.

In general, radiated materials can go through a series of successive phase changes (solid to liquid to vapor) each requiring additional energy. The liquid phase is desirable for joining and the vapor phase is desirable for removal of materials [12].

c) **Thermal Effects of Extremely High Powered Lasers**: A very recent application of lasers as an industrial tool is in the field of metal working [24,26]. One of the most important uses of lasers in this field is for the removal of metal from a workpiece by means of local vaporization.

When a continuous beam of laser radiation (of the order of several hundred watts) is focused to a small spot upon a piece of metal, the spot merely gets hot (but not hot enough to vaporize) since most of the heat absorbed from the beam is rapidly conducted away—heating the entire workpiece. This is undesirable since heat is detrimental to the mechanical properties of a metal, and
no metal removal takes place until the entire area is heated. The method that has been successful in metalworking applications [25,27] is to operate the laser in a pulsed mode*. This is done simply by incorporating a pulser into the power supply. Although the time-averaged power output is essentially as if it were operating continuously, the effect of the pulser is to concentrate the energy into short bursts, i.e., each burst is at an enormously high power level. By applying the laser energy in such a highly concentrated fashion, the thermodynamic balance around the focused spot changes radically. During the short time of the pulse, the energy is being applied at a rate far in excess of the rate at which the heat can be dissipated by conduction and convection effects. The result, therefore, is to cause the area of the spot to rapidly heat up to the vaporization temperature. In this manner, part of the material may be effectively removed from the area of concentrated energy input.

A notable advantage of the pulsed mode of operation is that generalized heating effects are dramatically reduced with the result that the temperature of the workpiece rises less than a few degrees centigrade at a short distance (of the order of a centimeter) from the focused spot. Photomicrographic studies indicate that there are no metallurgical changes immediately adjacent to the focused spot.

d) **Ionization:** As energy is absorbed by the material, the electrons attain higher allowable energy levels. This could cause a

* A continuous laser can be adapted to this mode by Q switching.
bound electron to be freed thus ionizing the particle. As far as CO₂ laser radiation is concerned, this process is only a minor effect since a relatively high energy density is required for complete ionization. The ionized particles may recombine with electrons thus reemitting a characteristic radiation [7].

e) Reactions: Chemical substances present under favorable thermal conditions react to form a compound. Reactions can also take place by absorption of the optical energy as in photoelectric processes. Another thermal effect is that of dissociation, in which a compound will decompose into several constituents with the expulsion of a certain amount of energy.

Rock Damage Due to Laser Radiation

The major mechanisms of laser induced damage to rocks are due to heating, while the other previously mentioned effects are secondary. A laser beam is a very efficient carrier of heat energy by virtue of the fact that it consists of coherent infra-red radiation which affords it the property of transmitting power on a very concentrated and localized basis.

In analyzing the phenomena of weakening or fracturing of rock by heat, two different assumptions have been made [2]:

(i) The material is completely homogeneous and the damage done is only dependent upon thermally induced shock and the resulting stress distribution.

(ii) The material is granular and its response depends on the characteristics of the constituent grains and the resultant of their reactions, rather than that of the rock mass.
Brown [2,13] has postulated various mechanisms that may be responsible for the weakening and fracture of rocks due to heating. Usually a combination of several of these mechanisms is responsible for laser induced weakening and/or failure of rocks.

a) **Intergranular Separation due to Phase Transformations:** Polymorphic phase transformations are capable of forcing adjacent grains in a rock to part along their boundaries.

b) **Gross Chemical Changes:** Such effects have been observed in heat treated quartz and are attributable to molecular changes.

c) **Intergranular Corrosion:** This has been suggested as a cause of thermal weakening of rock, since it has been known to be a major cause of weakening in other materials.

d) **Gas or Water Pocket Expansion:** This could easily be a cause of fracture in rock since heated gases in small enclosed volumes can exert very severe pressures. Such activity is usually accompanied by fragmentation of the specimen and by the reports of small explosions.

e) **Intergranular Separation Due to Anisotropic Thermal Expansion:** Differential thermal expansion of adjacent grains in a rock can force them to separate along their grain boundaries. This process depends on the rate and mode of heating. Usually, a large temperature gradient is required in order for some grains to expand more rapidly than others, thus producing differential movements. This leads to the subsequent formation of intergranular spaces. When an aggregate consisting of non-isotropic grains is heated, these grains expand in different directions and by different amounts.
This causes them to push each other apart and produce cracks. The damage thus produced is permanent, since the cracks do not close up upon cooling.

f) Thermally Induced Stresses Leading to Failure in Compression or Tension: Localized heating, such as that caused by the incident beam of a laser, may produce temperature gradients which will create stresses in the material. This is quite significant in the case of rocks which have low thermal conductivity and appreciable thermal expansion. If the temperatures are high enough and the gradients steep enough, then the induced stresses may be sufficient to overcome the strength of the material, thus causing fractures either in compression (spalling) or tension (cracking). The consideration and evaluation of tensile failures is in fact one of the main areas of interest with regards to recent experimental work.

The relative importance of each of these mechanisms is dependent upon the nature of the rock and the manner in which the heat is applied. In other words, the mechanism whereby a laser damages materials depends on the type of laser and the absorption of its radiation (as heat) by the material.

In conclusion, it is worth reiterating that the most important damage mechanism regarding the interaction of laser radiation with rocks is due to heat, and other effects are secondary. To be even more specific, it may be worth mentioning as a preview of the results of the work conducted here that the weakening of rock produced by exposure to laser radiation is simply and primarily due to the tensile and compressive stresses induced by differential thermal expansion. Other more complicated actions which have been
hypothesized, seem to have little effect on the weakening action.

One of the main objectives of this literature survey is to obtain an analysis of laser thermal interaction mechanisms. J.F. Ready [5] formulated several methods whereby one may calculate the thermal effects of high powered laser radiation. The main idea with which we are concerned is his premise that the heating effects at levels where no phase change occurs can be treated by ordinary thermodynamics. An applied three-dimensional heat flow model may be used to relate theoretically the power density input to the temperature distribution as a function of space and time.

Material Properties Relevant to a Heat Flow Analysis

An outline is given here of the various material properties which must be considered in formulating a heat flow analysis for the thermodynamic problem illustrated in Figure 4, in which it is required to find the temperature in the specimen as a function of spatial distance and time of exposure.

a) Thermal Conductivity: The rate at which heat energy is taken away from the area of impingement is dependent upon the thermal conductivity. This is usually denoted by the symbol, K, which is the amount of heat energy that flows from one face of a unit cube to the opposite face when there is a unit temperature difference between the two faces. In a more generalized elemental notation it is given as follows: [See Figure 5].

Thermal Conductivity, \( K = \frac{\partial q}{\partial a} \frac{\partial l}{\partial T} \)
Figure 4. Thermodynamic Problem Under Consideration

Figure 5. Elemental Notation for Thermal Conductivity
Usually the thermal conductivity of a material is dependent upon temperature. For marble and granite, the two rock materials of interest in this study, the values are as follows for temperature, \( T \), in degrees Fahrenheit:

(i) Marble: (28)

\[
K = \frac{1}{24000.0 + 30.0T} \quad \text{BTU in sec }^\circ\text{F}
\]

(ii) Granite: (17)

\[
K = \frac{1}{31500.0 + 21.6T} \quad \text{BTU in sec }^\circ\text{F}
\]

b) **Specific Heat:** The amount of heat required to raise the temperature of unit weight of material by unit temperature is defined as the specific heat. It determines how fast the material heats up. For marble and granite the specific heats are as follows:

(i) Marble: (28)

\[
\text{Specific Heat} = 0.415 \quad \text{BTU} \quad \frac{1\text{b}}{1\text{b} \cdot ^\circ\text{F}}
\]

(ii) Granite: (29)

\[
\text{Specific Heat} = 0.210 \quad \text{BTU} \quad \frac{1\text{b}}{1\text{b} \cdot ^\circ\text{F}}
\]
Another material property that is usually encountered in thermal analysis is the heat capacity. This is merely the product of specific heat and material density. The density of marble and granite are as follows:

(i) Marble: [29]

\[
\text{Density} = 0.97 \, \frac{\text{lbs}}{\text{in}^3}
\]

(ii) Granite: [29]

\[
\text{Density} = 0.94 \, \frac{\text{lbs}}{\text{in}^3}
\]

c) **Reflectivity:** The reflectivity of the surface of a material is an important consideration since, depending on the surface finish, a considerable portion of the incident energy may be reflected. Granite and marble, the materials of interest in this study are essentially non-reflecting with respect to laser radiation of 10.6 micron wavelength.

d) **Properties of Changed Phases:** If the material reaches such high temperatures that phase changes occur, then a whole new set of properties will have to be known. In the analytical and experimental work presented in this thesis it is assumed that no phase changes occur prior to any phenomenological occurrence of interest, such as cracking and spalling.

e) **Geometric Considerations:** For the purpose of the analysis the dimensional characteristics defining the shape and size of the specimen must be known. Furthermore, the internal structure of a
material can have significant effects on the radiational interaction with that material. The end properties, for example, can be affected by porosity inclusions, grain boundaries and discontinuities.

f) **Lasing Configuration**: The power level of an input laser beam determines how much heat energy is being applied to the specimen in a given time interval. In addition geometry of laser beam aiming with respect to the specimen must be taken into account.

**Other Thermodynamic Effects**

The following phenomena are of lesser importance than the points mentioned previously but nevertheless are relevant in regards to the thermal effects of laser radiational interaction with materials:

a) **Black Body Radiation of the Heated Material**: In any heated material the surface will act as a radiator of heat energy. The total radiation, $\phi$, of any solid body is given by the Stephan-Boltzmann relationship (for a surface area $A$): (8)

\[
\phi = \sigma T^4 A \\
\phi = C_{\text{gray}} \sigma T^4 A
\]

for a black body

for a gray body

where

- $T$ is the surface temperature
- $C_{\text{gray}}$ is the gray body coefficient
  - $= 0.94$ for marble [28]
  - $= 0.96$ for granite [28]
- $\sigma$ is the emissivity constant

However, according to J.F. Ready [5], this effect is minor when
compared to the amount of laser radiation energy required to raise a material to that given temperature. Hence the relative heat loss is negligible. Nevertheless, this phenomenon is of importance since the black body radiation of a heated material is later on exploited for the purpose of monitoring temperatures of a laser heated disc.

b) **Expulsion:** The heat carried away by small quantities of expelled solid or liquid is usually very small compared to the heat carried away by conduction and vaporization. At very high power densities mechanical expulsion may be significant. The quantity of heat stored per unit time in a volume, \( V \), of a medium of density, \( \rho \), and specific heat, \( C_p \), when the temperature increases \( \Delta T \) in a time interval, \( \Delta t \), may be given by:

\[
\frac{\Delta q_1}{\Delta t} = \rho C_p \frac{V \Delta T}{\Delta t}
\]

(c) **Convection:** The heat loss due to convection is small. For example, the heat transferred through a stationary air mass 1mm thick for a temperature gradient of 10,000°C per cm is only 0.5 cal/cm² [12]. The time rate of heat flow by convection is given by Newton's law of cooling [8]:

\[
\frac{dq_2}{dt} = hA\Delta T
\]

where \( h \) = coefficient of heat transfer. Even for low velocity flowing gases, the heat transfer is small. The time rate of heat flow resulting from forced laminar gas parallel to a surface is formulated in Jakob [8], and is essentially an expansion of Newton's law of cooling.
Finite Element Model of Thermal Interaction Mechanisms

For homogeneous, isotropic solids of simple geometry, the classical methods of solving for temperature or stress distribution can be used to determine the influence of laser radiation on the temperature and the corresponding thermal stresses. To overcome the difficulties associated with solutions of stress distribution problems where the geometry of the body is complex and, or when the body is not completely homogeneous and isotropic, use has been made of the finite element technique [23]. In this method the body is divided into small finite sized elements which are kept compatible with each other and also satisfy overall thermal equilibrium. Essentially the heat flow problem is transformed from solving a differential equation with boundary conditions to one of solving ordinary simultaneous equations. In addition a computer program has been written and is available for solving heat flow problems by the finite element method [23]. A listing of this program is given in Appendix IV. The input to the program includes the initial conditions, joint coordinates, material properties, boundary conditions and nodal-element relationships. For material properties the specific heat and the conductivity must be given. They may be functions of temperature. The nodal points of each element must also be input. The program then calculates the elements at each node. This is printed out as it makes a good check on input. There is other input required such as number of iterations, amount of output to be printed, etc. The marching is then started and carried to the required time.
Figure 6a. Test Cylinder

Figure 6b. Axi-symmetric Approximation with Elements: This illustrates the type of problem that can be handled by the finite element heat flow analysis.
The temperature distribution found from this thermal analysis can then be used as input for a finite element analysis program to evaluate the strains within the body. This strain analysis program is presently available in the literature [20,21]. For the case of thin discs lased in an axi-symmetric manner, a simplified strain analysis routine is presented in this thesis.
SCOPE OF ANALYTICAL AND EXPERIMENTAL WORK

The purpose of the analytical and experimental work is to identify and evaluate the mechanisms whereby laser radiation interacts with rock materials and subsequently causes failure. The mechanisms which have been hypothesized may be summarized as follows: When a beam of laser radiation strikes the surface of a material, a temperature distribution is induced which then causes a certain state of stress in the specimen. If at any point in the specimen, the stress is sufficiently high to overcome the strength of the material either in tension or compression then local failure will be initiated. In order to substantiate these assertions, the following steps have been taken which constitute the remainder of this thesis:

Verification of Laser Induced Temperature Distributions

A short description of the finite element heat flow analysis [23] has been given in the previous section. This analysis has the capability of calculating the temperature-time-space relationships for a given laser input configuration and specimen geometry. In order to test the hypothesis regarding laser induced temperature distributions, certain rock specimens were subjected to laser irradiation and the experimentally observed temperatures were compared with the theoretical predictions as made by the analysis.

Verification of Laser Induced Thermal Stresses

In the section entitled "Design of Experiments" the desirability of using thin discs for the purpose of experimental and analytical
work is explained. For the simplified geometry of a thin disc, a thermal stress analysis* is developed for two different boundary conditions (constrained and unconstrained periphery). In order to test the hypothesis regarding laser induced thermal stresses, several unconstrained rock discs were subjected to laser irradiation and the experimentally observed strains were compared with the theoretical predictions as made by the analysis.

Verification of Laser Induced Failure Phenomena

The hypothesis regarding laser induced failure phenomena states that if at any material point the state of stress is sufficiently high to overcome the strength of the material either in tension or compression, then local failure will be initiated. We therefore consider two types of failure phenomena in thermally stressed thin discs, in order to test the hypothesis:

a) Tensile Failures in Unconstrained Discs: In an unconstrained disc that is axi-symmetrically lased at the center, a tensile failure is manifested by the formation of a crack that propagates in the radial direction. By using the heat flow analysis in conjunction with the thermal stress analysis, determination can be made of the time of lasing, at a given power level, required to induce a state of stress in the specimen such that at a certain material point, the tensile strength is exceeded. This may then

*The input for this analysis consists of the properties of the rock material and the temperature distribution induced by exposure to the laser beam. The latter may consist, either of experimental observations, or of the results from the finite element heat flow analysis.
be compared with the experimentally observed time and location of crack initiation.

b) **Compressive Failures in Constrained Discs**: In a constrained disc that is axi-symmetrically lased at the center, a compressive failure is manifested by the formation of a "spall". This constitutes small pieces of rock material rapidly flaking away from the spalled area. By using the heat flow analysis in conjunction with the thermal stress analysis, determination can be made of the time of lasing, at a given power level, required to induce a state of stress in the specimen such that at a certain material point, the compressive strength is exceeded. This may then be compared with the experimentally observed time and location of spalling initiation.

It may be worth mentioning, as a preview, that the results of the above work were successful thus placing much confidence in the original hypothesis underlying the mechanisms whereby laser radiation interacts with rock materials.
DESIGN OF EXPERIMENTS

Suitability of Thin Discs for the Purpose of Analysis

As discussed in the literature survey, the major mechanism of damage by laser radiation is due to heat. It is, therefore, desirable that the heating of material bodies by laser irradiation be studied, and experimental techniques be developed to verify the application of the thermodynamic heat distribution in materials to the analysis of damage caused by laser irradiation. To do this, thin circular discs of rocks* were used as the first step.** A two-part theoretical analysis is available in the literature for the determination of heat distribution and the associated stress distribution in such bodies. In order to apply this analysis to the experimental results of this study, the following assumptions were made:

a) If the disc is irradiated by a laser in an axisymmetric fashion (i.e. radiation is uniform about the center of the disc) then a one-dimensional heat flow analysis can be made to determine the temperature distribution in the disc as a function of radius and time.

*Specifically, in this thesis, the rock types marble and granite have been studied.

**It may be interesting to note that Marovelli, Chen and Veith [14] have studied thermal stress distributions in thin circular disc subjected to a peripheral thermal shock at various rates of heat transfer. The purpose was to predict the thermal shock response of a rock body of finite size. Their theoretical analysis was based on radial heat flow by conduction in the disc and heat exchange by convection between the disc and the surroundings. From solutions of the stress distribution for both cooling and heating shocks, they formulated an average stress theory.
b) The disc will fail either in tension (cracking) or in compression (spalling) when the thermally induced stresses exceed the strength of the material. Since the temperature distribution is known (either from the theoretical analysis or from actual measurements), the stress distribution may be calculated and then compared with the mode of failure.

Another advantage of using a thin circular disc for the analysis is that it lends itself easily to the experimental verification. Temperatures may be observed by using either temperature sensitive paints or thermocouples. Strains may be measured by attaching strain gauges to the surface of the specimens.

Once the results of the finite element heat flow analysis and the thermal stress analysis have been verified experimentally, more complex body geometries and laser radiation patterns can be used to study the mechanism of damage due to laser heating. The analytical and experimental techniques used to verify laser induced temperatures, stresses and strains, and failure phenomena are now described.

Temperature Distributions in Thin Circular Discs

a) Analytical Technique: The finite element heat flow analysis in its computerized form [23] is used, with the input parameters of conductivity, specific heat and density as defined in the literature survey section entitled "Material Properties Relevant to a Heat Flow Analysis". In order to account for the lasing configuration and power level, the following procedure was adopted:
Figure 7. Nodal and Elementary Notation Regarding Thin Marble Discs: In the actual analysis, a "pie shaped" wedge, one radian wide, is considered for computational purposes. This is indicated in the diagram by the dotted lines. The numbers on the outside of the solid rectangle indicate the nodes whereas the numbers inside the triangles indicate the elements. It should be noted that the axis coincides with the center axis of the disc.
Assuming a laser beam at a power level of $x$ watts, or $0.00095 \times Btu/sec$, the actual power that enters the pie shaped wedge* in Figure 7 is $(0.00095 \times x)/2\pi = 0.00015 \times Btu/sec$. From an approximate knowledge of the distribution of laser power across the beam and from calculations based upon the impingement areas, the following figures are arrived at (See Figure 7): One third of the power (or $0.00005 \times Btu/sec$) enters node 1, and two-thirds of the power (or $0.00010 \times Btu/sec$) enters node 3.

When all of the above variables have been put into the computer analysis, the temperatures for each node as a function of time are calculated and then printed out.

b) **Experimental Technique**: In order to measure the temperature of a laser heated disc without physically touching it or mechanically interfering with it, a sensitive "radiometric microscope" was used (Figure 8). This instrument had the capability of measuring the "black body" radiation from a point on the surface of the material. If properly calibrated, then a direct reading of temperature in °C could be made.

The radiometric microscope instrument was calibrated as follows: Since it was decided to measure the temperature of the surface of a marble disc, it was necessary to find the emissivity of marble. This was done by placing a thin marble disc on a hotplate thus heating it evenly. One half of the disc had been painted dull black, thus making

---

*This is the pie shaped wedge that is considered in the finite element heat flow analysis [23].
Figure 8. The Radiometric Microscope: The eyepiece (top) is used to aim the microscope by centering the point whose temperature is to be measured on a set of crosshairs.

Figure 9. The Instrument Panel of the Radiometric Microscope: The knob settings from the top left and going in a clockwise direction, are emissivity setting, zero adjust, ambient temperature setting, and readout scale setting.
it a perfect black body radiator in comparison to the unpainted side. The readout scale was set on the most sensitive setting (Figure 9) and alternate readings were taken of the painted and unpainted sides. The emissivity of the plain marble is the ratio between the two and was found to be 0.942. This indicates that marble is almost a perfect black body radiator*. The emissivity setting was then adjusted to this value, the zero and ambient temperature settings were arranged and the readout scale was set to give a direct full scale reading from 15°C to 165°C. For a few experiments it was necessary to go to higher temperatures and so a different scale had to be used.

Thermal Stresses in a Thin Unconstrained Circular Disc

a) **Analytical Technique:** In order to determine the stresses developed in a thin circular disc when it is subjected to a known heat input on one side (see Figure 10) the following assumptions were made by Timoshenko [15]:

1) temperature is symmetrical about the center, i.e.
   \[ T = F(r), \]
2) temperature does not vary over the thickness of the disc,
3) no radial stresses exist at the perimeter of the disc,
4) material is homogeneous, isotropic and linear elastic,
5) material constants are independent of temperature, and

*It has been pointed out in the Literature Survey of this thesis that a material which behaves as a black body radiator is usually an equally good absorber of radiant heat energy. For this reason it has been assumed in all experimental and analytical work that marble absorbs 100% of the incident laser energy beam.
Figure 10. Cross Section of Unconstrained Disc: The boundary condition is that the peripheral radial stress is zero.
For the purpose of analysis, the major equations are:

(i) Equilibrium Equation:

\[
\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0
\]

(ii) Stress-Strain Relations:

\[
\epsilon_r - \alpha T = \frac{1}{E} \left( \sigma_r - \nu \sigma_\theta \right)
\]

\[
\epsilon_\theta - \alpha T = \frac{1}{E} \left( \sigma_\theta - \nu \sigma_r \right)
\]

Final expressions for the stresses are then given as follows:

(i) Radial Stress:

\[
\sigma_r = \alpha E \left( \frac{1}{b^2} \int_0^t \frac{d}{dr} Tr dr - \frac{1}{r^2} \int_0^t Tr dr \right)
\]  

(ii) Tangential Stress:

\[
\sigma_\theta = \alpha E \left( -T + \frac{1}{b^2} \int_0^b Tr dr + \frac{1}{r^2} \int_0^t Tr dr \right)
\]

The appropriate notation is as follows:

- \( T \) is temperature \([f(r)]\),
- \( \sigma_r \) is radial stress component,
- \( \sigma_\theta \) is stress component in tangential direction,
- \( \epsilon_r \) is radial strain component,
- \( \epsilon_\theta \) is strain component in tangential direction,
- \( \alpha \) is coefficient of expansion,
- \( E \) is modulus of elasticity,
t is thickness of disc,
b is radius of disc,
u is Poisson's ratio.

A computer program which solves equations (1) and (2) by numerical integration is given in Appendix III, part a.

It should be noted that, in reality the laser beam impinges upon one side of the thin disc, and thus there will be a temperature variation from one side of the disc to the other. In all analytical work, however, the average temperature of the two sides is taken and used as input for the stress analysis presented herein. Thus, in actuality, we are evaluating membrane (mean) stresses.

Additional input for the stress analysis program consisted of the material properties, E, α and u. These were obtained from [28] and verified in the laboratory:

**Granite:**

\[ E = 2.4 \times 10^{-6} \text{ psi} \]
\[ \alpha = 0.72 \times 10^{-5} \text{ °C}^{-1} \]
\[ u = 0.10 \]

**Marble:**

\[ E = 8.3 \times 10^{-6} \text{ psi} \]
\[ \alpha = 1.22 \times 10^{-5} \text{ °C}^{-1} \]
\[ u = 0.30 \]

The computer program reads in the material properties and the temperature distribution averaged over the two sides of the disc, and then prints out membrane stresses as a function of radius.
b) **Experimental Technique:** A Tektronix Type 3C-66 oscilloscope (Figure 13) was used to measure strains directly from simple wire wound strain gages in a variety of bridge circuits. The gages used were the SR-4 type manufactured by Baldwin, Lima and Hamilton, Inc. The strain measuring plug in unit of the oscilloscope was calibrated as described in Appendix V.

The following criteria had to be considered in order to determine the appropriate locations for attaching the strain gages:

1) Compensation for temperature changes: Strain gages are extremely sensitive to even the smallest changes in temperature, and therefore some means of either compensating or accounting for this effect had to be devised. This was done by measuring the difference between the radial and tangential strains at a point on the disc, since any changes in temperature affect both strains by the same amount and therefore this effect disappears in the subtraction.

2) Elimination of bending effects: As it was mentioned previously, we are concerned with membrane stresses (and strains) i.e. the stresses and strains on a fictitious membrane disc which has a temperature distribution equal to the average of the temperature distributions on the two faces of the actual disc. In performing an experiment, the bending effects may be eliminated i.e. the membrane strains may be found by taking the average of the two strains at points on opposite faces of the disc.

Using criteria 1 and 2, the discs for this experiment were instrumented as shown in Figure 11 and connected to the oscilloscope plug in unit as shown schematically in Figure 12 and pictorially in Figure 14. With these four strain gages set up in the bridge circuit as described,
Figure 11. Strain Gage Instrumentation of 1.5" Diameter by 0.05" Thick Marble Disc: Strains are measured at a radial distance of 0.60" from the center of the disc. It should be noted that the quantity to be measured, \( \Sigma \varepsilon = \varepsilon_{\theta 1} + \varepsilon_{\theta 2} - \varepsilon_{r 1} - \varepsilon_{r 2} \); or alternatively, \( \Sigma \varepsilon = 2\varepsilon_{\theta} - 2\varepsilon_{r} \) where \( \varepsilon_{\theta} \) and \( \varepsilon_{r} \) are the tangential and radial membrane strains respectively, at \( r=0.60" \). The actual radial and tangential strains on sides one and two are \( \varepsilon_{r 1}, \varepsilon_{\theta 1}, \varepsilon_{r 2}, \varepsilon_{\theta 2} \) respectively.
Figure 12. Schematic Diagram of Oscilloscope Bridge Circuit.
Figure 13. Photograph of Tektronix Type 3C-66 Oscilloscope

Figure 14. Photograph of a Thin Disc Instrumented With Strain Gages.
the oscilloscope will measure the following parameter as the y ordinate on the screen:

\[ \Sigma \varepsilon = 2 \varepsilon_\theta - 2 \varepsilon_r \bigg|_{r = 0.60"} \]

By utilizing the stress-strain relations the following expression is obtained for the stresses:

\[ 2\varepsilon_\theta - 2\varepsilon_r = \frac{2(1 + \nu)}{E} (\sigma_\theta - \sigma_r) \]

so that

\[ (\sigma_\theta - \sigma_r) = \frac{E}{2(1 + \nu)} \Sigma \varepsilon \]

This quantity may then be compared with the value determined by the theoretical analysis.

**Thermal Stresses In a Thin Constrained Disc**

By modifying the stress - temperature equations for the unconstrained disc, the following relationships have been derived for the constrained case which is illustrated in Figure 15.**

a) Radial Stress:

\[ \sigma_r = \alpha E \frac{1}{r^2} \int_0^r \frac{E}{1-\nu^2} \left[ -\frac{(1+\nu)^2 \alpha}{b^2} \frac{1}{\nu} \int_0^b \text{Trdr} \right] \]

\[ + \alpha E \left[ - \frac{1+\nu}{1-\nu} \frac{1}{b^2} \int_0^b \text{Trdr} \right] \]

\[ + \frac{1}{r^2} \int_0^r \frac{E}{1-\nu^2} \left[ -\frac{(1+\nu)^2 \alpha}{b^2} \frac{1}{\nu} \int_0^b \text{Trdr} \right] \]

\[ \text{(3)} \]

*\( \varepsilon_\theta \) and \( \varepsilon_r \) are the tangential and radial membrane strains respectively. The quantity \( \Sigma \varepsilon \) is measured at a radial distance of 0.60" from the center of the marble disc.

**It should be noted that in equations (3) and (4), the notation is the same as for the case of the unconstrained disc. [Equations (1) and (2)]
Figure 15. Cross Section of Constrained Disc: The boundary condition is that the peripheral radial strain is zero.
b) Tangential Stress

\[ \sigma_{\theta} = \alpha E \frac{l}{r^2} \int_{0}^{r} \tau dr - \alpha ET \int_{0}^{r} \frac{E}{1-u^2} [-1+u]^2 \alpha \frac{l}{b^2} \int_{0}^{r} \tau dr \]

\[ + \alpha E \left( -T - \frac{1+u}{1-u} \frac{l}{b^2} \int_{0}^{r} \tau dr + \frac{l}{r^2} \int_{0}^{r} \tau dr \right) \tag{4} \]

These equations were formulated in a computer program, the listing of which is given in Appendix III, part b.
EXPERIMENTAL INVESTIGATIONS

The experimental work and the analysis of the results presented in this chapter are divided into five sections:

I - Verification of Finite Element Heat Flow Analysis

II - Verification of Stress Analysis Technique

III - Crack Initiation in Large Disc Shaped Specimens

IV - Tensile Failures in Small Marble and Granite Discs

V - Compressive Failures in Constrained Granite Discs

Verification of Finite Element Heat Flow Analysis

A special three point holder was used for securing the 1-1/2" diameter by 1/10" thick marble discs. This is illustrated in Figure 16. Each of the three arms were spring loaded very lightly so as to automatically center the disc within the holder yet not impose any appreciable mechanical loading. By this means, the holder could be clamped in place after having aimed the laser at the beginning of the experiment, and then discs could be removed and replaced at will without changing the orientation of the laser beam. Figure 17 illustrates the overall setup in conjunction with the laser. In these temperature measuring experiments, consistency of laser beam aiming and accuracy of the microscope aiming were of great importance toward obtaining meaningful results.

In the first four experiments 1 1/2" diameter by 1/10" thick marble discs were used. In order that temperatures could be verified for discs of two different thicknesses, the fifth experiment consisted of 1 1/2" diameter by 1/20" thick marble discs.
Figure 16. Technique for Supporting the Marble Disc: The laser beam is aimed towards the reader, i.e. impinging upon the far side of the marble disc. The radiometric microscope is aimed at the centerspot of the near side of the disc. The other side is half coated with "Detectotemp" paint [23] as a convenient means of checking where the laser beam actually hits the disc. The color changes can be seen through the disc since it is so thin.

Figure 17. Typical Set-Up Involving Disc and Holder, Radiometric Microscope and Laser: The laser is out of the picture, on the left.
Table 1 contains the theoretically predicted temperatures and the experimentally observed temperatures at the locations indicated for each of the five cases of specimen geometry and laser input power. Figures 18 through 22 display graphically the two sets of results for each experiment.

**Discussion of Results:** The consistency of the experimental results with that predicted from the finite element analysis shows that this analysis, which was developed in Reference [23], is correct and the assumptions upon which it is based are valid. Furthermore, it indicates that the values chosen for thermal conductivity, specific heat and density are acceptable.

An interesting point to note is that in all the experiments performed in this section the time of lasing was short (of the order of less than 10 seconds). The induced temperatures that resulted (either by observation or calculation) seemed to be almost linearly increasing with time. Due to the complexity of this particular heat flow problem this is not an obvious inference, and probably is limited only for short times of lasing since when temperatures become very high the heat losses due to convection and black body re-radiation become significant. In other words the temperature profile for a given node will level off to a finite value as illustrated in Figure 23.

This is in fact true, since it is known from an optical pyrometric experiment, that for a 1000 watt beam, the maximum temperature attained by the lased area on the surface of granite is about 2000°C and this occurs after 1-2 minutes of lasing. At this time, the loss of heat from any given point due to conduction, convection and black body radiation balances the rate of heat input by the laser beam.
Table 1. Calculated and Observed Temperatures for Experiments 1 through 5.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>10 watts</td>
<td>10 watts</td>
<td>20 watts</td>
<td>30 watts</td>
<td>10 watts</td>
</tr>
<tr>
<td>Spec. Diam. Thick</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/20&quot;</td>
</tr>
<tr>
<td>Location</td>
<td>Backside Centerspot</td>
<td>0.125&quot; from Front-side Centerspot</td>
<td>Backside Centerspot</td>
<td>Backside Centerspot</td>
<td>Backside Centerspot</td>
</tr>
<tr>
<td>TIME (Secs)</td>
<td>CALC.</td>
<td>OBS.</td>
<td>CALC.</td>
<td>OBS.</td>
<td>CALC.</td>
</tr>
<tr>
<td>1</td>
<td>29</td>
<td>35</td>
<td>36</td>
<td>30</td>
<td>43</td>
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<tr>
<td>2</td>
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<td>48</td>
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<td>65</td>
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<td>143</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>185</td>
<td>178</td>
<td>119</td>
<td>125</td>
<td></td>
</tr>
</tbody>
</table>
Figure 18. Observed and Calculated Temperatures for Experiment No. 1: This consisted of lasing a 0.10" thick marble disc at a power level of 10 watts.

Figure 19. Observed and Calculated Temperatures for Experiment No. 2: This consisted of lasing a 0.10" thick marble disc at a power level of 10 watts.
Figure 20. Observed and Calculated Temperatures for Experiment No. 3: This consisted of lasing a 0.10" thick marble disc at a power level of 20 watts.

Figure 21. Observed and Calculated Temperatures for Experiment No. 4: This consisted of lasing a 0.10" thick marble disc at a power level of 30 watts.
Figure 22. Observed and Calculated Temperatures for Experiment No. 5: This consisted of lasing a 0.05" thick marble disc at a power level of 10 watts.

Figure 23. Typical Profile of Temperature Rise vs. Time for the Lased Spot of a Large Granite Block Exposed to a 1000 Watt Beam.
Three 1 1/2" diameter by 1/20" thick marble discs (unconstrained) were instrumented with strain gages and exposed to a 1/4" diameter laser beam at a power level of 5 watts. This experiment is illustrated schematically in Figure 24. The quantity \( \Sigma \varepsilon = 2\varepsilon_\theta - 2\varepsilon_\Gamma \) was measured as a function of time. Using the finite element heat flow analysis in conjunction with the thermal stress analysis, the value of \( \Sigma \varepsilon \) was calculated. These two sets of values are given in Table 2 and also displayed graphically in Figure 25, which indicate excellent consistency in measured and predicted values of strains.

**Crack Initiation in Large Disc Shaped Specimens**

The 5 1/2" diameter by 1/5" thick marble discs were prepared and instrumented with silver rings for the purpose of detecting the location of crack initiation in conjunction with an electronic interrupt circuit. The details of this are given in Appendix I.

The apparatus was set up as shown in Figures 26 and 27. The "Detectotemp" painted side faced the laser (this is the side shown in Figures 26 and 27). The laser beam was turned on and a stopwatch started. As soon as a glow tube on the display board lit up (i.e., a crack had started) the laser was shut off and the time observed. The lased specimen ("Detectotemp" painted side) is shown in Figure 28.

Several discs of marble and granite (4" in diameter and about 1/5" thick) were exposed at the center to about 200 watts of laser radiation. The diameter of the radiated area was about 1" and one side of the discs was coated with temperature sensitive paint.

Cracks were generally noticed in these specimens after they had been irradiated for 5 to 15 seconds. The cracks appeared to start
Table 2. Calculated and Observed Membrane Strains at a Distance of 0.60" from the Center of the Disc, as a Function of Time

<table>
<thead>
<tr>
<th>TIME (Sec)</th>
<th>CALCULATED $\sigma_\theta$ (psi)</th>
<th>OBSERVED $\Sigma e = 2 e_\tau - 2 e_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$-38.9$</td>
<td>$+177.1$</td>
</tr>
<tr>
<td>4</td>
<td>$-76.2$</td>
<td>$+339.2$</td>
</tr>
<tr>
<td>6</td>
<td>$-114.1$</td>
<td>$+519.7$</td>
</tr>
<tr>
<td>8</td>
<td>$-154.4$</td>
<td>$+703.2$</td>
</tr>
<tr>
<td>10</td>
<td>$-197.4$</td>
<td>$+891.6$</td>
</tr>
<tr>
<td>12</td>
<td>$-271.3$</td>
<td>$+1225.5$</td>
</tr>
</tbody>
</table>

Where $\sigma_\theta$ and $\Sigma e$ are strained. The calculated and observed strains are shown for various times.
The Disc is Instrumented to Measure Radial and Tangential Strains at a Distance of 0.60" From the Center, on Both Sides.

Figure 24. Schematic Diagram of Strain Measuring Experiment

![Diagram of Strain Measuring Experiment](image)

---

Strain, $\Sigma \varepsilon \times 10^{-6}$

- Experimental Values
- Analytically Computed Values

Figure 25. Comparison of Experimental and Analytical Values of Membrane Strains

![Graph of Strain vs. Time](image)
between the center and the periphery of the disc and then propagate radially in both directions, extending to the perimeter and the center. The cracks had the semblance of being clean, sharp and neat with little or no spalling noticeable (Figure 29).

The development of the cracks would tend to indicate that they were the result of "tensile failures" caused by the stresses acting in the tangential direction (i.e. normal to the direction of crack propagation).

From the changed color of the thermosensitive paints the temperature in the vicinity of the lased area could be determined. This temperature was generally of the order of a few hundred degrees centigrade (up to about 400°C). No melting occurred, and the outer regions of the disc were roughly at room temperature.

**Experimental Results:** In order to determine the applicability of the thermal analysis presented in previous sections for thin discs to laser irradiated samples of rocks, three sets of experiments were done. Each set consisted of lasing three samples* under identical conditions in order to obtain reproducible results.

For each set of experiments, individual data for each sample are presented in Tables 3, 4 and 5. These tables include the time of lasing required to cause a crack, and the observed location of crack initiation. It was found that the prevailing temperatures in the disc at the time of crack initiation were very consistent (i.e., in any given

---

*All samples were discs of 15 cms. diameter and 0.4 cms. thickness*
Figure 26. Holder for Instrumented Disc and Connection to Crack Detection Circuit

Figure 27. Overall Set-Up in Conjunction With the Laser
Figure 28. "Detectotemp" Painted Side After Lasing

Figure 29. Picture of a Crack Due to Laser Induced Thermal Stresses: In the initial experiments, the formation of anywhere from one to four radial cracks was noticed.
Table 3

Experiment Number 1

laser power = 300 watts

diameter of irradiated area = 2.5 cm.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Time of lasing until crack starts</th>
<th>Radius at which crack initiation was detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6 seconds</td>
<td>7 cms.</td>
</tr>
<tr>
<td>B</td>
<td>5 seconds</td>
<td>6 cms</td>
</tr>
<tr>
<td>F</td>
<td>9 seconds</td>
<td>5.5 cms</td>
</tr>
</tbody>
</table>

Time of lasing required for crack initiation, and the radius at which the crack was detected by noting which silver ring on the disc broke first.

<table>
<thead>
<tr>
<th>Radius</th>
<th>Temperature</th>
<th>Radial Stress σ_r</th>
<th>Tangential Stress σ_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm.</td>
<td>220°C</td>
<td>-10300 psi</td>
<td>-10300 psi</td>
</tr>
<tr>
<td>.75 cm.</td>
<td>220°C</td>
<td>-10300 psi</td>
<td>-10300 psi</td>
</tr>
<tr>
<td>1.5 cm.</td>
<td>145°C</td>
<td>-9030 psi</td>
<td>-4550 psi</td>
</tr>
<tr>
<td>2.25 cm.</td>
<td>65°C</td>
<td>-5960 psi</td>
<td>+880 psi</td>
</tr>
<tr>
<td>3.00 cm.</td>
<td>0°C</td>
<td>-3720 psi</td>
<td>+5140 psi</td>
</tr>
<tr>
<td>3.75 cm.</td>
<td>0°C</td>
<td>-2130 psi</td>
<td>+3540 psi</td>
</tr>
<tr>
<td>4.50 cm.</td>
<td>0°C</td>
<td>-1260 psi</td>
<td>+2680 psi</td>
</tr>
<tr>
<td>5.25 cm.</td>
<td>0°C</td>
<td>-740 psi</td>
<td>+2160 psi</td>
</tr>
<tr>
<td>6.00 cm.</td>
<td>0°C</td>
<td>-400 psi</td>
<td>+1820 psi</td>
</tr>
<tr>
<td>6.75 cm.</td>
<td>0°C</td>
<td>-160 psi</td>
<td>+1580 psi</td>
</tr>
<tr>
<td>7.50 cm.</td>
<td>0°C</td>
<td>0</td>
<td>+1420 psi</td>
</tr>
</tbody>
</table>

** Room temperature is taken as base, i.e., zero

Temperature Measurements and Stress Computations
Note 1. In this and all other experiments the laser beam was "stopped down" by passing it through a hole in a fire brick before impingement on the disc. Since a portable power meter was not available at the time of the experiments, only a rough estimate of the impingement power could be obtained by multiplying the output power of the laser by the ratio of the area of the impingement beam to the area of the laser output beam.

Note 2. Temperatures were obtained from the color of the thermosensitive paint. The radial and tangential stresses were then computed using the analysis program listed in Appendix III.

Note 3. Positive stresses are tensile while negative stresses are compressive.
Table 4
Experiment Number 2
laser power = 200 watts
diameter of irradiated area = 1.25 cm.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Time of lasing until crack starts</th>
<th>Radius at which crack initiation was detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>9 seconds</td>
<td>7 cms.</td>
</tr>
<tr>
<td>D</td>
<td>9 seconds</td>
<td>4.5 cms.</td>
</tr>
<tr>
<td>H</td>
<td>9 seconds</td>
<td>4.5 cms.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radius</th>
<th>Temperature</th>
<th>Radial Stress $J_r$</th>
<th>Tangential Stress $\sigma_{\theta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>340°C</td>
<td>-16800 psi</td>
<td>-16800 psi</td>
</tr>
<tr>
<td>.5 cm</td>
<td>220°C</td>
<td>-12800 psi</td>
<td>-8790 psi</td>
</tr>
<tr>
<td>1.0 cm.</td>
<td>100°C</td>
<td>-8790 psi</td>
<td>-790 psi</td>
</tr>
<tr>
<td>1.5 cm.</td>
<td>30°C</td>
<td>5080 psi</td>
<td>+5510 psi</td>
</tr>
<tr>
<td>2.0 cm.</td>
<td>0°C</td>
<td>2770 psi</td>
<td>+3190 psi</td>
</tr>
<tr>
<td>2.5 cm.</td>
<td>0°C</td>
<td>1690 psi</td>
<td>+2120 psi</td>
</tr>
<tr>
<td>3.0 cm.</td>
<td>0°C</td>
<td>1110 psi</td>
<td>+1540 psi</td>
</tr>
<tr>
<td>3.5 cm.</td>
<td>0°C</td>
<td>760 psi</td>
<td>+1180 psi</td>
</tr>
<tr>
<td>4.0 cm.</td>
<td>0°C</td>
<td>530 psi</td>
<td>+960 psi</td>
</tr>
<tr>
<td>4.5 cm.</td>
<td>0°C</td>
<td>380 psi</td>
<td>+800 psi</td>
</tr>
<tr>
<td>5.0 cm.</td>
<td>0°C</td>
<td>260 psi</td>
<td>+690 psi</td>
</tr>
<tr>
<td>5.5 cm.</td>
<td>0°C</td>
<td>180 psi</td>
<td>+610 psi</td>
</tr>
<tr>
<td>6.0 cm.</td>
<td>0°C</td>
<td>120 psi</td>
<td>+540 psi</td>
</tr>
<tr>
<td>6.5 cm.</td>
<td>0°C</td>
<td>70 psi</td>
<td>+490 psi</td>
</tr>
<tr>
<td>7.0 cm.</td>
<td>0°C</td>
<td>30 psi</td>
<td>+450 psi</td>
</tr>
<tr>
<td>7.5 cm.</td>
<td>0°C</td>
<td>0</td>
<td>+420 psi</td>
</tr>
</tbody>
</table>
Table 5

Experiment Number 3

laser power = 100 watts
diameter of irradiated area = 0.62 cm.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Time of lasing until crack starts</th>
<th>Radius at which crack initiation was detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>10 seconds</td>
<td>2 1/2 cms.</td>
</tr>
<tr>
<td>G</td>
<td>11 seconds</td>
<td>3 cms.</td>
</tr>
<tr>
<td>E</td>
<td>10 seconds</td>
<td>3 1/2 cms.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radius</th>
<th>Temperature</th>
<th>Radial Stress $\sigma_r$</th>
<th>Tangential Stress $\sigma_\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm.</td>
<td>340°C</td>
<td>- 16800 psi</td>
<td>- 16800 psi</td>
</tr>
<tr>
<td>.5 cm.</td>
<td>220°C</td>
<td>- 12800 psi</td>
<td>- 8800 psi</td>
</tr>
<tr>
<td>1.0 cm.</td>
<td>65°C</td>
<td>- 8100 psi</td>
<td>- 1950 psi</td>
</tr>
<tr>
<td>1.5 cm.</td>
<td>0°C</td>
<td>- 4340 psi</td>
<td>+ 4700 psi</td>
</tr>
<tr>
<td>2.0 cm.</td>
<td>0°C</td>
<td>- 2360 psi</td>
<td>+ 2720 psi</td>
</tr>
<tr>
<td>2.5 cm.</td>
<td>0°C</td>
<td>- 1450 psi</td>
<td>+ 1810 psi</td>
</tr>
<tr>
<td>3.0 cm.</td>
<td>0°C</td>
<td>- 950 psi</td>
<td>+ 1310 psi</td>
</tr>
<tr>
<td>3.5 cm.</td>
<td>0°C</td>
<td>- 650 psi</td>
<td>+ 1010 psi</td>
</tr>
<tr>
<td>4.0 cm.</td>
<td>0°C</td>
<td>- 450 psi</td>
<td>+ 820 psi</td>
</tr>
<tr>
<td>4.5 cm.</td>
<td>0°C</td>
<td>- 320 psi</td>
<td>+ 680 psi</td>
</tr>
<tr>
<td>5.0 cm.</td>
<td>0°C</td>
<td>- 230 psi</td>
<td>+ 580 psi</td>
</tr>
<tr>
<td>5.5 cm.</td>
<td>0°C</td>
<td>- 150 psi</td>
<td>+ 520 psi</td>
</tr>
<tr>
<td>6.0 cm.</td>
<td>0°C</td>
<td>- 100 psi</td>
<td>+ 460 psi</td>
</tr>
<tr>
<td>6.5 cm.</td>
<td>0°C</td>
<td>- 60 psi</td>
<td>+ 420 psi</td>
</tr>
<tr>
<td>7.0 cm.</td>
<td>0°C</td>
<td>- 30 psi</td>
<td>+ 390 psi</td>
</tr>
<tr>
<td>7.5 cm.</td>
<td>0°C</td>
<td>0</td>
<td>+ 360 psi</td>
</tr>
</tbody>
</table>
experiment the temperature distributions in the three samples, when they cracked, were the same). For this reason, only one temperature distribution is presented in these tables for each set of the three samples. From the temperature distribution, stresses were computed using the analysis program listed in Appendix III, and their values are shown in the same tables containing the temperature measurements. Graphs were then plotted for the temperatures and the stress distributions as functions of radius across the disc at the time of crack initiation. The location of crack initiation for each sample is indicated in each experiment. These plots are shown in Figures 30 through 35 for the three sets of experiments reported herein.

Discussion of Results: The results of temperature determination, using thermosensitive paints, indicate that the temperature distribution in such thin discs can be considered to be axi-symmetric. This indicates that the response of the material to change in temperature can be assumed to be similar to that of an isotropic and homogeneous body.

The pattern of cracking indicates that the tensile stresses developed in the specimens are in the tangential direction. This corresponds with the hypothesis underlying the formation of radial tensile failure in the discs.

It should also be noted that in all three sets of experiments the maximum computed tensile stresses ($\sigma_0$) at the time of crack initiation were within 15% of each other. That is, 5140 psi in the first experiment, 5510 psi in the second and 4700 psi in the third. The value
Figure 30. Temperature Distribution for Experiment No. 1

Figure 31. Stress Distribution and Location of Crack Initiation for Experiment No. 1: The downward vertical arrows indicate the radius at which the crack was detected to start in each of the three samples. A started at 7cms; B at 6cms; and F at 5.5cms.
Figure 32. Temperature Distribution for Experiment No. 2

Figure 33. Stress Distribution and Location of Crack Initiation for Experiment No. 2
Figure 34. Temperature Distribution for Experiment No. 3

Figure 35. Stress Distribution and Location of Crack Initiation for Experiment No. 3
of the tensile strength from the literature is about 3500 psi.

As it can be noted from the results presented in Figure 30 through 35, however, the display board is detecting crack initiation further out from the center of the disc than the predicted location of the maximum tangential stress ($\sigma_\theta$). A possible explanation for this is that when the crack first starts it is very small and must travel a certain distance outwards before it gets big enough to break a silver line.

Consistent results have been obtained for laser induced temperatures, and for the time to crack initiation. The results thus far indicate that the material can be treated as homogeneous and isotropic for the determination of temperature and stress distributions throughout thin disc shaped specimens. The failure of these specimens appears to be caused by tensile stresses which exceed the strength of the material.

**Tensile Failures in Small Marble and Granite Discs**

A high output crystal phonograph cartridge was placed in contact with the unconstrained thermally stressed disc. When the disc cracks, the sound wave is picked up by the cartridge needle and detected on the oscilloscope screen. The oscilloscope trace is started on a slow sweep when the laser is turned on and thus the time to crack initiation may be measured by observing the point on the screen where the first "kick" occurs. (See Figure 36.)

Eight experiments were performed each of which consisted of exposing several 1 1/2" diameter marble and granite disc specimens of two different thicknesses to a laser beam at three different power
Figure 36. Schematic Diagram Illustrating Method of Detecting Crack Initiation in an Unconstrained Thermally Stressed Disc, Using a Phonograph Cartridge.

Figure 37. Schematic Diagram Illustrating Typical Disc Cracking Experiment.
levels. Figure 37 illustrates a typical experiment. For each experiment the time of lasing required to initiate cracking (tensile failure) was found.

Knowing the time of lasing until crack initiation, it was possible to determine the temperature distribution at that instant using the finite element heat flow analysis. The average temperatures of the two faces of the disc were taken as the membrane temperatures. When these values are put into the thermal stress analysis program, it is possible to find the radial and tangential components of the membrane stresses, $\sigma_r$ and $\sigma_\theta$, respectively, at the time of crack initiation.

The results for Experiments 1 through 8 are given in Table 6. Since the purpose of this section is to evaluate tensile failures in small discs, the maximum tensile (i.e. positive) stress for each experiment is underlined in the table to facilitate future reference to it. It should be noted that in all these experiments, cracks formed and propagated in the radial direction. Thus the tensile stresses that cause these failures are always perpendicular to the direction of crack propagation, i.e. in the tangential direction. Furthermore, it should be noted that the units for membrane stresses in Table 6 are ksi or psi x $10^3$. The results for temperature and stress distributions for each experiment are displayed graphically in Figures 38 through 45.

Discussion of Results: It is evident that cracks, which form and grow in the radial direction of these discs, are tensile failures brought about when the maximum induced tangential stress exceeds the tensile strength of the rock material. It is inferred, therefore, that the location of crack initiation is at the radial distance from the center where the maximum tangential stress, $\sigma_\theta \text{ max}$, exists.
Table 6. Temperature and Stress Distributions for Experiments 1 through 8

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>10 watts</td>
<td>20 watts</td>
<td>30 watts</td>
<td>.5 watts</td>
</tr>
<tr>
<td>Rock Type</td>
<td>Marble</td>
<td>Marble</td>
<td>Marble</td>
<td>Marble</td>
</tr>
<tr>
<td>Diameter, Thickness</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/10&quot;</td>
<td>1 1/2&quot;, 1/20&quot;</td>
</tr>
<tr>
<td>Time to Crack</td>
<td>10 sec.</td>
<td>5 sec.</td>
<td>3 1/2 sec.</td>
<td></td>
</tr>
<tr>
<td>RADIUS (inches)</td>
<td>TEMP. (°C)</td>
<td>STRESSES (ksi)</td>
<td>TEMP. (°C)</td>
<td>STRESSES (ksi)</td>
</tr>
<tr>
<td>.075</td>
<td>163</td>
<td>-8.90</td>
<td>-4.82</td>
<td>189</td>
</tr>
<tr>
<td>.150</td>
<td>63.6</td>
<td>-5.28</td>
<td>+1.63</td>
<td>53</td>
</tr>
<tr>
<td>.225</td>
<td>33.8</td>
<td>-2.91</td>
<td>+2.28</td>
<td>27</td>
</tr>
<tr>
<td>.300</td>
<td>24.6</td>
<td>-1.67</td>
<td>+1.97</td>
<td>22</td>
</tr>
<tr>
<td>.375</td>
<td>22.6</td>
<td>-0.99</td>
<td>+1.55</td>
<td>22</td>
</tr>
<tr>
<td>.450</td>
<td>21.1</td>
<td>-0.59</td>
<td>+1.26</td>
<td>22</td>
</tr>
<tr>
<td>.525</td>
<td>21.1</td>
<td>-0.35</td>
<td>+1.01</td>
<td>22</td>
</tr>
<tr>
<td>.600</td>
<td>21.1</td>
<td>-0.19</td>
<td>+0.85</td>
<td>22</td>
</tr>
<tr>
<td>.675</td>
<td>21.1</td>
<td>-0.08</td>
<td>+0.74</td>
<td>22</td>
</tr>
<tr>
<td>.750</td>
<td>21.1</td>
<td>-0.00</td>
<td>+0.67</td>
<td>22</td>
</tr>
<tr>
<td>Experiment #</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Laser Power</td>
<td>10 watts</td>
<td>5 watts</td>
<td>10 watts</td>
<td>20 watts</td>
</tr>
<tr>
<td>Rock Type</td>
<td>Marble</td>
<td>Granite</td>
<td>Granite</td>
<td>Granite</td>
</tr>
<tr>
<td>Diameter, Thickness</td>
<td>1 1/2&quot;, 1/20&quot;</td>
<td>1 1/2&quot;, 1/20&quot;</td>
<td>1 1/2&quot;, 1/20&quot;</td>
<td>1 1/2&quot;, 1/20&quot;</td>
</tr>
<tr>
<td>Time to Crack</td>
<td>4 1/2 sec.</td>
<td>12 sec.</td>
<td>6 1/2 sec.</td>
<td>3 1/2 sec.</td>
</tr>
<tr>
<td>RADIUS (inches)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEMP. (°C)</td>
<td>Stresses (ksi)</td>
<td>TEMP. (°C)</td>
<td>Stresses (ksi)</td>
<td>TEMP. (°C)</td>
</tr>
<tr>
<td>σ_r</td>
<td>σ_θ</td>
<td>σ_r</td>
<td>σ_θ</td>
<td>σ_r</td>
</tr>
<tr>
<td>0.000</td>
<td>358</td>
<td>-16.76</td>
<td>-16.76</td>
<td>513</td>
</tr>
<tr>
<td>0.075</td>
<td>185</td>
<td>-10.90</td>
<td>-5.10</td>
<td>303</td>
</tr>
<tr>
<td>0.150</td>
<td>50.7</td>
<td>-5.88</td>
<td>+3.48</td>
<td>133</td>
</tr>
<tr>
<td>0.225</td>
<td>26.2</td>
<td>-2.91</td>
<td>+2.99</td>
<td>67.8</td>
</tr>
<tr>
<td>0.300</td>
<td>21.9</td>
<td>-1.57</td>
<td>+2.09</td>
<td>40.0</td>
</tr>
<tr>
<td>0.375</td>
<td>21.2</td>
<td>-0.90</td>
<td>+1.49</td>
<td>28.4</td>
</tr>
<tr>
<td>0.450</td>
<td>21.1</td>
<td>-0.54</td>
<td>+1.14</td>
<td>23.7</td>
</tr>
<tr>
<td>0.525</td>
<td>21.1</td>
<td>-0.32</td>
<td>+0.91</td>
<td>21.9</td>
</tr>
<tr>
<td>0.600</td>
<td>21.1</td>
<td>-0.17</td>
<td>+0.77</td>
<td>21.1</td>
</tr>
<tr>
<td>0.675</td>
<td>21.1</td>
<td>-0.07</td>
<td>+0.68</td>
<td>21.1</td>
</tr>
<tr>
<td>0.750</td>
<td>21.1</td>
<td>0.00</td>
<td>+0.61</td>
<td>21.1</td>
</tr>
</tbody>
</table>
Note:
Time to Crack Initiation = 10 sec
Power Level = 10 watts
Thickness = 1/10 in.
Marble Disc

Figure 38. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 1 at Time of Crack Initiation

At \( r = 0.0 \), \( \sigma_r = \sigma_\theta = -13.03 \) ksi
Figure 39. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 2, at Time of Crack Initiation

At \( r = 0.0 \),
\[
\sigma_r = \sigma_\theta = -16.35 \text{ ksi}
\]

Note:

Time to Crack Initiation = 5 sec
Laser Power: Level = 20 watts
Specimen Thickness = 1/10" 
Marble Disc
Temperature, °C

Temperature Distribution

Tangential Stress, $\sigma_\theta$

Radial Stress, $\sigma_r$

At $r=0.0$, $\sigma_r = \sigma_\theta = -18.26$ ksi

Note:

Time to Crack Initiation = 3.5 sec.
Laser Power Level = 30 watts
Specimen Thickness = 1/10
Marble Disc

Figure 40. Membrane Stresses in the disc as a Function of Radius for Experiment No. 3, at Time of Crack Initiation
Temperature, °C

Temperature Distribution

Stress, ksi

Tangential Stress, $\sigma_\theta$

Radial Stress, $\sigma_r$

Radius, inches

Note:
Time to Crack Initiation = 10 sec
Laser Power Level = 5 watts
Specimen Thickness = 1/20"
Marble Disc

Figure 41. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 4, at Time of Crack Initiation

At $r=0.0$, $\sigma_r=\sigma_\theta=-14.03$ ksi
Figure 42. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 5, at time of Crack Initiation

At $r=0.0$, $\sigma_r = \sigma_\theta = -16.76$ ksi

Temperature Distribution

Tangential Stress, $\sigma_\theta$

Radial Stress, $\sigma_r$

Note:
Time to Crack Initiation = 4.5 sec.
Laser Power Level = 10 watts
Specimen Thickness = 1/20"
Marble Disc
Figure 43. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 6, at Time of Crack Initiation

Note:
Time to Crack Initiation = 12 sec.
Laser Power Level = 5 watts
Specimen Thickness = 1/20" Granite Disc
Figure 44. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 7, at Time of Crack Initiation

Note:

Time to Crack Initiation = 6.5 sec.
Laser Power Level = 10 watts
Specimen Thickness = 1/20"
Granite Disc
Figure 45. Membrane Stresses in the Disc as a Function of Radius for Experiment No. 8, at time of Crack Initiation

Temperature Distribution.

Temperature, °C

Stress, ksi

Radius, inches

Tangential Stress, $\sigma_\theta$

Radial Stress, $\sigma_r$

At $r=0.0$, $\sigma_r = \sigma_\theta = -8.91$ ksi

Note:

Time to Crack Initiation = 3.5 sec.
Laser Power Level = 20 watts
Specimen Thickness = \(\frac{1}{20}''\)
Granite Disc
At this point, it is in order to introduce a new parameter, which shall be called the Disc Tensile Failure Energy (D.T.F.E.) With regard to the experiments performed previously, this is defined as the amount of laser energy input required to cause tensile failure in a rock disc divided by the volume of the specimen:

\[
\text{D.T.F.E.} = \frac{\text{Laser Power} \times \text{Time of Lasing}}{\pi R^2 \times \text{Specimen Thickness}} \quad \text{JOULES INCH}^3
\]

With the above criteria in mind, we may now summarize the experimental results for tensile failures in marble and granite discs in the more compact form of Table 7. The following observations are now made from the results presented in this table:

1. **Variation of Breaking Stress vs. Time Duration of Experiments:**
   It is expected that if a material is loaded in tension, then the value of the tensile stress required to cause failure is dependent upon the rate of the loading. Usually a higher rate of loading results in a higher breaking strength. In these disc-cracking experiments the rate of loading is taken as the reciprocal of the time duration from start of lasing to crack initiation. The results of this observation are shown in Figure 46.

2. **Variation of Breaking Stress vs. Thickness of Specimen:** When a material is mechanically loaded, local failure is initiated when the stress level is sufficiently high to cause the largest sized flaw to propagate. This is the critical flaw, and the larger the critical flaw, the lower the stress level that is required to cause failure. In a large specimen, the probability of having large sized flaws is greater than in a small specimen. It is therefore expected that the breaking strength of a
Table 7. Summary of Data From Results of Experiments 1 through 8

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Specimen Thickness (inches)</th>
<th>Rock Type</th>
<th>Laser Power (watts)</th>
<th>Time of Lasing to Crack Initiation (sec)</th>
<th>Laser Energy Input (Joules)</th>
<th>Volume of Specimen (in(^3))</th>
<th>Disc Tensile Failure Energy (Joules/in(^3))</th>
<th>Maximum Tangential Stress, (\sigma_\theta) max (psi)</th>
<th>Radial Location Of (\sigma_\theta) max i.e. Location of Crack Initiation (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
<td>Marble</td>
<td>10</td>
<td>10.0</td>
<td>100</td>
<td>0.177</td>
<td>568</td>
<td>2278</td>
<td>0.225</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>Marble</td>
<td>20</td>
<td>5.0</td>
<td>100</td>
<td>0.177</td>
<td>568</td>
<td>3378</td>
<td>0.150</td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
<td>Marble</td>
<td>30</td>
<td>3.5</td>
<td>105</td>
<td>0.177</td>
<td>595</td>
<td>4391</td>
<td>0.150</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>Marble</td>
<td>5</td>
<td>10.0</td>
<td>50</td>
<td>0.0885</td>
<td>568</td>
<td>2403</td>
<td>0.225</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
<td>Marble</td>
<td>10</td>
<td>4.5</td>
<td>45</td>
<td>0.0885</td>
<td>510</td>
<td>3483</td>
<td>0.150</td>
</tr>
<tr>
<td>6</td>
<td>0.05</td>
<td>Granite</td>
<td>5</td>
<td>12.0</td>
<td>60</td>
<td>0.0885</td>
<td>680</td>
<td>645</td>
<td>0.300</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>Granite</td>
<td>10</td>
<td>6.5</td>
<td>65</td>
<td>0.0885</td>
<td>738</td>
<td>1084</td>
<td>0.225</td>
</tr>
<tr>
<td>8</td>
<td>0.05</td>
<td>Granite</td>
<td>20</td>
<td>3.5</td>
<td>70</td>
<td>0.0885</td>
<td>791</td>
<td>1417</td>
<td>0.225</td>
</tr>
</tbody>
</table>
Figure 46. Variation of Tensile Breaking Stress With Rate of Laser Thermomechanical Loading of Disc Shaped Specimens of Marble and Granite. Note that variation in loading rates is achieved by varying the power level of the laser.

Figure 47. Variation of Tensile Breaking Strength With Thickness of Marble Disc Specimens
material will be decreased as the specimen size is increased. The results of this observation are shown in Figure 47.

3. Variation of Disc Tensile Failure Energy with Laser Power:

In a recently published report [30] it was found that in order to produce a given amount of damage in a rock specimen, there was an optimum laser power level corresponding to the minimum amount of energy required to cause that damage. Figure 50 illustrates this finding. The damage in this case is the lowering of the strength of the flexural sample to 50% of its original value. For the experiments done in this thesis the damage is the "cracking" of a unit volume of rock material in the form of a disc shaped specimen. The energy to cause this is the Disc Tensile Failure Energy (D.T.F.E.). The results are illustrated in Figure 48. These graphs correspond to the portions of the graphs to the right of A B in Figure 50. It is conceivable that the experimental graphs could be interpolated (dotted lines C and D in Figure 48) to yield minima similar to those in Figure 50. Within the context of these experiments, however, it was not possible to obtain failures in the discs at any significantly lower power levels since the rate of heat losses in the sample would then be comparable to the rate of heat input, thus preventing the buildup of a requisite thermal gradient which is necessary to cause failure in the specimen. It would probably be possible, nevertheless, to obtain such minima if sufficiently large diameter disc specimens could be used. With present cutting machinery, however, it was only possible to obtain the 1 1/2" diameter specimens with good
Figure 48. Variation of Disc Tensile Failure Energy With Laser Power

Figure 49. Radial Location of Crack Initiation vs. Rate of Thermal Loading. Note that the radial location of crack initiation is taken as the location of maximum tangential stress.
Figure 50. Laser Input Energy (as a Function of Power Level) Required to Lower the Strength of the Flexural Sample to 50% of its Original Value. [30]
quality control on thickness. (Note that large diameter samples could be obtained, but the quality control on thickness was so poor that there would be large variations in results from one specimen to another).

4. Radial Location of Crack Initiation vs. Rate of Thermal Loading: It should be observed that as the rate of thermomechanical loading increases the location of crack initiation moves towards the center of the disc. This is because rapid heating rates (i.e. high power levels) produce a very steep temperature gradient that is more localized in the center of the disc than would be the case for lower heating rates. This causes the peak of the tangential stress to be closer to the center of the disc. This effect may be seen by comparing the temperature distribution and associated stress distribution in Figures 38 and 39, for example. The results of this observation are illustrated in Figure 49.

Compressive Failures in Constrained Granite Discs

It was first necessary to develop a method of inducing compressive failures in thin granite discs. This was achieved by placing a heavy constraining ring around the disc thus prohibiting any peripheral radial strains and causing a state of high radial compression in the disc when it is lased at the center.* The point of maximum radial

*The stress analysis for this case is given in the chapter entitled "Design of Experiments" under the section "Thermal Stresses in a Thin Constrained Disc".
Figure 51. 1.5" Diameter by 0.10" Thick Granite Disc Constrained by Steel Ring

Figure 52. Microphone Pickup System for Detecting Spalling in a Constrained Disc that is Thermally Stressed
compressive stress then is at the center of the disc where it is being lased. This is the location where thermal spalling should occur.

The process of spalling constitutes little "flake-like" pieces of rock material shooting off due to a failure in compression.

Some granite discs (1 1/2" diameter x 1/10" thick) were prepared by first coring out a cylinder and then slicing off the discs. They were constrained in steel rings as shown in Figure 51 using epoxy glue. The effect of the constraining ring is to set the displacement at the edge of the disc equal to zero. This causes the disc to go into compression when it is lased. After a certain time of lasing the thermal stresses exceed the compressive strength of the granite and failure occurs which is manifested by spalling at the centerspot of the disc.

**Detection of Spalling:** In a manner analogous to the phonograph cartridge set up (for detection of cracking), a high impedance directional microphone was aimed at the centerspot of the disc and its output terminals connected to the preamplifier unit of the oscilloscope. The oscilloscope trace was started on a slow sweep when the laser was turned on. The time to the first spall (initiation of compressive failure) was measured by observing the point on the screen at which the first "kick" occurred. This technique is illustrated in Figure 52.

The confined disc was exposed to a 3/8" diameter laser beam at a power level of 90 watts as shown in Figure 53. Five specimens were used and spalling occurred after an average of 7 seconds of lasing time. Times to spalling were measured with the microphone and oscilloscope arrangement as described previously. Knowing the time of lasing
First Spall Occurred
After 7 Seconds of
Lasing

Laser Beam of 90
Watts, Total Power

CONSTRAINED GRANITE DISC

3/8"

1 1/2"

1/10"

Radius, r

Figure 53. Schematic Diagram Illustrating Confined Disc Experiment
Table 8. Temperature and Stress Distributions for the Constrained Disc Experiment.

Laser Power 90 watts
Rock Type Granite
Diameter, Thickness 1 1/2", 1/10"
Time To Spall 7 secs.

<table>
<thead>
<tr>
<th>RADIUS (inches)</th>
<th>TEMP, °C</th>
<th>MEMBRANE STRESSES, ksi</th>
<th>$\sigma_T$</th>
<th>$\sigma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>1618</td>
<td>-15,071</td>
<td>-15,071</td>
<td></td>
</tr>
<tr>
<td>0.075</td>
<td>1218</td>
<td>- 8,100</td>
<td>-15,164</td>
<td></td>
</tr>
<tr>
<td>0.150</td>
<td>769</td>
<td>- 9,123</td>
<td>- 6,349</td>
<td></td>
</tr>
<tr>
<td>0.225</td>
<td>302</td>
<td>- 7,158</td>
<td>- 2,446</td>
<td></td>
</tr>
<tr>
<td>0.330</td>
<td>113</td>
<td>- 5,271</td>
<td>+ 1,135</td>
<td></td>
</tr>
<tr>
<td>0.375</td>
<td>50</td>
<td>- 4,016</td>
<td>+ 968</td>
<td></td>
</tr>
<tr>
<td>0.450</td>
<td>30</td>
<td>- 3,226</td>
<td>+ 524</td>
<td></td>
</tr>
<tr>
<td>0.525</td>
<td>23</td>
<td>- 2,721</td>
<td>+ 139</td>
<td></td>
</tr>
<tr>
<td>0.600</td>
<td>22</td>
<td>- 2,834</td>
<td>- 179</td>
<td></td>
</tr>
<tr>
<td>0.675</td>
<td>21</td>
<td>- 2,152</td>
<td>- 394</td>
<td></td>
</tr>
<tr>
<td>0.750</td>
<td>21</td>
<td>- 1,985</td>
<td>- 561</td>
<td></td>
</tr>
</tbody>
</table>
until initiation of spalling, it was possible to determine the temperature distribution at that instant using the finite element heat flow analysis. The average temperatures of the two faces of the disc were taken as the membrane temperatures. When these values are put into the thermal stress analysis program, it is possible to find the radial and tangential components of the membrane stresses, $\sigma_r$ and $\sigma_\theta$ respectively, at the time of spalling.

The results for this experiment are given in Table 8. Since the purpose of this section is to evaluate compressive failures in small discs, the maximum compressive (i.e. negative) stress for the experiment is underlined in the table to facilitate future reference to it. The temperature and stress distributions are also displayed graphically in Figure 54.

**Discussion of Results:** The point of maximum compressive stress is at the center of the disc. This is where the compressive failure in the form of spalling occurs. The value of the calculated stress at this point was -15,071 psi. From the literature [28] it was found that the compressive strength of granite is between 19,000 and 30,000 psi. These results, therefore, indicate that the compressive strength is considerably lowered due to the severe heating at the center of the disc, but nevertheless, failure occurs when induced thermal compressive stress exceeds the strength of the granite material.
Figure 54. Membrane Stresses as a Function of Radius for the Constrained Disc Experiment, at Time of First Spalling Occurrence.
CONCLUSIONS

The results obtained for temperature and stress measurements of laser irradiated discs have shown that the analytical programs developed in Reference [23] for theoretically determining the thermal and mechanical response of rock to laser radiation are correct and the assumptions made therein are valid. In addition, the assertions stated in this thesis concerning the mechanisms whereby laser radiation causes failure in rock specimens have been well substantiated.

For the experiments involving the cracking of thin unconstrained discs, consistent results were obtained between experimental observations and theoretical predictions for time and location of failure initiation. Similar success was encountered in regards to the spalling of thin constrained discs.

For thermally induced rock fractures, it has been shown experimentally that the onset of failure is sensitive to the rate of thermal loading and to the size of the specimen.
SUGGESTIONS FOR FUTURE WORK

The whole concept of laser assisted rock fracture was undertaken in the context of finding a more efficient means of hard rock tunneling. So far this thesis has only dealt with the fracture of rock due to laser radiation alone. Mechanical disturbances have not been considered. Eventually, a field application of the laboratory techniques will be developed and it will probably consist of a combination of thermal and mechanical excitation of rock masses.

It is therefore suggested, as a plan for the future work, that large sized three dimensional specimens be subjected to laser irradiation in conjunction with mechanical loading devices (such as cutter wheels, grinders, etc.). The response may then be analyzed in a manner similar to the techniques presented herein.
REFERENCES AND SELECTED BIBLIOGRAPHY


To obtain the disc shaped specimens a 12" x 12" x 6" block of marble was sliced off into 12" x 6" x 1/5" slabs using a diamond saw (Figure 55). Two 5 1/2" diameter circles were drawn and discs were cut using a small circular saw (Figure 56). The electrical conducting rings were applied to the surface of the disc in the pattern shown in Figure 57, using a silver paint.* The reason for having this pattern is so that if the crack starts in one of the gaps then it will, at least, break the next circuit closest to it, and that will be detected. A specially made template with the appropriate circuit pattern was held on the surface of the specimen and the paint was sprayed from a distance of about 12" so that it fell evenly over the whole diameter of the disc (Figure 58). Attempts were made to obtain as thin a coat as possible in order to achieve the most intimate possible contact with the rock surface thus providing maximum breakage sensitivity to crack initiation. At the ends of each ring, wire leads were attached by means of a conducting paste ** (Figure 59).

**Electronic Apparatus for Detecting Broken Circuit:**

The purpose of this circuit is to detect which one of the nine conducting ring circuits is the first to break due to the formation of a crack. The corresponding glow tube on the display board will then

---

* Eccocoat CC-2, Emerson & Cuming, Canton, Massachusetts
** Eccocoat 56-C, Emerson & Cuming, Canton, Massachusetts
Figure 55. Diamond Saw Cutter

Figure 56. Circular Saw
Figure 57: Silver Ring Pattern on Surface of Disc: Leads will be connected to the ends of each circuit and then go to the circuit break detector.
Figure 58. Procedure for Application of Conducting Rings: For the 5 1/2" diameter disc, nine rings were applied of radii 3/4", 1", 1 1/4", 1 1/2", 1 3/4", 2", 2 1/4", 2 1/2", 2 3/4". Ring thickness was 1/16".

Figure 59. Picture of Instrumented Disc.
light up. A schematic diagram of the circuit is shown in Figure 60 (the leads, A, go to the silver rings, B is the common lead to all rings). The system contained ten NE-2 detector glow tubes though only three are shown in the circuit diagram. When all the silver ring circuits are complete, the NE-2 glow tubes are all shorted out and none are lit. When one of these circuits is broken, then the corresponding NE-2 tube is no longer shorted out and hence it lights up. When this happens, the circuit through the 560KΩ resistor is complete and has the effect of shorting out all the other tubes, thus preventing them from being lit should their corresponding silver ring circuits be broken (Figure 61).

Thus the effect is to display by means of a lighted tube only the "first" circuit to break. This is an important feature, since the crack in the disc travels very fast and therefore breaks many rings in rapid succession.

Application of Temperature Sensitive Paints:

Temperature sensitive paints are available in the form of a pigment. The type used was "Detectotemp" No. 915-0934 (Hardman, Inc., Belleville, N.J.). It undergoes four color changes as follows:

<table>
<thead>
<tr>
<th>Original Color:</th>
<th>Changed Color:</th>
<th>Color Change Temperature:</th>
</tr>
</thead>
<tbody>
<tr>
<td>light green</td>
<td>light blue</td>
<td>65°C 149°F</td>
</tr>
<tr>
<td>light blue</td>
<td>yellow</td>
<td>145°C 293°F</td>
</tr>
<tr>
<td>yellow</td>
<td>black</td>
<td>220°C 428°F</td>
</tr>
<tr>
<td>black</td>
<td>brown</td>
<td>340°C 644°F</td>
</tr>
</tbody>
</table>
Figure 60. Schematic Circuit Diagram
Figure 61. Picture of Circuit Board for Detecting the First Broken Circle on the Marble Disc

Figure 62. Paint Spraying Technique
The pigment was then dissolved in ethyl alcohol and the solution was placed in an atomizer, attached to an air pressure can. The discs were then supported vertically against a wall and sprayed with this paint on the side opposite the one with the silver rings (Figure 62). Appendix II discusses the interpretation of temperature distribution from color changes.
Since the disc was exposed to a laser beam of circular cross section, the temperature distribution in the disc was axi-symmetric and the color changes were manifested in the form of concentric rings. For example:

![Diagram showing color changes](image)

Temperatures are as follows:

A  \(<149^\circ F\)
B  \(149^\circ F\)
C  \(>149^\circ F\) but \(<293^\circ F\)
D  \(293^\circ F\)
E >293°F but <428°F
F 428°F
G >428°F but <644°F
H 644°F
I >644°F

A Note on the Sensitivity of the Paints

The color change temperatures given by the "Detectotemp" manufacturers is based on a 30 minute heating time. That is, from commencement of warming until the "Detectotemp" coating attains the color change temperature. The manufacturer provided a conversion chart for heating times less than 30 minutes. This is shown on the next page. (Figure 63.)

These paints do have a great disadvantage in that they only tell us the surface temperature of the material. Furthermore, once the last color change has taken place, there is no way of knowing how high the temperature actually was in that region. In our future experiments, therefore, it will be more desirable to use thermocouples embedded in the disc.
Figure 63. Color Change Temperature vs. Heating Time
a) Program Listing for Unconstrained Thermally Stressed Disc

```plaintext
// JOB T
// FOR
*IOCS (CARD, TYPEWRITER, 1132 PRINTER)
*LIST ALL
  DIMENSION TRI (100), STRI (100), SIGMR (100),
  DIMENSION T (100), SIGMT (100), R (100)
99  CONTINUE
  READ (2,5) N, E. ALPHA
  WRITE (3,5) N, E, ALPHA
5    FORMAT (112, 2E12.5)
  DO 15 I=1,N
  READ (2,5) I,R(I), T(I)
15  CONTINUE
  DO 16 I=1,N
  WRITE (3,5) I,R(I), T(I)
16  CONTINUE
  NMI=N-1
  DO 10 I=1,NMI
  IF (I-1) 8,8,9
8    STRI (I)  = .0
  GO TO 10
9    STRI (I) = STRI (I-1) + TRI (I-1)
10   CONTINUE
  STRI (N) = STRI (N-1) + TRI (N-1)
  SIGMR (I) = ALPHA*E*(STRI(N)/R(N)**2 - T(1)/2.
  SIGMT (I) = ALPHA*E* (-T(1)+STRI(N)/R(N)**2 + T(1)/2. )
  DO 20 I=2,N
  SIGMT (I) = ALPHA*E* (-T(I)+STRI(N)/R(N)**2+STRI(I)/R(I)**2)
  SIGMR (I) = ALPHA*E*(STRI(N)/R(N)**2 - STRI(I)/R(I)**2)
20   CONTINUE
  DO 62 I=1,N
  WRITE (3,5) I,TRI(I),STRI(I)
62   CONTINUE
  DO 51 I=1,N
  WRITE (3,5) I, SIGMR (I), SIGMT (I)
51   CONTINUE
  IF (2-I) 98,98,99
98  CONTINUE
CALL EXIT
END
```
The following is a sample output:

<table>
<thead>
<tr>
<th>No. of input points, E, $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 0.10000E 01 0.10000E 01</td>
</tr>
<tr>
<td>1 0.00000E 00 0.34000E 03</td>
</tr>
<tr>
<td>2 0.50000E 00 0.22000E 03</td>
</tr>
<tr>
<td>3 0.10000E 01 0.10000E 03</td>
</tr>
<tr>
<td>4 0.15000E 01 0.00000E 00</td>
</tr>
<tr>
<td>5 0.20000E 01 0.00000E 00</td>
</tr>
<tr>
<td>6 0.25000E 01 0.00000E 00</td>
</tr>
<tr>
<td>7 0.30000E 01 0.00000E 00</td>
</tr>
<tr>
<td>8 0.35000E 01 0.00000E 00</td>
</tr>
<tr>
<td>9 0.40000E 01 0.00000E 00</td>
</tr>
<tr>
<td>10 0.45000E 01 0.00000E 00</td>
</tr>
<tr>
<td>11 0.50000E 01 0.00000E 00</td>
</tr>
<tr>
<td>12 0.55000E 01 0.00000E 00</td>
</tr>
<tr>
<td>13 0.60000E 01 0.00000E 00</td>
</tr>
<tr>
<td>14 0.65000E 01 0.00000E 00</td>
</tr>
<tr>
<td>15 0.70000E 01 0.00000E 00</td>
</tr>
<tr>
<td>16 0.75000E 01 0.00000E 00</td>
</tr>
</tbody>
</table>

Note: $E$ is the elastic module
ALPHA is the thermal expansion coefficient

input data

<table>
<thead>
<tr>
<th>point no., radius, temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 0.32500E 02 0.00000E 00</td>
</tr>
<tr>
<td>2 0.57500E 02 0.32500E 02</td>
</tr>
<tr>
<td>3 0.29166E 02 0.90000E 02</td>
</tr>
<tr>
<td>4 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>5 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>6 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>7 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>8 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>9 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>10 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>11 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>12 0.00000E 00 0.11916E 03</td>
</tr>
<tr>
<td>13 0.00000E 00 0.11916E 03</td>
</tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>3-0.8781E 02-0.78814E 01</td>
</tr>
<tr>
<td>4-0.50844E 02 0.55081E 02</td>
</tr>
<tr>
<td>5-0.29673E 02 0.31910E 02</td>
</tr>
<tr>
<td>6-0.16948E 02 0.21185E 02</td>
</tr>
<tr>
<td>7-0.11122E 02 0.15359E 02</td>
</tr>
<tr>
<td>8-0.76093E 01 0.11846E 02</td>
</tr>
<tr>
<td>9-0.53293E 01 0.95664E 01</td>
</tr>
<tr>
<td>10-0.37662E 01 0.80632E 01</td>
</tr>
<tr>
<td>11-0.26481E 01 0.68851E 01</td>
</tr>
<tr>
<td>12-0.18208E 01 0.60579E 01</td>
</tr>
<tr>
<td>13-0.11916E 01 0.54287E 01</td>
</tr>
<tr>
<td>14-0.70199E 00 0.49390E 01</td>
</tr>
<tr>
<td>15-0.31345E 00 0.45504E 01</td>
</tr>
<tr>
<td>16-0.46193E-06 0.42370E 01</td>
</tr>
</tbody>
</table>

intermediate calculations

<table>
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<th>final output</th>
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</thead>
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<td>1-0.16788E 03-0.16788E 03</td>
</tr>
<tr>
<td>2-0.12788E 03-0.8781E 02</td>
</tr>
<tr>
<td>3-0.8781E 02-0.78814E 01</td>
</tr>
<tr>
<td>4-0.50844E 02 0.55081E 02</td>
</tr>
<tr>
<td>5-0.29673E 02 0.31910E 02</td>
</tr>
<tr>
<td>6-0.16948E 02 0.21185E 02</td>
</tr>
<tr>
<td>7-0.11122E 02 0.15359E 02</td>
</tr>
<tr>
<td>8-0.76093E 01 0.11846E 02</td>
</tr>
<tr>
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</tr>
<tr>
<td>10-0.37662E 01 0.80632E 01</td>
</tr>
<tr>
<td>11-0.26481E 01 0.68851E 01</td>
</tr>
<tr>
<td>12-0.18208E 01 0.60579E 01</td>
</tr>
<tr>
<td>13-0.11916E 01 0.54287E 01</td>
</tr>
<tr>
<td>14-0.70199E 00 0.49390E 01</td>
</tr>
<tr>
<td>15-0.31345E 00 0.45504E 01</td>
</tr>
<tr>
<td>16-0.46193E-06 0.42370E 01</td>
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</tbody>
</table>

point no., $\sigma_r$, $\sigma_\theta$
### Program Listing for Constrained Thermally Stressed Disc

```
// JOB T
// FOR
*IOCS (CARD, TYPEWRITER, 1132 PRINTER)
*LIST ALL
   DIMENSION TRI(100), STRI(100), SIGMR(100), SIGMT(100), R(100)
   DIMENSION T(100)
99 CONTINUE
   READ (8,5) N,E,ALPHA,XNU
   WRITE (5,5) N,E,ALPHA,XNU
5  FORMAT (112, 3E12.5)
   DO 15 I=1,N
   WRITE (5,5) I, R(I), T(I)
15 CONTINUE
   DO 16 I=1,N
      TRI(I+1)=.5*T(I)*(R(I+1)**2-R(I)**2)+(T(I+1)-T(I))*(2.*R(I+1)**3
         -3.*R(I)*R(I+1)**2+R(I)**3)/(6.*(R(I+1)-R(I)))
      STRI(I) = STRI(I-1) + TRI(I)
      STRI(I)=0.0
10 CONTINUE
   STRI(I) = T(I)/2.
   DO 20 I=1,N
      SIGMT(I) = ALPHA*E*(-T(I)-(1.+XNU))/(1.-XNU)/R(N)**2*STRI(N)+STRI(I)
      SIGMR(I) = ALPHA*E*(-1.+XNU)/(1.-XNU)/R(N)**2*STRI(N)
         -STRI(I)/R(I)**2)
20 CONTINUE
   WRITE (5,5) I,TRI(I),STRI(I)
62 CONTINUE
   DO 51 I=1,N
   WRITE (5,5) I,SIGMR(I),SIGMT(I)
51 CONTINUE
   IF (2-I) 98,98,99
98 CONTINUE
   CALL EXIT
END
```

The output routine for the radial and tangential stresses ($\sigma_r$ and $\sigma_\theta$ respectively) is the same as for the case of the unconstrained disc.
APPENDIX IV

COMPUTER PROGRAM FOR HEAT FLOW

ANALYSIS BY THE FINITE ELEMENT METHOD [23]

Definition of Symbols Used in Computer Program

KMAX = Maximum number of iterations
KTPRT = Number of iterations between information printouts
NODES = Number of nodes (joints)
NOEL = Number of elements
DENS = Density of material
SPHET = Specific heat of material
DTIME = Time increment
COND = Thermal conductivity of material
BTEMP = Temperature at boundary
KSTOP = Number of iteration at time of printout
LNOD(I,J) = The three nodes at element I
X(I) = x coordinate at node I
Y(I) = y coordinate at node I
T(I) = Initial temperature of node I
F(I) = Heat generation in element I
NFIX(I) = Parameter defining boundary nodes
Computer Program Listing

// JOB T
// FOR
*I0CS(2501 READER, 1403 PRINTER)
*LIST ALL

DIMENSION X(80), Y(80), T(80), F(8), NFIX(80), LNOD(80, 3)
1AREA(80), THICK(80), HCAP(80), L(80), NODL(80, 8), TCAP(80),
2B(80), C(80), Q(8), TNOEL(80), TC(80)
READ (8, 1) KMAX, KTPRT, NODES, NOEL, DENS, SPHET, DTIME, COND, BTEMP
WRITE (5, 2) KMAX, KTPRT, NODES, NOEL, DENS, SPHET, DTIME, COND, BTEMP
DO I=1, NODES
READ (8, 2) X(I), Y(I), T(I), F(I), NFIX(I)
WRITE (5, 2) X(I), Y(I), T(I), F(I), NFIX(I)
10 CONTINUE
DO 11 I=1, NOEL
READ (8, 3) LNOD(I, 1), LNOD(I, 2), LNOD(I, 3)
WRITE (5, 3) LNOD(I, 1), LNOD(I, 2), LNOD(I, 3)
11 CONTINUE
1 FORMAT (4E5, 5E10.3)
2 FORMAT (4E12.5, I9)
3 FORMAT (3I9)
5 FORMAT (4E18.5)
CONDX = COND
CONDY = COND
DO 20 I=1, NOEL
L1=LNOD(I, 1)
L2=LNOD(I, 2)
L3=LNOD(I, 3)
AREA(I)=X(L2)*Y(L3)+X(L3)*Y(L1)+X(L1)*Y(L2)-X(L2)*Y(L1)-X(L3)*
1Y(L2)-X(L1)*Y(L3)
AREA(I)=AREA(I)/2.
THICK(I)=(X(L1)+X(L2)+X(L3))/3.
20 HCAP(I)=DENS*SPHET*AREA(I)*THICK(I)
WRITE (5, 200) (AREA(I), I=1, NOEL)
200 FORMAT (7E17.5)
DO 22 I=1, NODES
L(I)=0
DO 22 J=1, NOEL
DO 25 K=1, 3
IF (I=LNOD(J,K)) 25, 21, 25
25 CONTINUE
GO TO 22
21 L(I)=L(I)+1
LI=L(I)
NODL(I, LI)=J
22 CONTINUE
DO 501 I=1, NODES
WRITE (5, 104) I
LI=L(I)
M=LI
WRITE (5, 400) (NODL(I, J), J=1, M)
FORMAT (2016)

CONTINUE

DO 23 I=1, NODES
   THCAP(I)=0.0
   LI=L(I)
DO 23 J=1,LI
   N=NODL(I,J)
23  THCAP(I)=THCAP(I)+HCAP(N)/3.
   M=NODES
   WRITE (5,200) (THCAP(I), I=1,M)
   KSTOP=0
   KTIME=0

30  KSTOP=KSTOP+1
DO 32 I=1, NODES
   N=NFIX(I)
   IF(N)32,137,137
137  IF(KSTOP-1)33,33,31
33  T(I)=T(I)+BTEMP/2.
   GO TO 32
31  T(I)=BTEMP

CONTINUE

DO 34 I=1, NOEL
   L1=LNOD(I,1)
   L2=LNOD(I,2)
   L3=LNOD(I,3)
   TNOEL(I)=(T(L1)+T(L2)+T(L3))/3.
   B(I)=((Y(L3)-Y(L2))*T(L1)+(Y(L1)-Y(L3))*T(L2)+(Y(L2)-Y(L1))*
   1T(L3))/2./AREA(I)
34  C(I)=((X(L3)-X(L2))*T(L1)+(X(L1)-X(L3))*T(L2)+(X(L2)-X(L1)*
   1T(L3))/2./AREA(I)
DO 40 I=1, NODES
   Q(I)=F(I)
   LI=L(I)
DO 40 J=1,LI
   NOIJ=NODL(I,J)
   CONDX = 1. / (24000. + 30.*TNOEL(NOIJ))
   CONDY = CONDX
   QX = - B(NOIJ)*CONDX*THICK(NOIJ)
   QY = - C(NOIJ)*CONDY*THICK(NOIJ)
   K=0
35  K=K+1
IF (K-3) 42,42,41

CONTINUE

WRITE (5,102)
WRITE (5,104) I
WRITE (5,105) J
104 FORMAT (3H I=I3)
105 FORMAT (3H J=I3)
GO TO 57
102 FORMAT (5H KBIG)

CONTINUE
IF (I-LNOD(NOIJ,K)) 35,36,35
36 IF (K-2) 37,38,39
37  LA=LNOD(NOIJ,3)
    GO TO 401
36  LA=LNOD(NOIJ,3)
    LB=LNOD(NOIJ,1)
    GO TO 401
39  LA=LNOD(NOIJ,1)
    LB=LNOD(NOIJ,2)
401  Q(I)=(Y(LB)-Y(LA))*QX/2.+(X(LB)-X(LA))*QY/2.*Q(I)
40  CONTINUE
    KTIME=KTIME+1
    DO 50 I=1,NODES
50  T(I)=T(I)+Q(I)*DTIME/THCAP(I)
C THE THREE CARDS FOR FAHRENHEIT TO CENTIGRADE CONVERSION ARE HERE
    DO 979 I=1,NODES
        TC(I) = (T(I)-32.) * (5./9.)
    979  KTIME = 0
    WRITE (5,120) KSTOP
120  FORMAT (7H KST,'P=I4)
52  WRITE (5,5) (TC(I), I=1,NODES)
54  IF (KSTOP-KTMAX) 30,57,57
57  CONTINUE
    CALL EXIT
END
APPENDIX V - CALIBRATION OF THE OSCILLOSCOPE UNIT

A 1018 beam of cold rolled steel with the following dimensions was
loaded on the Instron tester thus:

The analysis for the beam is as follows:

\[ S = \frac{bd^2}{6} \]

Moment at Center, \( M_c = 4P \)

Stress at Center, \( \sigma_c = \frac{M_c}{S} \)

For 1018 CR Steel, the Modulus of Elasticity, \( E = 30 \times 10^6 \) psi

\[ \varepsilon_c = \frac{\sigma_c}{E} = \frac{8P}{bd^2} \times 10^{-7} \]

A convenient calibration unit for strain measurements is taken as \( 10^{-4} \)
(100 micro units per unit). The forces, \( P \), required to develop this
are
\[ p = \frac{10^{-4} \times 10^7}{8 \times 16} \times \frac{1}{2} = 3.9 \text{ lbs} \]

Using the Instron testing machine, this value of the loading was applied and then the gain of the oscilloscope was adjusted to give a deflection of one division. Thus for all future experiments, it would be known that a deflection of one division corresponds to a strain of 100 micro units per unit.
### APPENDIX VI - DEFINITION OF SYMBOLS AND SPECIAL TERMS

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<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>Q</td>
<td>Heat quantity</td>
</tr>
<tr>
<td>BTU</td>
<td>British Thermal Units</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Radiation Energy From Black Body</td>
</tr>
<tr>
<td>( \sigma_e )</td>
<td>Emissivity Constant</td>
</tr>
<tr>
<td>( \sigma_p )</td>
<td>Specific Heat</td>
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<td>( \sigma_r )</td>
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<tr>
<td>( \sigma_\theta )</td>
<td>Stress Component in Tangential Direction</td>
</tr>
<tr>
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</tr>
<tr>
<td>( \alpha )</td>
<td>Coefficient of Thermal Expansion</td>
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<tr>
<td>E</td>
<td>Modulus of Elasticity</td>
</tr>
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<td>t</td>
<td>Thickness of Circular Disc</td>
</tr>
<tr>
<td>b</td>
<td>Radius of Disc</td>
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<td>( \nu )</td>
<td>Poisson's Ratio</td>
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<td>D.T.F.E.</td>
<td>Disc Tensile Failure Energy: Amount of Energy Required to Cause Cracking in a Rock Disc of Unit Volume</td>
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<td>Manifestation of Compressive Failure in a Thermally Stressed Disc</td>
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