United States Patent

[11] **3,539,221**

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[54] **TREATMENT OF SOLID MATERIALS**
18 Claims, 8 Drawing Figs.

[52] **U.S. Cl.** **299/14;** 175/16; 219/121; 241/1; 125/1
[51] **Int. Cl.** **E21c 37/16**
[50] **Field of Search** .... 299/14; 175/11–16(Inclusive); 331/94.5; 241/1; 125/ (Inclusive) (Examiner); 219/12(Laser)

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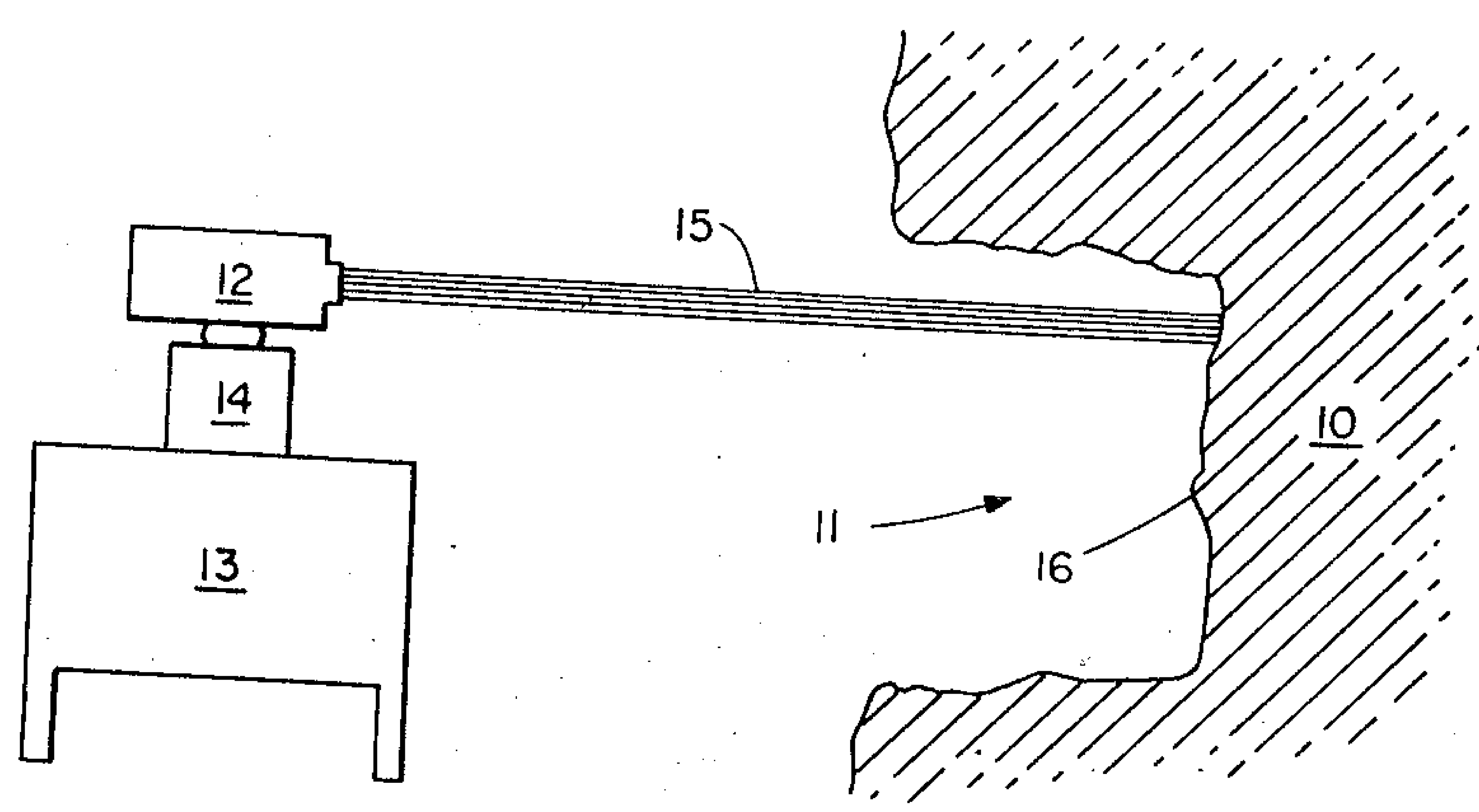
ABSTRACT: A method for weakening a solid material, such as a rock formation, by directing a beam of electromagnetic energy generated, for example, from a laser source toward the material to cause it to impinge thereon and to penetrate beneath the surface thereof. The energy is preferably in the form of a collimated beam having a wavelength selected so that the energy is substantially absorbed by the material.



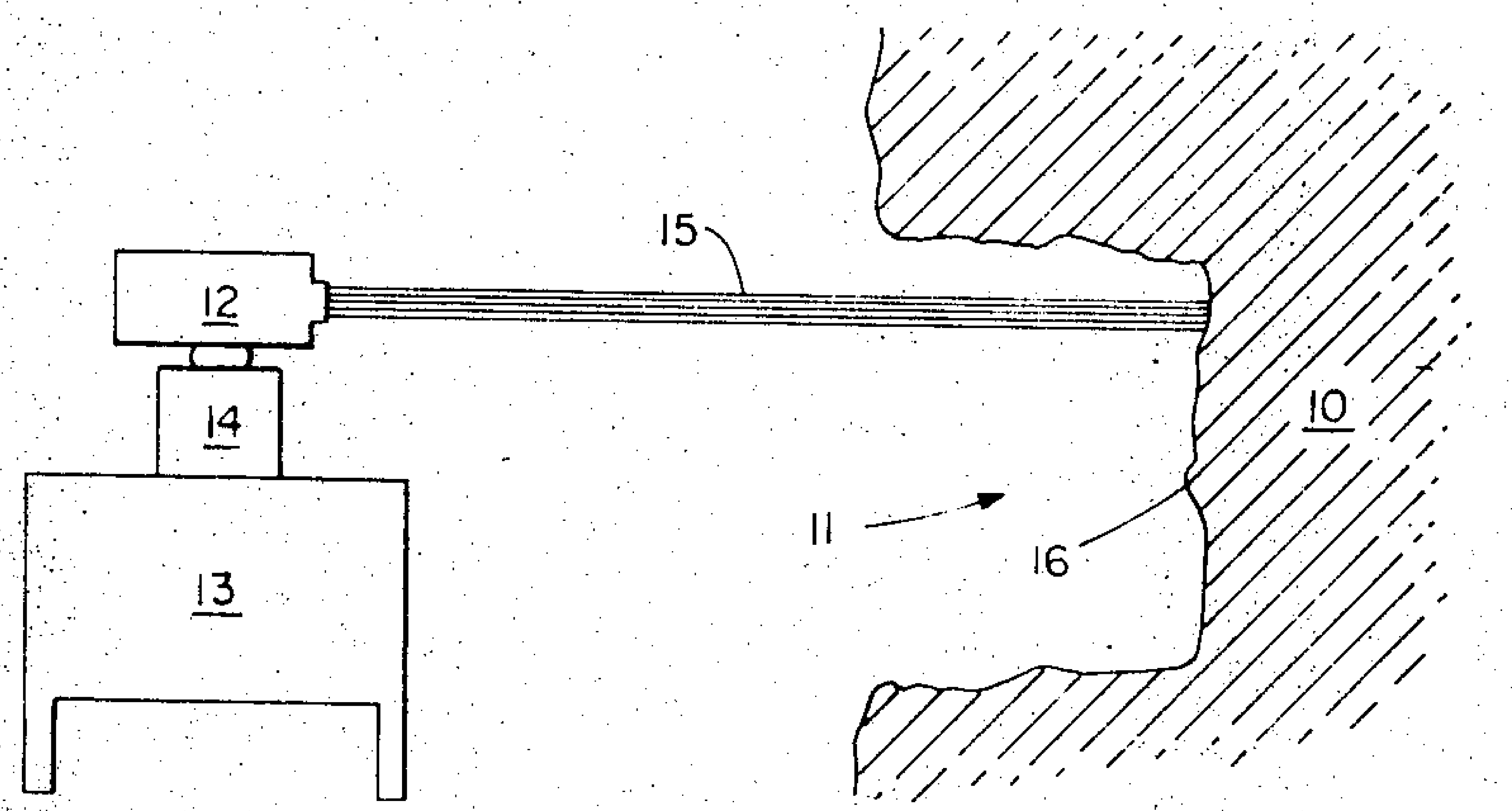


FIG. 1

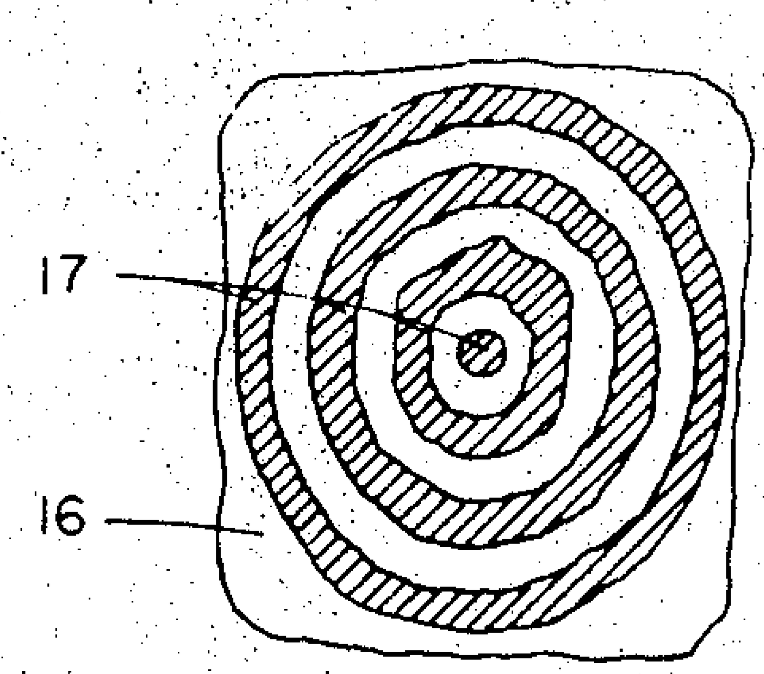


FIG. 2

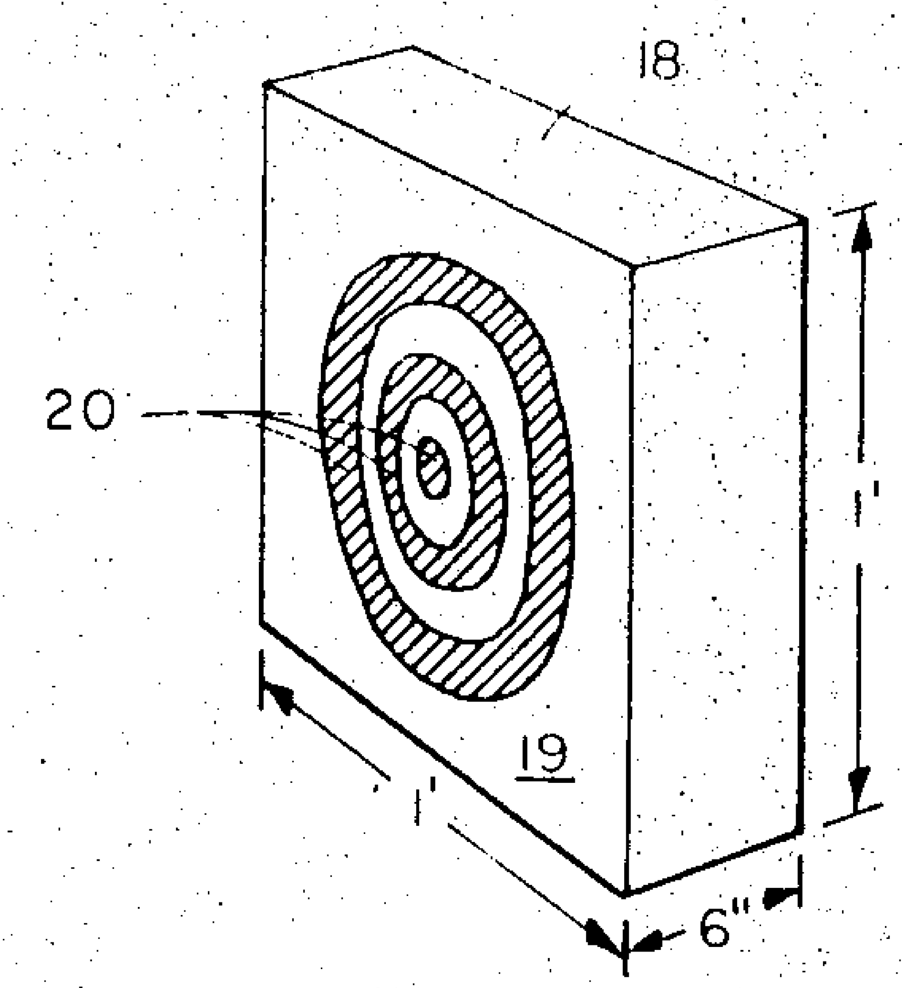


FIG. 3

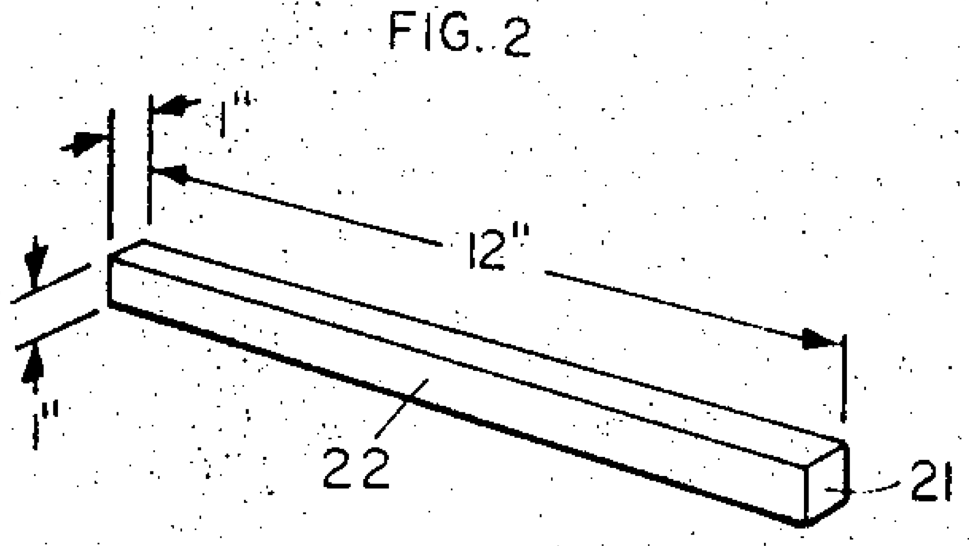


FIG. 4

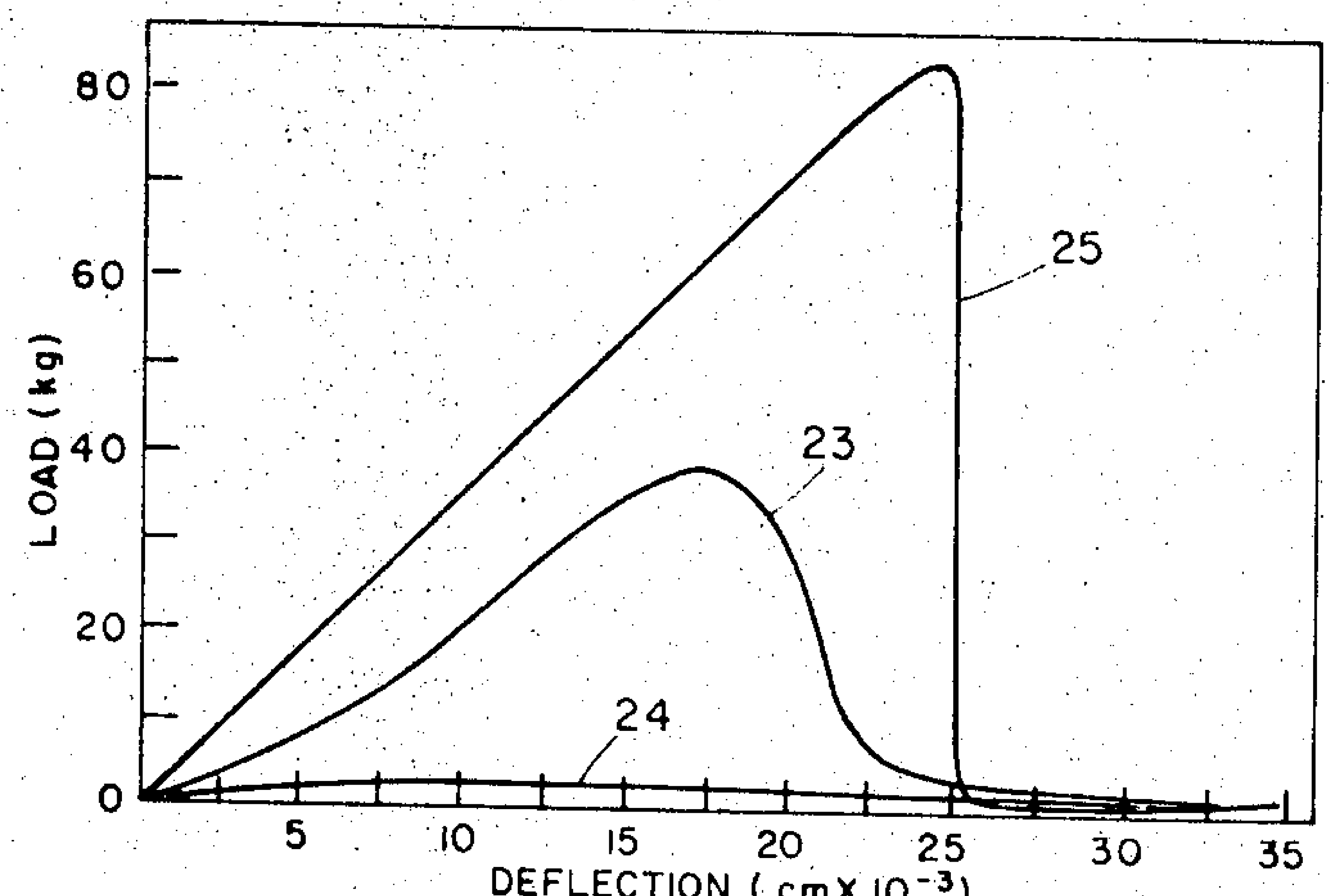


FIG. 5

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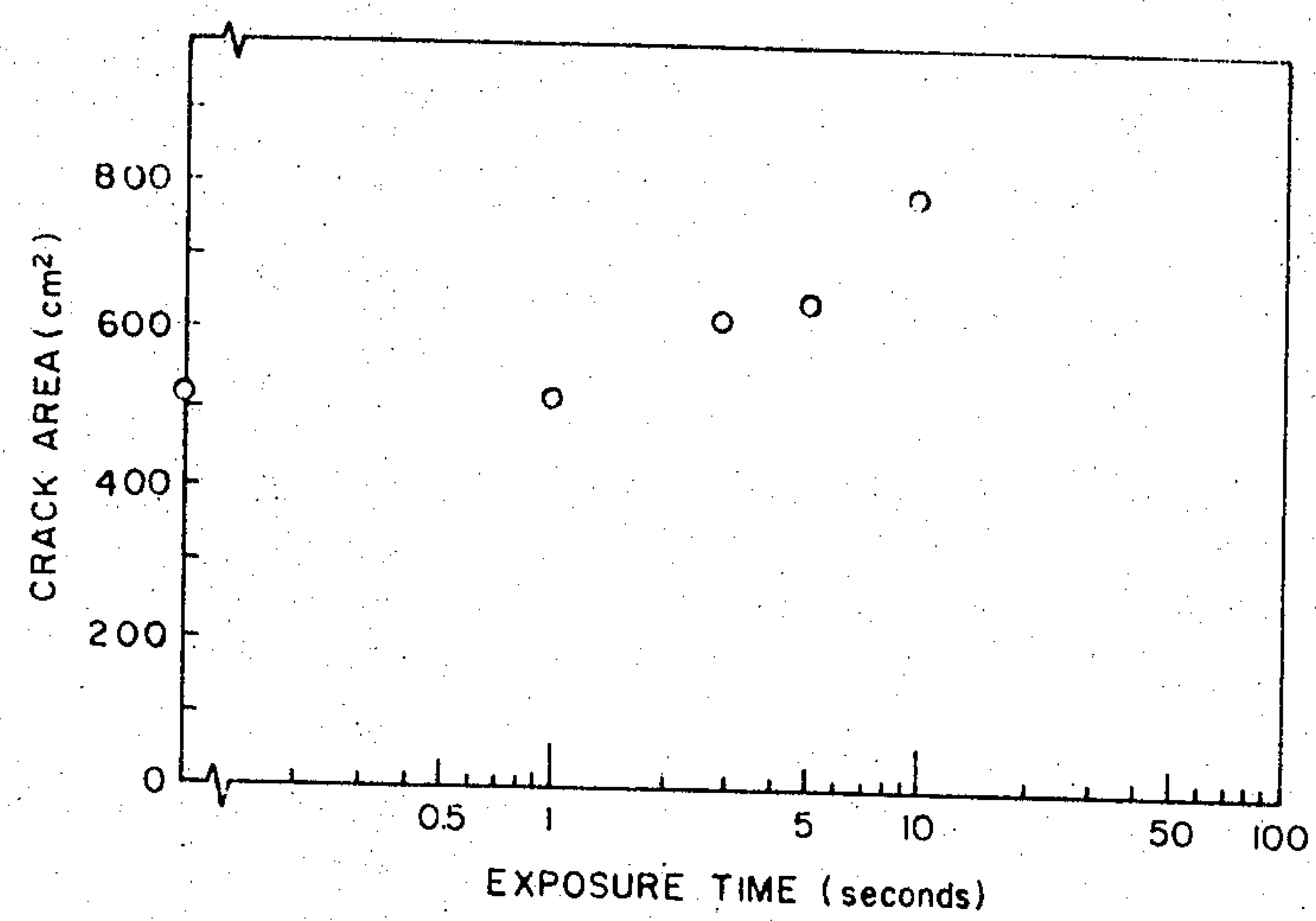

FIG. 6

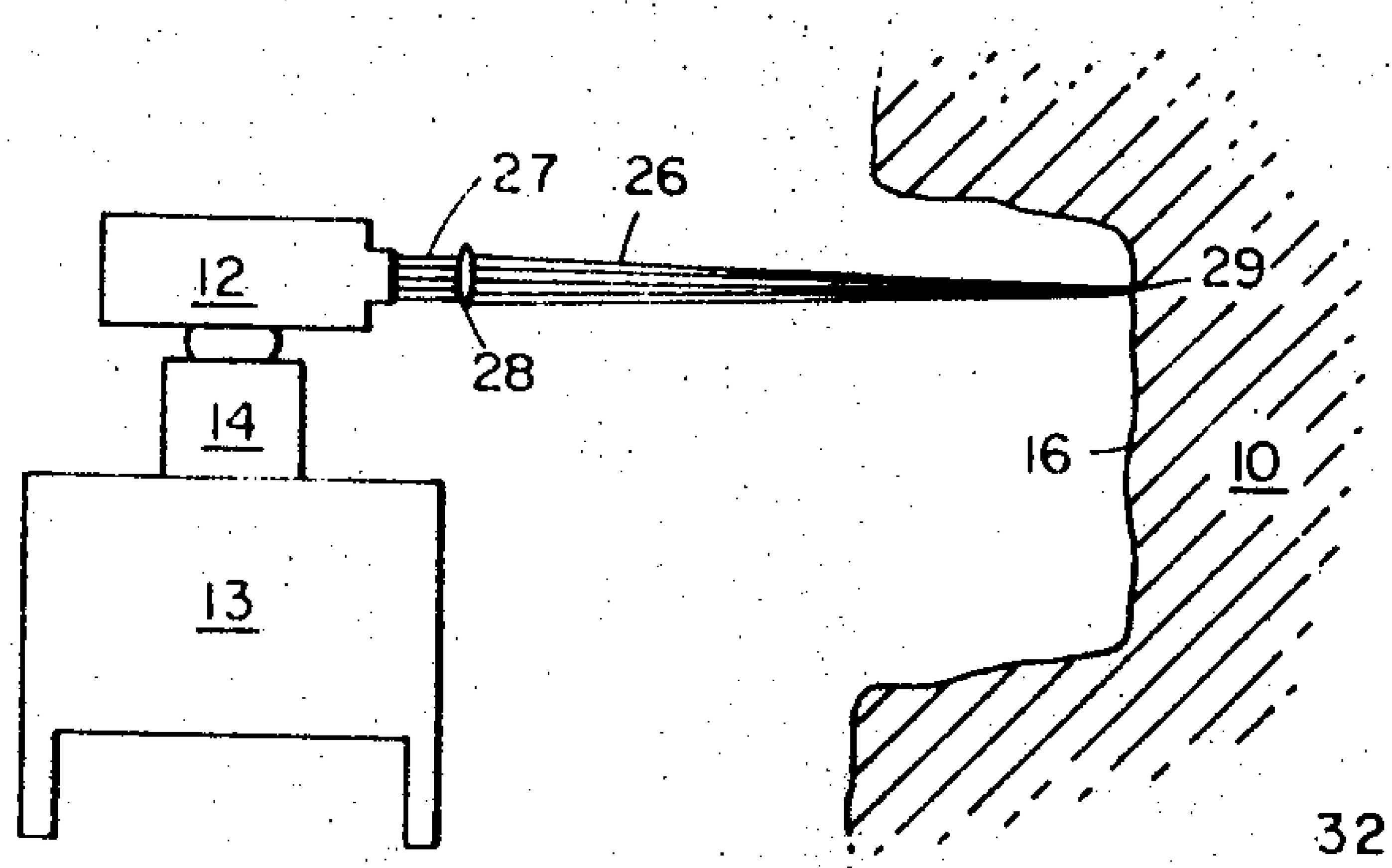

FIG. 7

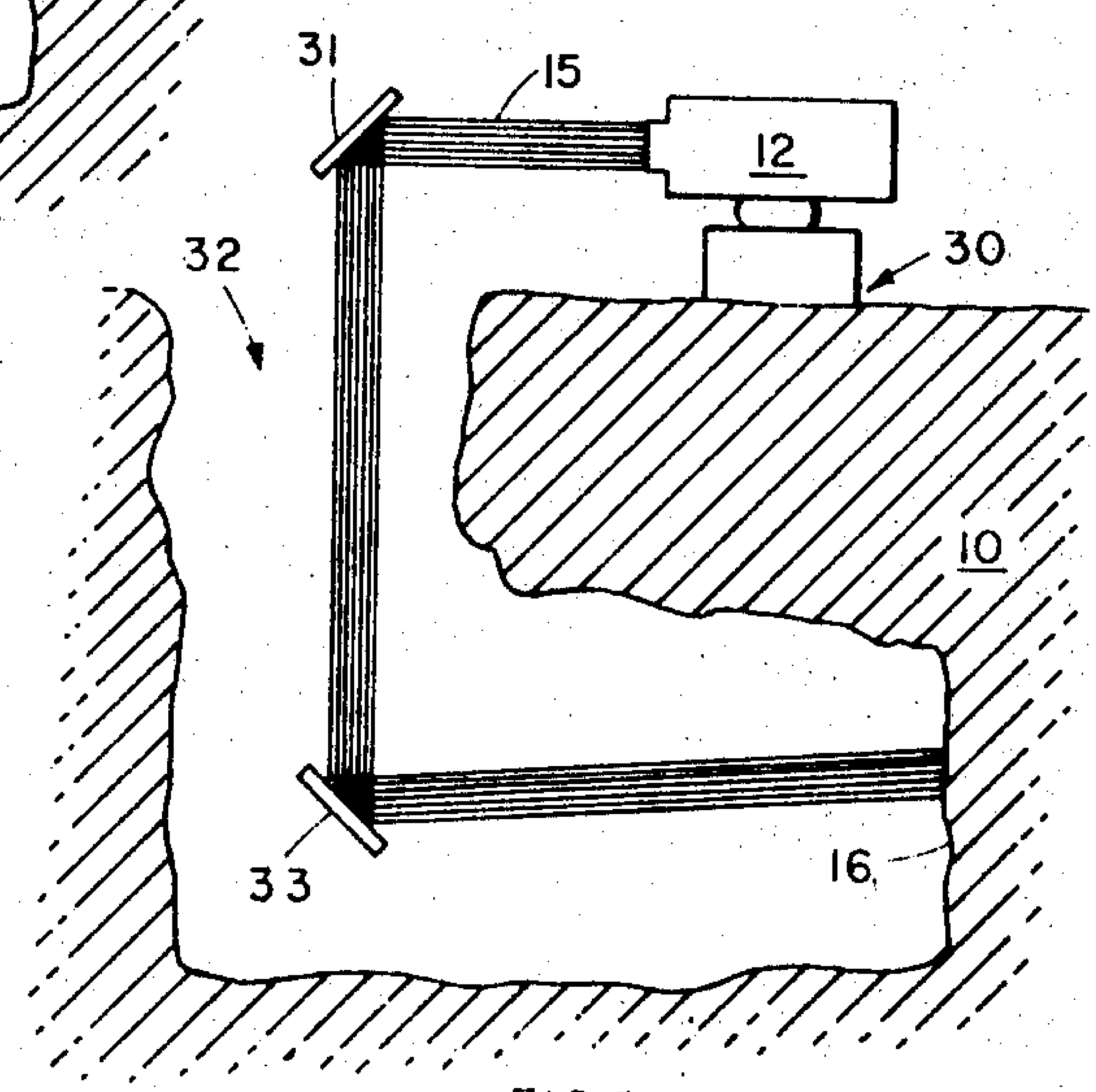

FIG. 8

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TREATMENT OF SOLID MATERIALS

This invention relates generally to methods for treating solid materials and, more particularly, to methods for treating hard rock formations or other solid mineral, or minerallike, materials with electromagnetic energy, as from a laser beam, so as to weaken their mechanical structure and thereby make easier the excavation of, or tunneling through, such formations.

In earth excavation processes as, for example, underground tunneling or well drilling, the presence of hard rock minerals in the form of granite, marble, gneiss, schist, and the like, increases the cost and reduces the efficiency of such operations by increasing the time required for such excavation and by causing excessive wear or damage to machine tools used therein. It is desirable, therefore, to devise economic and efficient methods of treatment for weakening the structure of such hard rock formations prior to the application of excavation machinery thereto. By causing fractures or otherwise weakening the material its strength can be reduced to a point where such machinery can more easily and quickly remove the treated debris with less expenditure of mechanical energy and less wear on or damage to the removal machinery.

Conventional excavation methods which involve drilling, charging and blasting the hard rock formation, and finally removing the resulting debris with suitable heavy duty machinery are extremely slow and potentially dangerous. Moreover, such procedures in the case of tunneling operations may require costly and complicated ventilation schemes. Because of the discontinuous nature of the steps involved, such methods must be performed in a sequentially repetitive manner by many highly paid workers requiring different skills and training. The inconvenience and costs of such processes make it highly desirable that other operating procedures be devised to provide faster, safer, less expensive and more efficient excavation systems.

Other more sophisticated methods have been suggested and used to cause a deterioration of the mechanical strength of the materials. Such processes, for example, involve the direct application of heat to the material, the heat being generated conventionally by a suitable flame source, such as an oxygen-gas torch. In the use of such a method, further improvement in the weakening operation has sometimes been obtained by quenching the material with water or other suitable cooling liquids immediately or at least shortly after the firing operation. The thermally induced shocks and resulting stress distribution that occur generally weaken the structure of a rock formation so that it can ultimately be more easily removed by appropriate machinery. Such a firing process, however, is relatively cumbersome to set up and gives rise to problems related to proper heat dissipation, oxygen supply requirements and toxic fume generation. Further, severe flashback and other surface or boundary problems may arise to affect adversely the safety and efficiency of the operation. Moreover, an excessive amount of time may be required to generate sufficient surface heat to cause an effective fracturing or weakening of the rock material.

Other methods which have been tried, at least experimentally, have utilized means for generating electric or magnetic shocks or for producing sonic vibrations in an effort to cause a fracturing of the material. Such methods generally have not proved to be sufficiently effective or commercially feasible at least at the present time.

This invention utilizes a method which overcomes the deficiencies of the above methods and, more particularly, greatly reduces the time previously needed to cause a sufficiently effective weakening of the hard rock structures involved. The invention additionally appears to show promise in effectively reducing the overall operating costs of the excavating or tunneling process. In the method of the invention an electromagnetic energy source, such as a laser device, is used for generating an energy beam which is directed toward at least one exposed surface of a rock formation which is to be treated. Heretofore, when laser beams have been applied to solid materials, such as metals, they have been known to penetrate such materials and to form well-defined holes therein. However, when applied to rock materials, no appreciable weakening effects have been noticed. In the latter cases, the beams in some cases have appeared to melt or at least partially vaporized the material in localized areas, thereby causing the formation of vitreous or glasslike zones around the edges of such localized areas of penetration. Such zones have tended to achieve a greater hardness than that of the original material and it was believed that their presence may have tended to enhance the strength of the materials rather than to weaken it. In some cases, application of a laser beam has even appeared to cause previously existent fissures within such materials to become sealed by fusion and thereby the material had also seemed to be further strengthened. Moreover, a substantial amount of the beam energy has appeared to be wasted because it had been reflected and thereby reradiated from the material before it had served any useful purpose.

The lack of success in using laser beams for weakening or fracturing rock materials has tended to prevent those in the art from further investigating the possibility that electromagnetic energy would prove useful in the field of hard rock excavation. This invention, however, provides a successful method for utilizing electromagnetic energy, as obtained from a laser, to weaken rock formations by using an electromagnetic energy beam having a wavelength selected so that the energy is substantially highly absorbed by the rock material at or near the surface thereof. It is found that the absorption of such energy having a frequency within an appropriately selected frequency range causes a reduction in the tensile strength of the material and thereby produces an effective overall degradation of its mechanical strength. Contrary to the prior art, but in accordance with the principles of the invention, a nonconverging beam, preferably collimated, may be used to achieve this result.

A specific type of laser device that has proved to be effective for providing such electromagnetic energy is a molecular-gas laser utilizing a combination of selected gas molecules as the lasing medium. Selected areas on an exposed surface of the rock structure are irradiated with the laser beam from such device for appropriately designated time periods. In one preferred embodiment, for example, the laser beam which has been found useful in treating marble or granite structures has a frequency in the far infrared region of the frequency spectrum.

Appropriate tests show that the effective depth of penetration of such a laser beam may be several inches. The thermal stresses which are produced because of the intense heat generated at or near the surface of the material by absorption of the laser beam energy cause the formation of a plurality of primary cracks or fissures within the material accompanied by an additional plurality of side cracks. As discussed in more detail below, the treatment of sample specimens of such materials show considerable reduction in the value of a load, applied in tension, that is required to deflect the material to its failure, or breaking, point as well as a considerable increase in the crack area which is formed.

In some applications a preferred embodiment of the invention utilizes a system in which electromagnetic energy from a laser is in the form of a collimated beam in which the energy rays making up the beam are all essentially parallel. Such a system provides advantages in applications where laser energy, for example, is generated at a remote location from the rock formation and such collimated beam energy can be easily transmitted from the source to the rock surface under treatment by an appropriate mirror transmission system. In other applications it may be desirable to produce a high concentration of energy at a small localized surface area in which case a noncollimated, converging beam of energy may be utilized.

The invention can be described most easily with the help of the accompanying drawings wherein:

FIG. 1 shows a partially pictorial, partially diagrammatic representation of a simple version of a proposed configuration which utilizes the method of the invention;

FIG. 2 shows a diagrammatic representation of one form of a laser beam irradiation pattern useful in practicing the method of the invention;

FIG. 3 shows a representative sample of a block of granite used for testing the effects of laser beam irradiation applied in accordance with the invention;

FIG. 4 shows another representative sample of a material used in testing the effects of the use of the method of the invention;

FIG. 5 shows a graph of representative load-deflection curves comparing the weakening effect of untreated materials and materials treated in accordance with the method of the invention;

FIG. 6 shows a graph of representative curves showing incremental crack areas produced as a function of exposure time for such treated and untreated materials;

FIG. 7 shows a partially pictorial, partially diagrammatic representation of an alternative configuration of the invention which utilizes a converging beam of electromagnetic energy; and

FIG. 8 shows a partially pictorial, partially diagrammatic representation of a proposed configuration of the invention using a remotely located electromagnetic energy generator.

With reference to FIG. 1, it is desired, for example, to excavate a rock formation **10** so as to form a tunnel having an opening **11** therein. In the figure a laser device **12** is mounted on a suitable structure **13** on an appropriate pivotal mount **14** which allows the beam **15** from laser device **12** to be controllably directed toward rock structure **10**. Structure **13** may be used to house suitable control and power supply circuitry as well as monitoring or other peripheral equipment. Any suitable mounting means well known to those skilled in the art can be used and, consequently, such a structure is shown only schematically and the details thereof are not further discussed here. The laser beam **15** may be controllably maneuvered to impinge generally upon the front exposed surface **16** of rock formation **10** within opening **11** in some suitable selected pattern. Such a pattern may be of the form shown in FIG. 2 comprising a plurality of substantially concentric rings **17** which tend to cover an appropriate portion of the overall area of the front surface **16**.

Laser device **12** is a device presently well known to those in the art for producing a beam of energy through a process generally referred to as stimulated emission. In one particular embodiment, for example, although not necessarily limited thereto, such laser device may be of the molecular-gas type which utilizes as a lasing medium a combination of gaseous materials in which a required population inversion of the molecules within such medium occurs. One particularly useful gaseous combination includes carbon dioxide, nitrogen and helium which produces an output radiation beam in the far infrared region of the frequency spectrum, such beam having a wavelength of approximately 10.6 microns. Molecular-gas lasers of this type are known, at the present time at least, to produce higher efficiencies than many other presently known laser devices which, for example, may utilize a combination of noble gases or which may utilize solid state mediums, such as ruby or semiconductor materials.

In the particular embodiment discussed herein, the laser is arranged to produce an appropriate output beam of electromagnetic energy which, when applied to the exposed surface of the rock formation, produces a substantial weakening of the rock structure. In such a laser device, for example, the output beam is arranged in the form of a collimated beam of energy, that is, a beam in which the rays are all substantially parallel, such as is shown by collimated laser beam **15** of FIG. 1. Typical effects of such beam on the strength of the rock material being irradiated can be generally discussed with reference to FIG. 3. In such FIG. the rock formation is conveniently represented by a sample block **18** of granite having a front surface area of approximately 1 foot square and a depth of approximately 6 inches. The front surface **19** of block **18** is irradiated in a pattern of concentric circular areas **20** in a manner similar to that shown in FIG. 2. Tests on the effectiveness of laser beam irradiation on such a block show that the weakening effects of the beam occur both near the surface and well into the interior of the block up to depths of 4 to 5 inches below the surface on which the laser beam is impinging. Maximum weakening effects appear to occur generally in those interior volumes of the block which are essentially directly behind the areas **20** which are irradiated, the effects of fracturing of the block generally being less in those interior volumes not in line with the radiated areas. Such effective weakening was achieved in one instance by utilizing laser beam irradiation over a time period of approximately 30 seconds for each 4 square centimeters of surface covered. For a similar size block of marble, weakening effects were found to exist up to depths of approximately 3 to 4 inches. Thus, the severity of damage to the rock formation appears to be somewhat dependent upon the type of material being irradiated.

The weakening effects may be demonstrated in more detail if consideration is given to the curves shown in FIGS. 5 and 6. Such curves are representative of the weakening effects noted with respect to the application of a collimated laser beam having a wavelength substantially equal to 10.6 microns to typical samples of material fabricated in the form of rectangular beams which are substantially 1 foot in length and 1 square inch in cross section. One such sample **21** is illustrated, for example, in FIG. 4. The results of tests performed upon samples of marble material are discussed with reference to FIGS. 5 and 6. Similar results have been obtained on samples of other rock materials. A collimated laser beam, as from laser device **12**, is directed toward the central portion **22** of various samples **21** for varying amounts of time. Each sample is thereupon subjected to a load which produces a tensile stress on the irradiated surface of the sample so as to deflect the sample. Curves **23** and **24** showing the relationship between the applied load and the deflection of the sample are shown in FIG. 5 for irradiation times of 3—5 seconds and 10 seconds, respectively. Such curves can be compared to a similar curve **25** for an untreated sample specimen. The area under each of the curves represents the input energy requirement and is much less for the treated samples shown by curves **23** and **24** than for the untreated sample shown by curve **25**. Moreover, the maximum load required for failure is reduced considerably even for such relatively low exposure times.

Further evidence of structural weakening is shown in FIG. 6 where appropriate micrographs of the specimen were used to measure the crack area produced by electromagnetic energy irradiation for varying exposure times as compared to the original crack area existing for the untreated condition of the sample.

The increase in effective crack area and the decrease in input energy requirements to produce failure indicate the usefulness of the method of the invention for weakening hard rock formations. Once such formations have been effectively weakened, the excavation process can proceed more quickly and easily since the weakened material can be then removed with far less wear, or possible damage, to the removal machinery.

FIG. 7 shows an alternative embodiment of the invention in which a noncollimated beam of energy is utilized. In such embodiment the noncollimated beam having a wavelength such that the energy will be absorbed by the material under treatment is in the form of a converging beam **26** which is formed by focusing a parallel or collimated beam **27** from laser device **12** by a suitable lens **28**. The beam is caused thereupon to focus at a localized point **29** located in a plane essentially corresponding to the plane of the surface **16** of rock formation **10**. The use of a noncollimated, converging beam provides similar weakening effects on the rock formation in the same manner described above with reference to collimated beam **15** of FIG. 1. In the case of the converging beam, graphical results similar to those shown in FIG. 5 and FIG. 6 are obtained in which the area under the load-deflection curve, and hence, the energy requirements are reduced considerably, the maximum load required for failure is reduced over that required for an untreated rock sample and the effective crack area is increased upon treatment with a converging beam.

The advantages of utilizing either a collimated or a converging beam system may depend upon the particular applications involved. For example, while the converging beam system allows a higher concentration of energy at a relatively small localized area, it requires the laser to be located substantially at a specified distance from the rock formation surface so that the focal point of convergence lies, at least approximately, in the appropriate plane of the exposed surface of the formation. If a collimated beam is used, the location of the laser becomes much less critical since substantially little or no energy is lost in the transmission from the electromagnetic laser energy source to the rock formation and the diameter of the collimated beam remains substantially constant for relatively long distances.

The collimated beam system may also find advantageous application in situations illustrated in FIG. **8**. In such a system the electromagnetic energy source, such as laser **12**, may be located at a position **30** above the ground over which the excavation is taking place. The output collimated beam **15** from laser source **12** may be directed toward a suitable reflective surface, such as a mirror **31**, which will thereupon direct the energy downward through an appropriate opening **32** in the ground toward a second reflective surface, such as mirror **33**, located underground. Mirror **33** then directs the beam toward surface **16** of underground rock formation **10**. Mirror **33** may be pivotally mounted so that the position of the mirror can be varied and beam **15**, as reflected therefrom, can be controllably directed to impinge on any portion of the overall exposed surface **16** of rock formation **10**. In this way the energy source can be remotely located to provide greater convenience in operation and to prevent any damage to the source, which damage may be more likely to occur if the source is located underground during the excavation operation. Since there is substantially little or no energy loss or increase in beam diameter in the transmission of energy beam **15** from laser source **12** to surface **16**, such an arrangement may prove highly advantageous in many applications.

In providing an effective weakening in the structure of the materials being excavated, whether by using a collimated or noncollimated beam, the wavelength (or, correspondingly, the frequency) of the electromagnetic energy used must be selected to provide a high degree of energy absorption by the material. An appropriate irradiation time and pattern can then be selected to cause the beam to impinge upon portions of an exposed surface of the material which is to be weakened. For certain rock formations, such as marble, granite, gneiss and schist, and the like, the energy has been found preferably to have a frequency in the far infrared region of the frequency spectrum and can be applied in a preselected pattern for time periods over a range as low as from one or a few seconds to approximately half a minute or more.

We claim:

1. A method for weakening a rock formation comprising the steps of:

generating a collimated beam of electromagnetic energy by a laser device having a wavelength such that the energy from said beam is capable of being substantially absorbed by said formation; and

directing said beam towards said formation to cause said beam to impinge thereon and to penetrate beneath the surface thereof.

2. A method for weakening a rock formation in accordance with claim **1** wherein said electromagnetic energy has a wave length in the far infrared region of the frequency spectrum.

3. A method for weakening a rock formation in accordance with claim **1**, wherein said electromagnetic energy has a wavelength of approximately 10.6 microns.

4. A method for weakening a rock formation in accordance with claim **1** wherein said laser beam is in the form of a non-converging collimated beam of energy.

5. A method for weakening a rock formation in accordance with claim **3** wherein said laser beam is generated at a location remote from said rock formation and further including the step of transmitting said collimated beam from said remote location to said rock formation.

6. A method for weakening a rock formation in accordance with claim **1** wherein said laser beam is in the form of a converging beam of energy, the focal point of said converging beam being located approximately at said surface of said rock formation.

7. A method for weakening a rock formation comprising the steps of:

generating a laser beam of electromagnetic energy having a wavelength in the infrared region of the frequency spectrum; and

directing said beam toward at least one surface of said rock formation to cause said beam to impinge thereon and to penetrate beneath the surface thereof so as to reduce the tensile strength of said rock formation.

8. A method for weakening a rock formation in accordance with claim **7** wherein said beam is caused to impinge on the surface of said rock formation for a preselected time period sufficient to cause a weakening of said formation.

9. A method for weakening a rock formation in accordance with claim **7** wherein said beam is caused to impinge on the surface of said rock formation in accordance with a preselected pattern.

10. A method of claim **7** wherein said beam is nonconverging.

11. The method of claim **7** wherein said beam is converging.

12. A method for excavating a rock formation comprising the steps of:

generating a laser beam of electromagnetic energy having a wavelength in the infrared region of the frequency spectrum;

directing said beam toward at least one surface of said rock formation to cause said beam to impinge thereon and to penetrate beneath the surface thereof so as to weaken the mechanical structure of said rock formation; and

removing said weakened rock formation.

13. A method for controllably fracturing an object of solid material comprising the steps of generating a laser beam having a wavelength such that the energy from said beam is susceptible of being substantially absorbed by the particular material of said object; directing said beam toward said object to cause said beam to impinge thereon and to penetrate beneath a surface thereof whereby mechanical weakening of said material at and beneath said surface is achieved.

14. The material fracturing method in claim **13** wherein said laser beam has a wavelength of approximately 10.6 microns.

15. The material fracturing method recited in claim **13** wherein the duration of time said beam is directed toward any part of said object is a function of the dimension of said object along the direction of said beam and is longer as said dimension is greater.

16. The material fracturing method in claim **13** wherein said laser beam is collimated.

17. The material fracturing method in claim **13** including the step of moving said beam over said surface of said object in accordance with a preselected pattern to cause fracturing of said object along the path of said beam's movement defined by said pattern.

18. The material fracturing method of claim **17** wherein said pattern is curvilinear.