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(54) HEAT TRANSFER COMPONENTS FOR STIRLING-CYCLE, RECIPROCATING, THERMAL MACHINES.

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Description

This invention relates to Stirling-cycle engines, also known as regenerative thermal machines, and more particularly to the materials chosen for the design and construction of heat transfer components and their adjuncts. The desire for high thermal efficiency in Stirling engines, as in all heat engines, dictates that all heat transfer components should have the highest practicable thermal conductivity while all other components should be thermal insulators having the lowest practicable thermal conductivity.

The Stirling-cycle engine was first conceived and reduced to practice in Scotland 164 years ago. A hot-air, closed cycle prime mover based on the principle was patented by the Reverend Robert Stirling in 1817 as an alternative to the explosively dangerous steam engine. Incredibly, this event occurred early in the Age of Steam, long before the invention of the internal combustion engine and several years before the first formal exposition of the Laws of Thermodynamics.

A Stirling-cycle engine is a machine which operates on a closed regenerative thermodynamic cycle, with periodic compression and expansion of a gaseous working fluid at different temperature levels, and where the flow is controlled by volume changes in such a way as to produce a net conversion of heat to work, or vice-versa.

A typical Stirling-cycle engine comprises an expansion block enclosing an expansion space, a compression space enclosing a compression space, a regenerator, a working fluid enclosed in said spaces and in ducts permitting oscillatory flow of said fluid between said spaces through said regenerator, a heater for transmitting heat from an external heat source to working fluid in the expansion space and a cooler for transmitting heat from working fluid in the compression space to an external heat sink. The regenerator is a device which in prior art takes the form of a porous mass of metal in an insulated duct. This mass takes up heat from the working fluid during one part of the cycle, temporarily stores it within the machine until a later part of the cycle, and subsequently returns it to the working fluid prior to the start of the next cycle. Thus the regenerator may be thought of as an oscillatory thermodynamic sponge, alternatively absorbing and releasing heat with complete reversibility and no loss.

For efficient operation of a Stirling-cycle engine there should be as little heat transfer between the heater and the cooler respectively and the adjacent parts of the machine and as little thermal stress between adjacent components at different temperatures as possible.

The use of ordinary engine construction materials in Stirling-cycle engines, such as cast iron or aluminium alloys, for example, often results in unnecessary thermal losses and unacceptable thermal stresses between heat transfer elements and adjacent components. Prior art solutions to these problems have resulted in increased complexity and cost.

Typical solutions to the problems of heat transfer involve the introduction of insulating seals or gaskets between parts of the engine operating at different temperatures, (see for example GB-A-2051961, US-A-3403508 and US-A-3950947).

Typical solutions to the problem of thermal stress have involved the use of complicated stress absorbing structures (see for example GB-A-2051961 and US-A-4183213).

Despite clearly superior technical performance characteristics, therefore, contemporary Stirling engines are invariably not cost competitive from the standpoint of economical mass production.

Thus it is an object of the invention to provide a substantial increase in performance and efficiency of Stirling-cycle engines through the deliberate and judicious utilization of construction materials, especially composite materials and structural ceramics, in the design and construction of heat transfer components and their adjuncts.

According to the invention, in a Stirling-cycle reciprocating thermal machine comprising an expansion block enclosing an expansion space, a compression block enclosing a compression space, a regenerator, working fluid enclosed in said spaces and ducts permitting oscillatory flow between the expansion space and the compression space through said regenerator, a heater for transmitting heat from an external source to working fluid in the expansion space, a cooler for transmitting heat from working fluid in the compression space to an external heat sink, at least the heat transfer elements of the heater and the cooler being constructed of materials of high thermal conductivity, the heat transfer element of the heater is directly connected to the expansion block and the heat transfer element of the cooler is directly connected to the compression block, the expansion block and the compression block are each constructed of materials of low conductivity and the materials of the heat transfer element of the heater and of the expansion block have substantially the same linear coefficient of thermal expansion and the materials of the heat transfer element of the cooler and the compression block have substantially the same linear coefficient of thermal expansion.

One combination of material that fulfills the requirements of the invention is, for example, dispersion strengthened copper for the heater or cooler and a manganese-copper eutectic or near eutectic alloy for the expansion block or compression block, respectively. Another combination of suitable materials is a silicon carbide ceramic material for the heater or cooler and a boron carbide ceramic for the expansion block or compression block, respectively.

Preferably, according to the invention, the heater and/or cooler is formed of one or more heat pipes designed and arranged to provide a passage therethrough with the highest practicable ratio of exposed surface area to cross sectional flow area.

The invention will now be described in greater detail by way of example with reference to the drawings in which Fig. 1 is a partially exploded perspective view illustrating the component arrangement of a Stirling-cycle engine and Fig.2. shows the elevated temperature technical properties of a specific dispersion strengthened copper sold under the trade name "Glidcop" which is preferred for use as the heater and cooler in the Stirling-cycle engine according to the invention.

Fig. 1 shows the component arrangement of a specific single-acting, multiple-piston, Stirling-engine. It will be seen that all compression spaces 20 are collocated within a single stationary right-circular cylindrical compression block 26 made of material having comparatively low thermal conductivity.

Likewise all expansion spaces 21 are collocated within a single stationary right-circular cylindrical expansion block 28, also made of material having comparatively low thermal conductivity.

Compression block 26 and expansion block 28 are conjoined by four regenerator housings 25 and also by four longitudinal struts 24. At the extreme opposite ends of each of both compression block 26 and expansion block 28, a series of shallow segmented annular depressions 31 connect each piston-cylinder working volume with an adjacent regenerator duct 27 and serve as a housing for the internal heat transfer surfaces of either cooler 22 or heater 23. Working fluid is conveyed into each piston-cylinder working volume by means of tank valves 32 located on the periphery of compression block 26.

The individual heat exchange elements for each of the aforedescribed separate but inter-connected working volumes are naturally and conveniently collocated within a single component, cooler 22 or heater 23. These consist of a flanged plate made of material possessing comparatively high thermal conductivity, each having a plurality of radial flow passages on the exterior face and plurality of segmented annular flow passages on the interior face. Cooler 22 serves upon assembly and in conjunction with cooler head 29 to close and connect compression volumes 20 with adjacent regenerators 27 and to transfer heat from the internal working fluid to an exterior sink. Heater 23 serves upon assembly and in conjunction with heater head 30 to close and connect expansion volumes 21 with adjacent regenerators 27, and to transfer heat from an exterior source to the internal working fluid.

This design of machine is an arrangement which involves a minimum number of separate components, and wherein the hot and cold regions of the machine are inherently located at extreme ends. It should be readily apparent to those skilled in the art that the collocation of cooler elements within a compact cooler head at one end of the machine and of heater elements within a similarly compact heater head at the other end of the machine, has the highly desirable effect of reducing heat losses from conduction and radiation to improve the overall thermal efficiency of the machine. It also leads to a substantial simplification in the design and manufacture of not only the heat transfer elements but also of other mechanical components of the machine.

In this regard, the materials chosen for the design of the heat transfer components and of the heater and cooler head components in a Stirling prime mover present the greatest challenge. According to the invention the heat transfer components (heater and cooler) possess high thermal conductivity and high strength at a nominal use temperature of at least 750°C (1382°F) for the heater 23 and cooler 22 as well as a thermal expansion coefficient that is closely matched to that of any adjacent component or components. The adjacent components, the expansion block 28 and compression block 26 and also heater head 30 and cooler head 29 are made of materials possessing low thermal conductivity. Pure copper has the most desirable thermal conductivity of any of the common engineering materials, but its notorious loss of strength and creep resistance at high temperatures precludes its use in such applications. Certain copper alloys have improved high temperature mechanical properties, beryllium copper for example, but their corresponding thermal properties are typically no better than those of high temperature steels, which are stronger and often less expensive.

It is an important specific teaching of this invention, therefore, to use a new materials technology development of the type exemplified by a product of the Glidden Metals Division of SCM Corporation known as GLIDCOP. GLIDCOP is a dispersion strengthened copper composite material offering both high temperature strength and high thermal conductivity. It consists of a high purity copper with submicroscopic particles of insoluble aluminium oxide finely distributed throughout the copper matrix. Dispersion strengthening offers one of the most promising methods of improving the elevated temperature properties of copper without seriously degrading its thermal conductivity.

The strengthening mechanism in GLIDCOP is a finely dispersed phase that acts as a barrier to dislocation movement in the composite material. In GLIDCOP and other materials of similar nature, but different origin, the dispersed phase remains insoluble in the copper matrix, and hence no overaging in the usual sense can occur at elevated temperatures as it does in heat treatable alloys. The dispersed phase particles interfere with dislocation movement, raise the re-crystallization temperature, and exert a powerful effect on elevated temperature strength and hardness. The graphs of Fig. 2 illustrate some of the unique elevated temperature mechanical properties of GLIDCOP. The terms AL-20 and AL-35 refer to materials having .20 and .35 weight percent aluminium present as oxide, while the term CA-182 refers to a standard well-known high temperature copper alloy.

It is appropriate at this point to re-emphasize that the material for the insulative components of the heater head and the expansion block of a Stirling engine should have, in conjunction with the adjacent heater, a closely matched thermal expansion co-efficient and the lowest possible thermal conductivity. It is therefore, another important specific teaching of this invention that the use of eutectic or near-eutectic manganese-copper alloys can satisfy both of these requirements and provide a high degree of vibration damping capacity as well. That is, referring back to FIG. 1 for example, it is proposed that heater 23 should be made of GLIDCOP, whereas both expansion block 28 and heater head 30 should be made of manganesecopper eutectic alloy to achieve maximum utility with minimum thermal stress or strain.

Since the Stirling-cycle engine, according to the Carnot principle and the well-known laws of thermodynamics, achieves maximum efficiency by virtue of a large difference in temperature between the expansion volume and the compression volume, there is a strong incentive to raise the normal operating temperatures of the heater head and expansion block components in prime movers beyond the normal limits of ordinary materials. Recent advances in the research and development of high temperature structural ceramics promise to greatly extend the performance limitations of current Stirling-cycle prime movers. It is well known, for example, that hot-pressed and reaction-bonded silicon carbide, silicon nitride, and the oxygen substituted silicon nitride compounds SIALONS retain high strength temperatures as high as 1400°C (2552°F).

Advanced structural ceramics are also attractive choices because of their low density, high strength-to-weight ratio, low cost compared to the super alloys, and excellent hot gas corrosion resistance. But the promise of these materials will be ultimately realized only for conceptual designs which retain sufficient component level simplicity to allow economical mass production an absolutely essential prerequisite for success in the market. The advantages inherent in the various embodiments of this invention may permit, for the first time in history, the mass production and competitive introduction of a ceramic-enhanced Stirling-cycle engine into world markets.

In this regard, it is yet another important specific teaching of this invention that an ideal combination of both mechanical and thermal properties is to be found in the use of silicon carbide (SiC) for the heat conducting components in conjunction with boron carbide (B C) for the heat insulating components of an advanced ceramic-enhanced Stirling-cycle prime mover. The coefficient of linear thermal expansion (from O-1000°C) for these materials is very closely matched (4.5 × 10exp-6 cm/cm/°C), while the ratio of their thermal conductivities is nearly 80 to 1. Boron carbide is also an excellent choice for piston and cylinder construction because of its low density and extreme hardness; it is well known to resist abrasive wear better than any other readily available engineering material.

Since the closed cycle Stirling prime mover operates solely on the basis of the difference in temperature in the working fluid between the hot expansion space and the cold compression space, the development of useful power output is not specific to the source of heat available for use. Therefore, the design of the heat source can be any one of a large variety of possible types. A rather simple combustion system can be produced, for example, which will cleanly and efficiently burn various kinds of both liquid fuels and gaseous fuels without any modification whatsoever. Thus it will be appreciated by those familiar with the art that a single prime mover may be made to operate on regular or premium gasoline, diesel oil, alcohol, crude oil, lubricating oil, vegetable oil, propane, butane, natural gas, and synthetic coal gas.

It should also be appreciated that through the inter-mediary of a suitable heat transport system, a heat pipe exchange unit for example, virtually any heat source at a sufficiently high temperature can be adapted, including radioisotopes, nuclear reactors, solar collectors, thermal storage devices, and the burning of coal, wood, or even municipal solid waste. The heat pipe is a well know device for passive heat transfer in which a fluid within a sealed envelope vaporizes when heated and condenses when cooled, transferring heat by vapour transport before being returned to the heat source as liquid again, generally by capillary action. The historical development, theory of operation, and details of construction of the heat pipe are amply set forth in US patents Nos. 2,350,348 and No. 3,229,759.

Referring again to Fig. 1, for example, heaters 23 and coolers 22 could be substantially hollow instead of solid structures containing both working fluid and wick common to the heat pipe for improved heat transfer.

It is important at this point to re-emphasize the fact that each small segment of a well-designed regenerator transfers heat to and from the working fluid with minimal temperature differences. Thus all stages in the regenerator are reversible in an actual thermodynamic sense. Therefore, the entire machine cycle is reversible in function; that is, the direction of the flow of heat and work can be reversed. The Stirling engine is truly unique in that it is the only practical example of a thermodynamically reversible machine.

The design concepts disclosed herein for Stirling prime movers are also applicable to the design and development of other Stirling machines, such as, refrigerators, heat pumps, air conditioners, and the like. It is another important specific teaching of this invention that machines of this kind would be appreciably more efficient than conventional vapor cycle reciprocating refrigerators or thermally-activated absorption refrigerators, with a substantial savings in size and weight. In addition, a hybrid device obtained from the combination of a Stirling prime mover mechanically coupled to a Stirling heat pump will permit both multifuel and nonfuel powered refrigeration units to be developed and applied to specialized applications.

Claims

1. A Stirling-cycle reciprocating thermal machine comprising an expansion block (28) enclosing an expansion space (21) a compression block (26) enclosing a compression space (20) a regenerator (25), working fluid enclosed in said spaces (20,21) and ducts (27) permitting oscillatory flow between the expansion space (21) and the compression space (20) through said regenerator (25), a heater (23) for transmitting heat from an external source to working fluid in the expansion space (21), cooler (22) for transmitting heat from working fluid in the compression space (20) to an external heat sink, at least the heat transfer elements of the heater (23) and the cooler (22) being constructed of materials of high thermal conductivity, characterised in that the heat transfer element of the heater (23) is directly connected to the expansion block (28) and the heat transfer element of the cooler (22) is directly connected to the compression block (26), the expansion block (28) and the compression block (26) are each constructed of materials of low conductivity and the materials of the heat transfer element of the heater (23) and of the expansion block (28) have substantially the same linear coefficient of thermal expansion and the materials of the heat transfer element of the cooler (22) and the compression block (26) have substantially the same linear coefficient of thermal expansion.

2. A machine according to claim 1, wherein the heat transfer elements of the heater (23) and the cooler (22) are of the same materials and the expansion block (28) and the compression block (26) are of the same materials.

3. A machine according to claim 1 or claim 2, in which the heat transfer elements of the heater (23) and/or the cooler (22) are constructed of dispersion strengthened copper, and the expansion block (28) and/or the compression block (26) are of manganese-copper eutectic or near-eutectic alloy.

4. A machine according to claim 1 or claim 2, in which the heat transfer elements of the heater (23) and/or the cooler (22) are constructed of silicon carbide ceramic and the expansion block (28) and/or the compression block (26) is of boron carbide ceramic.

5. A machine according to any one of claims 1 to 4, in which the heat transfer element is constructed in the form of one or more heat pipes collocated at the remote ends of the machine, said heat pipes being designed and arranged to provide a passage therethrough with the highest practicable ratio of exposed surface area to cross-sectional flow area.

Patentansprüche

1. Eine Stirling-Hubkolben-Wärmekraftmaschine, bestehend aus einem Expansionsblock (28), der einen Expansionsraum (21) umschließt, einem Kompressionsblock (26), der einen Kompressionsraum (20) umschließt, einem Regenerator (25), Arbeitsflüssigkeit, welche in den besagten Räumen (20, 21) eingeschlossen ist, und Kanäle (27), die den oszillierenden Fluß zwischen dem Expansionsraum (21) und dem Kompressionsraum (20) durch besagten Regenerator (25) gestatten, einem Heizer (23) für die Übertragung von Wärme aus einer außenstehenden Quelle Zu der Arbeitsflüssigkeit im Expansionsraum (21), einem Kühler (22) für die Übertragung won Wärme von der Arbeitsflüssigkeit im Kompressionsraum (20) Zu einer außenstehenden Wärmesenke, wobei mindestens die Wärmeübertragungselemente des Heizers (23) und des Kühlers (22) aus Materialien won hoher Temperaturleitfähigkeit herhgestellt sind, dadurch gekennzeichnet, daß das Wärmeübertragungselement des Heizers (23) unmittelbar mit dem Expansionsblock (28) werbunden ist, und das Wärmeübertragungselement des Kühlers (22) unmittelbar mit dem Kompressionsblock (26) werbunden ist, und daß der Expansionsblock und der Kompressionsblock (26) beide aus Materialien won niedriger Leitfähigkeit hergestellt sind, und die Materialien des Wärmeübertragungselements des Heizers (23) und des Expansionsblocks (28) wesentlich denselben linearen Wärmeausdehnungskoeffizienten haben und die Materialien des Wärmeübertragungselements des Kühlers (22) und des Kompressionsblocks (26) wesentlich denselben linearen Wärmeausdehnungskoeffizienten haben.

2. Eine "Maschine entsprechend dem Anspruch 1, in welcher die Wärmeübertragungselemente des Heizers (23) und des Kühlers (22) aus denselben Materialien sind, und in welcher der Expansionsblock (28) und der Kompressionsblock (26) aus denselben Materialien sind.

3. Eine Maschine entsprechend dem Anspruch 1 oder Anspruch 2, in welcher die Wämeübertragungselemente des Heizers (23) und/oder des Kühlers (22) aus dispersionsverstärktem Kupfer hergestellt sind, und der Expansionsblock (28) und/oder der Kompressionsblock (26) aus mangankupfereutektischer oder fast-eutektischer Legierung sind.

4. Eine Maschine entsprechend dem Anspruch 1 oder Anspruch 2, in weucher die Wärmeübertragungselemente des Heizers (23) und/oder des Kühlers (22) aus Siliziumkarbid-Keramik und der Expansionsblock (28) und/oder der Kompressionsblock (26) aus Borkarbid-Keramik hergestellt sind.

5. Eine Maschine entsprechend jeder der Ansprüche 1 bis 4, in welcher das Wärmeübertragungselement in Form einer oder mehrerer Heizungsröhren besteht, die an den entfernten Enden der Maschine angeordnet sind, wobei die besagten Heizungsröhren so ausgelegt und argeordnet sind, daß ein Zischenraum durch sie hindurch entsteht mit dem praktisch höchstmöglichen offenen Flächenbereich im Verhältnis zum durchschnittlichen Durchflußbereich.

Revendications

1. Machine thermique à mouvement de va-et-vient et à cycle de Stirling comprenant un bloc d'expansion (28) enfermant un espace d'expansion (21), un bloc de compression (26) enfermant un espace de compression (20), un régénérateur (25), un fluide de travail enfermé dans lesdits espaces (20, 21) et des conduites (27) permettant un écoulement oscillant entre l'espace d'expansion (21) et l'espace de compression (20) passant par ledit régénérateur (25), un radiateur (23) pour transmettre la chaleur d'une source externe au fluide de travail dans l'espace d'expansion (21), un refroidisseur (22) pour transmettre la chaleur provenant du fluide de travail se trouvant dans l'espace de compression (20) à un dissipateur de chaleur externe, les éléments de transfert de chaleur du radiateur (23) et du refroidisseur (22) au moins étant construits en des matériaux de conductivité thermique éleée, caractérisée en ce que lélément de transfert de chaleur du radiateur (23) est directement relié au bloc d'expansion (28) et l'élément de transfert de chaleur du refroidisseur (22) est directement relié au bloc de compression (26), le bloc d'expansion (28) et le bloc de compression (26) sont chacun construits en des matériaux de faible conductivité et les matériaux de l'élément de transfert de chaleur du radiateur (23) et du bloc d'expansion (28) ont sensiblement le même coefficient linéaire d'expansion thermique et les matériaux de l'élément de transfert de chaleur du refroidisseur (22) et du bloc de compression (26) ont sensiblement le même coefficient linéaire d'expansion thermique.

2. Machine selon la revendication 1, caractérisée en ce que les éléments de transfert de chaleur du radiateur (23) et du refroidisseur (22) sont dans les mêmes matériaux et le bloc d'expansion (28) et le bloc de compression (26) sont dans les mêmes matériaux.

3. Machine selon la reve'ndication 1 ou la revendication 2, caractérisée en ce que les éléments de transfert de chaleur du radiateur (23) et/ ou du refroidisseur (22) sont construits dans du cuivre renforcé par dispersion, et le bloc d'expansion (28) et/ou le bloc de compression (26) sont en un alliage manganèse-cuivre eutectique ou presque eutectique.

4. Machine selon la revendication 1 ou la revendication 2, charactérisée en ce que les éléments de transfert de chaleur du radiateur (23) et/ ou du refroidisseur (22) sont construits en céramique au carbure de silicium et le bloc d'expansion (28) et/ou le bloc de compression (26) est en céramique au carbure de bore.

5. Machine selon l'une quelconque des revendications 1 à 4, caractérisée en ce que l'élément de transfert de chaleur est construit sous la forme d'un ou plusieurs tubes de chaleur rassemblés aux extrémités éloignées de la machine, lesdits tubes de chaleur étant conçus et aménagés pour déterminer un passage qui les traverse, avec un rapport entre aire de surface exposée et aire d'écoulement en section transversale le plus élevé que possible.

FIG. 1.

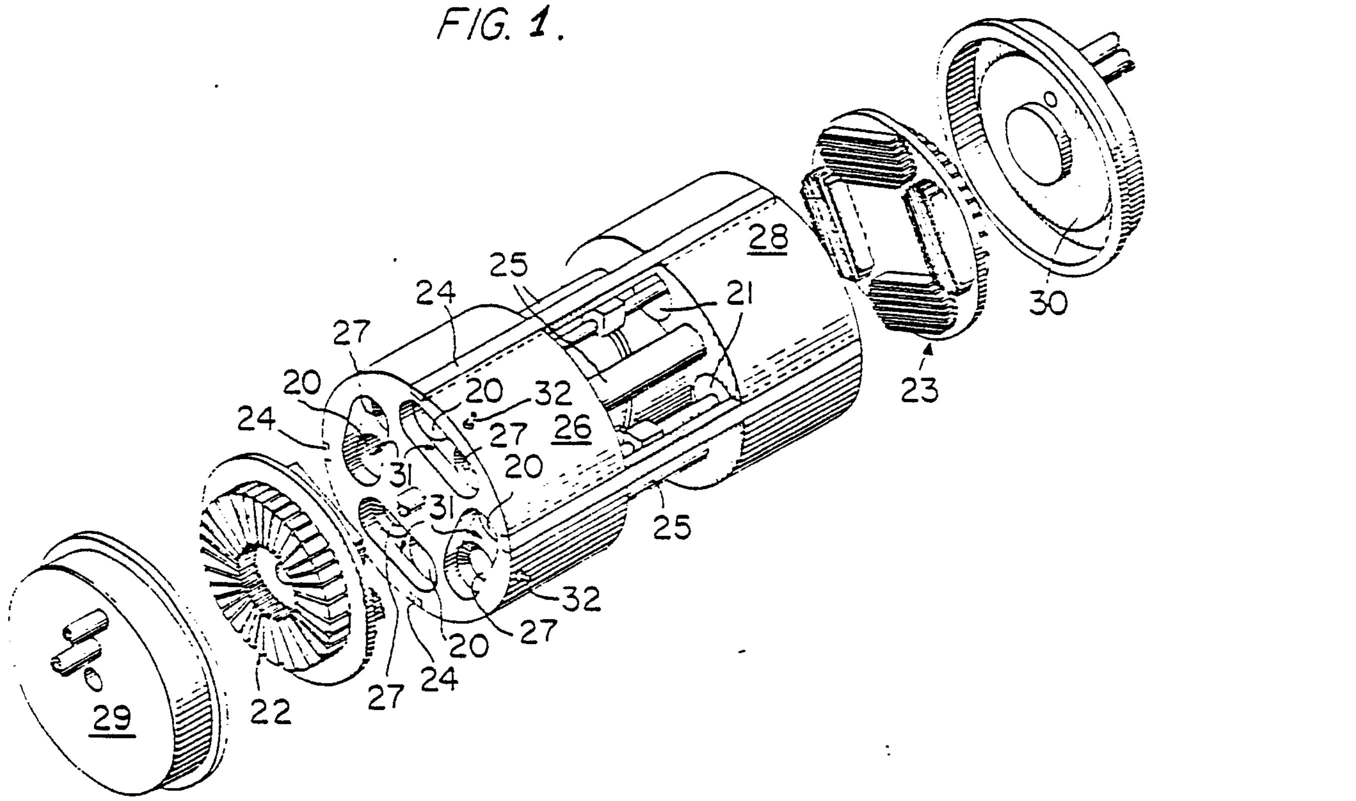
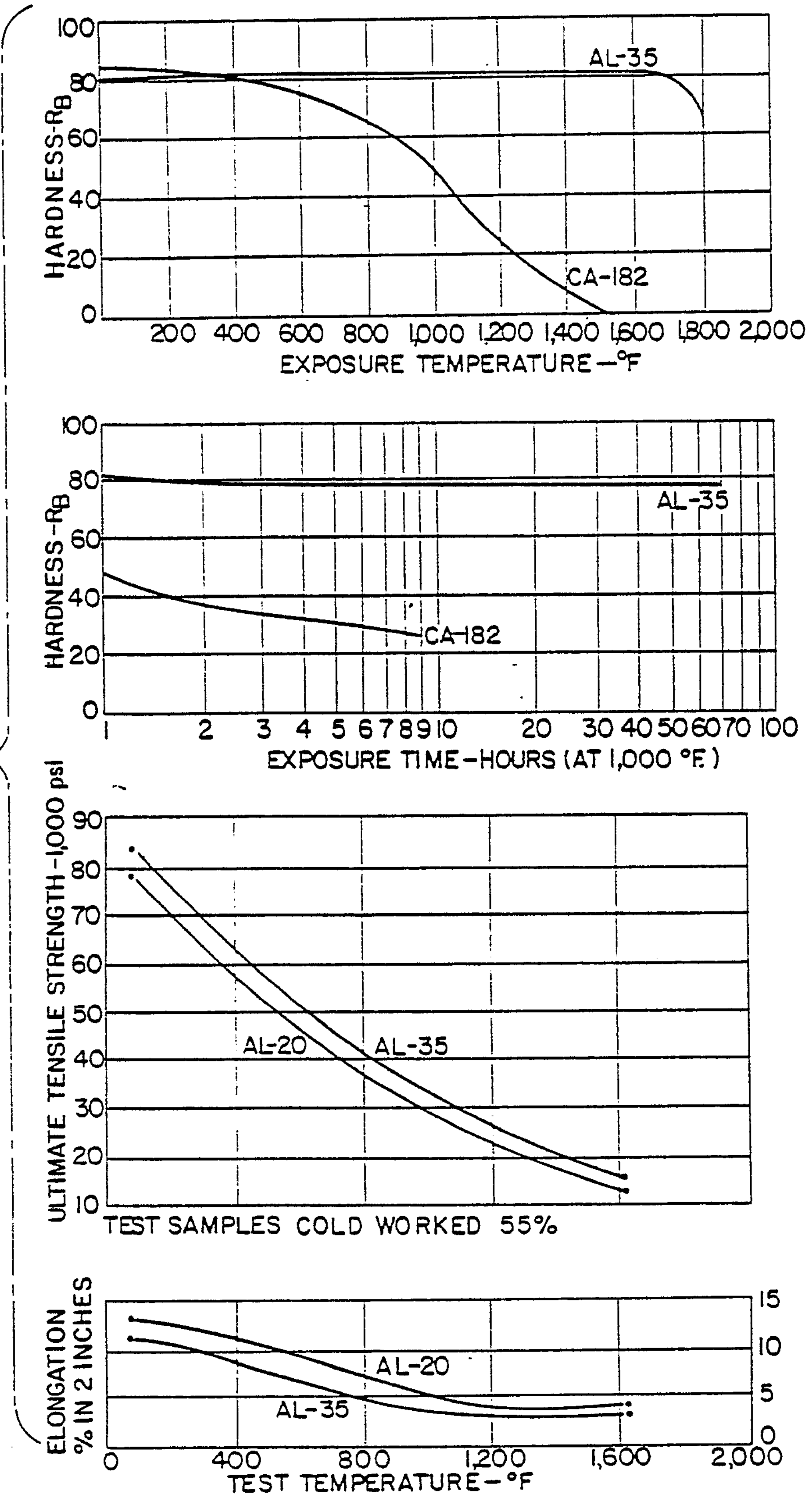


FIG. 2


HARDNESS-R_B
100
80
60
40
20
0
AL-35
CA-182
200 400 600 800 1,000 1,200 1,400 1,600 1,800 2,000
EXPOSURE TEMPERATURE—°F
HARDNESS-R_B
100
80
60
40
20
0
AL-35
CA-182
1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 100
EXPOSURE TIME-HOURS (AT 1,000 °F.)
ULTIMATE TENSILE STRENGTH-1,000 psi
90
80
70
60
50
40
30
20
10
AL-20
AL-35
TEST SAMPLES COLD WORKED 55%
ELONGATION % IN 2 INCHES
15
10
5
0
AL-20
AL-35
0 400 800 1,200 1,600 2,000
TEST TEMPERATURE—°F