A COLLAGEN ENGINE: ITS DESIGN, CONSTRUCTION AND EVALUATION

by

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Submitted in Partial Fulfillment

of the Requirements for the

Degree of Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1968

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Department of Mechanical Engineering, May 17, 1968

Certified by. Thesis Supervisor

Accepted by. Chairman, Departmental Committee on Thesis
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ABSTRACT

Collagen, a protein fiber used by the mammalian body primarily as a stress-bearing component, has under certain conditions the property of shrinking to a fraction of its length and being able to return to approximately its original size. The shrinking of the fiber can be brought about by the wetting of the fiber with a concentrated solution of lithium bromide. The fiber can be restored to approximately its original length by diluting the salt solution. This thesis consists of the design, construction and evaluation of a simple prototype collagen engine. The engine will deliver useful mechanical work by the exploitation of this reversible shrinking phenomenon.
INTRODUCTION

Collagen is a protein fiber which serves the mammalian body primarily as a stress-bearing component. It is found in abundance in every part of the body to meet requirements of mechanical strength. Commercially, collagen is available as a very strong tough fiber.¹

The molecules of collagen are long and thin. The fiber contains two main types of bonds. Primary bonded atoms form long protein chains. The macromolecule is a triple helix built from three protein chains hydrogen bonded together. An applied stress causes protein chains to align with each other by breaking the hydrogen bonds. Once the chains have been straightened further elongation requires the stretching of the chains in opposition to the primary bonding forces.²

Collagen can occur in a normal or contracted state. The contraction can be induced by heating the fiber in water to approximately 70⁰C or by the use of chemical reagents. The contraction of the fiber in both cases is similar, the fiber contracting to about one third of its length, with lateral swelling.³ However, the chemical reaction is reversible while the thermal contraction is not. One possible theory which explains the contraction is that the macromolecular helices change from their almost straight aligned state to one of randomly oriented coils.⁴

The driving force behind this thesis was the
possible use of this contraction to deliver useful work. By alternating between the contracted and elongated states of the collagen an engine would be designed to deliver useful mechanical work. It would be possible to do this on a continuous basis, alternately wetting the fiber with salt and diluting solutions.

A schematic of the design used is shown on pages 7 and 8. The operational flow chart is on page 9. Useful shaft energy can be obtained by attaching a cam shaft to the beam. A schematic of one possible assembly to do this is on page 10.

It was possible to derive equations which approximate the movements of this design. The equations were based on results of the experiments carried out on the fiber and the mechanism. Calculations of the amount of energy available for useful work were derived. A theoretical derivation was made to account for the forces and energy produced by the engine.

A model of this engine was constructed. It has successfully run.
FIGURE 1
Schematic of Engine Design
FIGURE 2
Top View of Engine

FIGURE 3
Left End View of Engine
FIGURE 4
Operational Flow Chart

FIBER A in diluting solution and elongating
FIBER B in contact with LiBr saturated sponge B
and contracting
WEIGHT moving towards fiber B

WEIGHT moves past equilibrium point B
Beam moves

WEIGHT moves past equilibrium point A
Beam moves

FIBER A in contact with LiBr saturated sponge A
and contracting
FIBER B in diluting solution and elongating
WEIGHT moving towards fiber A
FIGURE 5
Energy Converter Assembly
EXPERIMENTS

Tests were conducted on collagen fibers to determine the force exerted while the fiber contracted in a lithium bromide solution. The fiber was contracted under various stresses. The length of the contracted fiber was observed. After each contraction the fiber was put into a diluting solution. The fiber was elongated under various stresses. The length of the fiber was measured. This length was called the elongation length. A fatigue study was made to determine if these lengths were constant over many contractions and elongations.

The mechanism used in Test 1 is shown in Figure 6. One end of a fiber of known length was tied to a weight. The other end was tied to a piece of string and the string was tied to an anchor. The size of the weight was varied. The assembly was moved from the bath of 8 molal lithium bromide solution to the diluting solution. This was done for each of the various weights. Five minutes were allowed for the fiber to reach a stable length. Measurements of the length of the fiber were made after each soaking. The fiber was taken out of the solution for measurement. The same test was conducted using an 11 molal solution of lithium bromide. This was Test 2.

A fatigue study using a constant weight was made. The fiber was moved from an 11 molal lithium bromide solution...
Assembly for Tests 1, 2, and 3
solution to the diluting solution and visa versa. This was Test 3 and was done for twenty cycles.

Test 4 was made in which two fibers were attached to each other by a string. The other ends of the fibers were attached to a rigid support as shown in Figure 7. An allowance for a contraction of 50% of the original length of one fiber was made before the string was fastened. One fiber was immersed in an 11 molal lithium bromide solution. The other fiber was in a diluting solution of water. A weight was attached to this fiber. After allowing five minutes for the fibers to reach stable lengths the assembly was removed from the baths. The lengths of the fibers were measured. The weight was then attached to the other fiber. The fibers were immersed in the other baths. The state of the system was alternated five times.
Collagen Fiber ————
String ————

FIGURE 7
 Assembly for Test 4
EXPERIMENTAL RESULTS

The fibers used in Test 1 and Test 2 both show elastic tendencies over the range of forces tested. In Test 1 for the elongated state of the fiber each gram weight extends the fiber 0.06 inches. For the contracted fiber each gram extends the fiber 0.03 inches. The ratio of the contracted length to elongated length slopes downward for increasing force. (Figures 8 and 9)

In Test 2 with the fiber in the elongated state each gram causes an extension of 0.06 inches. For the fiber in the contracted state each gram causes an extension of 0.03 inches. The ratio of contracted length to elongated length remains stable as force increases. There is a difference in the value of this ratio between Test 1 and Test 2. (Figures 8 and 9)

Test 3, the fatigue test, shows that there is no significant change in the reaction of the fiber over a period of twenty cycles.

In Test 4 the fibers were able to lift a 5 gram weight.

In the process of lifting a 5 gram weight by the contraction of the collagen fiber the amount of work done by the fiber (per inch length of elongated fiber pulled by a weight of 5 grams) equals: for Test 1, $6.0 \times 10^{-4}$ joules; for Test 2, $7.0 \times 10^{-4}$ joules; for Test 3, $7.0 \times 10^{-4}$ joules; and for Test 4, $5.0 \times 10^{-4}$ joules.

(15)
FIGURE 8
Force verses Ratio of Fiber Lengths

FIGURE 9
Force verses Fiber Lengths

(16)
EXPERIMENTAL CONCLUSIONS

1. The higher the molality of the lithium bromide solution the smaller the ratio of contracted length to elongated length at a given force.
2. The higher the molality of the lithium bromide the larger the amount of work done by the contracting fiber.
DESIGN CRITERIA OF ENGINE

Design criteria for the engine shown on pages 7 and 8 can be approximated (Fig. 10). For the weight to move the pulling force on the weight, $F_p$, must be greater than 0. It must equal the pulling force of the contracting fibers, $F_F$, minus the component of the gravitation force on the weight along the beam, $F_{wb}$, minus the resistive force of the sliding weight, $F_{rw}$, and minus the resistive force of the sliding string, $F_{rs}$. This can be stated by the equation

$$F_p = F_F - F_{wb} - F_{rw} - F_{rs} > 0 \quad (1)$$

From the geometry of the assembly

$$F_{wb} = F_w \sin \theta \quad (2)$$

The sliding weight resistive force can be stated by

$$F_{rw} = C_f F_w \cos \theta \quad (3)$$

Equations (2) and (3) can be substituted into equation (1) giving

$$F_p = F_F - F_w (\sin \theta + C_f \cos \theta) - F_{rs} > 0 \quad (4)$$

The other criteria equation is the torque equation. In order for the engine to function the amount of torque provided by the weight in the vertical direction must be greater than the resistive torques. This can be stated by

$$T_w > -T_b + T_e + T_f + T_s \quad (5)$$
FIGURE 10

Geometry of Engine
In this equation $T_w$ is the torque of the weight in the vertical direction, $T_b$ is the torque in the vertical direction due to buoyancy, $T_e$ is the torque of the engine in the vertical direction due to its weight, $T_f$ is the fluid drag torque in the vertical direction, and $T_s$ is the torque due to the surface tension of the lithium bromide solution on the sponge holding the fiber to the sponge.

From the geometry shown in Figure (10)

$$T_w = m_w g (d \cos \theta - (h + p) \sin \theta). (6)$$

Assuming that the part of the engine that moves through the water can be approximated by two cylinders of radius $r$, length $l$, and velocity in the vertical direction $V$, the drag coefficient, $C_d$ can be obtained. The equation for the drag force is

$$F_d = 2 C_d \rho \omega V^2 \pi r^2. \quad (7)$$

The drag torque can be then approximated by the equation

$$T_f = F_d L, \quad (8)$$

where $L$ is one half the length of the beam plus arms.

The torque supplied by the engine itself in the vertical direction can be stated as

$$T_e = m_e g p \sin \theta, \quad (9)$$

with $p$ and $\theta$ defined in Figure (10).

The buoyancy torque is created by the water that is displaced by the submerged arm. This torque can be approximated by
\[ T_b = -\rho_w v g L , \quad (10) \]

where \( \rho_w \) is the density of water and \( v \) is the volume of the water displaced by the arm.

Substituting equations (6), (7), (8), (9) and (10) into equation (5)

\[ m_w g (d \cos \theta - (h + p) \sin \theta) - \rho_w v g L + m_{eq g} \sin \theta + 2C_d \rho_w v^2 \tau^2 L + T_s . \quad (11) \]

The amount of energy the engine develops in moving from one state to the other is given by

\[ E_e = m_w g y , \quad (12) \]

where \( y \) is the distance that the center of gravity of the weight is lifted in the vertical direction. From Figure (10), it is seen that

\[ y = x \sin \theta , \quad (13) \]

where \( x \) is the distance the weight is pulled along the beam. Substituting equation (13) into equation (12)

\[ E_e = m_w g x \sin \theta . \quad (14) \]
CONSTRUCTION OF MODEL

The model shown in Figure (11) was constructed. The list of materials is contained in Table (1). The list of important parameters is contained in Table (2). The beam and arms, beam support, superstructure, and assembly supports were bent into the required shapes. All of the steel parts were soldered together. The razor edge hinges were soldered to the assembly supports.

Cut pieces of sponge were cemented to the tops of the jars. Holes were punched in the tops. The flow rate of the lithium bromide solution into the sponges was regulated by tightening or loosening the tops of the jars. This varied the pressure inside the jars.

One end of each collagen fiber was tied to a different anchor. The string was attached to each of the other ends. A slack length of 1 inch was allowed in the string to permit contraction of the fibers. The weight support was tied to the middle of the string. The weight was tied to the weight support with a piece of string.
FIGURE 11

Model of Collagen Engine
LIST OF MATERIALS FOR MODEL ENGINE

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor</td>
<td>1/16 in. diameter 1020 steel rod</td>
</tr>
<tr>
<td>Assembly support</td>
<td>&quot;</td>
</tr>
<tr>
<td>Beam and arms</td>
<td>&quot;</td>
</tr>
<tr>
<td>Beam support</td>
<td>&quot;</td>
</tr>
<tr>
<td>Slip point</td>
<td>&quot;</td>
</tr>
<tr>
<td>Superstructure</td>
<td>&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td>5 gram brass weight</td>
</tr>
<tr>
<td>Weight support</td>
<td>1/64 in. diameter steel wire</td>
</tr>
<tr>
<td>LiBr solution</td>
<td>11 molal</td>
</tr>
<tr>
<td>Cement</td>
<td>Dupont &quot;Duco&quot; Cement</td>
</tr>
<tr>
<td>Collagen fibers</td>
<td></td>
</tr>
<tr>
<td>Jars</td>
<td>4 Oz. glass jars, metal tops</td>
</tr>
<tr>
<td>Solder</td>
<td></td>
</tr>
</tbody>
</table>

TABLE (1)

PARAMETERS FOR MODEL ENGINE

\[ \begin{align*}
\theta &= 15 \text{ degrees} \\
h &= 0.58 \text{ inches} \\
p &= 0.15 \text{ inches} \\
d &= 0.35 \text{ inches} \\
x &= 0.80 \text{ inches} \\
\rho_w &= 1 \text{ gram/cm}^3 \\
m_e &= 15 \text{ grams} \\
\end{align*} \]

TABLE (2)
RESULTS

1. The model engine was successfully run for 19 hours before being stopped.

2. For the duration of the test the model averaged approximately one cycle every 6 minutes.

3. The amount of useful mechanical energy produced was $5.0 \times 10^{-4}$ joules/cycle.
DISCUSSION

At the time the weight reaches the equilibrium point the sum of all forces acting on the weight in the direction of the beam is 0. This can be stated by

\[ F_F - F_{wb} - F_{rw} - F_{rs} = 0. \]  \( \text{(15)} \)

Using the values from Table (9)

\[ F_{rs} = 1.2 \times 10^{-2} \text{ Nt.} \]  \( \text{(16)} \)

The total friction force on the weight, \( F_{rT} \), is

\[ F_{rT} = F_{rw} + F_{rs} = 3.6 \times 10^{-2} \text{ Nt.} \]  \( \text{(17)} \)

This value is approximately 75% of the force developed by the contracting fiber. Since energy is proportional to force the amount of energy dissipated by friction is about 75% of the available energy.

From the results of Test 4 the maximum amount of energy that could be made available per inch of elongated fiber length was \( 5 \times 10^{-4} \) joules. The fiber used in this model had an elongated length of 2 inches. The total amount of available energy was therefore \( 10^{-3} \) joules. The amount of energy available for useful work from Table (9) is \( 2.5 \times 10^{-4} \) joules. The friction loss of energy was about 75%. This agrees with the estimate made using force considerations.

At the point where the engine starts to move the torque provided by the weight approximately equals the sum of all other torques acting in the vertical direction. This can be stated by
\[ T_w = -T_b + T_e + T_f + T_s \]  

Inserting values from Table (9) and solving for \( T_s \)

\[ T_s = 1.2 \times 10^{-4}\text{ Nt.-M.} \star \]  

The amount of torque presented by the surface tension of the sponge is a significant value to the operation of the engine.

\* \( \text{Nt.-M.} = 10^7 \text{ dyne cm.} \)
REMARKS AND RECOMMENDATIONS

Friction plays a very important part in the operation of this engine, using up 75% of the energy and 75% of the force generated by the contracting fiber. Little effort was made in this model to reduce this friction effect. By coating the slip points and the beam with teflon the friction effect could be greatly reduced. Oiling these surfaces would also help.

The surface tension of the lithium bromide solution on the sponge has a large effect on the operation of the engine. The surface tension of the diluting solution presents resistance to the movement of the engine. These resistances could be reduced by adding soap or another surface tension reducer to these solutions.

Increasing the concentration of the lithium bromide solution would increase the force and energy available. This was seen to be the case in Tests 1 through 4. This increase in concentration would also reduce the amount of time required for the engine to complete a cycle. More fibers could be added in parallel to those already on the engine. The addition of these fibers would produce a larger per cent of available energy to the engine than the first fibers. This would happen because they would not increase the friction as much as they would the force and energy.

Reducing the weight of the engine through the use of lighter construction materials would reduce the
moment of inertia. This would make the engine more responsive to the torque applied by the weight.

Some problem was noted in regulating the flow of the lithium bromide solution into the sponges. A more accurate means of adjusting the pressure inside the jars would be of help. A small valve could be attached to the jars to regulate this pressure.

One advantage of this type of engine is the fact that the lithium bromide solution does not become diluted after operation of the engine.
CONCLUSIONS

1. An engine was designed, constructed and operated.

2. Friction was found to play an important part in the operation of the engine.

3. It is possible to obtain useful mechanical work from an engine of this type.

4. The engine developed $5.0 \times 10^{-4}$ joules per cycle.
APPENDICES
**APPENDIX 1**

DATA FROM TEST 1

<table>
<thead>
<tr>
<th>Weight (gm)</th>
<th>Elongated Length (in)</th>
<th>Contracted Length (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.36</td>
<td>0.22</td>
</tr>
<tr>
<td>1</td>
<td>0.44</td>
<td>0.26</td>
</tr>
<tr>
<td>2.5</td>
<td>0.52</td>
<td>0.30</td>
</tr>
<tr>
<td>3.5</td>
<td>0.58</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>0.66</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**TABLE (3)**

DATA FROM TEST 2

<table>
<thead>
<tr>
<th>Weight (gm.)</th>
<th>Elongated Length (in.)</th>
<th>Contracted Length (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.42</td>
<td>0.21</td>
</tr>
<tr>
<td>1</td>
<td>0.51</td>
<td>0.23</td>
</tr>
<tr>
<td>2.5</td>
<td>0.60</td>
<td>0.27</td>
</tr>
<tr>
<td>3.5</td>
<td>0.65</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**TABLE (4)**

(32)
DATA FROM TEST 3

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>Fiber Length</th>
<th>Cycle Number</th>
<th>Fiber Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.64</td>
<td>11</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
<td></td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>1.64</td>
<td>12</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td></td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>1.67</td>
<td>13</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>4</td>
<td>1.64</td>
<td>14</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td></td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>1.67</td>
<td>15</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td></td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>1.70</td>
<td>16</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>7</td>
<td>1.65</td>
<td>17</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>8</td>
<td>1.63</td>
<td>18</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>9</td>
<td>1.64</td>
<td>19</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>10</td>
<td>1.63</td>
<td>20</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td></td>
<td>0.73</td>
</tr>
</tbody>
</table>

* First length in cycle is elongation length, second length is contraction length.
+ Lengths are given in inches.

TABLE (5)
DATA FROM TEST 4

Weight = 5 grams

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>Length of Fiber 1 (in.)</th>
<th>Length of Fiber 2 (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.54</td>
<td>0.90</td>
</tr>
<tr>
<td>2</td>
<td>0.90</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>0.89</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
<td>0.54</td>
</tr>
<tr>
<td>5</td>
<td>0.54</td>
<td>0.90</td>
</tr>
</tbody>
</table>

* In odd numbered cycles fiber 1 is contracted and fiber 2 is elongated. In even numbered cycles fiber 1 is elongated and fiber 2 is contracted.

TABLE (6)
DATA FROM MODEL ENGINE TEST

Engine was run for 19 continuous hours before being stopped. Cycle times were taken at intervals during operation period.

<table>
<thead>
<tr>
<th>Timing Test Number</th>
<th>Cycle Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 minutes</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>6</td>
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<td>8</td>
<td>5</td>
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<tr>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

TABLE (7)
EXPERIMENTAL CALCULATIONS

The ratio of contracted length to elongated length at a given force for the fibers used in Test 1 and Test 2 are given below: Table of Force and Ratio of Lengths

Test 1

<table>
<thead>
<tr>
<th>Force</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 gr.</td>
<td>0.61</td>
</tr>
<tr>
<td>1</td>
<td>0.59</td>
</tr>
<tr>
<td>2.5</td>
<td>0.58</td>
</tr>
<tr>
<td>3.5</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Test 2

<table>
<thead>
<tr>
<th>Force</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
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</tr>
<tr>
<td>2.5</td>
<td>0.45</td>
</tr>
<tr>
<td>3.5</td>
<td>0.46</td>
</tr>
<tr>
<td>5</td>
<td>0.47</td>
</tr>
</tbody>
</table>

TABLE (8)

The distance, \( d \), through which a 5 gram weight is carried for each inch of elongated length is given by the relationship

\[
d = \frac{\text{elongated length} - \text{contracted length}}{\text{elongated length}}.\]

The work done by the fiber in moving the weight this distance, \( E \), can be stated by the relationship

\[
E = m_wg d.
\]

This equation when applied to Test 1 through Test 4 yields the following results:

for Test 1, \( E = 6 \times 10^{-4} \) joules;

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for Test 2, $E = 7 \times 10^{-4}$ joules;
for Test 3, $E = 7 \times 10^{-4}$ joules;
for Test 4, $E = 5 \times 10^{-4}$ joules.
CALCULATIONS

The following approximations are made:

\[ V = 10 \text{ cm./sec.}, \ L = 3.5 \text{ inches} \]
\[ C_d = 2.5 \]
\[ C_f = 0.5.6 \]

Using these approximations and the data from Tables (1) and (2), the values calculated for the equations contained in the Design Criteria of Engine section are: Calculations for Model Engine

\[ F_F = 4.9 \times 10^{-2} \text{ Newtons}, \]
\[ F_{ wb} = 1.3 \times 10^{-2} \text{ Nt.}, \]
\[ F_{ rw} = 2.4 \times 10^{-2} \text{ Nt.}, \]
\[ T_w = 1.8 \times 10^{-4} \text{ Nt.-M.}, \]
\[ T_e = 1.5 \times 10^{-4} \text{ Nt.-M.}, \]
\[ T_f = 7.2 \times 10^{-6} \text{ Nt.-M.}, \]
\[ T_b = 9.9 \times 10^{-5} \text{ Nt.-M.}, \]
\[ E_e = 2.5 \times 10^{-4} \text{ Joules} \]

TABLE (9)
APPENDIX 2

Materials which exhibit rubbery behavior are those made of long chain molecules in which the chains are cross linked at various intervals. In the elongated state, the portions of the chains between points of cross linking are randomly coiled. They change rapidly from one coiled configuration to another. When the chain is contracted by its reaction with a salt solution, as collagen is when put into contact with lithium bromide, the distance between cross links decreases. The number of possible coiled configurations is thus increased. This leads to an increase in entropy.

The kinetic theory of rubber elasticity helps to explain the highly recoverable deformation possible in elastomers such as collagen, due to chemical reactions. The deformation of an elastomer in this theory is analogous to the compression of an ideal gas. Assuming that the force exerted by the collagen as it contracts is constant, Gibbs equation combined with mechanical energy consideration leads to the equation

$$\frac{dE}{TdS - p\, dV + \mu dN + FdL}$$

where $\mu$ is the chemical potential and $N$ is the number of ions of lithium bromide reacting with the fiber.

In rubbery materials Poisson's Ratio is approximately $\frac{1}{3}$. Thus tensile contraction does not cause an appreciable change in volume. If an ideal rubber is subjected to reversible isothermal contraction equation (20) predicts

$$F = - T(\partial S/\partial L)_{T, V, N} + (\partial N/\partial L)_{T, V, S}. \quad (21)$$
**SYMBOLS**

- $C_d$ - Drag coefficient
- $C_f$ - Friction coefficient
- $d$ - Distance measured from center of beam
- $E$ - Work done by fiber
- $E_e$ - Energy developed by engine
- $F_d$ - Drag force
- $F_F$ - Pulling force of contracting fiber
- $F_P$ - Resultant pulling force on weight
- $F_{rs}$ - Friction resistant force of string on slip point
- $F_rT$ - Total friction force
- $F_{rw}$ - Friction resistant force due to sliding weight
- $F_w$ - Gravitational force on weight
- $F_{wb}$ - Component of $F_w$ along beam
- $g$ - Gravitational constant
- $h$ - Distance from beam to center of gravity of engine
- $m_e$ - Mass of engine
- $m_w$ - Mass of weight
- $N$ - Number of ions reacting with fiber
- $p$ - Distance from pivot point to c.g. of engine
- $P_o$ - Pressure
- $S$ - Entropy
- $T_o$ - Temperature
- $T_b$ - Torque due to buoyancy in vertical direction
- $T_e$ - Torque of engine in vertical direction
- $T_f$ - Drag torque in vertical direction

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$T_s$ - Resistant torque of sponge in vertical direction due to surface tension

$T_w$ - Torque in vertical direction due to weight

$v$ - Volume of water displaced by beam

$V$ - Velocity of engine in vertical direction

$V_o$ - Volume

$x$ - Distance weight moves along beam

$\rho_w$ - Density of water

$\theta$ - Angle beam makes with horizontal

$\mu$ - Chemical potential

TABLE (10)
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1 Fiber donated by Dr. Richard Kronenthal, Ethicon Inc., Sommerville, N.J.


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