Mechanical Testing System Coupled with an Environmental Chamber for Interpenetrating Networks and Hydrogels

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ABSTRACT

Interpenetrating networks (IPNs) and hydrogels have many biomedical applications, such as tissue scaffolds and drug delivery systems, requiring a wide range of mechanical properties. These properties are dependent on their chemical composition, as well as the temperature and pH of their surroundings. The goal of this project is to design a testing system(s), which will allow researchers to identify the stress-strain relationship and creep under varying temperatures and pH levels. This semester, our design efforts were focused on completing the creep testing system. Future work may include further prototype testing, modification, and validation.

1. INTRODUCTION

Interpenetrating networks (IPNs) are formed by combining two or more different macromolecules in an intertangled structure (i.e. a gelatin and a polymer chain). These molecular structures can be formed through photopolymerization allowing for the conversion of photoreactive solutions into gels or solids under varying physiological conditions. Hydrogels are produced by cross-linking gelatin backbones to different chemicals (i.e. gelatin and glutaraldehyde), and does not involve a photoreactive procedure. Hydrogels are excellent in helping to create or maintain a moist environment, and provide absorption, desloughing and debriding capacities to necrotic and fibrotic tissue [1]. Despite these desirable properties, many hydrogels, like those used by our client, involve the use of toxic cross-linkers, such as glutaraldehyde-fixed agent. This makes IPNs more suitable than hydrogels for biomedical applications, such as drug delivery, tissue engineering scaffolds, and wound healing. In the past, our client's research has focused on using gelatin and poly(ethylene glycol) (PEG) diacrylate (PEG-dAc) [4, Appendix F] as the two main components in the IPN formulation. For the purpose of clarity, IPNs and hydrogels will both be referred to as "gels" for the duration of this paper.

Although gels have been extensively used in biomedical research, there is limited published work that presents findings on the physical changes of gels in response to specific environmental conditions, and how these changes affect the specific gels' biofunctions and applications [2]. Because knowledge of the mechanical properties of biomedical gels allows researchers to evaluate the material intended for a particular application [3], an understanding of the mechanical characteristics of gels is essential. Thus, the overall goal of this project has been to design a testing system(s) that will be used to elucidate the tensile and creep properties of gels in response to changes in their environment, such as pH and temperature.

During the two preceding design courses (BME 301 and BME 400), efforts were focused toward the development of a stencil procedure and an environmental chamber to be used for tensile testing with the Instron 1000 material testing system. A thorough background of the project and a complete recount of previous design proceedings can be found in the design team's final paper for BME 400 [4]. The primary focus of the BME 402 design team was to further develop a creep-testing system to test the viscoelasticity of the gels, which is reflected in this paper.

Creep tests are performed in a distinct manner from tensile tests, and provide additional information about a gel's mechanical properties. Specifically, a creep test records the plastic deformation of a material under a constant load over time, whereas a tensile test induces a constant rate of elongation, and records the resulting stress within the specimen. A creep test shows the plastic deformation of a material. Both viscoelastic (creep) and tensile properties for a given material will depend greatly on the surrounding environment and applied load. In particular to creep testing, certain materials may not exhibit creep at absolute temperatures below one-half of their melting point [5].

To perform a creep test of a gel, a constant tensile load is applied to a specimen, and the elongation of the specimen is measured over time. The test is usually performed to the point of failure of the specimen using a relatively light load (0-500 g), so the duration of the test can often be notably long (30 minutes – 24 hours or longer).

Creep testing machines are traditionally composed of five main components: a chamber, a pair of grips, a loading apparatus, and an extensometer. In general, there are two fundamental design concepts for loading the material: the sample can be loaded from the bottom, by a suspended weight; or the sample can be loaded from the top using a lever or pulley system with an attached weight.

Currently, there are no commercially available material testing systems that perform creep tests on soft biomaterials, like gels. Our client, Dr. Kao, is interested in researching the creep properties of gels and consequently must obtain a device with which these properties can be investigated.

2. DESIGN OBJECTIVES

The client, Prof. Weiyuan John Kao, is a professor in the School of Pharmacy and also has an appointment in the College of Engineering’s Department of Biomedical Engineering, both at the University of Wisconsin-Madison. Prof. Kao is interested in learning more about the following mechanical properties of gels: the dynamic stress-strain relationship, creep, and the yield and ultimate stresses and strains. He would also like to observe these properties under varying temperature (37 ± 3°C) and pH levels (4.5–8), which mimic physiological conditions. These environmental factors are critical in affecting the mechanical and chemical properties of biomedical materials. Research has shown that gels whose surroundings undergo changes in pH and temperature, often degrade, exhibit changes in swelling, and change their mechanical strength [5]. These physical modifications of the gels are also dependent on their own chemical composition. Therefore, our client will test gel specimens of different chemical composition and under varying environmental conditions, in order to determine the effects on their mechanical properties.

The goals of the BME 402 design team consisted of completing the tensile testing portion of the project, and finishing the design and prototype construction of a creep testing system. To avoid confusion, all persons from Dr. Kao's lab involved in using the creep testing systems will be referred to as "researchers".

3. PAST WORK

3.1 Stencil Procedure

During BME 301 and BME 400, a stencil procedure was developed in accordance with ASTM standards. This procedure provides researchers with a clear set of instructions to fabricate a PDMS stencil, which is then used in the fabrication of dog-bone shaped gel specimens. Please refer to BME 400 Final Paper [4, Pages: 6-7, 9-11, and Appendices A, C, D, & H] for design details and background information regarding the stencil procedure.

3.2 Tensile Testing

Also, during BME 301 and BME 400, an environmental chamber was developed to provide a controlled, physiological environment during tensile testing of gels. The chamber was determined to be compatible with the Instron 1000 material testing system (Figure 1), as the design aimed to do. Testing of this chamber and the Instron 1000 was conducted, yielding unfavorable results for the continued use of the Instron 1000 in testing soft biomaterials. Please refer to BME 400 Final Paper [4, Pages: 7-8, 11-22, and Appendices B, F, & G] for design details and background information regarding tensile testing and the environmental chamber.

Figure 1. The environmental chamber was designed for use with the Instron 1000 material testing system, located at 1313 Engineering Hall Materials Testing Laboratory.

3.3 Creep Testing

Over the course of BME 400, a subset of the design team focused their efforts on designing a creep testing system. This design process consisted of: researching components of creep testing systems, including numerous extensometers; performing preliminary creep tests; and selecting a final design. A non-functioning prototype was constructed in accordance with the selected final design. The following includes a recount of the consideration of design parameters and specifications, and a full description of the final design selected for prototype construction. For further background information concerning preliminary creep testing and design alternatives, please refer to BME 400 Final Paper [4, Pages: 22-35, and Appendix E]. Please note that much of the original design has since been altered, and in many cases, contradicts what is included below from previous work.

3.3.1 Design Components

Creep testing will be performed in a creep chamber, which is separate from the environmental chamber for tensile testing, and which allows the gel specimen to be tested in a solution of desired pH (4.5-8) and temperature (37 ± 3ºC). The material of the creep chamber should be durable, non-corrosive, easy to manufacture, and transparent in order to observe the sample during testing. In addition, the creep chamber must maintain a relatively constant temperature (± 3°C) over the course of a creep test, which may be more than 24 hours. Therefore, the creep chamber must also be insulating, and may require a heater and/or circulation mechanism to maintain an evenly distributed temperature. The pH should not vary by more than ± 0.5 pH units for the duration of a test. A system may be required to either change the buffer during testing, or adjust the pH to keep it at a constant level. The creep chamber must allow for researchers to adjust the sample inside the chamber prior to testing. Alternatively, a removable grip apparatus could be designed to address this requirement. The sample would be aligned outside of the creep chamber, and then secured inside the chamber just prior to a creep test. As mentioned earlier, a typical creep testing system is composed of five components: a chamber, a pair of grips, a loading apparatus, and an extensometer.

The grips, which are also separate from those used for tensile testing with the Instron 1000 material testing system, function by holding the sample in place during testing. The samples should be gripped at the bottom and top of the gel specimen, in the same manner as the tensile testing system, and should allow for fracture at gauge length. The grips must not slip once they are attached to the gel, and they must remain in the same plane during testing, to prevent any torque in the sample. Because the grips will be immersed in pH solution during testing, they must also be made of a non-corrosive material, or be inexpensive, so they can be discarded before rusting occurs.

A constant load must be applied to the sample in order for creep properties to be measured. This can be accomplished by suspending weights from the bottom of the sample (Figure 2, left), or by loading a lever or pulley system, which then applies an upward force to the top of the sample (Figure 2, right). The interface between the weights and the grip must have small to negligible creep properties, and must not apply shear force to the sample. This will ensure that change in displacement is due to the applied load and properties of the gel alone, and will eliminate any confounding variables, that may skew experimental results.

The extensometer is responsible for measuring the creep displacement of the gel. It should be capable of taking measurements for more than 24 hours, and not interfere with the creep test itself.

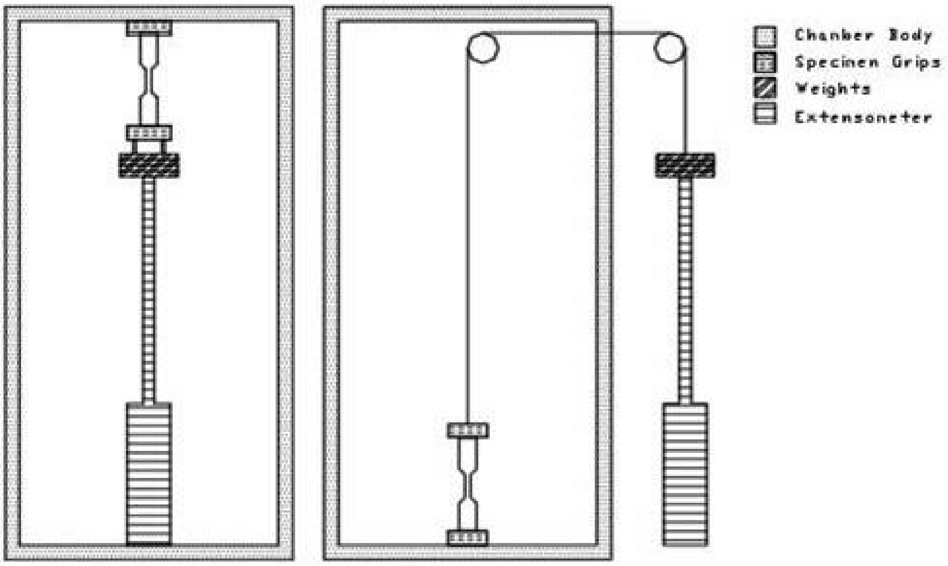

Figure 2. The components of the creep testing system: chamber, grips, loading apparatus, and extensometer. The sample in the left testing system is loaded from the bottom, whereas the sample in the right testing system is loaded from the top.

3.3.2 Final Design

The final design of the creep testing apparatus consists of an LVDT, creep chamber, pulley assembly, analog to digital converter, a pair of grips, and weights. The LVDT will be located outside the chamber, and the sample will be loaded at the top, using a pulley system. The bottom grip will be attached to a 500g weight to oppose the theoretical maximum applied load, and prevent any displacement of this grip. The top grip will be attached to weights positioned outside of the chamber, via a pulley system. The core of the LVDT will be attached to the bottom of the weight rack. This design locates all of the electrical components of the system outside of the chamber. If the electrical components were positioned inside of the chamber, sealing or waterproofing would be necessary to prevent electrical shorts in the aqueous environment. Figure 3 is a three-dimensional rendering of the proposed design.

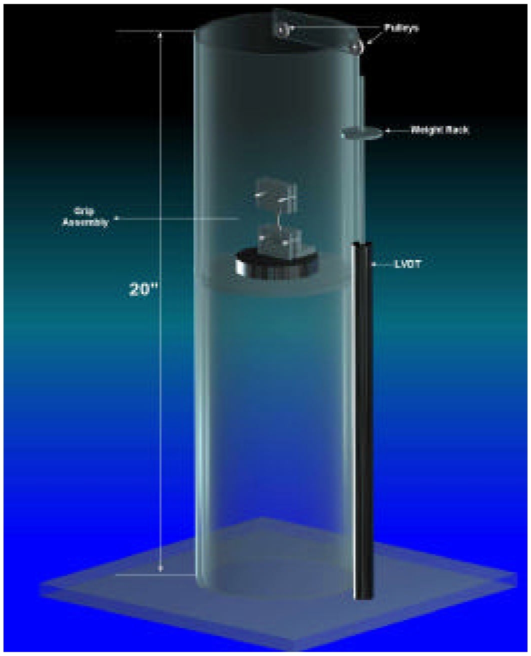

Figure 3. 3D rendering of proposed final design

3.3.2a LVDT

An LVDT, model number 75S2DC-2000SR, was selected and purchased from Sentech Inc. This transducer has a displacement measurement range of 0 to 4.000 inches and a DC output signal ranging from 1 to 10V. Complete specifications for this LVDT are available on the manufacturer's website at http://sentechlvdt.com/pdf/75S2DC.pdf. The main body of this LVDT is 13 inches tall. In order to eliminate friction from the travel of the core of the LVDT, it must be upright, as the core does not contact the transducer in this orientation.

3.3.2b Creep Chamber

The body of the creep testing chamber is constructed from a cylindrical shell of acrylic plastic purchased from www.mcmaster.com. The cylinder has an outer diameter of 6 inches and a wall thickness of 0.25 inches. Although a larger thickness is desirable to provide better insulation for temperature control, the next highest available thickness cylinder is roughly three times more expensive, and it was decided that the extra insulation was not worth the extra cost. In order to account for the length of the LVDT, the chamber must be raised from the level of the bench-top. A cylindrical shell of the same diameter and thickness is placed beneath the chamber for this purpose.

3.3.2c Pulley Assembly

Two pulleys are designed into the system to translate the downward force of the weights to an equal upward force on the top grip, and hence the gel specimen. The pulleys used were also purchased from www.mcmaster.com, part number 3434T12. Bill Hagquist recommended a nylon sheave with ball bearings for this application. A nylon pulley will have a lower moment of inertia than a metal one, and the ball bearings will decrease friction. The lowest available diameter was chosen to minimize the force required to rotate the pulley. If any force is required to cause rotation of the pulley, the force translated to the specimen will be less than the load applied. The two pulleys are "sandwiched" between two rectangular supports attached to the top of the chamber. A small screw between the two supports acts as an axle for the pulleys.

3.3.2d Analog to Digital Converter

An analog to digital converter (ADC) was included in the design to facilitate computerized data acquisition and logging. Since creep typically occurs slowly, manual data logging is impractical, as it would require the researcher to be present for the entire duration of the test (1hr – days). In selecting an ADC, four criteria were considered: resolution, conversion rate, signal range, and output type.

It was determined that a resolution of at least 10 bits is required to achieve a precision of 0.1 mm. There are 1016 divisions of 0.1 mm in 4 inches. A resolution of 10 bits gives 1024 measurement levels, which is satisfactory for the purpose of this system.

As previously discussed, creep processes are time dependent and usually occur very slowly. Therefore, the output signal of the LVDT is expected to have a very low bandwidth. Accordingly, measurements of displacement will only be taken at intervals of several minutes or more, and hence, the conversion rate of the ADC is not required to be very high. Most commercially available ADCs have conversion rates that well exceed the requirements for this creep testing system, so this does not limit our selection. Beneficially, this allows us to sacrifice a higher conversion rate for an ADC at a lower cost. The LVDT has an output of +1V to +10V. Therefore, the ADC have a compatible input range.

With these considerations in mind, the DI-154RS ADC from www.dataq.com was purchased. This converter has a 10 bit resolution, 240 Hz conversion rate, a ±10V input, and a RS-232 serial port output. The input voltage range is almost twice as large as the output range of the LVDT (+1V to +10V). In order to have a precision of 0.1mm, the output of the LVDT will have to be scaled and adjusted to the range of the ADC.

3.3.2e Grips

Small (~1 cm length) binder clips that have been modified for testing serve as grips for the creep testing system. However, because there is much variability in the stiffness of binder clips that are otherwise identical to each other, our client did not approve of this selection. An alternative to using binder clips would be to purchase a pair of the Instron 2711 grips, which were used in the tensile testing system. A less expensive solution will also be considered.

3.3.2f Weights

A set of laboratory weights ranging from 0.5g to 500g was obtained from the University of Wisconsin–Madison Physics department. The weights are circular with a radial slot on one side that allows them to be easily added to and removed from a rack. Figure 4 below, is a diagram of one weight. A thin rod of acrylic, with a diameter of 4.8mm (3/16”) is attached to the core of the LVDT. A small disk of radius 30 mm is attached to the rod, and will serve as a base upon which the weights will be placed (Figure 4).

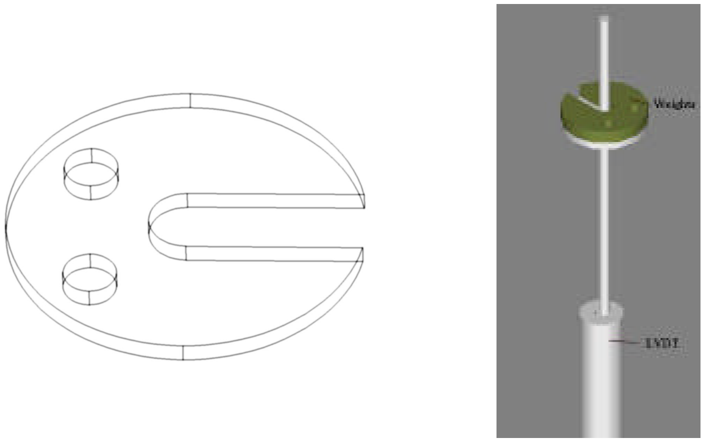

Figure 4. Left: Illustration of one weight obtained for the creep testing system. Right: The weight is added to the rack, which is attached to the LVDT.

4. CURRENT PROGRESS

4.1 Tensile Testing

Last semester, the mechanical properties of 4G6P and 6G4P (i.e. 4G6P indicates gels containing 40 weight percent gelatin and 60 weight percent PEGdA and vice versa) were unable to obtain using the Instron 1000 material testing system [4, Appendix F]. The issue of sensitivity has been brought up several times, as it seems that the Instron 1000 does not have load cells sensitive enough for gels. Table 1 summarizes some of the characteristic loads that were obtained when using the Instron 5548 [7], which helped us address this issue.

Table 1. Tensile testing results using Instron 5548. Young's Modulus includes mean ± stand. error.

Sample	Time (hr)	Range of Load Sensitivity (N)	Young's Modulus (MPa)
6G4P-pH 7.4	2	0	0
4G6P-pH 7.4	2	0.003 - 0.20	0.59±0.03
6G4P-pH4.5	2	0	0
4G6P-pH 4.5	2	0.003 – 0.21	1.55±0.13

The tensile group met with John Dreger (1313 Engineering Material testing laboratory director) regarding the accuracy of the Instron 1000 material testing system. According to the literature, +/- 1.0% of the applied force or 0.2% of the maximum deflection (whichever is greater) is listed as the error for the 44.48 kN load cell. To determine the accuracy of the machine, one must use a 5 kN weight to calibrate, and then apply very small weights (10 N, 50 N, 100 N) and record the readout on the digital display. The deflection on the chart can be then measured. Essentially, with the load cell we used, and setting the Instron 1000 to its most sensitive setting, the smallest force that it can differentiate (theoretically) is 10 N. This means that the smallest force that the Instron 1000 can differentiate is greater than the load of the sample under test, as established by testing on the Instron 5548 material testing system (Table 1).

Other issues with the Instron 1000, which may worsen the system's sensitivity problems include: unstable grips that cause torsion; a chart recorder that does not work properly; and the lack of a digital data-logging system.

Therefore, it was concluded that the Instron 1000 does not differentiate between small changes in force, while samples are in controlled environmental conditions. Upon meeting with our client, it was agreed that although we the Instron 1000 is not sensitive for gels, it may be adequate to test other biological tissues.

4.2 Creep Testing

4.2.1 Testing Chamber Development

The design team began this semester with a critical evaluation of the creep testing system prototype developed during BME 400. This evaluation revealed the following design issues and possible solutions.

4.2.1a Environmental Chamber

The environmental chamber of the creep testing system consisted of an acrylic cylindrical tube with an outer diameter of 6 inches. To set up a creep test experiment, the researcher would have to reach both hands into the chamber to load the gel sample into the grips. This would be extremely difficult due to the small space.

To solve this problem, the acrylic cylindrical tube was replaced by the tensile testing environmental chamber previously developed for use with the Instron 1000. The chamber was modified so it could be secured on the creep testing base by fitting over two steel pins (~ 1" length) that were permanently embedded in the base. Finally, an acrylic cylinder (2" Ø, 6" length) was secured to the creep testing base. This cylinder has two functions: to form a seal with the O-ring of the chamber's inner cylinder; and to provide a surface for mounting the bottom grip. This setup allows the environmental chamber to be easily installed and removed.

4.2.1b Grips

Each grip had two sets of one screw and one nut, which required tightening to secure the gel. The fact that the hardware was small (nuts ~ 4mm Ø) and that both sets must be adjusted simultaneously made for tedious adjustment.

These grips were replaced with plastic tube clamps purchased from McMaster-Carr online catalog (http://www.mcmaster.com, part #5192K12). This design allows for an individual researcher to secure and align a sample by adjusting only one knob instead of two small screws/nuts. Additionally, these grips are inexpensive, corrosion-resistant, and easily replaceable. Figure 5 is an illustration of a tube clamp.

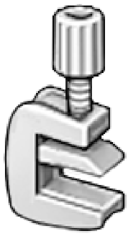

Figure 5. Tube clamp purchase from McMaster-Carr online catalog. Picture taken from **www.mcmaster.com**, catalog page 151.

4.2.1c LVDT Stability

The LVDT must be in a perfectly upright position, so that the core will not touch the inside of the LVDT. This will prevent any frictional force and experimental error. The original creep testing system design did not address this specification.

A cylindrical hole (0.75" Ø) was machined in an acrylic cylinder (3" Ø, 4" length.) using a lathe machine, to address this issue. The LVDT was placed inside the hole, and the cylinder was then secured to the creep testing base with two screws to ensure its perpendicularity. Figure 6 is a three dimensional rendering, showing the LVDT in this mounting cylinder.

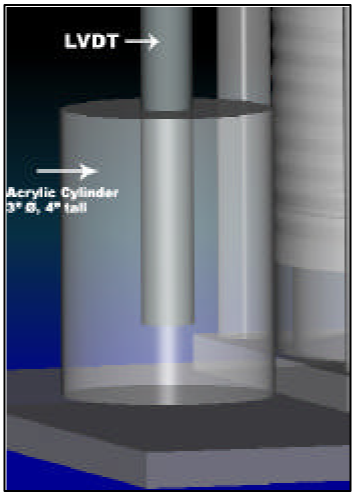

Figure 6. 3D illustration of LVDT and mounting cylinder.

4.2.1d Balancing of LVDT Core & Top Grip

The difference between the weight of the LVDT core and the weight of the top grip must be accounted for by adding weight to the grip side of the pulley assembly. This will ensure that the load applied to the sample is equal to the weights added to the weight rack. No counterbalance was present in the original design.

To counterbalance this difference in weight, a small aluminum weight was machined and tied into the pulley line. The weight of the LVDT core, including the acrylic rod attachment and weight rack, is 24.90g. The weight of the top grip is 5.59g. The counterweight was machined to weigh 19.27g, which is 0.04g less than the target weight of 19.31g. Figure 7 shows the setup of the grips with the counterweight attached.

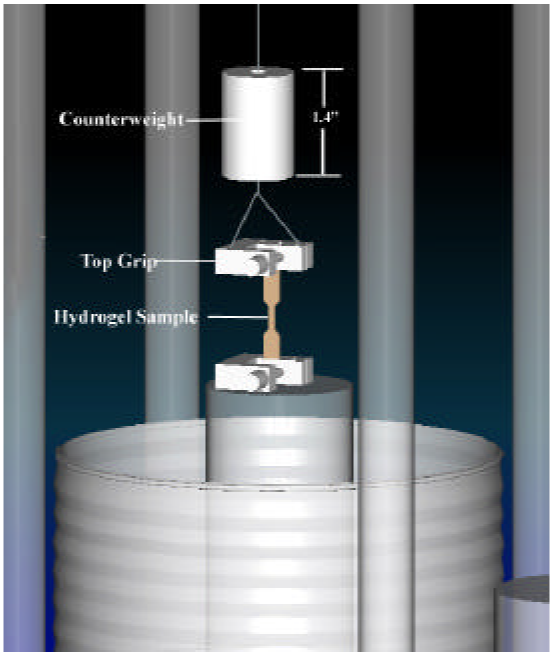

Figure 7. Attachment of counterbalance weight to pulley line and top grip.

Figure 8 below displays 3-D renderings of the old design and the new design for comparison.

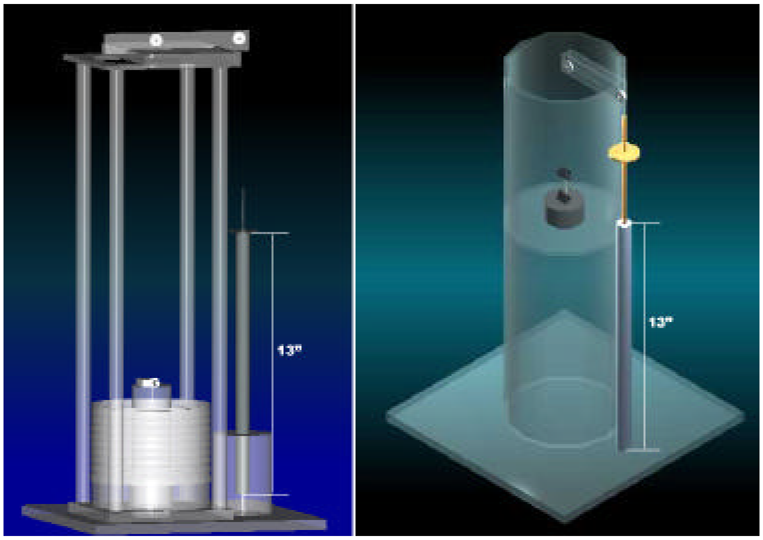

Figure 8. Left: New design incorporating tensile testing environmental chamber. Right: Original design with acrylic cylindrical tube.

4.2.2 Data Acquisition

A DI-194RS data acquisition kit, purchased from Dataq Instruments (Akron, OH) was used to record the voltage output from the LVDT during creep testing. The DI-194RS module, shown in Figure 9, plugs into a PC serial port, and digitizes the analog signal from the LVDT. The data acquisition kit includes software with a waveform browser to observe the output signal. The signal can be calibrated before each use to convert voltage into position. Additional software from Dataq, called WinDaq/XL, was used to deposit the data into Microsoft Excel® in real time. An AC-DC power module, purchased from Mouser Electronics (Mansfield, TX) was used during creep testing to apply 24V to the LVDT. See Appendix B for instructions on how to use the WinDaq software to run a creep test.

Figure 9. DI-194RS module: serves as an interface between LVDT and PC.

4.2.3 Preliminary Creep Testing

One creep test was performed on a gel in 40°C distilled water. The 4G6P sample was made approximately eight hours prior to testing, and stored in an airtight container over the interim. Figure 10 is a picture of the testing set-up, before the distilled water was added to the chamber.

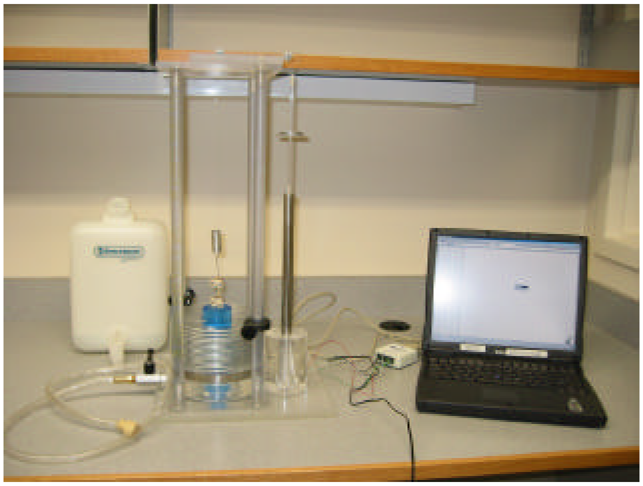

Figure 10. Creep Testing System setup with ADC and laptop for data logging.

The elongation of the sample versus time is plotted in Figure 11. The sample elongated approximately 2.3 mm, over 140 minutes.

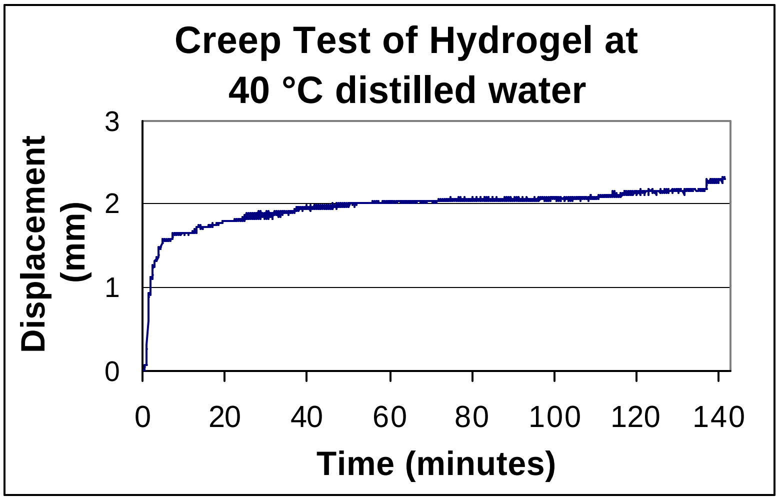

Figure 11. Elongation of gel versus time. The creep of the gel was tested in 40 °C distilled water.

5. FUTURE WORK

The creep testing system will need further testing and validation. A new BME 400 team will continue working on this project next fall. The team leader has been informed of several aspects that need to be addressed. The first one is the addition of a temperature regulation system. Given that creep tests have varying and unpredictable time durations, it is advised that a temperature regulating system is added, so that temperature remains constant during the duration of any creep test. Secondly, the buoyancy of certain materials in water will need to be considered to adjust the counterweight balance in the pulley-grip system. Lastly, to verify the creep system's validity, it is recommended that researcher study the creep properties of a known material determined by other experiments, and compare the results of that obtained using the creep testing system.

6. ETHICS AND SAFETY ISSUES

The most significant ethical dilemma associated with this project is that of data manipulation and forgery, as part of the creep testing system. The data acquisition system records data constantly. Given this record option, it should be made clear between the user and the research advisor to have a consistent way on identifying non- and meaningful-data. Eliminating data without prior consideration it's considered an unethical decision, and is subject to penalties from research journal review boards.

For any mechanical testing using physiological environmental conditions, given that 37^{o}C is normal body temperature, acute exposure to solutions with this temperature during setting up of the experiment, caused by any unforeseen spills, would not be harmful to the researcher. However, for longer exposure to solution at temperatures above 25.5^{o}C, the body begins to absorb heat. It's important to mention that the body will only adapt to changes as great as 20 % within the comfort range (mouth to foot, 26.7–37.8 ^{o}C) through evaporative cooling [6].

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APPENDIX A

The Product Design Specification of the Mechanical Testing System Coupled with an Environmental Chamber for Hydrogels:
Creep Testing System

Charlie Haggart, Gabriel Martínez-Díaz, Darcée Nelson, and Mike Piché

Last updated: 5/2/02

Function: To measure creep properties of hydrogels in a pH and temperature controlled environment.

Client Requirements:

- Stand-alone system to measure creep properties of hydrogels.
- Maintain the pH of a solution from 4.5-8.
- Maintain the temperature of a solution at approximately 37 ± 3 ºC.

Design Requirements:

1. Physical and Operational Characteristics

a. *Performance Requirements:* The creep testing system should be capable of being used for consecutive creep tests. Once the creep test has started, the system should require no observation/maintenance until after test is over.

b. *Safety:* The chamber should be securely sealed to prevent potentially acidic, basic, very hot, and/or very cold solutions from escaping and causing injury to both the user and any surrounding lab equipment or electronics. Gloves should be worn when handling the solutions to be used in the chamber. Oven mitts should be worn if the solution to be used is very hot.

c. *Accuracy and Precision:* The temperature should not vary more than ± 3 ºC of the desired temperature, and the pH should not vary by more than ± 0.5 pH units. Extensometer must be as accurate to 0.01 mm and as precise as possible.

d. *Life in Service:* The chamber should maintain the temperature and pH of a solution over a time period of one creep test (approximately 1 hour-2 days). The acquisition system should record displacement at least once every second during this time.

e. *Shelf Life:* The testing system should be stored in a cool, dry place. It should be covered to prevent dust, dirt, etc. from collection on the surface.

f. *Operating Environment:* The chamber is to be used at room temperature, local atmospheric pressure and humidity. It will be exposed to solutions of 4.5-8 pH and temperatures of 37 ± 3 ºC. As the sample breaks, the weight rack will contact the top of the LVDT with a force of approximately 0.0098 N (1 gram weight) to 4.9 N (500 g weight), although its likely that most hydrogels will exhibit creep under lighter loads than 500 g. The testing system will be handled by lab researchers.

g. *Ergonomics:* The testing system should enable the researcher to have adequate access to the sample before the creep test. The space surrounding the sample should have a diameter of at least 10 inches, so the sample can be adjusted by hand. The testing system should sit on a standard lab bench, to minimize reaching of the researcher during test preparation.

h. *Size:* The testing system should accommodate for tripling of hydrogel sample length (4 inches) during creep testing.

i. *Weight:* The chamber should be less than 33 lbs, as recommended by the Human Factors Design Handbook [6].

j. *Materials:* The materials of the chamber should be durable, transparent, easy to manufacture, affordable, insulating, and able to withstand changes in temperature from 37-40 degrees Celsius and changes in pH from 4.5-8. Materials immersed in solution should have high corrosion resistance, and high density to decrease buoyancy. The connection between the LVDT core and the weight rack must be a non-ferromagnetic material, as this will interfere with LVDT operation.

k. *Aesthetics, Appearance, and Finish:* The chamber should have a transparent shell so that the user can see the hydrogel sample inside. It should also have no sharp edges or extrusions.

2. Production Characteristics

a. *Quantity:* One creep testing system is needed.

b. *Target Product Cost:* See Appendix C.

3. Miscellaneous

a. *Standards and Specifications:* Testing system should accommodate hydrogel samples of ASTM approved dog-bone shape.

b. *Customer:* See client requirements.

c. *Patient-Related Concerns:* N/A

d. *Competition:* None commercially available.

APPENDIX B

WinDaq Software Instructions for Creep Testing

1. Connect all hardware (DI-194RS module, LVDT, AC-DC transformer, PC)
2. Under start menu, select WINDAQ? WinDaq 194.
3. Under view menu, select format screen? 1 waveform.
4. Under edit menu, select low calibration. Move LVDT core to zero position. Enter 0.00 as Low Cal Value, and mm as Engr. Units.
5. Under edit menu, select high calibration. Move LVDT core to maximum displacement position. Enter 101.6 as High Cal Value, and mm as Engr. Units.
6. Under edit menu, select sample rate in S/s.
7. Open Microsoft Excel.
8. Press the play button (circle) on the WinDaq/XL toolbar.
9. Select DI-194 Serial Device (xx) in the pop-up window.
10. Do not enable looping.
11. Select A1 as the starting cell.
12. Select 32000 rows to fill.
13. Press start.
14. Close Microsoft Excel before the WinDaq software when finished.

APPENDIX C

BME 402 Cost Summary			
Item	Units	Unit Cost ($)	Total Cost
3/16"Ø x 1" Steel dowel pin	4	0.15	0.6
Plastic Tube Screw Clamp (1/4")	4	3.25	13
Silicone Foam Rubber Strip (1/2" x 15')	1	12.74	12.74
Fluorescent Cast Acrylic (2"Ø)	0.5	32.72	16.36
Clear Acrylic Disc (2"Ø x 0.118" thick)	1	1.59	1.59
Clear Acrylic Disc (3"Ø x 4" thick)	1	16.25	16.25
Stainless Steel Teflon Coated Wire Rope (ft.)	5	1.73	8.65
Polycarbonate Rod (3/4"Ø x 2' long)	4	9.61	38.44
Crimp-on Spade Std. #6 Stud (pack)	1	5.43	5.43
Stainless Steel (1/4") flat head bolt	4	0.17	0.68
1/4 - 20 x 3/2" FHMS	2	0.08	0.16
1/56 Drill Bit	1	0.53	0.53
Brass J-Hook w/ cap (package) - 0.072" wire	1	9.4	9.4
Sub Total (BME 402)			123.83
Total (BME 301)			1,470.00
Total (BME 400)			715.72
Total (Overall Project)			**2,309.55**