Welcome to the inaugural volume of *The Tower*.

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*The Tower* is an interdisciplinary research journal for undergraduate students at the Georgia Institute of Technology.

The goals of our publication are to:

- showcase undergraduate achievements in research,
- inspire academic inquiry,
- and promote Georgia Tech’s commitment to undergraduate research endeavors.

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COVER DESIGN

MERCEDA FUSIA  Undergraduate, Computational Media
People always remember their firsts—first step, first word, and, in our case, the first print journal. In celebration of printing the very first print journal, I feel that it is only appropriate to welcome our readership with a brief introduction of how we came to be.

*The Tower* was found by a group of research-passionate undergraduate students with guidance from supportive faculty members to showcase the undergraduate achievements in research and to inspire academic inquiry as well as to promote Georgia Tech’s commitment to undergraduate research endeavors.

As part of the Founding Editorial Board, Mark Youngblood, who served as the first Editor in Chief, and Dianne Palladino, who served as the first Associate Editor for Submissions and Review and proceeded to serve as Editor in Chief after Mark’s graduation, laid a strong foundation on which Yixiao Zou and I were able build this journal into what it is today. Yixiao joined us after Mark’s graduation. With his strong research background and sharp analytical skills, he was able to take the submission and review system that Dianne had initially established and put it into practice, jump-starting the submission and review process of this journal and setting it up for success in the future. Though he did not continue his position with the journal after serving as the Associate Editor for Submissions and Review for a year, he was an integral part of this journal’s history and I would like to sincerely thank him for his contributions. In addition to these three people, *The Tower* received a tremendous amount of support from various faculty members. I would especially like to thank Dr. Karen Harwell who worked with the journal as the Faculty Advisor, and other student organizations such as the Student Publications Board and its Manager, Mr. Donald Pitts.

I would also like to thank the current editorial board, staff members, faculty reviewers, and the authors for their amazing work and support for *The Tower*, as well as to congratulate them on their production of the very first print version of the undergraduate research journal at Georgia Tech. I look forward to another successful year working with this dedicated group of people, producing journals that I hope would be a great learning opportunity for those who are involved in any shape or form. It’s been a great experience working for this journal, and I urge you to read the reflections on working with *The Tower* by Mark and Dianne in the following pages.

Best,

CHUYONG YI  
EDITOR-IN-CHIEF, 2008-2009
One of my most rewarding experiences at Georgia Tech was participating in the undergraduate research program. Seeing practical applications of what I learned in class while contributing to a new area of knowledge helped me grow as both a student and an engineer. It is very exciting to see that student researchers at Georgia Tech will now have the opportunity to share their own experiences and publish their research in a peer-reviewed, printed journal on campus.

Over the last two years, I’ve eagerly watched *The Tower* develop from an exploratory proposal into its first printed edition. When I became involved with the journal in early 2007, the organizing committee consisted primarily of faculty with a few students providing input on the shape and goals of the publication. An early white paper on the journal stated that it would be used ‘primarily to promote undergraduate research on campus through the publication of an annual online journal’. Since that time, *The Tower*’s goals have grown to accommodate the considerable interest that students have shown on campus. With the release of its inaugural printed edition, Georgia Tech will join other peer institutions in producing a high quality, well-circulated undergraduate research journal. It is truly an exciting time for undergraduate research at Tech.

*The Tower*’s publication allows undergraduates to take part in an academic process typically encountered only after entering a graduate program. Students not only get the opportunity to plan, write, and defend a research paper, but can also play the important role of research reviewer. For those interested in further pursuing research through graduate school or industry, having participated in the publishing process will be a critical advantage over their peers.

There are many faculty, staff, and students who have committed countless hours towards making this publication possible. In particular I would like to thank our faculty advisor, Dr. Karen Harwell for her leadership and enthusiasm over the last two years. We have been very lucky to have her support and guidance during our formation.

I hope you enjoy this issue as much as we have enjoyed producing it over the last two years. Congratulations to the current staff of *The Tower* and I look forward to many editions to come.

**Mark Youngblood**

**Founding Editor, 2007**
It is exciting to see the first release of *The Tower* become a reality. Several years ago, when Dr. Harwell asked if I would be interested in joining a team that was investigating the possibility of starting a new undergraduate research journal at Georgia Tech, I was simultaneously intrigued and honored. After all, I had chosen Tech because of its strong emphasis on undergraduate research, and had certainly been impressed with the Institute’s commitment to that promise. Creating the journal seemed like the perfect opportunity to provide the Institute with a way to showcase the frequently superb research findings of undergraduates, to inspire students to get involved in research from early in their academic careers, and to promote the high quality of Georgia Tech’s undergraduates’ research skills to the community. It was my hope that, through this publication, research that was typically only known by the students’ departments would be made public knowledge, leading to more potential for interdisciplinary collaboration. For journal staff members and those who were interested in pursuing research as a career, the journal would also provide a unique opportunity to obtain first-hand experiences in the operational processes behind a peer-reviewed research journal. To be an integral part of creating such an instrument of pride for the Tech community was to me a perfect opportunity to leave a small legacy for its future, and I enthusiastically embraced the offer. It was by far the most valuable experience I had while at Georgia Tech, and I am honored to have participated.

I congratulate Chuyong and the rest of the Editorial Board on their hard work to take the journal from where it was when I graduated last May to this beautiful first print release. I also wish all of those involved in the future the pride and feeling of accomplishment that we all in the Georgia Tech community feel on this day. I am certain that *The Tower* will rapidly rise to be one of the prominent undergraduate research journals in the country, and I look forward to reading it regularly for many years to come.

**Dianne Palladino**
**Founding Editor, 2007–2008**
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MeMBL (α-methylene-γ-methyl-γ-butyrolactone) is a biomass-derived compound known to be polymerizable to make an acrylic material with a high glass transition temperature. Presence of a lactone ring in the structure of MeMBL can be opened to create a pathway to modification of a MeMBL polymer. This would expand the range of uses for poly(MeMBL) as a plastic. A polymer composed of pure MeMBL and a polymer composed of MeMBL and styrene were prepared and subjected to reactions with sodium hydroxide in alcohols, water, or dimethyl sulfoxide. Evidence of ring-opening was determined either by observation of a change in the polymer’s solubility or by NMR analysis. Both the pure MeMBL polymer and MeMBL/styrene copolymer showed evidence of ring-opening when exposed to sodium hydroxide in water, while no reaction was observed with the same treatment in alcohols. The poly(MeMBL) ring was observed to close over time. Ring-opening was found to be achievable, but ring-opening with hydroxide was found to be an ineffective pathway to further work on the opened ring.
INTRODUCTION

Renewable alternatives to petroleum-based plastics have become a topic of significant interest for the field of polymer chemistry, as they have the potential to reduce dependence upon oil for plastic products. One commercially available example is polylactic acid, or PLA, which is derived from corn and is used to make biodegradable shopping bags (Oksman, 2004) and biodegradable food packaging (Natureworks LLC, 2005). Another is the use of lactone-derived poly(esters) for use as biodegradable sutures or as “scaffolds” for use in tissue engineering (Martin, 2003). PLA and lactones are polymerized by opening the lactone ring, but lactones composed of five-member rings are known to be especially difficult to open because of the stable nature of this ring size (Moore, 2005).

In addition to ring-opening polymerization, there are also renewable polymers that are produced via free radical polymerization. While ring-opening polymerization typically occurs by breaking an ester or amide bond on a monomer and forming a new ester or amide bond with another opened monomer, free radical polymerization occurs by inserting a “free radical” electron into a carbon-carbon double bond. This forms a new bond at the site of insertion as well as a new free radical that continues the growing polymer chain. MeMBL, or α-Methylene-γ-methyl-γ-butyrolactone, is a renewable monomer that can be polymerized via radical means, as MeMBL’s methylene group permits it to polymerize without opening its lactone ring. This leads to the production of an acrylic polymer that is similar in structure to the non-renewable polymer methyl methacrylate (MMA), but with a higher glass transition temperature (Manzer, 2004). Structures of MeMBL, MMA, and the other mentioned monomers and polymers are in Figure 1. While MeMBL’s lactone ring remains an unopened side group during polymerization, one could open the ring to attach various new functionalities onto the backbone polymer, and thereby change the

![Figure 1](structures.png)

Figure 1. Structures and polymerizations of the renewable resource monomers lactide, DVL, and MeMBL, along with the non-renewable MMA. MeMBL, the molecule of interest, is currently of interest for its potential to replace MMA, and for its high glass transition temperature.

![Figure 2](pathway.png)

Figure 2. General pathway for polymerization and ring-opening of MeMBL. In this pathway, a nucleophile (-Nu) is inserted in the lactone ring, which opens it. Reaction pathway is adapted from pathway suggested by Pittman and Lee (2003, p.1759).
polymer’s behavior as a plastic. This would broaden the range of the polymer’s potential applications beyond both replacing MMA and raising the glass transition temperatures of other polymers through copolymerization. In order to do this, a pathway for opening the lactone ring of MeMBL must be developed first. A pathway for opening a polymer with lactone side groups has been proposed by Pittman and Lee (2003), but to the best of the author’s knowledge the pathway has not been investigated for MeMBL. This pathway is shown in Figure 2, and is of particular interest to this study.

While the Pittman and Lee paper is the only one known to suggest a ring-opening method for poly(MeMBL), others have investigated ring-opening of five-member lactone rings on different molecules. Work by Pevarello et al. (2005) and Kawahata et al. (2002) includes insertion of organo-amines into molecules containing a γ-butyrolactone (GBL) ring to produce a variety of lactam compounds. In addition, Lange et al. (2007) report a method to ring-open γ-valerolactone (GVL) in the synthesis of methyl penta-oxoate, under conditions of catalytic distillation. These papers may demonstrate that modification of a five-member lactone to another molecule can be done, but demonstration of ring-opening and modification of a polymer containing five-member lactone rings currently remains an open question.

**MATERIALS & METHODS**

**Preparing Polymers**

MeMBL was supplied by DuPont, and the inhibitor hydroquinone was removed by passing the monomer through an inhibitor-removing column. Styrene was purchased from Fisher Chemical and used as received. Azobisisobutyronitrile (AIBN) was purchased from Sigma-Aldrich and used as received.

Polymerization of MeMBL homopolymer was carried out as a free radical polymerization in chloroform. In a typical polymerization, 5.61 g of MeMBL and 0.0164 g of AIBN (a 500:1 molar ratio) were combined with 50 mL of chloroform in a round-bottom flask. The polymerization was carried out in a nitrogen-only environment at 60 °C for 24 hours. The resulting polymer was precipitated in methanol, and dried under vacuum at room temperature for 24 hours.

Polymerization of a MeMBL/styrene copolymer was carried out as a free radical polymerization in bulk. In a typical polymerization, 2.24 g of MeMBL and 2.08 g of styrene (equimolar ratio) were placed in a small vial with 0.0164 g of AIBN (a 400:1 monomer/initiator ratio), and allowed to react in a nitrogen-only environment at 80 °C for 24 hours. The polymer was then removed from the vial, dissolved in chloroform, and the polymer was precipitated in methanol. The polymer was dried in vacuum at ambient temperature for 24 hours.

**Ring Opening**

Sodium hydroxide and dimethyl sulfoxide (DMSO) were purchased from Fisher Scientific, ethanol was purchased from Sigma-Aldrich, and deionized water was acquired by reverse-osmosis purification. All listed materials were used as received.

The methods for reactions using water, DMSO, and ethanol, both for the MeMBL homopolymer and MeMBL/styrene copolymer, were the same. In a typical experiment, 1.12 g (0.01 moles) of polymer, 1.2 g (0.03 moles) of NaOH, and 30 mL of solvent were combined in a round-bottom flask. The flask was sealed, but not in a nitrogen-only atmosphere. The mixture was allowed to react at the boiling point of the selected solvent for 24 hours, with the exception of DMSO, in which the reaction was carried out at 115 °C for 24 hours. This exception was made because higher temperatures...
under the reaction conditions for DMSO led to severe polymer degradation.

Upon completion of the reaction (noted by a change in color), the solution and any remaining solid were added to 200 mL of water, and stock HCl was added dropwise until the polymer precipitated. The MBL/Styrene copolymer precipitated in deionized water only, as acid was not needed to effect precipitation. The precipitate was then filtered, and washed with a mild acid solution (<1 mL HCl per 25 mL water) three times, and allowed to dry in vacuum. Samples of the dried polymer were placed in a battery of solvents to test for changes in polymer solubility. Finally, the polymer was analyzed using \(^1\)H nuclear magnetic resonance spectroscopy (proton NMR), to look for changes in the number and chemical shifts of protons (H atoms) on the polymer. If the ring-opening reaction proceeds according to Figure 2, one would expect a single new peak between 2 and 5 ppm in the product polymer that corresponds to the proton on the alcohol group (OH), with relatively little change on other protons.

**RESULTS & DISCUSSION**

For the MeMBL polymer, a change of solubility (from insoluble starting material to a product fully soluble in water) was noted after reaction with sodium hydroxide in water. After the reaction of poly(MeMBL), which is insoluble in water, the polymer/water mixture became a yellow solution, indicating a change in solubility. However, in the 24 hours taken to dry the product, the polymer's solubility changed to that of the original polymer, and NMR revealed that the starting polymer had been reformed. This is believed to be caused by ring-closing after ring-opening, and subsequent tests revealed the ring-opened polymer, when dissolved in methanol, would precipitate out of solution after approximately one hour. The recovered precipitated product was identified by \(^1\)H NMR as the original, closed-ring polymer. This pattern was found to be repeatable over several (>5) reactions. When DMSO was used as a solvent, MeMBL again underwent a change in solubility, indicating a ring-opening. However, this ring-opened polymer also underwent ring-closing and reformed the original, closed-ring polymer within an hour. This was confirmed over several repetitions. No reaction was observed with the use of ethanol as a solvent.

The failure of the reaction in ethanol has a number of possible causes. First is the issue of temperature. Ring-opening experiments in water were found not to proceed at 60 or 70 °C, and since the reaction in ethanol was carried out at its boiling point of just 78.5 °C, the temperature may have been too low for the reaction to proceed. Meanwhile, higher temperatures used with water (100 °C) and DMSO (115 °C) appeared sufficient. A second possible cause for failure stems from ethanol's properties as a protic solvent. During the reaction, ethanol may have reacted with sodium hydroxide to form water and sodium ethoxide, in which case the nucleophilic attack shown in Figure 2 would be one of ethoxide instead of hydroxide. Since ethoxide is a larger nucleophile, and MeMBL’s lactone ring is very small, steric hindrance could have prevented ring-opening by ethoxide.

Also of interest were two solutions of ring-opened poly(MBL) that were not precipitated immediately after the reaction. These solutions were held for approximately one week before the precipitation step. Upon neutralization with acid (in accordance with the experimental method), the ring-opened products would revert to the ring-closed form quickly.

Reaction of the MeMBL/Styrene copolymer in DMSO yielded no change in solubility, and \(^1\)H NMR revealed a new peak at a chemical shift of 2.9 ppm, which should correspond to the alcohol group...
seen in Figure 2. The new peak was consistently observed for approximately one week. After that time, $^1$H NMR of the copolymer revealed a polymer equivalent to the starting material, and this is again hypothesized to be due to ring-opening followed by ring-closing. Reactions of the copolymer in water or ethanol did not proceed.

Literature shows that GBL, which has the same five-membered rings as MeMBL, heavily favors a closed-ring state (Duda, 1996 and Houk, 2008). This may help explain the fleeting nature of the ring-opened compound observed in this experiment. Work by Carothers et al. also indicates that ring-opened GBL is most likely to close if the end groups on the open ring are a carboxylic acid and alcohol, while other end groups are less likely to undergo ring closing (1962). Combining this information with the observation that the ring-closing phenomenon occurs rapidly upon addition of acid suggests that a more stable product than an alcohol and carboxylic acid are formed during the ring-opening reaction. A likely candidate is a sodium salt on one of the end groups of the open ring, as no other reactive molecules are present in water or DMSO to create other groups. Furthermore, $^1$H NMR of the copolymer reveals the creation of an alcohol group during the ring-opening reaction, which would imply the creation of the carboxylic sodium salt shown in Figure 3. The acid used during the precipitation step, therefore, plays an important role in the ring-closing of poly(MeMBL). Upon exposure to water or acid, the salt is converted to a carboxylic acid. This permits a ring-closing reaction to take place, yielding the original polymer. Future work on ring-opening, therefore, should avoid using precipitation in acid as a method to purify ring-opened poly(MeMBL). Other reactions to investigate include using nucleophiles other than hydroxide, which may lend some resistance to ring-closing.

![Figure 3](image)

**CONCLUSIONS**

Lactone ring-opening of poly(MeMBL) has been demonstrated by the solubility changes observed in poly(MeMBL), and by $^1$H NMR in poly(MeMBL+Styrene). The opened lactone ring was found to be unstable over time and rapidly closed in the presence of an acid. The goal of this research, to find a pathway to an open lactone ring for further chemical reactions, was met using hydroxide as a ring-opening nucleophile, although the ring reformed after a relatively short time. Nonetheless, the evidence of ring-opening in the presence of hydroxide indicates that a pathway is plausible, and should be tried using other nucleophiles, particularly amine nucleophiles. Once this can be done, further side group modification of the polymer can be carried out, and MeMBL’s candidacy as a renewable, chemically customizable plastic can be evaluated.

**ACKNOWLEDGMENTS**

The author would like to thank Dr. Christopher Jones for his guidance and support on this project. The author would also like to thank Genggeng Qi, as well as the Jones research group for guidance and advice given over the course of this project.
REFERENCES


Knowledge of how the radiotoxicity of spent nuclear fuel changes over time is essential when designing and evaluating spent fuel storage and treatment methods. The common method of obtaining these data is to use standardized transmutation codes, which are computer programs with solution methods to a given set of problem types. Currently widespread transmutation codes are time-intensive and access to them is not universal. The purpose of this work was to use one of these codes, EASY2003, to develop a simpler and faster solution algorithm. The basic methodology employed was to perform EASY2003 calculations separately on all relevant isotopes, and then to generate an algorithm that can amalgamate these individual results into a solution of any given fuel mixture and amount. For verification purposes, the generated algorithm was applied to a sample spent fuel mixture, and the solution was compared with a more traditional solution method generated by the transmutation code ORIGEN-ARP.
INTRODUCTION
The Global Nuclear Energy Partnership (GNEP), announced in February 2006 (Stevens, 2006), is a program led by the United States Department of Energy intended to, among other things, incorporate fuel reprocessing in the American nuclear fuel cycle. One motivation behind this policy is to extract more energy from a given amount of mined uranium while, at the same time, reducing the amount of high level radioactive waste that must be dealt with at the end of the fuel cycle. Some important factors in determining what methods are most effective to this end are the total activity, dose rates, and heat production of given spent fuel compositions as they change over long periods of time (Stacey, 2007). Typically, standardized transmutation codes are used to obtain these data. The codes are essentially computer programs with built-in solution methods to a given set of problem types. Currently available transmutation codes, such as EASY2003 (Forrest, 2002) and ORIGEN-ARP (Bowman, S. M., Gauld, I. C, & Horwedel, J. E., 2006) can perform these calculations, but various factors can make these methods unappealing. The purpose of this work was to develop a means to more rapidly determine how the radiotoxicity of a given spent nuclear fuel composition changes over very long periods of time, up to 100,000 years in this case, and to make this method more accessible.

EASY2003 and ORIGEN-ARP are codes capable of performing calculations that are immensely more complicated and demanding than those addressed in this paper. The scenarios addressed in this paper, however, do not require the complex nature of these transmutation codes, as the case of spent nuclear fuel decaying over time does not require consideration of neutron irradiation, a factor that makes calculations of this nature far more complex and numerically intensive. If one wishes only to perform this relatively simplified case, though, some of the same challenges of setting up the codes to solve those more complex problems must be faced if EASY2003 is utilized. Firstly, access to these codes is not universal. They are maintained and distributed by centralized organizations, and access is limited by issues such as cost and export controls. These codes incorporate large amounts of isotopic cross-section data, which correspond to the likelihood of interaction between a given neutron as it moves through a material of a given isotope. Codes such as these also tend to come with a steep learning curve that a user may not wish to overcome if he only wishes to use a given code for its more simple capabilities. Thus, the goal of this research endeavor was essentially to develop a simple and accessible solution method to this simplified case that allows one to circumvent these demanding and complicated solution methods.

The nuclear engineering software package EASY2003 was used to develop values of contribution by all relevant actinides, as the long-term characteristics of spent nuclear fuel are primarily governed by these actinides (Stacey, 2007). Actinides consist of the fifteen chemical elements between actinium and lawrencium on the periodic table of elements. Several actinides are considered relevant in this paper, because they have a propensity to build up during operation of a nuclear reactor. The contributions of these individual actinides are not interdependent, and can thus be calculated separately and later incorporated in a simple algorithm to sum these individual components based on an initial spent fuel composition (Stacey, 2007). This system characteristic, the lack of interdependence, is the basis for simplifying the process of determining spent fuel characteristics as they evolve over time; given an initial spent fuel composition, the time-dependent properties can be instantly obtained once these individual source terms are known. In order to verify the final algorithm developed by this process, the decay characteristics of a typical light-water reactor spent fuel composition were solved and compared with a solution generated by the
software package ORIGEN-ARP.

Both ORIGEN-ARP and EASY2003 are capable of performing a wide array of decay and transmutation calculations, including the ones described in this paper, but they were developed independently of one-another, and thus can be seen as offering a higher degree of confidence in the event of both yielding the same result for a given calculation.

METHODS

The core function of the module FISPACT within EASY2003 is to solve the governing body of differential equations that describes the composition of a given mixture of radioactive isotopes as it changes with time. This calculation can be performed with or without the presence of an incident neutron flux. Each individual isotope present in the material mixture is represented by a single differential equation of the form in Equation 1 (Forrest, 2002):

\[
\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i \phi) + \sum_{j=1}^{N} N_j(\lambda_{ij} + \sigma_{ij} \phi) + S_i
\]  

(1)

Where:
- \( N_i \) is the amount of isotope \( i \) at time \( t \) (cm\(^{-3}\)).
- \( \lambda_i \) is the decay constant of isotope \( i \) (s\(^{-1}\)).
- \( \lambda_{ij} \) is the decay constant of isotope \( j \) producing \( i \) (s\(^{-1}\)).
- \( \sigma_i \) is the total cross section for reactions in \( i \) (cm\(^2\)).
- \( \sigma_{ij} \) is the reaction cross section for reactions on \( j \) producing \( i \) (cm\(^2\)).
- \( \sigma_k^f \) is the reaction cross section (f indicating fission) for reactions on actinide \( k \) (cm\(^2\)).
- \( \phi \) is the neutron flux (n cm\(^{-2}\) s\(^{-1}\)).
- \( S_i \) is the source of isotope \( i \) from fission.
- \( Y_{ik} \) is the yield of isotope \( i \) from the fission of isotope \( k \).

In the case of spent nuclear fuel decay, as is being addressed here, the neutron flux is zero, since there is no source of neutrons as in an online nuclear reactor, and the Equation 1 can be simplified to Equation 2:

\[
\frac{dN_i}{dt} = -N_i \lambda_i + \sum_{j=1}^{N} N_j \lambda_{ij}
\]  

(2)

The important aspect of the EASY2003 solution method that allows it to be used in the generation of a simpler, faster algorithm for solving spent fuel decay characteristics is that the solution to each isotope’s differential equation is not dependent upon the solution of any other isotope. Once the solution for each isotope \( j \) is known for a given amount of elapsed time \( i \), the total activity, or number of decays per second, of a given spent fuel mixture can be calculated as in Equation 3:

\[
A_{\text{total},i} = M \sum_{j} f_j A_{ij}
\]  

(3)

Where:
- \( A_{\text{total},i} \) is the total activity of the fuel composition at time \( i \) (Bq).
- \( M \) is the total mass of the fuel (kg).
- \( f_j \) is the mass fraction of isotope \( j \) (unitless).
- \( A_{ij} \) is the activity of isotope \( j \) at time \( i \) (Bq/kg).

The same solution method can be applied to the values of heat output and gamma ray dose rate at a given point in time. If all relevant values are already calculated, the decay characteristics (total activity, heat generation, gamma dose rate) of any fuel composition can be very simply obtained by Equation 3 without the need to re-solve the entire set of differential equations described in Equation 1.
RESULTS

Solutions were obtained at one-hundred steps of elapsed time, logarithmically distributed from zero to one-hundred thousand years. Results were obtained for all actinides with long enough half-lives such that they are relevant to long-term fuel storage, as listed in Table 1. A half-life longer than approximately two years is considered relevant, as spent-fuel is allowed to lie dormant for much longer than this time period before being considered for long-term waste storage.

Sample total activity solutions can be seen for the individual isotopes of Am-241, Cm-244, and Np-237, summed with their respective progeny, in Figure 1. These are three of the most important isotopes in spent nuclear fuel (Stacey, 2007). The gamma dose rate data for these isotopes can be seen in Figure 2 and the heat output data can be seen in Figure 3.

For purposes of verification, the overall decay characteristics of a typical light water reactor spent fuel composition were calculated using the algorithm generated from EASY2003 and then compared with the results obtained when using ORIGEN-ARP with the same initial composition. This is intended to be a wholesale comparison between the method generated and the results obtained from EASY-2003 and an alternative transmutation code, ORIGEN-ARP. Presuming that the solution method detailed within this paper is exactly representative of the more complex EASY-2003 solution method, minor differences between it and ORIGEN-ARP results

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Table 1. List of relevant isotopes accounted for in final algorithm.

Figure 1. Activity of the sum of the given isotope and its progeny for three particularly relevant actinides, intended to be a sample of the twenty-seven actinides solved in this study.

Figure 2. Gamma dose rate of the sum of the given isotope and its progeny for three particularly relevant actinides, intended to be a sample of the twenty-seven actinides solved in this study.
are only indicative of differences between the two codes, not a degree of error inherent in the simplified solution method. Because of this, minor differences can only be explained by delving deep into the workings and merit of EASY2003 and ORIGEN-ARP, a task far beyond the scope of this paper. This is also the reason why one composition is used as representative, as minor changes in the composition would only indicate a similar style of error, not one indicative of the simplified solution method. In general, the comparison only offers proof that a significant user error was not made in generating the algorithm, something that would only appear in the form of one or more orders of magnitude difference. The spent fuel mixture used was generated using the sample fuel burn-up calculation included with the TRITON module within the SCALE5 software package (Stevens, 2006). SCALE5 is a nuclear code package that includes a wide array of modules for modeling a plethora of nuclear engineering systems, including a case of light-water reactor fuel irradiation and neutronic behavior. The spent fuel composition used can be seen in Table 2.

The total activity and total heat output obtained from the algorithm generated from EASY2003 and the results obtained from ORIGEN-ARP can be seen in Figures 4 and 5. The results obtained from ORIGEN-ARP are nearly identical to those obtained from the EASY2003-based algorithm, and the differences are small enough to strongly indicate that no error was made in the algorithm’s development.

**DISCUSSION**

The algorithm for solving long-term decay characteristics of spent nuclear fuel previously outlined was proven correct by the very close correlation with a more traditional solution in the case of a typical spent-fuel composition. As results were obtained for 3 characteristics (total activity, heat generation, gamma dose rate) of 27 isotopes relevant to spent nuclear fuel at 100 points of elapsed time, the solutions of nearly any spent fuel composition can be readily obtained by the very simple summation in Equation 3. This algorithm has the potential to be very useful in future research corresponding to

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**Figure 3.** Heat output of the sum of the given isotope and its progeny for three particularly relevant actinides, intended to be a sample of the twenty-seven actinides solved in this study.

**Table 2.** Example spent fuel composition.
As different breeder reactor and chemical reprocessing scenarios are evaluated, the ultimate costs and benefits related to long-term fuel storage needs can be instantly and simply acquired when composition before and after a given fuel treatment is known.

Aside from offering a solution method employing benefits previously outlined to those wishing to perform calculations of this nature, this simpler and more easily accessible form may encourage researchers to perform these calculations at times when they otherwise would not. These may include times when spent fuel radio-toxicity is not the primary issue of concern for a given research endeavor, but adding such calculations would be beneficial. The final form of the results outlined in this project was an exhaustive Microsoft Excel 2007 spreadsheet. This is a format easily understood and employed by most researchers, though the data could be transferred to a variety of other forms, depending on the needs of those wishing to use them. It is clear that entering a composition into a Microsoft Excel 2007 spreadsheet is a simpler and more efficient method for acquiring and becoming proficient in the use of an esoteric transmutation code such as EASY2003 or ORIGEN-ARP.

**ACKNOWLEDGMENTS**

The author would like to thank Dr. Cassiano de Oliveira for introducing him to the world of nuclear engineering research, Dr. Wilfred van Rooijen for his benevolent guidance and counsel on this and other projects, PURA for project funding, and his parents for everything else.
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We present an experimental investigation of the dynamics of an acoustically excited swirl combustor. Simultaneous measurements were taken of the acoustic pressure, mean velocity, CH* and OH* radical chemiluminescence, and OH concentrations through planar laser induced fluorescence (PLIF) over a range of forcing frequencies, amplitudes and nozzle exit velocities. As the flame response grows linearly and monotonically with increasing forcing amplitude, the flame’s behavior becomes more complex at higher levels. The observed dynamics of the flame to some extent occur simultaneously, resulting from a combination of at least five flame/flow processes: (1) the oscillating velocity of the annular jet, oscillations in (2) position and (3) strength of the vortex breakdown bubble and separation bubble, (4) unsteady liftoff of the flame, and (5) an oscillating turbulent flame speed.

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INTRODUCTION

This work is motivated by combustion instabilities in lean (oxygen rich), premixed combustors and continues recent studies by Thumuluru, S.K., Bobba, M.K., & Lieuwen, T. (2007). Combustion instabilities are characterized by pressure oscillations of the acoustic modes of the combustor (Lee & Santavicca, 2003; Richards, Straub, & Robey, 2003). Every object has a natural frequency at which it oscillates when disturbed. For example: blowing into a bottle filled a quarter of the way with liquid would yield a different sound than blowing into the same bottle half-filled. The natural frequency is determined by the materials and the geometry involved. The acoustics produced from the disturbance cause instabilities in the combustion process, which can result in structural vibrations, thrust oscillations, and enhanced heat transfer that can substantially reduce the life of the combustor. In addition, this could also compromise efficiency and the surrounding environment, forcing the combustor to be operated at lower levels and can even cause catastrophic failure. Figure 1 is a pictorial representation of the complex, non-monotonic, acoustic dynamics of the combustion zone.

To simulate the disturbances, two speakers were used to produce a driving amplitude, $H(A)$. $D(A)$, the damping amplitude represents losses that dampen the driving (sound) amplitude within the system. The flame's heat release response, which is the amount of heat released by the flame due to a disturbance, at first increases linearly over a certain range of low amplitudes, then saturates (levels out) at higher amplitudes (Lieuwen, 2002 and Dowling, 1997). The saturation is analogous to the following in the bottle setup noted above: increasing excitation amplitude (blowing harder) into the bottle would yield higher response (louder sound) until a certain input amplitude is reached. At this point, the response amplitude will no longer increase with an increase in input; at some point blowing into the bottle harder will no longer produce a louder sound. The location of this point is also known as the limit-cycle (ALC). The low amplitude linear dynamics control the balance between driving and damping of the disturbances while the high amplitude nonlinear dynamics control the location of the limit-cycle.

Combustion instabilities spontaneously occur when the forcing of the oscillations from the combustion processes is greater than the dampening of oscillations. The limit-cycle amplitude (ALC) describes the point where the driving force equals the damping force (i.e., steady-state), causing saturation if forcing continues to increase. Identifying this steady-state point is essential because it could serve as a threshold of maximum efficiency at safe operating conditions for combustors. Proceeding past the threshold could result in some of the failures listed above along with the possibility of flame blowoff (flame is extinguished) or flashback (flow goes back into the nozzle). Predicting the limit-cycle entails a deep understanding of how the flame’s heat release is influenced by the
fluctuation of the excitation amplitude. The key objective of this work is to characterize the physics behind the mechanisms causing such instabilities.

**EXPERIMENTAL SETUP**

The experimental combustor is swirl stabilized with a center-body and operates at atmospheric pressure and 10-20 KW thermal power. Swirl stabilizing the flow is achieved by passing the flow through a swirler, which produces a toroidal flow structure that has stabilizing properties. The center-body is a physical body that contains the swirler, the ducts leading from the swirler, and is the body the flame sits on. Figure 2 is a schematic of the combustor setup. The fuel (natural gas) and air were premixed upstream of a choke point to prevent the occurrence of fuel/air ratio oscillations. The equivalence ratio, also known as the air-fuel ratio, was maintained throughout the experiments at a constant value of 0.8. The premixed fuel and air were passed through a flow swirler with a 40° swirl angle. The resulting flow was then passed through the center-body then expanded into a quartz tube of a 70 mm diameter and 190 mm length. This specific length was selected to avoid the natural frequency of the quartz tube and thus, prevent any self-excited oscillations. Acoustic oscillations are introduced using two amplifiers (Radio Shack MPA – 101 100 Watts) connecting to two drivers (SK144 100 Watt speakers), which were mounted upstream of the combustor. Two pressure transducers (Model 211B5 Kistler) positioned downstream of the swirler, located 5.85 cm and 7 cm upstream of the nozzle, are used to determine the acoustic velocity at the nozzle exit using the two microphone method (Allam & Åbom, 2005).

In order to provide some context for interpreting the results of this study, Figure 3 depicts common fluid mechanical processes and basic flame configurations. Figure 3(a) breaks down the combustion zone into three main regions: (1) The outer recirculation zone (ORZ), which is a toroidal re-circulating regime generated by the rapid expansion of the jet into the combustor, (2) the inner recirculation zone (IRZ), due to vortex breakdown accompanying the swirling flow, and (3) the high velocity, annular fluid jet that divides these regions. Figure 3(b) – (e) depicts common flame configurations that are heavily dependent on the equivalence ratio and flow velocity. Disturbances to the velocity before the nozzle exit alter the velocity of the annular fluid jet, which causes the flame to surge up and down axially. This causes both the ORZ and IRZ strength to fluctuate and its location to shift back and forth.

Phased locked OH Planar Laser Induced Fluorescence (PLIF) was used to visualize the spatial dynamics of the flame while measurements of the global CH* and OH* radical chemiluminescence with photomultipliers (PMT) were used to characterized the heat

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**Figure 2.** Combustor schematic (all dimensions are in mm). Adapted from Thumuluru, Ma et al., (2007).
release fluctuations. A schematic of the laser system is shown in Figure 4 and detailed specifications are given in Thumuluru, Bobba et al. (2007).

The key limiter of using the PLIF images is that the flame edges are captured manually and consequently subjected to biases. Every edge detection software applied to the flame images returns with several errors due to the complexity of each picture; however, determination of the flame edge manually is trivial in most cases, except when the flame reflects itself off of the combustor walls and/or where there is back mixing of OH laden products. In the latter case, the OH gradient helps distinguish between whether the OH levels correspond to a flame or a product.

IMAGE ANALYSIS
To trace the changes in the flame structure, OH PLIF images were recorded and analyzed for specific conditions within the range of: (1) frequency: 100 Hz to 410 Hz and (2) excitation amplitude: 100 mV to 1500 mV. The interpretation of these images is limited by the fact that they are only two-dimensional projections of a highly three-dimensional flow, offering only a sliver of the combustion zone. This limited view into the combustion zone only reveals interactions on a two dimensional plane, while the flow is changing and interacting three dimensionally. Also, despite the images being phased locked, the images are actually taken several cycles apart and do not represent consecutive cycles.

A typical set of PLIF images of a flame were taken at six different phases of an acoustic cycle at selected excitation amplitudes (produced by the speakers) as shown in Figure 5. The forcing frequency here was 140 Hz and the phase angles correspond to the phase angles within an acoustic cycle. The Reynolds number (ratio of inertial forces to viscous forces) was defined at the nozzle exit at 44,000.

Figure 3. (a) Common fluid mechanical processes. (b) – (e) Common flame structures. Adapted from Thumuluru, Ma et al., (2007).

Figure 4. Schematic of the OH PLIF setup. Adapted from Bellows et al., (2006).
Figure 5. OH PLIF images showing flame structure at the forcing frequency of 140 Hz, $R_e = 44,000$ and amplitudes of (a) $u'/u_o = 0.07$, (b) $u'/u_o = 0.1$, (c) $u'/u_o = 0.17$ & (d) $u'/u_o = 0.24$. Figure adapted from Thumuluru, Ma et al., (2007).
The ratio $u'/u_o$ is the acoustic velocity to the mean velocity of the flow. This ratio provides a valuable insight into the magnitude of oscillations in the flow with zero being no fluctuations. As excitation amplitude increases, $u'/u_o$ will also increase. The flame shape at this condition is similar to Figure 3(c) where the flame is attached on the outer walls. Note the nozzle is located at the bottom of each image.

Figures 5(a) and (b) are snapshots of the flame at low excitation amplitudes, which would fall under the linear regime of the flame response as shown by Figure 1 with the $H(A)$ curve. The curve rises linearly before turning and saturating. Notice that in the IRZ region, the flame is almost attached to the center-body. The significance of this phenomenon is explained later in this section. Figure 5(c) and (d) show the flame under large excitation amplitudes where the flame response saturates and recovers, respectively. In Figure 5(d) specifically, the flame edge in the IRZ region is far away at phase angle 120°, stabilizes at phase angles 180° and 240°, and recovers at 300°. In general, Figure 5 provides an illustration of the flame as it surges back and forth axially, due to oscillating flow velocity in the annular jet region shown in Figure 3(a). A closer look into this phenomenon is well illustrated in Figure 5(d). As the excitation amplitude grows, the overall level of fluctuation of the flame length grows, which can be seen in the ORZ region as the flame edge shifts axially.

Applying this process of image analysis over a range of conditions, it was observed and cataloged that there are five basic flame and/or flow processes. These processes are the following:

**Fluctuating annular jet velocity.** As noted above, oscillations in flow velocity cause perturbations in the annular jet velocity between the IRZ and ORZ, causing a fluctuation in flame length.

**Vortex rollup.** The oscillating shear in the inner and outer re-circulation zones generates vortical structures whose strength and size are a function of the perturbation amplitudes. These vortices roll up the flame and cause rapid destruction of the flame area. Figure 6 illustrates that significant vortex rollup occurs in both the IRZ (left) and the ORZ (right). Figure 5(c) shows the evolution of a vortex rollup through a cycle of phase angles.

**Unsteady Liftoff.** The flame’s stabilization point is heavily dependent on the excitation amplitude and can be pushed downstream. At higher excitation amplitudes, the flame extinguishes locally between the swirler exits as shown in Figure 7 and re-stabilizes downstream. Notice, at 0° phase angle, the flame edge is clearly at-

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Figure 6. PLIF images showing vortex rollup in IRZ (left) and ORZ (right) at forcing frequency of (a) 130 Hz, $R_e = 21,000, u'/u_o = 0.9$ & (b) 210 Hz, $R_e = 44,000, u'/u_o = 0.2$. Adapted from Thumuluru, Ma et al., (2007).
tached to the center-body while at 225° phase angle the flame edge has completely lifted off. The bulk of the heat release has moved away from the IRZ and towards the walls of the combustor. This phenomenon is apparently the cause of the saturation (non-linear regime) of the flame response to excitation. When the flame is attached to the center-body as shown in Figure 3(d) and (e), the flame edge grows linearly with excitation amplitude and stretches axially. Once the flame detaches and is blown downstream as shown in Figure 3(b) and (c), the flame responds to the higher excitation amplitude by shifting up and down in bulk. This is accompanied with a decrease in flame area, which results in lower heat release.

Vortex breakdown bubble movement. The vortex breakdown bubble also known as the IRZ moves up and down axially and changes shape with forcing as seen in Figure 8 taken at 410 Hz. Comparing Figure 5 and Figure 8, it appears that the recirculation bubble responds to frequencies instead of excitation amplitude.

Turbulent flame speed oscillations. The turbulent flame speed (speed of propagation) of the unburned reactants varies throughout the cycle of phase angles. In a previous qualitative observation by Bel-

![Image](image_url)
MA

lows, Bobba, Seitzman, & Lieuwen (2006), it was observed that the flame topology varies with excitation amplitude. In Figure 5, where the excitation amplitudes are small, the amount of “flame wrinkling” (flame physically changes to appear as if it were wrinkled) fluctuates throughout an acoustic cycle as the excitation amplitude increases. In Figure 6(b) and Figure 7 at a phase angle of 225° where the excitation amplitudes are high, the flame wrinkling becomes virtually unpredictable. This implies that the turbulent flame speed oscillates with a fluctuation level that increases with the excitation amplitude.

CONCLUSION
The results presented show that the observed dynamics to some extent occur simultaneously, resulting from a combination of at least five flame/flow mechanical processes – the oscillating velocity of the annular jet, oscillations in position and strength of the vortex breakdown bubble and separation bubble, unsteady liftoff of the flame, and an oscillating turbulent flame speed. These five flame/flow mechanical processes shed valuable insight into the interactions within the combustion zone. These results cannot be applied directly to industry, but they are the fundamental building blocks of a more in-depth investigation. A key conclusion from this study is that investigation into flame dynamics through pattern analysis is not enough. Further work includes taking particle image velocimetry (PIV) to capture the velocity field of the flame. PIV is an optical method used to measure velocity fields and other properties in fluids. The flow is seeded (particles are introduced into the flow) with small reflective particles that reflect light created by a laser. The reflected light is then captured on camera every few milliseconds, revealing the velocity magnitude and direction of the flow. The PIV method should provide more quantitative data to integrate these fluid mechanic descriptions into phenomenological descriptions of the phenomenon.

ACKNOWLEDGMENTS
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Inherited Realities: Eugenics, Oliver Wendell Holmes, Jr., and Buck v. Bell

John Warren Akin

This paper examines the Buck v. Bell Supreme Court decision that declared involuntary sterilization of state mental health patients constitutional and the judicial reasoning of Justice Oliver Wendell Holmes, Jr. that influenced the outcome. Where previous studies portray Holmes as an uncaring and insensitive aristocrat, this paper, using Supreme Court opinions, published personal works, and the previously unreleased hospital records of patients in the state of Georgia, argues that it is a misplaced faith in the efficacy of the employed procedural safeguards that led him to support the practice.
INTRODUCTION

Eugenics and the American Progressive Movement

The Progressive Era in American political history is largely heralded for contributing significant social reforms to the United States and for promoting many rights on behalf of the less fortunate in society. Unfortunately, not every endeavor advanced by the Progressives was as beneficial and even-handed as child labor laws, women’s suffrage, organized labor, and the secret ballot. Few reforms, before or after, had consequences as grave as those of the American Progressive’s eugenics movement.

It was the first cousin of Charles Darwin, Sir Francis Galton, who originally coined the term “eugenics” by deriving it from the Greek term meaning “well born” (Engs, 2005, p. 82). Contemporary doctrines from the fields of mental health and criminal psychology in the late 1800s dictated that problems of mental incompetence, criminal behavior, degeneracy, epilepsy, schizophrenia, and many other conditions were not only beyond treatment in many cases, but were almost always the direct result of heredity and lineage. As such, the belief arose that many individuals who were deemed “feeble minded” or otherwise mentally deficient needed to be prevented from procreating for the ultimate good of society.

These beliefs manifested themselves in both positive and negative ways. Positive eugenics encouraged the unions of those perceived to be of the best genetic stock, and often came in the form of “better baby” or “fittest family” contests at state fairs and other locales throughout the nation. Negative eugenics, however, is most closely associated with the eugenics movement and encompassed four fundamental strategies to prevent the unions of those deemed least genetically fit for society: sexual segregation, marriage prohibitions, immigration controls, and sexual sterilization (Engs, 2005, p. xv). Although they all played a role in the overall eugenics movement, the specific focus of this paper is the involuntary sterilization of American citizens at the hands of state health workers.

Initially, the eugenics movement was driven not by widespread popular support, but rather by an almost fanatical base of professionals in the fields of law and medicine and federations of women’s clubs (Engs, 2005, p. xiv). In fact, the American eugenics movement can be viewed in many respects as one of the greatest successes of pre-suffrage political activity by women before the 19th Amendment. Supporters of the movement ranged from Margaret Sanger, the “mother” of modern birth control and staunch advocate of reproductive rights, to those closely associated with Hitler’s Nazis, who shared strikingly similar goals and means (Larson, 1996, p. 140).

Although programs for involuntary sterilization existed as early as 1907 in Indiana and 1909 in California, they were initially relatively modest operations. The early history of these social programs was often marked by repeated judicial interpretation at the state level, frequent re-legislation, and relative restraint by the hands of practicing physicians to actually recommend or perform these operations. However, in 1927 the U.S. Supreme Court heard the case of a young woman named Carrie Buck who had been sentenced to involuntary sterilization by the Virginia State Board of Health. At question was the adequacy of the procedural safeguards employed by the state. After the trial, the legal landscape of the nation was never quite the same.

Buck v. Bell

Only 18 years old at the time of her original trial in 1924, Carrie Buck (1906–1983) was a white inmate of the Virginia State Colony for Epileptics and Feeble Minded and a prime example of an unfortunate person that procedural safeguards are necessary to protect. With a father that either abandoned her or died, and a mother...
that, by many accounts, worked as a prostitute, three-year-old Carrie Buck was placed with a foster family, the Dobbs. She progressed normally every school year until she turned 12, when she was withdrawn from school to help at home. Two years later, Mr. Dobbs petitioned a judge and had Carrie’s biological mother committed on a finding she was “feeble minded” (Engs, 2005, p. 2).

When she was 17, Carrie Buck was raped by the Dobbs’ nephew and bore an illegitimate child. Immediately afterwards she was institutionalized by her parents and declared “epileptic and feeble minded” by the very same judge who helped to commit her mother. Years later, both Carrie and her daughter were found to have normal mental faculties. Though her daughter only lived to be eight years old before dying of infectious disease, she even made the honor roll on one occasion (Thompson, 2004, p. 14).

What makes Carrie’s case even worse is that it was deliberately devised to test the constitutionality of new sterilization laws. Dr. Albert S. Priddy, the Superintendent of the Virginia Colony and the main advocate who secured the law’s passage, saw Carrie Buck as an ideal candidate for sterilization. Dr. Priddy readied the application and submitted it to the Board of the Virginia Colony for approval. Advising the Board as attorney was Mr. Aubrey Strode, a former Virginia State Senator, who had also helped draft the sterilization law.

The Board approved the application, and upon the recommendation of both Dr. Priddy and Mr. Strode, a Constitutional challenge to the law was arranged to enable them to proceed without fear of liability. Appointed as attorney for Ms. Buck in her appeal was Mr. Irving P. Whitehead, a former Virginia Colony Board member and lifelong friend of Strode, who had even participated in Dr. Priddy’s selection as Superintendent (Berry, 1998, p. 9). The appeals process began, and by 1927 the case had been appealed all the way to the U.S. Supreme Court, on the contention that it was, “void under the Fourteenth Amendment as denying to the plaintiff in error due process of law and the equal protection of the laws” (Buck v. Bell, 1927).

The judgment of the Supreme Court was handed down in May of 1927, and the results rocked the foundations of the mental health system. The opinion was authored by Justice Oliver Wendell Holmes, Jr., a highly respected jurist and Civil War veteran. Only two pages in length, the opinion not only upheld the fundamental constitutionality of these programs, but forever framed into history his relentlessly analyzed belief that “three generations of imbeciles are enough” (Buck v. Bell, 1927). Based on an analysis of the procedural safeguards contained within the statute, Holmes and the majority held that the statute afforded adequate protection to satisfy the requirements of the 14th Amendment. Addressing the substantive legal question at hand, Holmes deferred to the elected legislature and ruled the practice constitutional.

The effect was immediate. Now armed with what was viewed as “model legislation” in the Virginia statute, efforts to legalize compulsory sterilization for the mentally deficient gained new vigor. The opinion was wielded by eugenics advocates as a precision instrument to further the movement, and the consequences were tremendous: seventeen states enacted or revised similar sterilization statutes in the four years that followed the decision (Larson, 1996, p. 119). Two state legislatures, Alabama and Florida, had new bills proposed and under discussion within days of the ruling. Furthermore, actual usage of such statutes dramatically increased in the following years. During the first twenty years that eugenics laws were in place in the United States, from 1907 until 1927, approximately 8,500 patients had been sterilized in state institutions.
In the 1930s, after the Supreme Court condones such measures, “the annual number of such sterilizations typically exceeded twenty-five hundred, and once nearly reached four thousand, before dropping to about fifteen hundred in the 1940s and then petering out during the 1950s and early 1960s” (Larson, 1996, p. 119).

**RESEARCH OBJECTIVES**

*Research Questions and Objectives*

How, and why, could the nation’s highest judicial body deem legislation empowering state officials to sterilize citizens against their will legal and appropriate?

In attempting to answer this larger question, there are a number of other areas that must also be examined. How did Justice Holmes view the case and the legal issues before him? Is the decision based on sound reasoning, or did personal bias drive any part of the resolution?

More important are the actual results. Do the records indicate that the judicial intent of the decision is in accordance with the sterilizations as they were performed, or is there a more systemic problem indicated in the case records, suggesting a consequence unintended by the Supreme Court? Present interpretations of Justice Holmes and the *Buck v. Bell* decision are largely based on an understanding of him as a judicial ogre, oppressing those beneath him with a purposeless cruelty, with no greater end in the sight than the extinction of the lower classes. This is far too simplistic of an explanation for a complicated man and a complicated event, and this study seeks to develop an alternative hypothesis for the formulation of *Buck v. Bell*. By placing the decision, the results, and Justice Holmes himself within the broader context of their contemporary social, political, and historical atmospheres, a deeper understanding of the decision and a more accurate insight into the results can be obtained.

**Research Methodology**

To accomplish this objective, research focused on a variety of factors surrounding the social, political, and historical context of the *Buck v. Bell* decision. Extensive review of the literature surrounding American eugenics, the Progressive Era, Justice Holmes, and *Buck v. Bell* was done to gather a greater context for analysis. Eventually, dissecting the Justice’s opinions and the realities they created came to the forefront of the project.

In order to examine and better understand the procedural safeguards that were held as being so fundamental to the constitutionality of these programs, an investigation into previously unreleased medical records of involuntary sterilizations from the state of Georgia was launched. Selected for their particularly compelling need of procedural safeguards, African-Americans in the Milledgeville State Hospital served as a sample of the population for investigation. Special emphasis was paid to patient correspondences, or the lack thereof, included in the medical files of these patients. These letters were frequently the family or guardians of inmates responding to intent-to-sterilize notices sent by the state, and provide an invaluable window into the procedural workings between the state health systems, the families, and the patients themselves. Using hospital files locked away for decades in the Georgia Archives, the aim of this paper is to provide original contributions to the debate over the legacy of Justice Holmes and to shed new light on the *Buck v. Bell* decision.

**BUCK V. BELL AND OLIVER WENDELL HOLMES, JR.**

*Oliver Wendell Holmes, Jr.*

Justice Oliver Wendell Holmes, Jr. has been called many things in historical retrospectives: “inconsistent” (Swisher, 2007, p. 579), a “utilitarian” (Thompson, 2004, p. 5), “liberal,” “conservative,” a “political fascist,” and an “aristocrat” (Duggan, 2007, p. 3). He has
variously been accused of bathing “the law in ‘cynical acid’ to remove its moral import” (Swisher, 2007, p. 579), having “morally bankrupted the practice of the bench and bar” (Swisher, 2007, p. 2), and acting as “a bulwark against those who would infringe upon the liberties of the people and an insensitive, detached, and uncaring rubber stamp for abuse of the weak by the powerful” (Berry, 1998, p. 16).

However, at the same time, the “Great Dissenter,” as his often highly critical dissenting opinions led him to be known, was also one of the most highly respected jurists ever to sit on the bench (Simons, 2007, p. 862). His writings are widely cited, and his book The Common Law has been called “without a doubt the most important treatise in the American legal canon” (Duggan, 2007, p. 14). Holmes is widely regarded as a bit of an “intellectual chameleon,” but his incongruence of opinion is overstated (Duggan, 2007, p. 4). Holmesian academic dissections are almost entirely void of middle ground and habitually reduce Holmes to either a fair and even-handed justice or to a cruel and callous overlord, “making him a sort of philosophical Rorschach test” (Duggan, 2007, p. 3).

Born into a time period of revolutionary ideals, Holmes was most likely influenced by the Progressive Era. It is within this context that Holmes and his decisions must be considered. Meant to better all aspects of society, Progressive politics brought broad sweeping reforms in nearly all areas of civilized life. Unfortunately, this same fervor extended to thoughts of blood and lineage, and how human-kind could improve the human stock by its own hand as well.

Among the politically active, eugenics quickly became a cause on equal moral ground with other Progressive advancements. It is important to note how strong these beliefs were at the time, representing a current so strong that many celebrated minds were caught up in it. W.E.B. Du Bois, even as he argued for the advancement of the rights of African-Americans, championed his belief in eugenics just as ardently. Eugenics was endorsed by Theodore Roosevelt, a Progressive Republican, Woodrow Wilson, a liberal Democrat, and Calvin Coolidge, a conservative Republican. It would be easy to write off the decision as the result of faulty science and a mob mentality. However, in the words of Paul Lombardo, “while the case did represent the peak of public acceptance of eugenic thought, characterizing Buck v. Bell merely as the result of 1920’s pseudoscientific thought ignores the unique confluence of events and interplay of personalities without which the case never would have occurred” (Lombardo, 1985, p. 32). In this sense, the strength of thought, character, and mind of Oliver Holmes may have played every bit as crucial a role in guiding the history of the eugenics movement as the context surrounding it.

A strongly developed sense of independence may be the very reason Chief Justice William Howard Taft chose Holmes to author what was sure to become a controversial opinion for the majority of the court. Over the silent dissent of only one jurist, Holmes carefully dissected the case of Carrie Buck as he saw fit. The case was brought to the Supreme Court primarily as an alleged violation of Fourteenth Amendment protections, but in the eyes of Holmes it could be plainly seen that “the attack is not upon the procedure but upon the substantive law” (Buck v. Bell, 1927).

The Buck v. Bell Opinion
The opinion itself represents a succinct but meticulous deconstruction of the challenge presented with a three-part defense to the Virginia statute. First addressing due process, Holmes offers a detailed recollection of the procedural safeguards enacted by the Virginia statute to protect those facing sterilization. Holmes assures that “there can be no doubt that so far as procedure is concerned the
rights of the patient are most carefully considered,” and later analysis will suggest that this faith in procedure is at the very heart of the problem (Buck v. Bell, 1927).

Next addressing the substantive question, whether or not such an operation could ever be constitutional, Holmes exhibits a striking deference to the wishes of the elected legislature. Citing the text of the Virginia statute, which requires that the patient be a probable “potential parent of socially inadequate offspring, likewise afflicted,” and thus “may be sexually sterilized without detriment to her general health and that her welfare and that of society will be promoted by her sterilization,” Holmes acknowledged that according to the facts presented, Carrie Buck did indeed fall under the order of the statute (Buck v. Bell, 1927). He failed to acknowledge, however, in regards to the operation being a “detriment to her general health,” that at this point in time some procedures to sterilize females killed about 2% of the patients on which they were performed (Larson, 1996, p. 28).

However disagreeable the outcome, there is no denying the presence of logic framing this opinion. Reaching back to a previous decision, Holmes recalled Jacobsen v. Massachusetts (1905), and the principles underlying compulsory vaccines for smallpox as justification. That opinion, as explained by Dr. Phillip Thompson, declared:

Mandatory smallpox vaccinations were permissible because the compulsory vaccination laws did not violate the due process and equal protection provisions of the Constitution. Such restraints were upheld if “reasonable” and beneficial to the “common good.” In words prescient for the Buck decision, the Supreme Court concluded that where there was “the pressure of great dangers,” the “interests of the many” should not “be subordinated to the wishes or convenience of the few” (Thompson, 2004, p. 11).

Rather succinctly, as Holmes put it, “the principle that sustains compulsory vaccination is broad enough to cover cutting the Fallopian tubes” (Buck v. Bell, 1927).

Finally, Holmes addressed the third prong of the attack, the claim that the statute violated equal protection under the Constitution by applying only locally to those within a mental institution. This suggestion appears to almost irritate Holmes, who calls it the “usual last resort of constitutional arguments to point out shortcomings of this sort” (Buck v. Bell, 1927). His response is an unusual interpretation of equal protection, but with the final lines of the opinion he clarified that:

The answer is that the law does all that is needed when it does all that it can, indicates a policy, applies it to all within the lines, and seeks to bring within the lines all similarly situated so far and so fast as its means allow. Of course so far as the operations enable those who otherwise must be kept confined to be returned to the world, and thus open the asylum to others, the equality aimed at will be more nearly reached.

Though not equality in the traditional sense, Holmes argues for equality among all defectives the statute intended to affect. These lines only strengthen notions of these institutions operating as mills, where efficiency and speed could be employed in industrial quantities to rid the nation of those seen as unfit.

Present Legal Status
While it is true that if Buck v. Bell were to face a direct challenge today, it most likely would be reversed, much of the logic contained
in the decision still holds. In fact, *Roe v. Wade* (1973) cites both *Jacobsen v. Massachusetts* and *Buck v. Bell* as good law in determining the scope of one’s rights over their own body. Amicus briefs in *Roe v. Wade* asserted an unlimited right to one’s own body, to which the court responded that “it is not clear to us that the claim... that one has an unlimited right to do with one’s body as one pleases bears a close relationship to the right of privacy previously articulated in the Court’s decisions” and that “the Court has refused to recognize an unlimited right of this kind in the past” (*Roe v. Wade*, 1973). In that sense, *Buck* and *Jacobsen* clarify a principle: that the right to privacy means a woman can have an abortion, but it is balanced against other interests and rights at a certain point. At that point, the rights of the child are introduced and considered. Hence, a woman’s claim to an unlimited right to her own body is false, based upon the precedential value of *Buck v. Bell* and *Jacobsen v. Massachusetts*.

In fact, the case of *Buck v. Bell* has never been overturned. The closest the Supreme Court has come to overruling the decision came in 1942 with *Skinner v. Oklahoma* (1942), in a decision that many incorrectly believe overturned compulsory sterilization. *Skinner* was a challenge to an Oklahoma law permitting involuntary punitive sterilization for criminals convicted of three felonies involving moral turpitude. Since the targeted crimes excluded white collar felons from sterilization, punitive sterilization was found to be in violation of equal protection clause of the Constitution (*Skinner v. Oklahoma*, 1942). However, in keeping with the narrow window through which most Supreme Court decisions are judged, the decision only pertained to punitive sterilization, without touching on eugenic sterilizations of the “feeble-minded.” This had little practical effect, since punitive sterilizations made up a negligible amount of the total sterilizations performed during this period.

**PROCEDURAL SAFEGUARDS**

*Examining the Raw Data*

After Holmes deferred to the legislature on the substantive legal question of whether compulsory sterilization was ever constitutional, the two remaining fronts on which he defended his decision were the procedural safeguards and the claims of equal protection. In order to examine his assertion that “there can be no doubt that so far as procedure is concerned the rights of the patient are most carefully considered,” a small subset of the roughly 65,000 total compulsory sterilizations performed in the United States was chosen for deeper investigation (*Buck v. Bell*, 1927).

Selected for their particularly great need of procedural protections, African-Americans in the pre-Civil Rights era Deep South present ideal candidates for research. Often subject to abuse by segregated society, these citizens found themselves at the mercy of a legal process in which they had little control. Georgia has records of 4,933 patients being involuntarily sterilized, and after obtaining 1,649 cases, a sub-sample of all the African-American patients from Milledgeville’s large integrated state hospital was chosen for study. They represent a time period spanning from 1939 through 1953, and provide a glimpse into the inner-workings of the South’s eugenics programs.

Procedural safeguards required that when the State Board of Eugenics was scheduled to meet and pass on the recommended sterilization of a patient, the next of kin (or, in their absence, the County Solicitor) was to be notified. After ten days, lack of protest or correspondence from the notified kin constituted both *de facto* and *de jure* approval of the operation. If there was any such correspondence concerning the patient, copies were retained in their medical file for the record.
Of the several hundred files examined, only 52 contained any correspondence on behalf of the patient. The vast majority contained only the four requisite documents: an application to the Board by the Doctor or superintendent, the notice of the Board meeting sent to the guardian or next of kin, a report of the operation, and the original recommendation letter from the doctor or superintendent to the Board. Far too many of these patients simply lacked anyone on the outside who understood or cared for their plight. It must also be noted that national census data from 1940 indicates the illiteracy rate for blacks was over five times the rate for whites. The reality in the South was certainly even worse than that, and in the previous century 80% of black Americans were illiterate ("National Assessment of Adult Literacy", 2008).

Of the 52 files containing correspondences, 33 were either dictated because of an individual’s inability to read or write, written in confusing and incredibly poor child-like handwriting, or contained multiple serious grammatical errors that, at best, evidenced a grade school education. 26 exhibited a fundamental misunderstanding of the entire basis for the operation. All eugenic operations shared a common goal explicitly stated in the notices from the Board of Eugenics: the betterment of society’s gene pool. These 26 letters, however, all consented to the procedure on the basis that these operations were in the best interests of the patients and not society, and that they would somehow help alleviate the medical conditions of the individual. These people simply did not understand what they were being notified of. One mother even begged in a barely legible note, “I don’t want you to kill my son” (GA Case 1528), while another note was scratched out on the back of an index card with a return order from a retail store on the reverse (GA Case 1367). “Whatever you think is best for my...” is a sentiment commonly found throughout the letters, while anything even remotely relating to the betterment of society is conspicuously absent. In many cases, eugenic sterilization was a condition for patients’ release back to their families.

Particularly striking are the appeals. Of the 52 correspondence case files, 11 cases did not give consent. Yet of these 11, ten were sterilized anyway with no record of resolution in their files, only the objections of their family members and the dates they were ultimately sterilized. What unique characteristic allowed the one remaining patient to have their case dropped and forego sterilization? This inmate also has the distinction of being the only one who retained a lawyer, and was subsequently able to file a proper appeal in accordance with their strict guidelines. Only one other appeal, filed without the aid of legal counsel, is found in the record. This appeal was rejected without consideration because it was “filed incorrectly,” and the patient was subsequently sterilized (GA Case 1636).

Ultimately, the most conspicuous problem that arises in these case studies is that the law and the procedural safeguards it contains both presuppose a very high level of literacy and legal competence. In dealing with mental defectives and the “feeble-minded,” these attributes appear to be the very antithesis of the group that the law was drafted to target. Moreover, this entire time period occurred prior to Gideon v. Wainwright’s (1963) declaration that legal counsel is of fundamental importance to due process, a paradigm shift that could have clearly influenced legal thought on this matter. In the end, in the eyes of one legal scholar, “a broadening conception of personal liberty, including civil rights for the handicapped and reproductive rights for women, provided the surest protection against compulsory eugenic programs” (Larson, 1996, p. 168). By leaving these patients on their own to prove that they ought not to be sterilized in the face of a machine few understood and even fewer could fight, the law effectively abandoned these citizens and irrevocably altered their lives in the most fundamental of ways.
CONCLUSIONS
The literature almost universally condemns Holmes as callous and cruel for his role in the Buck v. Bell decision and paints him as a man disconnected and dispassionate towards the lower classes. However, after thorough investigation, new evidence appears to exonerate Holmes in many senses. Though there were a number of failures in the process, but malicious judicial intent or callous disregard for the minority do not appear to be among them.

One principal failure of Holmes in this case lies in not applying his own philosophy. A key component of the predictive legal theory advanced by Holmes in “the Path of Law” was what he referred to as the “bad man” test of a law: what would be the consequences, should someone of ill-intent attempt to subvert or use the law for malicious purposes (Holmes, 1997)? It clearly lacked application in the Buck case, as Carrie Buck’s own personal case history is a testament to the inadequacy of the protections provided by the law. Serious though it may be, this was not the greatest failure that occurred.

The ultimate failure of Justice Holmes in the Buck v. Bell decision was in deciding the case based upon the word of the law, and not the reality. For someone often credited with founding the Legal Realism school of thought, this may seem to many to be an egregious error. Though procedural safeguards were in place, and may even have theoretically offered adequate protection to the rights of the patient, the Georgia record clearly demonstrates the problems inherent to the system. In requiring far too high a level of literacy and legal competency for safeguards to ever offer any protection in practice, they deprived patients of their basic due process requirements. Further, literacy and access to legal resources led to dramatically different outcomes for patients in the Georgia record. Since the availability of these necessary skills and resources differed dramatically across socio-economic lines, the Constitution’s equal protection clause was also violated. These were not differences that fell along lines of inmates or free citizens; these were differences that fell along lines of class, race, wealth, and power.

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This project examines the utility of adding a predictor to a crane system in order to test the response with different filtering methods: notch filter, low-pass filter, and input shaping. The use of filtering and shaping methods allows payloads to be moved to their destinations faster and with less residual oscillation. The goal of filter and input shaper comparison is to provide the means to experimentally validate the superiority of the input shaper to the conventional filter. Previously, work was done with WinCC software in order to create a user interface in which the position of the tower crane trolley and payload are displayed on a WinCC graphical user interface (GUI) along with the available workspace and a set of controls for actuating the crane. The project further develops the user interface by providing a predictor, with the goal of demonstrating an improvement in user efficiency.
INTRODUCTION

Cranes, as well as all flexible systems, vibrate during their use, reducing the accuracy of their desired operations. Filters and input shapers are devices which attempt to reduce vibration in a flexible system by convolving the input signal in some way. Digital notch filtering, digital low-pass filtering, and input shaping are three well-known methods for modifying reference commands to reduce vibration in flexible systems. Reference commands are inputs which, in this case, drive the crane to a desired location and are actualized through some form of user interface. Flexible systems are systems containing a flexible body which would be modeled as a spring that causes some vibration in the system. Like filtering, input shaping has been shown to effectively reduce vibration (Smith, 1957, Bhat, 1990). In unshaped signal generation of tower cranes, the load on the crane will always have residual oscillation or swaying due to the crane’s motion. The first sections of the project pertain directly to the comparison of these different filtering methods on reducing such vibration.

In mechanical systems, filtering and input shaping are primarily used for vibration reduction. Filtering reduces vibration by suppressing certain frequencies. For example, a low-pass filter allows low frequencies to pass while suppressing all other frequencies. Notch filtering allows low and high frequencies to pass while suppressing a defined range of frequencies.

Input shaping specifically reduces vibration by taking an input command into a system and modifying it by convolution into two or more impulse sequences which add up to the original signal. These impulses are timed such that the residual vibration resulting from them will be 180 degrees out of phase and thus cancel out. Figure 1 shows a hypothetical system response to a step input. The system is assumed to be undamped, meaning that it is free to oscillate without any reduction due to friction or other effects.

Suppose this input signal instead was separated into two impulses, each at 50% of the desired original impulse. Each of these impulses would have a residual vibration associated with it. Through proper spacing of these impulses in time, one can theoretically cancel the vibration by spacing these impulses such that the residual vibrations of both impulses are 180 degrees out of phase and thus cancel each other. Such a system would provide zero residual vibration, as illustrated in Figure 2.

![Figure 1. Hypothetical system response (right) to a step input (left). The desired step input is red, while the actual system response is in blue.](image1)

![Figure 2. Example of input shaping using a hypothetical response (right) to a convolved step input (left). The blue line is the residual vibration of the first impulse, while the dotted black line is the residual vibration of the second impulse. The solid black line represents the total vibration of the system.](image2)
Since the introduction of robust input shaping, substantial evidence has led to the assessment that input shaping is superior to both notch and low-pass filtering for suppressing vibration in mechanical systems (Singer, 1999). In this project, input shapers and conventional filters were compared using simulations based on 3 criteria: filter duration or the “filter length is a lower bound on the move time,” residual vibration in the system, and robustness to system uncertainties (Singer, 1999). It was found that, based on the aforementioned criteria, input shapers should always be equal or superior to conventional filters. In the project, experimental data was tabulated which will be used to attempt to further previous research regarding the superiority of input shapers.

There are, however, tradeoffs to a reduction in vibration. Such vibration reduction results in a longer filter and shaper duration because the command is convolved into a more complex series of pulses. This slower response causes a tendency for the user to drive the system past a desired location. To attempt to reduce this problem, a predictor was designed which predicts the end position of the crane after the user has given it a command response. By using a predictor, a user can navigate to a desired location and know that, when the system response ceases, the predicted end position will coincide with the actual end position, preventing the overshoot problem. As such, a predictor should allow faster response times. The purpose of the project is to provide a means by which future experiments can prove whether a predictor improves operator performance using input shaping.

**METHODS**

The first task of the project was to generate oscillation data for the bridge crane regarding a low-pass filter, a notch filter, and an Extra Insensitive (EI) shaper. The EI shaper is a robust form of input shaper which suppresses vibration for a wide range of frequencies.

For each trial, a model tower crane was given a full velocity step input for a fixed duration. In order to ensure that these velocities remained constant, a previously generated straight line trajectory was used for the trials. The oscillation data was recorded by measuring the distance which the payload swayed from the trolley position via a camera mounted on the trolley. The camera works by generating light at a desired frequency and then detecting the reflection of that light off of a reflective surface attached to the hook of the tower crane. Then, the camera takes the data it receives from the hook at a specific angle and stores that data in a position matrix. An algorithm designed in MATLAB then determines the displacement by converting camera output data into centimeters of displacement. This is done using a conversion factor determined experimentally, by comparing a measured hook displacement to its corresponding camera output.

The three filters were then compared based on their vibration amplitude at different frequencies. Specifically, peak-to-peak vibration amplitude resulting from different shaper types for different cable lengths of the crane was measured using a tape measure. These oscillation amplitudes, resulting from the different commands, were tabulated at cable lengths of 15, 16, 18, 20, 22, 24, 26, 30, 34, 38, 42, 46, 54, and 62 inches. The vibration reduction methods that were tested include: unshaped (no filters or shaping), low-pass filter, notch filter, and the EI shaper. The next task was to generate shaper results for different pass band frequencies. The insensitivity of low-pass and notch filters was examined at different edge frequencies, ranging from 0 to 0.5, in order to determine its effect on filter duration by plotting the edge frequency versus the filter duration. The insensitivity of a filter or shaper is essentially a measure of the robustness of that filter/shaper to reduce vibration despite changes in frequency. The final task was to create a predictor for input shaper position to use with tower crane Programmable Lan-
language Controller (PLC) and Windows Control Center (WinCC) software. The PLC is used to interface the tower crane with a computer and the WinCC allows the user to interface with the PLC program via a graphical user interface. The purpose of this task was to create a predictor for use in tests to assess any increase or decrease in efficiency resulting from having the predictor.

DATA ANALYSIS FOR FILTERS AND COMMAND GENERATION

Figure 3 shows average data from three trials for each of the filters and shapers analyzed. The low-pass filter generally maintained the lowest peak-to-peak amplitude of the filters. Note that the unshaped command dips at roughly 38 inches to provide almost no residual vibration. This occurs because, at that particular length of the cable, the corresponding command acts like a filter. The filtered and shaped methods were all expected to produce less vibration than the unshaped case.

As previously mentioned, a major measure of the robustness of a filter or shaper is its insensitivity. When modeling error increases, the actual frequency differs more from the theoretical modeled frequency and results in vibration; the insensitivity is a measure of how much the actual frequency can differ from the modeled frequency while remaining within a certain tolerable level of vibration. Insensitivity data was tabulated based on camera data associated with Figure 3, generated using previously mentioned methods. Figures 4, 5, and 6 show both theoretical and experimental magnitude curves for the low-pass filter, notch filter, and EI shaper, respectively, at various normalized frequencies. Data generally deviates from the model due to actuator limits on the crane. Actuators, in the case of the crane, are electric motors, and they are limited by physical constraints such as a maximum speed and torque. These system actuator limits prohibit the crane from accurately matching
The next task was to generate shaper results for different pass band frequencies. Pass band frequencies are the range of frequencies that a band pass filter allows to pass while suppressing all other frequencies. Figure 7 shows an example of a band pass filter. At frequencies below \( \omega_{p1} \) and above \( \omega_{p2} \), the signal is suppressed by the filter. Between those two pass band frequencies, however, the signal is not suppressed.

For this experiment frequencies ranged from 0.05 Hz to 0.5 Hz in intervals of 0.05 Hz. In order to generate these values, MATLAB’s shaper toolbox was employed. These durations were generated based on theoretical models rather than direct experimentation. The goal of the band pass generation was to determine the validity of previously generated data in hopes of improving on previous results.

The data deviates farther from the model for a notch filter. This discrepancy arises due to the fact that the notch filter is a significantly more complex filter than the other cases discussed. Notch filter complexity makes the command more difficult for the crane to track, which leads to vibration. Therefore, the results from the notch filter are more prone to deviation from the model.

**DURATION AND INSENSITIVITY DATA ANALYSIS FOR FILTERS**

The desired signal input sent to the system. In all cases, the vertical axis is the magnitude of the insensitivity while the horizontal axis is the normalized frequency, found by dividing each frequency by their maximum values in each case. The blue line represents the expected insensitivity for each normalized frequency while the red squares represent the experimental data at various frequencies. The red bars represent an estimated error associated with the experimental values. The \( V_{\text{tol}} \) term is the tolerable amount of vibration for the system, arbitrarily decided to be 5%. The EI shaper works based on a given tolerable level of vibration and so this value may be chosen at will.

The data deviates farther from the model for a notch filter. This discrepancy arises due to the fact that the notch filter is a significantly more complex filter than the other cases discussed. Notch filter complexity makes the command more difficult for the crane to track, which leads to vibration. Therefore, the results from the notch filter are more prone to deviation from the model.

**Figure 5.** Magnitude of the insensitivity \( |I(s)| \) versus normalized frequency for an EI shaper, determined both theoretically and empirically.

**Figure 6.** Magnitude of the insensitivity \( |I(s)| \) versus normalized frequency for a notch filter, determined both theoretically and empirically.
increasing the frequency of the filters has little effect on the filter duration, as shown in Figure 8. Edge frequencies, $\omega_{p1}$, were generated using 10 Hz, 20 Hz, 50 Hz, and 100 Hz sampling rates.

The sample time versus the filter duration at two different pass band frequencies $\omega_{p1}$ and $\omega_{p2}$ is shown in Figure 9. Note that as the sample time increases, the filter duration remains nearly constant for both pass band frequencies.

The next focus of the project was to evaluate the insensitivity of the low-pass and notch filters and determine how these changes in insensitivity affect the duration of the filter. The insensitivity of a filter is a built in measure of the robustness of that filter. Unfortunately, to produce a more robust filter, the filter will often require a longer duration (Vaughan, 2007). Filter insensitivities do vary from filter to filter so comparison between various filters is necessary. These effects for the low-pass filter are demonstrated in Figure 10. Note that when the insensitivity of the filter is increased, the duration for that filter also increases. Furthermore, as the pass band frequency is increased, the duration increases asymptotically.
Similar trends occur in the notch filter as shown in Figure 11. As the insensitivity of the filter increases, the duration also increases. Likewise, as the bandpass frequency is increased, the duration increases. Further, as pass band frequencies are increased, durations approach an asymptote and their calculation no longer becomes feasible. Therefore, the low-pass filter was only run at pass band frequencies ranging from 0.05 to 0.45 Hz while the notch filter ran at frequencies ranging from 0.05 to 0.40 Hz. The tremendous increase in filter duration required to get robust filters shows the inherent superiority of using input shaping which does not require such increases in duration (Singer, 1999).

FUNCTIONALITY OF A WINCC PREDICTOR FOR A TOWER CRANE PLC

The final goal of the project was to create a predictor for input shaper position for use with the tower crane PLC and WinCC software. In order to create the predictor, the associated parts of the GUI including buttons and subroutines had to be created. This predictor will then be used in future experiments to determine if it too improves the control effort. Previous work had been done with the WinCC software, provided by Siemens, in order to create a user interface in which the position of the tower crane trolley and payload are displayed on the WinCC along with the available workspace.

Figure 10. Effect of insensitivity change on both duration and frequency for a lowpass filter.

Figure 11. Effect of insensitivity change on both duration and frequency for a notch filter.
and a set of controls for actuating the crane. The basic workspace design for the crane is shown in Figure 12.

This workspace was modified by adding a predictor which predicts the final destination of the input shaper as a total displacement of the unshaped case. Recall that by adding a shaper to an unshaped command, the shaper essentially modifies the input signal at percentages of its maximum allowable motion. The total distance output by the shaper command will match that of the unshaped command but using a longer duration, thereby creating the potential for the user to overshoot the destination. Therefore, by using the unshaped command as a predictor, a driver will know by the predictor where the trolley will eventually finish when the shaped command is passed through the system thus predicting its final destination. Figure 13 shows the modified user interface.

Likewise, Figures 14(a) and Figure 14(b) show the predictor being actuated on a path. In Figure 14(a), the predictor has begun moving while in Figure 14(b), the predictor has finished its motion. As the predictor moves along the path at the unshaped command velocity, the actual trolley position trails behind at its respective percentage of the maximum velocity. Eventually, the predictor and trolley come to rest at the desired end location, shown in Figure 15.

**CREATION OF THE WINCC AND PLC PREDICTOR**

In order to communicate between the WinCC and PLC program, entities called tags are created in the WinCC. These tags are identified with various components of the user interface. Each tag references a symbolic variable in the PLC program. In turn, this symbolic variable communicates with various parts of the PLC program and may be modified and re-entered into the WinCC to update data values. Symbolic variables may also update data blocks in the PLC. Data blocks are used to store data passing into the PLC through symbols, the PLC program and the tower crane. Figure 16 shows a graphical representation of the WinCC and PLC interface with the tower crane.

The PLC program is itself divided into various types of blocks: data blocks provide storage for variable values and other forms of data; function blocks contain both data and functions. Functions contain the bulk of the script which tells the PLC program what to do. One such function, the organization block, is type of master function which drives the other functions. This function is necessary to control the subroutines.

A function was created to determine and update the predictor position so that the user can visually account for and adjust to the command delay that is caused by input shaping and filtering methods. The function is cycled every 100 ms and inputs the current trolley and slewing velocities. The trolley velocity is measured by the rate at which the trolley position moves radially in or out.
The slewing velocity is the velocity of the trolley moving either clockwise or counterclockwise around its axis. After the function inputs the current velocities, it then outputs an updated predictor position to the data blocks. At the start of the program, a counter starts which will set the position of the predictor to the position of the trolley while the counter is less than 10 cycles (1 second). The counter cycles each time the function is called so the counter will set the predictor to the position of the trolley for the first 1 second of the program. This counter functionally resets the predictor for the user when the user performs a new motion. The function also contains a variable corresponding to the reset predictor button on the WinCC. Whenever the reset predictor button is pushed, the counter is reset to zero, causing the predictor to re-align itself with the position of the trolley for 1 second. A reset button is necessary for the predictor because there is no feedback between the predictor and the trolley position. Without feedback, the predictor would become more inaccurate with continued use. Predictor

Figure 13. Modified interface, with predictor. The yellow circle now represents the payload position, while the green rectangle is again the trolley position. The red target (behind the rectangle) is now the predictor position.

Figure 14. (a) Actuated predictor motion begins. (b) Actuated predictor motion ceases.

Figure 15. Trolley position ends at predictor position.

Figure 16. Tower crane interface with WinCC and PLC.
inaccuracy could occur for several reasons: sometimes the motor speed will perform differently, causing a discrepancy between the predictor position and the actual position. The calibration of the predictor is performed experimentally and is subject to some calibration error. As such, there is need for the reset button.

Several changes were also made to the WinCC program aside from the creation of the predictor. A button was added to toggle the predictor on and off. This option is done in order to perform comparative tests to demonstrate that operator effectiveness increases with the addition of a predictor. For example, one trial would be done with the predictor activated and another without it in order to compare the trials. Moreover, button sizes were enlarged on the GUI in order to make operating the trolley easier using the WinCC.

CONCLUSIONS
Results of the comparison between different filtering methods conformed with previous experimentation. However, tabulated data in Figure 3 does not take the filter duration into account, skewing the results toward favoring the low-pass filter. Figure 8 illustrates that, for a low-pass filter, the edge frequency causes drastic changes to the filter duration. Edge frequency values in Figure 4, using different band pass frequencies, contained higher filter durations than values previously tabulated which was probably due to the usage of MATLAB’s filter toolbox which uses less robust techniques. Edge frequencies were calculated using a best initial guess representing the number of pulses. Previously generated data may have used more robust techniques for determining an optimal value, thereby producing a shorter filter duration. Additionally, the insensitivity of low-pass and notch filters was examined at different edge frequencies in order to determine the effect on filter duration. Results of this analysis yielded an increase in edge frequencies as well as increasing insensitivity as shown in Figures 10 and 11.

Once the superiority of the input shaper was evaluated experimentally, the added effect of a predictor could be evaluated. A predictor was constructed which accurately predicts the final location of the tower crane motion. This predictor provides real-time predictor position as the tower crane is actuated by the operator, allowing the operator to more accurately determine the end location of the trolley and greatly reducing the likelihood of overshoot. The purpose of the last task was to create a predictor for the user interface such that later tests would be conducted to verify its utility. These tests will consist of a user navigating an obstacle course using an unshaped command, an input shaper, and an input shaper with a predictor. The improved usefulness of the predictor will be measured based on number of collisions, time required to navigate the course, final displacement from the target, and number of button presses. Should the predictor prove to provide faster navigation, it could greatly improve the efficiency of moving payloads to desired destinations in numerous real world applications.
REFERENCES


**SUBMISSION GUIDELINES**

*The Tower* accepts papers from all disciplines offered at Georgia Tech. Research may discuss empirical or theoretical work, including, but not limited to, experimental, historical, ethnographic, literary, and cultural inquiry. The journal strives to appeal to readers in academia and industry. Articles should be easily understood by bachelors-educated individuals of any discipline. Although *The Tower* will review submissions of highly technical research for potential inclusion, submissions must be written to educate the audience, rather than simply report results to experts in a particular field. Original research must be well supported by evidence, arguments must be clear, and conclusions must be logical. More specifically, *The Tower* welcomes submissions under the following three categories: articles, dispatches, and perspectives.

**FORMATTING**

*Articles*
An article represents the culmination point of an undergraduate research project, where the author addresses a clearly defined research problem from one, or sometimes multiple approaches.

A properly formatted article must: be between 1500 and 3000 words (not including title page, abstract, and references); include an abstract of 250 words or less; and have at least the following sections:

- Introduction / Background Information
- Methods & Materials/Procedures
- Results
- Discussion / Analysis
- Conclusion
- Acknowledgements

*Dispatches*
A dispatch is a manuscript in which the author reports recent progress on a research challenge that is relatively narrow in scope, but critical toward his or her overall research aim.

A dispatch should: not be more than 1500 words (not including title page and references); and have at least the following sections:

- Introduction / Background Information
- Methods & Materials / Procedures
- Results
- Discussion / Analysis
- Future work
- Acknowledgements, as a separate page

*Perspectives*
A perspective reflects active scholarly thinking in which the author provides personal viewpoints and invites further discussions on a topic of interest through literature synthesis and/or logical analysis.

A perspective should: not be more than 1500 words (not including title page and references); address some of the following questions: Why is the topic important? What are the implications (scientific, economic, cultural, etc.) of the topic or problem? What is known about this topic? What is not known about this issue? What are possible methods to address this issue?

*General*
The following formatting requirements apply to all types of submissions and must all be satisfied before a submission will be reviewed. All papers must: adhere to APA formatting guidelines as
specified in the Publication Manual of the American Psychological Association, 5th ed. (Washington, DC: American Psychological Association, 2001); be submitted in Microsoft Word format; be set in 12-point Times New Roman font, double-spaced; not include identifying information (name, professor, department) in the text, reference section, or on the title page. Papers will be tracked by special software that will keep author information separate from the paper itself; be written in standard U.S. English and utilize standard scientific nomenclature define new terms, abbreviations, acronyms, and symbols at their first occurrence; acknowledge any funding, collaborators and mentors; not use footnotes — if footnotes are absolutely necessary to the integrity of the paper, please contact the AESR at review@gttower.org; reference all tables, figures, and references within the text of the document; adhere to the Georgia Institute of Technology honor code regarding plagiarism and proper referencing of sources; and keep direct quotations to an absolute minimum — paraphrase unless a direct quote is absolutely necessary.

**ELIGIBILITY**

Submitters must be enrolled as undergraduate students at the Georgia Institute of Technology to be eligible for consideration. Authors have up to three months after graduation to submit papers regarding research completed as an undergraduate.

**SUBMITTING**

To submit a paper, authors must register on our Online Journal System (OJS) at http://ejournals.library.gatech.edu/tower. Once the author fills out the required information and registers as an author, he or she will have access to the submission page to begin the multi-step submission process.

For more detailed submission guidelines, as well as current deadlines and news, please visit: http://gttower.org.

**DEADLINES**

Submissions are accepted on a rolling basis throughout the year. The Tower publishes several issues per year. Due to the review and production process, for submissions to be considered for each issue they must be submitted before the publicized deadline, which can be found at gttower.org. Submissions received after this deadline will be considered for the following issue. If the quality of their submission were to be compromised to meet the deadline, authors are encouraged to further develop their work and only submit it once it is fully realized.
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BME, ’89

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