CIFE Seed Proposal Summary Page
2005-2006 Projects

Proposal Title: Computational Modeling of Nonadaptive Crowd Behaviors for Egress Analysis

Principal Investigator(s): Kincho H Law, Jean-Claude Latombe, and Ken Dauber.

Research Staff: Xiaoshan Pan

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Total Funds Requested: $69,191

First Submission? No **If extension, project URL:** http://eil.stanford.edu/egress/

Abstract (up to 150 words):

Safe egress is one of the key design issues identified by facility planners, managers and inspectors. Current computational tools for the simulation and design of emergency egress rely heavily on assumptions about human individual and social behaviors, which have been found to be oversimplified, inconsistent and even incorrect. This research aims to develop a framework for modeling human and social behaviors from the perspectives of human decision-making and social interaction and to incorporate such behaviors in a dynamic computational model suitable for emergency egress analysis. For the year-1 project, we have developed a theoretical framework of crowd behavior and a proof-of-concept, multi-agent based crowd simulation model. In the year-2 project, we plan to study the scalability and modularity issues of the simulation framework, to validate the models, and to incorporate engineering analyses, such as performance-based assessment of facilities, design of egress and emergency plans.

Computational Modeling of Nonadaptive Crowd Behaviors for Egress Analysis

1. ENGINEERING PROBLEM

The main objective of this research is to develop a computational framework that can facilitate the study of human and social behavior for emergency exits in buildings and facilities. Design of egress for places of public assembly is a formidable problem in facility and safety engineering. Although provisions governing egress design are prescribed in code, the actual performance of evacuation systems is difficult to assess. There have been numerous incidents reported regarding overcrowding and crushing during emergency situations. In addition to injuries and loss of lives, the accompanying post-disaster psychological suffering, financial loss, and adverse publicity have long-term negative effects on the individuals and organizations – the survivors, the victims' families, the corporations involved and the communities [1].

In a crowded environment, it has been observed that most victims were injured or killed by the so called "nonadaptive" behaviors of the crowd, rather than the actual cause (such as fire or explosion) of the disaster. Nonadaptive crowd behaviors refer to the destructive actions that a crowd may experience in emergency situations, such as stampede, pushing, knocking, and trampling on others, etc.; these actions are responsible for a large number of injuries and deaths in man-made and natural disasters. For example, in the Iroquois Theatre fire (in 1903), the initial fire was brought under control quickly; however, 602 people were trampled to death in the end. Another example is the Hillsborough English FA Cup Stampede (in 1981); there were no real causes of emergency but still 95 people died and over 400 people were injured. To study nonadaptive behavior in a crowded environment, we need to take into consideration the human and social behavior in emergency situation from both psychological and sociological perspectives.

Building codes contain "means of egress" provisions designed to ensure the safety of a building [2]. However, these codes only provide basic guidelines and are not exhaustive and often insufficient for many practical situations [7]. First, current codes and guidelines contain inconsistencies which may lead to misinterpretations. An effective computational tool can test whether a specific guideline is appropriate for a particular situation. Second, each building is unique, and compliance with design guidelines does not automatically ensure safety. Often, local geometries – shapes and sizes of spaces and obstacles – can have significant influence to egress, albeit in a subtle way. To date, very few studies can be found in existing literature in terms of understanding how environmental constraints and local geometries impact crowd behaviors and movements. This type of studies is difficult since it often requires exposing real people to the actual, possibly dangerous, environment. A good computational tool which takes into consideration of human and social behavior of a crowd could serve as a viable alternative. Computational tools are now commercially available for the simulation and design of emergency evacuation and egress. However, these tools focus on the modeling of spaces and occupancies and aim mostly to animate crowd movements but they rarely take into consideration human and crowd behaviors.

This research proposes to study human behaviors and social interactions, and to incorporate such behaviors in a dynamic computational model suitable for safe egress analysis. The computational model will be able to adapt egress analysis suitable for specific design circumstances and provide insight to current prescriptive and often, ambiguous codes and provisions for egress design. Also, the model can serve as a means to study safety engineering, such as assessing building codes and designs, testing safety and evacuation procedures, and crowd management.

For the year-1 seed project, we have so far developed a theoretical framework of crowd behavior and built a proof-of-concept crowd simulation model. In the year-2 project, we plan to study the scalability and modularity issues of the simulation framework, to validate the models, and to incorporate engineering analyses, such as performance-based assessment of facilities, design of egress and emergency plans.

2. POINTS OF DEPARTURE

The proposed research will build upon the current understanding of nonadaptive crowd behavior in emergencies. Generally speaking, existing theories on crowd behavior in emergency situation can be classified into three basic categories: (1) panic [9-12], (2) decision-making [13,14], and (3) urgency levels [15]:

- *Panic* theories deal primarily with the factors that may cause panic during emergencies. The basic premise is that when people perceive danger, their usual conscious personalities are often replaced by the unconscious personalities which in turn lead them to act irrationally unless there is a presence of a strong positive social (such as a leader) influence.
- *Decision-making* theories assume that a person, even under dangerous situation, can still make (albeit limited) rational decisions, attempting to achieve good outcomes and objectives in the situation [14]. These “rational” decisions however may or may not improve the overall emergency evacuation. In a situation such as a fire, cooperating with others and waiting one’s own turn can likely be beneficial to the group and, in turn, increasing the individual’s likelihood of exiting a facility. On the other hand, if some people are pushing, then an individual may feel threatened if he/she does not react; the best course of action for the individual may be to join the competition and push, in order to maximize his/her chance of exiting.
- Another theory suggests that the occurrence of (human) blockages of exiting space depends on the *levels of urgency* to exit [15]. There are three crucial factors that could lead to such situation: the severity of the penalty and consequence for not exiting quickly, the time available to exit, and the group size. A problem arises when the urgency to leave reaches a high level of anxiety – for example, too many people try to exit quickly at the same time. Thus, any efforts that can reduce the number of people having a high urgency to leave will likely cause a decrease in jams and less entrapment.

There have been a wide variety of computational tools, many of them are now commercially available, for egress simulation and design of exits. Most existing models can be categorized into fluid or particle systems, matrix-based systems, and emergent systems:

- Many have considered the analogy between *fluid* and *particle* motions (including interactions) and crowd movement. Two typical examples of fluid or particle systems are the Exodus system [4] and the panic simulation system built by Helbing et al. [6]. Coupling fluid dynamic and “self-driven” particle models with discrete virtual reality simulation techniques, these systems attempt to simulate and to help design evacuation strategies. However, as noted by Still [7], “the laws of crowd dynamics have to include the fact that people do not follow the laws of physics; they have a choice in their direction, have no conservation of momentum and can stop and start at will." Fluid or particle analogies also contradict with some observed crowd behaviors, such as herding behavior, multi-directional flow, and uneven crowd density distribution.

- The basic idea of a *matrix-based* system is to discretize a floor area into cells. Cells are used to represent free floor areas, obstacles, areas occupied by individuals or a group of people, or regions with other environmental attributes. People transit from cell to cell based on occupancy rules defined for the cells. Two well known examples of the matrix-based systems are Egress [3] and Pedroute [5], which have been applied to simulate evacuation in buildings as well as train (and underground) stations. It has been revealed that existing matrix-based models cannot simulate crowd cross flow and concourses; furthermore, the assumptions employed in these models are questionable when compared with field observations [7].
- The concept of *emergent systems* is that the interactions among simple parts can simulate complex phenomena such as crowd dynamics [16]. One example of the emergent systems is the Legion system [7]. It should be noted that Legion was not designed as a crowd behavioral analysis system but an investigation tool for the study of large scale interactive systems. Current emergent systems typically oversimplify the behavioral representation of individuals. For example, the Legion system employs only four parameters (goal point, speed, distance from others, and reaction time) and one decision rule (based on assumption of the least effort) to represent the complex nature of individual behaviors. All individuals are considered to be the same in terms of size, mobility, and decision-making process. Finally, the model ignores many important social behaviors such as herding and leader influence.

In summary, as noted by the Society of Fire Protection Engineers [8], "These [computational] models are attractive because they seem to more accurately simulate evacuations. However … they tend to rely heavily on assumptions and it is not possible to gauge with confidence their predictive accuracy," and "the fundamental understanding of the sociological and psychological components of pedestrian and evacuation behaviors is left wanting [17]."

3. PROPOSED RESEARCH

3.1 Research Methods

Figure 1 depicts the basic iterative approach undertaken to study the human and social behaviors and to develop a computational framework for egress simulation and analysis. The research starts with literature studies and field interviews on crowd behaviors in the areas of human decision-making, social interaction, safety engineering, and computer simulation. We then derive the variables, hypotheses, and human behavior rules and patterns, which are then formalized and incorporated into a multi-agent based simulation framework. The results are in turn analyzed to capture the patterns of crowd behavior. The research results are evaluated and validated through comparing with prior observations and historical cases as well as by practicing experts in the field. Observed and derived information are then incorporated to the framework for further simulation.

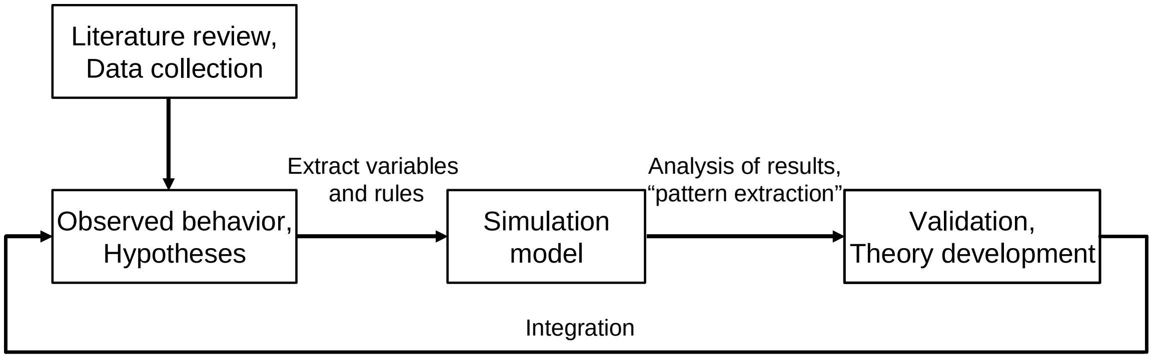

Figure 1: Research process

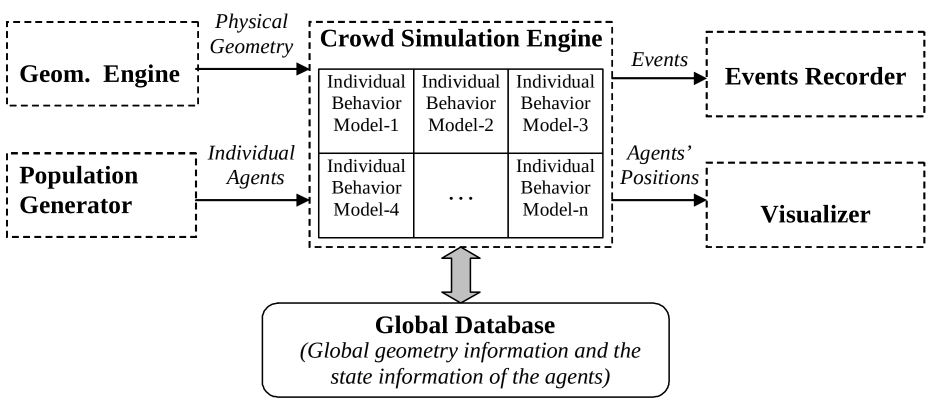

Figure 2: System Architecture

The proposed system architecture of the simulation framework is schematically shown in Figure 2. The current system is based on a multi-agent simulation framework which consists of five basic components: a Geometric Engine, a Population Generator, a Global Database, a Crowd Simulation Engine, an Events Recorder, and a Visualization Environment.

- Geometric Engine: The purpose of this module is to produce the geometries representing the physical environments (e.g., a building or a train station, etc.). AutoCAD/ADT (Architectural Desktop Software from AutoDesk, Inc.) is employed in this study. The geometric data is sent to the Crowd Simulation Engine to simulate crowd behaviors.
- *Population Generator*. This module generates virtual agents to represent a crowd based on the distribution of age, mobility, physical size, and type of facility (hospital, office building, train station, stadium, etc.) to be investigated. The population and its composition for each type of facility would be different. For example, we can assume most (not all) of the occupants in an office building will likely be familiar with the facility; on the other hand, the same assumption cannot be applied to a theme park. This module also generates random populations for statistical study of individual human behaviors and crowd behaviors.
- *The Global Database.* The database module is to maintain all the information about the physical environment and the agents during the simulation. Although the multi-agent system does not have a centralized system control mechanism, the state information (mental tension, behavior level, location) of the individuals are maintained. This database is also needed to support the interactions and reactions among the individuals.

- *The Events Recorder.* This module is intended to capture the events that have been simulated for retrieval and playback. The events captured can be used to compare with known and archived scenarios for evaluation purpose.
- *The Visualizer.* The visualization tool is to display the simulated results. We have developed a simple visualization environment that is able to receive the positions of the agents, and then generates and displays 2D/3D visual images.
- *The Crowd Simulation Engine.* This module is the core module of the multi-agent simulation system. Each agent is assigned with an "individual behavior model" based on the data generated from population generator. The Individual Behavior Model is designed to represent an individual human's decision-making process. Each agent responds to its environment using the decision rules and initiate actions and reactions accordingly. The internal mechanism of *the Individual Behavior Model* consists of the following *iterative* steps: (1) internally trigger for decision; (2) perceive information about the situation (i.e., crowd density, sensory input, tension level); (3) interpret and choose decision rule(s) to make a decision; (4) conduct collision check and execute the decision. Each autonomous agent will proceed to the (exit) goal subjected to the constraints imposed, acquire the behavior rules, select appropriate actions, interact with and update the Global Database as simulations proceed over time.

In addition to the simulation of crowd behaviors, the outputs of the system will also include overall and individual evacuation time, individual paths, and blockage locations. The simulation system is designed with sufficient modularity to allow further investigation of crowd dynamics and incorporation of new behavior patterns and rules as they are discovered.

3.2 Summary of Research Accomplishments and Further Investigations

For the first year seed project, we have studied a number of fundamental issues and built a prototype system. The following briefly summarize our accomplishments so far in this project.

- *Thorough review of human and social behavior literatures in the field of psychology, sociology, safety engineering, and egress simulation*. These literatures have confirmed the originality of the proposed work and supported the fundamental behavioral theories that are being investigated. Furthermore, a series of interviews with emergency personnel (fire marshals, police personnel, faculty members in social science, police science at Stanford University and other campuses). We have also evaluated a number of egress simulation tools (such as Exodus, Simulex, Egress, Pedroute, Legion and others) and "behavior animation" tools (such as Massive, Koga, etc..). The review so far has revealed the lack of human and social behavior in current simulation and animation systems.
- *Establishing a theoretical framework to study human and social behavior in emergencies.* The framework dissects the study of complex human and social behavior into three interdependent levels: individual, interaction among individuals, and group. Some fundamental factors and behavior pattern of crowd behavior are identified and formalized for constructing a simulation framework. This theoretical framework will also allow us to further investigate the dynamic changes of behavior during an emergency situation.
- *Developed a proof-of-concept prototype to simulation some frequently observed crowd behaviors*. A multi-agent based prototype has been built and is currently able to demonstrate some typical crowd behaviors such as competitive, queuing, herding behaviors and bi-directional crowd flow (as illustrated in Figure 3). Incorporating more

behaviors including some fatal overcrowding conditions are currently underway. Shortcomings of the current computational models have also been identified.

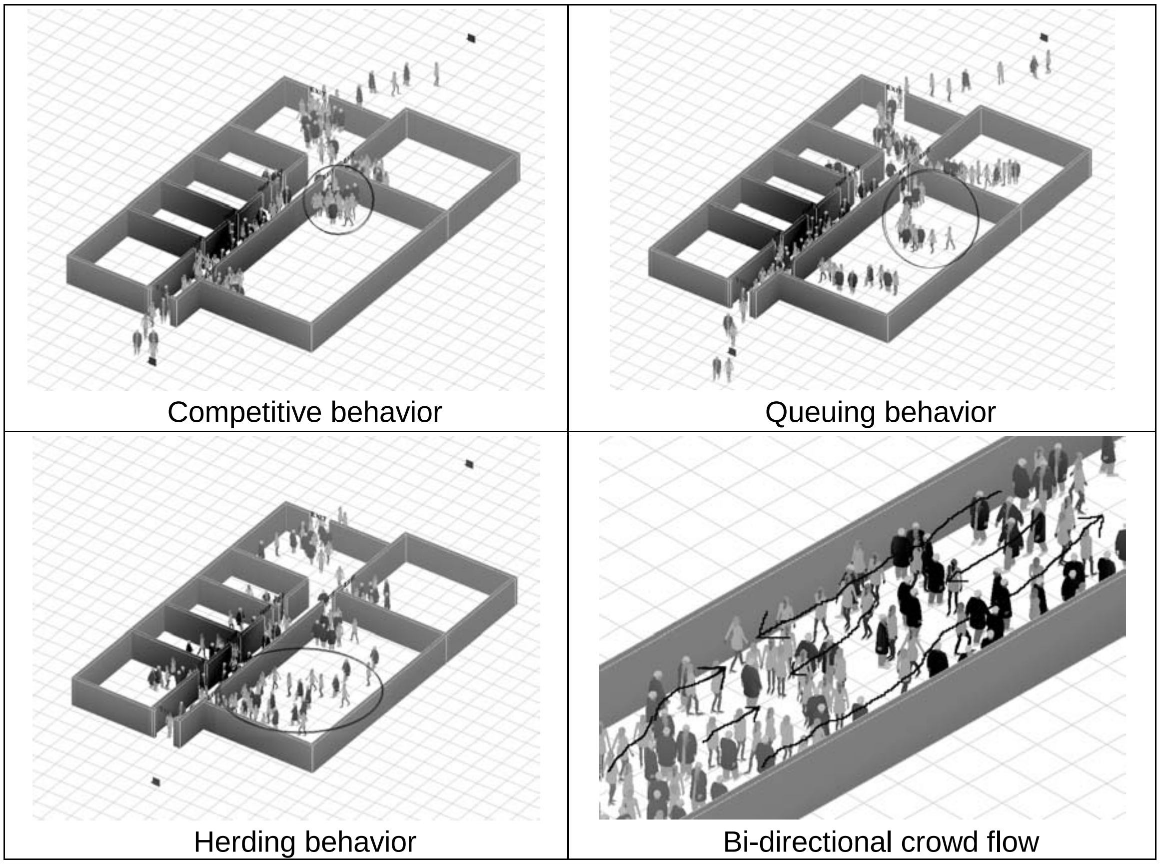
Competitive behavior | Queuing behavior
Herding behavior | Bi-directional crowd flow

Figure 3: Some behavioral patterns demonstrated using the prototype.

The research results so far have been accepted for publication and presentation at a number of academic and building engineering conferences [18-20]. These publications and the simulation results can be found in the project website: http://eil.stanford.edu/egress.

Results from current prototype study are indeed encouraging, judging from the interviews with the safety personnel and comments received during the advisory meetings. However, much research efforts, ranging from the study of human and social behaviors to the development of simulation framework, remain. In addition to continuing the work described in the first year funding proposal, the second year seed project will include fundamental research study on the following critical issues:

- So far, we have studied and incorporated some selected behaviors (competitive, herding, queuing, etc..). However, the so called “non-adaptive” behaviors, which are the causes of the injuries and fatalities, have not been formalized and systematically studied. This continuing effort will develop models that will include into consideration of pushing and other psychological factors (such as audible sounds).
- While we have demonstrated the prototype system successfully with a population of over 400 agents, the scalability of the system will be a key issue that needs to be studied carefully. Fast algorithms developed in the AI and Robotics program of the CS department will be adopted to improve the sensory capabilities and the crowd

movements. We envision that these fast algorithms can provide a scalable platform to handle thousands of agents for crowd simulation.

- We envision that the prototype system will be extended and used to integrated with other engineering analyses, such as performance-based assessments of facilities and spaces, design of egress and safety/emergency plans. The framework is currently being re-designed to provide sufficient modularity for such integration.

3.3 Research Impact

In safety engineering, because few efforts have been conducted to study the core of crowd safety problem – nonadaptive crowd behavior – from human psychological and sociological perspectives, the proposed research is expected to fulfill this gap and will subsequently lead to significant contributions to the field of crowd safety research, which, due to recent natural and man-made events, is fast becoming an important issue in facility design. A simulation tool such as the one proposed can be used to help facility design, emergency exits, evacuation plan. In addition, these types of simulation can help develop a wider range of possible solution to crowd problems. The tool can provide valuable information to guide the planning process, for construction, to develop crowd management strategies and for dealing with emergencies.

3.4 Milestones and Anticipated Risks

We anticipate that by the end of the first year period, the basic issues related to "non-adaptive crowd behaviors" will be thoroughly reviewed and the prototype system will be re-designed for modularity and scalability. For the proposed second year research period from September 2005 through August 2006, the research milestones are set up as follows:

- By the end of Fall Quarter 2005 – we plan to complete the preliminary implementation of a scalable simulation system, which allows (1) simulations for a significant number of agents in the crowd, and (2) predefined deterministic or random assignments of individuals in design spaces.
- By the end of Winter Quarter 2006 – we plan to test and to complete the implementation so that we can compare the simulated results and replicate the patterns of some historical overcrowding incidents and case studies on some real-life crowd settings (e.g., sport events and subway stations).
- By the end of Spring Quarter 2006 – we plan to analyze our findings and, if necessary, to develop a tool that will enable the analysis of large scale simulated results which may involve hundreds of randomized simulations for particular settings.
- By the end of Summer Quarter 2006 – we plan to complete a detailed report on this study. Furthermore, we anticipate that we will produce a range of experimental results by applying the simulation system to assess the performance of a variety of real facilities.

This research is a high-risk, high-payoff, interdisciplinary project (with participants from Civil Engineering, Computer Science and Sociology) that could lead to significant advancement in facility engineering and design. We anticipate the following risks:

- Human and social behaviors are complex subjects. The crowd behavior model that we aim to develop may not be sufficiently general for a broad range of scenarios. We address this risk by design the system with sufficient flexibility and modularity to allow further investigation of crowd dynamics and incorporation of new behaviors as they are discovered.

- The simulation of large number of crowds may require a significant amount of computations. We anticipate that a number of fast algorithms developed by the AI and Robotics group will be incorporated to ensure system scalability. If necessary, the PIs have significant experience in distributed and parallel computing research, and we do expect available computational platforms available to the PIs are sufficient to ensure the usability of the simulation systems.

4. RELATIONSHIP TO CIFE GOALS

Safe egress is one of the most critical issues in facility engineering and design. This research supports the “function” thrust area of this year’s Call For Proposal through developing a framework to help “assess how well the occupied facility meets the initial and then-current functional objectives” from safety engineering perspective. This research is highly interdisciplinary and can lead to immediate industrial applications, which closely match the CIFE mission.

5. INDUSTRY INVOLVEMENT

This project has received significant feedbacks from industries (e.g., Sydney Olympic Park, IR Security & Safety, and Disney) and other agencies. We will work with any organizations who have interests to be involved in our continuing research effort.

6. NEXT STEPS

Research proposal is currently under preparation for the new Human and Social Dynamics Program initiative from NSF. Furthermore, the PI is a member from Stanford in a pre-proposal for an NSF’s Engineering Research Center for Fire Engineering and Safety. We will continue to pursue government funding opportunities such as NSF, NIST, FEMA, Office of Homeland Security and others. This research towards the development of simulation system for emergency exits and egress design could have impact on emergency responses due to natural and man-made disasters. Successful demonstration of this research may lead to practical products needed by the industry.

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Project: CEE-FY05-290 --LAW: CIFE PROPOSAL BUDGET FOR 2005-2006

Department: Civil Engineering

Principal Investigator: LAW, KINCHO (Prof) - CE

Administrator: L. Unerdem

		Period 1		All Periods
		10/01/05 - 9/30/2006		10/01/05 - 09/30/06
		%	Amount	Total Amount
Salaries				
Senior Personnel				
Law, Kincho (Prof)	acad	0	0	0
	smmr	16	6,823	6,823
Latombe, J. (Prof)	acad	0	0	0
	smmr	8	4,477	4,477
Dauber, Kenneth (Assoc Dir)	cal	3	3,787	3,787
Graduate Students				
PhD Student, CE (Res Asst)	acad	50	21,154	21,154
	smmr	50	7,052	7,052
Total Salaries			43,293	43,293
Benefits				
Faculty			4,783	4,783
Graduate			959	959
Total Salaries and Benefits			49,035	49,035
Travel, Domestic				
Domestic Travel			1,500	1,500
Costs Not Subject to IDC Costs				
Tuition				
Tuition			18,656	18,656
Total Direct Costs			69,191	69,191
Modified Total Direct Costs			50,535	50,535
University IDC Costs				
Annual Amount Requested			**69,191**	**69,191**

Rates Used in Budget Calculations

Benefit Rates

Faculty: UFY06 31.70%; UFY07 31.70%;

Graduate: UFY06 03.40%; UFY07 03.40%;

Indirect Cost Rate

Special Rate: UFY06 00.00%; UFY07 00.00%;