Name of Organization:

Montana Tech
1300 W. Park Street
Butte, MT 59701

Title of Proposed Project:

Constructing a Combustion Tube Apparatus to Study In-Situ Combustion of Heavy Crude Oil including Toe Heel Air Injection, Shallow Reservoirs and Solvent and Catalyst Enhancements

Requested Amount: $500,000
Project Duration: 24 months

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High Degree: B.S.
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Project Summary

Intellectual merit

This proposal is to request funding to build a combustion tube apparatus to study in-situ combustion of heavy oil. In-situ combustion is a promising technique in the area of heavy oil recovery. Heavy oils are dense, viscous crudes that do not flow easily and cannot be produced by conventional means. In-situ combustion remedies this by using heat to lower the viscosity of the oil and break the long hydrocarbon chains. Through burning the heavy residuals, lighter, upgraded oil is produced. In-situ combustion has been used in the oilfield and improvements of the method are currently being studied.

The combustion tube setup we are proposing would allow properties of the upgraded oil, temperatures, rates of growth of heated areas and properties of effluent gasses to be measured. This instrumentation grant would allow for the construction, testing and application of a versatile in-situ combustion tube apparatus, with precise mass flow control, heat control, thermal imaging equipment, gas chromatography and various tube set-ups. It will be used in conjunction with a newly developed simulation model and when completed will help tune the simulator. The combination of lab apparatus and computer simulation will be an effective tool to study in-situ combustion and propose new enhancements to the process.

Broader impact

Montana Tech is in a good position to study heavy oil recovery. US reserves of heavy crude are nearby, and with our transfer agreement with two Alberta schools, many students arrive at Tech with a strong interest in working with heavy oil. The undergraduate class in Thermal Recovery is very popular, and a new graduate class is being developed to specifically study in-situ combustion and work with this apparatus. Graduate students will be able to work with this apparatus, and a number of graduate and undergraduate students will be able to obtain funding to assist with the construction and testing of the apparatus. This new equipment will also be a centerpiece of various engineering outreach events, and could be used to help generate enthusiasm about petroleum engineering among K-12 students.

In addition to the various educational uses of this equipment, this equipment will allow the department to conduct research in enhanced in-situ combustion, such as experimenting with different well configurations, solvents, and catalysts. Another important research opportunity will be in studying the effluent gasses produced, mainly CO and CO_2, and modeling how they are sequestered or migrate. We will also make this apparatus available to industry partners to conduct the preparatory laboratory analyses required to implement a field scale in-situ combustion project.

1. Project Description

1.1 Objectives and Expected Significance

The main objective is to build a versatile combustion tube apparatus to simulate in-situ combustion of heavy crude oil. In order to predict recovery or other important parameters of a proposed in-situ combustion operation, specific lab tests need to be run using this type of apparatus. Establishing this lab will also allow for the conduction of research into improvements of the in-situ process and provide a controlled environment to study explosions in industrial settings. In addition, this lab will provide students with hands-on experience with this important recovery technique and establish Montana Tech as a resource for local industry as they design recovery operations for eastern Montana heavy crudes. The in-situ combustion process will also be modeled with a newly developed thermal reservoir simulator model. The laboratory results will be initially used to calibrate the simulator, and the simulator will then be able to help design and verify new combustion tube experiments.

1.2 Background and Technical Need

In Situ Combustion Background

It has been reported that up to 70% (1) of the world's remaining oil resources are heavy oils, including reserves in Canada and in eastern Montana. Recoverable reserves in the range of 1 billion barrels are believed to exist in the Jurassic Swift formation in Montana. (2) These heavy oils are produced using a variety of enhanced oil recovery techniques that lower the viscosity of the crude thus allowing it to flow to the producing wells. Common thermal recovery techniques include injecting steam to heat the oil and the reservoir, and creating a combustion process in the reservoir itself. This latter process, known as in-situ combustion, has a lot of advantages along with many challenges. The process of in-situ combustion involves injecting oxygen, air, or oxygen enhanced air into an oil reservoir. This injected air creates a burning front which moves away from the injector wells in the direction of the producers. Ahead of this burning front is a mobile bank of upgraded oil which can be produced. Multiple processes are taking place during in-situ combustion. When oxygen is initially injected, a low-temperature oxidation takes place causing a release of heat and an increase in temperature. This temperature increase can lead to a spontaneous ignition and create the burning front (3). The high temperatures ahead of the burning front cause cracking of the heavy oil, producing a coke-like substance that serves as the fuel for the combustion (4). The remaining oil is lighter and less viscous, and moves ahead of the burning front towards the producing wells. The in-situ combustion process not only makes the oil less viscous, thus allowing it to be produced, it also upgrades the heavy oil, thus reducing the amount of refining required.

A number of methods have been proposed in order to enhance this in-situ process, including following the injection of air/oxygen with water in a process known as wet combustion (5). The heat in the recently burned zones will vaporize the water, thus creating the benefits of a steamflood along with the fireflood. Other enhancements include reversing the direction of the combustion to prevent a cold oil bank from forming around the producing well and restricting flow (6) and adding catalysts or solvents (7). The proposed laboratory equipment will be able to model these enhancements and investigate new ones as well.

In-situ combustion is a promising technique in many respects. It produces a high percentage of the original oil in place, the oil that is produced has been upgraded to lighter crude, and the injected air is abundant and cost effective. It has been noted, however, that in-situ combustion may not have reached its full potential (8) in field applications, and more research into both basic in-situ combustion and enhanced techniques is necessary.

Laboratory results from combustion tubes

In many forms of thermal recovery, such as steamfloods, basic calculations can be done quickly to estimate oil recovery and the size and growth rate of the heated area. These calculations are based on general reservoir information such as permeability and porosity, basic and easily measured oil and gas properties such as specific gravity and viscosity, and tabulated heat properties of water and reservoir rock (9,10). Such calculations can be a first step in deciding whether to proceed with a project. In the case of an in-situ combustion proposal, however, significant laboratory work is required in order to estimate oil recovery.

One of the first things that need to be determined to evaluate a potential fireflood is the amount of fuel that will be consumed per bulk reservoir volume. This is typically found in the lab by saturating a core or sandpack with a sample of the crude from the reservoir, placing it in a combustion tube, and measuring the amount of fuel used. This amount is then corrected due to the difference in porosity of the lab sand pack and the reservoir rock using equations such as Nelson and McNiel's (11).

$$m_R = \frac{1-\phi}{1-\phi_E} m_E \quad \text{(1)}$$

m_R: mass of fuel burned per bulk reservoir volume

m_E: mass of fuel burned per bulk volume of lab sample (core or sandpack)

φ: porosity of the reservoir

φ_E: porosity of the core or sandpack

The mass of fuel burned per unit volume in the lab will be able to be obtained by a mass balance based on careful measurements of the initial elements in the combustion tube, the remaining elements in the tube, and the liquids and gases collected at the end. With the knowledge of fuel consumed, it is possible to estimate the amount of air or oxygen required for a field scale project. Since in-situ combustion involves a chemical reaction of the oil with the oxygen, the parameters of that chemical reaction are also relevant to the process. While combustion of a single hydrocarbon in oxygen or air can be described as a fairly simple chemical equation, the combustion of a complex mixture of hydrocarbons in oxygen results in an equation with two important unknowns.

$$CH_x = (1 - 0.5m' + 0.25x)O_2 \rightarrow (1 - m')CO_2 + m'CO + \frac{x}{2}H_2O \text{..................} (2)$$

These unknowns are x, the atomic hydrogen/carbon ratio for the heavy oil and m', the ratio of CO to the total amount of CO_2 and CO produced by the reaction. Both of these can be measured using this lab apparatus using a relationship such as: (10)

$$x = 4(1 - m')\left(\frac{0.27c_{N_2} - c_{O_2}}{c_{CO_2}}\right) + 2m' - 4 \text{.....................................} (3)$$

c_{N2}: concentration of N_2
c_{O2}: concentration of O_2
c_{CO2}: concentration of CO_2

In addition, other kinetic parameters can be determined experimentally that will allow for the prediction of time to ignition in a reservoir (12) and with all these factors determined, it is possible to predict the amount of oil produced from an in-situ project using a method such as the one described in Nelson and McNiels (11) paper, in which the oil produced is calculated as a function of the burned volume of the reservoir, which is in turn a function of the parameters described above, such as the mass of fuel burned and the air used.

Simulation Model

As a companion to the lab apparatus, a numerical model of the combustion tube was built to run in the Eclipse Thermal reservoir simulator. When the combustion tube apparatus is built and tested, this numerical model can be tuned to the actual experiments. Once that is done, it can be used to help understand issues relating to scale, such as the effects of the boundary of the combustion tube; as a first step to suggest new experiments; and to determine if the lab equipment is performing as expected with each new project.

The simulator was built to model a core of the same size as the actual core in the combustion tube apparatus. The porosity and permeability were set to reasonable values for an oil sand, with permeability in all directions of 2000 mD and a porosity of 30%. . The simulation experiment runs for approximately two months, with an initial air injection rate of 0.1 mcf/day which is raised to 0.4 mcf/day after the first month.

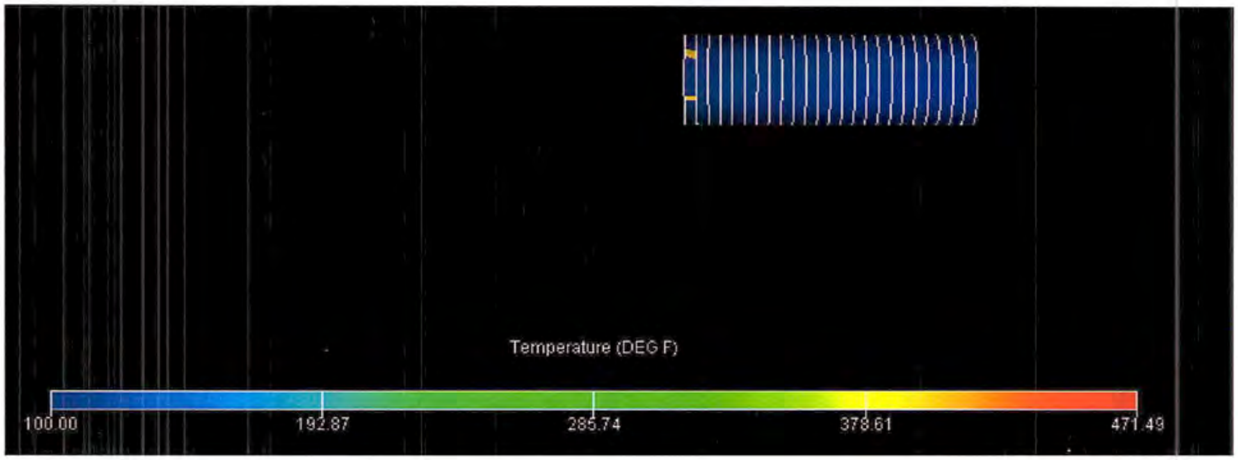

Figure 1: Temperature profile in the core at the beginning of the combustion.

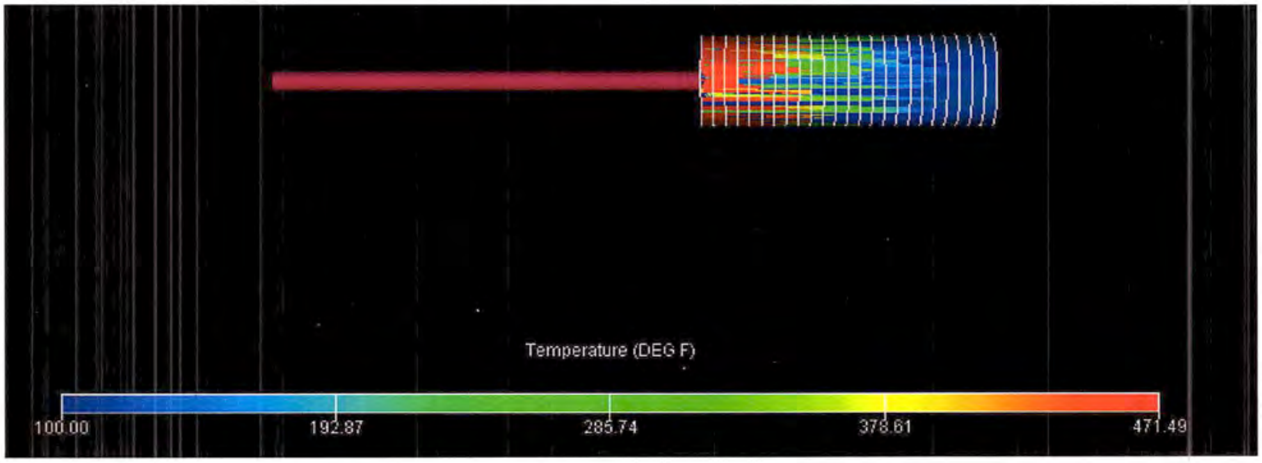

Figure 2: Temperature profile the end of the simulation run.

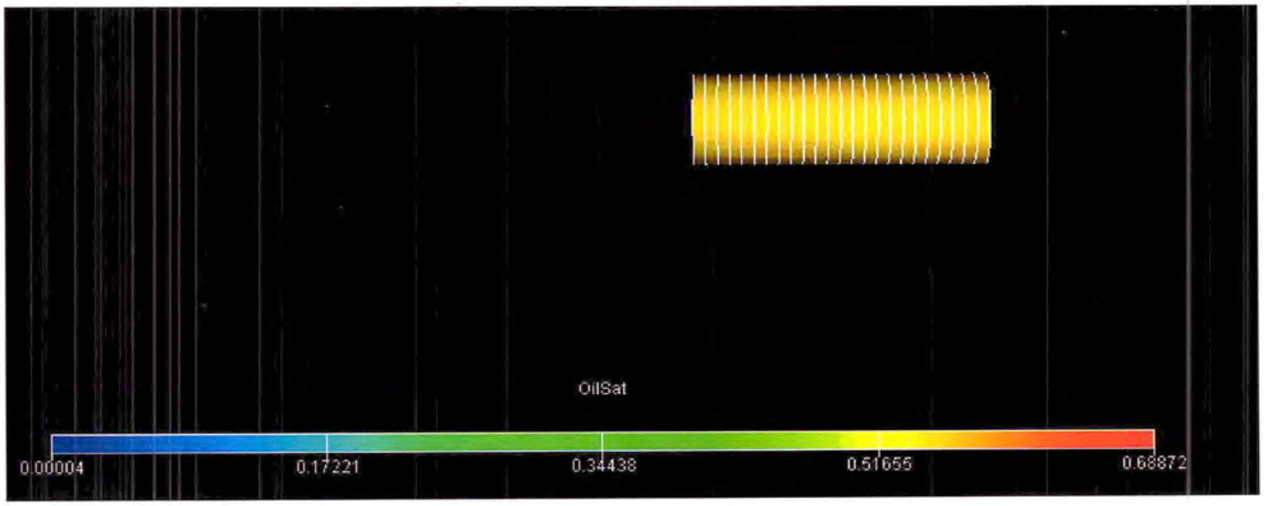

Figure 3: Oil Saturation at beginning of saturation run

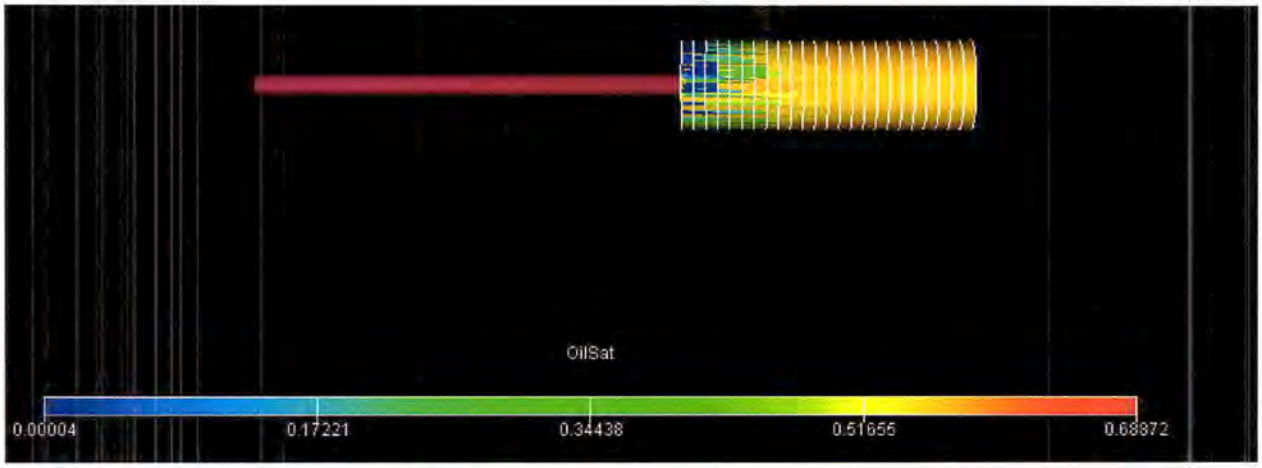

Figure 4: Oil Saturation at a later point in the saturation run, showing areas where the displaced oil has moved to increase the saturation at later places.

The simulation runs indicate that the combustion fronts are not stable. Unstable combustion fronts are considered one of the major drawbacks of in-situ combustion (13), therefore a major research goal of both the in-situ combustion tube and the simulated combustion tube is to determine if adding catalysts or solvents can lead to a more parabolic front.

In addition to the lab scale combustion tube simulation shown above, a second simulator model was created of a field scale in-situ combustion project. This model is currently being tuned by using the parameters described in a paper presented at the 1987 SPE Reservoir Simulation Symposium that provides valuable case study data of field and simulation tests (14).

1.3 Instrument Description

The work proposed here is to construct an in-situ experimental apparatus or combustion tube apparatus. Figure 5 illustrates the basic apparatus, and figure 6 is a more detailed description of a proposed combustion tube.

The combustion tube apparatus will consist of an insulated two-part combustion tube with an inner tube which will typically be filled with either a water, sand and heavy crude oil mixture or a core sample, modeling a typical heavy oil reservoir. A second tube will also be developed that will allow for a horizontal producing well to be modeled.

This inner combustion tube will be placed in the center of an outer tube filled with sand or another insulating material such as vermiculite. For in-situ experiments, the combustion tube will have heating bands on the outside that are controlled with thermocouples inside the tube to minimize heat loss to the tube, enabling us to model a large reservoir that has little to no heat loss to the surrounding formations. This design of the external heaters is motivated by the work of Vossoughi, et al (15).

The outer tube serves two purposes, it insulates the combustion tube and it provides a safety barrier in case of a rupture of the inner combustion tube. Temperature measuring sensors will be placed in both the inner and outer tubes in order to plot temperature profiles.

The tube is connected to an oxygen and/or air tank, and the flow of air from the tanks is controlled by a mass flow controller. A pressure transducer allows the pressure of the air going into the combustion tube to be monitored. A small separator will be located at the other end of the combustion tube to separate out the produced oil and effluent gases. A gas chromatograph will be used to determine the composition of these produced fluids, as well as the composition of the initial heavy oil, so that upgrading of the heavy crude can be observed and measured. Using the work of M. Greaves et al as a starting point (18) we will also construct a second tube better designed to model the horizontal producer of the THAI configuration.

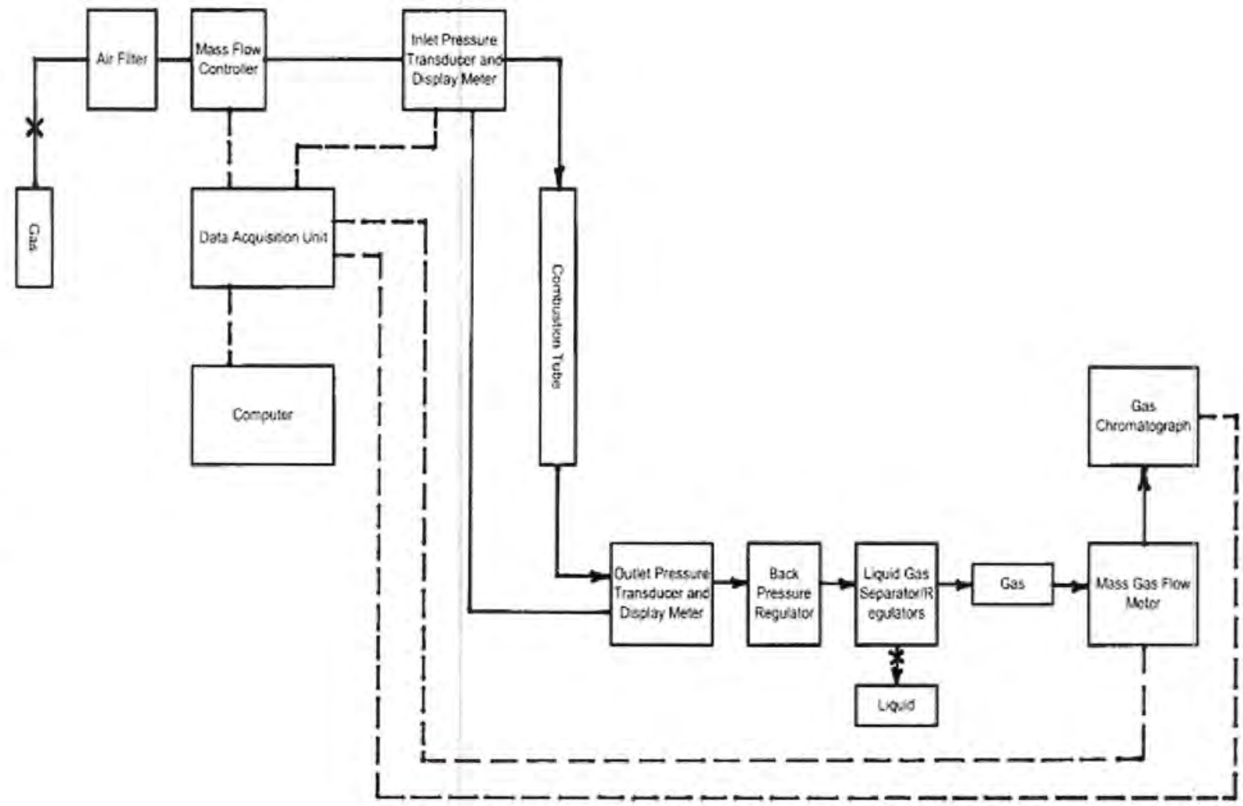

Figure 5: Diagram of Combustion Tube Apparatus

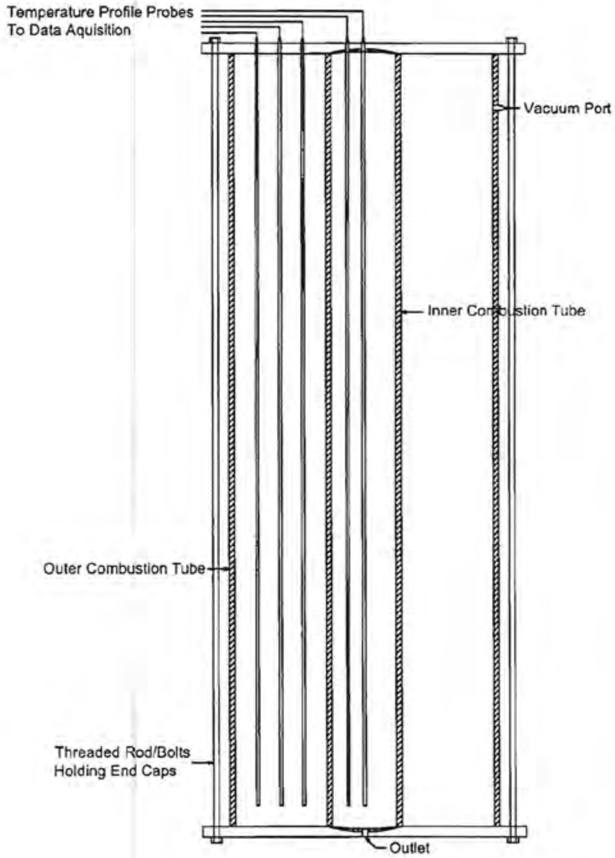

Figure 6: Detail of the combustion tube

1.4 Education and Research Applications

The purposes of constructing this equipment are to use it in conjunction with the undergraduate and graduate courses in thermal recovery and mine safety, provide research opportunities for graduate students, provide a tool for local producers to evaluate proposed in-situ projects prior to pilot tests, and developed research projects involving testing solvent and catalyst enhanced in-situ and mine safety.

Educational applications

PET 4420 Thermal Recovery Operations: In-situ combustion is challenging to visualize and model mathematically, so providing a means for students to actually observe the process would greatly aid their understanding. In this course, which is currently taught every spring semester, students would participate in setting up, running and analyzing the results of a simple forward in-situ combustion experiment and would have the opportunity to observe whatever additional experiments are currently in process. By working on the equipment, students would learn how to prepare samples, measure the compositional changes of the oil, the rate of combustion and the properties of the effluent gases.

PET 5080 Thermal Recovery Methods: This class is listed in the Montana Tech catalog but has not been offered in recent history and has a very open ended course description. It is planned to make this course a regular offering for graduate students and interested undergraduates, with a focus on the in-situ combustion process and its enhancements. The combustion tube lab apparatus would play a significant role in the exercises and activities in this class. Students would gain hands on experience with the apparatus, and use it to run both simple forward combustion tests and more advanced processes. The data they collect would be used to design in-situ field tests. This will be valuable experience as the students will be entering an industry where heavy oil dominates the remaining reserves.

Graduate and Undergraduate Research: Work on this equipment, both in its development and later use can provide topics for undergraduate research projects, Master's thesis topics for students in our graduate petroleum engineering program and doctoral level work for students in our current joint Ph.D. programs with the University of Montana and Montana State and our proposed doctoral programs at Montana Tech. This proposal also includes funding for three students, two graduate and one undergraduate, who will participate in the construction, testing and maintenance of the apparatus.

K-12 Education: Although the main focus of this proposal is to construct an apparatus for undergraduate education, graduate education and research, there may be opportunities to demonstrate this instrument to area K-12 students to encourage interest in the field of petroleum engineering. The petroleum industry is facing a workforce crisis, and while enrollment is up in many petroleum engineering programs including Montana Tech's, there is concern that it will not be enough to meet the needs of the industry as it is facing what is commonly referred to as the 'Big Crew Change' (16). In 2006, a survey of high school students was developed to gauge the students' interest in pursuing a career in petroleum engineering. One perception that was common among these students was that the petroleum industry was low tech, and didn't capture their interest like perceived high tech fields did (17). One proposed solution was to expose students at an earlier age to some of the high tech research and modeling utilized by the industry. A demonstration of the in-situ combustion process in the combustion tube, paired with 3D graphic movies of the simulation model may be a good method of showing students this side of the industry and encourage them to consider careers in the oil and gas industry.

Montana Tech has a long history of inviting K-12 students to the campus to participate in various activities that showcase science, math and engineering, and a demonstration of this apparatus would be a good fit for many of these events.

Research Applications

In Situ Combustion: The research plans for this apparatus in the area of heavy oil recovery fall into two categories. The first is to perform the necessary laboratory work to determine the appropriate parameters for pilot projects utilizing basic forward in-situ combustion. The availability of the apparatus will be made know to area oil companies that are working in this area and they will be invited to work with our department to design the required tests. As many Montana Tech alumni are working in thermal recovery, the process of making the proper contacts will be simplified. The second research category involves looking at enhancements and modifications to the in-situ combustion process. These fall into four general groups: reverse combustion, where the combustion front moves in reverse from the producing well towards the injecting well; wet combustion, where the forward combustion process is followed by a water injection which is turned to steam by the remaining heat in the burned zone; the addition of solvents or catalysts to stabilize the combustion front, and toe heel air injection (THAI), where a vertical injection well is placed at the toe of a horizontal producer. Of these four groups, the first three can be modeled with this apparatus. Future plans will include developing a third combustion tube setup for THAI studies that can be used with this apparatus.

Funding sources for this research include the DOE and RPSEA (Research Partnership to Secure Energy for America) in addition to corporate support. Results of the research will be disseminated through articles and presentations in SPE conferences and journals, reports to project sponsors, and graduate thesis and dissertations.

1.5 Plan of Work

Stage 1: (approximately 6 months) At the start of this period graduate and undergraduate students will be hired, and the equipment required will be ordered and set up. Training will be scheduled on the set up and use of the gas chromatograph for heavy oil and of the use of the Eclipse combustion tube model.

Stage 2: (approximately 9 months) During this period, the combustion tube apparatus will be assembled and basic component testing will be performed. Any changes that need to be made to the simulation deck will be made at this time so that the dimensions and other relevant parameters of the model are the same as for the combustion tube.

Stage 3: (approximately 6 months) At this stage, three tests of the apparatus will be completed, a basic test involving the forward in-situ combustion of heavy oil as would be done for a classroom demonstration, a second enhanced combustion test, and an explosion test. For the first two tests, a corresponding simulation run will be conducted using Eclipse, and the combustion tube results will be compared with the simulation results.

Stage 4: (approximately 3 months) During this stage, improvements based on the test results will be made to the combustion tube apparatus and any problems discovered will be corrected. The simulation deck will also be tuned based on the combustion tube results. More in-situ runs may be performed at this time to further test the system. At this point a user's manual will be written as well.

1.6 Management Plan

Once the equipment is developed, there will need to be a management plan in place to ensure that it continues to be useable in the future. One major step in doing this will be to include the writing of a comprehensive user's guide in the project's plan of work. This user's guide will be useful in bringing new students, faculty and researchers up to speed on the operation and maintenance of the equipment. It will include sections on setup, packing combustion tubes, operation, data collection, safety, repair, parts replacement, and the simulation model, and will reference the user's guides that come with the auxiliary equipment, such as the gas chromatograph.

The lab apparatus will be stored and utilized in the research lab in the Petroleum Engineering department, except for when performing explosive experiments, at which point the necessary components will be moved to an outside pad. The in-situ combustion tube and the auxiliary equipment will become the property of the Petroleum Engineering department, and maintenance costs will be covered by program fees, new research funding generated by the apparatus and corporate support. The PI will coordinate the management of the apparatus.

2. References

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17. Schrader, S.M., Balch, R.S., and Bunnell, D., "Where Will the Next Generation of Petroleum Engineers Come From? Disturbing Observations from a Texas Oil Town." paper SPE 110686, presented at the SPE Annual Technical Conference and Exhibition, Anaheim, 2007.

18. Greaves, M., et al, "THAI – New Air Injection Technology for Heavy Oil Recovery and In Situ Upgrading", Journal of Canadian Petroleum Technology (March 2001), 38-47.

3. Budget

Equipment		**$106,000**
Gas chromatograph	$75,000	
Profile temperature probes	$6,000	
Heating bands and controllers	$20,000	
Data acquisition unit	$5,000	
Computer		**$10,500**
Supplies		**$51,200**
Mass flow controller	$1,700	
Inlet pressure transducer and meter	$4,200	
Backpressure regulator	$1,000	
Liquid gas separator	$500	
Mass flow meter (gas)	$800	
Combustion tubes	$4,000	
Misc tubing, valves, fittings and supplies	$17,000	
Gas and regulators	$2,000	
Machine shop time/equipment	$15,000	
Furniture, benches, insulation	$5,000	
Salary		**$158,852**
4 Months Summer Salary S. Schrader	$33,432	
4 Months Summer Salary R. Schrader	$25,320	
2 graduate students	$78,000	
2 undergraduate students	$22,100	
Benefits		**$17,691**
Faculty Benefits 25%	$14,688	
Student Benefits 3%	$3,003	
Tuition		**$78,080**
Indirect costs (30.5% of salaries and benefits)		**$77,660**
Total		**$499,983**

Budget Justification

1. Equipment
    a. Gas chromatograph: The gas chromatograph is necessary to determine the chemical make-up of the heavy oil prior to combustion and of the lighter oil produced at the end of the combustion process. This allows the amount of upgrading caused by the in-situ combustion process to be measured. The likely choice will be an Agilent GC with a low thermal mass column suitable for heavy oil.
    b. Temperature probes: Custom temperature probes by Omega will be inserted in both the inner and outer combustion tubes will allow for accurate mapping of the temperature profile of both in-situ combustion and industrial explosion experiments.
    c. Data acquisition unit: Necessary to collect pressure and temperature data from inside the combustion tube and at the inlet and outlet.
    d. Heating bands and controllers: These will be used to raise the temperature of the metal combustion tube to match the internal temperature so that heat loss to the tube is minimized.

2. Computer hardware and software: A PC or laptop is necessary to work with the data acquisition unit ($500), and the remaining funds ($10,000) will be to pay for the non-donated portions of the Eclipse/Petrel software suite which will be used for modeling the in-situ combustion tube experiments and visualizing the results.

3. Supplies
    a. The mass flow controller, pressure transducers and meters, backpressure regulator, liquid-gas separator and mass flow meter are all components of the combustion tube apparatus as seen in Figure 5.
    b. Combustion tubes: This item is for the materials to build multiple inner and outer combustion tubes.
    c. Miscellaneous tubes, fittings and supplies: This item covers all the necessary connections, tubes and fittings as well as any unforeseen expenses or replacement of components damaged during shipment, construction or testing.
    d. Gas and regulators: This item will cover the necessary nitrogen, oxygen and other tanks and regulators.
    e. Machine shop equipment: This item will cover the purchase of small machining tools including a metal lathe for building the combustion tubes.

f. Furniture, benches and insulation: This item will cover the construction of the concrete table that the combustion tube will sit on, as well as a computer table and other chairs and tables as necessary.

4. Salaries and Benefits
   a. Summer salary for PI and Co-PI's: Susan Schrader and Richard Schrader will each draw two months summer salary per project year and be responsible for the supervising and participating in the construction of the apparatus, design experiments and tests and supervise students. In addition, Dr. Schrader will work with the simulation deck
   b. Graduate students: Two Masters-level graduate students will be funded with this project. The funding will cover a salary at the school's current rate plus 4 semesters of tuition at the out-of-state level per graduate student. The graduate students may also be given summer employment at a full time rate.
   c. Undergraduate students: Two undergraduate students will also work on this project during the academic year helping with the construction and use of the equipment. Undergraduate participation in this project is desirable as it will provide some continuity as a student who begins work on this project may be around for a second project after the combustion tube is completed.

4. Facilities and Special Considerations

The Petroleum Engineering department has just completed a move into a new building, with new state of the art research and teaching lab space. This equipment will be built and used in the reservoir engineering and research laboratory in this new building. A special concrete table will hold the combustion tube apparatus, which along with the nested tubes will provide a safety margin in case of a rupture of the inner tube. After construction, the equipment will be maintained along with the other equipment in the research lab, including a state of the art fracture conductivity system.

Biographical Sketch for Susan M. Schrader, PI

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Butte, MT. 59701, (406) 496-4796, sschrader@mtech.edu

Educational Experience

New Mexico Tech	BS Mathematics	1988
University of New Mexico	MA Applied Mathematics	1993
New Mexico Tech	PhD Petroleum Engineering	2004

Professional Experience

Montana Tech	Assistant Professor	2008-Present
UT of the Permian Basin	Assistant Professor	2006-2008
New Mexico Tech	Post-doctoral Researcher	2004-2006
New Mexico Tech	Research Assistant	2001-2004
ENMU-Roswell	Mathematics Faculty	1996-2003

Selected Publications

1. Steinberg, S., Das, B., Schaffer, S. and **Weber, S.M.**: "Finite Difference Methods for Modeling Porous Media Flows," in *Transport in Porous Media*, v 17 (1994) p. 171-200.
2. Balch, R.S., Ruan, T., and **Schrader, S. M.**: "Automating Basic Exploration Processes Using an Expert System: Applications to the Delaware Basin", in *The Permian Basin: Back to Basics*: West Texas Geological Society, Publication No. 03-112, p. 285-294.
3. **Schrader, S.M.**: "A New Method of Recoverable Reserves Estimation Using an Expert System," presented at the 2004 SPE Annual Technical Conference International Student Paper Contest, Houston, September 26.
4. **Schrader, S.M.** and Duettra, P., "Mathematics", in Lyons, B. and Pligsa, G.J.: *Standard Handbook of Petroleum and Natural Gas Engineering*, 2nd ed., Butterworth-Heinemann, 2004.
5. **Schrader, S.M.**, Balch, R.S., Ruan, T.: "Using Neural Networks to Estimate Monthly Production: A Case Study for the Devonian Carbonates, Southeast New Mexico," paper SPE 94089, presented at the 2005 SPE Production and Operations Symposium, Oklahoma City, April 17-19.
6. Li, G., **Schrader, S.M.**, Balch, R.S., and Ruan, T.: "Interpretations of Stratigraphic Inclines and Fractures of the Low Hill Carbonate Reservoirs, Liaohe Depression, Northeast China," presented at the 2006 AAPG Annual Convention, Houston, April 9 – 12.
7. **Schrader, S.M.**, Balch, R.S., and Bunnell, D.: "Where Will The Next Generation of Petroleum Engineers Come From? Disturbing Observations from a Texas Oil Town." presented at the 2007 SPE Annual Technical Conference and Exhibit, Anaheim, November 11-14.
8. Balch, R.S., **Schrader, S.M.**, and Ruan, T.: "Knowledge Engineering: Collection, Storage and Applications of Human Knowledge in Expert System Development," in *Expert Systems*, v 24(5), November 2007 p 346-355

9. **Schrader, S.M.**, Balch, R.S., and Ruan, T.: Understanding Neural Networks and their Applications in Petroleum Engineering." presented at the 2008 Southwestern Petroleum Short Course, Lubbock, April 23-24.
10. **Schrader, S.M.**, Balch, R.S., and Ruan, T.: The Fuzzy Expert Exploration Tool for the Delaware Basin, Development, Testing and Application, in *Expert Systems with Applications*, 2008, doi:10.1016/j.eswa.2008.08.004

Synergistic Activities

- Developed and taught courses in the thermal recovery of heavy oil and in reservoir simulation.
- Research assistant and post-doctoral researcher on DOE project involving the development of a successful expert system for oil exploration
- Has attended courses in Eclipse and Eclipse Thermal reservoir simulation
- Reviewer for ARPA-E and for the Society of Petroleum Engineers Journal of Reservoir Evaluation and Engineering
- Active member of the Society of Petroleum Engineers and a licensed professional engineer (Texas #100571, MT #19748)

Collaborators and Other Affiliations

Collaborators and Co-Editors

Dr. Paul Conrad	Montana Tech
Dr. David Bunnell	Montana Tech
Dr. Robert Balch	New Mexico Petroleum Recovery Research Center
Dr. Roger Ruan	New Mexico Petroleum Recovery Research Center
Dr. Stanly Steinberg	University of New Mexico
Mr. Guohui Li	PetroChina / China University of Petroleum

Graduate Advisors and Postdoctoral Sponsors

Dr. Robert Balch	New Mexico Petroleum Recovery Research Center
Dr. Lawrence Teufel	New Mexico Tech
Dr. Tom Engler	New Mexico Tech
Dr. Bob Bretz	New Mexico Tech
Dr. Jerry Parkinson	Los Alamos National Laboratory

Thesis Advisor for:

Joshua Isaiah	Montana Tech
Issac Attoborah	Montana Tech
Kesiena Doghor	Montana Tech
Brad Doyle	Montana Tech

Biographical Sketch for Richard J. Schrader, Co-PI

Department of Petroleum Engineering, Montana Tech of the University of Montana
Butte, MT. 59701, (406) 491-1489, ootigik@hotmail.com

Educational Experience

New Mexico Tech	BS Petroleum Engineering	1985

Professional Experience

Montana Tech	Research Staff/Lab Associate	2009-Present
New Mexico Tech	Senior Laboratory Associate	1985-2006

Selected Publications

1. Sydansk, R.D., Al-Dhafeeri, A., Xiong, Y., Schrader, R., and Seright, R.S.: "Characterization of Partially Formed Polymer Gels for Application to Fractured Production Wells for Water-Shutoff Purposes," SPE Journal of Production and Facilities, Vol. 20, No. 3 (August 2005) 240-249.

Synergistic Activities

- Principal laboratory staff for eight major funded projects on enhanced oil recovery
- Significant experience with the design and construction of core flooding equipment and core confinement systems
- Laboratory competencies include conducting high pressure, high temperature experiments and rheological and PVT studies using state of the art syringe pumps, rheometers, data acquisition units, total organic carbon analyzers, quartz precision differential pressure transducers and other lab equipment
- Proficient in machine shop practices
- Active member of the Society of Petroleum Engineers

Collaborators and Other Affiliations

Dr. Paul Conrad	Montana Tech
Dr. Susan Schrader	Montana Tech
Dr. Randy Seright	New Mexico Petroleum Recovery Research Center
Dr. Abdullah Al-Dhafeeri	Saudi Aramco
Dr. Robert Lane	Texas A&M
Dr. Jenn-Tai Liang	University of Kansas

CONSTRUCTING A COMBUSTION TUBE APPARATUS TO STUDY IN-SITU COMBUSTION OF HEAVY CRUDE OIL

A proposal to the Montana Board of Oil and Gas

December 14th, 2011

Dr. Sue Schrader

MOTIVATION

- It has been reported that up to 70% (1) of the world's remaining oil resources are heavy oils, including reserves in Canada and in eastern Montana.
- Recoverable reserves in the range of 1 billion barrels are believed to exist in the Jurassic Swift formation in Montana. (2)
- This puts Montana Tech in a good position to study heavy oil recovery. US reserves of heavy crude are nearby, and with our transfer agreement with two Alberta schools, many students arrive at Tech with a strong interest in working with heavy oil.
- The undergraduate class in Thermal Recovery is very popular, and a new graduate class is being developed to specifically study in-situ combustion and work with this apparatus

1. "Worldwide Heavy Oil Reserves by Country." HeavyOilInfo.com. Schlumberger. March 10, 2009. http://www.heavyoilinfo.com/blog-posts/billion_bbls_6_usa.pdf

2. Sandomierski, A. E., Drenth, B. J., Trisch, S. P. "Heavy Oil Prospecting in Montana." presented at the 2002 Undergraduate Expo, Department of Geological Engineering and Sciences, Michigan Tech. http://www.geo.mtu.edu/FIELD_TRIPS/images2/index.html

IN SITU COMBUSTION

- The process of in-situ combustion involves injecting oxygen, air, or oxygen enhanced air into an oil reservoir. This injected air creates a burning front which moves away from the injector wells in the direction of the producers. Ahead of this burning front is a mobile bank of upgraded oil which can be produced
- The in-situ combustion process not only makes the oil less viscous thus allowing it to be produced, it also upgrades the heavy oil reducing the amount of refining required
- Toe Heel Air Injection or THAI, removes the biggest obstacle to successful ISC, loss of control of the combustion front, by turning it into a short distance displacement process

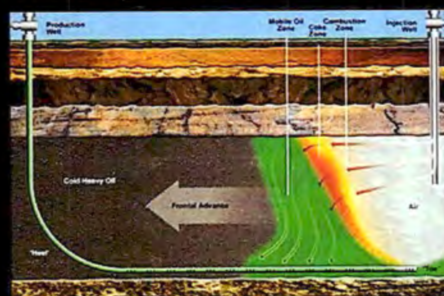


Fig. 1: THAI process

SIMULATION RESULTS

- To the right are preliminary results of the Eclipse 300 simulation of a combustion tube. They indicate that the saturation front and temperature fronts are not stable, an issue in both the modeling and successful field application of this process.

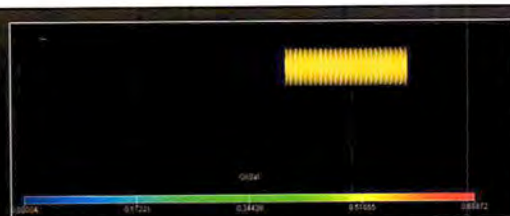


Fig. 2: Oil Saturation at beginning of run

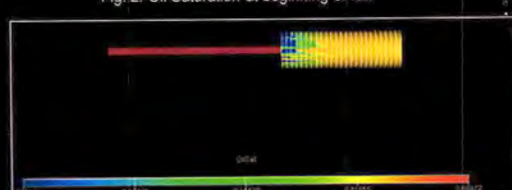


Fig. 3: Oil saturation at a later point

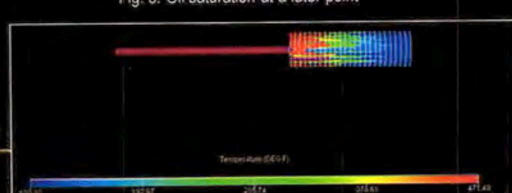


Fig. 4: Corresponding temperature profile

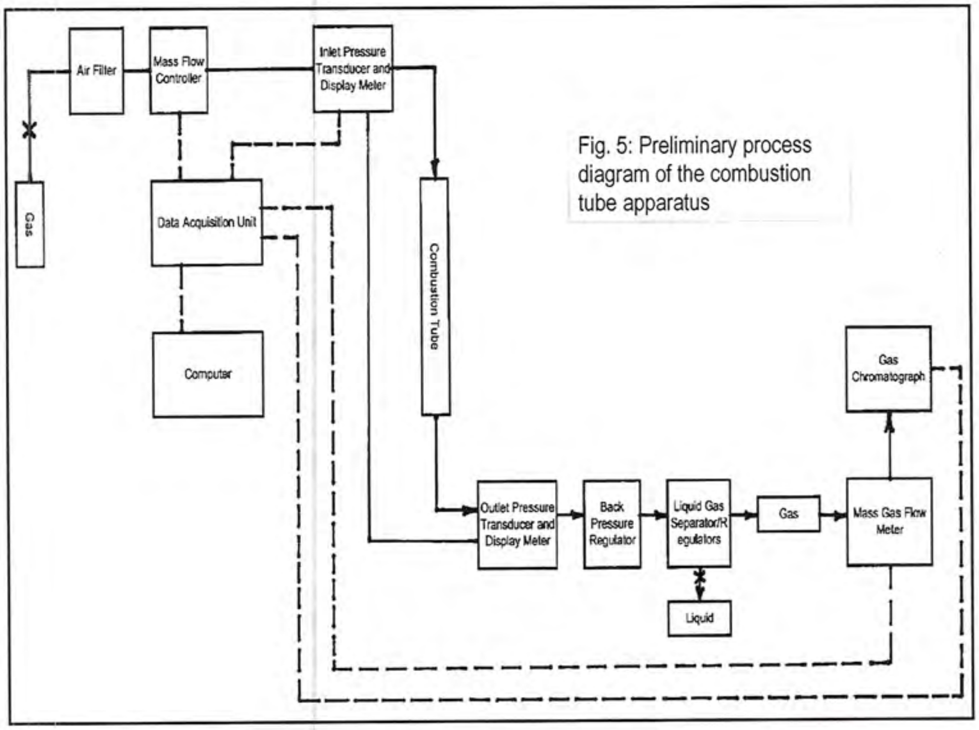
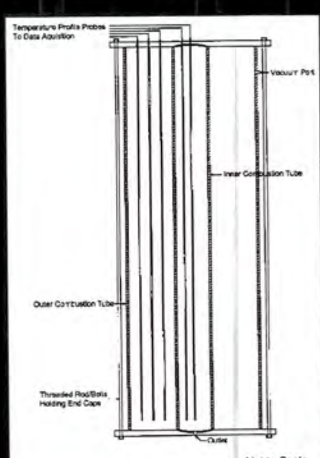


Fig. 5: Preliminary process diagram of the combustion tube apparatus

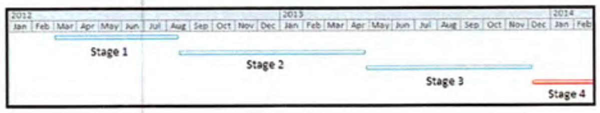
DIAGRAMS OF THE COMBUSTION TUBE APPARATUS



- The image to the left is the vertical combustion tube designed by the project team.
- It consists of two chambers, an inner tube with a heavy crude sandpack and an outer tube with insulation.
- Temperature probes run through the length of both tubes to measure the temperature profile, and upgraded oil is collected at the output.
- Heat tape can be used on the outside of the inner tube to counter boundary effects
- A vertical production line will replace the outlet to model THAI

Fig. 6: Diagram of conventional combustion tube

TIMELINE



Stage 1:
- Collecting and ordering materials
- Hiring graduate students
- Training on equipment
- Duration: 6 months

Stage 2:
- Assembly of unit
- Duration: 9 months

Stage 3:
- Testing of unit
- Coordination with simulator
- Duration: 6 months

Stage 4:
- First experimental runs
- Duration: 3 months

Fig. 7: Timeline for project

Project Budget

Equipment		$106,000
Gas chromatograph	$75,000	
Profile temperature probes	$6,000	
Heating bands and controllers	$20,000	
Data acquisition unit	$5,000	
Computer		$10,500
Supplies		$51,200
Mass flow controller	$1,700	
Inlet pressure transducer and meter	$4,200	
Backpressure regulator	$1,000	
Liquid gas separator	$500	
Mass flow meter (gas)	$800	
Combustion tubes	$4,000	
Misc tubing, valves, fittings and supplies	$17,000	
Gas and regulators	$2,000	
Machine shop time/equipment	$15,000	
Furniture, benches, insulation	$5,000	
Salary		$158,852
4 Months Summer Salary S. Schrader	$33,432	
4 Months Summer Salary R. Schrader	$25,320	
2 graduate students	$78,000	
2 undergraduate students	$22,100	
Benefits		$17,691
Faculty Benefits 25%	$14,688	
Student Benefits 3%	$3,003	
Tuition		$78,080
Indirect costs		$77,660
Total		$499,983