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(NASA-CR-192317) [VIEWGRAPH DESCRIPTION OF PENN STATE'S PROPULSION ENGINEERING RESEARCH CENTER: ACTIVITY HIGHLIGHTS AND FUTURE PLANS] Annual Report (Pennsylvania State Univ.) 75 p

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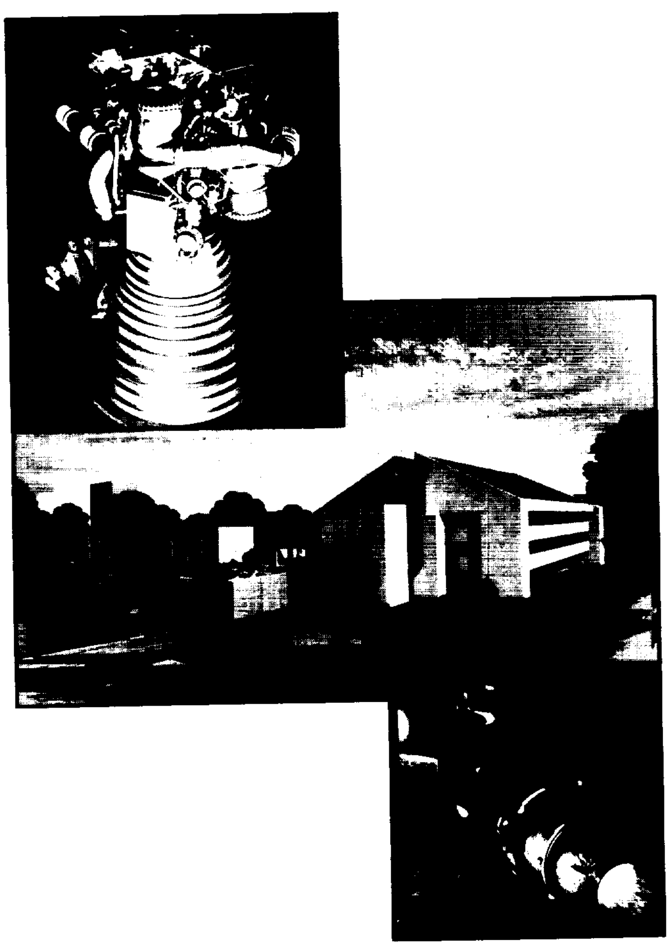
# PROPULSION ENGINEERING RESEARCH CENTER

## A University Space Engineering Research Center



Annual Report
January 1991

PENNSTATE

# PENN STATE
# PROPULSION ENGINEERING RESEARCH CENTER

**presentation for**

**Annual Review Meeting**
**University Space Engineering Research Program**
**NASA Headquarters**
**January 22-23, 1991**

**Charles L. Merkle**
**Director**

# OVERVIEW

The present viewgraphs describe the progress and status of Penn State's Propulsion Engineering Research Center. The Center was established in July, 1988 by a grant from NASA's University Space Engineering Research Centers Program. After two and one-half years of operation, some 16 faculty are participating, and the Center is supporting 39 graduate students plus 18 undergraduates. In reviewing the Center's status, we briefly review our long-term plans and goals and then summarize the present status of the Center and the highlights and accomplishments of the past year. We conclude with an overview of our plans for the upcoming year.

# OVERVIEW

- LONG RANGE PLAN
- CURRENT STATUS
- HIGHLIGHTS OF PAST YEAR
- PLANS FOR UPCOMING YEAR
- SUMMARY

## OBJECTIVES AND PROJECTED IMPACT

The primary objective of the Propulsion Center is to provide a focused research effort in space propulsion that will attract students to space engineering opportunities and will provide a continuing supply of graduates at all degree levels with interest and expertise in space propulsion. A parallel objective is to enhance participation in engineering by both women and under-represented minorities. As space exploration and development mature, space activities will have a larger and larger impact on world economics. The United States needs to ensure an adequate supply of engineers and scientists with expertise in these areas if we are to compete in this emerging world market. The Center's goal is to provide graduates for this significant field, as well as to provide new research advances which will lead to improved technologies.

After two full years of operation, the Center has, indeed, had a major impact on graduate student enrollment in both the Aerospace and the Mechanical Engineering Departments. In addition, it has enabled us to develop and maintain a modestly sized, but highly successful, minority program. The Center is currently supporting 39 graduate students with an additional 35 in related propulsion areas for a grand total of 74. We had seven minority students in our summer undergraduate program and have had two undergraduate and two graduate minority students working in the Center during the academic year.

## Long Range Plan

# OBJECTIVES AND PROJECTED IMPACT

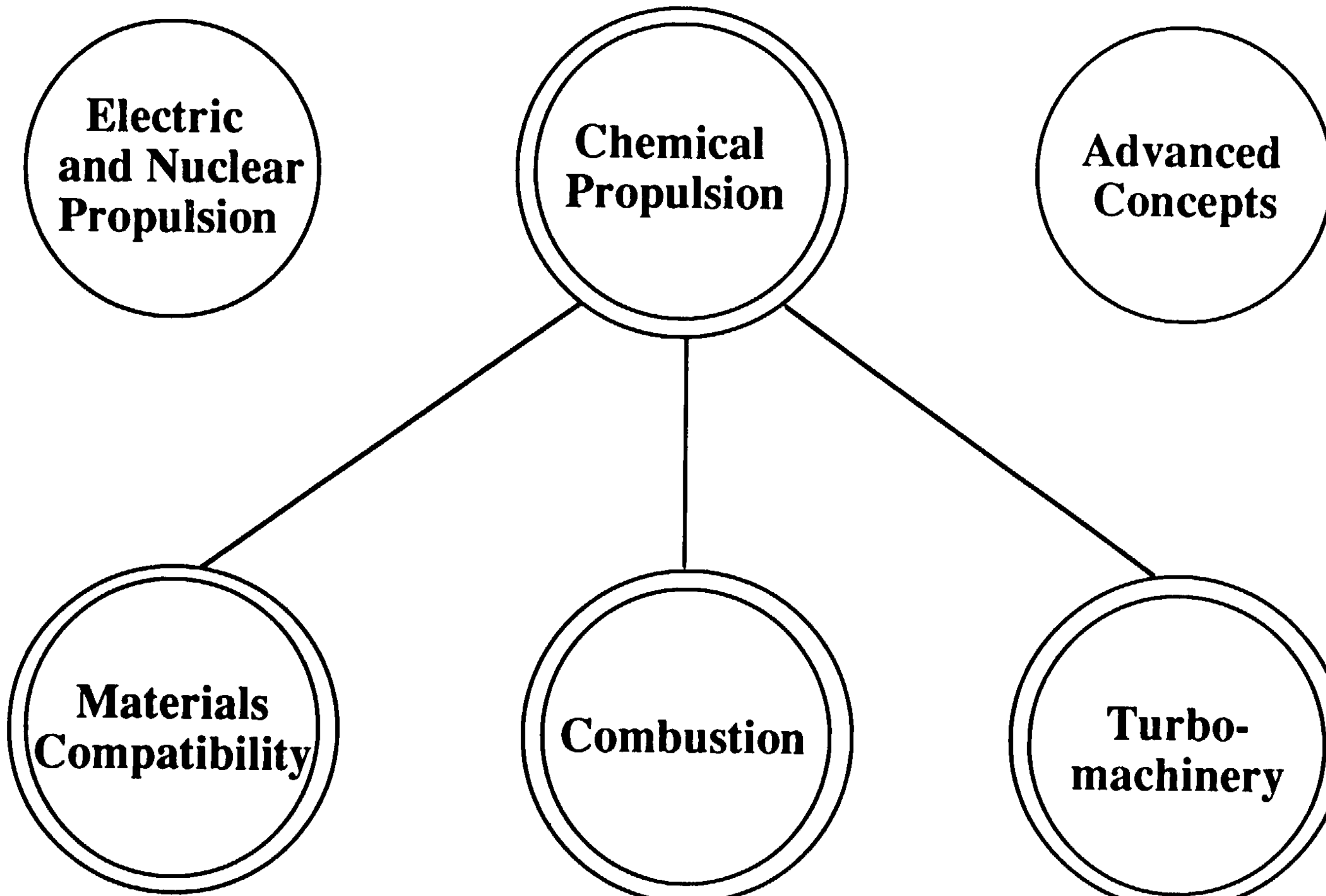
- ATTRACT STUDENTS TO SPACE ENGINEERING OPPORTUNITIES
- PROVIDE CONTINUING SUPPLY OF NEW GRADUATES
  --- Interest/Capabilities in Space Propulsion
- PROVIDE FOCUSED RESEARCH EFFORT IN SPACE PROPULSION
- ENHANCE MINORITY PARTICIPATION IN ENGINEERING
- ESTABLISH JOINT RESEARCH PROGRAMS WITH NASA
  --- Mutual Exchange of Personnel
  --- Shared Use of Facilities
- PROVIDE CONCENTRATED AREA OF PROPULSION EXPERTISE
  --- Research Capabilities
  --- Visiting Staff
  --- Future Permanent Employees

## TECHNICAL FOCUS

The long range plan of the Center is to cover a broad array of aerospace propulsion concepts, including chemical, electric, nuclear, and advanced propulsion concepts with additional support in advanced airbreathing areas. Our primary area of focus continues to be on chemical rocket propulsion with a concentration on liquid propulsion, but with additional efforts in solid propulsion and some effort on hybrids. We also have efforts underway in advanced propulsion areas. The liquid propulsion efforts are focused on combustion, turbomachinery, and materials compatibility. The highlights in the viewgraph below indicate that these areas are the primary focus of the Center.

# Long Range Plan

## TECHNICAL FOCUS: Propulsion



## FACULTY/STUDENT/MINORITY INVOLVEMENT

The Center includes participation from the College of Engineering and the College of Science at Penn State. In addition, we have a cooperative agreement with Lincoln University. Graduate student involvement is through two paths. We offer NASA Traineeships which are funded through the Center itself, as well as Research Assistantships which are funded through the individual projects which compose the Center. We are just beginning a special Industry Traineeship program. Undergraduate involvement is fostered by a summer research program that is open to students from all universities; we also have Penn State undergraduates involved at the Center during the school year. Our summer undergraduate program is focused on minorities.

We are placing special emphasis on recruiting women students and under-represented ethnic minorities into the program through a special focus program for women and a cooperative program with minority institutions.

# Long Range Plan

## FACULTY/STUDENT/MINORITY INVOLVEMENT

- PARTICIPATION FROM COLLEGES OF
  --- Engineering
  --- Science

- GRADUATE STUDENT INVOLVEMENT
  --- Traineeships
  --- Assistantships

- UNDERGRADUATE STUDENT INVOLVEMENT
  --- Summer Employment (Focused on Minorities)
  --- Experience During School Year

- SPECIAL RECRUITING PROGRAM FOR WOMEN/MINORITIES
  --- Special Focus Program for Women
  --- Cooperative Program with Lincoln University

## UNIVERSITY COMMITMENT AND SUPPORT

The University is continuing to provide strong emphasis and support for the Center. Current commitments include 18,000 square feet of office/lab space where most Center faculty and students are located in a central place. The University is also sharing the administrative costs of the Center, is providing matching funds for major equipment, and has provided new faculty slots in propulsion. The state is similarly providing additional matching funds.

# Long Range Plan

## UNIVERSITY COMMITMENT AND SUPPORT

- 20,000 $FT^2$ FOR EXPERIMENTS, CO-LOCATED OFFICES
- HALF ADMINISTRATIVE COSTS OF CENTER
- 50% MATCHING ON EQUIPMENT
- SUPPORT THROUGH STATE MATCHING FUNDS
- NEW FACULTY SLOTS IN PROPULSION
- FACULTY RELEASE TIME FOR PROPULSION-RELATED COURSE DEVELOPMENT

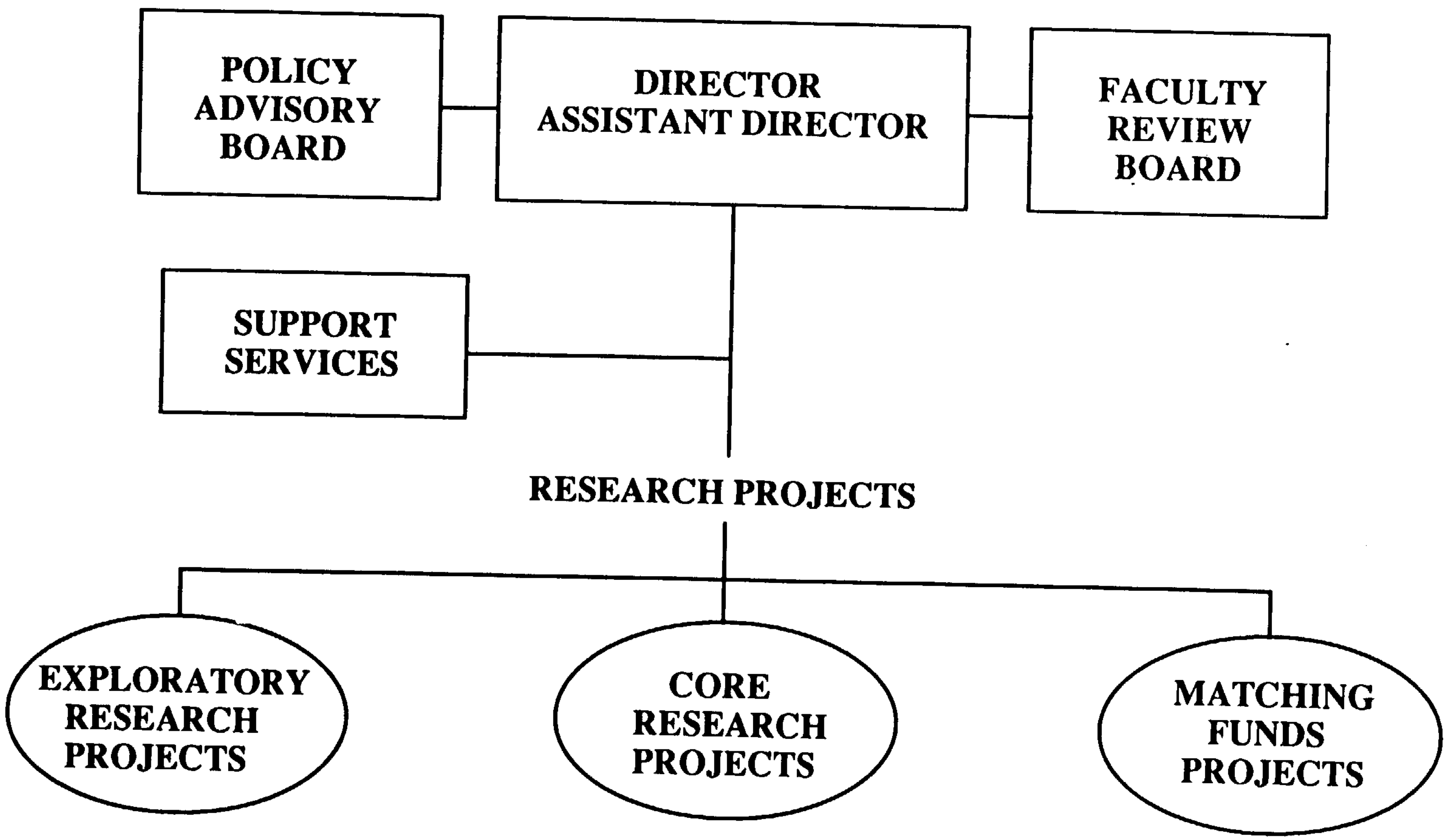
## ORGANIZATION AND MANAGEMENT STRUCTURE

As the last aspect of our long range plan, we describe the organizational structure of the Center. The purpose of this structure is to ensure that the Center is responsive to national space goals. The Director has responsibility for overall leadership of the Center and for ensuring that it works in an integrated fashion toward a common goal. Day-to-day operation of the Center is coordinated by the Director and the Assistant Director. To assist in matters of policy and research emphasis, we have an external Policy Advisory Board, while an internal Faculty Review Board assists in decision-making. The Policy Advisory Board is composed of leaders from government, industry and academia and is charged with guiding the long range development of the Center. The Policy Board has one formal meeting and one informal meeting per year to evaluate Center progress, and to advise as to appropriate technical direction. The Faculty Review Board reviews internal proposals for research projects, including in their deliberations evaluations from members of the Policy Advisory Board. In addition, the Faculty Board provides general guidance on policy and goals. The Faculty Review Board is composed of senior faculty plus the Senior Vice-President for Research and Graduate Studies.

The responsibilities for directing the individual research projects are delegated to individual faculty in a mix of three categories of research programs: Core Research Projects, Matching Funds Projects and Exploratory Projects. The first two of these provide for long term, adequately funded research projects. Core Projects are funded by the Center; Matching Projects receive shared funds from the Center and outside agencies. Exploratory projects are small, short-term efforts to establish feasibility of new ideas. As the Center matures, primary emphasis is being shifted toward Matching Projects. The individual PI's work in close cooperation with each other, the Director and the Assistant Director to provide the cross-fertilization that makes the whole of the Center's output more than the sum of its parts.

# Long Range Plan

## ORGANIZATION AND MANAGEMENT STRUCTURE



## CURRENT PROGRAM FOCUS

As indicated above, the current program focus is on liquid rocket engines with special interest areas directed towards combustion, turbomachinery and materials. These three areas cover most aspects of liquid propulsion systems except for health monitoring studies which are being conducted at the University of Cincinnati USERC. In all three areas, there is an integrated treatment of experimental and analytical efforts with close interaction among both faculty and students. This interaction is facilitated by the co-location of all faculty and students in the Center and through the shared use of the new Cryogenic Combustion Laboratory which is described next. The Cryogenic Laboratory is to be used for both combustion and materials testing by several Center projects.

At the outset of the Center, we deliberately chose a start-up philosophy that focused the attention of the Center toward the combustion aspects of liquid rocket propulsion systems. This allowed us to begin in an orderly fashion with a truly integrated "Center" concept while preparing for later expansion into a broadened program. This choice was made because it is an area of importance in liquid rocket engines as well as an area of strength at Penn State. The combustion focus included both gas dynamic and materials aspects of combustion problems. We have since initiated an effort in turbomachinery which is currently approaching our combustion effort in size. Programs in turbomachinery are directed towards cryogenic bearings and aero/hydrodynamics.

# Current Status

## PROGRAM FOCUS: LIQUID ROCKETS

- COMBUSTION
  - --- Key Research Area for Liquids
  - --- Existing Strength at Penn State
  - --- Provides Coordinated Research

  } *Experiment Analysis*

- CRYOGENIC TURBOMACHINERY
  - --- Key Research Area for Liquids
  - --- Complements Combustion Emphasis
  - --- Focus on Bearings/Seals and CFD

  } *Experiment Analysis*

- MATERIALS COMPATIBILITY/RELIABILITY
  - --- Critical Aspect of Liquid Engines
  - --- Close Interaction with Combustion and Turbomachinery

## ADDITIONAL RESEARCH EMPHASES

An area of secondary focus is on Advanced Propulsion concepts. The Center is currently providing some support for a research effort on antimatter propulsion which is primarily supported by JPL and AFAL. There are also auxiliary efforts on microwave thermal propulsion and other advanced electric concepts. Additional emphasis on these areas as well as in nuclear propulsion is being considered.

To complement our focus on liquid rocket propulsion, we also have a strong on-going program in solid propulsion. This well-established program pre-dates the NASA Center, and has proven to be an important source of synergism for our liquid propulsion work. The Center is also beginning a modest effort on hybrid rockets to complement the more active programs in solid and liquid propulsion.

The second major supporting area is that of combustion research in airbreathing and internal combustion engines. As in the liquid rocket area, this focus includes the three primary areas of combustion, turbomachinery, and materials. The combustion work is closely allied with Center efforts, and we are currently starting increased interactions with the airbreathing turbomachinery programs at Penn State.

## Current Status

# ADDITIONAL RESEARCH EMPHASES

- ADVANCED PROPULSION
  - --- Antimatter Propulsion
  - --- Microwave Thermal Propulsion
- SOLID PROPULSION
- HYBRID PROPULSION
- AIRBREATHING PROPULSION
  - --- Combustion
  - --- Turbomachinery
  - --- Materials

## CRYOGENIC COMBUSTION LABORATORY

An important part of our Center is the development and use of a major new cryogenic laboratory with current capability for liquid oxygen and gaseous hydrogen. Continued development of this laboratory is scheduled to enable us to use liquid hydrogen and liquid hydrocarbon propellants also. Detail design and construction of this laboratory was begun shortly after Center start-up. Our first hot firing (with gaseous propellants) was made in December 1989, some 15 months later. Our first tests with LOX took place in early January of this year (1991). This unique laboratory is currently the only one of its kind in U.S. universities. (Similar university systems used in the sixties have all been mothballed or torn down.) Now that the facility is operational for both gaseous and liquid oxidizers, we are beginning testing and diagnostics at appropriate conditions of interest. Evolution of the capabilities of the laboratory is continuing.

The Cryogenic Laboratory enables us to do small scale tests (generally uni-element injectors) with actual propellants under realistic conditions. The laboratory also enables us to give students experience in handling cryogenic fluids that are generally used in space propulsion applications. The construction of this laboratory would have been totally impossible without the Center.

# Current Status

## CRYOGENIC COMBUSTION LABORATORY

- **CURRENT CAPABILITY FOR**
  - --- GOX, LOX, $GH_2$
  - --- Thrust Levels to 500 lbs.

  } *Unique Capability*

- **DEVELOPMENT SCHEDULE**
  - --- Start Detail Design/Fabrication — September, 1988
  - --- Initial Run with GOX/$GH_2$ — December, 1989
  - --- Initial Run with LOX/$GH_2$ — January, 1991

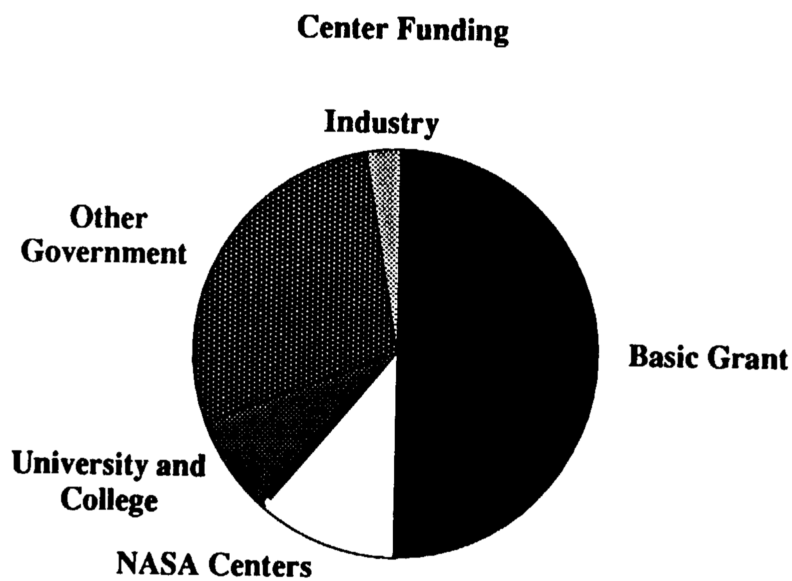
- **PLANNED TESTS (GASEOUS PROPELLANTS)**
  - --- Combustion Experiments
  - --- Materials Testing
  - --- Heat Transfer

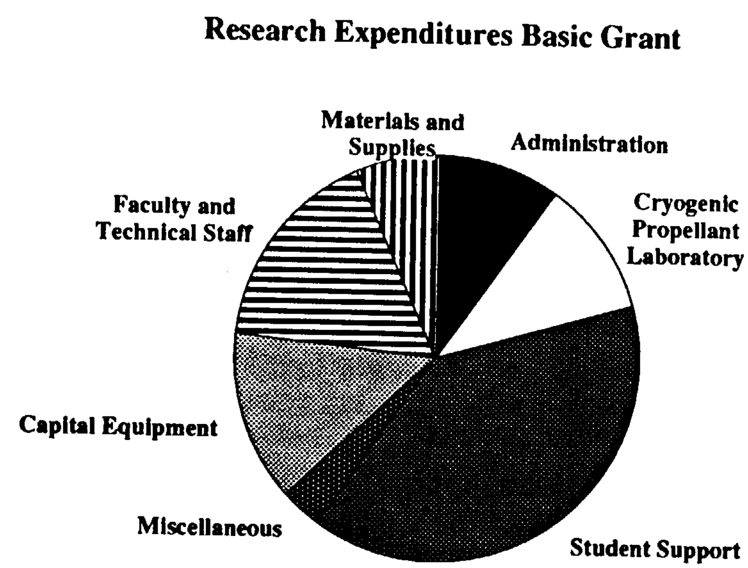
## PROGRAM FOCUS - FUNDING SPLIT

The Center as a whole includes a wide variety of propulsion topics. In general, we divide these topics into research efforts (and their derivatives) that existed at Penn State before the USERC was awarded, and those that were initiated afterwards which can be directly attributed to the presence of the Center. The funding split for the overall Center is given in the left below, showing the origin of funding for the larger global Center. The chart on the right shows the manner in which the basic USERC grant was expended.

# Current Status

## PROGRAM FOCUS - FUNDING SPLIT



# FACULTY/STUDENT PARTICIPATION

We currently have 16 faculty involved in research at the Center. These faculty represent the Departments of Aerospace Engineering, Engineering Science and Mechanics, and Mechanical Engineering in the College of Engineering and the Department of Physics in the College of Science. A total of 39 graduate students including 13 NASA Trainees and 26 Research Assistants are supported by the Center and are involved in educational and research programs in space propulsion that have been developed as a result of the Propulsion Center. Of these, 31 are U.S. citizens. The quality of these students, as judged by both GPA's and GRE scores, continues to be very high. The Center is having a particularly significant impact in increasing enrollment of U.S. citizen PhD students. In addition to these 39 graduate students supported by the NASA USERC grant and related projects, an additional 35 are affiliated with the Center through complementary propulsion research projects bringing the total to 74. A total of 19 undergraduates have also been associated with the Center during the past year including students in our summer program and during the academic year.

# Current Status

## FACULTY/STUDENT PARTICIPATION

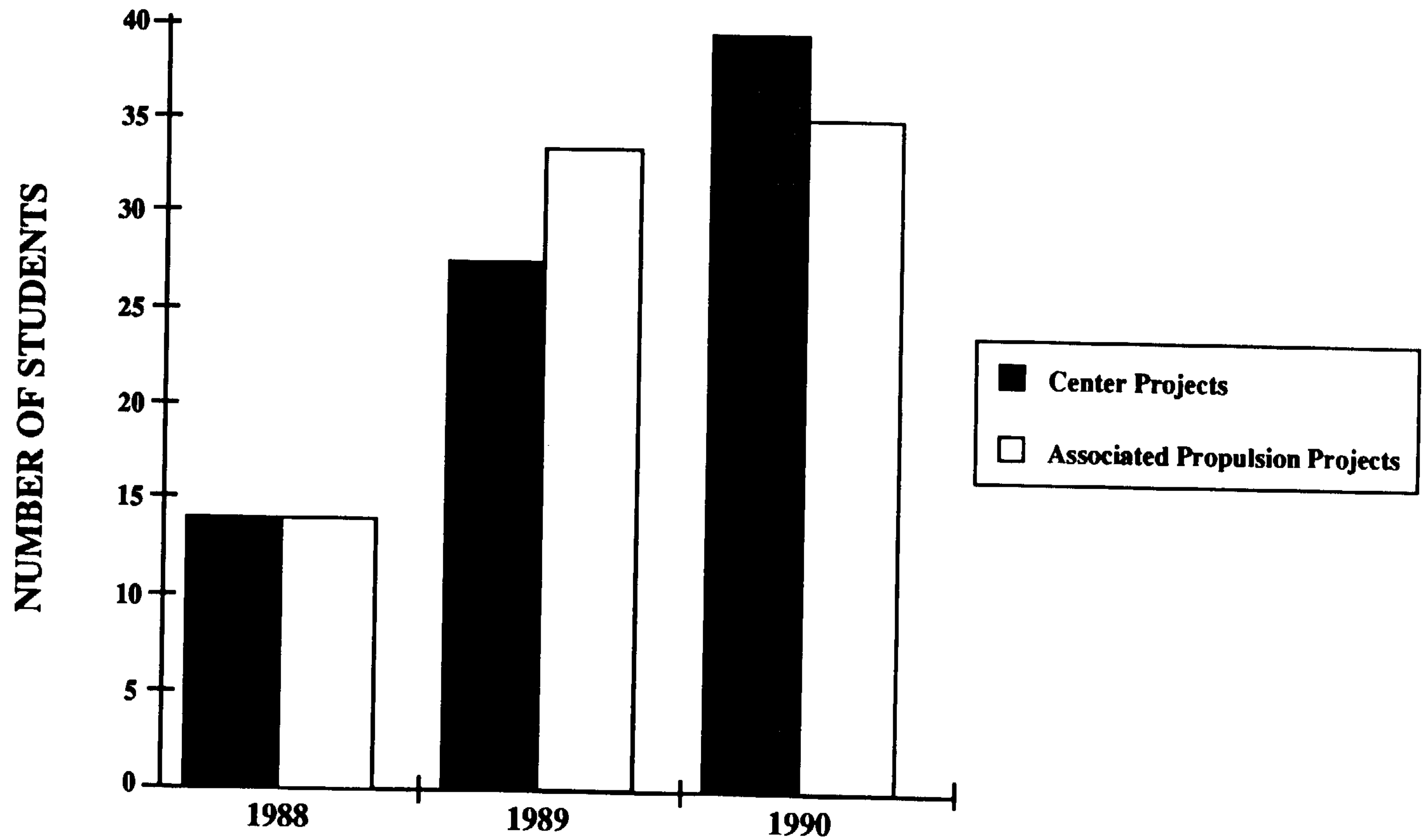
- **TOTAL FACULTY INVOLVED: 16**
  - --- Mechanical Engineering
  - --- Aerospace Engineering
  - --- Engineering Science and Mechanics
  - --- Physics
- **TOTAL GRADUATE STUDENTS: 39 (74)**
  - --- 12 NASA Trainees
  - --- 27 Graduate Assistants
  - --- 35 Additional Students in Associated Propulsion Areas
- **TOTAL UNDERGRADUATE STUDENTS: 19**
  - --- 11 Summer Employees
  - --- 11 Part-time School Year

## STUDENT ENROLLMENT

The history of student enrollment in the Center is shown on the following figure. Student enrollment has continued to grow from 14 the first year, to 27 the second year, to the current value of 39. The total number of graduate students in the propulsion center, including those on complementary propulsion research programs, has likewise grown substantially from 28 the first year to the present 74, indicating the impact of the Center on student enrollments in allied areas as well. Much of this growth arises because many of our first year students still remain in the program as PhD students. We expect student enrollments to level off as increased numbers of students graduate and leave the program.

# Current Status

## STUDENT ENROLLMENT

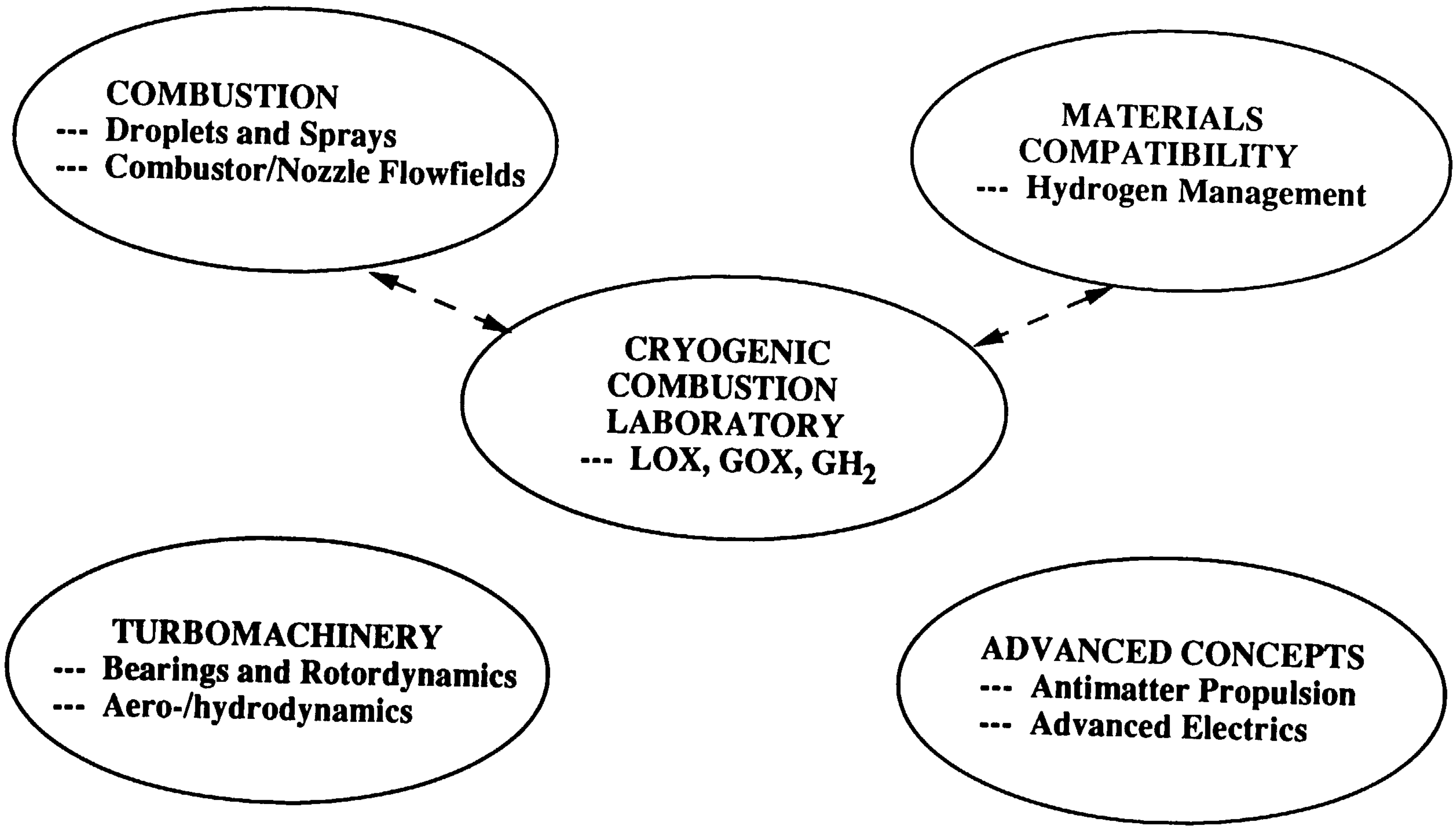


# CENTER RESEARCH PROJECTS

The projects supported by the Propulsion Engineering Research Center are focused on a broad array of critical technology issues in space propulsion. In general, all these efforts include a substantial experimental component with coordinated support in computational fluid dynamics (CFD) and other analytical areas. In the area of combustion, we are studying droplet and spray combustion for steady and nonsteady burning conditions using advanced non-intrusive diagnostic techniques and complementary CFD analysis. Additional combustion work includes combustor/nozzle flowfield analyses and experiments with emphasis on small rocket applications. In cryogenic turbomachinery, our bearings efforts include a coupled fluid-structure model for foil bearings, and an experimental/analytical effort on advanced control algorithms for magnetic bearings. Projects involving the aero-/hydrodynamics of turbomachines include CFD efforts on turbulence modeling in complex rotating flows and cavitation in LOX pumps. Our materials capability efforts are focused on hydrogen management considerations through the use of multi-layered laminates to document and control diffusion at high temperatures and pressures. In the area of advanced concepts, we are studying the possibility of using antiproton induced fission fragments to ignite DT pellets for propulsion by inertial confined fusion.

# Current Status

## CENTER RESEARCH PROJECTS



## INTERACTIONS WITH NASA/INDUSTRY

The Center's interactions with NASA and industry continue to grow. We continue to have strong, positive interactions with both the Lewis and Marshall Centers and are particularly indebted to them for their cooperation and help. We have three matching grants with LeRC, one with MSFC, and one with AFPL. In addition, we are currently discussing potential liquid propellant research efforts with both MSFC and AFOSR. MSFC is also supporting one Graduate Student Researcher. We also have grants from Pratt and Whitney and MBB, Inc. Faculty and students from the Center have visited Lewis and Marshall many times during the year, and we have likewise hosted many NASA employees at the Center. A highlight of the past year was the Space Transportation Propulsion Technology Symposium which drew 230 attendees from NASA, industry and academia.

In terms of student interactions, since the Center's inception, we have placed two advanced degree graduates at LeRC, two at MSFC, one at Ames, and one at Rocketdyne. Several other of our students are working in NASA efforts through contracts with their employers. We also have two MSFC employees studying at Penn State on NASA graduate study programs.

Our external policy advisory board has been very active and effective. The Board has two regular meetings per year including a formal, structured visit in the Spring with symposium style presentations, and a more informal visit in the fall featuring detailed discussions with individual faculty and their students. The board also evaluates internal proposals each year, and most board members visit the Center at least once in addition to the regular board visits.

# Highlights of Past Year

## INTERACTIONS WITH NASA/INDUSTRY

- POLICY ADVISORY BOARD
  - --- MSFC ---Rocketdyne ---Pratt & Whitney
  - --- LeRC ---Aerojet ---Air Products
- MATCHING FUNDS/GRANTS
  - --- Three Grants with LeRC
  - --- One Grant with MSFC
  - --- Three Grants from Industry
  - --- One Grant with AFPL
- DESIGN/SAFETY SUPPORT ON CRF
  - --- LeRC ---Rocketdyne ---Air Products
- PERSONNEL INTERCHANGE
  - --- Graduates to Propulsion Community
    - 1 MS/1 PhD to LeRC
    - 1 MS to Rocketdyne
    - 2 MS to MSFC
    - 1 MS to ARC
  - --- Returning Students for Degrees (Fall '90)
    - 2 Employees from MSFC
  - --- Graduate Student Researchers Program (MSFC)
- REPRESENTATION ON PROFESSIONAL COMMITTEES
  - --- JTEC ---Technology Assessment of Rocket Propulsion in Japan
  - --- AIA ---Rocket Propulsion Roadmap
  - --- JANNAF ---Combustion Instability Panel
  - --- JANNAF ---Rocket Performance Panel

## SPACE TRANSPORTATION PROPULSION TECHNOLOGY SYMPOSIUM

A special highlight of the past year was the opportunity to host the NASA Space Transportation Propulsion Technology Symposium at Penn State in June. The meeting attracted a total attendance of 230 including 85 NASA employees, and 108 industrial representatives. The purpose of the symposium was to bring the propulsion research and development community together with the propulsion operations and user communities to reach a common focus on propulsion technology requirements for the next decade.

# Highlights of Past Year

## SPACE TRANSPORTATION PROPULSION TECHNOLOGY SYMPOSIUM

- **HOSTED BY PENN STATE PROPULSION CENTER**
  - --- June 25-29, 1990

- **SYMPOSIUM PARTICIPANTS**
  - --- NASA (86) --- University (30)
  - --- Industry (109) --- Other Government (5)

- **NASA PARTICIPATION**
  - --- Headquarters --- MSFC --- JSC
  - --- KSC --- SSC --- LeRC
  - --- LaRC

## ANNUAL NATIONAL SYMPOSIUM

In selecting a time and site for our Annual National Symposium, it is important that we interface it properly with the existing regularly scheduled meetings in propulsion. Meetings of direct interest to our Center include the AIAA Joint Propulsion Meeting which is held every summer, the JANNAF Propulsion Meeting that is held every eighteen months, and the Propulsion Meeting of the International Astronautical Federation that is held every two years. This year, we were fortunate to host a special NASA-sponsored propulsion symposium, the Space Transportation Propulsion Technology Symposium (STPTS) at Penn State, and we chose to hold our Annual Symposium in conjunction with, and as a part of, the STPTS Symposium. The Annual Symposium consisted of two parts: an Open House at the Center; and formal symposium presentations of the projects in the Center. During the Open House, we gave tours of our laboratories to some 200 NASA, industry and academic guests. These tours were highlighted by in-depth, informal discussions with faculty and students. The formal symposium presentations were given later after the attendees had had opportunities to visit our labs. The schedule included dual, concurrent sessions and was integrated with the main STPTS agenda.

# Highlights of Past Year

## ANNUAL NATIONAL SYMPOSIUM

- HELD AT PENN STATE, JUNE 26-JUNE 29, 1990
  - --- In Conjunction with NASA Space Transportation Propulsion Technology Symposium
  - --- Total Attendance: 230
- PROPULSION CENTER OPEN HOUSE
  - --- Laboratory Tours
  - --- Informal Discussions with Faculty and Students
- FORMAL SYMPOSIUM PRESENTATIONS
  - --- Faculty/Student Presentations on Center Projects
  - --- Dual, Concurrent Sessions

## NASA SEMINAR SERIES

One of the outcomes of the Space Transportation Propulsion Technology Symposium (STPTS) was the initiation of a monthly NASA Seminar Series. The purpose of this series is to bring representatives from various NASA locations to Penn State to spend a day interacting with students and faculty including informal discussions, visits to our laboratories, and an overview of the Center's projects, status, and goals. A special highlight is a round table discussion at lunch between the NASA visitor and a group of 6 to 8 students. The seminars themselves are intended to give students and faculty alike an exposure to "real-world" issues ranging from programmatic to technical issues. The seminars also serve to familiarize students and faculty with NASA capabilities and potential career options. Seminars to date have included speakers from Headquarters and Kennedy Space Center. Speakers from Lewis and Marshall are lined up for the next two months with plans to bring in people from Stennis, Houston, and another Headquarters person to finish this first year. As a variation in this series, the Honorable Robert S. Walker, Vice-Chairman of the House Space, Science and Technology Committee, spent a day at the Center as our December speaker.

# Highlights of Past Year

## NASA SEMINAR SERIES

- **September 25, 1990** — Edward Gabris, Headquarters<br>"Challenges in Propulsion Engineering"
- **November 20, 1990** — Russell Rhodes, Kennedy Space Center<br>"Space Propulsion from an Operations Perspective"
- **December 13, 1990** — Congressman Robert S. Walker,<br>Space, Science and Technology Committee<br>Open Comments and Discussion Regarding NASA
- **January 29, 1991** — Bryan Palaszewski, Lewis Research Center<br>"The Metallized Propellant Program"
- **February 19, 1991** — John Hutt, Marshall Space Flight Center<br>"Combustion Stability Analysis of<br>Liquid Rocket Engines"

## MINORITY INVOLVEMENT

Our minority program has had positive results on several fronts. Our summer undergraduate program with Lincoln University continues to be highly successful, and this year, we have increased our scope to include minority students from Penn State's Commonwealth campuses also. The students are individually assigned to Center faculty and spend the summer doing research alongside our graduate students. The program is concluded by a symposium at which students give individual presentations of their research. Attendance included parents of all students, grandparents and younger siblings of some, and several gifted minority high school students who represent prospective science/engineering students. A total of seven minority students were involved this summer. Additional expansion in next summer's undergraduate program is afforded by a grant from NSF for an undergraduate research opportunities program for minorities in our College of Engineering.

In addition to the summer program, the Center had three minority undergraduate students working during the academic year on a part-time basis, as well as two minority graduate students, and one handicapped student. Our participation by women includes one faculty member, five graduate students, and five undergraduates.

# Highlights of Past Year

## MINORITY INVOLVEMENT

- **FACULTY PARTICIPATION**
  --- One Woman Faculty Currently Involved

- **GRADUATE STUDENT PARTICIPATION**
  --- Five Women Students
  --- Two Minority Students
  --- One Handicapped Student

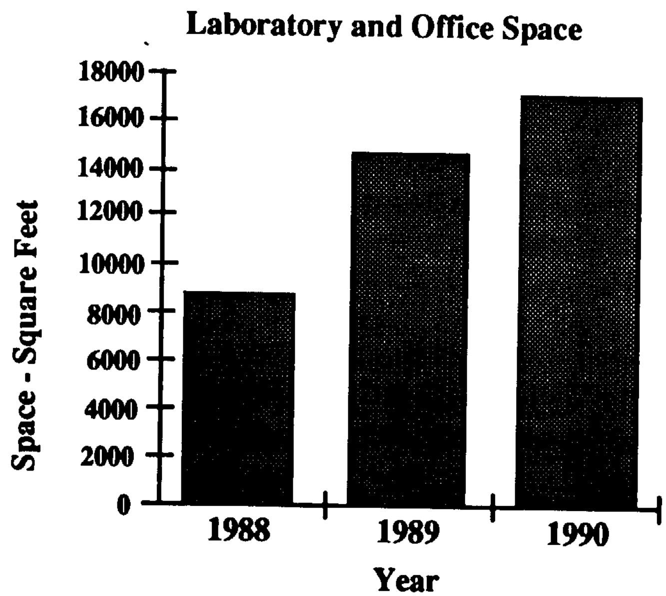
- **UNDERGRADUATE STUDENT PARTICIPATION**
  --- Seven Minority Students
  --- Five Women Students

## UNIVERSITY SUPPORT

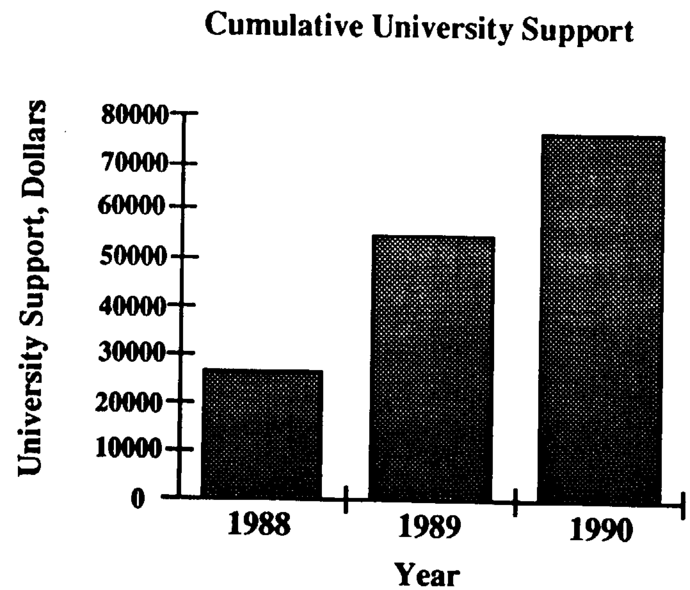
The University indicated strong commitment to the Center in the original proposal and continues to provide strong backing. The University is paying for half the administrative costs of the Center and has provided matching dollars on major equipment purchases. We presently occupy the first floor, part of the second floor, and all of the lower level of a newly completed research building. Remote test cells for the Cryogenic Laboratory have also been allocated and refurbishment to allow storage and use of LOX has been supplied by the university. Present space allocated to the Center is about 18,000 square feet of lab and office space. This co-located space is proving very effective in fostering the type of daily interactions that are necessary in a Center. Additional support by the university includes the award of several university sponsored fellowships to our students. An overview of our space allocations and university matching funds is given below.

# Highlights of Past Year

## UNIVERSITY SUPPORT




- Co-located Laboratory/Office Space
- Cryogenic Laboratory




- Administrative Support
- Equipment Matching
- Facility Preparation
- Student Fellowships

## ADDITIONAL HIGHLIGHTS

Below is a listing of some of the many additional activities and highlights of the Center during the past year.

# Highlights of Past Year

## ADDITIONAL HIGHLIGHTS

- CENTER VISITS BY:
  - --- J. R. Thompson, Deputy Administrator, NASA
  - --- Honorable Robert Walker,<br>Vice-Chairman, House Space, Science and Technology Committee
- POLICY ADVISORY BOARD MEETINGS
  - --- April 25-26 (Formal)
  - --- November 13-14 (Informal)
- PSU SELECTED AS SPACE GRANT UNIVERSITY
- CENTER PARTICIPATED IN SPACE GRANT COLLEGE SUMMER ACADEMY
- INSTALLED IBM 6000 RISC SYSTEM WORKSTATIONS
  - --- 1 Model 530 (File Saver)
  - --- 6 Model 320's
- NEW ASSISTANT DIRECTOR, W. E. ANDERSON
- INITIAL LOX/$H_2$ FIRING IN CRYOGENIC LABORATORY

# Highlights of Past Year

## ADDITIONAL HIGHLIGHTS
(Continued)

- BOARD OF DIRECTORS,
  PENNSYLVANIA RESEARCH CORPORATION (November 16)
  --- Overview of Center and Tour of Facilities
- CENTER FACULTY MEMBER (M.MICCI) ON SABBATICAL WITH ONERA
  --- Liquid Rocket Combustion Instability
- JANNAF COMBUSTION INSTABILITY WORKSHOP ON DIAGNOSTICS, ORGANIZED/CHAIRED BY R. SANTORO, NOVEMBER, 1990
- CENTER FACULTY REPRESENTATIVES ON AIAA TC'S:
  --- Liquid Propulsion TC
  --- Combustion and Propellants TC
  --- Hybrid Propulsion TC
- FIVE CENTER FACULTY INVOLVED IN JANNAF LIQUID ROCKET PANELS:
  --- Combustion Instability Panel
  --- Liquid Rocket Performance Panel

# Highlights of Past Year

## ADDITIONAL HIGHLIGHTS
(Continued)

- **SEVEN CENTER FACULTY INVOLVED WITH MSFC CFD CONSORTIA:**
  --- Combustion Driven Flows
  --- Pumps
  --- Turbines

- **CENTER FOR UNDERGRADUATE RESEARCH OPPORTUNITIES FOR MINORITIES**
  --- NSF Grant, Fall 1990
  --- Center Director on Advisory Board

- **LABORATORY TOURS FOR "VISIONS OF OUR FUTURE' PROGRAM**
  --- Gifted High School Students in Math and Science

## TECHNICAL FOCUS FOR UPCOMING YEAR

During the coming year, we expect to continue our transition toward more co-funded projects and to continue to increase the fraction of the basic Center grant that goes to support students. Our research efforts in combustion are well-established and broad in perspective, and are expected to remain at about their present level. Our turbomachinery efforts are expected to grow in size incorporating more aero/hydrodynamics emphasis to complement our bearings and seals work.

# Plans for Upcoming Year

## TECHNICAL FOCUS

- COMBUSTION
  - --- Maintain Current Level of Effort
  - --- Secure Additional Matching Funds
- MATERIALS
  - --- Maintain Current Level of Effort
  - --- Secure Additional Matching Funds
- TURBOMACHINERY
  - --- Maintain Projects in Cryo-Bearings/Seals
  - --- Anticipate New Start in Aero/Hydrodynamics
- CRYOGENIC COMBUSTION FACILITY
  - --- Initial Cold Flow Experiments
  - --- $GH_2$/ $GO_2$ Experiments -- Combustion Instability
  - --- $GH_2$/ $LO_2$ Shakedown Experiments
- POSSIBLE NEW EFFORTS
  - --- Hybrid Propulsion
  - --- Nuclear Propulsion

## PLANNED EVENTS FOR UPCOMING YEAR

Key events planned for the upcoming year include holding our Third Annual Symposium at the JANNAF Propulsion Meeting in San Antonio in November. Planning is already underway for this event to ensure inclusion of our session in the overall program.

We are looking forward to continuing our Summer Undergraduate Minority Program with plans for 8 minority students this year. Additional support for our minority program is expected from the recently awarded NSF program on research opportunities for minority students.

We also hope to maintain our strong ties with NASA and our relationships with industry.

# Plans for Upcoming Year

## PLANNED EVENTS

- THIRD ANNUAL SYMPOSIUM
  --- In Conjunction with JANNAF Propulsion Meeting
  San Antonio, TX
  November, 1991
- SUMMER UNDERGRADUATE MINORITY PROGRAM
  --- 8 Undergraduate Students
  --- Jointly Supported from NSF CUROMES Program
- CONTINUED STRONG INTERACTIONS WITH NASA
- CONTINUE STRONG INTERACTIONS WITH INDUSTRY
- ESTABLISH INDUSTRY AFFILIATES PROGRAM

# GOALS

Some specific quantitative goals for the Center in the coming year are identified on the present viewgraph. These goals, along with the items on the two previous viewgraphs, give an overview of the planned direction of the Center in the next year. Implicit in both these lists is a close interaction with those NASA Centers with emphasis and expertise in propulsion.

# Plans for Upcoming Year

## SYNOPSIS -- GOALS

- MAINTAIN STRONG GRADUATE RECRUITING PROGRAM
  --- Eleven Additional Students
- MAINTAIN SAME FACULTY INVOLVEMENT
- INCREASE MATCHING TO 30%
- INCREASE NUMBER OF WOMEN STUDENTS

## SUMMARY

In summary, we initially restricted the focus of the Center to the combustion aspects of liquid propulsion for the purpose of establishing a strong Center concept as well as preparing for expansion into additional technical areas. We now have an ongoing effort in cryogenic turbomachinery bearings with planned expansion into the aero/hydrodynamics of turbomachinery. Some carefully planned expansion to other propulsion areas has occurred during this past year and additional broadening of the Center's focus is planned for the coming year. We have established strong ties with NASA Centers and industry, and are expanding to other government agencies. We have a solid minority program in place and are placing strong emphasis on attracting women students. Our Cryogenic Combustion Laboratory, which is now on line, is a unique facility that should enable us to make effective contributions both in terms of research and student education.

# SUMMARY

- CURRENT TECHNICAL FOCUS
  - --- Liquid Rockets
    - --- Combustion
    - --- Turbomachinery
    - --- Materials
  - --- Auxiliary Efforts in
    - --- Solid Rockets
    - --- Airbreathing Propulsion
- STRONG TIES WITH NASA CENTERS CONTINUING
  - --- Numerous Visits
  - --- Matching Research Funds
  - --- Students Both Ways
- SUCCESSFUL MINORITY PROGRAM WITH LINCOLN UNIVERSITY
- CONTINUE EMPHASIS ON RECRUITING WOMEN STUDENTS
- EXPECT MODEST GROWTH THROUGH MATCHING
- CRYOGENIC COMBUSTION FACILITY ON-LINE

# APPENDIX I

## CURRENT LIST OF PERSONNEL AND PROJECTS ASSOCIATED WITH THE CENTER

### A. CENTER PROJECTS

1990 FUNDING FROM ALL SOURCES: $2,040,000

| Project Title | P.I. and Department | Agency | Students Supported |
|---|---|---|---|
| **1. CORE PROJECTS** | | | |
| Cryogenic Combustion Laboratory | R. J. Santoro, ME<br>K. K. Kuo, ME | PERC | Bernard Chatman, Jr. (BS)<br>Charlene D'Amore (BS)<br>Marlow Moser (PhD)<br>Roger Woodward (PhD) |
| Hydrogen Management in Materials for High Pressure H/O Engines | R. A. Queeney, ES&M<br>R. N. Pangborn, ES&M | PERC | Jennifer Miller (PhD)<br>Eric Roll (PhD) |
| Low Reynolds Number Nozzles | M. M. Micci, AE | PERC | Troy Dunn (MS) |
| Robust and Real-Time Control of Magnetic Bearings for Advanced Propulsion Rockets | A. Sinha, ME<br>K.-W. Wang, ME | PERC | Kevin Mease (MS)<br>Scott Lewis (PhD) |
| Spray Combustion Under Oscillatory Pressure Conditions | H. R. Jacobs, ME<br>R. J. Santoro, ME | PERC | Sibtosh Pal (Post-doctoral)<br>Harry Ryan (MS) |
| Study of Methods to Investigate Nozzle Boundary Layer Transition | L. L. Pauley, ME | PERC | Samir Dagher (MS) |
| A Review of F-1 Engine Combustion Instability | V. Yang, ME | PERC | Joe Oefelein (PhD) |

**A. CENTER PROJECTS (Continued)**

**2. CO-FUNDED PROJECTS**

| | | | |
|---|---|---|---|
| Analysis of Foil Bearing for High Speed Operation in Cryogenic Applications | M. Carpino, ME | LeRC/PERC | Alexander Bealles (MS) |
| CFD Analysis of Rocket Chamber/ Nozzle Flowfield | C. L. Merkle, ME | LeRC/PERC | Russell Daines (PhD)<br>Ashvin Hosangadi (PhD)<br>Carlos Soares (MS)<br>Jonathan Weiss (PhD) |
| Ignition and Combustion Characteristics of Metallized Propellants | S. R. Turns, ME | LeRC/PERC | Laura M. DeSimone (MS)<br>Donn C. Mueller (PhD)<br>Margaret J. Scott (PhD) |
| Laser Spark Ignition | D. A. Santavicca, ME | LeRC/PERC | Chi Ho (PhD)<br>Brian Reilly (BS) |
| Liquid Jet Break-up and Atomization Under Dense Spray Conditions | K. K. Kuo, ME<br>F.-B. Cheung, ME | MSFC/PERC | Michael Kline (MS)<br>Rob Malony (BS)<br>Roger Woodward (PhD) |
| Droplet-Turbulence Interactions in Subcritical and Supercritical Evaporating Sprays | D. A. Santavicca, ME | MSFC/AFOSR/ PERC | Edward Coy (PhD)<br>Young-Hoon Song (PhD)<br>Timothy Spegar (MS) |
| The Effect of Droplet Vaporization on the Initiation and Growth of Combustion Instabilities | D. A. Santavicca, ME | AFOSR/PERC | Michael Ondas (MS) |
| An Experimental Study of Characteristic Combustion-Driven Flow CFD Validation | R. J. Santoro, ME<br>C. L. Merkle, ME | MSFC/PERC | Jeff Grenda (PhD) |

A. CENTER PROJECTS (Continued)

| | | | |
|---|---|---|---|
| Combustion Instability Phenomena of Importance to Liquid Propellant Engines | R. J. Santoro, ME | AFOSR/PERC | W. E. Anderson (PhD) |
| Monograph on Combustion Instabilities in Propulsion Systems | V. Yang, ME | AL/PERC | |
| Reliability Enhancement of Navier-Stokes Codes | G. Dulikravich, AE<br>C. L. Merkle, ME | MSFC/PERC | Jennifer Yagley (MS) |
| Turbulence Modeling in Rotating Machinery | B. Lakshminarayana, AE | MSFC/PERC | |
| Flow Modeling in Cryogenic Pumps | C. L. Merkle, ME | Pratt & Whitney/ PERC | Manesh Deshplande (PhD) |

3. EXTERNALLY-FUNDED CENTER PROJECTS

| | | | |
|---|---|---|---|
| Rocket Engine Nozzle Analysis | V. Yang, ME<br>C. L. Merkle, ME | MBB | J. Y. Oh (PhD) |
| Supercritical Droplet Vaporization and Combustion | V. Yang, ME | MSFC | Mark Fisher (MS)<br>William Greene (MS)<br>Josef Wicker (MS) |
| Acoustic Waves in Complicated Geometries and Interactions with Liquid Propellant Droplet combustion | V. Yang, ME | AFOSR | M. W. Yoon (PhD) |
| Liquid Rocket Combustion Instability and Performance Analyses | V. Yang, ME | MSFC | James Withington (PhD) |
| System Study of the Hybrid Plume Plasma Rocket | M. M. Micci, AE | LaRC | |

## B. ADDITIONAL PROJECTS IN PROPULSION

1990 FUNDING: $920,000

| Title | P.I. | Agency/Duration | |
|---|---|---|---|
| Combustion Processes in VH BR Propellants | K. K. Kuo, ME | ARO | 5/87-4/91 |
| Experimental Investigation of Microwave Propulsion | M. M. Micci, AE | AFOSR | 2/89-1/91 |
| Radiation Gas/Dynamic Interactions in Propulsion Systems | C. L. Merkle, ME | AFOSR | 2/89-1/90 |
| Combustion Chemistry of Solid Propellants | T. A. Litzinger, ME | | 10/88-10/91 |
| Residual Stress Measurements on Coated Test Specimens by X-ray Diffraction Technique | R. N. Pangborn, ME | GE | 11/89-3/91 |
| Excitation of Nuclei by Antiproton Annihilation at Rest | G. A. Smith, Physics | AFOSR | 5/87-4/91 |
| A Study of an Antiproton Driver for an Inertial Confinement Fusion (ICF) Propelled Rocket | G. A. Smith, Physics | Jet Propulsion Lab | 10/88-10/91 |
| Fundamental Combustion Process of Particle-Laden Shear Flows in Solid-Fuel Ramjets | K. Kuo, ME<br>V. Yang, ME<br>T. Litzinger, ME | ONR | 6/86-3/91 |
| Direct Numerical Simulation of Velocity-Coupled Combustion Response of Solid Rocket Propellants | V. Yang, ME | AFAL | 9/86-11/90 |
| Structural/Ballistic Risk Assessment Methodology | K. Kuo, ME<br>V. Yang, ME<br>H. R. Jacobs, ME | AFAL | 8/88-7/93 |

## B. ADDITIONAL PROJECTS IN PROPULSION (Continued)

| Title | P.I. | Agency/Duration | |
|---|---|---|---|
| Transverse Acoustic Oscillations in a Turbulent Boundary Layer | H. R. Jacobs, ME<br>C. L. Merkle, ME | NSF | 10/90-9/92 |
| High Altitude Relight | D. A. Santavicca, ME | AFOSR, Garrett | 1/88-12/91 |
| Low NOx Gas Turbine Combustion Research | D. A. Santavicca, ME | AFOSR, GE | 10/90-12/93 |

## C. RELATED GRANTS

1990 FUNDING: $740,000

(NOTE: This is a partial list of closely associated research only)

| Project | P.I. | Agency | Duration |
|---|---|---|---|
| Ausforming of Surfaces | R. A. Queeney | USN, Chrysler Corp. | 9/88-9/90 |
| Glass Reinforced Composites | R. N. Pangborn | GM | 1/89-1/90 |
| One Dimensional Material Erosion Code Development | F.-B. Cheung | FMC | 8/90-1/91 |
| Spark Ignited Turbulent Flame Kernel Growth | D. A. Santavicca | AFOSR, DOE | 10/89-9/92 |
| Flame-Turbulence Interaction | D. A. Santavicca | AFOSR | 11/89-10/92 |
| Fundamental Mechanisms for CO and Soot Formation in Diffusion Flames | R. J. Santoro | NIST | 5/90-4/93 |
| Metal Oxide Particle Formation | R. J. Santoro | DuPont | 3/89-3/92 |
| Oxides of Nitrogen Emissions from Turbulent Hydrocarbon/Air Jet Diffusion Flames | S. R. Turns | GRI | 1/90-6/92 |
| Soot Particle Inception and Growth Processes in Combustion | R. J. Santoro | AFOSR | 1/90-1/92 |

# APPENDIX II

## PROPULSION ENGINEERING RESEARCH CENTER STUDENTS

### A. PLACEMENT OF GRADUATES

| NAME | DEGREE | CURRENT EMPLOYMENT |
|---|---|---|
| Mahesh Athavale | PhD, 1989 | CFD Research (NASA Marshall) |
| Kristina Cairns | MS, 1990 | Garrett |
| Gelsomina Cappuccio | MS, 1990 | NASA Ames |
| Yun Ho Choi | PhD, 1989 | Sverdrup (NASA Lewis) |
| Anthony Colozza | MS, 1989 | NASA Lewis |
| Laura DeSimone | MS, 1990 | Naval Surface Warfare Center |
| Mark Fisher | MS, 1990 | NASA Marshall |
| Kenneth Garner | MS, 1990 | Westinghouse Electric |
| William Greene | MS, 1990 | Martin-Marietta (NASA Marshall) |
| Ashvin Hosangadi | PhD, 1990 | SAIC |
| Ellsworth Minor | PhD, 1989 | Post-doctoral Scholar, Laboratory for Elementary Particle Science, PSU |
| Sibtosh Pal | PhD, 1990 | Research Associate, Propulsion Engineering Research Center |
| Kwang-Seo Park | MS, 1990 | Hyundai |
| Charles Simchick | MS, 1990 | Frick Company |
| Ronald Ungewitter | PhD, 1989 | Rocketdyne |
| Sankaran Venkateswaran | PhD, 1990 | Research Associate, Propulsion Engineering Research Center |

## B. GRADUATE STUDENTS, 1990-1991

| NAME | DEGREE | MAJOR | ADVISOR | BS | MS |
|---|---|---|---|---|---|
| Bulent Alatas | PhD | ME | Santavicca | Bogazici University | |
| William Anderson | PhD | ME | Santoro | Arizona State | University of Arizona |
| * Philip Balaam | PhD | AERO | Micci | University of Southampton | |
| Doug Berlin | MS | ME | Santoro | Haverford | |
| Robert Burch | MS | ME | Santoro | Northwestern University | |
| * C.-L. Chen | MS | ME | Kuo | National Taiwan University | |
| Edward Coy | PhD | ME | Santavicca | Worchester Polytech | |
| Samir Dagher | MS | ME | Pauley | University of Maryland | |
| Russell Daines | PhD | ME | Merkle | Brigham Young | Brigham Young |
| Manish Deshplande | PhD | ME | Merkle | University of Boona | Clemson |
| * Troy Dunn | MS | AERO | Micci | Penn State | |
| Chris Fetting | MS | ME | Santavicca | Milwaukee School of Eng. | |
| Y.-T. Fung | PhD | ME | Yang | National Taiwan University | |
| Stuart Greenfield | PhD | ME | Santavicca | University of Illinois | |
| Jeffrey Grenda | PhD | ME | Merkle | University of Utah | |
| * Chi Ho | PhD | ME | Santavicca | Temple | |
| David Hoover | MS | ME | Santoro | Penn State | |
| * Chia-Chun Hsiao | MS | ME | Yang | Tsing-Hua University | |
| Shih-Yang Hsieh | MS | ME | Yang | Tamkang University | |
| John Hutt | PhD | ME | Yang | University of Alabama | University of Alabama-Huntsville |
| * Taras Jarymowycz | PhD | ME | Kuo | Drexel | |
| Ronald Kanzleiter | MS | AERO | Smith | Penn State | |
| Michael Kline | MS | AERO | Cheung | Penn State | |
| Jongquen Lee | PhD | ME | Santavicca | Seoul National University | |
| Scott Lewis | PhD | ME | Sinha | Clemson | |

* Graduating 1990-91

## II. PROPULSION ENGINEERING RESEARCH CENTER STUDENTS (Continued)

| NAME | DEGREE | MAJOR | ADVISOR | BS | MS |
|---|---|---|---|---|---|
| Norman Lin | PhD | ME | Yang | Chung-Chen Inst. of Tech. | |
| Deryuh Liou | PhD | ME | Santavicca | National Taiwan University | Auburn |
| Y.-C. Lu | PhD | ME | Kuo | National Chen-Kung University | |
| Kevin Mease | MS | ME | Wang | Penn State | |
| Jennifer Miller | PhD | E SCI | Queeney | Penn State | |
| Marlow Moser | PhD | ME | Santoro | Brigham Young | |
| Donn Mueller | PhD | ME | Turns | North Carolina State | |
| Juergen Mueller | PhD | AERO | Micci | University of Giessen | |
| * Frank Myhr | MS | ME | Turns | University of Michigan | |
| * Gary North | PhD | ME | Santavicca | Penn State | |
| David Nye | PhD | ME | Santavicca | Clarkson | |
| Joseph Oefelein | PhD | ME | Yang | Rutgers | |
| * Jong Oh | PhD | ME | Yang | Pusan National University | |
| Michael Ondas | PhD | ME | Santavicca | Purdue | |
| * Kirsten Pace | MS | ME | Kuo | Penn State | |
| Jih-Ping Peng | MS | ME | Carpino | National Taiwan University | |
| * Rahul Puri | PhD | ME | Santoro | Banaras Hindu University | |
| Darrell Rapp | PhD | ME | Santoro | Yale | |
| * Thomas Richardson | PhD | ME | Santoro | Case Western | |
| * Steve Ritchie | PhD | ME | Kuo | Drexel | |
| Eric Roll | PhD | E SCI | Pangborn | Gannon | |
| Harry Ryan | PhD | ME | Santoro | University of Maryland-Baltimore | |
| * Randy Salizzoni | PhD | ME | Kuo | Penn State | |
| David Schroeder | MS | ME | Santavicca | Penn State | |
| * Margaret Scott | PhD | ME | Turns | Purdue | Penn State |

* Graduating 1990-91

## II. PROPULSION ENGINEERING RESEARCH CENTER STUDENTS (Continued)

| NAME | DEGREE | MAJOR | ADVISOR | BS | MS |
|---|---|---|---|---|---|
| Wang Ping Shih | MS | ME | Santavicca | National Tsing Hua University | |
| Tim Snyder | MS | ME | Kuo | Penn State | |
| Yong Hoon Song | PhD | ME | Santavicca | Hanyung University | |
| * Robert Sonntag | MS | ME | Santavicca | Drexel | |
| Tim Spegar | PhD | ME | Santavicca | Penn State | |
| Peter Strakey | PhD | ME | Santoro | Penn State | |
| Daniel Sullivan | PhD | AERO | Micci | New York University | |
| Isadore Sutton | PhD | ME | Merkle | Southern University | |
| Frank Tseng | PhD | FUEL SCI | Kuo | Chung Cheng Institute of Technology | Michigan State |
| * I-Shih Tseng | PhD | ME | Yang | National Taiwan University | |
| Hsin-Hua Tsuei | MS | ME | Merkle | Tamkang University | |
| * Brian Videto | PhD | ME | Santavicca | Michigan State | |
| Jonathan Weiss | PhD | ME | Merkle | Lehigh | Penn State |
| Kevin Wert | PhD | ME | Jacobs | Penn State | |
| Joe Wicker | PhD | AERO | Yang | Penn State | |
| James Withington | PhD | AERO | Yang | Cornell | |
| Roger Woodward | PhD | ME | Kuo | Carnegie-Mellon | |
| S.R. Wu | PhD | ME | Kuo | Tsing-Hua University | |
| T.T. Wu | PhD | ME | Kuo | Tsing-Hua University | |
| Jennifer Yagley | MS | ME | Merkle | Villanova | |
| An-Shik Yang | PhD | ME | Kuo | Tsing-Hua University | |
| C.L. Yeh | PhD | ME | Kuo | Chung-Hsing University | |
| Myong Yoon | PhD | ME | Yang | Hanyang University | |
| Donna Zelesnik | MS | AERO | Micci | University of Dayton | |

* Graduating 1990-91

## C. UNDERGRADUATES, 1990-1991

| NAME | MAJOR | ADVISOR |
|---|---|---|
| David Belfiore | ME/PSU | Santavicca |
| Brad Bruno | ME/PSU | Santavicca |
| * Bernard Chatman, Jr. | EE/PSU | Santoro |
| Steven Couvillon | ME/PSU | Santavicca |
| Charlene D'Amore | ME/PSU | Santoro |
| * Tabbetha Dobbins | PHYSICS/Lincoln | Turns |
| Chuck Ferrell | ME/PSU | Santavicca |
| * Kendall Hayman | EE/Delaware | Santavicca |
| Rob Malony | ME/PSU | Kuo |
| * Brian Mackey | CHEMISTRY/Lincoln | Queeney |
| Ehren Maund | ME/PSU | Turns |
| Todd Martin | AERO/PSU | Micci |
| * Omaira Melendez | PHYSICS/Lincoln | Litzinger |
| Michelle Musso | DUS/PSU | Merkle |
| * William Reed | ME/PSU | Carpino |
| * Edward Reutzel | ME/PSU | Santavicca |
| * Julie Richards | E SCI/PSU | Queeney |
| Corey Weaver | ME/PSU | Santavicca |
| Josef Wicker | AERO/PSU | Yang |

*Participated in Summer Undergraduate Program

# APPENDIX III

## ADVISORY BOARDS

### I. TECHNICAL REVIEW COMMITTEE

William J. D. Escher, Chair - NASA Headquarters
Larry Diehl - NASA Lewis
John McCarty - NASA Marshall
Phillip Garrison - Jet Propulsion Lab

### II. POLICY ADVISORY BOARD

Larry Diehl - NASA Lewis
Thomas DuBell - Pratt & Whitney
Stephan Evans - Rocketdyne
Lee Gaumer - Air Products
Richard LaBotz - Aerojet
John McCarty - NASA Marshall
Dwayne McKay - University of Tennessee Space Institute
Warren Strahle - Georgia Institute of Technology
Richard Weiss - Astronautics Lab

### III. FACULTY REVIEW COMMITTEE

Charles Hosler - Acting Provost, Senior Vice President for Research and Dean of the Graduate School
Kenneth Kuo - Mechanical Engineering
Charles Merkle - Director, Propulsion Engineering Research Center
Michael Micci - Aerospace Engineering
Richard Queeney - Engineering Science and Mechanics

# APPENDIX IV

## NASA PROPULSION ENGINEERING RESEARCH CENTER AT PENN STATE
## SECOND ANNUAL SYMPOSIUM

**Session A: Liquid Propellant Combustion**
**Room 112 Kern**

**Session Chairman: Robert J. Santoro**

| | | |
|---|---|---|
| 2:00 | Dr. Charles L. Merkle, Director | Center Overview |
| 2:30 | Dr. Kenneth K. Kuo and Dr. Robert J. Santoro | Cryogenic Combustion Laboratory |
| 3:00 | Dr. Stephen R. Turns | Ignition and Combustion of Metallized Propellants |
| 3:30 | Dr. Vigor Yang | Theoretical Study of Combustion Instabilities in Liquid-Propellant Rocket Motors |
| 4:00 | Dr. Harold R. Jacobs and Dr. Robert J. Santoro | Spray Combustion Under Oscillatory Pressure Conditions |
| 4:30 | Dr. Fan-Bill Cheung and Dr. Kenneth K. Kuo | Liquid Jet Breakup and Atomization in Rocket Chambers Under Dense Spray Conditions with Compression/Shock Wave Interaction |
| 5:00 | Dr. Domenic Santavicca | Turbulence-Droplet Interactions in Vaporizing Sprays<br>Laser Spark Ignition |

## NASA PROPULSION ENGINEERING RESEARCH CENTER AT PENN STATE
## SECOND ANNUAL SYMPOSIUM
## (Continued)

**Session B: Liquid Propulsion Technologies**
**Room 101 Kern**

**Session Chairman: Michael M. Micci**

| | | |
|---|---|---|
| 2:00 | Dr. Charles L. Merkle, Director | Center Overview (Room 112 Kern) |
| 2:30 | Dr. Robert Pangborn and Dr. Richard A. Queeney | Hydrogen Management in Materials for High Pressure Hydrogen/Oxygen Engines |
| 3:00 | Dr. Alok Sinha and Dr. Kon-Well Wang | Robust and Real-Time Control of Magnetic Bearings for Advanced Propulsion Rockets |
| 3:30 | Dr. Marc Carpino | Analysis of Foil Bearings for High Speed Operation in Cryogenic Applications |
| 4:00 | Dr. Laura Pauley | A Study of Methods to Investigate Nozzle Boundary Layer Transition |
| 4:30 | Dr. Michael M. Micci | Optical Diagnostic Investigation of Low Reynolds Number Nozzle Flows |
| 5:00 | Dr. Charles L. Merkle | Flowfield Analysis of Low Reynolds Number Rocket Engines |

# APPENDIX V

## 1990 SUMMER UNDERGRADUATE PROGRAM

| STUDENT | PROJECT | ADVISOR |
|---|---|---|
| Bernard Chatman, Lincoln/PSU | "Cryogenic Combustion Laboratory" | R. Santoro |
| Tabbetha Dobbins, Lincoln | "Ignition and Combustion Characteristics of Metallized Propellants" | S. Turns |
| Kendall Hayman, Lincoln/Delaware | "Ignition Limit at the Simulated Gas-Turbine Operating Conditions" | D. Santavicca |
| Brian Mackey, Lincoln | "Fracture and Fatigue of Powder Metallurgy" | R. Queeney |
| Omaira Melendez, Lincoln | "High Pressure Oxidation of Methane in a Turbulent Flow Reactor" | T. Litzinger |
| William Reed, Ogontz/PSU | "Development of a User Interface for a Foil Bearing Code" | M. Carpino |
| Edward Reutzel, PSU | "Laser Spark Ignition of Methane Oxygen Mixtures" | D. Santavicca |
| Julie Richards, PSU | "Fabrication of Ceramic Reinforced Metals" | R. Queeney |

# APPENDIX VI

## Abstracts of Current Center Projects

# ANALYSIS OF FOIL BEARINGS FOR HIGH SPEED OPERATION IN CRYOGENIC APPLICATIONS

Marc Carpino

## ABSTRACT

The objective of this research project is to develop a general theoretical model for foil journal bearings and implement the model as a predictive analysis tool to support the design and development of bearings in cryogenic applications. Foil bearings are an attractive alternative to rolling element bearings in cryogenic applications, since they would use the process fluid, e.g. liquid oxygen or hydrogen, as the primary lubricant.

The analysis of these bearings requires the simultaneous solution of the lubricant fluid flow in the bearing clearance and the deflection of the foils. A coupled finite element based code has been developed for the implementation of different structural and fluid model formulations. Solutions are found through a modified direct iteration method. This approach imposes a neutral constraint, derived from the flow characteristics, on the structural deflection during the iterative process.

Results have been demonstrated for both flat rectangular and finite length journal bearing configurations utilizing incompressible fluids. Bending, membrane, and elastic foundation effects are included in the structural models. The models are being extended to semi-compressible fluids.

# SPRAY COMBUSTION UNDER OSCILLATORY PRESSURE CONDITIONS

H.R. Jacobs and R.J. Santoro

## ABSTRACT

A sequence of experiments have been conducted to study the effects of acoustic induced pressure oscillations on the breakup of liquid jets and the trajectories of the resulting droplets. Both mono-injector (water injection) and co-axial nozzles (water core; nitrogen annulus) were investigated towards this end. Experimental techniques used for this investigation involved high speed cinematography (Spin Physics and standard video cameras), planar laser imaging, phase doppler particle sizing, and simple flash photography. A 6 inch diameter, 24 inch steel chamber having two 120-watt Altec-Lansing speakers attached at the ends of speaker arms was used in these studies. These speakers are used to drive the acoustic modes in the chamber. The speakers can be driven with any desired phase separation and microphone measurements of the pressure field within the chamber show that peak to peak oscillations in excess of 4 psi can be maintained. Two windows, centered 6 inches from the top of the chamber, provide visual access. Optionally, one of the speakers can be replaced with a window to provide additional visual access. A moveable injector is used to position the injector face near the window for added visual access. Four circumferential microphone ports, at 90° intervals located 10 inches from the top of the chamber, are used to study the acoustic characteristics of the chamber. Experimental results for the mono-injector nozzles show that high frequency acoustic oscillations (1-4 kHz) play a dramatic role in the breakup of liquid jets at certain preferential modes that are characteristic of the injection chamber. These results are of potential importance for impinging-element type injectors for obvious reasons.

Acoustic oscillations were observed to dramatically breakup the liquid jet emanating from mono-injector nozzles (0.0625 inch and 0.1 inch diameter nozzles with a length to diameter ratio in excess of 10) in two distinct fashions. The Reynolds numbers of the jets ranged from 1250 to 50,000 and the corresponding Weber numbers based on the gas density ranged from 0.03 to 200. The first type of breakup occurred at 1140 Hz which corresponds to the first tangential mode. The jet was observed to breakup into a spray with droplet diameters of the same order of magnitude as the nozzle diameter. The corresponding pressure amplitude pattern at one phase angle, measured by traversing two microphones within the chamber, indicates that the mode is 1-T mode. It is postulated that the 1-T mode frequency couples preferentially to the breakup frequencies of the jet. The second type of breakup was also observed at frequencies of 1560 and 4350 Hz. For this type of breakup, the jet first acquires the shape of a two-dimensional fan (perpendicular to the speaker axis) which is reminiscent of the fan-structure observed with impinging nozzles. Droplets sheared from the bottom of the fan are visually at least more than an order of magnitude smaller than the diameter of the nozzle. Acoustic measurements of the mode in question show tangential mode-like characteristics as well. However, the sharp pressure gradient that exists along the center vertical plane of the chamber that seems to cause the jet to 'fan' out is not characteristic of a pure tangential mode. This mode could be the 3-Longitudinal/1-Tangential (calculated to be 1580 Hz) mode. Note that the pressure amplitude measurements were made 10 inches from the top of the chamber which places the measurement location close to the pressure antinode for the longitudinal component of this mode. Measurements have also been obtained at chamber pressures as high as 200 psi with similar results observed. The high pressure studies show even stronger effects of the imposed acoustic fields.

As a complementary effort to the atomization and spray studies described above, a diagnostic development program has been initiated to support the future measurement needs of this project. A planar laser polarization ratio approach along with a Phase Doppler Particle Analyzer are being used in these studies to provide quantitative droplet size measurements. Such capabilities will be useful in a wide range of spray and atomization studies presently planned.

# LIQUID JET BREAKUP AND ATOMIZATION IN ROCKET CHAMBERS UNDER DENSE SPRAY CONDITIONS

K. K. Kuo, F. B. Cheung, R. D. Woodward, and M. C. Kline

## ABSTRACT

This research project employs innovative diagnostic techniques to study the processes of liquid jet breakup and atomization in the near-injector region under simulated liquid rocket engine conditions. The main objective is to determine actual dense spray characteristics so as to provide realistic information needed to predict the performance of advanced liquid rocket engines for space propulsion, and to develop an effective means for enhancing mixing of liquid propellants. The experimental results to be obtained in this project will also provide a useful database for model development and validation.

Two advanced diagnostic techniques have been established and employed in the project. The first technique involves the use of a real-time X-ray radiography system along with a high-speed CCD Xybion camera and an advanced digital image processor to investigate the breakup processes of the liquid core. The focus of this part of the project is to determine the inner structure of the liquid jet and to correlate the core breakup length and local void fraction to various controlling parameters such as the characteristic Reynolds and Weber numbers. The second technique involves the use of a high-power copper-vapor laser to illuminate the liquid jet via thin sheets of laser light, with the scattered light being photographed by a Xybion electronic camera synchronized to the laser pulse. This technique, which is capable of recording the breakup event occurring within 25 nano-seconds, enables us to freeze the motions of the jet and liquid droplets. The focus of this part of the project is to determine the outer structure of the liquid jet and to discover the configuration of the surface waves, the spray pattern, and the droplet size distribution in the non-dilute region.

A specially designed liquid spray test rig has been fabricated, set up, and tested in the High Pressure Combustion Laboratory. The test rig consists of a fuel supply system, an injection unit, a jet-breakup and spray-observation station, and a liquid collection unit. The injection unit has interchangeable components for simulating both single and multiple (i.e., coaxial, triplet, etc.) injector configurations. A series of coaxial jet breakup experiments have been conducted under open-atmosphere conditions. The work has now been extended to study the breakup processes of a coaxial flow injected into a high-pressure chamber in order to simulate more closely the liquid rocket engine environment. An existing high-pressure, windowed test chamber has been modified for this purpose. The chamber pressure, to be monitored with a pressure transducer, is held constant during a test by the use of a back-pressure regulator. The pressurized windowed test chamber will be employed for both real-time X-ray radiography and laser-assisted flash-photography studies. In the former case, the image processing technique will be used whereas in the latter case, a secondary window will be machined at the top of the chamber to direct the laser sheet into the test chamber in order to illuminate the jet. Video data analogous to those obtained in the open atmosphere tests will be acquired for various chamber pressures ranging from 100 to 1000 psi.

# CFD ANALYSIS OF ROCKET CHAMBER/NOZZLE FLOWFIELD

C. L. Merkle, J. Weiss, R. Daines

## ABSTRACT

The detailed physical and chemical processes that take place in chemical propulsion engines are being investigated by means of CFD analyses. Primary emphasis is on small, auxiliary propulsion engines where low Reynolds number effects cause traditional design procedures to become ineffective. Improved design and analysis procedures should enable considerable performance improvement in these small engines.

Current efforts are focussed on analyzing the mixing and combustion patterns in a gaseous hydrogen-oxygen engine proposed for auxiliary propulsion on the space station. Toward this end, we are using a CFD code originally developed for hypersonic reacting flows. To improve effectiveness at the low subsonic speeds that are representatives of rocket engines, we have modified the solution algorithm and inflow boundary conditions. Present boundary conditions allow us to specify the incoming propellant flow rates so that the chamber pressure is determined as a part of the computation in a manner that mimics experimental test procedures.

The engine of interest has an internal oxygen-rich core stream which first combusts and then mixes with a hydrogen stream on its outer periphery. The external hydrogen provides wall cooling but also brings the overall mixture ratio to stoichiometric. Results based on an algebraic turbulence model show very little reaction between the two streams, but this simple turbulence model is insufficient for computing this complex flow. Consequently, a primary challenge for modeling this flowfield is to choose an appropriate turbulent combustion model. Toward this end, we are presently implementing a two-equation turbulence model with intentions of augmenting it with a turbulent combustion model next. Primary future plans are to compare the computer predictions with experimental measurements that are presently in progress to verify the accuracy of the analysis and to enable us to pursue parametric design studies on this and other auxiliary propulsion engines with confidence.

OPTICAL DIAGNOSTIC INVESTIGATION OF LOW REYNOLDS NUMBER NOZZLE FLOWS

Dr. Michael M. Micci

ABSTRACT

The vacuum facility in the Propulsion Engineering Research Center has been brought into operation this past year. The vacuum chamber measuring 1 meter in diameter and 5 feet long is connected to both a Stokes mechanical pump and a Stokes diffusion pump. A minimum vacuum of $1.9 \cdot 10^{-4}$ Torr has been achieved, equivalent to an altitude of 202 km. Chamber vacuum as a function of mass flow rate for both helium and nitrogen gas has been measured. The chamber pumping system can sustain a vacuum of $10^{-3}$ Torr, equivalent to an altitude of 92 km, with a helium flow rate of 0.06 gm/sec and a nitrogen flow rate of 0.002 gm/sec. These flow rates are of the same order of magnitude as the propellant flow rates in the Space Station Freedom drag make-up resistojets.

A pulsed Nd/YAG laser system combined with a tunable dye laser has been installed in the adjacent laboratory operated by Dr. Santoro. This will be a shared use laser used for laser induced fluorescence (LIF). A system to transmit the laser beam into the vacuum chamber is currently being installed. The LIF system will enable the simultaneous measurement of the profiles of velocity along a single axis, temperature and density. NO will be used as a seedant in the low Reynolds number investigations for the following three reasons:

1) Only very small quantities are required (20 ppm);
2) Detection can be obtained with low laser intensities (3 microJoule pulses);
3) LIF can be used down to the very low temperatures to be encountered in nozzle expansions to near vacuum conditions (28K).

Equipment to produce laser radiation at the NO wavelength in the near ultraviolet is currently on order. A Nichrome wire heating system will be initially used to examine the effects of gas stagnation temperatures up to 1000 K on the flow within low Reynolds number nozzles. Eventually, a microwave-heated plasma will be used to examine gas stagnation temperatures up to 12,000 K as well as the effects of stratified flows. Initial testing will be with conical nozzles with future testing examining bell and trumpet shaped nozzles.

A high resolution spectrometry system consisting of an electronically tunable Fabry-Perot etalon combined with an 0.5 meter Spex monochromator is in place to analyze the fluorescence signals from the gas in the nozzle expansion with a resolution of 0.004 Angstroms.

HYDROGEN MANAGEMENT IN MATERIALS FOR HIGH-PRESSURE HYDROGEN/OXYGEN ENGINES

R. Pangborn, R. Queeney, E. Roll, J. Miller

## ABSTRACT

This research program addresses the protection of propulsion system components, and the materials from which they are fabricated, from hydrogen-induced degradation. Specifically, the investigation will identify single and multiple-layer coatings which are effective in reducing hydrogen permeation, and resulting embrittlement, under a range of service temperatures and hydrogen partial pressures. The following summarizes the progress on the project.

The initial literature search has been completed. Previous work involving hydrogen diffusion and embrittlement in materials used in the SSME and in various proposed protective coatings has been reviewed and references dealing with diffusion measurements have been examined.

Computer models for steady-state hydrogen diffusion across 2, 3 and 4 layer laminates (coatings over base metal) have been completed. These models include the option of examining the effect of open porosity in one or both outer laminae. Work is ongoing on finite-difference transient-state diffusion models of the same laminate configurations. The models, which are implemented on a VAX 11/780 computer, will be available to optimize coating system performance once testing of the system components begins. They will also be available for prediction of levels of hydrogen intrusion into SSME components coated with protective materials examined in this study.

Various candidate metallic and ceramic coatings for the Inconel-718 base alloy have been chosen, including zirconia, chromia, alumina and NiCrAlY alloys. Design and fabrication of the high-pressure diffusion cell have been completed. This apparatus will allow determination of material diffusivity and solubility coefficients at high temperatures and pressures. These coefficients are needed as input to the models to verify that particular combinations will be effective barrier coatings. Design and fabrication of the low-pressure diffusion cell has also been completed, which will be used to determine the effects of both elastic stress fields and thermal-cycling damage on hydrogen diffusion in Inconel-718 and various coatings. Assembly of the experimental apparatus, including the vacuum pumping and measurement systems, is complete with system testing and troubleshooting ongoing. Future acquisition of a Hewlett-Packard computer data acquisition has been confirmed. While not essential for testing, this system will greatly enhance data acquisition and post-processing efficiency.

Work is underway to enhance the safety equipment of the test facility. Firefighting and first-aid equipment have been purchased and installed. Various explosive gas sensing equipment packages are being investigated, as well as various schemes of venting the facility to eliminate any hydrogen that may escape inadvertently.

Specimen fabrication for both the high- and low-pressure experiments is currently underway, with initial experimentation scheduled to begin by early February. Tight tolerancing of the high-pressure specimens necessitated design and manufacture of a precision grinding fixture, which is now being evaluated. Preliminary microstructural analyses of the Inconel-718 have been completed. Follow-up analyses will be performed after completion of diffusion testing. Testing of coated specimens will proceed as they become available, with completion of this testing planned by late June, 1991. As in the case of the monolithic specimens, pre- and post-permeation microstructural analysis of the applied coating systems will be performed.

# A NUMERICAL STUDY OF BOUNDARY LAYER TRANSITION WITHIN A HIGH-AREA-RATIO NOZZLE

Laura L. Pauley and Samir N. Dagher


## ABSTRACT

In this study, the conditions which cause a supersonic nozzle boundary layer to undergo transition to turbulence will be investigated. Two types of instabilities can develop along the concave surface of a nozzle: Tollmien-Schlichting waves and Görtler vortices. A stability analysis will reveal the type of instability and the wavelength of the instability that is amplified most rapidly. By determining the amplification of the fastest growing instability, the onset of boundary layer transition can be identified. The effects of pressure gradient, compressibility, and wall cooling will be considered.

The current research uses a boundary layer stability analysis to investigate the results obtained by Smith in the high area ratio nozzle at NASA Lewis[1]. Smith compared the experimental heat flux measurements from the nozzle tests with the results from laminar and turbulent boundary layer computations. At low chamber pressures, the wall heat flux measurements agreed with the laminar computations. As the chamber pressure was increased, the experimental results were between the laminar and turbulent computations but never reached the turbulent boundary layer predictions. It appears that the boundary layer is not fully turbulent at higher chamber pressures. The current study will investigate the stability of the laminar boundary layer and determine the location where transition begins.

Stability research in supersonic nozzles has been used by Chen, Malik, and Beckwith[2] to analyze the production of wind tunnel noise. In their study, both Tollmien-Schlichting waves and Görtler vortices were considered. It was found that the Görtler vortices grew more rapidly and were responsible for the transition of the laminar boundary layer to turbulence. A similar analysis is being conducted for the supersonic rocket nozzle tested by NASA Lewis.

In order to investigate the boundary layer stability, the laminar boundary layer development is first determined. Two methods have been used to obtain the laminar boundary layer information: a compressible Navier-Stokes program with fixed chemical composition, and a two-dimensional kinetics program coupled with a boundary layer program. Both computations resulted in wall heat flux distributions similar to those determined by Smith. At low chamber pressures, the heat flux predictions from the laminar boundary layer computations agreed with the experimental heat flux measurements. For higher chamber pressure cases, the computations underpredicted the experimental wall heat flux. This indicated that the nozzle boundary layer is not two-dimensional and laminar.

The disturbances which will grow and cause a transition of the laminar boundary layer can be determined by a stability analysis. Tollmien-Schlichting and Görtler instabilities are considered at different characteristic wavelengths. Instabilities that grow as the boundary layer develops can alter the two-dimensionality of the flow and the instability that grows most rapidly is responsible for transition. At the lowest chamber pressure, the stability analysis revealed that both Tollmien-Schlichting waves and Görtler vortices are stable everywhere in the nozzle. The analysis confirms that the nozzle boundary layer is laminar at low chamber pressures and the laminar computation should accurately describe the flow. At high chamber pressures, both Tollmien-Schlichting waves and Görtler vortices grew as the boundary layer developed downstream. The Görtler vortex structure grew more rapidly and the wavelength of the most unstable structure was identified. From the results, the location where transition occurs was identified. Future work will study the boundary layer transition at other chamber pressures investigated by Smith.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# DROPLET-TURBULENCE INTERACTIONS IN SUBCRITICAL AND SUPERCRITICAL EVAPORATING SPRAYS

D. A. Santavicca

## ABSTRACT

The objective of this research is to obtain an improved understanding of droplet-turbulence interactions in vaporizing liquid sprays under conditions typical of those encountered in liquid fueled rocket engines. The interaction between liquid droplets and the surrounding turbulent gas flow affects droplet dispersion, droplet collisions, droplet vaporization and gas-phase, fuel-oxidant mixing, and therefore has a significant effect on the engine's combustion characteristics. An example of this is the role which droplet-turbulence interactions are believed to play in combustion instabilities. Despite their importance, droplet-turbulence interactions and their effect on liquid fueled rocket engine performance are not well understood. This is particularly true under supercritical conditions, where many conventional concepts, such as surface tension, no longer apply. Our limited understanding of droplet-turbulence interactions, under both subcritical and supercritical conditions, represents a major limitation in our ability to design improved liquid fueled rocket engines. It is expected that the results of this research will provide previously unavailable information and valuable new insights which will directly impact the design of future liquid fueled rocket engines, as well as, allow for the development of significantly improved spray combustion models, making such models useful design tools.

The primary efforts to date have been devoted to the development of the experimental apparatus and diagnostic techniques required for this study. This includes the development of a flow system which is capable of simulating the broad range of turbulent flow conditions encountered in the peripheral regions of coaxial and impinging type rocket sprays. It is in this region where droplet-turbulence interactions are most important and have significant effects on droplet vaporization, droplet dispersion and droplet collisions, as well as, on gas-phase, fuel-oxidant mixing. A polydispersed spray of variable droplet density and size distribution is produce using a low pressure spray nozzle and skimmer combination. This spray is transversely injected into the one-dimensional turbulent flow, thereby providing a well-defined region of droplet-turbulence interactions. A single droplet generator is also being developed in order to study the interaction between individual droplets and turbulence.

An atmospheric pressure, room temperature version of this system is currently in operation and has been used extensively for diagnostic development. A high pressure (70 atm) elevated temperature (300°C) turbulent flow system has been recently completed. This system is capable of achieving supercritical conditions for a number of liquids including liquid oxygen and liquid nitrogen, as well as most liquid hydrocarbons.

# THE EFFECT OF DROPLET VAPORIZATION ON THE INITIATION AND GROWTH OF COMBUSTION INSTABILITIES

D. A. Santavicca

## ABSTRACT

Despite the fact that high frequency combustion instabilities in liquid propellant rocket engines have been studied for over thirty years, they are still not well understood and are often a major concern and limiting factor in the development of new engines. This is particularly true for liquid hydrocarbon fueled engines. Characteristic time scale analyses identify a number of fundamental processes which are most likely to contribute to the occurrence of high frequency combustion instabilities. Those which are most often considered to be of critical importance include atomization, droplet heating, droplet vaporization, mixing, and chemical kinetics. The role which these individual processes play in the initiation and growth of combustion instabilities, however, is not well understood. This is evidenced by the fact that current methods for eliminating high frequency instabilities are based on either a cut and try approach or introducing damping mechanisms which inhibit the growth of the instabilities (rather than eliminate their cause).

The objective of the current study is to characterize the role of droplet vaporization and dispersion in high frequency combustion instabilities. Experiments are conducted to identify the conditions under which the vaporization and dispersion of droplets in polydispersed, vaporizing sprays can be driven by imposed acoustic fields. Liquid propane and n-decane sprays are studied, injected into both subcritical and supercritical environments, i.e., up to 70 atm and 800 K. Of specific interest is the dependence of the spray-acoustic field interaction on the frequency and amplitude of the acoustic field; the droplet number density; the droplet size and velocity distribution; the droplet and gas temperatures; the turbulence properties of the gas; the pressure; and the thermophysical properties of the liquid droplets.

This research is intended to provide new information and understanding of the behavior of vaporizing droplets in acoustic fields under conditions which are typical of those encountered during the initiation and growth of high frequency combustion instabilities in liquid propellant rocket engines. This experimental study is conducted in close collaboration with a parallel theoretical study of the behavior of droplets in acoustic fields by C. L. Merkle of Penn State. From this collaborative effort, the conditions under which and the mechanisms by which droplet vaporization and dispersion play a major role in combustion instabilities will be determined. This information will, both directly and through its use in the development of improved combustion instability models, provide the understanding and insights which are necessary for the development of new strategies and approaches for designing more stable liquid propellant rocket engines.

# LASER SPARK IGNITION

D. A. Santavicca

## ABSTRACT

Laser spark ignition is one of several techniques currently being investigated for possible use in future liquid rocket engines. The advantages of laser spark ignition over other techniques include its safety, the ease of coupling the laser to the engine with optical fibers, and the ability to locate the laser spark at the optimum location within the rocket chamber. A major concern in the use of laser spark ignition is the effect of incomplete propellant mixing. The feasibility of using laser spark ignition in methane-oxygen fueled rockets is under study in a turbulent flow reactor which is capable of simulating the flow field conditions at the time of ignition in actual rocket engines. The effects of incomplete mixing, laser spark energy, turbulence, pressure and temperature are being investigated. Measurements of the ignition probability and the ignition kernel growth rate are made to characterize the laser spark ignition process.

# CRYOGENIC COMBUSTION LABORATORY

R.J. Santoro and K.K. Kuo

## ABSTRACT

Significant progress has been made during the past year in the establishment of the Cryogenic Combustion Laboratory. Most important among these achievements has been the first test firings of the gaseous hydrogen and gaseous oxygen system as well as the testing of the liquid oxygen system. Both of these test firings were achieved on schedule and mark major milestones in this project. Future work will proceed on a dual track, pursuing new experimental results using the current capabilities of the facility while also concurrently adding to the capabilities of the laboratory. Specifically, chilled hydrogen and liquid hydrocarbon fuel capabilities, along with enhanced diagnostic capabilities, will be pursued.

The Cryogenic Combustion Laboratory, space for which was made available to the NASA Propulsion Engineering Research Center in March, 1989, occupies a three-room complex which includes a reinforced concrete test cell. Adjacent to the test cell are the instrumentation and control rooms. The control room contains the equipment necessary to remotely operate the test facility and is isolated from the test area during all run sequences. The design of the gaseous hydrogen and oxygen supply systems closely follow those in an existing facility at the NASA Lewis Research Center (LeRC). Personnel at NASA LeRC have been instrumental in the timely development of this facility through the supply of detailed drawings and parts lists for the facility. Additional advice and guidance has been provided by the Marshall Space Flight Center, Rocketdyne, Air Products, the Astronautics Laboratory (Air Force Systems Command), Aerojet, and Pratt and Whitney, and their input is gratefully acknowledged.

The operation of the laboratory allows testing with gaseous and liquid oxygen burning gaseous fuels (hydrogen and methane have been used to date). The maximum operating pressure is approximately 1500 psi, a limit imposed by the present fire valves. The gaseous oxygen flow system has been designed to provide a maximum flow rate of 0.1 lbs/s of oxygen while the liquid oxygen system can provide 1.0 lbs/s. These flow rates are adequate for the sub-scale studies for which the laboratory is intended. Successful test firings of the gaseous system occurred near the end of December, 1989, and have continued periodically through March, 1990. Both hydrogen/oxygen and methane/oxygen test runs were conducted. These tests have provided a suitable basis for assuring the adequacy of the safety systems, run procedures, and operating components of the laboratory. Similarly, the liquid oxygen tests, which were conducted in early January, 1990, have demonstrated that cryogenic fluids can be handled and delivered to a test combustor. Combustion experiments have demonstrated that reliable ignition can be attained and sustained combustion runs of up to five seconds have been achieved.

Future activities at the Cryogenic Combustion Laboratory will emphasize the application of new measurements techniques to an optically accessible rocket chamber. These studies will initially concentrate on planar laser imaging of OH radical concentration profiles in a hydrogen/oxygen rocket. Further studies of spray combustion processes are also planned using both planar and point measurement techniques. Both a pulsed Nd-YAG dye laser and a cw argon-ion laser system have been acquired for these studies. Diagnostics for providing planar laser imaging of sprays in combusting environments is presently being developed in a separate laboratory for use with these lasers. These droplet techniques are complemented by a Phase Doppler Particle Analyzer which can be used for point measurements of droplet size and velocity.

In summary, during the past year, two major milestones in the Cryogenic Combustion Laboratory program have been achieved. Both gaseous and liquid oxygen capability has been developed and tested under combustion conditions. Additionally, a solid diagnostics effort has been initiated to be used in conjunction with the test facility which will yield new results and insight into rocket propulsion phenomena.

# ROBUST AND REAL-TIME CONTROL OF MAGNETIC BEARINGS FOR ADVANCED ROCKET ENGINES

A. Sinha, K. W. Wang, K. Mease, and S. Lewis

## ABSTRACT

The main objective of this research program is to develop a highly reliable magnetic bearing system, which can replace ball bearings in space engines. In particular, novel control algorithms for magnetic bearings are being developed to support the rotor shaft and to attenuate the vibration of the rotor shaft as well. These control algorithms will be insensitive to inevitable parametric uncertainties, external disturbances, spillover phenomena and noise. The research involves both analyses and experiments.

The development of the robust and real-time control algorithms is based on the sliding mode control theory. In this method, a dynamic system is made to move along a sliding hyperplane to the origin of the state space (zero vibration). The main advantage of this technique is that the robustness to parametric uncertainties and external disturbances can be guaranteed and on-line computational burden is extremely small.

Currently, the mathematical models for magnetic bearings and rotor dynamics have been completed and algorithms for rigid control have been developed. Computer simulations have been carried out to examine the performance of the control law, and promising results have been illustrated. A microprocessor controller has been set up and a rotor fixture is being assembled for experimental validation purposes. Control laws for flexible rotor systems are presently being synthesized.

# AN ANTIPROTON DRIVER FOR ICF PROPULSION*

R. A. Lewis, R. Newton, G. A. Smith and W. S. Toothacker
Laboratory for Elementary Particle Science
Department of Physics
and
K. Higman
Department of Nuclear Engineering
and
R. A. Kanzleiter
Department of Aerospace Engineering

## ABSTRACT

Systems driven by inertial confinement fusion (ICF) have come under consideration for propulsion applications. Such systems could derive thrust from a magnetically directed charged plasma resulting from laser-driven microexplosions in DT pellets [1]. We are studying the practicality of igniting the DT pellet with energy carried by heavy nuclear fragments from antiproton-induced fission. The driver system is comprised of a trap in which antiprotons are stored, an accelerator to deliver antiprotons to the pellet, and a uranium-clad pellet. The antiproton driver would be compact, making it especially attractive for space propulsion applications.

In 1981, S. Polikanov [2] foresaw the possibility of creating a hot, dense plasma through fission triggered by antiprotons in a solid uranium microsphere. Subsequently, fission neutrons [3] and gamma-rays [4] released by antiproton annihilation at rest in uranium were observed by our group under AFOSR sponsorship. Preliminary calculations indicate that peak shock pressures of several megabars or more could be realized in the center of a small hydrogen-laced uranium microsphere with short )10 ns) bursts of stopped antiprotons ($10^{10}$ or more).

An alternate scheme would utilize small numbers of antiprotons ($10^7$) as a catalyst to the microfission/fusion process. Injection would occur immediately after compression, but well in advance of ablation, of the pellet. In this case, compression could be provided by another driver system, such as light ion beams [5].

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* Supported in part by the Jet Propulsion Laboratory, California Institute of Technology, and the NASA Center for Space Propulsion Engineering, Penn State University.

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IGNITION AND COMBUSTION OF METALLIZED PROPELLANTS

Stephen R. Turns

ABSTRACT

The overall objective of this project is to experimentally and analytically characterize the ignition and combustion characteristics of Al/RP-1 slurry droplets, where droplet sizes are in the range of practical applications (ca. 10-100 µm).

Accomplishments for this period include the shakedown and calibrations of the burner/spray rig and particle sizing optical systems. Software for data acquisition and data analysis was completed and is currently in use. Experiments in progress are examining the secondary atomization characteristics of several different slurry formulations. Figures 1 and 2 show some typical results. Figure 1 shows drop size distributions and velocity-size scattergrams for JP-10, a pure hydrocarbon at various distances, x, from the burner face. These data are useful for comparison with results for slurries. Similar plots for a 55 wt. % Al in RP-10 slurry are shown in Figure 2.

For the JP-10 (Figure 1), we see the number of droplets decreases downstream as the droplets burn out. The sauter-mean diameter (SMD) increases slightly at first as the smallest particles burn out rapidly, and then decreases. The JP-10 droplet velocities by and large follow the gas stream velocity. Much different behavior is apparent for the slurry fuel (Figure 2). Here we see that the total number of particles actually increases with distance downstream of the burner face as the mean particle size decreases. This result is consistent, first, with the occurrence of fragmentation of the slurry droplets, and second with the formation of relatively large oxide product particles. Unlike for the hydrocarbon, the velocity scattergrams for the slurry show very large velocities, several times greater than the gas stream, at the x=5 and 7.5 mm locations. These large velocities result from fragmentation of the parent slurry droplets and/or ignition of aluminum particles. Both fragmentation, indicated by a bright bursting phenomenon, and aluminum ignition, indicated by erratic trajectories of brightly burning particles, were observed visually.

Future plans include the characterization of the fragmentation and ignition properties of several slurries as functions of temperature and stoichiometry.

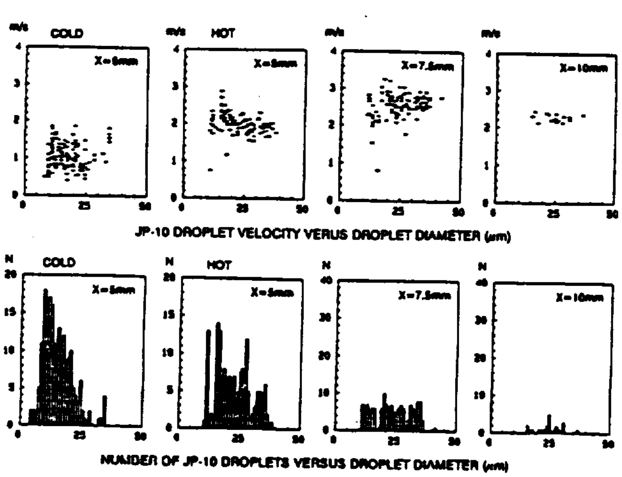


FIG. 1 JP-10 results.

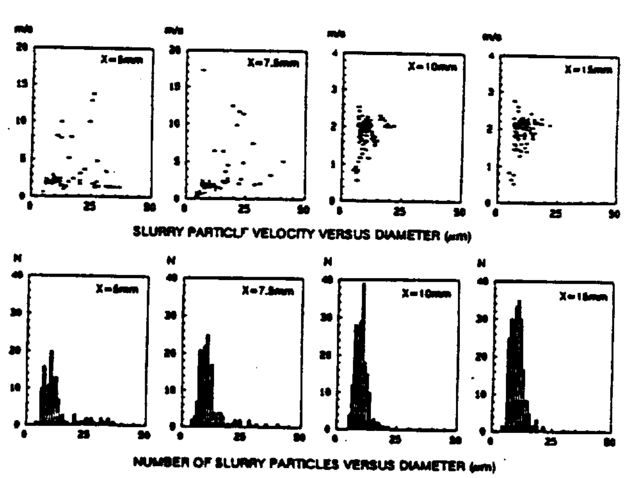


FIG 2. Aluminum slurry results.

# DROPLET VAPORIZATION AND COMBUSTION IN NEAR AND SUPER-CRITICAL ENVIRONMENTS

Vigor Yang


## ABSTRACT

The objective of this theoretical research is to study the transport processes and dynamics of liquid-propellant droplets at near and super-critical conditions. The work represents a series of attempts to analyze from first principals the detailed flow structures and the interface transport phenomena involved in high-pressure droplet vaporization and combustion. Results will not only enhance basic understanding of the problem, but will also serve as a basis for evaluation of existing correlations and/or establishment of new correlations for droplet heat, mass, and momentum transfer rates in high-pressure environments. In addition, the dynamic responses of droplet vaporization and combustion to ambient flow oscillations will be investigated.

During the past year, efforts have been made in three major areas: (1) development of a comprehensive theoretical model for treating droplet vaporization and combustion in both near- and super-critical conditions; (2) investigation of droplet vaporization and combustion responses to ambient flow oscillations; (3) review of combustion instabilities in F-1 engines. The droplet combustion model extends the previous analysis for vaporization and accommodates finite-rate chemical kinetics. It can handle the entire droplet history, including the transition from subcritical to critical states. Some of the results have led to two technical papers submitted to Combustion Science and Technology for publication and three conference papers to be presented at the 1991 AIAA Aerospace Science Meeting and AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

At present, we are conducting research on the vaporization and combustion of fuel droplets in a supercritical, forced-convective environment. The purpose is to study the effect of forced convection on the characteristics of droplet vaporization and combustion. As a specific example, the behavior of n-paraffin fuel droplet will be studied in depth.

# APPENDIX VII

## REPRESENTATIVE PUBLICATIONS OF CENTER FACULTY AND FACULTY HONORS

### A. PUBLICATIONS


Armstrong, T.A., R. Bishop, V. Harris, R.A. Lewis, E. Minor and G.A. Smith, "Energy Transfer by Intranuclear Cascade of Pi-Zeros Produced in Antiproton Annihilation at Rest in Nuclear Targets", Z. Phys., A332, 467 (1989).

Armstrong, T.A., D.M. Elias, R.A. Lewis, E.D. Minor, J. Passaneau, and G.A. Smith, "The Lear PS177 Low Energy K-Plus Detector", Nucl. Instru. and Methods, A289, 109 (1990).

Arold, M., C. Espey, T.A. Litzinger, D.A. Santavicca, and R.J. Santoro, "The Effect of Swirl on Spray and Combustion Processes in an Optically-Accessible, DI Diesel Engine", Soc. Automotive Engr. Transactions, SAE Paper No. 900396, 13 pp. (1990).

Burton, S.A., and M.M. Micci, "Magnetic Induction Thruster with Lithium Propellant", submitted to Journal of Propulsion and Power, Dec. 1988.

Carpino, Marc, and G.A. Domoto, "Investigation of a Flexible Disk Rotating Near a Rigid Surface", ASME Journal of Tribology, Vol. 110, No. 4, pp. 664-669, 1988.

Carpino, Marc, and G.A. Domoto, "Axisymmetric Solution of a Flexible Disk Rotating Near a Rigid Surface", ASME Journal of Tribology, Vol. 110, No. 4, pp. 674-677, 1988.

Carpino, Marc, "Analysis of a Low Speed Flexible Flat Land Thrust Bearing", ASME Journal of Tribology, Vol. 112, pp. 676-683, 1990.

Carpino, Marc, "The Effect of Initial Curvature in a Flexible Disk Rotating Near a Rigid Surface", accepted for publication in ASME Journal of Tribology.

Conroy, P.J., Y.P. Yeh, F.B. Cheung, T.A. Litzinger, and K.K. Kuo, "Jet Impingement and Ablative Materials Erosion Studies for a Vertical Launching System", Proceedings of the JANNAF Propulsion Conference, July 1989.

Chang, C.-L. and Merkle, C.L., "The Relation Between Flux Vector Splitting and Parabolized Schemes", Journal of Computational Physics, Vol. 80, No. 2, February 1989, pp. 344-361.

Chang, C.-L., Kronzon, Y. and Merkle, C.L., "Time-Iterative Solutions of Viscous Supersonic Nozzle Flows", AIAA Journal, Vol. 26, No. 10, October 1988, pp. 1208-1215.

Chen, S. and A. Sinha, "Probablistic Method to Compute the Optimal Slip Load for a Mistuned Bladed Disk Assembly with Friction Dampers", ASME Journal of Vibration and Acoustics, Vol. 112, April 1990, pp. 214-221.

Chen, D.M., W.H. Hsieh, T.S. Snyder, V. Yang, T.A. Litzinger, and K.K. Kuo, "Combustion Behavior and Thermophysical Properties of Metal Based Solid Fuels", AIAA Journal of Propulsion and Power.

Chen, S. and A. Sinha, "Probablistic Method to Compute the Optimal Slip Load for a Mistuned Bladed Disk Assembly with Friction Dampers", ASME Journal of Vibration and Acoustics, Vol. 112, April 1990, pp. 214-221.

Conway, J.C.,Jr., R.N. Pangborn, P.H. Cohen, and D.A. Love, "Dry Sliding Wear Behavior of a Sialon Ceramic", J. Wear, Vol. 126, 1, pp. 79-90 (1988).

Coy, E., and D.A. Santavicca. A Planar, Fluorescence Imaging Technique for Studying Droplet-Turbulence Interactions in Vaporizing Sprays. Presented at 27th JANNAF Combustion Meeting, Cheyenne, Wyoming (November, 1990).

Culick, F.E.C., and Yang, V., "Prediction of the Stability of Unsteady Motions in Solid Propellant Rocket Motors", (Invited Chapter), to appear in Nonsteady Burning and Combustion Stability of Solid Propellants, Progress in Astronautics and Aeronautics, eds., L. DeLuca and M. Summerfield.

Davis, R., Moore, E.F., Santoro, R. J. and Ness, J.R., "Isolation of Buoyancy Effects in Jet Diffusion Flames", Combustion Science and Technology, 82, p. 60 (1990).

Dobbins, R.A., Santoro, R.J. and Semerjian, H.G., "Analysis of Light Scattering from Soot Using Optical Cross Sections for Aggregates", The Twenty-Third Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA (in press).

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Hosangadi, A., Merkle, C.L. and Turns, S., "Analysis of Forced Combusting Jets", AIAA Journal, Vol. 28, No. 8, August 1990, pp. 1473-1480.

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K.K. Kuo, and J.N. Fleming, ed., Proceedings of the First International Symposium on Special Topics in Chemical Propulsion: Base Bleed, Athens, Greece, November, 1988, to be published by Hemisphere Publishing Corporation, 1990.

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Lee, W., Pal, S., Ryan, H.M., Strakey, P.A. and Santoro, R.J., "Planar Laser Imaging of Sprays for Liquid Rocket Studies", 27th JANNAF Combustion Meeting, November 5-9, 1990, Cheyenne, WY.

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Shin, Y.C., and K.W. Wang, "Design of an Optimal Damper to Minimize the Vibration of Machine Tool Structures Subject to Random Excitations", to appear in Journal of Engineering with Computers.

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Turns, S.R., and F.H. Myhr, "Oxides of Nitrogen Emissions from Turbulent Hydrocarbon/Air Jet Diffusion Flames," Semi-Annual Report (January-June 1990) to Gas Research Institute, Contract No. 5086-260-1308, Chicago, IL, August 1990.

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Turns, S.R., J.A. Lovett, and H.J. Sommer, III, "Visualization of Soot Zones in Turbulent Diffusion Flames", Combustion and Flame, Vol. 77, pp. 405-409, 1989.

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Videto, B.D., and D.A. Santavicca, "Flame Turbulence Interactions in a Freely Propagating Premixed Flame", Comb. Sci. and Tech., 70:47-73 (1990).

Videto, B.D., and D.A. Santavicca, A Turbulent Flow System for Studying Turbulent Combustion Processes. Accepted for publication in Combustion Science and Technology (1991).

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Wang, K.W. and Y.S. Kim, "Semi-active Structural Control via Variable Damping Elements", o appear in Journal of Mechanical Systems and Signal Processing.

Wang, K.W. and S.P. Liu, "A Review and Assessment of Chain Drive System Noise and Vibration Research", to appear in Shock and Vibration Digest.

Wang, K.W., Y.C. Shin and C.H.Chen, "Dynamic Analysis of high Speed Spindle Structures", to appear in IMeCH Journal of Mechanical Engineering Science.

Woodward, R.D., K.N. Garner, F.B. Cheung, and K.K. Kuo, "Breakup Phenomena of Coaxial Jet in the Non-Dilute Region Using Real-Time X-Ray Radiography", AIAA Paper No. 90-1958, 26th Joint Propulsion Conference, July 1990.

Yang, V., Sinha, A., and Fung, Y.T., "State Feedback Control of Pressure Oscillations in Combustion Chambers", Journal of Propulsion and Power, May 1990.

Yang, V., Kim, S.I., and Culick, F.E.C., "Triggering of Longitudinal Pressure Oscillations in Combustion Chambers. I: Nonlinear Gasdynamics", Combustion Science and Technology, August, 1990.

Yang, V., and Culick, F.E.C., "On the Existence and Stability of Limit Cycles for Transverse Acoustic Modes in a Cylindrical Combustion Chamber, I: Standing Modes," Combustion Science and Technology, 72:37-65 (July 1990).

Zamrik, S.Y. and R.N. Pangborn, "Fatigue Damage Assessment Using X-Ray Diffraction", J. Nuclear Engineering Design, Vol. 116, pp. 407-413 (1989).

## PRESENTATIONS

Carpino, Marc, "Analysis of Foil Bearings for Cyogenic Applications." Presented at the 1990 NASA Conference on Advanced Earth-To-Orbit Propulsion Technology, Huntsville, NASA Conference Publication 3092, May, 1990, Vol. II, pp. 432-441.

Carpino, Marc, "Analysis of Foil Bearings for High Speed Operation in Cryogenic Applications." Presented at the NASA Space Transportation Propulsion Systems Technology Symposium, University Park, PA, June, 1990.

Ho, C.M., and D.A. Santavicca. Comparison of Laser Spark and Electrode Spark Ignition in Laminar Propane-Air Mixtures. Presented at the Eastern State Section of the Combustion Institute Fall Meeting, Orlando, FL (December 1990).

Keiser, T.L., and M.M. Micci, "Application of Microwave Thrusting for Stationkeeping & Orbit Raising on the INTELSAT Series Communication Satellites." IAF Paper 90-228. Presented at the 41st Congress of the International Astronautical Federation, Dresden, Germany, October 6-12, 1990.

Lee, T.-W., G.L. North and D.A. Santavicca. Visualization of Turbulent Premixed Flame Fronts: Comparison Between MIE-Scattering and OH-Fluorescence Imaging. Presented at the Eastern State Section of the Combustion Institute Fall Meeting, Orlando, FL (December 1990).

Lee, W., Ryan, H.M., Strakey, P.A. and Santoro, R.J., "An Application of Two-Dimensional Imaging Techniques for Soot and Droplet Studies", 1990 ASME Winter Annual Meeting, The Symposium on Heat and Mass Transfer in Fire and Combustion Systems, November 25-30, 1990, Dallas, TX.

Lee, W., Pal, S., Ryan, H.M., Strakey, P.A. and Santoro, R.J., "Planar Laser Imaging of Sprays for Liquid Rocket Studies", 27th JANNAF Combustion Meeting, November 5-9, 1990, Cheyenne, WY.

Pal, S., Santoro, R.J., Ryan, H.M., Simchick, C., and Jacobs, H.R., "Jet Breakup Under Acoustic Pressure Oscillations." Presented at the Fall Technical Meeting, Eastern Section: The Combustion Institute, (December 3-5, 1990), Orlando, FL.

Sullivan, D.J., and M.M. Micci, "A Feasibility Study & Mission Analysis for the Hybrid Plume Plasma Rocket." AIAA Paper 90-2599. Presented at the AIAA/DGLR/JSASS 21st International Electric Propulsion Conference, Orlando, FL, July 18-20, 1990.

Mueller, J., and M.M. Micci, "Microwave Electrothermal Thrusters Using Waveguide Heated Plasmas." AIAA Paper 90-2562. Presented at the AIAA/DGLR/JSASS 21st International Electric Propulsion Conference, Orlando, FL, July 18-20, 1990.

Balaam, P., and M.M. Micci, "The Stabilization & Spectroscopic Study of Microwave Generated Resonant Cavity Plasmas." AIAA Paper 90-2635. Presented at the AIAA/DGLR/JSASS 21st International Electric Propulsion Conference, Orlando, FL, July 18-20, 1990.

Pauley, L.L., P. Moin, and W.C. Reynolds, "The Stability of Two-Dimensional Separation Bubbles", Proceedings of the Low Reynolds Number Conference, June 4-7, University of Notre Dame, Notre Dame, Indiana (1989). Also appeared in Lecture Notes in Engineering, Vol. 54, Springer-Verlag.

Pauley, L.L., P. Moin, and W.C. Reynolds, "On the Structure of Two- and Three-Dimensional Separation", AIAA 27th Aerospace Science Meeting, January 9-12, Reno, Nevada, Paper 89-0287 (1989).

Pauley, L.L., P. Moin, and W.C. Reynolds, "A Numerical Study of Unsteady Laminar Boundary Layer Separation", Report No. TF-34, Department of Mechanical Engineering, Stanford University, Stanford, CA (1988).

Pauley, L.L., and S.N. Dagher, "Boundary Layer Stability in a Supersonic Rocket Nozzle." Presented at APS Division of Fluid Dynamics Meeting, Ithaca, NY, November 18-20, 1990.

Richardson, T.F., Santoro, R.J. and Kirby, M.J., "The Effect of Inert Diluent Addition on Diffusion Flame Height in an Oxygen Atmosphere." Presented at the Fall Technical Meeting, Eastern Section: The Combustion Institute, (December 3-5, 1990), Orlando, FL.

Kuo, K.K., F.B. Cheung, R.D. Woodward, and K.N. Garner, "Jet Breakup Processes in the Non-Dilute Spray Region", NASA Workshop following the AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

Santavicca, D.A., Diagnostics for Liquid Rocket Combustion Instabilities Research. Presented at JANNAF Workshop on Diagnostics, Cheyenne, WY (November 1990).

Santavicca, D.A., Gas Turbine Combustion Research at Penn State. Presented at General Electric Aircraft Engines, Evendale, OH (May 1990).

Shin, Y.C., K.W. Wang, and C.H. Chen, "Dynamic Modeling and Analysis of High Speed Spindles", Transaction of NAMRI/SME, May 1990.

Shuen, J.S., and V. Yang, "Combustion of Liquid-Fuel Droplets in Supercritical Conditions." AIAA Paper 91-0078. Presented at the 29th AIAA Aerospace Sciences Meeting, January, 1991.

Sinha, A., "On the Design of Magnetic Suspension Systems", ASME 90-GT-239. Presented at the ASME International Gas Turbine Conference, 1990.

Smith, G.A., Invited Talk, Workshop on the Future of Low Energy Antiproton Physics at CERN, Genever, Switzerland, June, 1990, "Low Energy Antiprotons at Fermilab."

Lewis, R.A. and G.A. Smith, Invited Paper, "An Antiproton Catalyst for Inertial Confinement Fusion Propulsion." AIAA/SAE/ASMA/ASEE 26th Joint Propulsion Conference, Orlando, FL, July, 1990.

Smith, G.A., Invited Paper. "Anti-matter Applications to Inertial Confinement Fusion." NASA Symposium on Advance Propulsion Concepts, Jet Propulsion Laboratory, Pasadena, CA, November, 1990.

Strakey, P.A. and R.J. Santoro, "Two-Dimensional Imaging Techniques for Particle Size Characterization," Twenty-First Annual Meeting of the Fine Particle Society, August 21-25, 1990, San Diego, CA.

Turns, S.R., D.C. Mueller, and M.J. Scott, "Secondary Atomization of Aluminum/RP-1 Liquid Rocket Slurry Fuels." Presented at the Fall Technical Meeting 1990, Eastern Section: The Combustion Institute, December 3-5, 1990, Orlando, FL.

Turns, S.R. and F.H. Myhr, "Oxides of Nitrogen Emissions from Hydrocarbon Jet Flames: Fuel Effects and Flame Radiation." Presented at the Fall Technical Meeting 1990, Eastern Section: The Combustion Institute, December 3-5, 1990, Orlando, FL.

Videto, B.D., and D.A. Santavicca. Turbulence Measurements ina Propagating, Premixed Flame. Presented at the Eastern State Section of the Combustion Institute Fall Meeting, Orlando, FL (December 1990).

Withington, J.P., J.S. Shuen, and V. Yang, "A Time-Accurate Implicit Method for Chemically Reacting Flows at All Mach Numbers." AIAA Paper 91-0581. Presented at the 29th AIAA Aerospace Sciences Meeting, January, 1991.

Woodward, R.D., "Liquid Jet Breakup and Atomization in Rocket Chambers Under Dense Spray Conditions," Space Transportation Propulsion Technology Symposium, University Park, PA, June 28, 1990.

Woodward, R.D., F.B. Cheung, R.D. Woodward, K.N. Garner, and K.K. Kuo "Breakup Phenomena of a Coaxial Jet in the Non-Dilute Region Using Real-Time X-Ray Radiography," AIAA Paper 90-1958, AIAA/ASME/SAE/ASEE 26th Joint Propulsion Conference, Orlando, FL, July 16-18, 1990.

Yang, V., US/France DEA Workshop on "Solid Rocket Motor Internal Ballistics and Stability," July 19-20, 1990, Orlando, FL. Invited Speaker.

Yang, V., Workshop on "Combustion Instabilities in Solid-Propellant Rocket Motors," August 8-11, 1990, Agency for Defense Development, Korea. Organizer and Lecturer.

Yang, V., "Supercritical Droplet Combustion and Combustion Instabilities in Liquid-Propellant Rocket Motors," January 25, 1991, NASA Marshall Space Flight Center. Contact point at Marshall: Charles F. Schafer

## B. HONORS

Cheung, F. B.:

Served on the NSF Presidential Young Investigator Review Panel.

Kuo, K. K.:

Appointed as Penn State Distinguished Professor in 1990.
Elected Fellow of AIAA.
Invited by the National Science Council of Taiwan, R.O.C., to give a series of distinguished engineering lectures in December, 1990.
Appointed as Mechanical Engineering Distinguished Alumni Professor, 1990.

Jacobs, H. R.:

Served as Academic Chairman, NASA Space Transportation Propulsion Technology Symposium, 1990.

Litzinger, T. A.:

Received College of Engineering Outstanding Teacher Award, 1990.

Merkle, C. L.:

Appointed as Mechanical Engineering Distinguished Alumni Professor, 1990.
Served as Academic Co-Chairman, NASA Space Transportation Propulsion Technology Symposium, 1990.
Participated in NASA Space Propulsion Synergy Group.

Micci, M. M.:

Led AIAA Propulsion Engineering Short Course, "Electric Propulsion for Space Systems," at 26th Joint Propulsion Conference, Orlando, FL, 1990.

Santavicca, D. A.:

Received College of Engineering Outstanding Researcher Award, 1990.

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