

THE NASA-LEWIS PROGRAM ON FUSION ENERGY FOR SPACE POWER AND PROPULSION, 1958-1978*

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Norman R. Schulze
NASA Headquarters
Washington, D.C. 20546

and

Prof. J. Reece Roth
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

ABSTRACT

This paper will provide an historical synopsis of the NASA-Lewis research program on fusion energy for space power and propulsion systems. This research program in fusion energy was initiated at the NASA Lewis Research Center in 1958 to explore the potential applications of fusion energy to space power and propulsion systems. This program involved several hundred man-years of effort, and included all aspects of fusion research such as theory, experiment, technology development, and advanced mission analysis. It ended in 1978. This effort was carried out within the NASA-Lewis Electromagnetic Propulsion Division, where the mission analysis and basic research on high temperature plasma physics was done by the Advanced Concepts Branch, and technology development, including the development of three pioneering high-field superconducting magnetic confinement facilities, was conducted in the Magnetics and Cryophysics Branch.

Some of the fusion-related accomplishments and program areas covered by the NASA-Lewis effort during this period include: basic research on the Electric Field Bumpy Torus (EFBT) magnetolectric fusion containment concept, including identification of its radial transport mechanism and confinement time scaling; operation of the Pilot Rig mirror machine, the first superconducting magnet facility to be used (in 1964) in plasma physics or fusion research; operation of the Superconducting Bumpy Torus magnet facility in 1972, the first such facility used in fusion research to generate a toroidal magnetic field; steady-state production of neutrons from DD reactions, starting in 1967; studies of the direct conversion of plasma enthalpy to thrust by a direct fusion rocket via propellant addition and magnetic nozzles; power and propulsion system studies, including D³He power balance, neutron shielding, and refrigeration requirements; development of large volume, high field superconducting and cryogenic magnet technology; studies of the direct conversion of plasma enthalpy to electrical power; advancing the state of the art in cryogenic and liquid helium technology; development of ferrofluids and studies of ferrofluidics technology; ion cyclotron resonance heating of plasmas at high power and in the steady state; development of the Hipp coil, a class of ICRH antenna which is now universally used in tokamak RF heating applications; development of heat pipe technology; development of the bundle divertor as the basis of a direct fusion rocket using a toroidal plasma; advancing the state of the art in plasma diagnostics, including fluctuation-induced transport, heavy ion beam probes, and Thomson scattering; and mission analyses and systems studies of fusion propulsion systems for interplanetary missions. Many of these accomplishments resulted in patents, were the first of their kind, and have been incorporated in the world fusion program.

*A full-length version of this paper, containing an extensive bibliography of NASA-Lewis Publications, will appear in Fusion Technology in Fall, 1990.

- **Duration of NASA Fusion Effort: 1958-1978**
- **NASA Centers Involved**
 1. **Lewis Research Center (98%)**
 2. **JPL (2% - mission studies only)**
- **Other Organizations Active in the 1960's**
 1. **AFOSR - D. George Samaras**
 2. **Aerojet-General (San Ramon) - John Luce**
- **Individuals Supervising NASA-Lewis Fusion Effort**
 1. **Gerald V. Brown**
 2. **Gerald W. Englert**
 3. **John Evvard**
 4. **Wolfgang (Wolf) E. Moeckel**
 5. **Warren D. Rayle**
 6. **John J. Reinmann**
 7. **Eli Reshotko**
 8. **J. Reece Roth**
 9. **Abe Silverstein**

- **Contractors to NASA-Lewis Fusion Space Power and Propulsion effort**
 1. **Prof. Edward J. Powers, University of Texas, Austin**
 2. **Prof. Andrew L. Gardner, Brigham Young University**
 3. **Profs. M. Kristiansen and M. O. Hagler, Texas Tech University**
 4. **Prof. George H. Miley, University of Illinois**
 5. **Prof. Robert Hickok, R.P.I.**
 6. **Prof. Benjamin Lax, M.I.T.**

- **Areas Within the NASA-Lewis Fusion Space Power and Propulsion Effort**
 - **Direct Relevance**
 1. **Mission Studies**
 2. **Basic Research in High Temperature Plasma Physics**
 3. **Engineering Development of Superconducting Magnet Facilities for Plasma Research**
 - **Collateral Relevance**
 1. **Superconducting and Cryogenic Magnet Technology**
 2. **Direct Convertor Technology**
 3. **Cryogenic/Liquid Helium Technology**
 4. **Ferrofluidic Technology**
 5. **Ion Cyclotron Resonance Heating Technology**
 6. **Heat Pipe Technology**
 7. **Space Nuclear Power Systems Testing Facility at Plum Brook, Ohio**
 8. **Plasma Diagnostic Development**

**Assumptions Underlying NASA-Lewis
Fusion Space Power and Propulsion Effort**

1. **DT reactors out of question because of shielding requirements**
2. **Program focussed on propulsion rather than power supply**
3. **Direct fusion rockets preferred**
4. **Fusion reactions with ~ 100% energy released in charged particles most desirable**
5. **High beta confinement concepts required**
6. **Steady-state operation required**
7. **Power source on board, not remote to spacecraft**

Screening Criteria Used at NASA-Lewis for Fusion Fuels and Confinement Concepts

1. Will it make a good fusion power or propulsion system?
 2. Is it technologically feasible?
 3. Is the physics of the concept known?
- If the answer to #3 was no, then basic research was initiated on otherwise promising concepts.
 - This approach lead to basic research in the following areas:
 1. Magnetoelectric confinement
 2. Steady-state ICRH for start-up
 3. Design studies of advanced fuel reactors

PERSONNEL ASSOCIATED WITH NASA-LEWIS BUMPY TORUS PROJECT

NASA Personnel

Physics Investigations

J. Reece Roth, P. I.
Walter M. Krawczonek

Superconducting Magnet Facility

Willard Coles
A. David Holmes
Thomas A. Keller

External Collaborators

Andrew L. Gardner, B.Y.U

Edward J. Powers, U. of Texas
Young Kim, U. of Texas

NASA-NRC Postdoctoral Associates

Hans Persson
George X. Kambic
Richard W. Richardson
Glenn A. Gerdin
Chandra M. Singh
Chitra Sen
Raghuveer Mallavarpu

Dumpy Torus Facility Data to Final Shutdown at Lewis

Days of Operation with Coils Charged	436
Working Days Since First Plasma	1337
Utilization Fraction	33%
Total Hours Experimental Operation	2620 Hours
Number of Coil Normalcies	189

RESULTS OF NASA LEWIS EFBT RESEARCH

- 1. Magnet facility operated satisfactorily until final shut-down**
- 2. D⁺ Ion kinetic temperatures up to 2500 eV, 3500 eV in He.**
- 3. Up to 45% of power into plasma appears in ion population**
- 4. Electric field has major effect on plasma density and confinement time-opposite polarities make a factor of 20 difference**
- 5. Fluctuation-induced transport identified as the dominant radial transport mechanism**
- 6. Geometric mean plasma emission discovered experimentally**
- 7. Scaling laws of ion kinetic temperatures, densities, and containment times with B, T, V_A are favorable**
- 8. No asymptotic limits on performance**

- **Accomplishments of the NASA-Lewis Fusion Space Power and Propulsion Effort:**

1. World's first superconducting magnet facility for plasma physics and fusion research (1964)
2. World's first superconducting magnet facility generating a toroidal magnetic field (1972)
3. Steady-state neutron production from DD reactions in an electric field dominated modified Penning discharge (1967)
4. Steady-state operation of the NASA-Lewis Electric Field Bumpy Torus (EFBT) at plasma parameters (T_i , N_e , τ_p) never equaled or exceeded by the EFBT experiment at ORNL
5. Steady-state DD neutrons from the electric field bumpy torus
6. Very encouraging mission studies vis-a-vis fission-electric and mission solar-electric systems
7. Development of steady-state ICRH technology
8. Development and demonstration of short, compact ICRH antenna (HIPP coil)
9. Discovery of continuity-equation plasma oscillation
10. Demonstration of fluctuation-induced transport as the dominant radial transport mechanism in EFBT plasma
11. Demonstration of radially-inward fluctuation-induced ion transport in EFBT Plasma
12. Operation of SUMMA magnet facility, 50 cm-Bore, 8.0-5.0-8.0 Tesla mirror configuration.

- **Low Visibility of NASA-Lewis Fusion Power and Propulsion Effort**

1. Mostly bootlegged and funded within NASA Lewis
2. Subject too long-term for many tastes
3. Subject too "far out" for public discussion in the midwest
4. Desire to avoid competition within NASA-Lewis, with the Space Nuclear Auxiliary Propulsion (SNAP) Office

- **Results of our Magnet Technology Engineering Development and Basic Research on High Temperature Plasmas was Freely and Extensively Published as NASA Reports and in the Archival Literature**

- **Reasons for Termination of NASA-Lewis Fusion Space Power and Propulsion Effort**

1. Retirement of administrators with vision
2. Lack of headquarters support
3. Ascendency of accounting over technical management
4. Budget pressures generated by the Shuttle program
5. Termination of the SNAP^P nuclear-electric program for lack of a mission
6. No approved mission for space fusion systems
7. Long term nature of goal