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(9) FINAL REPORT

(C) DEVELOP AND PERFORM EXPERIMENTS FOR HIGH
ENERGY DENSITY IMPLOSION SYSTEMS

September 20, 1978
Contract No. N00173-78-C-0420
Date of Contract: March 28, 1978

JAYCOR Project No. 6077
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78-6077-FR

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I. SUMMARY OF WORK

Work completed under this contract covers two facets of the development of high energy density plasma implosion systems. In the area of laser-guided discharges the following tasks have been accomplished:

A. A preliminary analysis of the laser-aerosol-air interactions, which are responsible for initiating laser breakdown, has been performed.

B. A detailed air chemistry code, CHMAIR, has been developed to follow the evolution of air plasmas created by CO_2 lasers and other heating or ionization sources to determine their temperature and chemical composition. Simple hydrodynamic calculations have been performed to predict channel radial growth.

C. An analysis of the evolution of hot air channels, formed by CO_2 lasers or other sources, has been performed.

D. The air-channel conditions necessary for guiding electrical discharges have been determined and shown to be consistent with laser-guided discharge experiments.

In the area of LINUS implosion systems the following tasks, in addition, have been performed:

A. Engineering designs have been provided for the HELIUS and LINUS-0 machines.

B. Experiments have been performed using the NRL "water model" to

measure the effect of duct shape and operating parameters on cylindrical and quasi-spherical implosions.

C. A fast valve system has been designed for HELIUS and tested, and a gas generator system has been designed for LINUS-0.

D. Preliminary high pressure experiments have been performed on HELIUS to investigate and control compression waves produced by imploding water.

II. LASER-GUIDED DISCHARGES

Introduction

Efficient transport of dense, high-energy electron beams requires charge and current neutralization of the beam. In recent experiments¹, a beam was transported along channels formed by exploding wires in an atmospheric-pressure background gas. Such a technique is not, however, suitable for pulsed systems. An alternative technique is to initiate an electrical discharge through the gas using laser breakdown of the gas. To investigate this possibility, experiments were performed at NRL to investigate the electrical guidance properties of ionized channels formed in laboratory air by a CO₂ laser.

A. Initiation of Laser Breakdown by Aerosols.

At the laser intensities used (10^7 - 10^9 w/cm²), it has been demonstrated that breakdown is initiated by the dust particles in the air. A condition was derived for the minimum laser fluence (~ 10 J/cm²) required for laser breakdown. This minimum value is predicted by calculations of thermodynamic heating of typical solid aerosols. The predicted value was confirmed by experiment.

¹. P.A. Miller, R. J. Butler, M. Cowan, J.R. Freeman, J.W. Roukey, T.P. Wright, and G. Yonas, Phys. Rev. Lett. 39,92 (1975).

B. Analysis of Air Plasma Evolution.

A detailed air chemistry code, CHMAIR, has been developed to predict the growth time of aerosol-initiated plasmas. CHMAIR predicts intensities, and predicts a growth time exceeding 100 μsec . However, the experimentally observed growth time is less than 2 μsec . This discrepancy in growth times is as yet unexplained.

The decay of hot air channels formed by CO_2 lasers was modeled by a simple hydrodynamic calculation which permitted the average channel temperature to be estimated. For the NRL experiments, these calculations yielded an initial temperature ranging from 2000 to 6000°K, depending upon radial location in the laser channel, and late-time pressure-equilibrium temperature of 1000-1500°K. The predicted initial temperatures are consistent with the observed shock speeds ($\sim 10^5$ cm/sec) and with the observed energy absorption (1-3 J/cm³).

C. The Evolution of Hot Air Channels.

Once pressure equilibrium has been obtained, the air channel remains relatively stable and quiescent for approximately 1 msec. Since conduction and radiation loss calculations predict channel lifetimes greater than 100 msec, it is postulated that the channel disrupts at 1 msec due to turbulence which originates in the initially localized laser-aerosol plasmas. This proposed turbulence mechanism is not, however, understood.

D. Electrical Guidance of Discharges.

The laser-produced channels have been shown at NRL to be capable of guiding electrical discharges for up to 2m along the channel, using a 3m

focal length lens for the CO_2 laser. Any theory purporting to explain this guidance must account for the following observations:

First, guidance occurred at an average electric field strength as low as 1 kV/cm, which is roughly one-fifth of the minimum field strength required for unguided discharges.

Second, the discharges propagated along the laser path even when this path was perpendicular to the strongest electric field.

Third, the average discharge velocity depended primarily on the applied voltage, and exceed unguided discharge velocities by an order of magnitude or more.

The preceding characteristics suggest that the guided discharges more closely resemble the return-stroke stage, rather than the earlier streamer or leader stages, of unguided discharges. This premise leads to the conclusion that guidance is favored provided the conductivity, or electron density, of the laser-produced channel is sufficiently high. From energy conservation and the known breakdown field strength of atmospheric air, one can show that an unguided streamer typically generates an electron density on the order of 10^{11} cm^{-3} . Hence, laser guidance is presumed favorable provided the channel electron density does not fall much below 10^{11} cm^{-3} .

The decay of the electron density, n_e , in the laser channel is controlled at late times by electron attachment, molecular detachment of negative ions, and dissociative electron recombination with the ion NO^+ . At gas temperatures of several thousand degrees, molecular detachment in effect negates the electron attachment loss, such that n_e decays by

$$n_e \approx \frac{1}{\alpha \tau}$$

where the dissociative recombination coefficient is $\alpha \approx 5 \times 10^{-8} \text{ cm}^{-3} \text{ sec}^{-1}$. Under these circumstances, the electron density decays to 10^{11} cm^{-3} in times $t \sim 0.1 \text{ msec}$, and to 10^{10} cm^{-3} in times $t \sim 1 \text{ msec}$. This model thus predicts that laser guidance should be good for times less than 0.1 msec , and should be poorer for times between 0.1 and 1 msec . Such guidance was confirmed by the NRL experiments. It should be noted that the onset of a cooling phenomenon such as turbulence can result in a rapid electron decay due to electron attachment. Attachment times are typically of the order of $0.1 \text{ } \mu\text{sec}$.

III. LINUS IMPLOSION SYSTEMS.

A. LINUS-0 and HELIUS design.

A number of design changes have been made to the LINUS-0 machine. These changes were made after engineering review and/or testing of LINUS-0 sub-systems.

1. Gas generator. The LINUS-0 concept originally called for 24 separate explosive charge boxes arranged around the rotor. Testing was performed on one of these boxes, and it was determined that the sealing problem was critical. The original design called for a flexible pair of plastic face seals which operated in grooves in the rotor outer diameter. Testing showed that the seal life could not be made to exceed one shot, and that the sealing was insufficient to maintain pressure for several milliseconds. It was proposed to change to a rigid compression-type seal (similar to an automotive piston ring) which would ride on the outer diameter of the rotor, thereby eliminating the grooves and allowing the rotor to move axially. Initial test seals were made of teflon and survived over 30 firings. Ryton, a polyphenylene sulfide-based plastic, was recommended as the first choice seal material, with Lennite, an ultra high molecular weight polymer as second choice. It was also proposed to reduce leakage by changing the design from 24 separate boxes to a single annular ring, split in half for assembly. This explosives chamber has been fabricated but not yet tested, so that a final determination of a seal material has not yet been made.

2. Piston. In order to maximize the work delivered to the piston, the piston shape was redesigned in such a way as to minimize the initial clearance volume contained between the piston seals and the explosive chamber. Reduction of this volume also reduces the pressure rise time behind the piston.

3. Braking System. It was decided rather late in the design phase of LINUS-0 to add a braking system. The system adopted utilizes the thrust disk as a brake disk, and relies on the viscous shear of the thrust bearing lubricant to dissipate energy. The original thrust bearing design employed a caliper and a single pair of opposed bearing pads. The new design employs an annular ring and four pairs of pads. Under braking operation the annular ring is flooded with oil. This system has been fabricated, and is waiting initial testing.

4. End Windows. The low transmissivity of the six-inch thick Lexan used in the original window design, plus the obstruction caused by the window support webbing, led to a re-design of the implosion chamber end windows. The new design allows the window to move axially, thereby preventing shock loads and relieving compressional waves caused by waterhammer. The window mass was reduced from 100 kg to 20 kg, and the thickness of the Lexan was reduced to two inches. The axial momentum of the window is absorbed by a shock absorber.

5. Emergency Shutdown System. In case of loss of oil flow to the main bearings, caused either by loss of house power or pump failure, it is essential that the bearings be lubricated until the rotor can be stopped. The system to do this incorporates an auxiliary generator to drive the coolant pump,

independent of house power. The coolant loop is isolated from the main bearing loop by a pair of solenoid valves, which are activated by loss of oil flow or house power to divert coolant flow to the main bearings.

6. Mounting Base. The system for mounting LINUS-0 to the floor in Building A100 at NRL was reviewed and re-designed. It was decided to reduce the number of 3"x 96" x 96" aluminum coil plates from 12 to 11, and to use the twelfth plate as a mounting pad. This provides an accurate level surface for mounting the bearing pedestals and the coil plates. The base plate is grouted into the floor, and relies mainly on the mass of the coil plates (14 metric tons) to keep it in place.

The HELIUS machine was proposed by JAYCOR in August, 1977 after an earlier review (Contract No. N00173-77-C-4162) had concluded that the data rate on LINUS-0 would be 5-10 shots per week. HELIUS uses stored helium charge at 2000 psi, and is capable of 50-100 shots per week. The first shot was made on 24 April 1978, and the machine is now operational. The major accomplishments have been:

1. Proven ability to balance a 4000 RPM, 200 kg, 58 cm. diameter rotor with bolt-together construction comprising five major components (shaft, plenum, poppet seal plate, rotor lower half and rotor upper half). By carefully maintaining tolerances, using piloting dowels, and serializing all hardware, the rotor balance can be maintained to within ± 50 oz-inches. Using a dynamic balancing technique (Center for Electromechanics, University of Texas, Austin), the final balance can be performed in place. For best results, it has been found necessary to perform final balance with the rotor filled with liquid.

2. A fast pilot valve was designed for HELIUS, capable of rapid opening to pressurize the annular piston. The valve has a 10 cm diameter, 45° seat, a 5 mm stroke, weighs 1 kg, and opens in 3-5 milliseconds, depending on pressure. The system has a sufficiently fast recycling rate that the projected data rate of 50-100 shots per week can be achieved.

3. The original HELIUS piston was RYTON R-1833, a filled polyphenylene sulfide. This material was chosen for high impact resistance, low coefficient of friction, and low coefficient of thermal expansion. The impact resistance was not as advertised, however, because the piston cracked in half on the first shot. The second piston is 6061-T6 aluminum, and has performed well.

4. Because of the downward rotor reaction to the upward motion of the piston, a number of design problems have appeared which are being corrected. The downward acceleration and deceleration has caused the driver pulley to slide down the shaft. This problem has been corrected by incorporating retaining rings. The pressure transducer measuring the supply pressure has failed, possibly due to the high (transverse) acceleration. This transducer has now been given a flexible, axial mount. The pressure transducer mounted in the window has suffered separation of the signal cable at the connector. This was corrected by changing the "window" to aluminum.

In the initial concept, the plenum was attached to the shaft with a compressively loaded Belleville spring to absorb the axial shock. This mounting system was sufficiently flexible that the rotor could not be balanced. The new design mounts the rotor to the mounting frame with a ½ inch thick rubber washer so that the entire shaft and bearings undergo axial acceleration. This technique has so far not proved harmful to the bearings.

5. Certain aspects of the HELIUS design remain to be tested.

These include magnet operation, operation at full pressure of 150 atm, and operation of the spark gap and elliptical mirror illumination system for taking high speed movies.

B. Operating Parameters and Duct Shaping.

An extensive series of experiments was performed on the NRL water model to determine operating parameters and internal duct shapes required for stable cylindrical and quasi-spherical implosions. We will discuss the latter aspect first.

It was thought that a quasi-spherical implosion of water could be achieved by two methods. Both of these failed, however. In the first, the implosion chamber, which normally consists of two parallel end walls perpendicular to the axis, was modified by making one end wall conical (Fig. 1.A.). The predicted free surface shape, as shown, would have created a quasi-spherical implosion. In practice, the implosion always went unstable, i.e., the center line of revolution of the imploding liquid free surface was never coincident with the axis of the cone, so that the implosion was highly asymmetrical (Fig. 1.A.).

In the second case (Fig. 1.B.) radial vanes were used with r - z plane shaping, which would give an axial distribution to the angular momentum of the imploding fluid. Fluid at the right-hand end wall, it was argued, would have higher angular momentum, and so would achieve a larger minimum radius. Movies showed, however, a high degree of azimuthal asymmetry to the free surface, as a jet of fluid was formed along one side of each vane (Fig. 1.B.). This technique was therefore abandoned, and all further work was done with parallel end walls

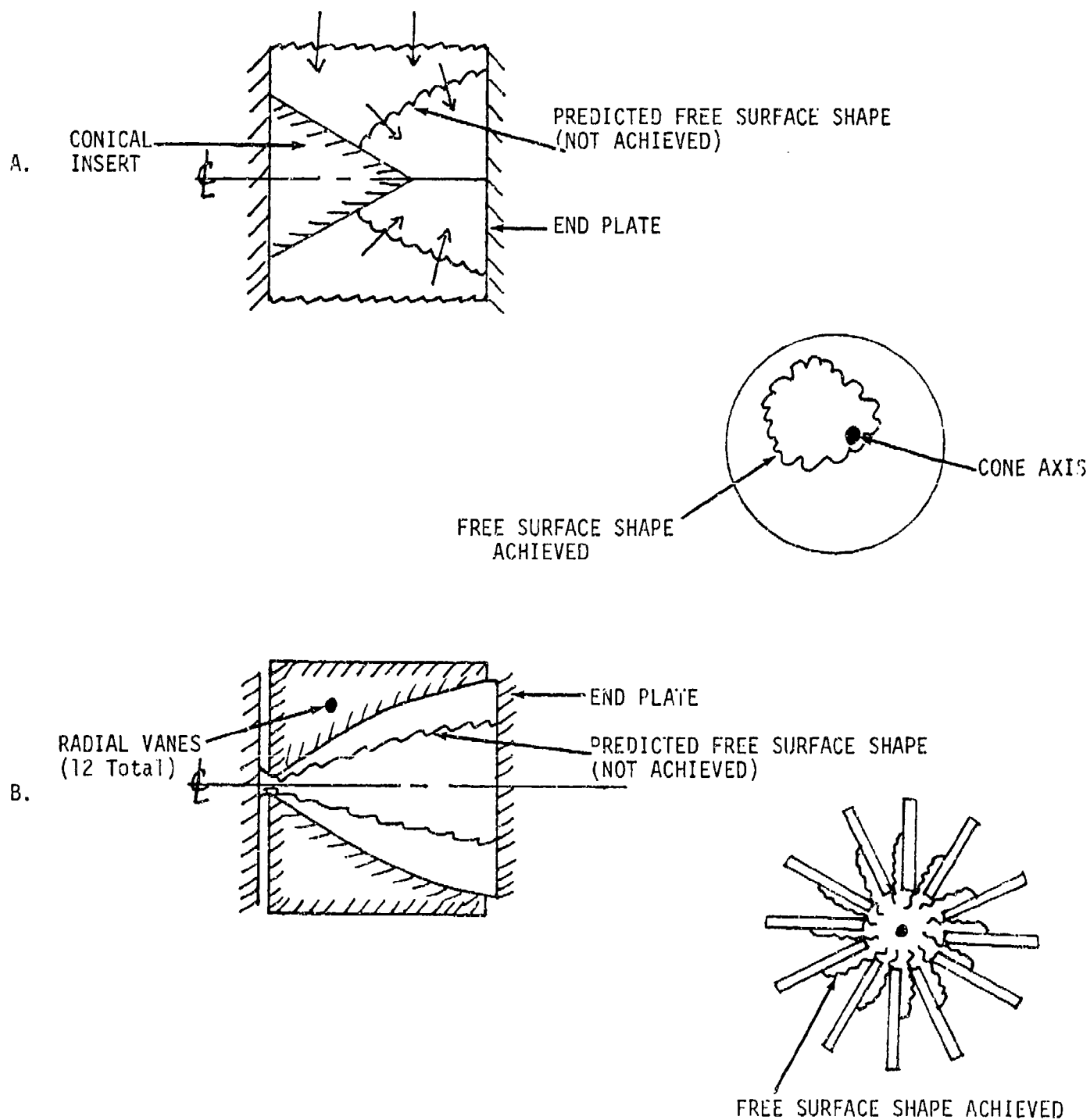


Fig. 1. Implosion Chamber Modifications for Creating Quasi-Spherical Implosions.

to produce cylindrical implosions.

Experiments on measuring the operating parameters associated with stability were completed using the NRL water model, and were successfully correlated with an analytical theory. The theory assumes incompressible flow and adopts a simple model for the streamline pattern in the turning flow from axial piston motion to radial implosion, and properly accounts for the piston pressure, the payload pressure and the angular momentum distribution to calculate the net acceleration term $\ddot{r} - v^2/r$ at the point of peak compression. This calculation permits prediction of the Rayleigh - Taylor stability condition for given values of piston drive pressure, payload pressure and radial compression ratio α . When the predicted stability was compared with the stability as visually determined from movies of the implosion, excellent correlation was achieved.

C. Fast Valve and Gas Generator Systems Development.

As discussed in part A above, a JAYCOR designed fast-opening pilot valve has been incorporated into the HELIUS design. The design opening time of 2-3 milliseconds has not yet been achieved, primarily because of the slower-than-expected dynamic behavior of the pilot system. The pilot gas pressure, which is dumped to trigger the valve, falls with a characteristic time of 20 msec primarily due to the slow (20-30 msec) opening time of the dump valve and the low valve flow coefficient. Design studies now being performed indicate that the pilot valve can be incorporated into the HELIUS rotor, thereby reducing the main valve opening time to the desired range.

It is likely, based on the experiments performed to date, that the piston mass of both HELIUS and LINUS can be optimized. A heavier piston would allow more time for the pressure to rise and would therefore deliver more energy to the payload. The penalty, of course, is that the implosion time is increased, which increases plasma heat loss and magnetic field loss by diffusion. A brass piston is being designed for HELIUS which will permit experimental studies to be made on the effect of mass. The energy transfer to the piston is also being increased by reducing the clearance volume between the valve (or in the case of LINUS-0, the explosive chamber) and the piston seals at zero stroke. This volume is being reduced by transferring material from the front of the piston to the back.

D. Preliminary high pressure experiments.

The HELIUS machine has been operated at 1100 psia and 1477 RPM, and high frequency pressure transducers have been used to monitor the pressure behind the piston and in the payload. The operation of these transducers is not yet considered completely satisfactory. The pressure measurement behind the piston is the most successful, but a systematic error has been discovered due to leakage past the poppet, which allows up to 100 psi pressure to exist behind the piston before firing. This problem is being corrected with a re-design of the poppet o-ring seal groove. The payload pressure is being measured with a transducer in the window, which was made of aluminum because of excessive diaphragming of the original Lexan. The pressure spike measured is believed to be occurring at the correct time, but is not of the correct

magnitude, since the peak value is approximately three times that predicted from the adiabatic compression of air.

In order to permit simultaneous recording of pressure and free surface trajectories, it will be necessary to install the pressure transducers in the lower plate. The impact load will then be reduced, and the transparent windows can be installed, without having the transducer block the view at minimum radius.

IV. APPROPRIATE DIRECTIONS FOR CONTINUING RESEARCH

A. Future Directions for Guided Discharge Research.

A general picture of the laser guided discharge problem has emerged. Although certain theoretical areas - notably, the initial laser breakdown stage and the turbulent cooling stage - require additional study, the major need is for additional experimental investigation of the proposed models. Specifically, temperature estimates and electron-density estimates would prove helpful in evaluating these models. Theoretical efforts should probably first focus on refinement of the air chemistry code CHMAIR, as well as on integration of this code with appropriate hydrodynamic codes. A reduced level of effort should be spent on the turbulence problem, because the turbulence occurs at relatively late times in the experiment.

B. Extension to the LINUS-1 Design.

LINUS-1 Designs. It has been suggested by JAYCOR that the LINUS-0 facility can be lengthened at relatively low cost. The concept calls for modifications to the rotor to allow the simultaneous firing of two opposed pistons. The bearing pedestals can be moved 10 inches apart, and an aluminum spacer ring inserted between the rotor halves. A second explosive chamber identical to the first will provide driving pressure. This design will increase the liner length from 15 to 40 cm. As a side benefit, the axial rotor reactive motion will be greatly reduced. If the LINUS-1 modification is carried out in parallel with the experimental program, it is estimated that the change-over can be made with about 1 month downtime.

V. PUBLICATIONS RELATED TO WORK PERFORMED

JAYCOR staff members have authored and co-authored a number of scientific papers relevant to the research described in this report. These publications are given below.

A. Guided Discharges (R.F. Fernsler, JAYCOR)

1. J. R. Greig, D. W. Kooperman, R. F. Fernsler, R. E. Pechacek, I.M. Vitkovitsky, and A. W. Ali, Phys. Rev. Lett. 41, 174 (1978).

2. A. W. Ali and R. Fernsler, "Chemistry of Air During and After Intense Heating of Atmospheric Channels", presented to the Propagation Physics Meeting, Lawrence Livermore Laboratories, September, 1978.

3. R. Fernsler, A. W. Ali, J. R. Greig, and I. M. Vitkovitsky, "An Air Chemistry Code", to be presented at the Twentieth Annual Meeting, Division of Plasma Physics, American Physical Society, Colorado Springs, October 30-November 3, 1978.

B. LINUS Implosion Systems (R. Burton, JAYCOR).

1. R. L. Burton, P. J. Turchi, D. J. Jenkins, D. K. Book and A. L. Cooper, "Techniques for Plasma Compression by Imploding Liquid Liners", presented to the 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

2. R. L. Burton and P. J. Turchi, "Compact Fusion Reactors Using Controlled Imploding Liners", Proc. of the 13th Intersociety Energy Conversion Engineering Conference, San Diego, August 20-25, 1978, p. 1372.

3. D. L. Book, R. L. Burton, et al, "Experimental and Theoretical Liner Fusion Studies", presented at the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, August 23-30, 1978. NRL Memorandum Report 3826, August 1978.

4. P. J. Turchi, D. L. Book, and R. L. Burton, "Optimization of Stabilized Imploding Liner Fusion Reactors", Proceedings of the Tenth Symposium on Fusion Technology, Padua, Sept., 1978. To be published.*

5. P. J. Turchi, D. L. Book, R. L. Burton and A. L. Cooper, "Stabilized Imploding Liner Research for High Magnetic Field Plasma Compression:, to be published in Journal of Magnetism and Magnetic Materials, North Holland, Amsterdam, and to be presented at the International Conference on Solids and Plasmas in High Magnetic Fields, MIT, September 18-21, 1978.

6. P. J. Turchi, R. L. Burton, A. L. Cooper and D. J. Jenkins, "Development of Stabilized Liner Implosion Systems for High Magnetic Field Pulsed Fusion", to be presented at the Twentieth Annual Meeting, Division of Plasma Physics, American Physical Society, Colorado Springs, October 30-November 3, 1978.

7. R. L. Burton, A. L. Cooper, P. J. Turchi, D. J. Jenkins, J. Cameron and R. D. Ford, "Imploding Liquid Liner Experiments at NRL", to be presented at the Twentieth Annual Meeting, Division of Plasma Physics, American Physical Society, Colorado Springs, October 30-November 3, 1978,

8. A. L. Cooper, R. L. Burton, et al, "Rotating Imploding Free Surface Flows", to be presented at the Thirty-First Meeting, Division of Fluid Dynamics, American Physical Society, Los Angeles, November 19-21, 1978.