# Vapor Clearing Rate and Condensation Study for IFE Liquid Chambers

A. YING, P. CALDERONI, T. GIANPAOLO, T. SKETCHLEY, AND M. ABDOU
Fusion Technology Group
University of California, Los Angeles, USA

**Abstract**

The aspects of the proposed vapor clearing and condensation experiment involve rapidly generating an IFE prototypical post-shot vapor density in a control volume using characteristic liquid chamber material (FliBe, $Li_2BeF_4$), and investigating the condensation rates for the proposed schemes. This experimental goal is achieved by: 1) a pulsed electrothermal plasma source that simulates the pellet explosion for rapid vapor generation and 2) an expansion chamber that represents the IFE liquid chamber. The study consists of two phases. Phase I is aimed at characterizing plasma source capability in terms of maximum quantity of material that can be ablated, and to setting guidelines for the design of the next phase. Phase II will study the condensation process. In the initial state, the condensation chamber will accommodate a pressurized reservoir of liquid FLiBe to generate droplet spray at the chamber entrance and porous film flow around the wall to study the effect of liquid/vapor interaction on the vapor clearing and condensation rate. Phase II activities are considered as part of the IAEA research collaboration.

## 1. Introduction

In the framework of the IFE liquid chamber protection scheme R&D at UCLA, a facility has been constructed to investigate vapor condensation and clearing rates for IFE liquid wall chamber concepts. This facility is designed to produce within 100 μs a high-density partially ionized vapor cloud of FliBe to simulate vapor generation by x-ray ablation from an IFE target. The generated vapor is driven into the expansion chamber by the pressure difference, and simulates the phenomena occurring in the IFE chamber. The plasma jet first undergoes abrupt expansion, generating alternate expansion and compression waves reflecting on the chamber walls. When the hydrodynamics phenomena extinguish, a uniform vapor pressure is reached and bulk condensation starts. Later, droplet spray and liquid jets will be introduced in the chamber to simulate the interaction of the vapor with the undisturbed liquid wall and the effect on enhancing condensation.

## 2. Phase I Activity of Vapor Clearing and Condensation Study

The focus of Phase I activity was to construct an electro-thermal plasma source facility to simulate IFE pulsed vapor generation.This included a FLiBe casting facility to manufacture solid flibe liners for flibe vapor generation. The data acquisition system was also tested during phase I. Pressure data from the coupled piezoelectric transducer and capacitance manometer transducer were analyzed to first characterize FLiBe condensation in the absence of any condensation enhancing techniques. In addition, auger analysis was performed for vapor chemical composition study.

The vapor clearing and condensation facility is composed of four main parts, each with a different function: the Pulse Forming Network (PFN), the Plasma Source, the

Condensation Chamber, and the Data Acquisition System. A picture of the facility is shown in Fig. 1 and its operating capability is listed in Table 1. The Pulse forming network is responsible for the generation and control of the pulsed current discharge delivered to the plasma source. Its design determines the duration of the vapor generation process. The plasma source is responsible for the generation of the Flibe ionized vapor ejected in the expansion chamber. Its design determines the quantity of produced vapor. The expansion chamber is where recombination, cooling and condensation of the ionized vapor takes place. It's made of transparent plastic to allow direct observation of plasma emission and condensed deposit. Initial chamber pressure is established with a vacuum pumping system. The diagnostic system is responsible for measuring the electrical parameters of the discharge and the pressure history inside the chamber during condensation.

Phase I Condensation Chamber

Pulse Forming Network

*FIG. 1. Vapor clearing and condensation study facility at UCLA*

| OPERATIONAL CAPABILITY | |
|---|---|
| Max. discharge voltage | 22 kV |
| Expected max. current | 500 kA |
| Discharge period | 100 μs |
| Max. energy storage | 154 kJ |

TABLE I VAPOR CLEARING AND CONDENSATION FACILITY OPERATIONAL CAPABILITY.

The PFN is a network of electric components designed to store up to 145 kJ energy necessary to produce the plasma jet and to deliver it to the source in a single pulse of around 100 μs duration under safe operational conditions. The circuit is formed by five main parts: four parallel capacitor banks, power supply with protection circuit, resistive dump load, trigger with protection circuit and the ignitron discharging unit. The secondary transformer of the trigger is connected with the high voltage during discharge, and has to be protected from backfiring when the voltage exceeds 10 kV. While charging, the power supply is also connected to the high voltage. In the event of accidental self-discharge of the banks, backfiring could damage the system therefore a protection circuit is needed also for the power supply. The connections are operated with four solenoid mechanical relays controlled from a remote panel.

The plasma source (PS) is designed to confine the discharge inside a hollow cylinder (liner) made of the material to be ablated as shown in Figure 2. The copper cathode is connected to the output of the spark gap, and is mechanically hold by an insulating carbon plastic component. The brass anode is connected to the chamber and electrically to ground. The only electrical path between anode and cathode is the dielectric gas (Argon is presently used) filling the hollow inner liner. Once the discharge is initiated in the plasma column, energy is injected in the column by Joule dissipation. The main mechanism for heat transfer from the plasma to the facing components is radiative heat. This is due to the low pressure and to the fast transient nature of the process. The liner surface is exposed to energy fluency in the 100 GW/m$^2$ order. and sublimation of the liner occurs. The incident radiation and particle flux from the plasma initially may cause melting followed by evaporation, or direct ablation of the surface.

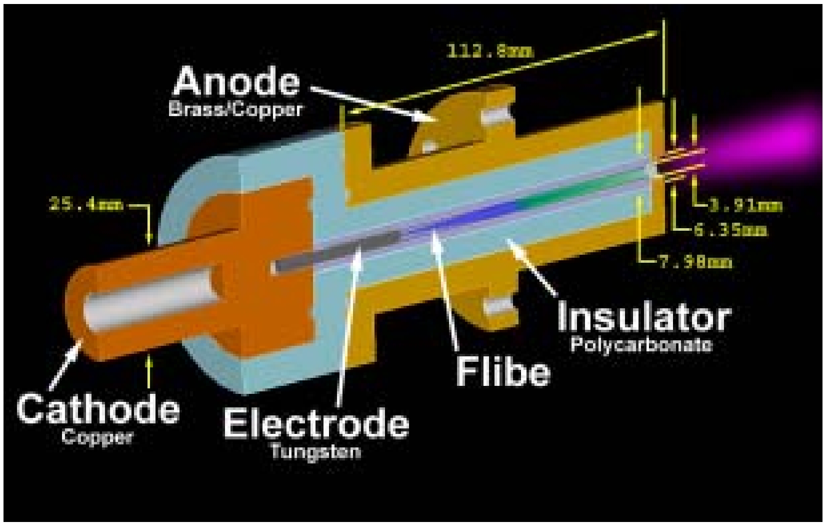



*FIG. 2 Schematic View of Plasma Source*

Phase I condensation chamber is aimed at characterizing plasma source capability in terms of maximum quantity of material that can be ablated, and to set guidelines for the design of the next phase. In order to simulate the IFE reactor effectively, the vapor density and the chamber volume have to be comparable to the reactor design. During this phase, a 3 liters plastic tube is used. The tube is held horizontally and closed with two aluminum flanges holding the plasma source on one side and with a view port on the other to allow direct observation.  A molecular pump is connected to vacuum the chamber before discharge, and a needle valve system to control the base pressure during operation.

The data acquisition (DA) system records the electrical parameters of the discharge and the pressure history. A 2 μs raising time piezoelectric transducer measures the high pressure signal during discharge, while a capacitance manometer measures the slower pressure drop that tends to restore the chamber base pressure. A residual gas analyzer detects the remaining non-condensed gas compositions near the end of the condensation period. The voltage drop at the cathode is measured by a high voltage probe and the discharge current by an inductive coil. A 1 MHz sampling oscilloscope captures both signals. Under the ideal plasma assumption, the resistivity of the plasma during discharge can be numerically modeled. The analysis of the current signal with the aid of the numerical code ODIN allows the extrapolation of other plasma parameters useful for the characterization of the condensation process. The amount of ablation can also be quantified by weight measurements of the liner prior to and after the shot.

Since the completion of the facility assembly in February 2000, shots were first performed using different polycarbonate liners to characterize the plasma gun and pulse forming network performance. It has been found that Lexan ($C_{16}H_{14}O_3$) shows a better resistance to cracking and fracturing under the thermo-mechanical load.

### 2.1 FliBe Casting

Solid FliBe has to be inserted in the plasma gun in the shape of the cylindrical liner for simulating IFE FliBe liquid chamber vapor generation. For this reason FliBe has to be cast into the desired shape before inserting it in the gun. A furnace as shown in Figure 3 has been built as part of the facility to fulfill this task. Because of the health hazard of Be particles and the corrosive properties of FliBe , the design and operation of the furnace present many technical challenges. Solid flibe is inserted at first in a graphite funnel that is connected to a vertical graphite (or quartz) tube. A graphite rod is than centered inside. the tube to obtain the desired annular shape of empty volume. Graphite and quartz have been chosen because they showed good interface properties during melting and re-solidification, allowing the extraction of the solid liner from the casting container (the process is facilitated by the negative expansion of flibe while cooling)After melting, flibe flows into the empty volume in the tube driven by gravity force. To allow direct observation of the melting process the

*FIG. 3 FliBe Casting Device*

chamber upper wall is a Pyrex slab and aligned holes have been placed in the funnel lid and in the reflecting shield.

For the safety handling of solid FliBe before and after casting the furnace has been assembled inside a beryllium safe glove box that was already available in our laboratory at UCLA. To minimize the presence of water vapor during melting and the heat transferred to the furnace structure the furnace enclosure is pumped and maintained in the 100 mTorr range. To minimize weight and corrosion problems, the structure has been made of aluminum and than nickel-plated. Inside the vacuum chamber we used a square furnace assembly composed of two ceramic radiative heating elements facing two metal reflectors and closed at the top and bottom by nickel shields. This design ensures a precise control of the furnace temperature and good temperature uniformity in the volume enclosed in the radiative area.

## 2.2 Phase I Experimental Results

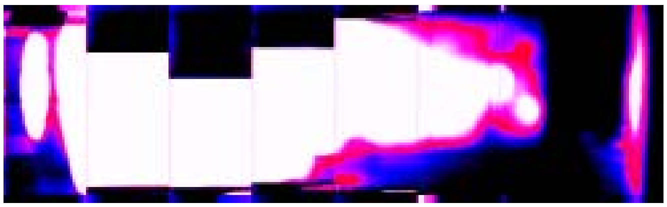
The first FliBe liner was inserted in the plasma gun and the characterization of the generated vapor started. To allow repeated shots without degradation of the liner's electrical and mechanical characteristics, only low energy shots were performed, with discharge current peaks up to 15 kA. Time sequences of colorized pictures of a FliBe glowing discharge were captured using a fast acquisition digital camera (shown in Figure 4). The series of FliBe shots has successfully proven the possibility of using this method in the plasma source, and the similarity of the discharge parameters with the other materials previously tested. The electric noise from the discharge and the presence of ionized particles in the chamber initially adversely affected data acquisition using a piezoelectric pressure transducer. This problem was solved by coating the sensor diaphragm with an insulating layer. An example of pressure history data with a peak pressure of 0.69 bar recorded during a FliBe shot are shown in Figure 5 (Pressure trace:100 μs /division). Pressure data from the coupled piezoelectric transducer and capacitance manometer transducer were analyzed to first characterize FliBe condensation in the absence of any condensation enhancing techniques.

The chemical composition of the vapor was studied to confirm that the vapor ablation is indeed from the solid FliBe liner. In this process, four nickel collecting coupons were placed inside the chamber facing the source to evaluate the chemical composition of the generated vapor (as shown in Figure 6). The results of auger analysis show evidence of deposition of Li and Be compounds (oxides and fluorides). Other elements detected include fluorine, carbon, and oxygen. Carbon contamination was due to the casting process in graphite units, while oxygen came from vacuum leaks. There was no evidence of heavy elements.

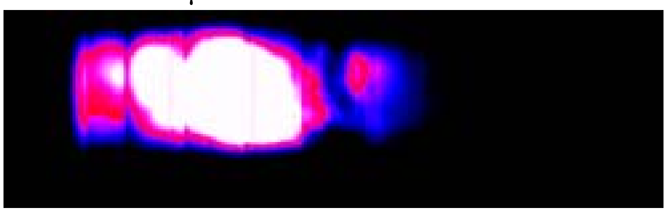
## 3. Phase II (and CRP) Planned Research Activities

The initial activity of phase II is the construction of the condensation chamber with a liquid FLiBe pressurized reservoir that will support the condensation enhancing tools. As

Time 0 µs



Time 820 µs



Time 1640 µs

*FIG. 4 FliBe Discharge Characterization: Colorized pictures of the glowing discharge with a fast acquisition digital camera*

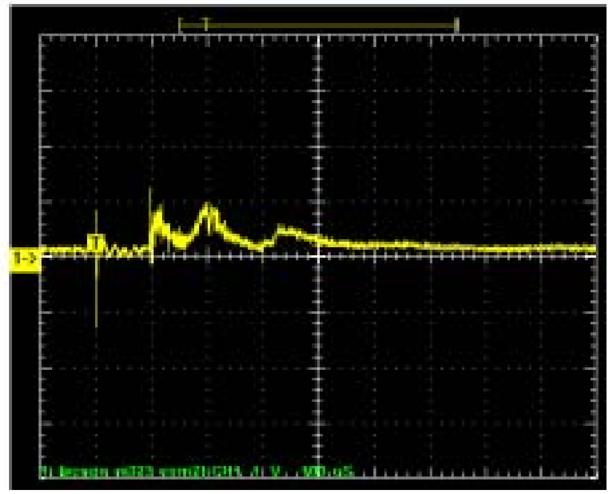
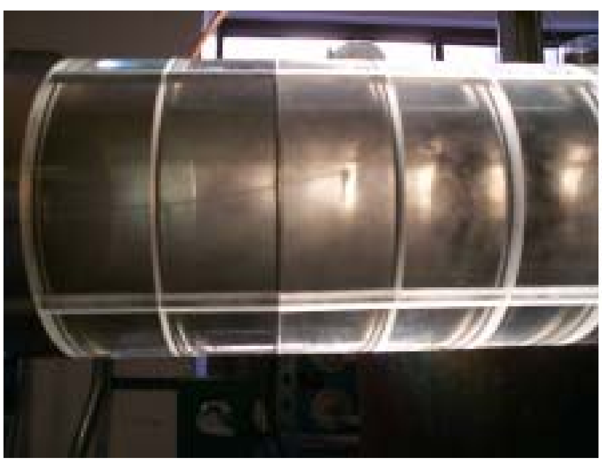
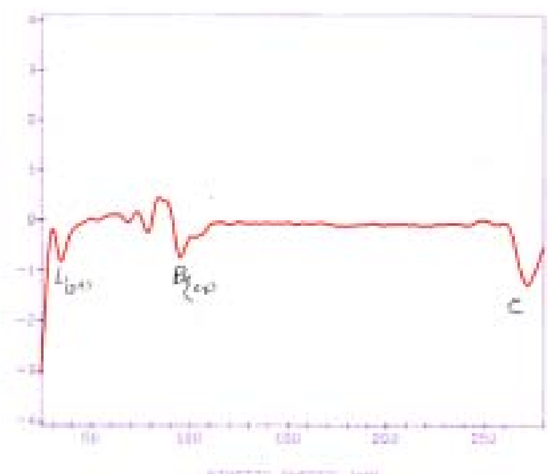


*FIG. 5 Pressure trace during a flibe shot (The hydrodynamic pressure waves travelling in the chamber vanish in less than 0.5 ms. Condensation process starts at the end of the discharge ( > 2ms) thus can be considered uniform in the volume.)*



*Nickel collecting coupons were placed inside the chamber facing the source to evaluate the chemical composition of the generated vapor*



*Auger analysis of light elements spectrum indicates the existence of lithium and beryllium compounds.*

*FIG. 6 FliBe Vapor Chemical Composition Study* soon as the construction of the phase II chamber is completed, the study of the effect of the interaction of the vapor with flowing liquid surfaces and liquid droplets begins. The two enhancing techniques are studied independently at first and then simultaneously to reproduce IFE reactor conditions. A nozzle sprays droplets of liquid FLiBe onto the wall of the chamber for a period of up to 0.2 seconds (to simulate 5 Hz operations) post shot. A separate droplet characterization study determining the relationship between reservoir pressure, droplet sizes, and flow rate is underway. This provides information necessary for defining FliBe pressure operating conditions to be incorporated into the condensation chamber spray droplet designs. The condensation chamber features a triple containment design including a safety external enclosure for FliBe handing, a vacuum vessel, and a modular condensation chamber as shown in Figure 7. The main parameters to be measured are pressure (density equivalent), temperature, velocity, and compositions. There are established methods for these global parameter measurements including dynamic pressure transducers, fast response absolute pressure gauges, residual gas analyzers, and various high resolution spectroscopes. However, there are new diagnostics development needs for measuring local parameters due to the high disturbing environment. Respectively, a new diagnostics technique to generate charge particles flow mapping is currently being tested as a mean to measure local vapor density.

In parallel with the construction and testing of phase II chamber, vapor condensation models will be developed. The numerical code Tsunami, developed at the University of California, Berkeley will be applied to the geometry and conditions of the facility in order to support and understand the experimental data. However, a 1-D, transient condensation model needs to be developed and incorporated into the Tsunami code to provide the boundary conditions for a complete estimation of bulk vapor condensation efficiency. In addition, a droplet condensation model taking into account convective motion inside the liquid as well as momentum exchange with the vapor phase needs to be developed. The developed droplet condensation model will be implemented into the Tsunami code acting as a volumetric source or sink.

The experimental data are analyzed and compared to the numerical simulation results. A further upgraded condensation chamber will accommodate a flowing loop of liquid FLiBe to generate columns at the chamber entrance that can be used to study the effect of liquid/vapor interaction on the vapor clearing rate. At the final stage of phase II activity, an assessment on the achievable repetition rates for an IFE HYLIFE-II like liquid chamber protection scheme will be performed and documented.

## 4. Summary

A facility that enables the study and evaluation of vapor clearing for IFE chambers with liquid walls is described in this paper. The facility includes two major parts fulfilling two different functional requirements: an electro-thermal plasma source to simulate IFE explosion and consequent chamber pressure built-up and vapor formation, and a vapor condensation chamber to simulate vapor clearing processes and phenomena. The first phase experimental results confirm the possibility of simulating IFE processes with this

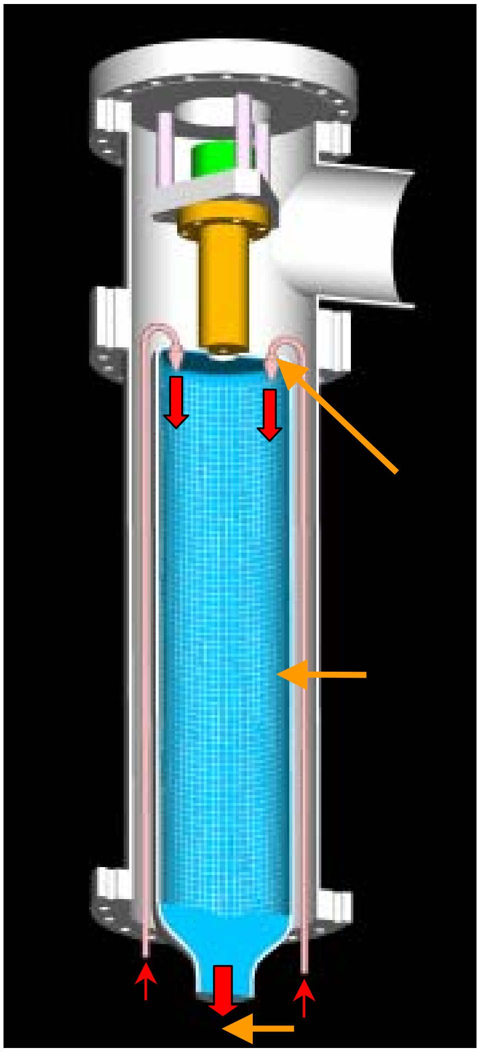


*FIG. 7 Schematic View of Phase II Condensation Chamber Incorporating Spray Droplets and Film Wetted Surface*

facility. It also provides design data in order to complete the design of the second condensation chamber and data acquisition system to analyze the condensation process

The research effort during phase II is oriented to study the vapor condensation process. A condensation chamber incorporates droplet sprays at the chamber entrance and a porous film flow around the wall is under construction to study the effect of liquid/vapor interaction on the vapor clearing and condensation rate. In parallel with the construction and testing of the phase II chamber, vapor condensation modeling will be developed. The experimental data will be analyzed and compared to the numerical simulation results. At the final stage of phase II activity, an assessment on the achievable repetition rates for an IFE HYLIFE-II like liquid chamber protection schemes will be performed and documented.