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CRYOGENIC CAPABILITY FOR EQUATION-OF-STATE MEASUREMENTS ON THE SANDIA Z PULSED RADIATION SOURCE (U)

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Abstract

Experimental cryogenic capabilities are essential for the study of ICF high-gain target and weapons effects issues involving dynamic materials response at low temperatures. We are developing a general purpose cryogenic target system for precision radiation driven EOS and shock physics experiments at liquid helium temperatures on the Sandia Z pulsed radiation source. Cryogenic sample cooling in the range of 6 - 30 K is provided by a liquid helium cryostat and an active temperature control system. The cryogenic target assembly is capable of condensing liquid deuterium samples from the gas phase at about 20 K, as well as cooling solid samples such as beryllium and CH ablators for ICF. The target assembly will also include the capability to use various shock diagnostics, such as VISAR interferometry and fiber-optic-coupled shock breakout diagnostics. We are characterizing the thermal and optical performance of the system components in an off-line cryogenic test facility and have designed an interface to introduce the cryogenic transfer lines, gas lines, and sensor cables into the Z vacuum section. Survivability of high-value cryogenic components in the destructive post-implosion environment of Z is a major issue driving the design of this cryogenic target system.

I. Introduction

The prediction and analysis of ICF high gain target performance and other weapons physics issues require models of dynamic materials response that can accurately describe thermodynamic properties and high-rate mechanical phenomena over an extensive range of pressures and temperatures. For ICF materials, modeling capabilities validated by experimental data are needed at cryogenic temperatures, since most ICF designs are based on performance of cryogenic multi-shell capsules. Recent advances in Z-pinch physics on the Sandia Z accelerator have resulted in an x-ray source producing 2.0 MJ of energy, 290 TW of power, and primary hohlraum temperatures of 140 eV for weapon physics configurations and 155 eV for target compression configurations. To provide a cryogenic capability for high energy density physics experiments in this environment, we have initiated a project [1] to develop a general purpose cryogenic target system for precision EOS and shock physics studies at liquid helium (LHe) temperatures on Z. A cryogenic target assembly for Z has to meet a number of requirements: (1) it must be capable of containing liquid samples, including hydrogen and deuterium, and also solid materials, such as polycarbonate and metallic ablators for ICF; (2) it must include the capability to use various shock diagnostics, such as VISAR interferometry and shock breakout diagnostics; (3) it must meet the operational and safety requirements for use on Z; and (4) if possible, it must allow for the survival of high value cryogenic components in the Z debris environment.

Simultaneous values?

DISCLAIMER

In the initial phase of this project (FY97), we have: (1) developed a detailed conceptual design for a cryogenic target system that meets the operational and safety requirements for shock physics experiments on the Z pulsed radiation source; (2) evaluated the safety requirements for performing liquid hydrogen experiments on Z; (3) assembled a cryogenic test facility to perform off-line bench testing of the thermal and optical performance of cryogenic target system components; and (4) designed and assembled cryogenic hardware to perform initial testing of the cryogenic target system. We have also completed the design and fabrication of an interface to introduce cryogenic transfer lines, gas lines, and sensor wires into the Z vacuum section and to record sensor output in the Z screenroom. Work currently in progress to prepare for initial shock physics experiments on Z includes the following: (1) full integration of the cryogenic target design into the Z facility; (2) testing of cryogenic system performance in Z add-on experiments; and (3) evaluation of laser windows for use with fiber optic VISAR and shock breakout diagnostics at liquid helium temperatures. Integration and testing of VISAR optics and fiber optic sensors in the cryogenic target assembly have been delayed because issues concerning operation of these diagnostics at room temperature in the harsh bremsstrahlung environment of Z are still being resolved in a separate research effort [2,3]. We plan to use the resulting system for EOS measurements on solid targets and liquid deuterium in late-FY98.

II. Motivation for Cryogenic EOS Measurements

With the loss of underground testing and the recent developments in teraflop computing capability, there is increased emphasis to ensure that the nuclear weapons laboratories sustain the capability for predicting and analyzing the performance of nuclear weapons through computational-based approaches. Similar modeling requirements exist for the ICF program. Present high-gain fusion targets rely on critical timing of external radiation deposition to simultaneously optimize fuel compression in the ICF capsule and suppress formation of Rayleigh-Taylor instabilities during compression. Recent rad-hydro simulations of high-gain ICF targets at LLNL and SNL indicate that capsule yields can be significantly reduced by variations of a few percent in the sound speeds of capsule materials at high pressures. This information is not generally available, which forces reliance on models existing in the codes, such as the Mie-Grueneisen model, which is known to contain inaccuracies for predicting off-Hugoniot properties such as sound speeds.

The need to accurately model ICF capsule performance results in stringent requirements on condensed matter and dense plasma theories to adequately model materials over a broad dynamic range. The models must predict dynamic material response for pressures of several Mbar, temperatures of several eV, and for loading rates approaching the vibration times of atomic motions. Rapid loading rates produce deformation mechanisms, dissipative effects, and phase transition kinetics that are not currently modeled well, but which can significantly influence material motion. For example, refreezing from melted states may not occur in the implosion times of materials used in weapon primaries. For simple materials such as metals, dissipative processes including the generation of dislocations and other defects are important to kinetic processes such as dynamic yielding, melting, refreezing, polymorphic transitions, and tensile failure. All of these properties must be accurately predicted in applications involving the performance, safety, and reliability of nuclear weapons and some ICF geometries. In more complex materials, such as DT fuels and polycarbonates, it is also necessary to model and predict the effects of molecular dissociation. The present theoretical ability to model these effects is extremely limited. Consequently, computational based approaches for analysis and prediction cannot be used with confidence. Precision measurements of stress wave profiles in materials over the relevant pressure range would be extremely valuable for identifying and quantifying the important mechanisms of material response.

Recent NOVA laser and gas gun studies on liquid deuterium by LLNL investigators [4-6] dramatically demonstrate the inadequacy of present models for predicting the pressurization of DT fuels. The LLNL results illustrate that deuterium undergoes a molecular dissociation to a metallic phase at pressures of about 1.4 Mbar and temperatures of about 3000 K (present theories predict this transition in the range of 1-20 Mbar at zero Kelvin). Under shock compression, dissociation of molecular deuterium also produces a much softer response than predicted by present theories. One consequence is that deuterium is about twice as dense as previously predicted for shock compression to 2 Mbar. This pressure is in the regime that weapons systems and ICF capsules operate. This EOS response was completely unexpected and has profound implications for both the ICF and the weapon physics programs. For ICF, it implies that fusion conditions may be achieved for lower driving pressures in ICF capsules and that the target will be more resistant to Rayleigh-Taylor instabilities.

A major limitation in the NOVA EOS experiments was the small size (less than 1.0-mm diameter) of the liquid deuterium samples. The resulting uncertainties in pressure and volume of 5-10% prevent a critical comparison of first-principles theories of molecular dissociation to the experimental results. In contrast, the relatively large sample sizes that are possible for study in Z EOS experiments provide an opportunity to significantly increase the accuracy of EOS measurements and thus allow a critical comparison with theories of molecular dissociation.

III. Conceptual Design for the Z Cryogenic Target System

The basic requirement of any cryogenic cooling system for EOS samples on Z is the ability to cool a compact sample holder which forms part of a secondary hohlraum assembly to a specified temperature T in the range $6\ K \leq T \leq 30\ K$. Sample holders must be designed which are capable of containing liquid samples, including liquid hydrogen (LH_2) and liquid deuterium (LD_2), and solid materials, such as polycarbonate or metallic ablators for ICF. The liquid sample holder must be capable of containing a liquid at a fixed temperature, with diagnostics to accurately measure the temperature and pressure so that the initial density ρ_0 of the sample can be determined with high precision ($\pm$ 0.1%). The cryogenic target assembly must also include the capability for various shock diagnostics, such as VISAR interferometry, shock velocity measurement, and Raman spectroscopy. Possible cooling options include cooling with an LH_2 reservoir, using a closed-cycle refrigerator, or cooling with a LHe cryostat. A major consideration driving the design is possible damage to the cryogenic system components from radiation and debris as the Z PRS dissipates in excess of 1 MJ of energy in the region of the Z-pinch.

Most of the cryogenic cooling requirements for weapon physics and ICF samples, such as LD_2, solid D_2 and DT, beryllium and CH, could be met by cooling the sample holder with a large LH_2 reservoir to access the temperature range from 15 K to 23 K. However, after considering the relevant operational and safety issues, we concluded [7] that the transfer and handling of small (few liter) quantities of LH_2 in the Z environment represented an unacceptable safety hazard, and that the best approach to cooling an EOS sample on Z is to use a LHe cryostat connected through a cold finger and a thermal link to a sample holder (as shown in Figs. 1-3 below) with an automatic temperature control system. The thermal link provides standoff of the cryostat from the sample holder for survivability. The design of the thermal link will depend on the required sample temperature. The high-value cryostat will be enclosed in a blast shield to ensure its survival, while the sample holder and associated instrumentation are sacrificed on each shot. Using various precision temperature control techniques, we can access a continuous range of temperatures from about 2 K to 75 K with LHe cooling. Because we are not tied to a narrow temperature range fixed by the boiling point of LH_2 or the operating limits of a closed-

cycle refrigerator, for example, this approach is applicable to EOS studies over a broad, continuous range of temperatures.

This approach can be used to generate small (1 - 2 cm^3) LD_2 samples by evacuating and cooling a copper sample holder cavity to about 22 K and then condensing sufficient LD_2 from a high purity external deuterium gas supply to fill the cavity [8,9]. At atmospheric pressure, D_2 will condense to a liquid in the temperature range between about 18 K and 23 K. The sample holder temperature and the pressure of gas over the liquid must be measured. A diagnostic must also be included to provide positive verification that the sample reservoir has been filled with liquid.

In summary, we have developed a detailed conceptual design for a Z-integrated cryogenic target system with the capability for cooling both solid and liquid samples. This system will use LHe cooling and active feedback temperature control to maintain a fixed sample temperature in the range 6 - 30 K. The sample volumes for EOS measurements on Z, while small, will be much larger than for the NOVA EOS experiments [4], so it should be possible to determine initial and dynamic pressure, temperature, and volume with significantly smaller errors.

IV. Cryostat Design

The cryostat and sample-holder design required for a cryogenic target system in the Z machine environment differs in several important ways from a typical closed laboratory LHe cryostat/sample-holder assembly. The Z cryostat is operated inside a large-volume, high-vacuum ($2x10^{-5}$ - $4x10^{-6}$ Torr) environment. This accelerator vacuum is used to provide the initial vacuum insulation within the cryostat and around the sample holder, so the thermal loading from gas convection will be determined largely by the quality of the Z vacuum. Some improvement in vacuum both inside the cryostat radiation shields and in the Z vacuum section itself can be expected to result from LN_2 and LHe cryopumping by the cryostat and unshielded cryogenic transfer lines. Cryogenic liquids must be delivered to the cryostat from a location external to the Z vacuum chamber through approximately 4 m of transfer line. Because of the possibility of an extended delay in the shot sequence, the system must be capable of maintaining the sample holder in a stable equilibrium state of temperature and gas pressure for up to 2 hours. Once established, the state of the cryostat and sample holder must be monitored and controlled from a remote screen room through a 70 m cable run. The sample holder, which we wish to cool to a specified temperature in the range of 6-30 K for most applications, must be directly connected to the hohlraum which is initially at room temperature. Thermal isolation must be maintained between the sample holder and hohlraum to avoid an excessive heat load on the sample holder. The hohlraum must also be maintained near room temperature during the shot sequence to avoid a change in wire resistivity and to avoid distortion of the wire array geometry by thermal contraction at low temperatures. This requires an effective thermal break between the sample holder and the hohlraum over a distance of less than 1 cm. The cryostat together with associated transfer lines and sensor cables, if unprotected, could be destroyed by shrapnel resulting from the dissipation of more than 1 MJ of energy in the region of the Z-pinch implosion. There is no feasible way to protect the sample holder which is directly connected to the hohlraum, but it is highly desirable to separate the cryostat from the sample holder with a high conductivity thermal link and then enclose the cryostat in an effective debris shield to ensure its survival.

For initial thermal testing of cryogenic sample holders, we fabricated a relatively simple and inexpensive continuous flow cryostat, shown in Fig. 1. The LHe reservoir is an OFHC copper cylinder. LHe is introduced through a top port and cold He exhaust gas leaving the reservoir flows through a cooling coil on the inner shield surrounding the reservoir body before exiting

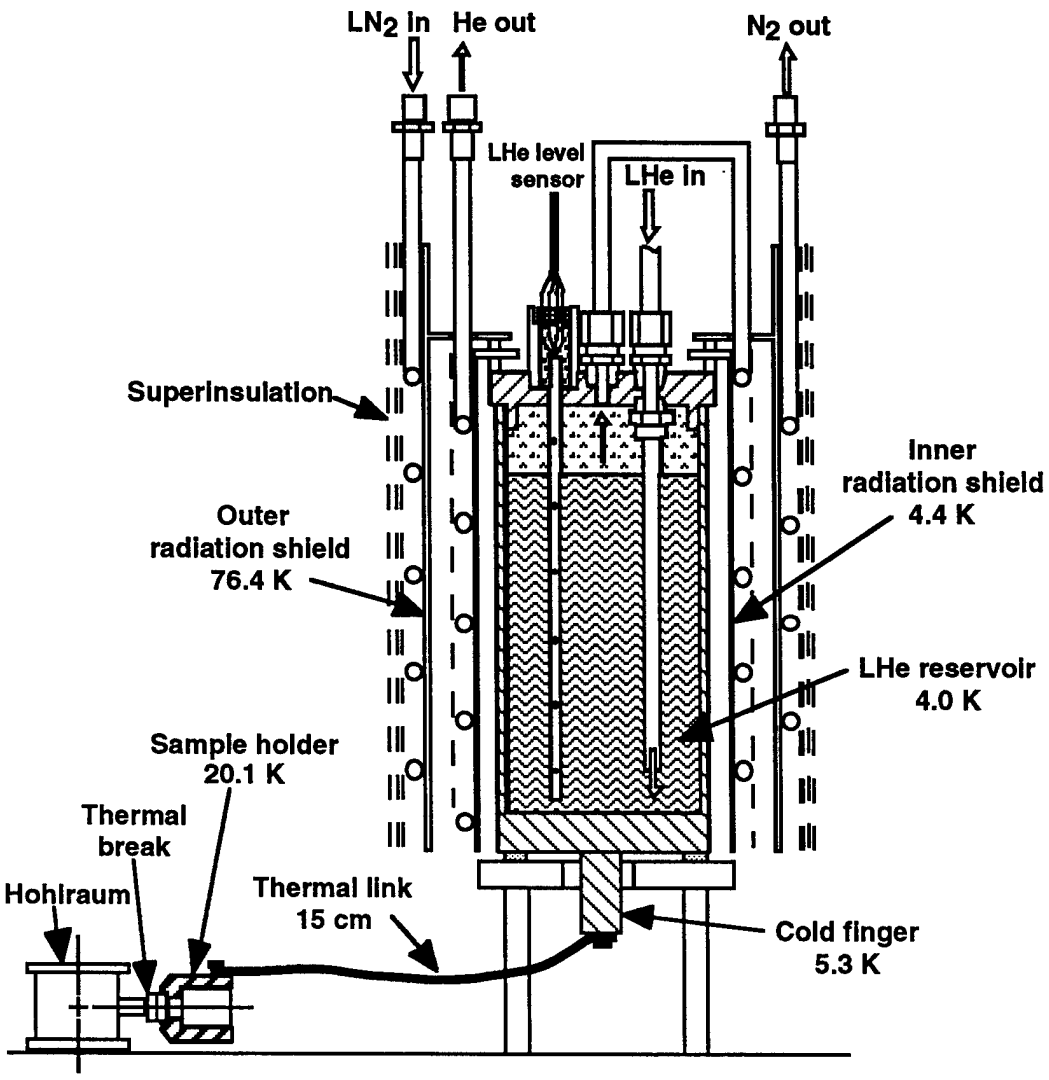

Fig. 1: Continuous flow LHe cryostat with LN_2-cooled outer radiation shield. The sample holder is connected to the cryostat cold finger through a thermal link consisting of OFHC copper wire.

the vacuum chamber. The LHe level in the reservoir can be measured with a LHe level sensor inserted through a feedthrough on the top cover. The LHe-cooled components are surrounded by an outer, LN_2-cooled radiation shield. The outer shield is wrapped in multilayer insulation to isolate it from the radiation heat load of the surrounding room temperature environment. The cold finger is a cylindrical extension from the center of the LHe reservoir bottom. The sample holder is connected to the cold finger through a thermal link consisting of a piece of OFHC copper wire. With adequate separation between cryostat and sample holder achieved in this way, the high-value cryostat and transfer lines can be enclosed in a debris shield and protected from blast damage.

The main shortcoming of this simple cryostat is that it is open at both ends and the LHe transfer lines are not thermally sinked to the shield at LN_2 temperature. The high radiation heat load on the ends of the LHe reservoir results in relatively rapid evaporation of LHe. The tradeoff of LHe

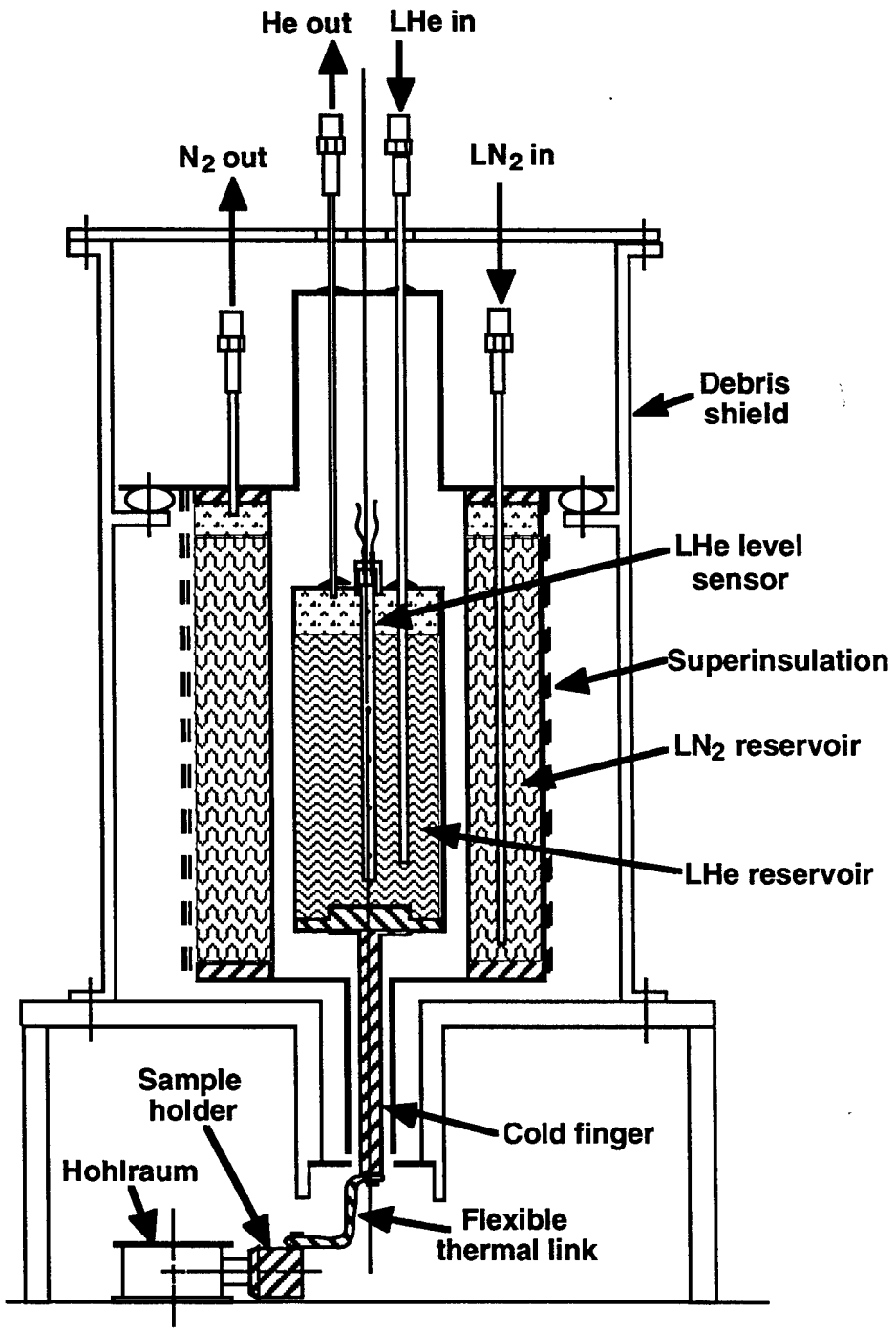

Fig. 2: Fully shielded static-fill LHe cryostat with LN_2 reservoir as outer radiation shield for more efficient use of LHe. The cryostat is shock-mounted inside a heavy debris shield for survivability in the Z blast environment.

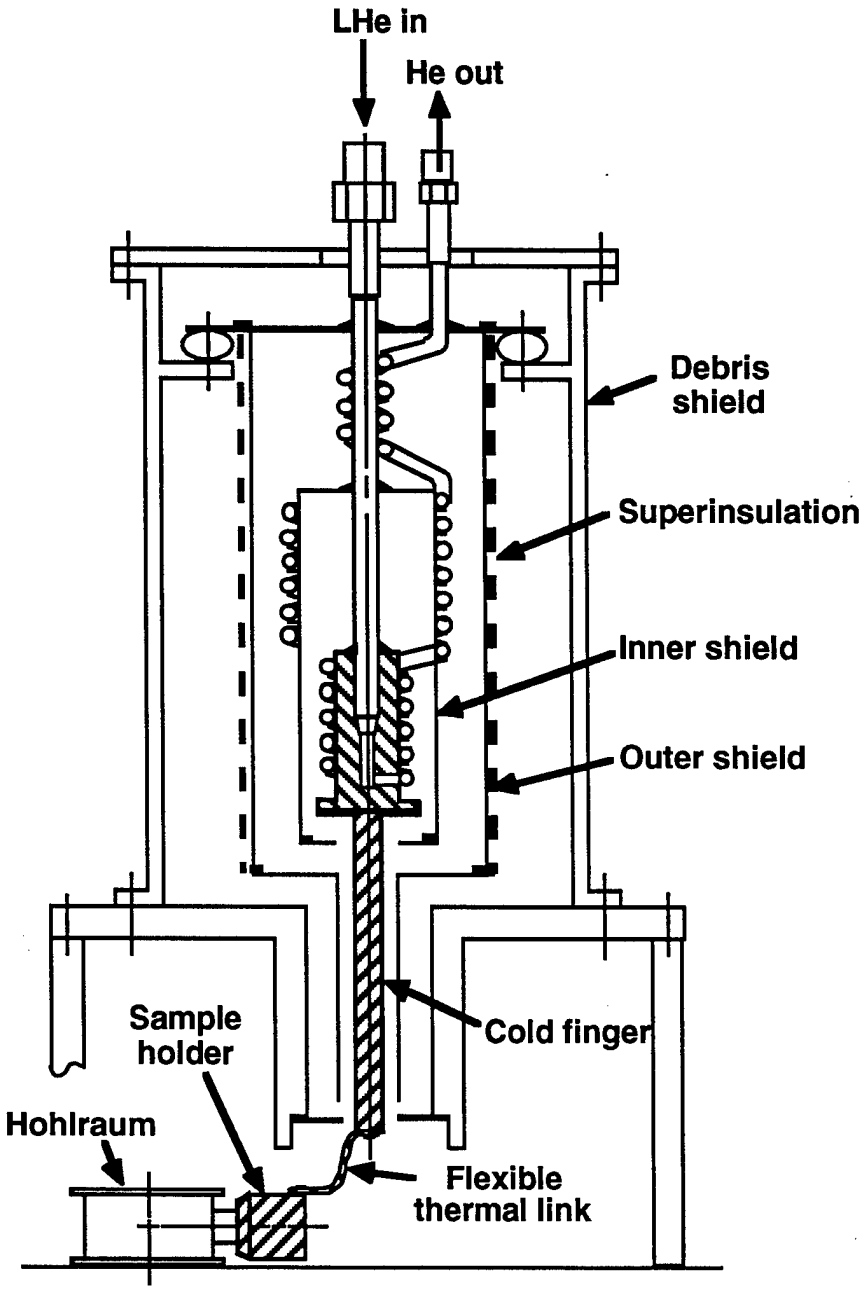

Fig. 3: Compact, continuous flow LHe evaporation cryostat shock-mounted inside a heavy debris shield.

efficiency for ease of cryostat construction proved quite satisfactory in the initial phase of testing where we were interested in quickly defining system requirements. However, we have recently designed two more conventional, fully-shielded cryostats which should make more efficient use of LHe. The static fill cryostat, shown in Fig. 2, should have a LHe hold time of an hour or more, depending on the sample heat load, and be more suitable for use on Z. The continuous flow LHe evaporation cryostat, shown in Fig. 3, is quite compact and does not require LN_2 for its operation. We would like to be able to maintain a steady equilibrium cold finger temperature

in a static fill mode (or with continuous LHe flow at a very low flow rate), rather than with a continuous flow system operated at a relatively high flow rate requiring constant attention.

V. Cryogenic Sample Holders

Several different cryogenic sample holders have been designed and fabricated to meet the requirements for cooling different types of sample materials. A cryogenic sample holder for containing liquid samples condensed from the gas phase is shown in Fig. 4. The configuration shown could be used for EOS measurements on liquid deuterium (LD_2) condensed from pure deuterium gas within the sample holder maintained at about 20K. The gas is introduced through a fill tube and gas line thermally-sinked to a cool surface. Access to shock wave diagnostics is provided through the back of the sample holder. A thermal break between the cold sample holder and the room temperature hohlraum is provided by a nested assembly of copper, stainless steel, and low-conductivity nylon cylinders. The sample holder and thermal break insert directly into the secondary hohlraum, forming a smooth gold-plated radiation channel between the primary hohlraum and the sample.

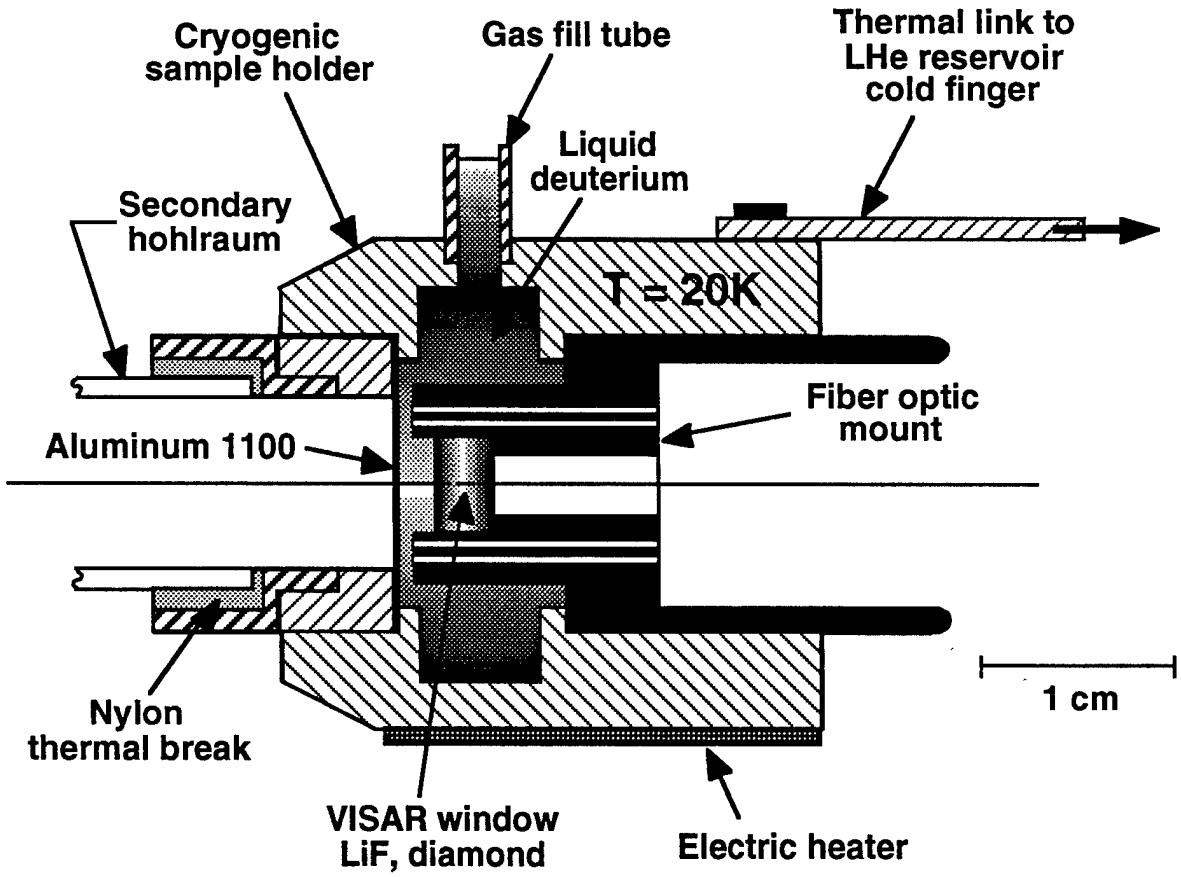

Fig. 4: Cryogenic sample holder (OFHC copper) for containing liquid samples (LH_2, LD_2) condensed from the gas phase. A thermal break is provided between the sample holder and hohlraum.

VI. Cryogenic Target System Test Results

We have assembled a cryogenic test facility to evaluate and refine the cryogenic target system components. Tests are performed in a large volume vacuum chamber with 14 large area ports and a vacuum system capable of ultimate chamber pressures of about 2×10^{-6} Torr. During cryogenic testing, additional cryopumping by the cryostat and cryogenic transfer lines have resulted in test chamber pressures as low as 1.0×10^{-7} Torr. A thermal model of the complete Z-pinch experiment, including the Z anode plate, primary and secondary hohlraums, a plug-in cryogenic sample holder, and a LHe cryostat, has been assembled for thermal testing. The system is instrumented with an array of eight temperature sensors, a LHe level sensor in the LHe reservoir, and pressure gauges to measure the vacuum in the test chamber.

Temperature control of the cryogenic sample holder has been demonstrated in a series of cooling tests performed in the cryogenic test facility chamber with the cryostat arrangement shown in Fig. 1. In a typical cooling sequence for the cryogenic target assembly, the cryostat outer shield is first cooled with LN_2 at full flow rate (40 L/hr) to about 82 K in 8 minutes (Fig. 5). The LN_2 flow rate is then reduced to less than 10 L/hr. LN_2 from a 110 L dewar will then flow continuously through the outer shield cooling coil without further attention for many hours. Reducing the LN_2 flow rate also reduces the pressure in the LN_2 transfer lines and cooling coil. As a result, the temperature of the outer shield decreases from 82 K to 76.4 K, the approximate boiling point of LN_2 at atmospheric pressure in Albuquerque. After about 25 minutes, LHe cooling of the LHe reservoir cold finger is started and temperatures below 10 K are reached in about 20 minutes. The cryostat cold finger is connected to the sample holder (Fig. 7) through a 15-cm-long, 0.41-cm-diameter section of OFHC copper magnet wire to provide standoff for blast protection of the cryostat. Both the sample holder and the wire thermal link are gold-plated to reduce the radiation heat load at the sample. The sample holder requires approximately 35 minutes after LHe cooling of the cryostat begins to reach its final equilibrium temperature of 20.1 K. The cryostat cold finger and the inner shield do not reach their final equilibrium temperatures of 5.3 K and 4.4 K, respectively, until the sample holder has cooled.

Control of the sample holder temperature stable to within 0.1 K is achieved using an automatic temperature controller. A small heater is attached to the body of the sample holder and the sample holder temperature is measured with a silicon diode temperature sensor operated by the temperature controller. A feedback circuit in the temperature controller supplies current to the heater to maintain the sample holder at the temperature setpoint. Fig. 8 shows an example of temperature control where the temperature setpoint was increased in a series of 0.5 K steps and then 2.5 K steps to 25.0 K, with the new equilibrium temperature of the sample holder maintained for a few minutes at each setpoint. (This exercise spans the temperature range required to condense LD_2.)

The effectiveness of the thermal break (Section V) between the sample holder and the hohlraum was evaluated by instrumenting the primary hohlraum top and base mounting flanges with silicon diode temperature sensors. During the entire cooling sequence for the sample holder, lasting about 3 hours, the primary hohlraum top flange near the secondary hohlraum pipe cooled to only 282.6 K (Fig. 9), a temperature change which will not produce significant resistivity or dimensional changes in the wire array hardware.

Cryopumping by surfaces in the cryostat and by unshielded cryogenic transfer lines should also be expected to improve the vacuum in Z prior to a shot. The improvement in vacuum in the smaller cryogenic test facility vacuum chamber as a result of sequentially cooling the cryostat outer shield with LN_2 and then the cryostat reservoir and inner shield with LHe is shown in Fig. 10. Starting at a base vacuum pressure of 1.8×10^{-5} Torr (a typical vacuum for Z operation), a pressure of 2×10^{-6} Torr was quickly reached by cryopumping water vapor and hydrocarbons with LN_2-cooled surfaces in the cryostat. A pressure of 3.2×10^{-7} Torr was achieved after about

90 minutes of cryopumping by the LHe-cooled cryostat surfaces. After cryogenic liquid flow is turned off and the cryostat surfaces warm, materials collected on these surfaces are released back into the vacuum, resulting in a large jump in pressure followed by a gradual recovery as the chamber vacuum system pumps away some of the released components.

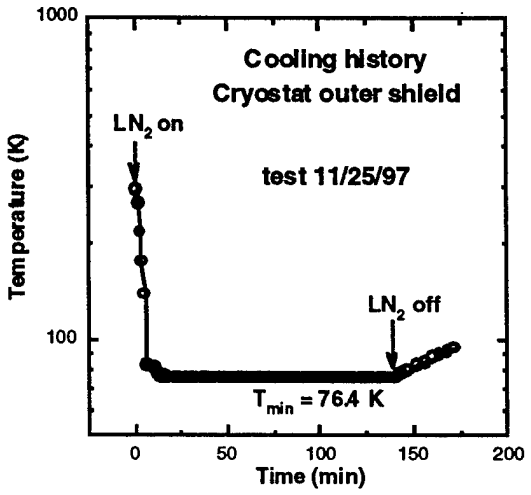

Fig. 5: Cooling history of LN_2-cooled cryostat outer shield (see Fig. 1). Shield temperature decreases from 82 K to 76.4 K as the LN_2 flow rate is reduced from 40 L/hr to 10 L/hr.

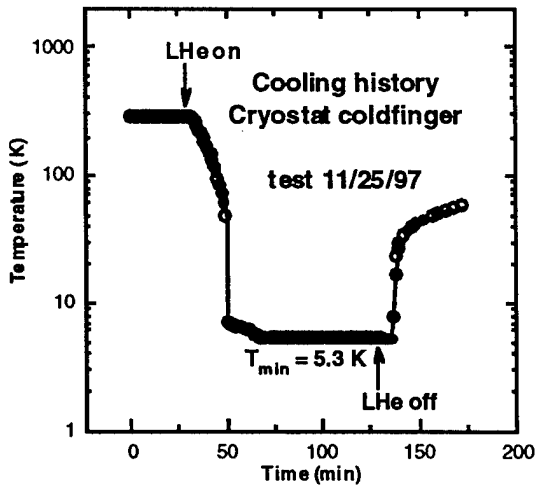

Fig. 6: Cooling history of the LHe cryostat cold finger (see Fig. 1) during a temperature control test. The minimum cold finger temperature (5.3 K) is reached after sample holder cooldown to an equilibrium temperature of 20.1 K.

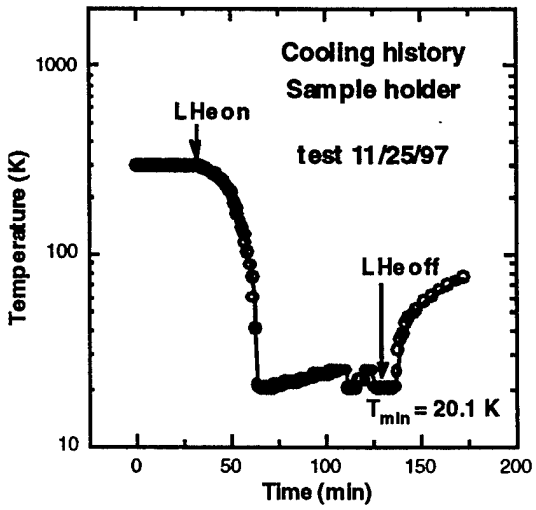

Fig. 7: Cooling history of the cryogenic sample holder connected to the cryostat cold finger through a 15-cm-long section of OFHC copper wire.

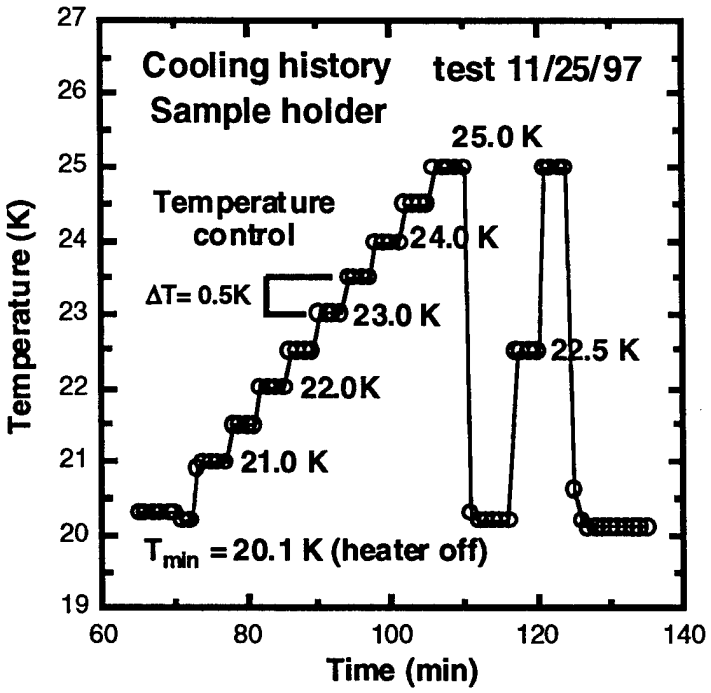

Fig. 8: Demonstration of temperature control of the sample holder with standoff (expanded view of Fig. 7). The temperature controller setpoint is increased in 0.5 K steps and then in 2.5 K steps to 25 K.

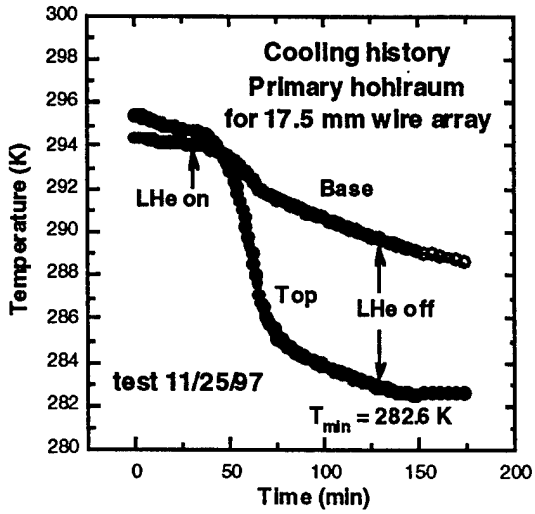

Fig. 9: Cooling history of the primary hohlraum connected to the sample holder through the thermal break and secondary hohlraum stub.

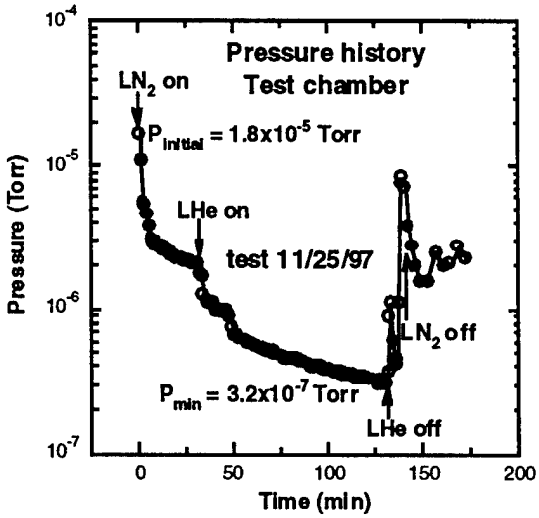

Fig. 10: Pressure history in the cryogenic test facility vacuum chamber. The improvement in vacuum is a result of cryopumping by cryogenic target system components during the cooling test.

VII. Summary and Future Work

We have made significant progress toward the development of a fully functional general purpose cryogenic target system for precision shock physics measurements on the Z PRS. We have generated a conceptual design and strategy for fielding cryogenic experiments on Z which is shaped by safety considerations and the need for survivability of high-value cryogenic hardware. We have assembled and instrumented a cryogenic test facility, and designed and fabricated cryostats, sample holders, cryogenic transfer, gas delivery, and temperature control systems, and a thermal model of the Z hohlraum. Cooling tests have demonstrated stable cooling of the LHe cryostat cold finger to 5K for greater than 150 minutes, thermal isolation of the sample holder from the hohlraum, spatial standoff of the LHe cryostat from the sample holder for survivability, automatic temperature control of the sample holder, and improvement of the experiment chamber vacuum through cryopumping. An interface to introduce cryogenic transfer lines, gas lines, and sensor wires into the Z vacuum section has been designed and is currently being fabricated. As soon as practical, we will begin integration of the system into the Z facility in preparation for full-scale Z add-on tests of cryogenic system performance. Before cryogenic EOS measurements are attempted on Z in FY98, we must select an optimum primary hohlraum and wire array size based on ongoing Z-pinch source characterization studies, design a secondary hohlraum configuration that can provide uniform temperature across the large EOS sample, and refine the details of the various shock physics target assemblies based on experience gained from EOS measurements on Z with uncooled samples. We must also evaluate the operation of VISAR optics and fiber optics integrated into a cryogenic sample holder cooled to LHe temperatures. Changes in component dimensions, optical properties, and signal attenuation in cold optical fibers could be important issues for shock physics measurements at low temperatures.

References

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[1] D. L. Hanson, R. R. Johnston, and J. R. Asay, "Development of a Cryogenic EOS Capability for the Z Pulsed Radiation Source: Goals and Accomplishments of FY97 LDRD Project," Sandia National Laboratories Report SAND98-0564, March 1998.

[2] J. R. Asay, C. H. Konrad, W. M. Trott, C. A. Hall, J. S. Lash, R. J. Dukart, D. L. Hanson, R. E. Olson, G. A. Chandler, L. C. Chhabildas, "Use of Z-Pinch Sources for High Pressure Shock Wave Experiments," Shock Waves in Condensed Matter 1997 - Proc. of APS 1997 Topical Conf. on Shock Compression in Condensed Matter.

[3] C. H. Konrad, J. R. Asay, C. A. Hall, W. M. Trott, B. F. Clark, G. A. Chandler, K. G. Holland, K. J. Fleming, J. S. Lash, L. C. Chhabildas, and T. G. Trucano, "Use of Z-Pinch Sources for High Pressure Shock Wave Studies," Sandia National Laboratories Report SAND98-0047, January 1998.

[4] L. B. Da Silva, P. Celliers, G. W. Collins, K. S. Budil, N. C. Holmes, A. Ng, T. W. Barbee Jr., B. A. Hammel, J. D. Killkenny, R. J. Wallace, G. Chiu, and R. Cauble, "Absolute Equation of State Measurements of Shocked Liquid Deuterium up to 200 Gpa (2 Mbar)," Phys. Rev. Lett. **78**, 483 (1997).

[5] R. Cauble, "NOVA Experimental Hugoniot of Liquid D_2 up to 2 Mbar," Memo to distribution, LLNL L-22, Livermore CA, 9/9/96.

[6] N. C. Holmes, M. Ross, and W. J. Nellis, "Temperature measurements and dissociation of shock-compressed liquid-deuterium and hydrogen," Phys. Rev. **B52**, 15835 (1995).

[7] D. L. Hanson and R. R. Johnston, "EOS Measurements on PBFA-Z: Conceptual Design for Cryogenic Sample Holder," Memo to J. R. Asay, Sandia National Laboratories, Dept. 9575, 2/4/97.

[8] K. D. Timmerhaus and M. A. Lechtenberger, "Vapor-Liquid Condensation on Cryogenic Surfaces," *Heat Transfer at Low Temperatures*, W. Frost, ed. (New York: Plenum Press, 1975) pp. 203 - 212.

[9] W. J. Nellis, A. C. Mitchell, M. van Thiel, G. J. Devine, R. J. Trainor, N. Brown, "Equation-of-state data for molecular hydrogen and deuterium at shock pressures in the range 2 -76 Gpa (20 - 760 kbar)," J. Chem. Phys. **79**, 1480 (1983).

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