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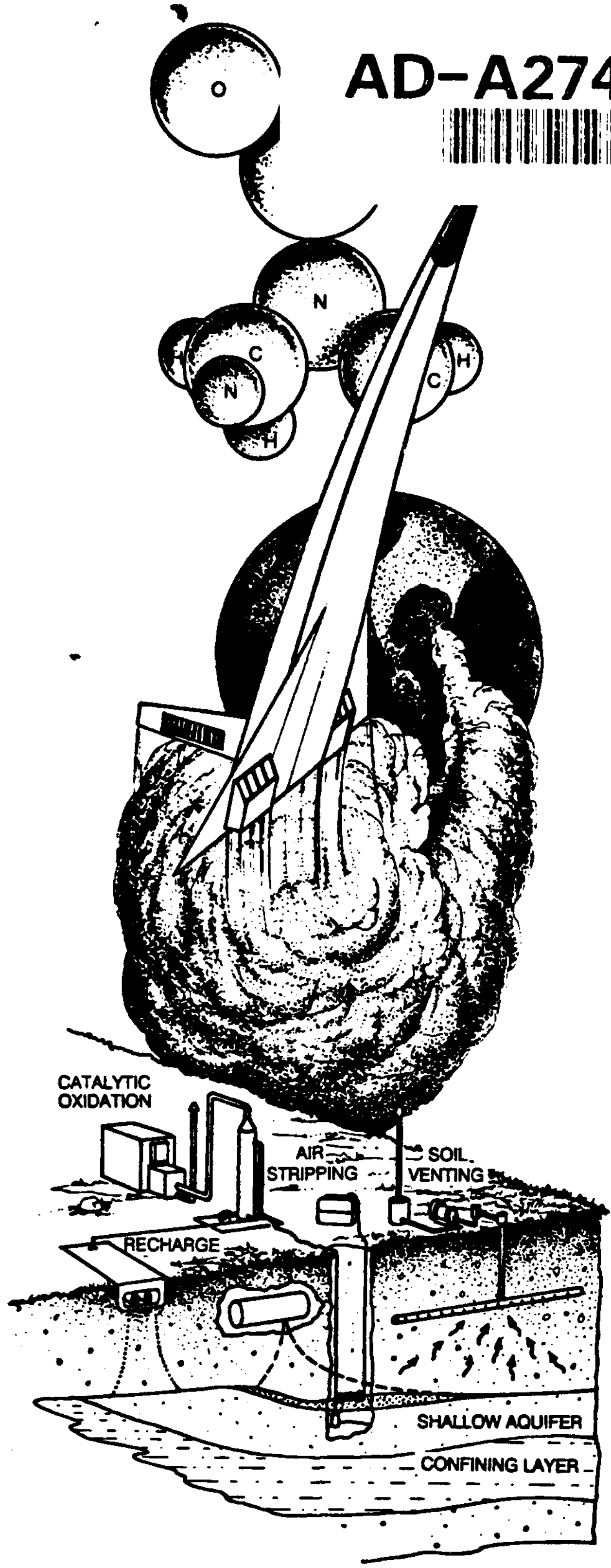

CRYOGENIC SIZE REDUCTION OF SOLID PROPELLANT

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13. ABSTRACT *(Maximum 200 words)*

A growing need exists to develop improved methods for the disposal and/or recovery of solid rocket propellants. Laboratory, bench-scale, and prototype tests were performed to develop the dry washout concept for size reduction and removal of solid propellants using cryogenic media. Three propellant types were investigated: Hazard Class 1.1 composite modified double base (CMDB), Hazard Class 1.1 cross-linked double base (XLDB), and Hazard Class 1.3 hydroxl terminated polybutadiene (HTPB). No propellant initiations were detected.

The laboratory tests established that essentially no change in the sensitivity of the test propellants occurs between ambient and cryogenic temperature. Impact, friction, low-level shock and electrostatic discharge sensitivity tests were conducted. Over 2000 trials were conducted.

The bench-scale tests demonstrated the safety of liquid nitrogen washout and established parameter ranges for effective propellant removal. Removal rates of greater than 60 pounds per hour were achieved for all propellant types.

The prototype tests demonstrated cryogenic washout of several reduced scale motors in a semiautomated process. Two motors were processed, one containing 40 pounds of XLDB propellant, the other containing 60 pounds of HTPB propellant. Propellant removal rates ranged from 8.3 pounds per hour to 156 pounds per hour with liquid nitrogen flow of less than 4 gpm.

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EXECUTIVE SUMMARY

A. OBJECTIVE: The objective of this work was to develop and demonstrate a new method for removal and size reduction of solid propellant - cryogenic washout.

B. BACKGROUND: Improved methods are needed for removal and size reduction of solid propellant. Traditional methods such as mechanical milling or water washout are slow, hazardous, or produce waste streams that are difficult and expensive to dispose of. Cryogenic washout, conceived and patented by General Atomics, offers advantages in safety and elimination of waste streams.

C. SCOPE: General Atomics has performed laboratory, bench scale, and prototype tests to develop the cryogenic washout concept (also called dry washout) for size reduction and removal of Class 1.1 double base and Class 1.3 composite propellants. Three propellant types were investigated: Class 1.1 composite modified double base (CMDB), Class 1.1 cross linked double base (XLDB), and Class 1.3 hydroxyl terminated polybutadiene (HTPB).

D. METHODOLOGY: Sensitivity tests were performed using standard laboratory methods. Bench-scale and prototype-scale tests were performed using a specially designed test rig featuring an enclosure to mount, rotate, and translate test samples while impacting the surface with cryogenic materials to cause removal and size reduction of the propellant.

E. TEST DESCRIPTION: In the laboratory tests (Task 1), standard methods were used to establish that there is essentially no change in the sensitivity of the test propellants between ambient and cryogenic temperatures. The bench-scale tests (Task 2) demonstrated the safety of cryogenic washout and established parameter ranges and test conditions for effective propellant removal. The prototype tests (Task 3) demonstrated cryogenic washout of several reduced scale rocket motors in a semiautomated process.

F. RESULTS: The Task 1 tests consisted of impact, friction, low-level shock, and electrostatic discharge sensitivity tests at ambient and cryogenic temperatures. In addition, electrical properties, such as dielectric breakdown, volume resistivity and dielectric constant were measured at ambient and cryogenic temperatures. In all over 2000 sensitivity tests or measurements were made which showed little, if any, change between ambient and cryogenic temperatures. These results were used in a detailed hazards analysis of the Tasks 2 and 3 equipment to minimize hazards.

Throughout the Task 2 testing, in excess of 1000 separate propellant impacts were performed with liquid nitrogen (LN_2) jets ranging in pressure from 10,000 psig to 16,500 psig. No initiations or reactions were detected. Propellant erosion rates were good with nominal removal rates greater than 60 pounds per hour achieved for all three propellant types at an LN_2 flow rate of less than 4 gpm through a single nozzle. A 200 scfm warm gaseous nitrogen (GN_2) flow was used to augment the LN_2 jet and prevent excessive cooldown of the propellant. Excellent size reduction of the propellants occurred during the tests. Most propellant particles were the size of course sand, with a few larger particles weighing about 20 gm, and a small amount of fine dust.

A wide range of propellant removal rates occurred during Task 3 testing using reduced scale rocket motors. Two motors were processed, one containing 40 pounds of XLDB propellant and another containing about 60 pounds of HTPB propellant. The most effective removal rate occurred during washout of the 40 pounds motor containing XLDB propellant, for which a mass removal rate of 156 pounds per hour was achieved. Propellant removal rates varied from 8.3 to 23.3 pounds per hour during washout of the 60-pound HTPB motor. The propellant removal rates generally improved at higher LN_2 jet pressures and with warm GN_2 flow. Most propellant particles were the size of course sand, with a few particles weighing from 50 to 90 gms, and a small amount of fine dust.

Carbon dioxide (CO_2) pellets were also evaluated as an alternate to LN_2 as a cryogenic medium. CO_2 pellet blasting was tested on each of the three propellant types at supply pressures ranging from 250 to 600 psig with a CO_2 flow rate of 150 pounds per hour. No initiations or reactions were detected. However, the mass removal rate was significantly worse than for high pressure LN_2 washout. The most effective removal rate was observed during testing with HTPB propellant at 425 psig where the maximum removal rate of 1.67 pounds per hour was achieved.

G. CONCLUSIONS: The test series demonstrated that cryogenic washout can be an effective means of solid propellant removal and size reduction. With modest scaleup to larger and/or multiple nozzles, propellant removal rates in excess of 500 pounds per hour should be possible. Based on an LN_2 price of about 25 cents per gallon, the demonstrated minimum LN_2 cost for propellant removal is about

38 cents per pound of propellant removed. This low cost should be competitive with alternate processes which require additional processing for recovery of propellant or elimination of waste streams. Improvements are also needed in the warm GN_2 system to increase the propellant removal rate for some propellant types such as HTPB.

H. RECOMMENDATIONS: Additional follow-on testing is recommended to establish the threshold initiation pressure for LN_2 jet impingement, and to optimize key propellant removal parameters such as jet pressure, surface speed, and effectiveness of GN_2 flow.

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PREFACE

This report was prepared by General Atomics (GA), San Diego, California 92121 under Contract No. F08635-91-C-0179 for the Department of the Air Force, Air Force Civil Engineering Support Agency, Tyndall AFB, Florida.

This report describes the test methodology and results for the Dry Washout Program which is aimed toward the development of a new rocket propellant removal and size reduction concept utilizing a cryogenic medium. The work was performed during the period of September 1991 through May 1992. This project was sponsored by the Civil Engineering Laboratory at Tyndall AFB under a Broad Agency Announcement (BAA-92-01). Captain Mark Smith was the project officer.

This technical report has been reviewed and is approved for publication.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AP	ammonium perchlorate
CMDB	composite modified double base
CO_2	carbon dioxide
CYH	a specific type of CMDB propellant
ESD	electrostatic discharge
FPC	forty-pound charge [40-pound motor filled with XLDB (WAY) propellant]
HMX	cyclotetramethylenetetranitramine (an explosive)
HTPB	hydroxyl terminated polybutadiene
i.d.	inside diameter
LAM	80-pound lightweight analog motor filled with HTPB (QDT) propellant
LN_2	liquid nitrogen
MNA	N-methylnitroaniline
NC	nitrocellulose
NG	nitroglycerin
o.d.	outside diameter
QDT	a specific type of HTPB propellant
TIL	threshhold initiation limit
WAY	a specific type of XLDB propellant
XLDB	cross-linked double base
2-NDPA	2-nitrodiphenylamine

SECTION I
INTRODUCTION

A. OBJECTIVE

A growing need exists to develop improved methods for the safe disposal and/or recovery of solid rocket propellants. Present methods generate waste streams that may limit or preclude their future use. Washout, using a cryogenic medium, can provide a safe, environmentally acceptable method of propellant removal and size reduction which eliminates aqueous waste streams. The objective of this program was to demonstrate the viability of the cryogenic washout process by performing safety tests and analyses, performing process development tests to establish effective process conditions, and demonstrate cryogenic washout of reduced-scale rocket motors in a semiautomated process.

B. BACKGROUND

The most common methods presently used for removal and/or disposal of propellant from rocket motors are open burning, static firing, and water washout. Open burning and static firing are both cost-effective methods of disposal, but environmental and public safety issues may limit their further use.

High-pressure water washout of ammonium perchlorate (AP)-based propellants (Hazard Class 1.3) from solid rocket motors has been used to recover motor casings and AP, but the process produces aqueous waste streams which are hazardous and costly to dispose of. Consequently, improved methods are needed that remove and size reduce propellants, while minimizing the associated hazards and waste streams.

Cryogenic washout has been proposed as a means to remove and size reduce solid rocket propellants while eliminating aqueous waste streams. In this process, a cryogenic medium such as LN_2 is used to remove the propellant from the inside of a solid rocket motor. The inert medium evaporates, eliminating waste streams. Subsequently, the propellant fragments can be fed to a recovery or disposal process. Cryogenic washout is expected to offer improvements in safety, waste minimization, protection of surface and groundwater, and control of air pollution.

C. SCOPE

The test program has been structured in three tasks: Task 1 was performed to determine the variation in propellant sensitivity for the three propellant types (HTPB, XLDB AND CMDB) at cryogenic temperatures (-109°F and -320°F). Task 2 was carried out to determine the safety of cryogenic washout of propellant using small samples, to establish process parameters for effective removal and size reduction of propellant, and to verify the adequacy of the process equipment design and safety measures. Task 3 demonstrated cryogenic washout of subscale rocket motors using process parameters and procedures established during Task 2. All tasks were performed first with inert propellant samples prior to live propellant operations. All live propellant testing was performed remotely. All testing was performed in accordance with the Test Plan (Reference 1). Test activities were performed in accordance with General Operating Procedures (Reference 2). Test observations and data were recorded in the Test Logs (Reference 3) and Data Sheets (Reference 4).

Subcontractors contributing to the test program were Hercules Incorported, Magna, Utah, and El Dorado Engineeing of Salt Lake City, Utah.

SECTION II
TEST REQUIREMENTS

A. TASK 1: PROPELLANT SENSITIVITY TESTING

Propellant sensitivity testing was performed to determine the change in sensitivity of propellants to various stimuli at cryogenic temperatures (Reference 5). This task was performed prior to the Task 2 (bench scale) and Task 3 (prototype) propellant tests. Specific Task 1 test requirements were as follows:

- Determine the sensitivity of QDT (HTPB propellant), WAY (XLDB propellant), and CYH (CMDB propellant) to impact, friction, electrostatic discharge (ESD), and low-level shock at -109°F, -320°F and ambient temperatures.
- Determine the sensitivity of the three propellants to impact, friction, ESD, and low level shock after repeated cycling to -109°F and -320°F.
- Determine the extent of electrical properties changes for all three propellants at -150°F.
- Determine the extent (if any) of nitroglycerin crystallization or migration and/or stabilizer depletion that might occur during planned Task 2 testing with the XLDB and CMDB propellants.

B. TASK 2: BENCH SCALE TESTS

Test were performed with two cryogenic media - LN_2 and CO_2 pellets.

1. LN_2 Washout

Task 2 propellant washout tests using an LN_2 jet were planned to be performed on both inert and live propellant samples. Propellant types were the same as for Task 1. Requirements for this testing were:

- Develop a high-pressure LN_2 system to achieve a high quality LN_2 jet.
- Verify that no initiations or reactions occur over the range of LN_2 test pressures for any of the three test propellants.

- Determine effective process parameters such as LN_2 pressure, LN_2 flow rate, and propellant surface speed to maximize propellant removal effectiveness for each propellant type.

2. CO_2 Pellet Blasting

CO_2 pellet blasting is a relatively new method for removal of paint and surface contaminants and was considered as a possible alternative method for cryogenic washout of solid propellant. Test requirements for the CO_2 pellet blasting were:

- Verify that propellant initiation or reactions do not occur during CO_2 pellet blasting for all three propellant types.
- Determine the propellant removal effectiveness of CO_2 pellet blasting for a range of delivery pressures.

C. TASK 3: PROTOTYPE TESTS

Task 3 was planned to demonstrate cryogenic washout of two reduced scale rocket motors containing propellant types tested in Tasks 1 and 2 using process parameters (i.e., LN_2 nozzle design, LN_2 pressure, LN_2 flowrate, GN_2 propellant heater design, surface traverse speed, and nozzle standoff distance) developed during the Task 2 bench scale tests. The primary requirements of the Task 3 were:

- Demonstrate that the process parameters established during Task 2 could be applied to remove propellant from reduced scale rocket motors safely and efficiently.
- Verify that the test rig design features are adequate for the safe handling of propellant particles during cryogenic washout operations.
- Demonstrate that propellant particles generated during the cryogenic washout can be safely removed from the gas stream and collected for further processing.

SECTION III
METHODOLOGY

A. TASK 1: PROPELLANT SENSITIVITY TESTING

A variety of sensitivity and electrical properties characterization tests were performed for Task 1 on HTPB, CMDB, and XLDB propellants at ambient temperature, cryogenic temperatures, and at ambient temperature following cyclic exposure to cryogenic temperatures. Table 1 shows the test matrix for Task 1. Four different sensitivity test series were performed to measure: (1) impact sensitivity, (2) friction sensitivity, (3) electrostatic discharge (ESD) sensitivity, and (4) low-level shock sensitivity. Additionally, electrical properties tests were performed to determine the effects of cryogenic temperatures on volume resistivity, dielectric constant and dielectric breakdown. Tests were initially performed at ambient temperature to establish baseline data. Data at cryogenic temperatures and for temperature cycled propellant were then compared to the baseline data to determine the relative change in propellant sensitivity or electrical properties. Temperature cycling tests were planned to determine if sensitivities increased because of nitroglycerin (NG) migration. Since HTPB propellant contains no NG, temperature cycling tests were not performed on this propellant.

Probit analyses were used for all but low-level shock sensitivity tests to determine by statistical methods the probability of initiation at a given energy level. For probit analyses, a sample is initially tested at a selected energy level. If no reaction is observed, the test is repeated at a higher energy level. If a positive reaction is detected, the input energy is decreased incrementally until no reaction is observed in 20 consecutive trials. The highest energy level at which no initiations occur is called the threshold initiation level (TIL). Ten trials are then conducted at each of four energy levels above the TIL, and the number of initiations at each level is determined. This quantal (all or nothing) propellant sample initiation data is then analyzed using statistical methods. These methods assume that the percentage of samples that initiate will increase in a fixed ratio as the magnitude of the energy input is increased. A linear regression equation is then used to describe the probability of response to the given stimulus from the measured regime to an extrapolated regime. The extrapolated regime represents the probability of initiation at low energy inputs. Probit analysis is further described in Reference 5.

TABLE 1. TASK 1 TEST MATRIX

TEST	SLICED PROPELLANT			TEMP. CYCLED SLICED PROP.		HAND GROUND PROP.	HAND GROUND TEMP. CYCLED PROP.
SENSITIVITY TEST	CMDB	XLDB	HTPB	CMDB	XLDB	CMDB	CMDB
Impact (Ambient)	X	X	X	X	X	X	X
Friction (Ambient)	X	X	X	X	X	X	X
ESD (Ambient)	X	X	X	X	X	X	X
Low Level Shock (Ambient)	X	X	X				
Impact (-109°F)	X	X	X				
Impact (-320°F)	X	X	X				
Friction (-109°F)	X	X	X				
ESD (-109°F)	X	X	X				
ESD (-320°F)	X	X	X				
Low Level Shock (-320°F)	X	X	X				
ELECTRICAL PROPERTY MEASUREMENT							
Dielectric Breakdown (Ambient)	X	X	X	X	X		
Volume Resistivity (Ambient)	X	X	X	X	X		
Dielectric Constant (Ambient)	X	X	X	X	X		
Dielectric Breakdown (-150°F)	X	X	X				
Volume Resistivity (-150°F)	X	X	X				
Dielectric Constant (-150°F)	X	X	X				
Taliani Compatibility (Ambient)	X	X	X				
DSC Compatibility (Ambient)	X	X	X				

Impact sensitivity tests determined the likelihood of propellant initiation as a result of an impact by a moving mass. In this test (conducted on a modified Bureau of Mines Tester), a 0.033 inch thick by 0.5 inch diameter propellant sample is compressed between a fixed anvil and a movable hammer, as shown in Figure 1. Impact energy (measured in energy per unit area) is supplied to the hammer by a 2-kilogram variable drop-height weight. The hammer (which has a known contact area) was positioned above the sample, and the weight was dropped from a predetermined height. Sample initiation was detected by sound and/or sight. Sample cooling was performed using LN_2 just prior to each trial. Propellant sample temperature was measured using thermocouples.

Friction sensitivity tests determined the probability that a sample will initiate when subjected to a sliding friction force at a given velocity. In this test, the propellant sample was placed on an anvil and a known force was applied hydraulically as shown in Figure 2. A pendulum then slid the sample under the force at constant velocity, resulting in a friction energy input to the sample. Sample initiation was again detected by audible and/or visual means.

ESD sensitivity tests determined the probability of propellant initiation in response to a spark discharge at a prescribed energy level. Electrostatic energy stored in a charged capacitor at 5,000 volts was discharged from a needle lowered towards the sample. Different capacitors were used to vary the energy delivered to a sample. Initiation was detected by infrared measurement of propellant decomposition products.

Low level shock sensitivity tests measured the sensitivity of propellants to explosive shock. For these tests, a 2 inch long by 3 inch diameter propellant sample was placed in a 1.25-quart stainless steel cylindrical pot. A circular piece of Detasheet® explosive was used as an explosive donor, and shock attenuation was provided by various thicknesses of stainless steel sheets. The shock impacted the sample through the bottom of the pot. Samples were cooled with LN_2 as required.

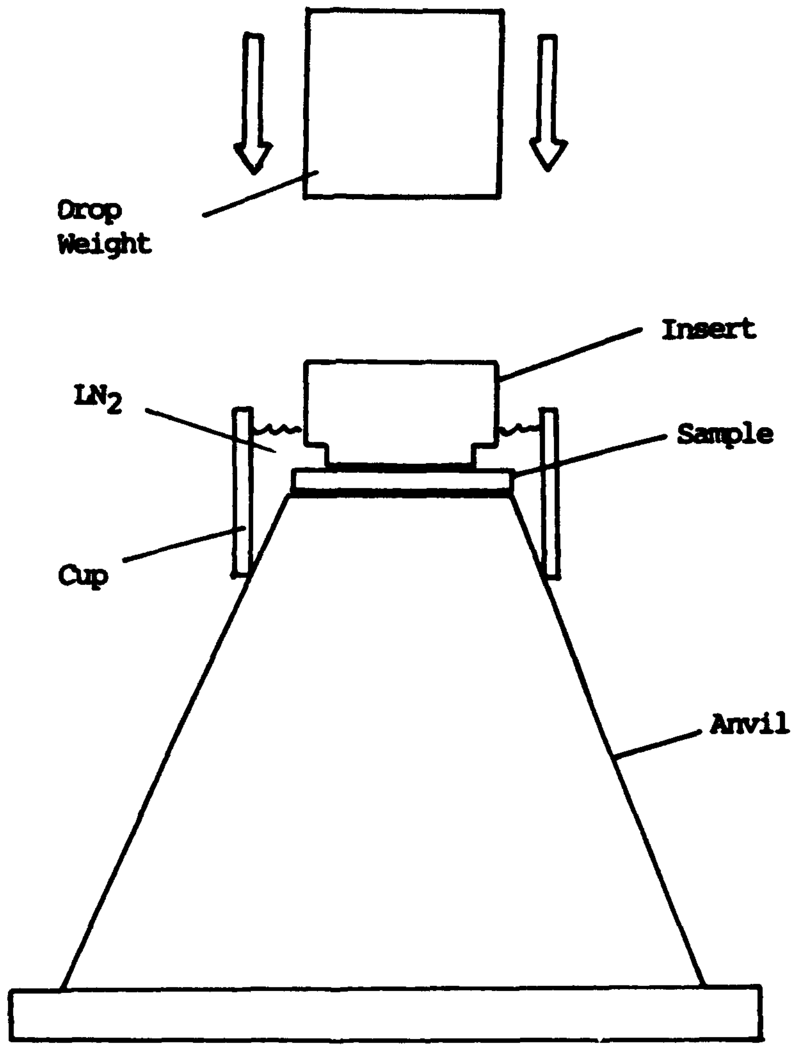

Figure 1. Task 1 Low-Temperature Impact Sensitivity Test Configuration

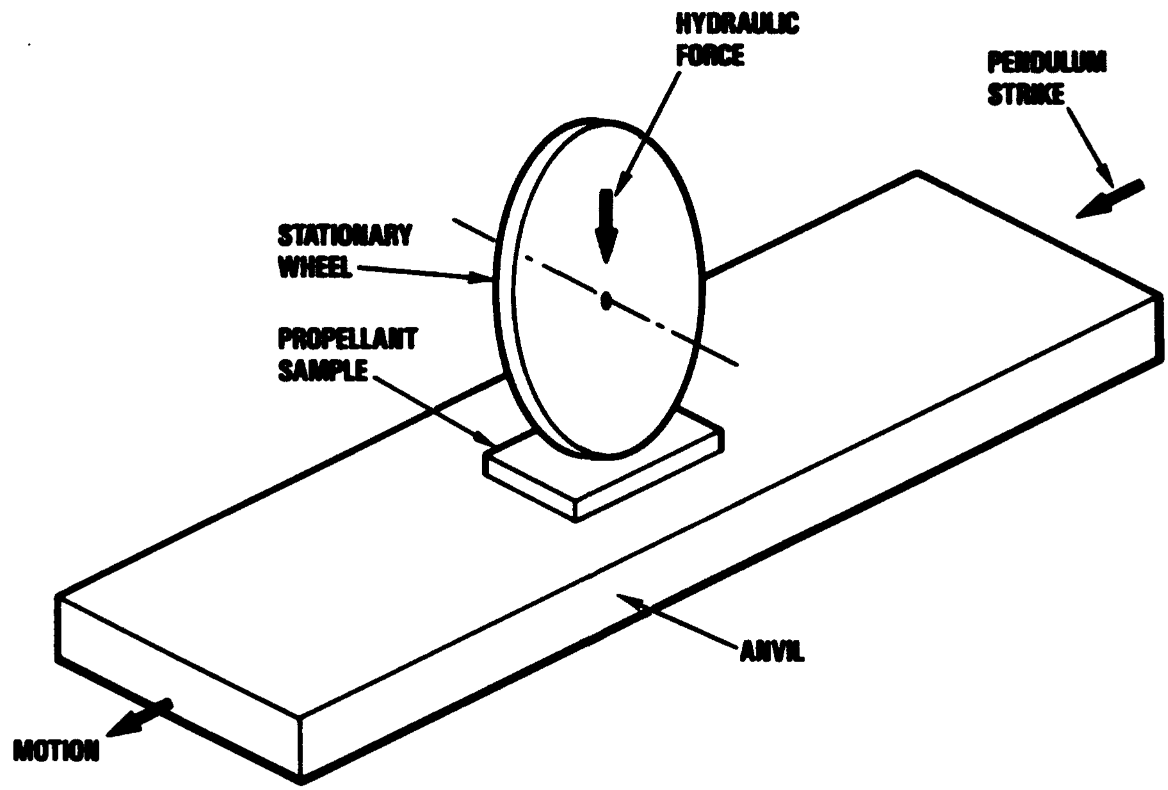

Figure 2. Task 1 Friction Sensitivity Test Configuration

B. TASKS 2 AND 3 TEST FACILITY

Tasks 2 and 3 were conducted using a common test rig that was adaptable to both LN_2 washout and CO_2 pellet blasting of propellant samples as well as LN_2 washout of a 40-pound charge motor (FPC) and lightweight analog motor (LAM). Initial assembly and debugging of the test rig was done at GA facilities in San Diego, CA as was early LN_2 system development and initial LN_2 washout testing (performed on inert propellant). Bench-scale (Task 2) and Prototype (Task 3) testing were conducted at the Pit 38, Site 2 explosive test facility at Hercules Inc. in Magna, Utah. The test equipment was shipped to the test facility and assembled as shown in Figure 3. This facility included an area to locate the test rig surrounded by a 20-foot high horseshoe-shaped dirt berm and covered by a heavy wooden blast mat. These were designed to contain both overpressure and debris in the event of an explosion. Propellant sample preparation was done in a dedicated building in another adjacent bermed area. Next to the bermed areas was a control bunker from which all testing was conducted remotely. Hazards analysis of the Task 2 and Task 3 testing showed that proper protection would be provided for personnel in the control bunker in the event of an explosion.

The cryogenic size reduction test equipment consists of a washout test rig, high pressure LN_2 supply system or CO_2 pellet supply system, warm gaseous nitrogen (GN_2) supply equipment, and a gas cleanup system which ensures proper containment of washed out propellant. Figure 4 shows a process schematic for the LN_2 washout system.

The washout test rig (Figure 5) consists of the washout enclosure and knockout pot (both mounted on a remotely operated computer controlled X-Y table), rotary drive equipment, an LN_2 lance/nozzle assembly, and a 15 degree inclined support stand on which the test rig is mounted. At both ends of the washout enclosure are rotors, between which either bench-scale propellant samples or subscale rocket motors can be mounted for propellant washout. The rotor between the washout enclosure and knockout pot (named the drive rotor) is driven by an DC electric motor at speeds from 0-38 rpm. Pin connections between the article to be washed out and both rotors ensure that the drive rotor, idler rotor, and propellant sample rotate as an assembly. The LN_2 lance extends into the washout enclosure through the idler rotor and provides structural support for the LN_2 nozzle mounted at the end of the lance. The LN_2 jet is about 0.035 inch diameter, depending on the nozzle installed. The jet points out of the side of the lance and impinges onto the propellant at 15 degrees from perpendicular. The lance is not mounted on

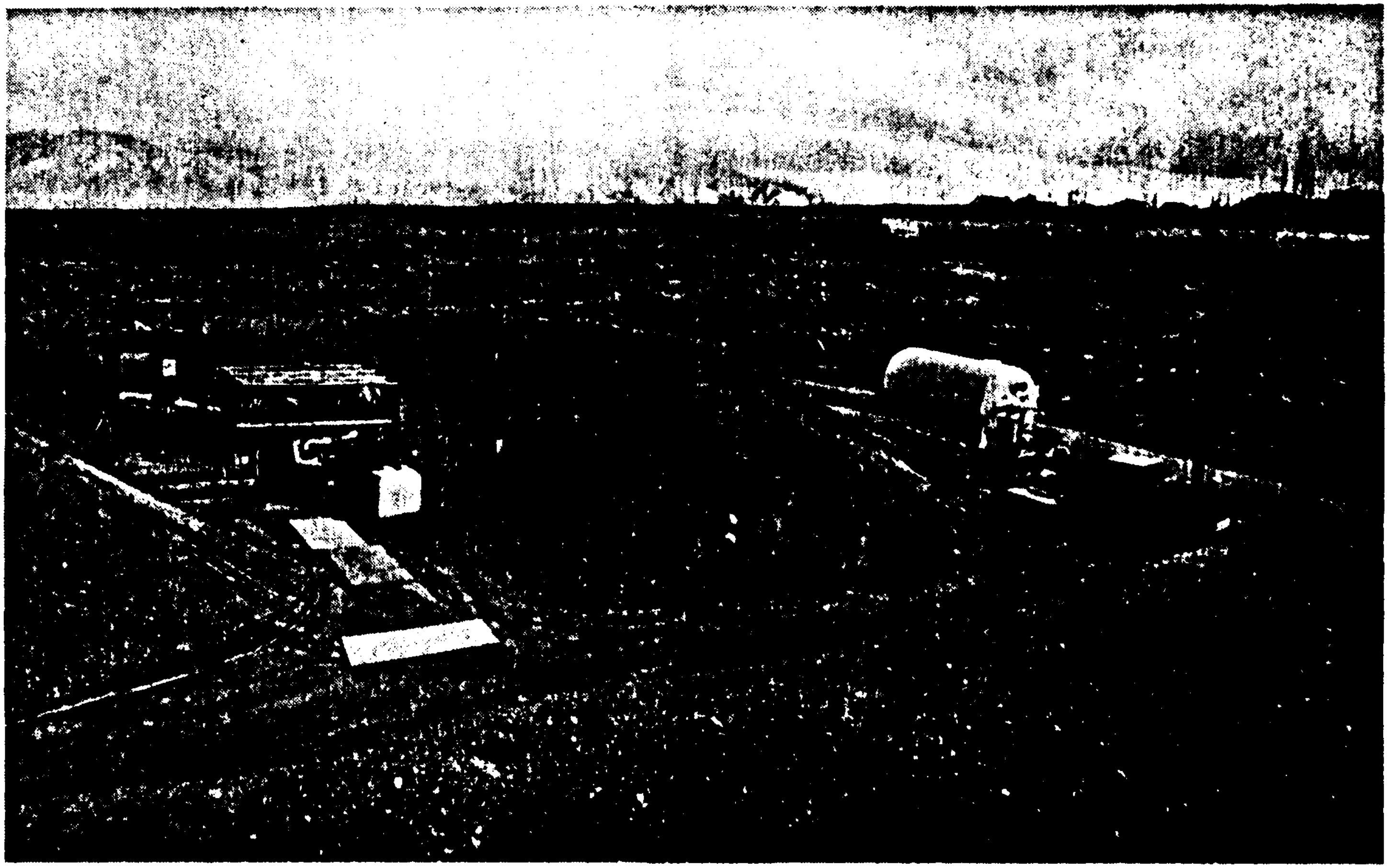

Figure 3. Task 2 and 3 Cryogenic size Reduction Test Equipment at Hercules, Inc.

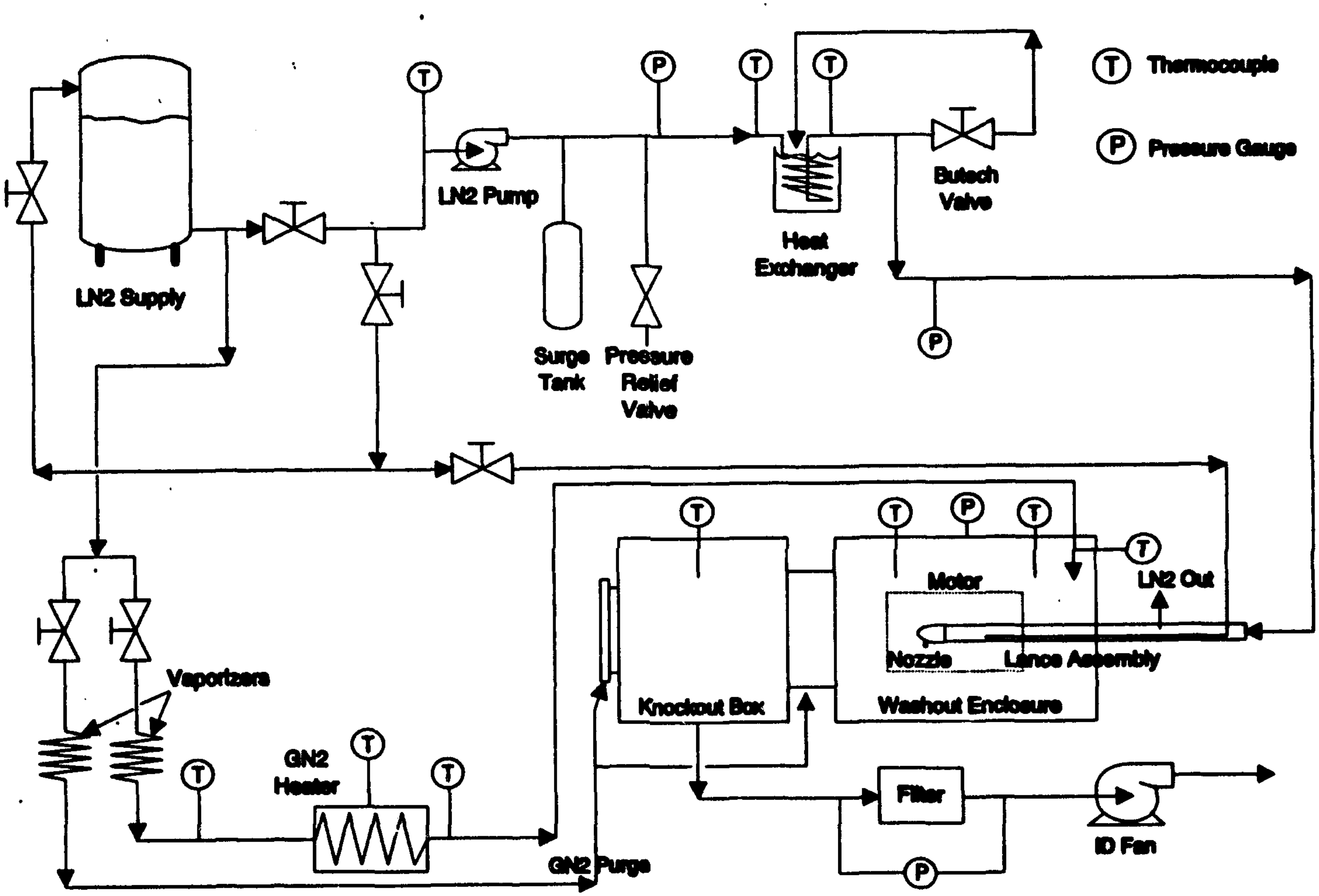

Figure 4. Tasks 2 and 3 LN_2 Washout System Process Schedule

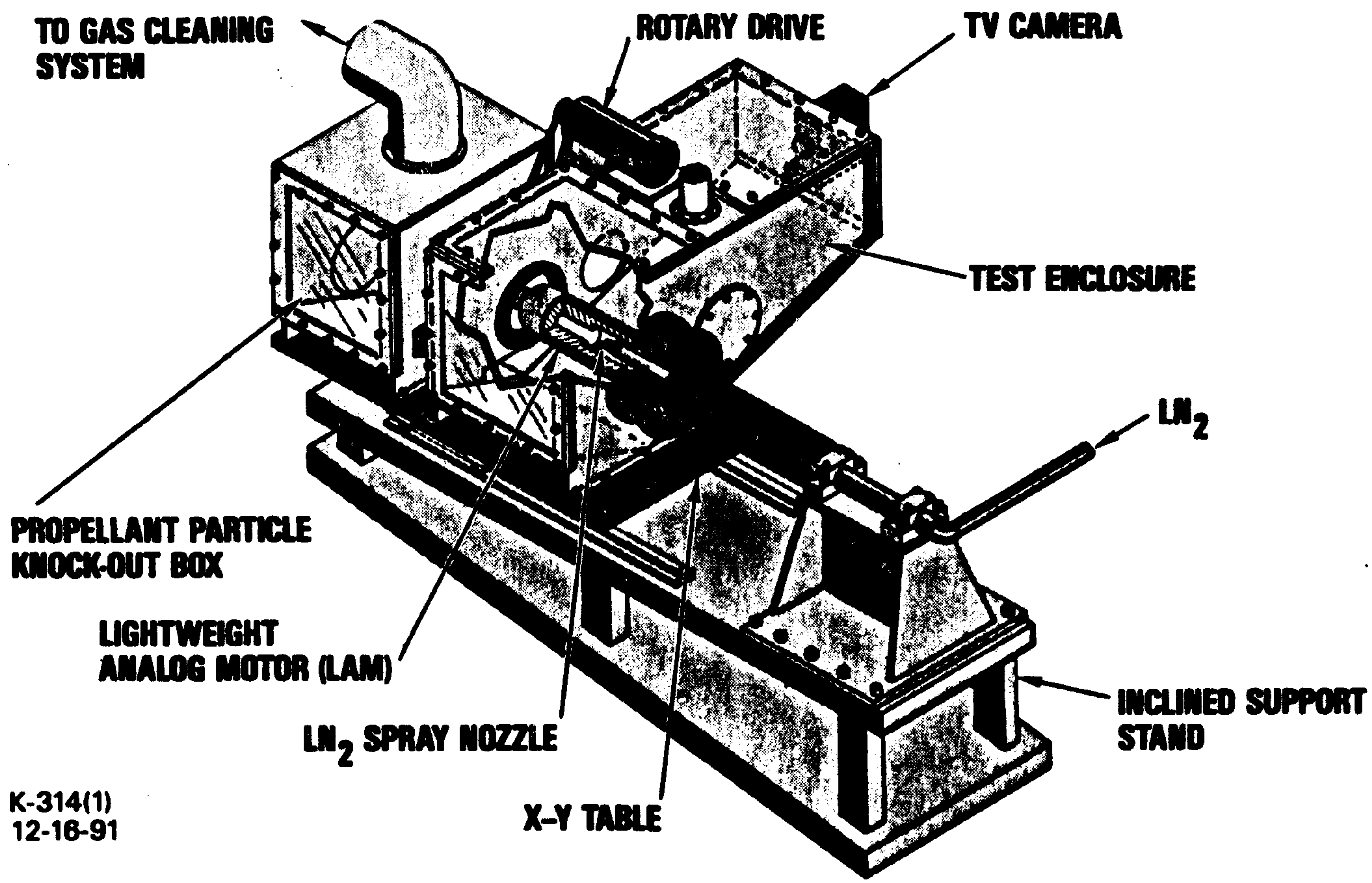

Figure 5. Task 2 and 3 Cryogenic Washout Test Rig

the X-Y table. The X-Y table therefore provides relative motion between a rotating propellant sample and the LN_2 nozzle. Cutting on the sample is done by rotating the sample in front of the LN_2 jet while the X-Y table slowly moves the jet across the sample.

The washout enclosure walls and roof are made primarily of transparent polycarbonate panels to allow external viewing of the rotating assembly and LN_2 lance. These walls are made strong and stiff enough so that the enclosure can be held at 2.0 inches of water vacuum. The floor of the washout enclosure and knockout pot was shaped so that propellant particles all tended to slide to a low spot at the knockout pot. This was facilitated by the inclination of the test rig. A port was installed at the low spot to allow faster cleanout of the enclosures. A closed-circuit television (CCTV) camera was mounted on an extension of the washout enclosure to allow remote monitoring of sample rotation and X-Y table function. Another CCTV camera was mounted on a pole adjacent to the site, and was used to monitor the entire facility.

Test rig components were designed for cryogenic service if required by their operating temperature. The test rig mechanical design was heavily driven by relative thermal contraction issues and cold bearing friction concerns. Materials selection was made to preclude component embrittlement. All cryogenic issues were resolved satisfactorily during the test rig design.

In addition, the test rig design was strongly influenced by the safety requirements for the design of machinery exposed to propellant. Key design issues were that threaded fasteners were highly undesirable. Grinding of all welds to a smooth finish was required, and sliding motion of metal components relative to one another was prohibited.

The high pressure LN_2 supply system consisted of a 3000-gallon LN_2 tank, a reciprocating LN_2 pump adjacent to the LN_2 tank, 125 feet of 20,000 psig rated cryogenic tubing, a coil of high pressure tubing immersed in an open bath of LN_2, and an air operated bypass valve. The LN_2 tank and pump were located to the south of the test rig, outside of the bermed area. 5/16-inch i.d. tubing that ran over the berm to the high pressure coil was wrapped with commercial foam piping insulation, as was the 2-inch diameter copper pipe between the tank and pump. The air operated bypass valve was located at the connection to the LN_2 lance. When open, this valve diverted flow from the nozzle to the open bath.

The bypass valve allowed the bath to be filled before starting washout operations, as well as cooling the pump discharge line.

Two pressure indicators were fitted to the LN_2 system: a gauge at the discharge of the pump, and a pressure transducer at the LN_2 lance. Both were rated to 20,000 psig service.

The cryogenic pump purchased for washout testing could be set to deliver either 1.83, 2.34, 3.40, or 3.92 gpm by changing the drive motor pulley. Therefore, the flow rate was constant for a given test. It was crucial to ensure that the feed to the pump was single-phase, i.e. liquid. If the liquid temperature was high enough, the suction side pressure drop could reduce the liquid pressure until a portion of the liquid within the pump boiled. This condition is called partial cavitation. The consequences of pump cavitation were potential pump damage, partial or total loss of system pressure, and significant fluctuations in pressure during operation. Therefore, steps were taken to ensure that pump cavitation was avoided to the greatest extent possible, the most significant step being LN_2 supply tank venting and repressurization. Early testing confirmed the need to routinely vent the LN_2 supply tank, and this procedure was followed prior to each day of testing.

By varying the pressure of the LN_2 supply tank prior to the start of a test, it was possible to take advantage of a high supply pressure while still delivering a low temperature liquid. The procedure involved took advantage of the fact that the liquid can be cooled relatively quickly but warmed relatively slowly. The supply tank was vented to atmospheric pressure and the contents boiled, eventually reaching a low equilibrium temperature associated with the lower pressure. Prior to a test, the tank was repressurized to the desired supply pressure (about 35 psig) using an external buildup coil. The repressurization took several hours. Warming of the LN_2 back to equilibrium temperature at the higher pressure, however, took several days because of the efficient tank insulation. If testing continued for successive days, blowdown of the supply tank required significantly less time, relative to blowdown with the tank initially at equilibrium, and the associated LN_2 usage was less.

If at equilibrium at 35 psig, approximately 13 percent of the tank volume would be lost while venting to atmospheric pressure. LN_2 use due to tank blowdown was not 13 percent for each test day, however, because the LN_2 storage temperature did not have time to rise to equilibrium between successive days of testing.

As delivered, the cryogenic pump was rated for a continuous working pressure of 10,000 psig. Soon after testing started, it became evident that significantly higher pressures would be required to achieve acceptable propellant removal rates. The pump manufacturer was contacted about the feasibility of operating the pump at 16,000 psig and responded with a cautious approval for short duration testing. The cold end (fluid contacting portion) of the pump was rated for 15,000 psig, but the warm end was rated for only 10,000 psig. However, the warm end could tolerate high pressures and accompanying high loads for an unspecified period of time. Pressures up to about 14,000 psig were used at GA and up to 16,500 psig at Hercules.

During CO_2 pellet blasting operations the LN_2 equipment was not used. Instead, commercial CO_2 blasting equipment was installed on the test rig. Other equipment, such as the gas cleanup and data acquisition systems were unmodified. CO_2 pellet blasting equipment was originally developed in order to offer an environmentally acceptable and clean alternative to chemical or grit blasting removal of surface coatings or contamination. In principle, the system operates in a similar way to grit blasting equipment: A 250-600 psig GN_2 source is connected with flexible hoses to a blasting gun, from which the gas exits at high velocity. The GN_2 source for this testing was three tube trailers, each containing 96 compressed gas cylinders. These trailers were parked adjacent to the LN_2 tank, outside of the bermed area. Inside the blasting gun, the high velocity gas stream passed through a venturi which was used to pull a low-velocity gas stream along a second flexible hose. The low-velocity gas stream contained the CO_2 pellets which were accelerated by the high-velocity gas stream before they impacted the surface to be cleaned. The pellets were metered into the low-velocity stream from a hopper. The metering equipment and hopper were mounted on a skid, installed adjacent to the test rig, within the bermed area.

The warm GN_2 supply equipment used during LN_2 washout testing consisted of two ambient LN_2 vaporizers connected in parallel to the LN_2 tank and installed just east of the tank, 2-inch PVC tubing running over the berm to a temperature controllable electric heater located adjacent to the test rig, and a 2-inch copper pipe at the discharge of the electric heater. This pipe was connected with a flexible hose to the Task 2 and Task 3 propellant heater systems installed on the test rig. The discharge of the warm GN_2 system was 200 scfm at approximately 200°F. To ensure that the discharge temperature remained within limits, a redundant control system was installed that shut off power to the electric heater if the gas temperature at the entrance to the test rig rose over 220°F.

The gas cleanup system incorporated a Torit 2DF4 dust collector unit with four cartridge filters totaling 904 square feet area, and an exhaust fan driven by a 7.5 hp electric motor. Installed between the dust collector filters and the exhaust fan was an Autolok® high efficiency (95 percent) filter designed to preclude propellant particles from impacting the fan if the dust collector filters ruptured. Maximum gas flow for this unit was 2000 scfm. The dust collector unit was installed on a platform built up from railroad ties and installed to the north of the test rig, within the bermed area. The connection between the test rig and the dust collector was made by a inexpensive 10 inch diameter flexible aluminum duct purchased at a building supply center. This allowed for motion of the test rig on the X-Y table. At the connection of the flexible duct to the dust collector a dampered inlet allowed ambient air into the gas stream to raise the temperature of the cold gas coming from the test rig. The exhaust of the dust collector was also dampered. The dampers were adjusted to maintain washout enclosure pressure below -1.0 inch wc for all LN_2 flows, while maintaining dust collector inlet temperature above -20°F.

The Torit dust collector unit was modified extensively to be suitable for use with propellant dust. Modifications included eliminating crevices and cracks that could collect dust, and eliminating all threaded fasteners from inside the contaminated area. Beneath the unit a "slum pot" was installed that collected dust. This dust was knocked off the cartridge filters by a blowback system that pulsed the filters with compressed air every 30 seconds. This precluded plugging of the filters. Photohelic gauges were installed at the test rig to monitor washout enclosure pressure and cartridge filter pressure drop. If these parameters moved out of limits an alarm signal was activated on the data acquisition computer (DAS).

Transient data from thermocouple, and pressure inputs were collected on the computer-based DAS. The Cryogenic Size Reduction DAS consisted of: (1) three Metrabyte EXP-16 signal conditioning boards (48 possible channels), (2) a DAS-8 controller, and (3) a Datel 386SX personal computer and monitor. All DAS equipment was located in the control bunker. Data were continuously displayed on the color monitors and updated every 5 seconds. Data were stored on hard disk every 5 seconds.

C. TASK 2: BENCH-SCALE TESTS

1. LN_2 Washout

Task 2 was designed to confirm using small propellant samples that no initiations would occur during propellant removal, develop process parameters for efficient removal and size reduction, and verify the adequacy of safety measures. To perform these functions a Task 2 mandrel was designed to fit between drive and idler rotors in the washout test rig. Small samples of propellant could then be mounted on the mandrel, which would rotate to allow washout of the samples. The configuration is arranged such that the LN_2 jet is directed radially inward against a sample that is installed on the circumference of the Task 2 mandrel. The mandrel is effectively a rocket motor turned inside out; however, the radially inward jet direction requires a different idler rotor than that for rocket washout (Task 3). The mandrel design (shown in Figure 6) incorporates three wedge shaped slots at 120 degrees into which propellant samples (like those shown in Figure 7) slide and are held in position. Propellant samples were mounted into one of the three slots for each trial. Three slots were incorporated in case it was necessary to wash out three propellant samples simultaneously for good propellant removal data, but this did not prove necessary. The entire Task 2 mandrel was fabricated from aluminum.

Task 2 was divided into two subtasks: Tasks 2A and 2B. Task 2A was originally planned to be conducted with small cubes of propellant installed in a hole on the Task 2 mandrel circumference. This did not work because the cubes of propellant were popped out of the hole by the jet. The solution to this problem was to make 3/4-inch long trapezoid section wedges to fit into the Task 2 mandrel slots and be held in place by a 4-inch long inert sample as shown in Figure 6. Cutting was done on the center 1/2 inch of the 3/4-inch long sample. Task 2B samples fit into the same slots as the Task 2A samples but cut length was 3 inches on longer (4-inch) propellant samples. Both Tasks 2A and 2B were originally planned to be conducted with wooden mandrels that would be replaced after each trial. This was done in an effort to match the erosion of the mandrel with the erosion of the propellant sample, and thereby limit the influence of edge effects on propellant washout data. However, it was determined that the wooden mandrels were heavily damaged by the LN_2 jet, and an aluminum mandrel was substituted. The aluminum mandrel was not damaged by the jet and was used for all Task 2 trials.

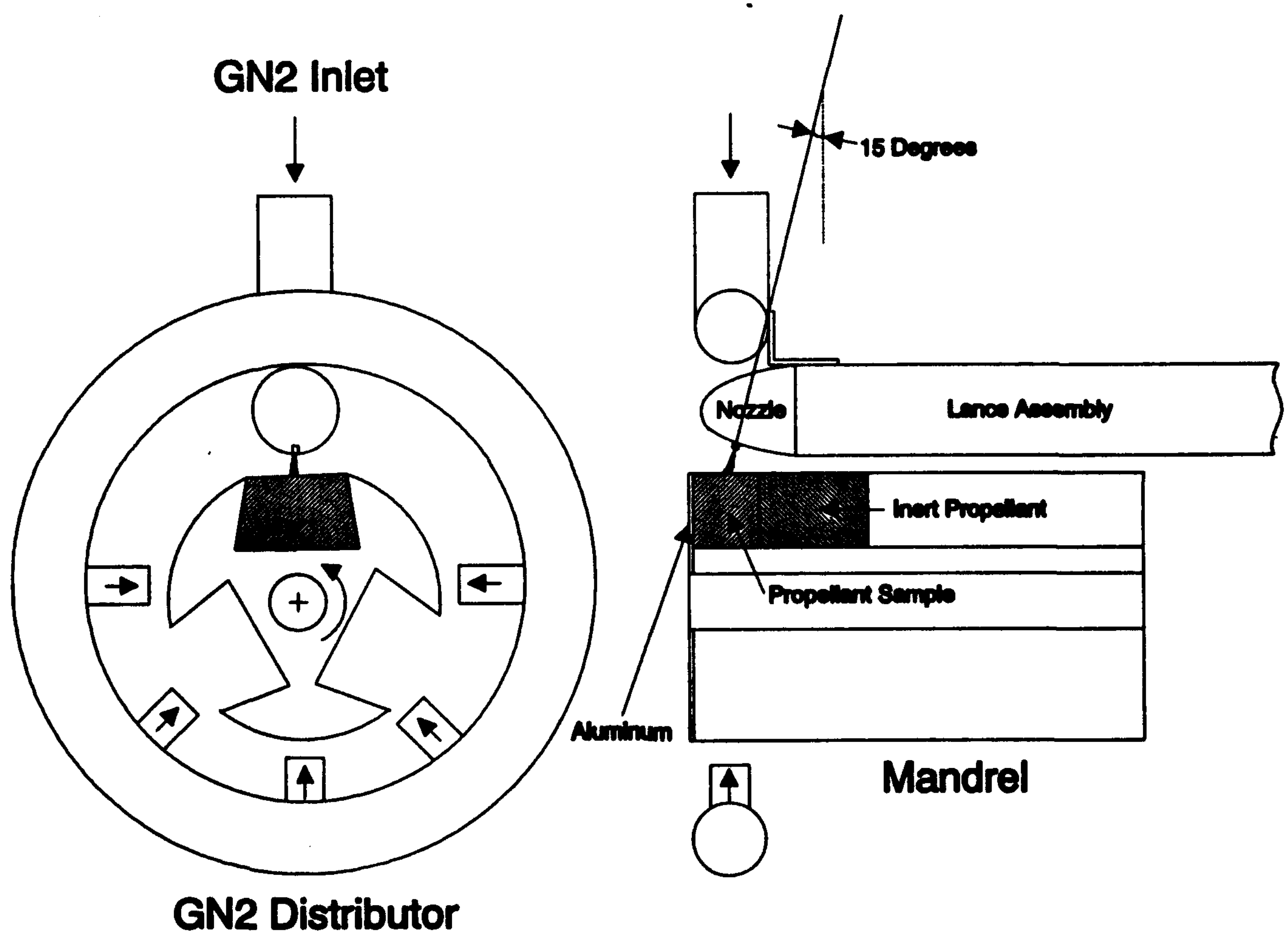

Figure 6. Task 2 LN_2 Washout Configuration

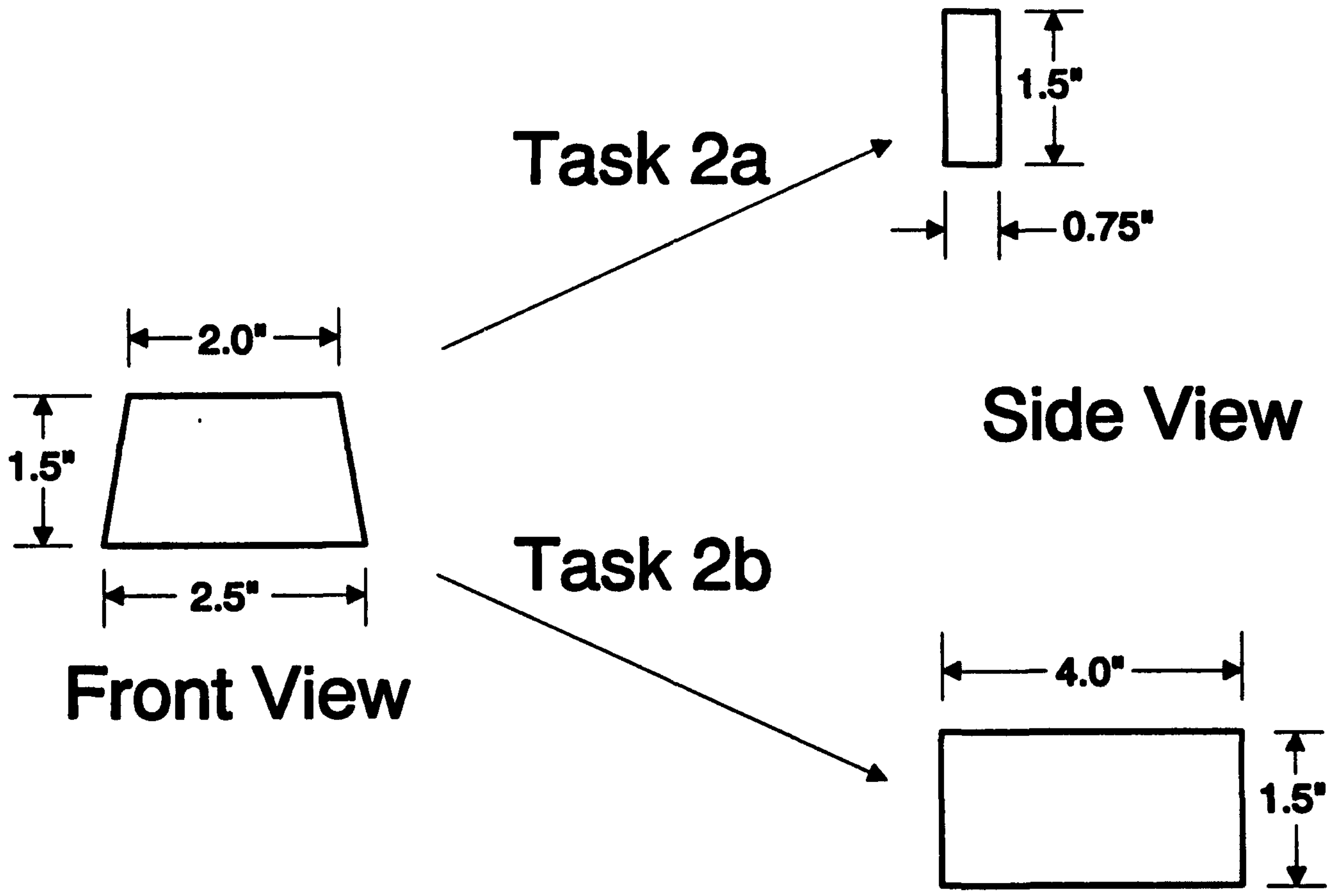

Figure 7. Task 2 Propellant Sample Configuration

The GN_2 heater design developed for Task 2 is also shown in Figure 6. This design incorporated a round aluminum manifold surrounding the Task 2 mandrel and bolted to the LN_2 lance. Pointing radially inward towards the Task 2 mandrel were five warm GN_2 nozzles. These nozzles covered 180° of the circumference of the mandrel and were aligned axially with the LN_2 nozzle so that the region of the propellant sample being cut was heated by the warm GN_2 gas stream as the mandrel turned. The GN_2 heater did not move with respect to the LN_2 lance, ensuring that the propellant sample was always heated in the correct location. The GN_2 nozzles were short stubs of 1/2-inch aluminum tubing positioned at 1/2-inch standoff with respect to the propellant sample. The measured gas pressure within the Task 2 GN_2 manifold was 8 psig.

The GN_2 manifold was connected to the warm GN_2 supply equipment with a 2-inch o.d. flexible hose routed through a fitting in the washout enclosure roof. This hose was band-clamped to a 3.5-inch long aluminum tube welded into the manifold.

The samples for Task 2 were cut from both inert and live propellant blocks. Inert propellant was developed by propellant manufacturers to simulate the physical properties of propellant while avoiding the explosion hazard. Inert samples were used to develop the LN_2 system for good jet cutting performance, develop the Task 2 configuration as described above, and create X-Y table programs for sample washout. The inert propellant composition is given in Table 2.

TABLE 2. INERT PROPELLANT COMPOSITION

DESIGNATION	WEIGHT PERCENT
R45M	6.33
DOS	3.565
POLUGARD	0.12
CYANOX	0.2333
HX-752	0.3
MA	0.03
DDI	1.39
AL(X-71)	37.2
NH_4SO_4	50.8

Three live solid propellants were tested in Task 2. These propellants were of composite modified double base (CMDB), cross-linked double base (XLDB), and hydroxyl-terminated polybutadiene (HTPB) compositions.

Solid propellants are categorized as Hazard Class 1.1 (mass detonating) or Hazard Class 1.3 (mass fire). Double base propellants like CMDB and XLDB are Hazard Class 1.1 and contain large amounts of nitroglycerin (NG), nitrocellulose (NC), and lesser quantities of other energetic materials. Composite propellants, such as HTPB, are Hazard Class 1.3. These propellants contain ammonium perchlorate (AP) and aluminum powder in a rubber-based binder. Class 1.1 propellants are more dangerous than Class 1.3 propellants because of the possibility of detonation following initiation. Table 3 provides compositions for the propellant types used during dry washout testing.

TABLE 3. LIVE PROPELLANT COMPOSITIONS

PROPELLANT TYPE	PROPELLANT DESIGNATION	STRATEGIC PROGRAM	PROPELLANT TYPE COMPOSITION RANGES
CMDB	CYH	Minuteman (Stage III)	Binder (50-60 Percent): Nitrocellulose, nitroglycerin, and inert triacetin plasticizer. Stabilizers are 2-NDPA Solids (40-50 Percent): Ammonium perchlorate, aluminum, and HMX.
XLDB	WAY	Peacekeeper	Binder (25-30 Percent): PEG polymer with nitroglycerin and nitrocellulose. Stabilizers are 2-NDPA and MNA (N-methylnitroaniline). Solids (70-75 Percent): Ammonium perchlorate, aluminum, and HMX.
HTPB	QDT	Titan IV	Binder (12 Percent): Polybutadiene with antioxidants. Solids (88 Percent): Ammonium perchlorate and aluminum.

A detailed procedure (Reference 2) was developed for this work that covered propellant sample preparation for Tasks 2 and 3, equipment preparation for testing, procedure for running washout trials, equipment lockout procedure, washout enclosure and dust collection system inspection and cleanup, and personnel requirements for each operation. This procedure, combined with the equipment installation and design, was subjected to Hercules Plant Process Control Board (PPCB) review and approval. This approval is required for all explosive operations at the test facility.

Preparation for daily washout testing during Task 2 consisted of equipment preparation and sample preparation. Equipment preparation included LN_2 tank preparation and pump cooldown, DAS system setup, air compressor startup, 480 V diesel generator startup, and exhaust fan startup. After the LN_2 system was ready for operation the LN_2 pump was started and the LN_2 bath filled. After fillup in the morning the bath was topped off two or three times during the day.

Samples for Task 2 were prepared before each day of testing, during equipment setup. This work was done in the sample preparation building. Samples were cut using a small hand operated shear. Knife trimming was then done as required to fit each sample into the Task 2 mandrel. After trimming was completed the samples were weighed. The sample number and weight (in grams) were then written on each sample.

Many inert Task 2 washout trials were conducted prior to live propellant trials. During inert trials development of the test rig and written procedure was carried out. Specific test rig development items were the LN_2 system, GN_2 heater system, Task 2 mandrel, and X-Y table programming. After enough inert testing had been performed to develop both the procedure and the hardware they were "frozen," (not changed) during the remainder of testing.

An important aspect of LN_2 system development was nozzle sizing. This determined the LN_2 pressure and velocity for a given LN_2 pump flow rate. For a given flow rate, the upstream pressure for an orifice is a very strong function of the orifice diameter. The governing equation for unchoked flow was used to generate the following relationship:

$$\Delta P = KW^2/D^4,$$

where ΔP = pressure drop across orifice in psi,

K = proportionality constant, 1.334 by 10^{-3},

W = LN_2 flow rate in gpm,

D = orifice diameter in inches.

Using the above equation the orifice diameters necessary to achieve the target operating pressures for a given series of tests were identified. Nozzles containing these orifices were then fabricated from 316 SS and used for testing. The pressures observed during cryogenic washout trials agreed very well with predicted values.

A Task 2 LN_2 washout trial was run as follows: the sample was loaded into the mandrel, and the LN_2 nozzle standoff was manually set using Y axis motion (Y motion) of the X-Y table. After standoff was set, the LN_2 nozzle was positioned (using X motion) almost completely outside from the washout enclosure, near the idler rotor. This position was called the pump-start position. The warm GN_2 system (if used) was then turned on and all personnel entered the control bunker. Mandrel rotation was then started and mandrel RPM set remotely from the control bunker. Mandrel RPM controlled cutting speed at the propellant surface. DAS system recording was then initiated, the LN_2 pump started and the bypass valve closed. This directed LN_2 flow through the nozzle allowing LN_2 pressure to build. After pressure stabilized the X-Y table program (named 2BMOVE) was run.

2BMOVE was written to control only X motion, the motion of the nozzle across the sample. Y position (the standoff of the LN_2 nozzle) was not varied during a trial. 2BMOVE initially moved the sample so that the LN_2 jet was positioned just inside the edge of the sample. The initial positioning was made at 1-inch/second. The program then slowed the table motion to about 0.020 inches per second, depending on the cutting pitch (distance between cuts) required. When cutting had progressed to the end of the sample, the table retracted at 1 inch per second. For Task 2A the cut width (slow X motion) was 1/2 inch on a 3/4-inch sample, for Task 2B the cut width was 3 inches on a 4-inch sample. Tasks 2A and 2B cutting durations were 25 seconds and 150 seconds, respectively. Due to Task 2 mandrel geometry the LN_2 jet was in contact with the propellant sample for 10.6 percent of the test trial time.

All significant events during a trial were recorded chronologically in the test logs (Reference 3). After each trial the sample was removed from the mandrel and weighed. The new weight was recorded, as were cutting depths at the start and finish of the cut. Data sheets (Reference 4) were prepared for each live propellant Task 2 washout trial. Cutting performance data, washout equipment data, and propellant sample/filter assembly inspection data were all recorded.

A total of 37 live Task 2 washout trials were completed on three types of propellant. These included 18 Task 2A trials and 19 Task 2B trials. Parameters varied were surface speed, cutting pitch, LN_2 nozzle standoff, LN_2 pressure at constant flowrate, LN_2 flowrate at constant pressure, GN_2 flow rate, and GN_2 temperature. The test matrix for Task 2 is presented in Table 4.

It was not possible, due to the huge number of combinations possible, to test every combination of each LN_2 washout parameter. During Task 2B the primary goal of testing was to maximize propellant mass removal rate. With this in mind, the most important parameters to investigate were LN_2 pressure and GN_2 supply system condition (warm, ambient, or off). Surface speed, LN_2 nozzle standoff, and cutting pitch were of somewhat lesser importance because although they effect the mass removal efficiency and provide data for design purposes they have a less dramatic effect on the ability of the LN_2 jet to cut propellant.

The testing completed reflects the priorities outline above. Task 2A was primarly intended to provide hazards data that would allow washout of larger propellant samples. Task 2B trials were designed to maximize cutting effectiveness and were run over a range of pressures from 10,000 psig to 16,500 psig. Most combinations of propellant type and pressure were tested. The effects of surface speed, LN_2 nozzle standoff, and cutting pitch were investigated at one combination of propellant type, LN_2 pressure, and GN_2 condition (XLDB propellant, 13,000 psi, GN_2 off). This gave a general understanding of the effects of these parameters. The choice of where to expand was made based on data requirements for Task 3, propellant sample availability, and possible future program requirements.

2. CO_2 Pellet Blasting

For CO_2 pellet blasting trials during Task 2 a bracket was constructed to attach two CO_2 guns to the LN_2 lance. The guns were not used simultaneously; one gun was used for trials with

TABLE 4. TASK 2 TEST MATRIX

		1/16 INCH PITCH 10000 PSI 3.4 GPM			1/16 INCH PITCH 13000 PSI 3.9 GPM			1/32 INCH PITCH 16000 PSI 2.34 GPM			1/16 INCH PITCH 16500 PSI 3.9 GPM		
TYPE OF PROPELLANT	CUT X-LENGTH, PROPELLANT NAME	WARM GN_2	AMB. GN_2	NO GN_2	WARM GN_2	AMB GN_2	NO GN_2	WARM GN_2	AMB GN_2	NO GN_2	WARM GN_2	AMB GN_2	NO GN_2
HTPB 1.3	1/2 inch, QDT	2A5B		2A6	2A11	2A14		2A17	2A20				
	3 inch, QDT	2B18		2B25	2B20		2B22			2B24	2B31		2B27
XLDB 1.1	1/2 inch, WAY	2A7		2A8	2A12	2A15		2A18	2A21				
	3 inch, WAY	2B19		2B36	2B21		2B23 2B34[(a)] 2B35[(b)] 2B32[(c)]				2B30		2B28
CMDB 1.1	1/2 inch, CYH	2A9	2A10		2A16	2A13		2A19	2A22				
	3 inch, CYH				2B33		2B26						2B29

[(a)]5/8 inch standoff; all other trials 3/8 inch standoff.
[(b)]3/32 inch pitch; all other trials 1/16 inch pitch.
[(c)]11 inch/second surface speed; all other trials 6 inches/second suface speed.

250 psig and 425 psi supply pressure and the other used for trials at 600 psig supply pressure. Pellet flow to the gun in use was controlled remotely from the control bunker. The CO_2 pellet gun mounting configuration is shown in Figure 8. The mandrel configuration for CO_2 pellet testing was identical to that for Task 2A LN_2 washout trials, as was the propellant sample geometry.

The CO_2 pellet nozzles were 0.5 inches in diameter. A standoff distance of 0.5 inches was used. Unlike for Task 2A LN_2 washout trials, translation of the sample past the nozzle was not required. Instead, the Task 2 mandrel was rotated in front of the CO_2 gun, making a 0.5 inch wide cut on the 0.75-inch wide sample. The X-Y table was not operated during CO_2 pellet blasting. No GN_2 heater was installed for Task 2 CO_2 pellet testing. In addition no components in the high pressure LN_2 system were operated during CO_2 pellet blasting.

A total of nine CO_2 pellet trials were conducted on all three types of propellant according to the test matrix shown in Table 5. Pellet mass flow was held constant at 150 pounds per hour.

TABLE 5. CO_2 BLASTING TEST MATRIX SHOWING TRIAL NUMBER DESIGNATION

PROPELLANT NAME	PROPELLANT TYPE	PRESSURE, PSIG 250[a]	425[a]	600[b]
QDT	HTPB	C3	C5A	C11A
WAY	XLDB	C6	C8	C10
CYH	CMDB	C7	C9	C12

[a]Pellet nozzle #1 used
[b]Pellet nozzle #2 used

The test procedure for CO_2 pellet blasting was similar to that for Task 2A. The propellant samples used for Task 2 CO_2 pellet blasting and Task 2A LN_2 washout were the same. Propellant preparation and weighing procedures were identical.

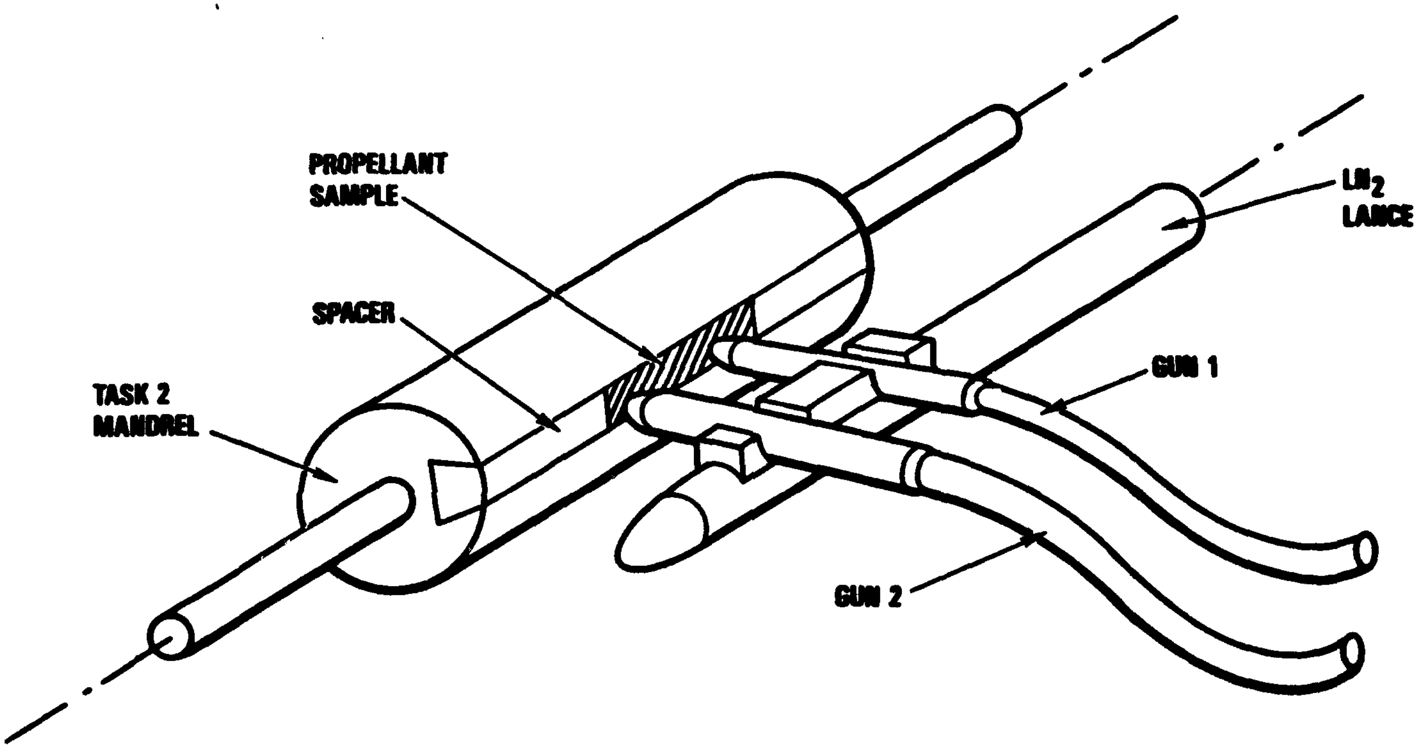

Figure 8. Task 2 CO_2 Blasting Configuration

Daily equipment preparation for CO_2 testing included DAS system setup, high-pressure GN_2 supply setup, and exhaust fan startup. High pressure GN_2 setup consisted of connecting the blasting equipment to a tube trailer having adequate pressure for the trial, or trials, to be run.

A Task 2 CO_2 pellet blasting trial was conducted as follows:

a. The high pressure GN_2 and pellet hoses were connected to the correct nozzle for the planned GN_2 operating pressure.
b. The X-Y table was moved manually to align the nozzle with the sample location.
c. The sample was loaded into the Task 2 mandrel.
d. The hopper was filled with adequate CO_2 pellets for the planned trial.
e. The high pressure GN_2 supply valve was opened.
f. GN_2 flow was started to the nozzle by opening the control valve located at the CO_2 pellet metering equipment skid.
g. The pressure regulator was set at the GN_2 supply to obtain the correct pressure at the CO_2 pellet metering skid.
h. All personnel moved into the control bunker.
i. Data acquisition system recording was started.
j. Sample rotation was started and timed.
k. Pellet flow was remotely started and maintained for six minutes.
l. Pellet flow and sample rotation were shut off. Personnel could leave the bunker.
m. High pressure GN_2 flow was shut off.
n. Sample was removed from mandrel and weighed. Manual data were recorded.

D. TASK 3: PROTOTYPE WASHOUT TESTS

Task 3 was designed to demonstrate cryogenic washout of two different design subscale rocket motors. Process parameters developed in Task 2 (LN_2 nozzle design, LN_2 pressure, LN_2 flow rate, GN_2 propellant heater parameters, surface traverse speed, and nozzle standoff) were applied. The two motors tested were a 40-pound charge (FPC) containing WAY (XLDB) Hazard Class 1.1 propellant, and a lightweight analog motor (LAM) containing QDT (HTPB) Hazard Class 1.3 propellant. The propellant types were the same as used for Task 2 testing, and described in Table 3. Prior to washout of the live motors, inert motors of both types were processed to insure correct operation of the test rig and X-Y table software. Both inert motors contained the same type of inert propellant as used for Task 2 (described in Table 2).

The live FPC Motor (shown in Figures 9 and 10) washed out during Task 3 was a cylindrical constant-section motor with an outside diameter of 8.8 inches, inside diameter of 4.8 inches, and a propellant web thickness of 1.8 inches. The outer casing or beaker was a 0.2-inch thick phenolic tube. The WAY (XLDB) propellant forming the propellant web was cast so as to be flush with one end of the phenolic beaker, and recessed 0.4 inches at the other end. The total weight of the FPC motor (including the beaker) was 40 pounds before washout.

The Titan LAM (Figure 11) is a larger, more sophisticated subscale motor than the FPC. The LAM outer case is 25.7 inches long, 10 inches in diameter and is constructed of filament-wound Kevlar®. The total weight of a Titan LAM is 84 pounds. The LAM does not have constant cross-section but rather has a rounded nose with a 2.75-inch diameter hole where an igniter can be flange-mounted. The aft skirt of the LAM is open, allowing access to the propellant, which is recessed 8 inches. The live LAM processed contained approximately 60 pounds of QDT (HTPB) propellant. The manufacturing drawings of the Titan LAM show the inside diameter as 3.4 inches, which was the i.d. of the inert motor tested. However, the live motor had 3.1 inches i.d.

The FPC motors were mounted in the washout enclosure with clamp-on aluminum adapters. These adapters allowed an FPC to be mounted between rotors inside the washout enclosure. The LAM was mounted in the test rig with aluminum pins that located the LAM between rotors at both nose and aft ends. At the aft end a ring was fabricated which was a slip fit on the i.d. of the aft skirt. Pins passed through this ring into holes that were hand-drilled into the aft skirt. The nose pins were screwed into the igniter flange.

Before washout of the FPC motors, washout trials were conducted on a bare phenolic beaker with no propellant. The trial on the bare beaker determined that the phenolic material was damaged by a 13,000 psig LN_2 jet. The mounting scheme for the FPC was originally designed so that the FPC would be self-supporting between the drive and idler rotors and therefore might fall from between the rotors if

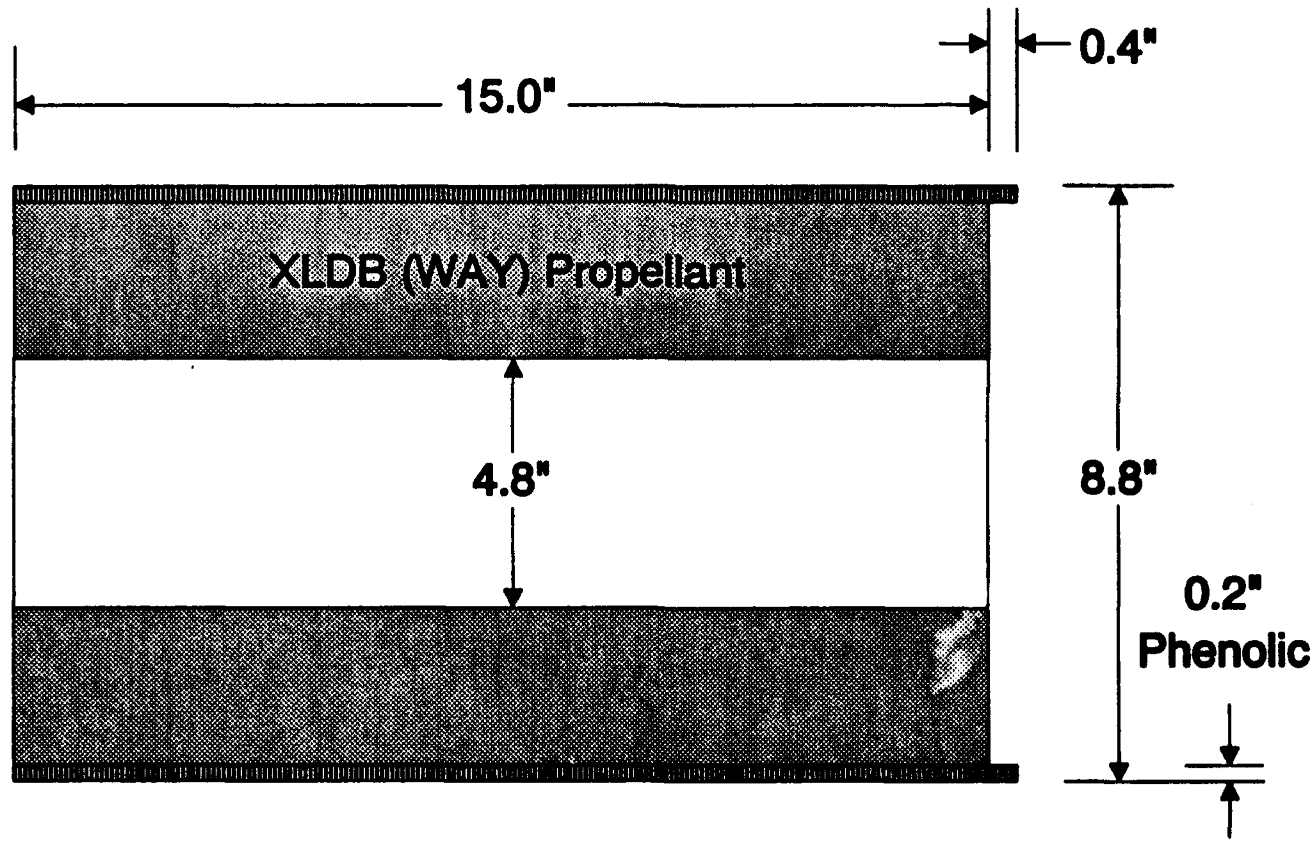

Figure 9. Forty Pound Charge (FPC) Rocket Motor Cross Section

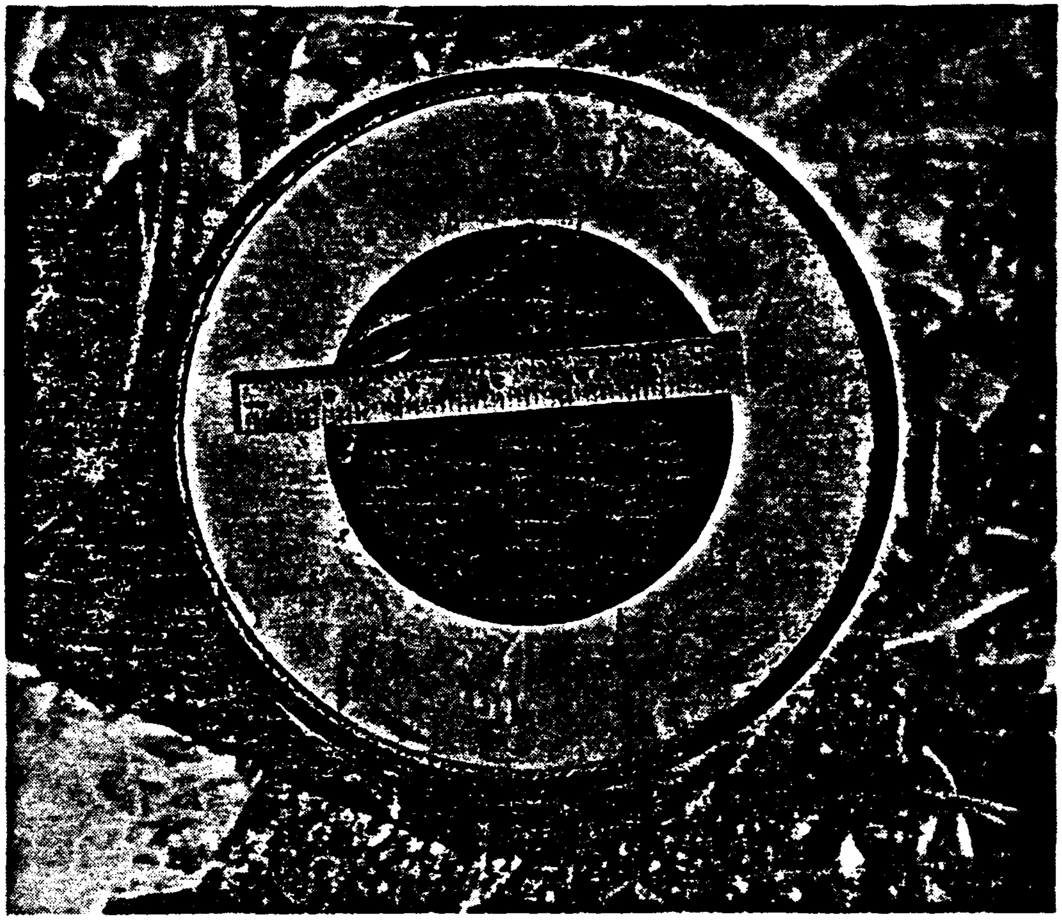

Figure 10. Live FPC End View prior to LN_2 Washout

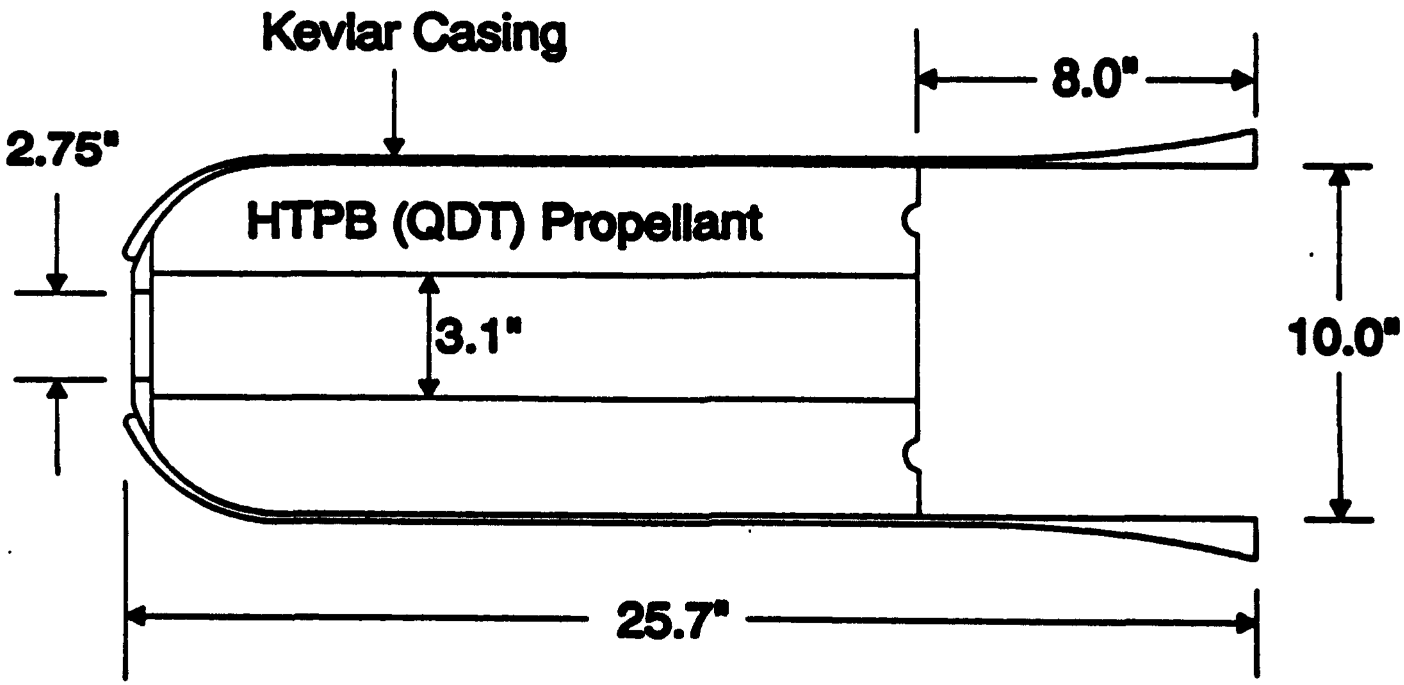

Figure 11. Live LAM Rocket Motor Cross Section

the phenolic beaker was heavily damaged. To solve this problem a 0.050-inch thick stainless steel sleeve was installed around the FPC.

During inert LAM testing it was determined that under some conditions the Kevlar® aft skirt (which is not coated with propellant) could be damaged by the LN_2 jet as the X-Y table advanced the jet from the pump start position to the propellant. To prevent this damage, a 0.1-inch-thick aluminum sleeve was fabricated which fitted inside the aft skirt.

For Task 3, the FPC and LAM rocket motors were washed out with a radially outward LN_2 jet direction impacting the propellant surface at a 15-degree angle. The LN_2 lance was positioned on the inside of the motor using the same nozzles as for Task 2. Nozzle standoff was adjusted with the X-Y table. For Task 3, a specific warm GN_2 nozzle arrangement (shown in Figure 12) was installed which attached to the LN_2 lance. This nozzle-directed gas flow radially outward through five holes positioned in the same plane as the LN_2 jet. The warm GN_2 nozzle was machined from a block of G10 fiberglass attached to the end of the LN_2 lance with a stainless steel bracket sandwiched between the LN_2 nozzle and lance. GN_2 was routed to the nozzle through two 3/4-inch PTFE insulated stainless steel tubes running parallel to the LN_2 lance. The assembly was designed to fit into a 3.4-inch diameter rocket motor bore. The standoff with this GN_2 heater nozzle arrangement varied as the rocket motor inside diameter increased during washout. Since the LN_2 nozzle standoff was held constant as the motor was washed out, the warm GN_2 nozzle standoff was increased after each pass. The increase in warm GN_2 nozzle standoff was twice the cutting depth during the previous pass. Increased GN_2 standoff affected the cutting performance during the washout of the LAM motor.

Prior to washout of each live motor, an inert motor was processed. This allowed development of the X-Y table software for each motor, verified that no problems would occur during the planned washout sequence, and provided experience required to gain PPCB approval for live motor operations. Both inert motors contained the same type of inert propellant as used for Task 2 (described in Table 2). Inert motors were about 50 percent washed out before live motor washout was initiated. Complete inert motor washout was not performed because efficient inert propellant removal required 16500 psig LN_2 pressure with 3.9 gpm flow. This combination (maximum possible pump flow with the highest pressure tested) caused intermittent pump cavitation. This phenomenon damaged the pump during inert FPC

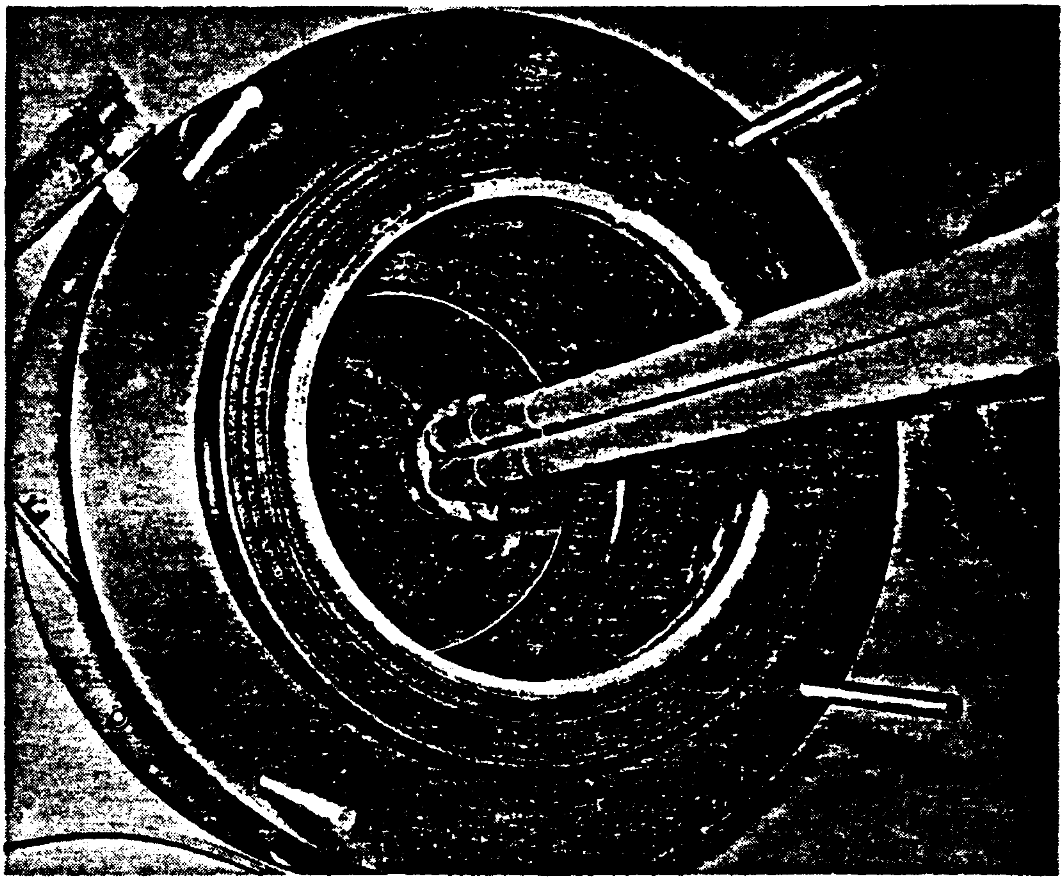

Figure 12. Task 3 Nozzle/GN_2 Heater Configuration

washout and subsequent operation under these conditions was as short in duration as possible. Partial washout was adequate for the purposes of inert rocket motor washout described above.

The procedure for washout operations during Task 3 was similar to that for Task 2 washout trials. Site setup, DAS setup, warm GN_2 system operation, and LN_2 system cooldown procedure and operation were the same. For the FPC motors the propellant was removed in a series of three LN_2 jet passes running lengthwise along the bore of the motor (X direction) while the motor rotated at 30 rpm. LN_2 pressure for live FPC washout was 13,000 psig. Each pass ran the length of the propellant grain starting form the idler end of the FPC and progressing towards the drive end. Prior to a pass the LN_2 system was pressurized with the nozzle positioned at the idler rotor end of the motor. This startup position allowed the LN_2 jet to be directed into the washout enclosure, through a slot in the idler rotor, prior to establishing proper LN_2 pressure. The live FPC bore was inspected after each pass to determine the cutting depth and manually adjust LN_2 nozzle standoff (Y direction motion). Y direction movements were not made during a pass. The X-Y table program was run without LN_2 flow, but with the warm GN_2 system operating. This warmed the FPC bore for inspection and may have helped cutting performance on the next pass.

The LAM was washed out with the same methodology as the FPC, except that each pass was a different X length because of the round nose shape of the LAM. Pass length was set so that the LN_2 lance extended as far as possible into the motor without hitting the inside of the rounded nose shape. The pass length changed as propellant was removed and the nozzle was moved in the Y direction to maintain 1/2-inch standoff. The pass length and standoff were set manually between passes.

The live HTPB filled LAM was completely washed out in a total of 21 passes. GN_2 flow was not used for the first five passes because the bore of the live LAM was 3.1 inches in diameter versus 3.4 inches on the manufacturing drawings. This meant that the Task 3 warm GN_2 nozzle did not fit. After the first five passes, the bore of the LAM was large enough so that the GN_2 nozzle could be installed and cutting rate was improved. Warm GN_2 only passes were made between each cutting pass after installation of the GN_2 heater nozzle.

The first six passes on the live LAM were made at 13,000 psig LN_2 pressure and 3.4 gpm flow rate. Due to the change in GN_2 nozzle configuration between Tasks 2 and 3 the cutting performance was less for the HTPB propellant in the LAM versus Task 2 HTPB samples. This is discussed in Section IV.C. To partially counteract this effect, a new nozzle was fabricated to increase LN_2 pressure to 15,000 psig at 3.4 gpm. This nozzle was installed after pass 6. This combination of pressure and flow was less prone to cause partial pump cavitation than the 16,500 psig/3.9 gpm combination used for inert propellant washout, primarily because the lower flow rate reduced pump inlet pressure drop.

SECTION IV
RESULTS

A. TASK 1: PROPELLANT SENSITIVITY TESTING

The results of Task 1 testing (Reference 5) show that propellant at cryogenic temperatures, whether CMDB, XLDB, or HTPB, was no more sensitive to initiation from impact, friction, low level shock, or ESD than ambient temperature propellant. In addition, propellant tested at ambient temperature after cycling to between ambient and cryogenic temperatures showed no increase in sensitivity to external stimuli.

Data for probit analyses, conducted as described in Section III, were generated for all sensitivity tests except low level shock sensitivity. The time and propellant samples required for each low-level shock-sensitivity trial precluded gathering enough data for complete probit analysis. Instead, enough low-level shock testing was done to establish the TIL for ambient, cryocooled, and temperature cycled propellant. Probit analyses generated plots of energy vs probability of initiation. Sensitivities for cooled or temperature cycled propellant samples were unchanged within the limits of the statistical analysis. The probit plots showing data for ambient, -109°F, and -320°F propellant samples, are presented in Figures A1 through A18 in Appendix A.

Electrical properties characterization tests determined that the hazard class 1.1 propellants (CMDB and XLDB), which are electrically conductive at room temperature, had high volume resistivity at -150°F. The hazard class 1.3 propellant (HTPB), which is normally nonconductive, showed a slight increase in volume resistivity at -150°F. The dielectric constants for CMDB and XLDB decreased significantly at -150°F, while the dielectric constant for HTPB was unchanged.

The data from electrical properties tests for 1.1 propellants show a tradeoff in the propensity for propellants to build static voltages high enough for electrostatic discharge. Propellants at -150°F require higher voltages relative to ambient propellant before they break down. This makes them less susceptible to ESD. However, their charge dissipation is much slower. This increases the possibility that charge will build up to the voltage required for breakdown. Table 6 contains the quantitative results for electrical properties testing.

TABLE 6. RESULTS OF TASK 1 ELECTRICAL PROPERTIES TESTING

PROPELLANT	TEST SERIES	VOLUME RESISTIVITY (ohm-cm)	DIELECTRIC CONSTANT (at 1 kHz)
	Baseline	17×10^2	51
CMDB	Cycled	7.5×10^2	70
	-150°F	2.2×10^{15}	3.6
	Baseline	6.2×10^6	1800
XLDB	Cycled	1.0×10^7	2200
	-150°F	1.4×10^{15}	4.3
HTPB	Baseline	1.1×10^{13}	9.1
	-150°F	1.3×10^{15}	6.4

Prior to testing there was concern that temperature cycling of Class 1.1 propellant during washout might lead to nitroglycerin (NG) migration out of its stable form in the propellant. Laboratory tests and a literature search were conducted that indicated that this phenomenon would be unlikely for the testing planned. After the completion of Task 3 (rocket motor washout testing) laboratory analyses were done on XLDB propellant washed out of the FPC motor. These analyses determined that no NG migration and no stabilizer depletion occurred as a result of LN_2 washout operations.

B. TASK 2: BENCH-SCALE TESTS

1. LN_2 Washout

a. Pretests at GA

During preliminary LN_2 washout system testing at GA, development work on the LN_2 system was completed. This development resulted in a good quality jet. In addition, simple cutting trials were performed using wood and inert propellant. Parallel cuts at 1/16 inch to 1/4 inch pitch were made. LN_2 pressure, LN_2 flow rate, and GN_2 heater configuration were varied to determine the approximate parameters that would be required for live testing using the Tasks 2 and 3 test rig.

The first tests of the LN_2 system resulted in a two-phase flow out of the nozzle that was ineffective at cutting soft wood. Thermocouple measurements showed that pumping to high pressure raised the temperature of the liquid between 30°F and 60°F, depending on pump discharge pressure. To counteract the pump heating a cooling coil was incorporated in the pump discharge line. This coil was immersed in LN_2 at ambient pressure and was effective at removing the heat added by the pump. Placement of the coil was as close to the nozzle as possible so that the liquid at the entrance the nozzle was at the minimum possible temperature.

Calculations indicated that the original nozzle design could be improved, resulting in less nozzle friction and attendant fluid heating. This improved nozzle design had a 40-degree included angle converging cone to gradually accelerate the fluid, followed by a short (0.080 inch) straight section. With these modifications the quality of the jet was markedly improved. Depending on pressure, cuts of up to 1 inch deep could be made through warm inert propellant. Surface speeds between 1 and 10 inches/second were tried with little difference in cutting depth. However, cryocooling the inert propellant by immersion in LN_2 resulted in very little erosion at 11,000 psig LN_2 pressure, due to the change in physical properties of the sample.

An increase in cutting depth on cryocooled inert samples was achieved by reheating the sample with warm air as it was cut by the LN_2 jet. Two configurations were tried, both utilizing approximately 200°F air. The first configuration utilized high supply pressure (100 psig), low flow rate (14.6 scfm) air directed through a 1/4 copper tube. This tube was pointed at the area cut by the LN_2 jet so that the sample was reheated after each cutting pass. Cutting depth for cryocooled inert samples was 3/8 inch with gas nozzle standoff of 3/8 inch. The second configuration utilized a room heater that blew a much higher volume of air across the sample at low velocity. The cutting efficiency was comparable to that achieved with the smaller flow, higher velocity air stream. Higher LN_2 pressures also increased cutting depth on cryocooled inert samples. Preliminary, short duration tests on inert propellant were performed at GA with LN_2 pressure as high as 14,000 psig. During these tests cutting depth as high as 1/2 inch was achieved with warm gas augmentation.

b. Task 2A and 2B Tests

After construction of the Tasks 2 and 3 test rig, all test equipment was shipped to the Hercules site installed and checked out. Task 2 testing then began. The GN_2 supply system and Task 2 GN_2 distributor described in Section III were designed using data from preliminary testing and installed. Dry GN_2 flow, instead of air, was used at the Hercules site to reduce condensation of water vapor inside the washout enclosure.

Inert Task 2A and 2B testing confirmed the need for high LN_2 pressures to effectively cut inert propellant. One-quarter inch cutting depth required 16,500 psig LN_2 pressure. Warm GN_2 was necessary for best mass removal. Cutting depth with the same LN_2 pressures was less than for preliminary testing at GA. This difference in performance may be due to the slight differences in test conditions such as atmospheric pressure between San Diego and Magna, Utah. Also, the testing at GA was conducted outdoors and the cooling effect of the LN_2 was less pronounced than inside the washout enclosure at the Hercules site.

During live Task 2 testing over 1000 impacts were made with high pressure LN_2 jets on samples of HTPB, XLDB, and CMDB propellant. No initiations or reactions occurred for the test pressure range of 10,000 to 16,500 psig. The best mass removal rates of 60 to 80 pounds per hour were achieved during Task 2B for the three propellants tested. LN_2 flow was less than 4 gallons per minute. All three live propellants required less LN_2 pressure for a given mass removal rate than inert propellant. The test parameters and mass removal for all Task 2 trials are given in Table 7.

Eighteen Task 2A propellant samples were tested; six HTPB samples, six XLDB samples, and six CMDB samples. The primary purpose of Task 2A was to demonstrate that no initiations would occur using small 75-gram samples (density for each of the propellants was the same). These samples would cause minimum equipment damage if they did initiate. Task 2A trials were run at 10,000, 13,000, and 16,000 psig LN_2 pressure. At each test pressure 16 or more total impacts were made. Each propellant type was impacted more than 50 times by the high-pressure jet. This resulted in a significant safety data base indicating that planned Task 2B and Task 3 LN_2 pressures were below the threshold initiation limit (TIL) for each propellant type.

TABLE 7. TEST PARAMETERS AND MASS REMOVAL FOR TASK 2 LN_2 WASHOUT TRIALS

Trial No.	Propellant Type	LN_2 Pressure (kpsi)	LN_2 Flowrate (gpm)	GN_2 Condition	Surface Speed (in./s)	LN_2 Nozzle Standoff (in.)	Pitch (in.)	Mass Removal (grams)
2A5B	HTPB	10	3.4	WARM	6	3/8	1/16	21
2A6	HTPB	10	3.4	OFF	6	3/8	1/16	9
2A11	HTPB	13	3.9	WARM	6	3/8	1/16	16
2A14	HTPB	13	3.9	AMBIENT	6	3/8	1/16	13
2A17	HTPB	16	2.34	WARM	6	3/8	1/16	10
2A20	HTPB	16	2.34	AMBIENT	6	3/8	1/16	9
2B18	HTPB	10	3.4	WARM	6	3/8	1/16	92
2B25	HTPB	10	3.4	OFF	6	3/8	1/16	28
2B20	HTPB	13	3.9	WARM	6	3/8	1/16	115
2B22	HTPB	13	3.9	OFF	6	3/8	1/16	48
2B24	HTPB	16	2.34	OFF	6	3/8	1/16	34
2B31	HTPB	16.5	3.9	WARM	6	3/8	1/16	162
2B27	HTPB	16.5	3.9	OFF	6	3/8	1/16	91
2A7	XLDB	10	3.4	WARM	6	3/8	1/16	21
2A7	XLDB	10	3.4	OFF	6	3/8	1/16	13
2A12	XLDB	13	3.9	WARM	6	3/8	1/16	12
2A15	XLDB	13	3.9	AMBIENT	6	3/8	1/16	17
2A18	XLDB	16	2.34	WARM	6	3/8	1/16	15
2A21	XLDB	16	2.34	AMBIENT	6	3/8	1/16	8
2B19	XLDB	10	3.4	WARM	6	3/8	1/16	8

TABLE 7. TEST PARAMETERS AND MASS REMOVAL FOR TASK 2 LN_2 WASHOUT TRIALS (CONTINUED)

Trial No.	Propellant Type	LN_2 Pressure (kpsi)	LN_2 Flowrate (gpm)	GN_2 Condition	Surface Speed (in./s)	LN_2 Nozzle Standoff (in.)	Pitch (in.)	Mass Removal (grams)
2B36	XLDB	10	3.4	OFF	6	3/8	1/16	74
2B21	XLDB	13	3.9	WARM	6	3/8	1/16	104
2B23	XLDB	13	3.9	OFF	6	3/8	1/16	116
2B34	XLDB	13	3.9	OFF	6	5/8	1/16	100
2B35	XLDB	13	3.9	OFF	6	3/8	3/32	85
2B32	XLDB	13	3.9	OFF	11	3/8	1/16	125
2B30	XLDB	16.5	3.9	WARM	6	3/8	1/16	138
2B28	XLDB	16.5	3.9	OFF	6	3/8	1/16	113
2A9	CMDB	10	3.4	WARM	6	3/8	1/16	8
2A10	CMDB	10	3.4	AMBIENT	6	3/8	1/16	15
2A16	CMDB	13	3.9	WARM	6	3/8	1/16	17
2A13	CMDB	13	3.9	AMBIENT	6	3/8	1/16	11
2A19	CMDB	16	2.34	WARM	6	3/8	1/16	8
2A22	CMDB	16	2.34	AMBIENT	6	3/8	1/16	3
2B33	CMDB	13	3.9	WARM	6	3/8	1/16	89
2B26	CMDB	13	3.9	OFF	6	3/8	1/16	105
2B29	CMDB	16.5	3.9	OFF	6	3/8	1/16	122

During Task 2A the LN_2 nozzle standoff was held at 3/8 inch. The Task 2A mandrel rotated at a surface speed of 6 inches per second while the mandrel translated 1/16 inch per revolution in the X (axial) direction. The LN_2 jet impinged on each Task 2A sample eight times. Trials were made with and without warm GN_2 flow. GN_2 temperature was varied from ambient to 200°F, and GN_2 flow was held constant at 200 scfm. Propellant erosion during Task 2A was very effective. Cutting depths as great as 0.9 inches were achieved. However, the short test duration caused a transient thermal effect that complicated interpretation of the mass removal data. This effect was caused by propellant cooling as each of the eight parallel cuts were made on the samples. The initial cut was the deepest, because the sample was at ambient temperature. Cutting depth then decreased for subsequent cuts. Equilibrium cutting depth was not reached during Task 2A testing because of the limited number of cuts on each sample. In addition, Task 2A samples occasionally displaced slightly along the mandrel slot due to the impact loading of the jet. This resulted in the sample moving too far under the jet, which invalidated the mass removal data.

A total of 19 Task 2B trials were performed. These trials were begun after the Task 2A trials for each propellant type were completed. LN_2 pressure, LN_2 flow rate, propellant surface speed, pitch (distance between cuts), LN_2 standoff, and GN_2 flow were varied to characterize propellant mass removal rate. Photographs of the Task 2B test configuration are presented in Figures 13 and 14.

The best mass removal rates during Task 2B for HTPB, XLDB, and CMDB propellants were 80.3, 68.4, and 60.0 pounds per hour, respectively. These rates were achieved during trials number 2B31 for HTPB, 2B30 for XLDB, and 2B29 for CMDB. Mass removal efficiencies (expressed in pounds of propellant removed per pound of LN_2) were 0.050, 0.042, and 0.038 pounds/pound for HTPB, XLDB, and CMDB. This performance is considered acceptable for scaleup to larger systems. Figure 15 is a photograph of representative Task 2B propellant samples following testing. A complete set of photographs of Task 2 propellant samples is presented in Figures B-1 through B-18 in Appendix B. Photographs of the eroded propellant particles are presented in Figures B-19 through B-21 in Appendix B. Figures 16-18 are plots of mass removal data versus LN_2 pressures, with and without warm GN_2 flow, for each of the propellant types.

Examination of the data in Table 7 shows that mass removal rates for the double base propellants (XLDB and CMDB) were less affected by the warm GN_2 flow than the HTPB

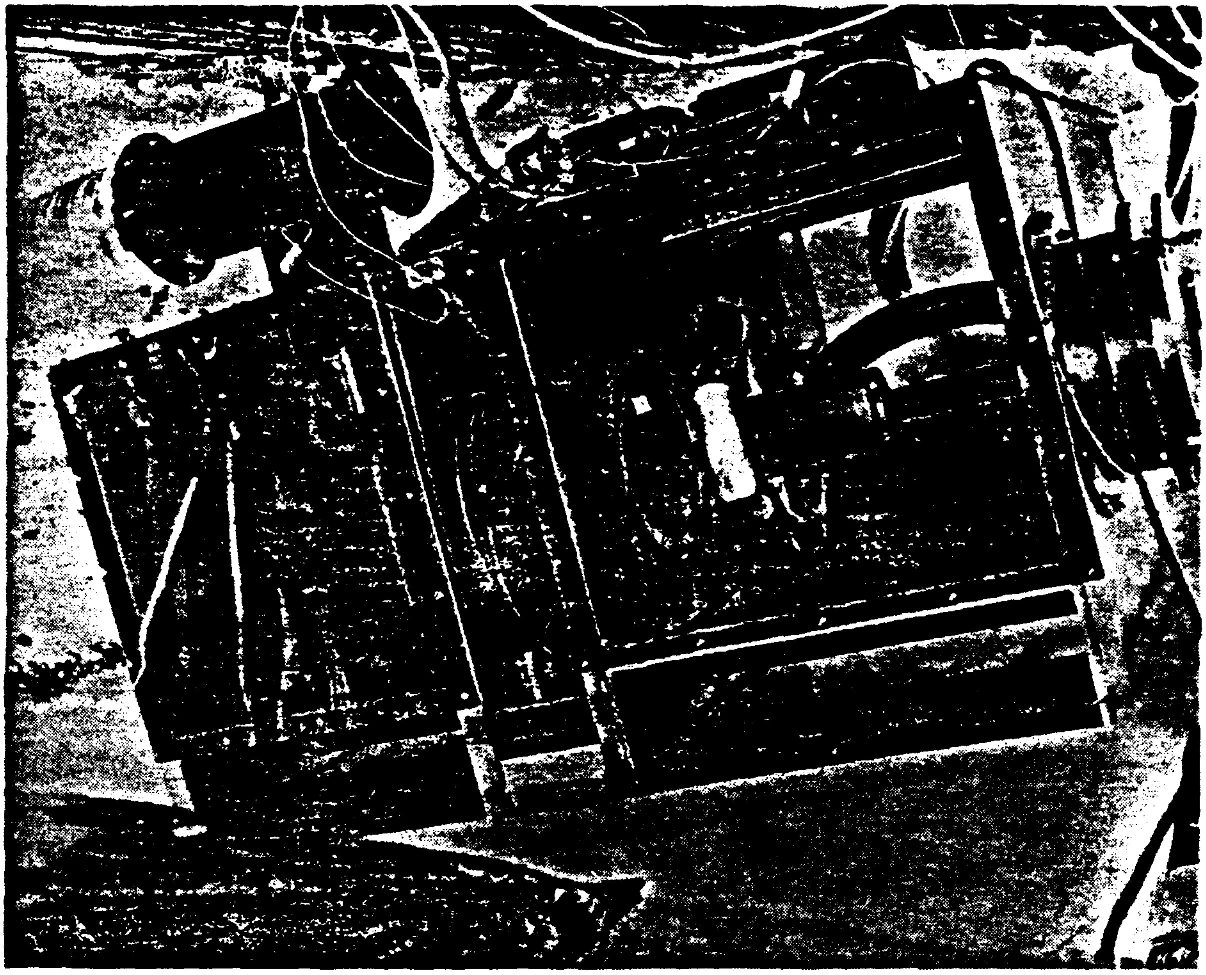

Figure 13. Photograph of Task 2 Test Setup

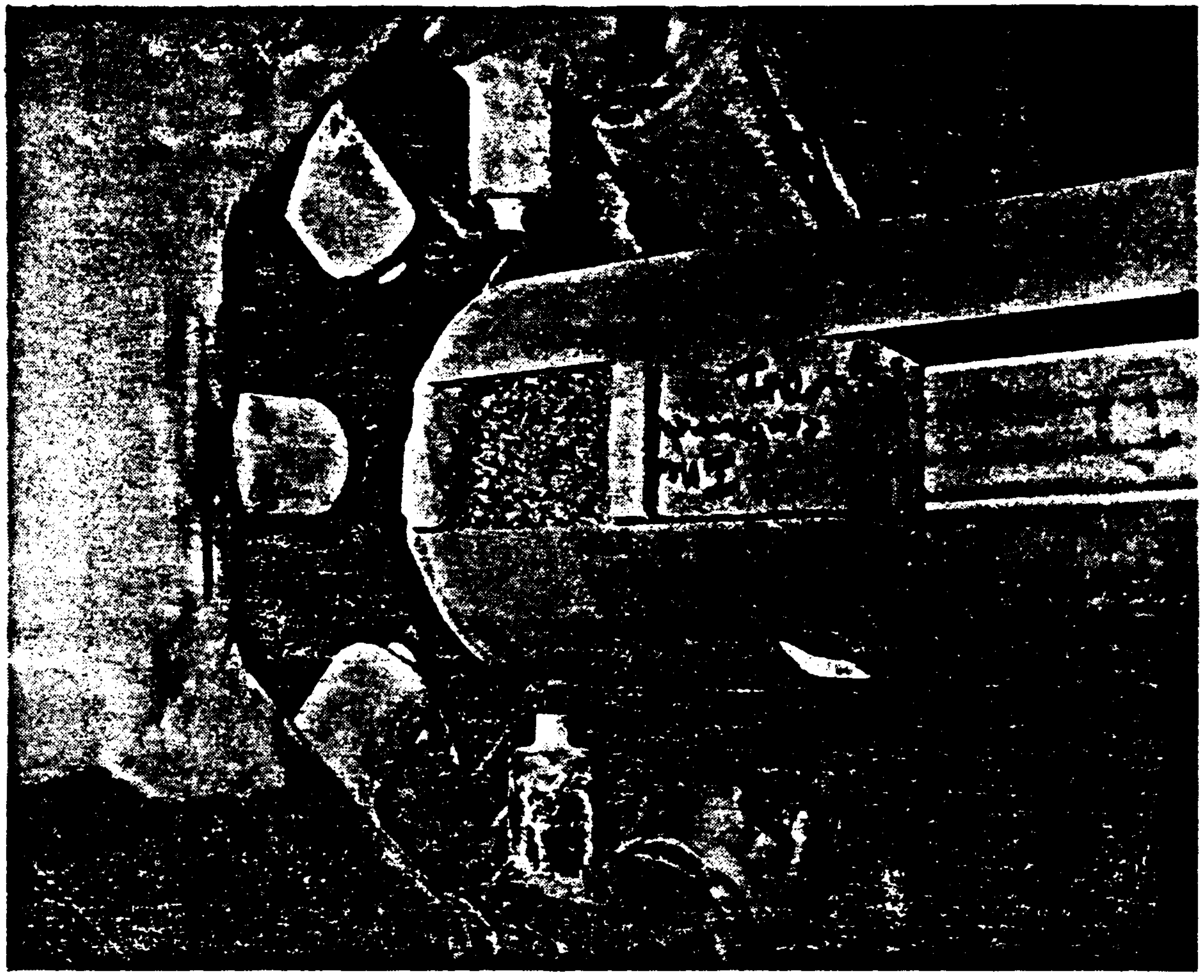

Figure 14. Photograph of Task 2B Propellant Sample in Mandrel

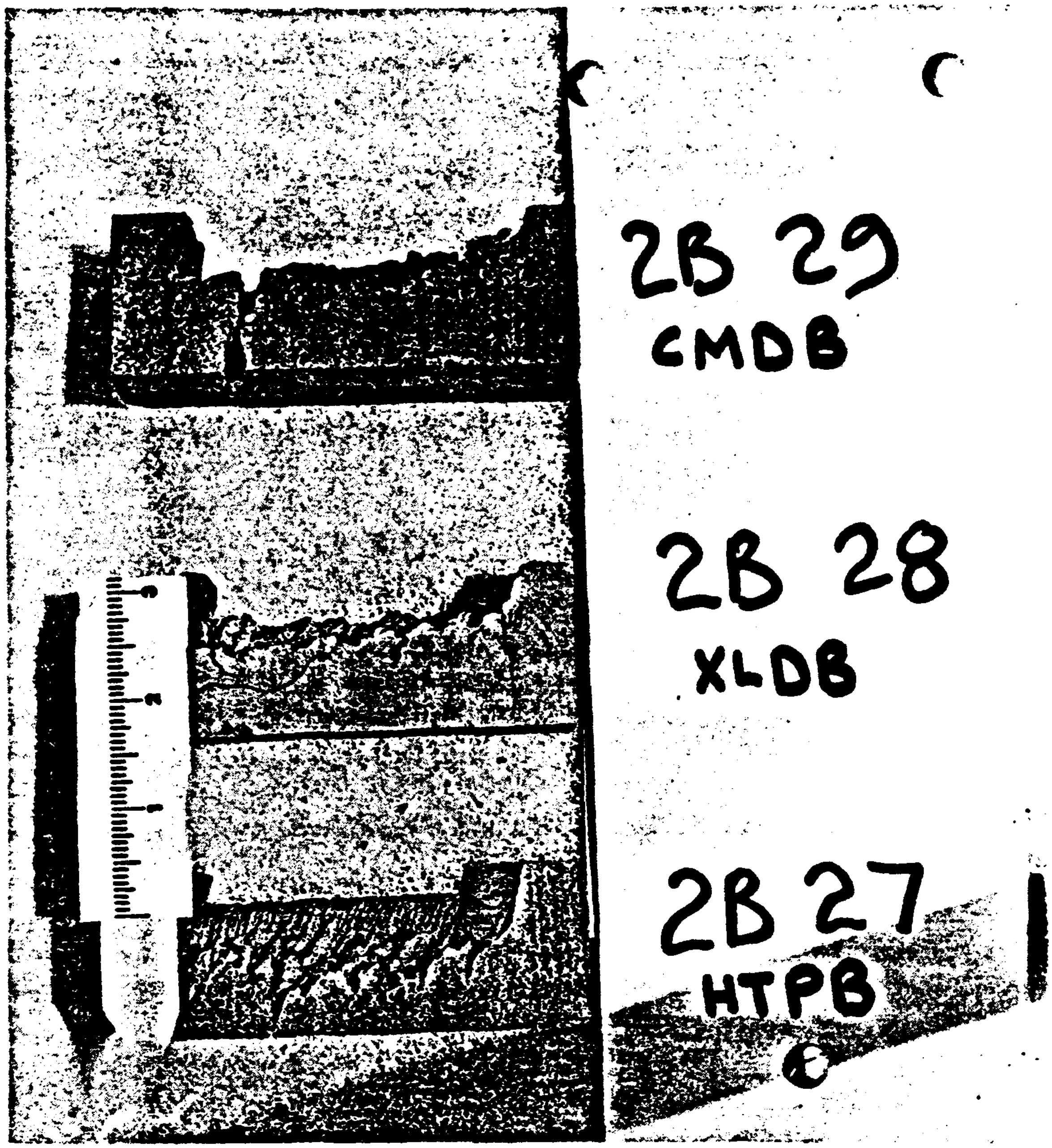

Figure 15. Representative Sectioned Task 2B LN_2 Washout Samples

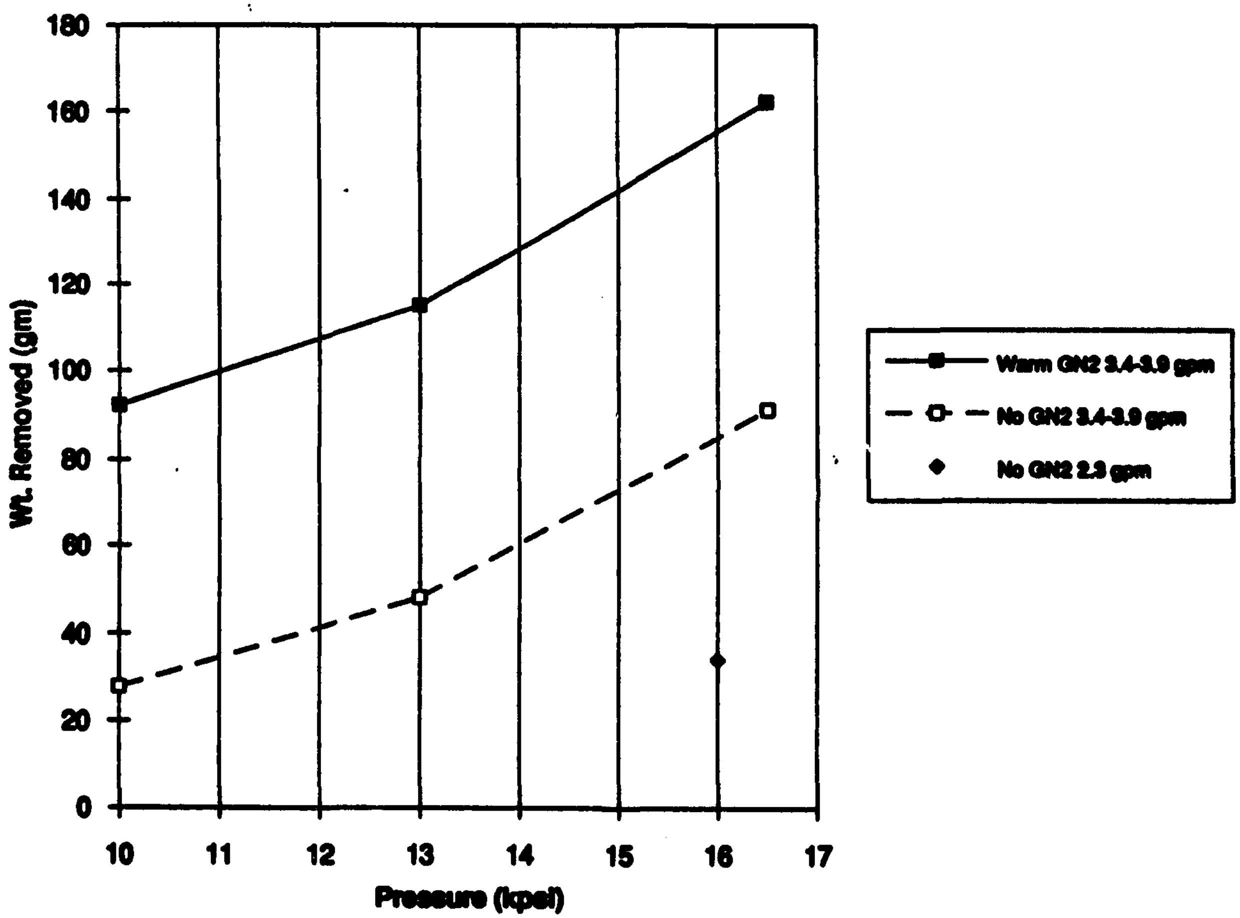

Figure 16. Mass Removal for HTPB (QDT) Propellant During Task 2B

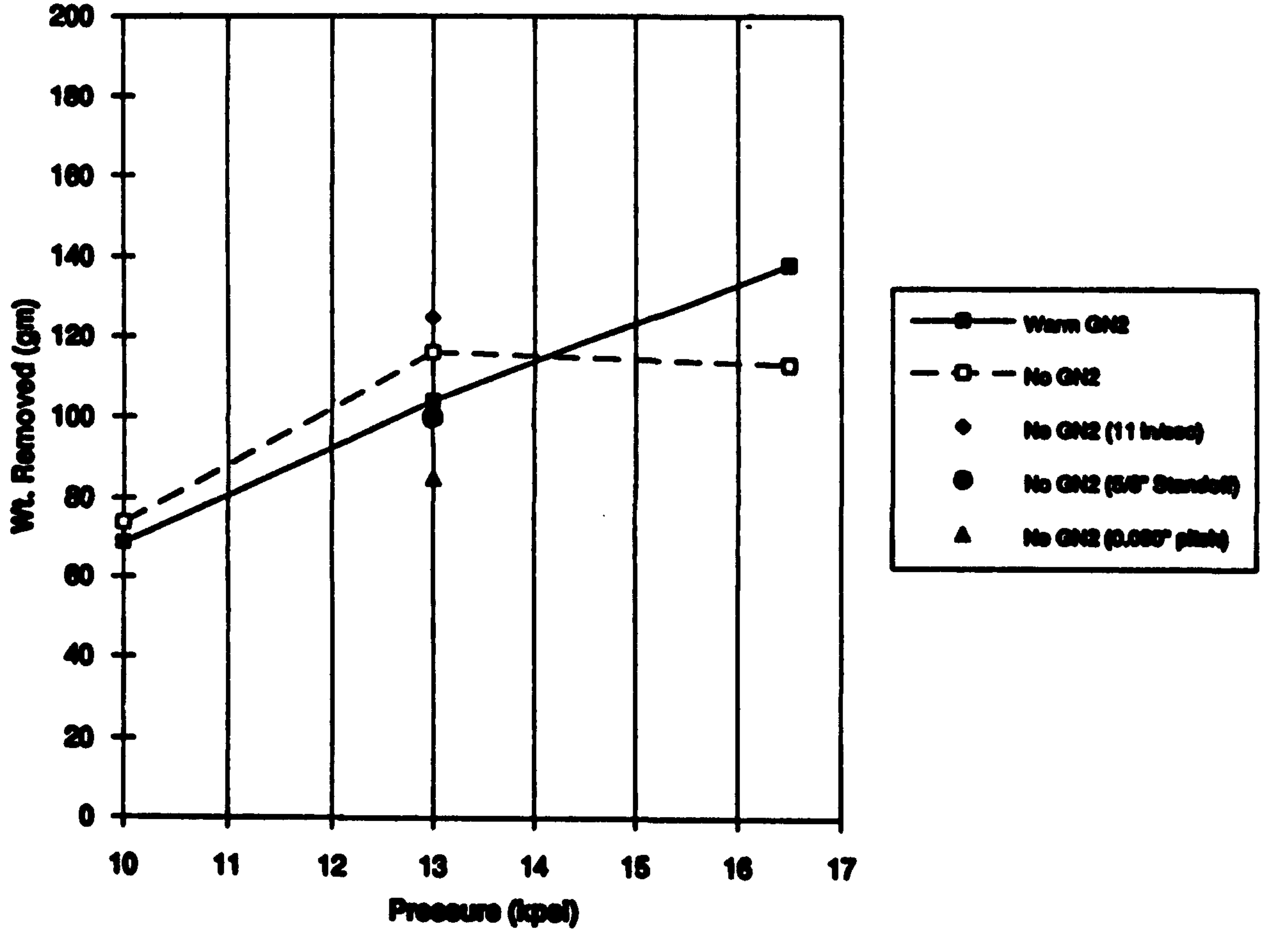

Figure 17. Mass Removal for XLDB (WAY) Propellant During Task 2B

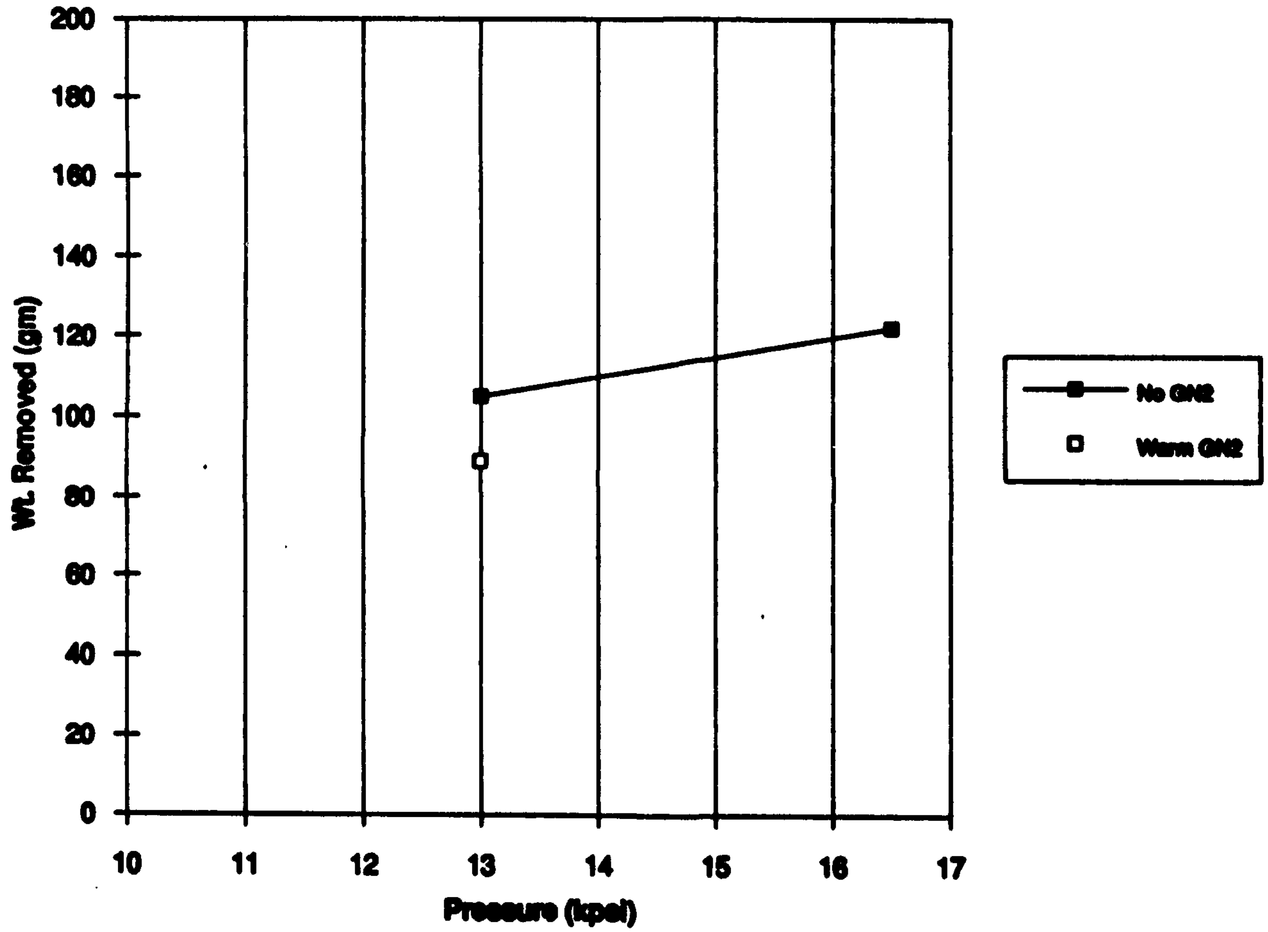

Figure 18. Mass Removal for CMDB (CYH) Propellant During Task 2B

propellant. The double base propellants tended to crack and break up when exposed to LN_2, which improved the mass removal rate. The mass removal rate for HTPB was more affected by the presence of warm GN_2 flow than for XLDB or CMDB. HTPB propellant did not tend to crack and break up as did the double base propellants. The Task 2 warm GN_2 system was very effective at limiting cryo-induced hardening of HTPB propellant, such that HTPB exhibited the highest Task 2B mass removal rate (80.3 pounds per hour).

In general, better mass removal rate and efficiency were produced with higher LN_2 pressure, as shown in Figures 16-18. However, XLDB propellant with no GN_2 flow, did not follow this trend (see Figure 17). For this case the mass removal was about the same at 13,000 and 16,500 psig. This can be explained by the fact the XLDB propellant tended to crack into larger chunks than the other propellants, and the mass removal rate was dependent on the pattern of cracks through a given sample. Comparison of the mass removal data at approximately 16,000 psig with either 2.34 or 3.9 gallons per minute appears to show a strong effect due to LN_2 flow rate at least for HTPB propellant (see Figure 16). The limited data available imply that increasing flow rate per nozzle (and thereby nozzle diameter) will increase cutting efficiency. One trial (2B35) was performed with pitch increased by a factor or approximately 1.5 (see Figure 17). This resulted in a significant decrease in cutting performance (relative to trial number trial 2B23). Another trial (2B32) was performed during which surface speed was increased by a factor of 1.83. Mass removal actually increased during this trial (again relative to 2B23), suggesting that the range of surface speeds used during this testing is low, and higher cutting efficiency will result from higher surface speed. Another trail (2B35) was performed with a standoff distance increased by a factor of 1.77 (see Figure 17). The mass removal decreased about 15 percent during this trial relative to trial 2B23, suggesting that small standoff distances should be maintained for effective propellant removal.

2. CO_2 Pellet Blasting

Table 8 shows the test parameters and results for the nine live Task 2B CO_2 pellet blasting trials conducted. No initiations or reactions were detected at any time during CO_2 pellet blasting trials. Very little propellant was removed for XLDB and CMDB samples at any blasting pressure between 250 and 600 psig. For HTPB samples some abrasion was apparent at 250 and 425 psig, but very little at 600 psig. The mass removed during the 250 psig and 425 trials was virtually the same: 7 grams

TABLE 8. TEST PARAMETERS AND MASS REMOVAL FOR TASK 2 CO_2 PELLET BLASTING TRIALS

TRIAL NO.	PROPELLANT TYPE	BLASTING PRESSURE (psig)	NOZZLE NO.	MASS REMOVAL (grams)	CUTTING DEPTH (inches)
C3	HTPB	250	1	7	0.2
C5A	HTPB	425	1	8	0.2
C11A	HTPB	600	2	1	0.04
C6	XLDB	250	1	1	0.04
C8	XLDB	425	1	<1	~0
C10	XLDB	600	2	<1	0.03
C7	CMDB	250	1	<1	~0
C9	CMDB	425	1	<1	~0
C12	CMDB	600	2	<1	~0

at 250 psig, 8 grams at 425 psig. The minimal mass removal at 600 psig may have been because a different, and possibly less effective, nozzle was used for all trials at this pressure. If the nozzle designed for 600 psig was less effective at accelerating the CO_2 pellets than the nozzle used for lower pressures, then mass removal could be less even though the driving force was higher.

It should be noted when comparing CO_2 pellet blasting trials with LN_2 washout trials that the trial length for CO_2 trials was 6 minutes - 14.4 times longer than for Task 2A trials, and 2.4 times longer than Task 2B trials. The best mass removal rate for CO_2 pellet blasting trials was 1.67 pounds per propellant blasting hour, during trial number C5A. This rate is significantly lower than for the Task 2B LN_2 washout trials.

On samples for which little or no mass removal occurred the surface of the sample and of the aluminum mandrel often changed slightly in texture, becoming slightly rougher. During LN_2 washout trials the liquid jet had no effect on the surface of the mandrel but was far more effective at cutting propellant. This implies that the physical mechanism for mass removal by pellet blasting is different than for LN_2 washout. LN_2 washout is a cutting process, dependent on the strength of the material being cut. In contrast, CO_2 pellet blasting is an abrasive process that removes mass very slowly but scrubs the surface very thoroughly, even for strong, hard materials.

C. TASK 3: PROTOTYPE WASHOUT TESTS

During Task 3 one inert FPC, one live FPC, one inert LAM, and one live LAM were processed in that order. About 50 percent of the propellant was washed out from the inert motors, in order to conserve LN_2 pump life. All of the propellant was removed from the live FPC and all but about five pounds were removed from the live LAM motor.

Inert motors were processed using 16,500 psig LN_2 pressure with 3.9 gpm flow rate. This was the highest flow and highest pressure used during testing and was required for washout of inert propellant. V[illegible] GN_2 flow was used for both inert motors because Task 2 results indicated that inert propellant was quite sensitive to propellant temperature.

During processing of the inert FPC, partial cavitation of the LN_2 pump began to occur. Symptoms were loss of pump prime and unstable LN_2 pressure. As inert FPC washout continued, LN_2 pressure became more and more unstable until variations of plus or minus 2000 psig were occurring. Washout operations were halted and an external inspection of the LN_2 system was made. No problems were found but upon resumption of testing LN_2 pressure would not rise above 3000 psig. A more detailed inspection was made which indicated that the LN_2 pump was faulty. The pump cold end was returned to the manufacturer, inspected and found damaged. The pump was returned with the recommendation to minimize operation at combined high flow rate and high pressure unless the LN_2 tank pressure could be raised to stop the cavitation problem. This was not possible with the tank at the test site so inert FPC washout was discontinued and live FPC washout was begun. Task 2 results indicated that the live FPC washout could be done with pump parameters that would not damage the pump.

The live FPC washout was performed in three passes. Table 9 lists the cutting parameters and mass removal results for each pass. The live FPC was rotated at 30 rpm throughout the washout operation. This resulted in surface speeds ranging from 7.5 inches per second for the first pass to 13.2 inches per second at the outermost propellant radius. Cutting pitch was 1/16 inch for all passes. Figure 19 contains a plot of propellant mass removed versus pass number. During the first pass, slightly over 2 pounds of propellant were removed using an LN_2 jet at 13,000 psig and 3.92 gpm. For the second pass warm GN_2 was used to augment the LN_2 jet and 21 pounds of propellant were removed. On the third pass, about 17 pounds of propellant was removed together with most of the phenolic beaker (liner). The last several pounds of loose propellant and phenolic pieces were removed by hand following completion of the third pass. Propellant removal was measured by cleaning out the washout enclosure between passes. A photograph of the removed propellant is presented in Figure 20. The removed propellant was examined to determine the size range of the particles. The particles ranged from 1 inch to less than 4 μm. Most particles were similiar in size to coarse sand.

Warm GN_2 flow was not used during the first pass because Task 2 results showed no increase in cutting effectiveness resulting from heating XLDB propellant. However, much improved mass removal rates occurred during the second and third passes, when warm GN_2 flow was utilized. This change in the effect of warm GN_2 likely results from the change in geometry between the Task 2 configuration and the Task 3 configuration. For the Task 2 configuration, the LN_2 falls away from the sample after impacting the propellant surface. In contrast, the LN_2 is relatively confined within the rocket motor bore

TABLE 9. LIVE ROCKET MOTOR CRYOGENIC WASHOUT TEST SUMMARY

ROCKET MOTOR	PASS NO.	LN_2 PRESSURE (kpsig)	LN_2 FLOW (gpm)	GN_2 CONDITION	MASS REMOVAL (POUNDS)	MASS REMOVAL RATE (POUND/HOUR)
FPC	1	13	3.92	OFF	2	14.9
	2	13	3.92	WARM	21	156.2
	3	13	3.92	WARM	17	126.4
LAM	1-2	13	3.4	NONE	2.5	8.3
	3	13	3.4	NONE	2.8	11.2
	4	13	3.4	NONE	3.1	20.7
	5	13	3.4	NONE	2.1	14.0
	6	13	3.4	WARM	3.5	23.3
	7	15	3.4	WARM	2.7	18.0
	8	15	3.4	WARM	2.1	14.0
	9	15	3.4	WARM	2.6	17.3
	10	15	3.4	WARM	2.4	16.0
	11-13	15	3.4	WARM	5.6	12.4
	14-16	15	3.4	WARM	5.7	12.7
	17-21	13	3.4	WARM	14.6	19.7

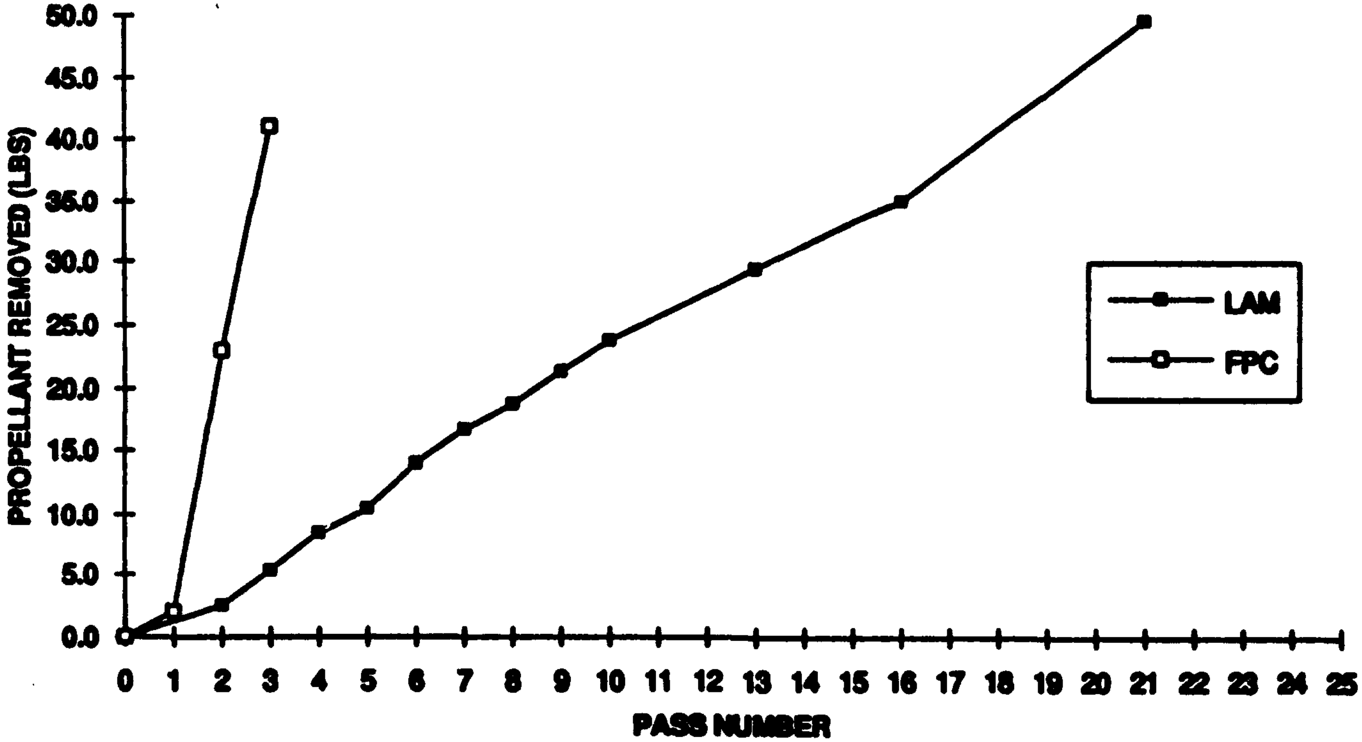

Figure 19. Mass Removal versus Pass Number for PFC and LAM Rocket Motor Washout

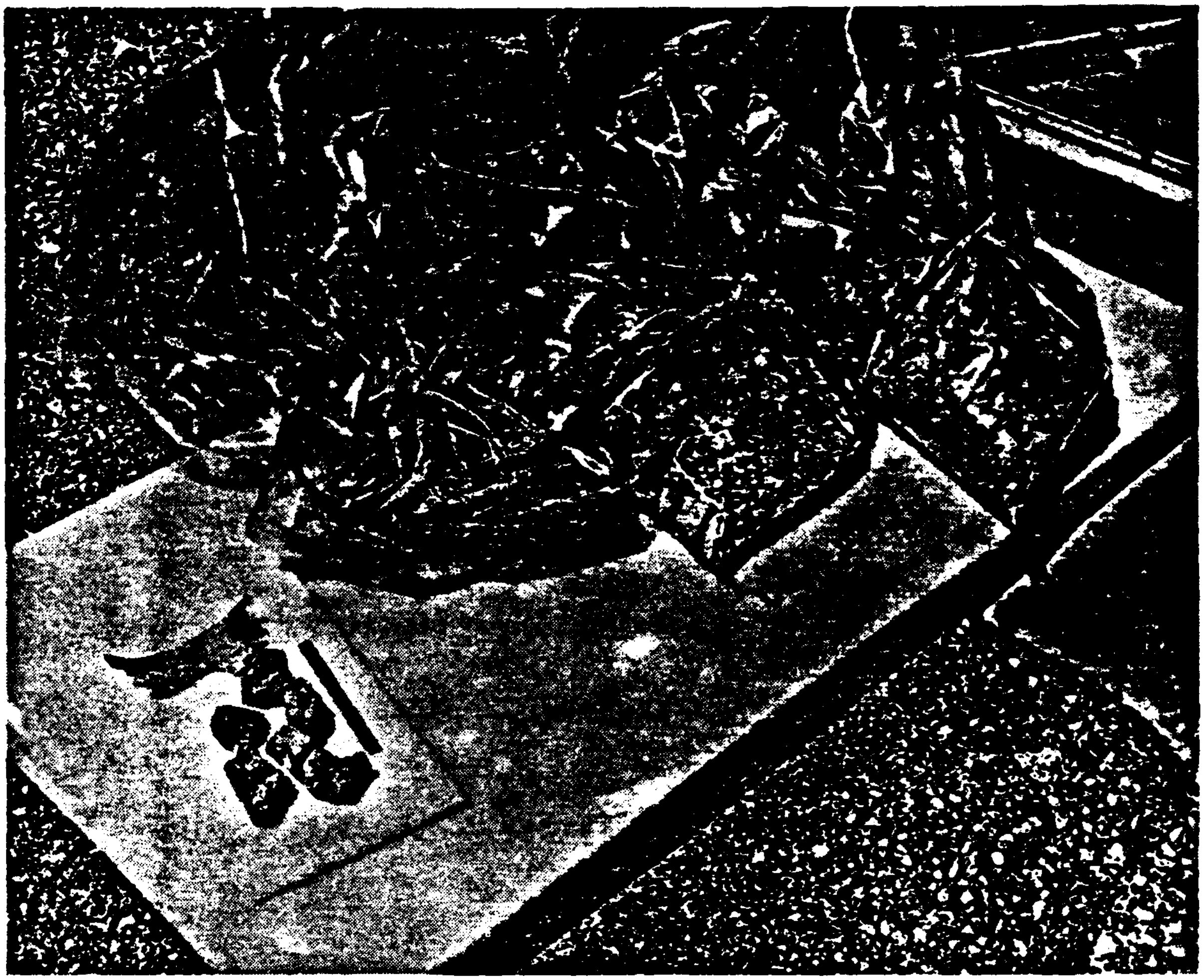

Figure 20. Washed Out Propellant from FPC Rocket Motor (Largest Propellant Particles at Left)

during Task 3 washout. Warm GN_2 helped to counteract the results of the confined rocket motor geometry, resulting in a higher mass removal rate.

During Pass 2 the mass removal rate was 156 lb/hr with a cutting efficiency of 0.10 pounds of propellant removed per pound of LN_2. This performance is an improvement over that achieved during Task 2, during which the best mass removal rate for XLDB propellant was 68.4 lb/hr at 0.043 pounds per gallon. The increase in mass removal rate likely results from the lack of support for the propellant web during Task 3. Mandrel edge restraint during Task 2 likely prevented many of the particles created by propellant cracking from being released from the surface of the sample. These edge effects were not present during FPC washout, resulting in the higher propellant removal rate. Photographs of the FPC testing are presented in Figures B1 through B21 in Appendix B.

During inert LAM processing the symptoms of partial cavitation again appeared. Therefore, washout was discontinued after enough operation to develop LAM washout methodology. The live LAM was then mounted in the test rig and washed out. The live LAM washout was performed in 21 passes. Table 9 shows the cutting parameters and mass removal for each pass. Figure 19 contains a plot of propellant mass removed versus pass number.

Prewashout inspection showed that the live LAM bore was undersize: 3.1 inches in diameter versus 3.4 inches stated on the drawings used for test rig design. The Task 3 warm GN_2 nozzle was designed to be a close fit inside the LAM bore and could not be inserted into the live motor. The first passes on the live LAM were therefore performed with the GN_2 nozzle removed and GN_2 flow off. After five passes the bore was large enough to accept the GN_2 nozzle and subsequent passes were made with warm GN_2 flow.

The design of the Task 3 GN_2 nozzle allowed increased clearance as the LAM was washed out. In addition, the small diameter motor bore and closed geometry resulted in an increased need for effective warm GN_2 flow, as discussed above for the live FPC. These combined factors resulted in lower mass removal rate for the live LAM, relative to Task 2 HTPB propellant washout trials. The best mass removal rate for HTPB propellant during Task 2 was 80.3 pounds per hour with mass removal efficiency equal to 0.050 pounds removed per pound of LN_2. During live LAM washout the mass removal was a maximum of 23.3 pounds per hour, with an efficiency of 0.014 pounds of propellant per pound of LN_2.

These results suggest that the design of the warm GN_2 nozzle system is an important consideration for improved cutting performance and efficiency. In addition, larger rocket motors with less confined internal geometry may be less sensitive to GN_2 nozzle performance.

During preparation for Pass 7, symptoms of partial cavitation began with LN_2 pressure set at 13,000 psig and flow equal to 3.92 gpm. This combination had not previously caused problems, indicating a possible degeneration in pump performance. Experiments determined that a lower flowrate and higher pressure combination did not cause pump cavitation, and the balance of live LAM washout was performed at 15,000 psig LN_2 pressure with 3.4 gpm flow. Cutting performance appeared to be unaffected by the change.

On the final five passes of live LAM, mass removal rate was markedly improved. As portions of the case were exposed the angled LN_2 jet could start to penetrate between the case and propellant, popping loose sections of propellant from the case.

Motor rotation was held at a constant 30 rpm during live LAM washout, with 1/16 inch pitch. Surface speed varied from 5 inches per second for the first pass to 16 inches per second at the case. Improved cutting efficiency would most likely have occurred if the motor was rotated faster for the first few passes. The washed out LAM case is shown in Figure 21. Most of the particles of removed propellant were similiar in size to coarse sand and much more uniform in size than for the XLDB propellant. A small amount of propellant (approximately 5 pounds) remained at the nose of the case. This could not be removed because of the fixed nozzle geometry used for the testing. Had resources allowed a nozzle with greater than a 15-degree angle could have been used to wash out this area without difficulty.

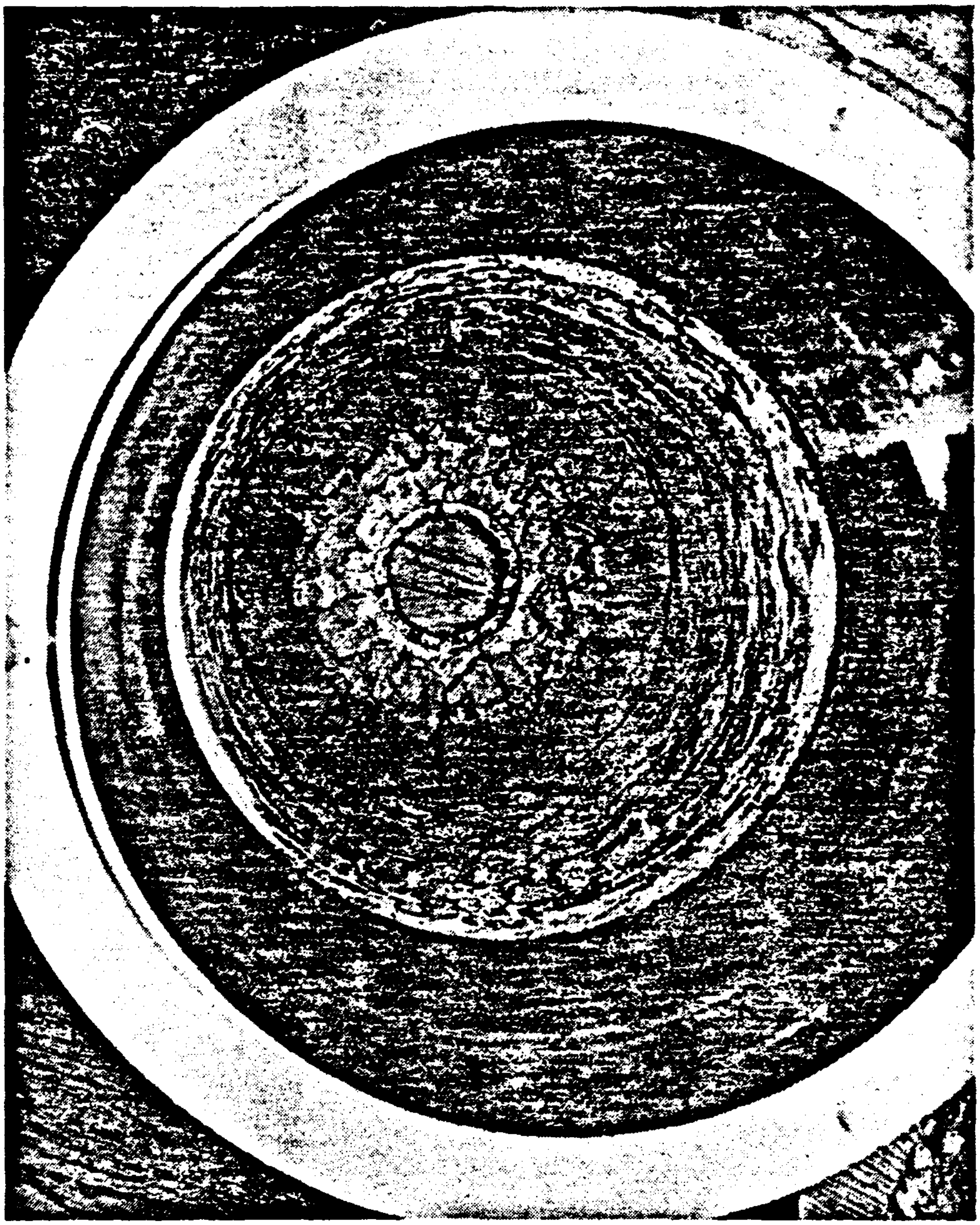

Figure 21. Live LAM Rocket Motor after LN_2 Washout of HTPB Propellant

SECTION V
CONCLUSIONS

Based on the results of the Task 1, 2 and 3 tests, the following conclusions are drawn:

- Good propellant cutting effectiveness was achieved during cryogenic washout of solid propellants. Maximum mass removal rates were 80.3 pounds per hour for HTPB propellant, 156 pounds per hour for XLDB propellant, and 60.0 pounds per hour for CMDB propellant. All testing was conducted at less than 3.92 gallons per minute LN_2 flow through a single nozzle. Maximum cutting efficiencies were 0.05, 0.10, and 0.038 pounds per pound of LN_2 for HTPB, XLDB, and CMDB propellants respectively.

- Sensitivity of the HTPB, XLDB, and CMDB propellants tested was essentially unchanged from room temperature to -320°F. The sensitivity of temperature cycled propellant (between ambient and -320°F) was also unchanged from uncycled propellant. No changes in nitroglycerin or stabilizer concentrations were observed during post test analysis of washed out XLDB propellant. Electrical resistance increased for all three propellants; markedly so for XLDB and CMDB propellants. However, the dielectric breakdown voltages decreased for all three propellants. Thus a tradeoff in electrical properties occurred at cryogenic temperatures which suggested that electrostatic charges build up more slowly, but reach breakdown more quickly.

- Warm GN_2 flow used to warm the propellant surface during LN_2 washout increased cutting effectiveness. HTPB propellant was particularly affected by the use of warm GN_2 flow.

- Cracking of the double base propellants (XLDB and CMDB) under thermal stress resulting from LN_2 jet impingment increased mass removal by promoting breakup of the propellant surface. HTPB propellant did not exhibit this tendency to crack during LN_2 washout.

- **A wide range of propellant particle sizes was produced during LN_2 washout. Most particles were similiar in size to course sand, with a few large chunks in the size range of 50 to 90 gms, and a small amount of fine dust.**

- **No initiations were detected during CO_2 pellet blasting trials. However, mass removal rates were poor compared with high pressure LN_2 washout.**

SECTION VI
REFERENCES

1. Test Plan: Cryogenic Washout of Solid Propellants, General Atomics Inc. Report No. 758001, January 1992.

2. DeNevers, C.C., Cryogenic Size Reduction General Operating Procedure, Hercules Aerospace Inc. CSR-001 Rev 1, May 1992.

3. Creedon, W.P., Test Logs (#1 - #2): Solid Propellant Cryogenic Size Reduction Program, General Atomics Inc. Report No. 758004, May 1992.

4. Creedon, W.P. Task 2 Data Sheets: Solid Propellant Cryogenic Size Reduction Program, General Atomics Inc. Report No. 758003, May 1992.

5. Risk Management/Hazards Analysis Report for Solid Propellant Cryogenic Washout Bench Scale (Task 2) and Prototype (Task 3) Tests and Laboratory Sensitivity and Hazard Test Report (Task 1), General Atomics Inc. Report No. 758002, March 1992.

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APPENDIX A

TASK 1 PROPELLANT SENSITIVITY PLOTS

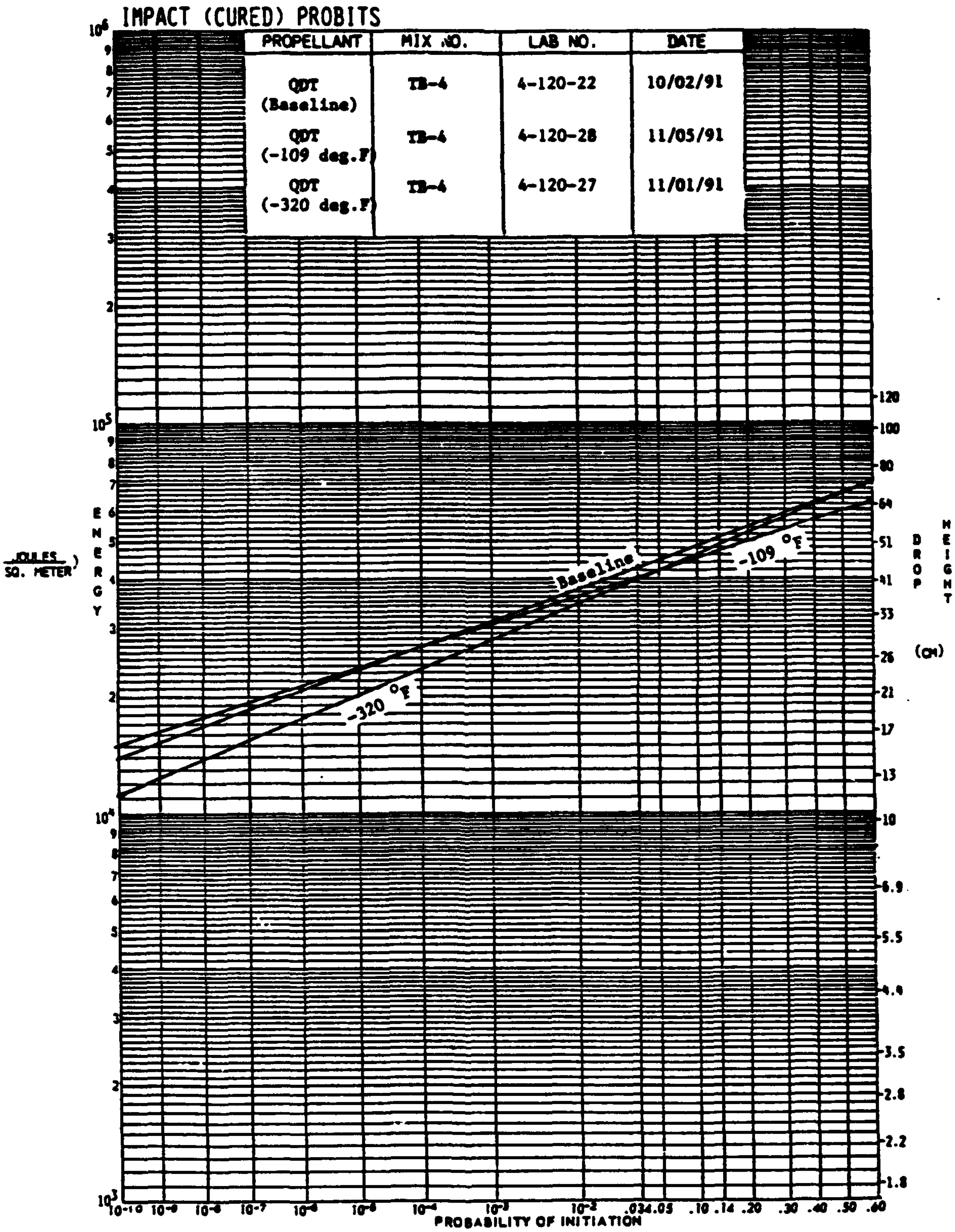


Figure A1. Impact Sensitivity for HTPB Propellant at Ambient and Cryogenic Temperatures

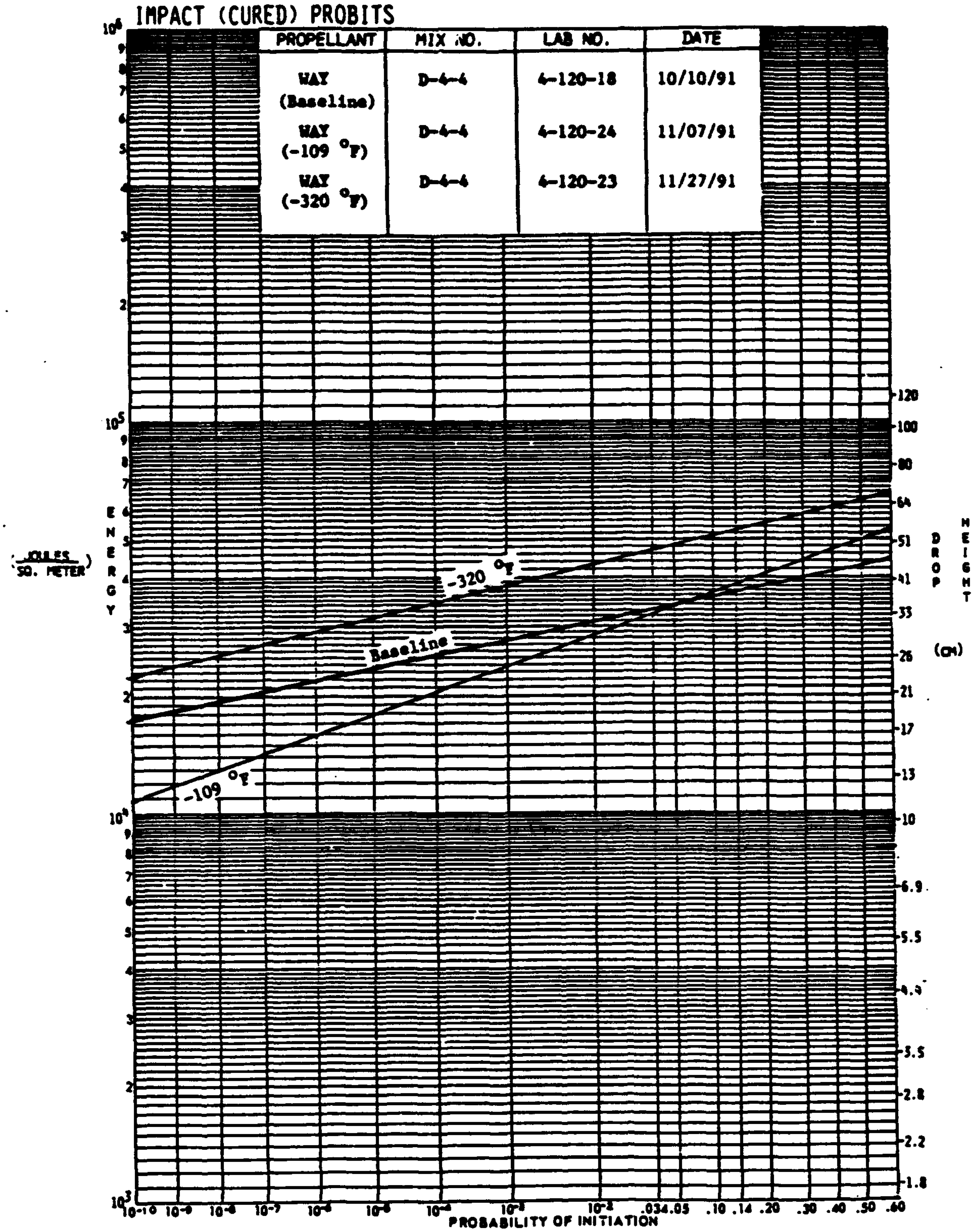


Figure A2. **Impact Sensitivity for XLDG Propellant at Ambient and Cryogenic Temperatures**

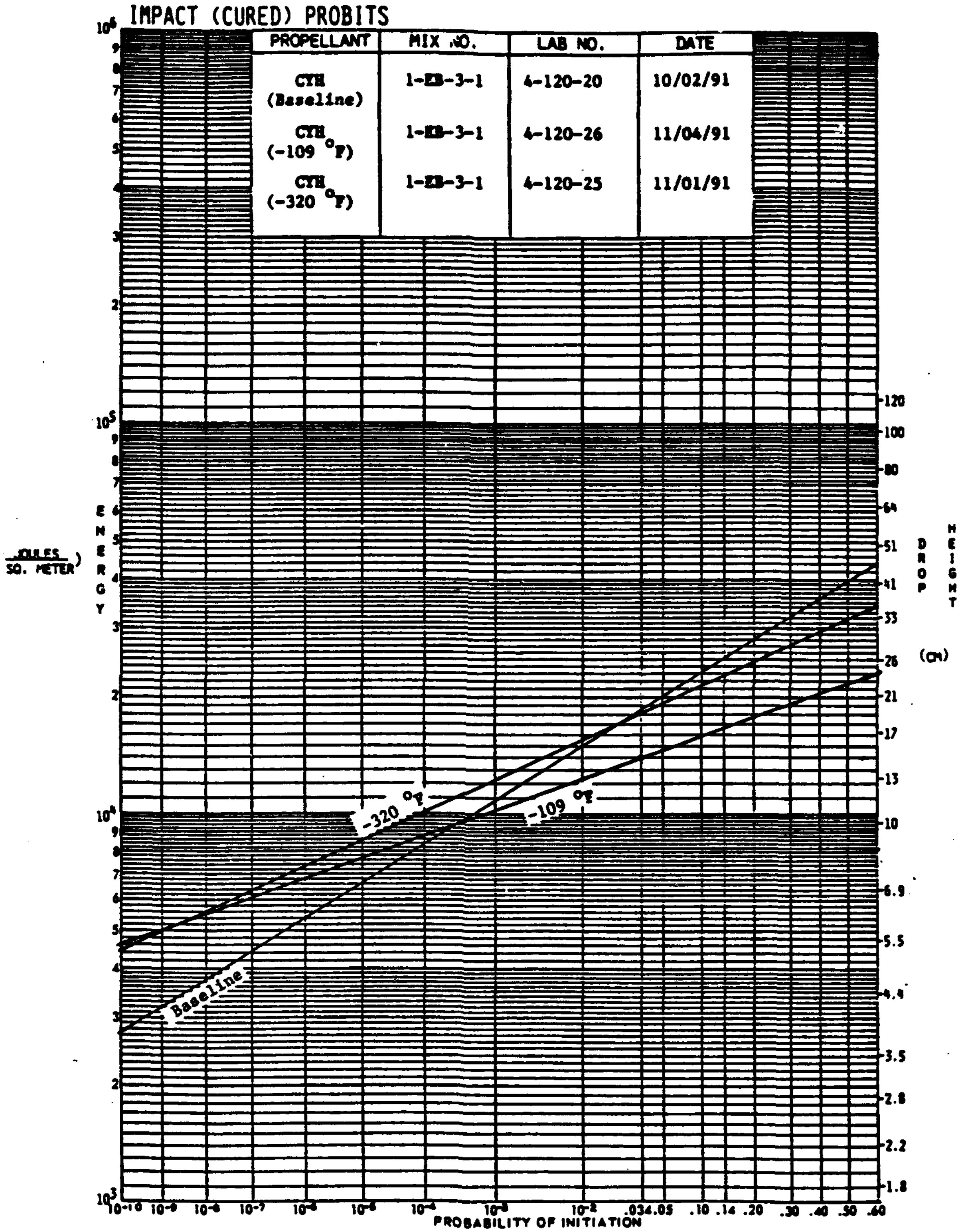


Figure A3. Impact Sensitivity for CMDB Propellant at Ambient and Reduced Temperatures

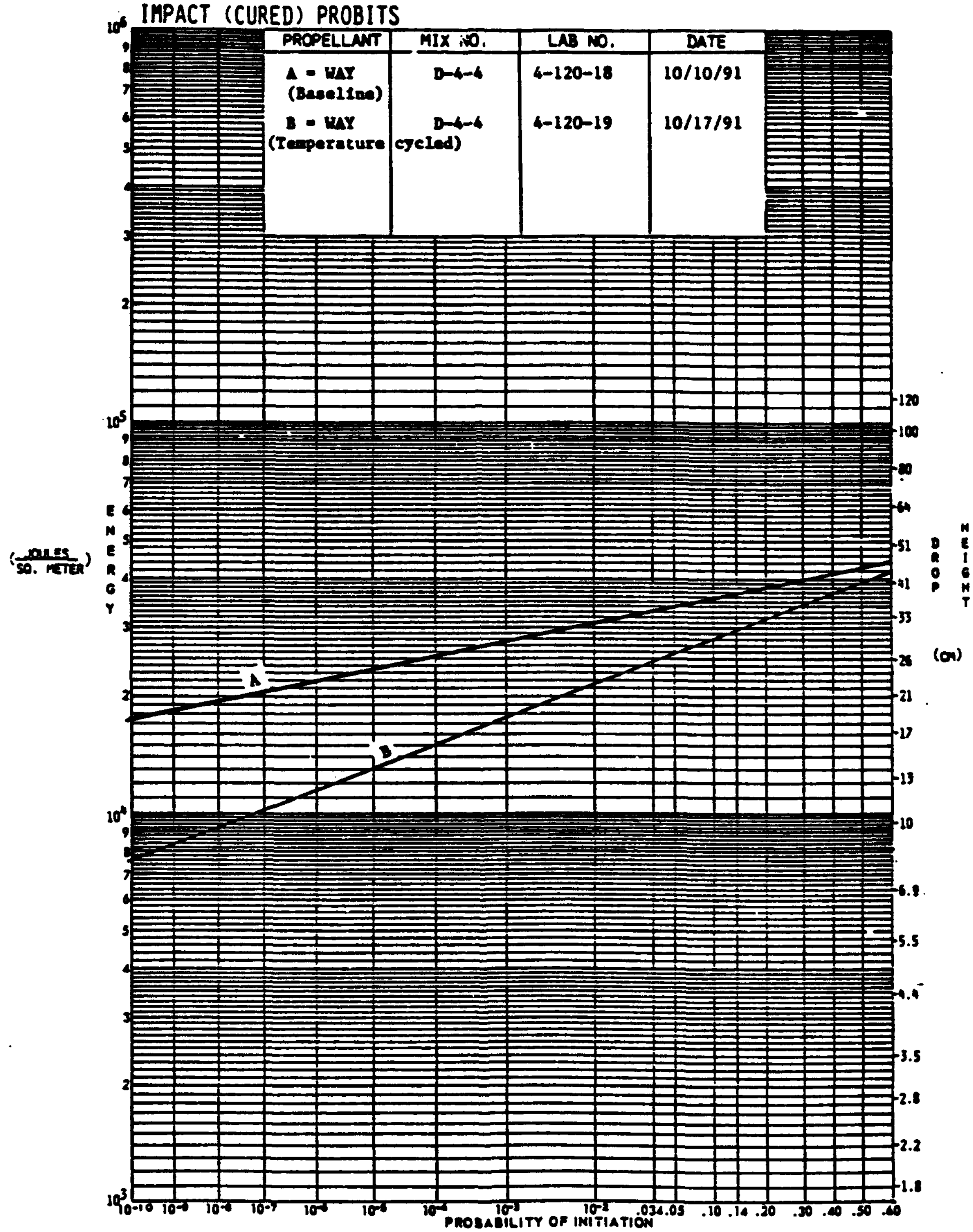


Figure A4. Impact Sensitivity for Temperature Cycled XLDB Propellant

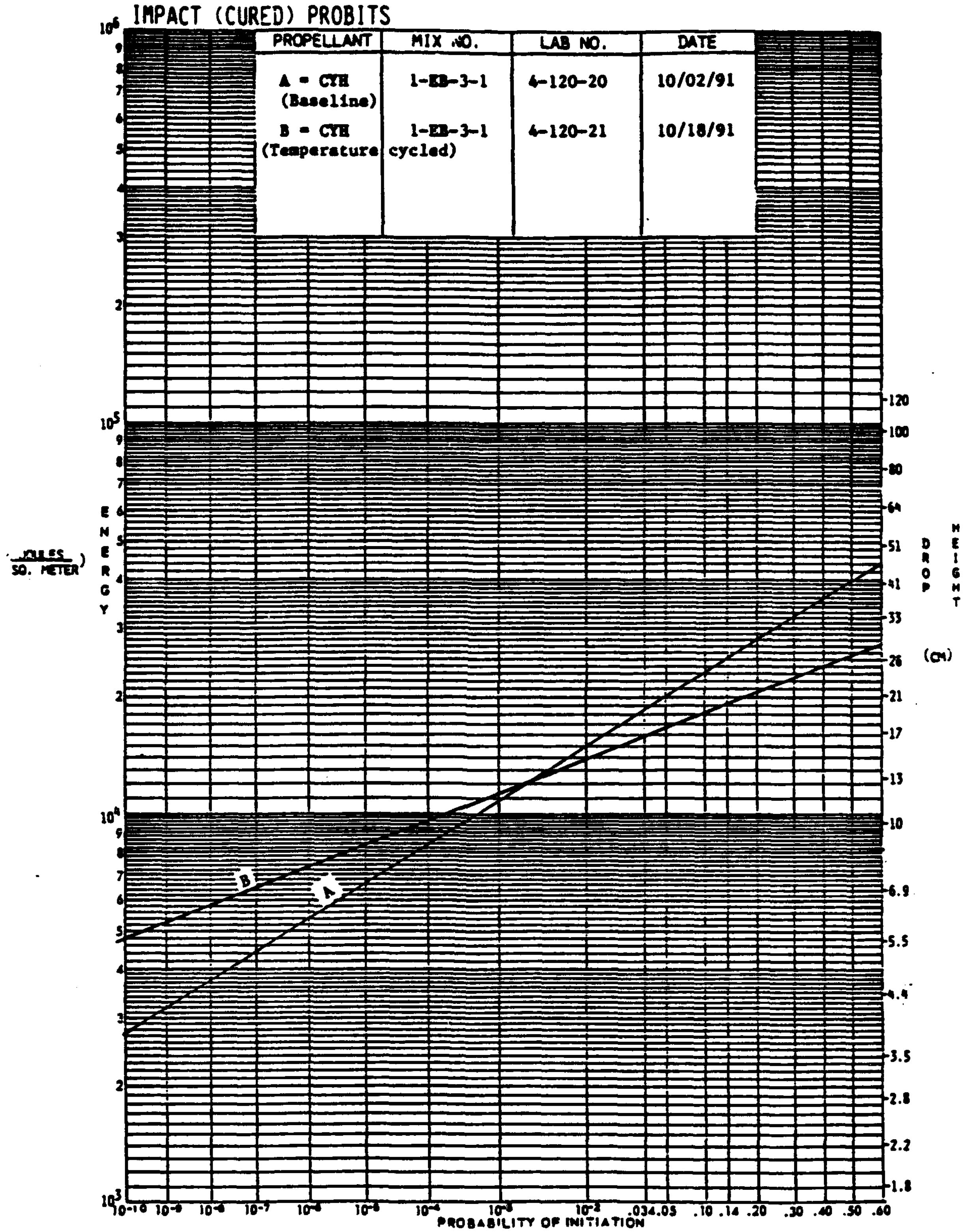


Figure A5. Impact Sensitivity for Temperature Cycled CMDB Propellant

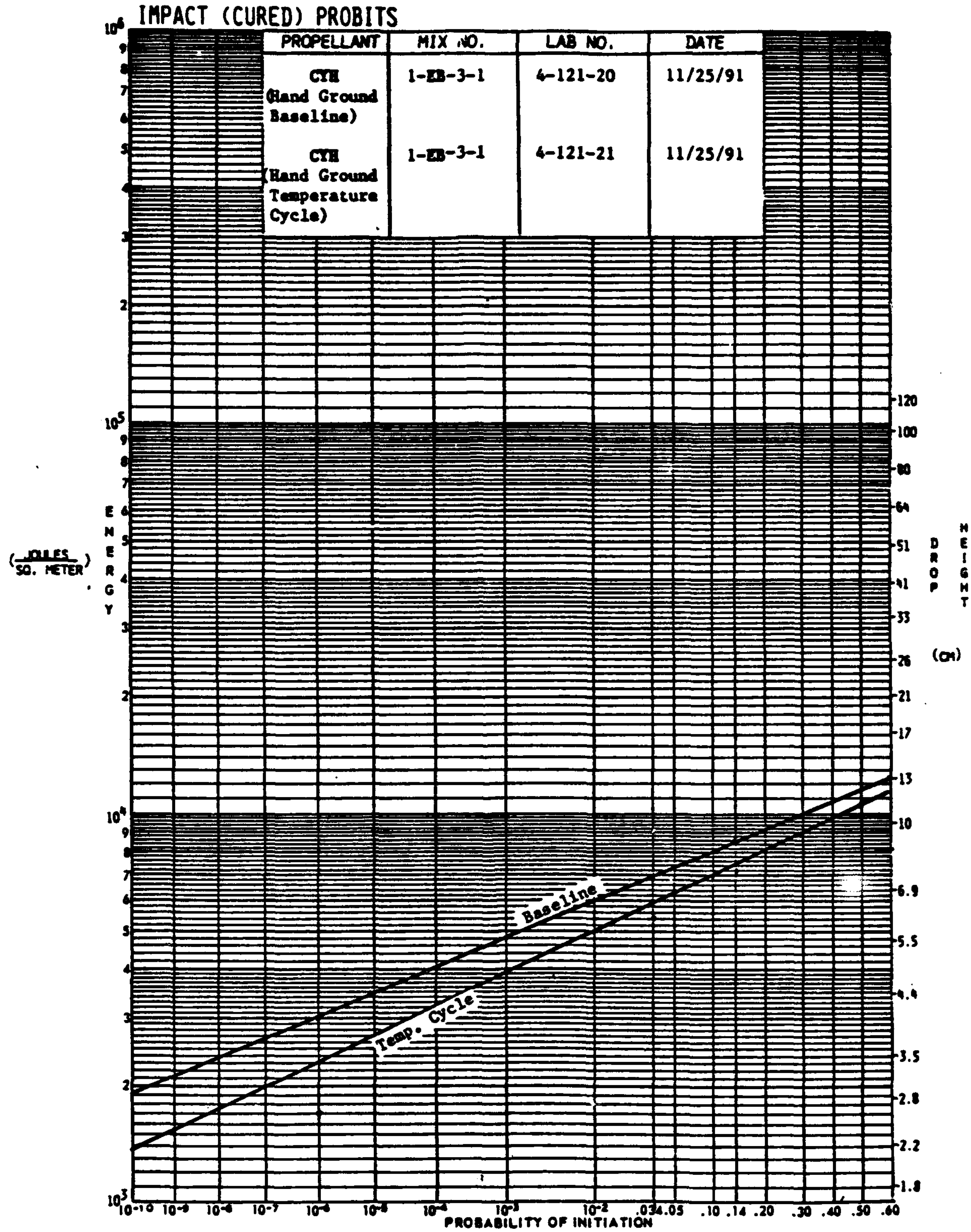


Figure A6. Impact Sensitivity for Temperature Cycled Hand Ground CMDB Propellant

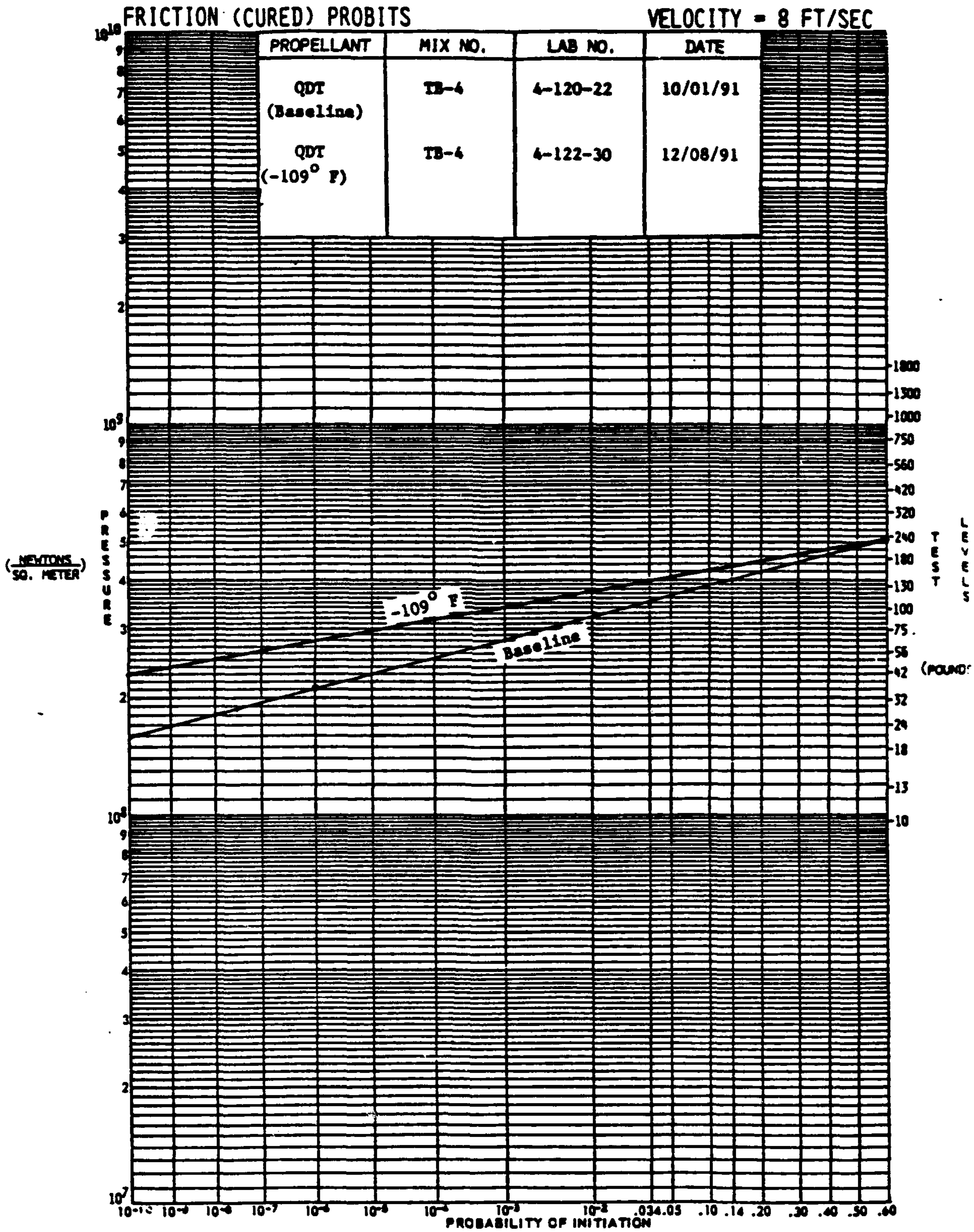


Figure A7. Friction Sensitivity for HTPB Propellant at Ambient and Cryogenic Temperatures

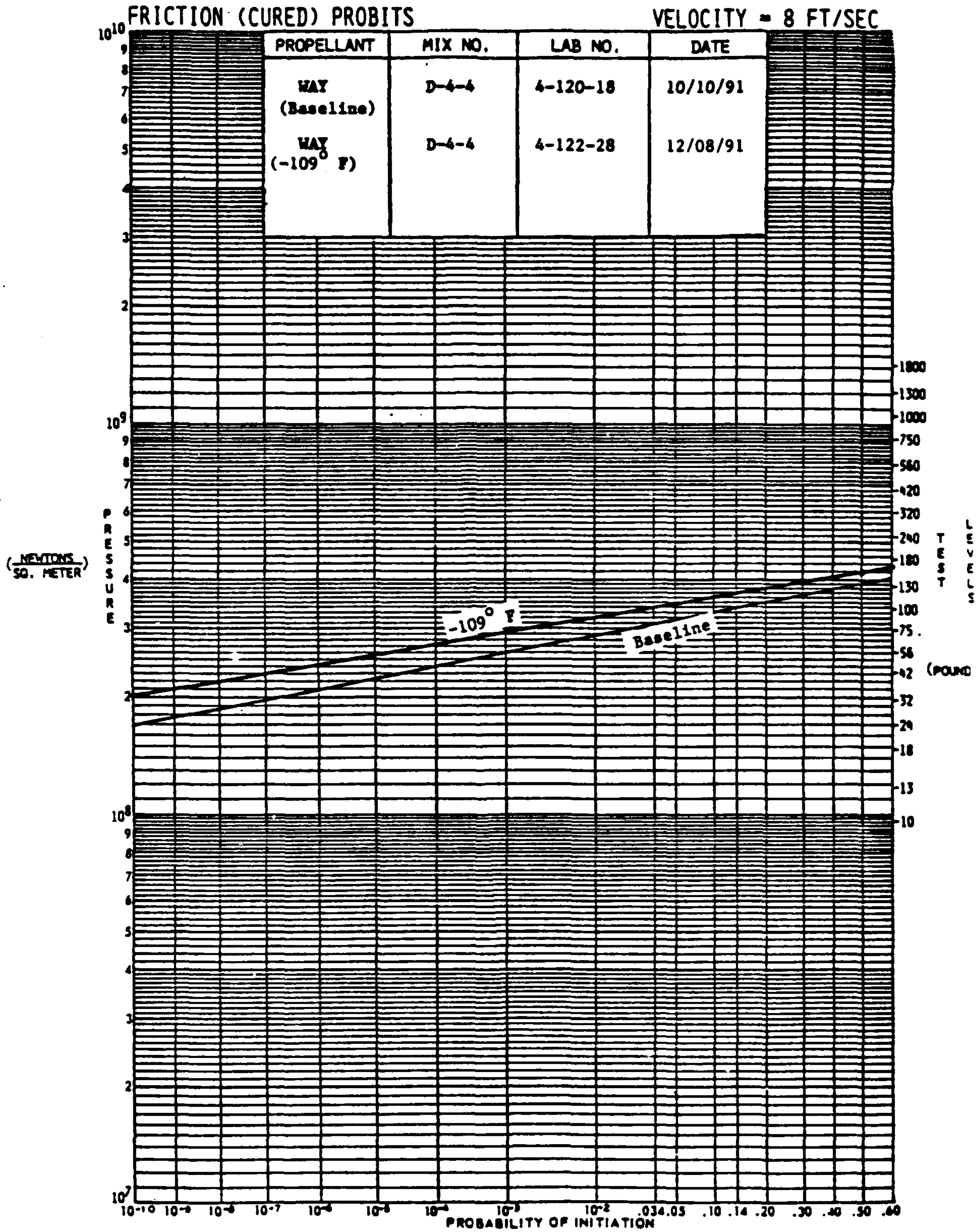


Figure A8. Friction Sensitivity of XLDB Propellant at Ambient and Cryogenic Temperatures

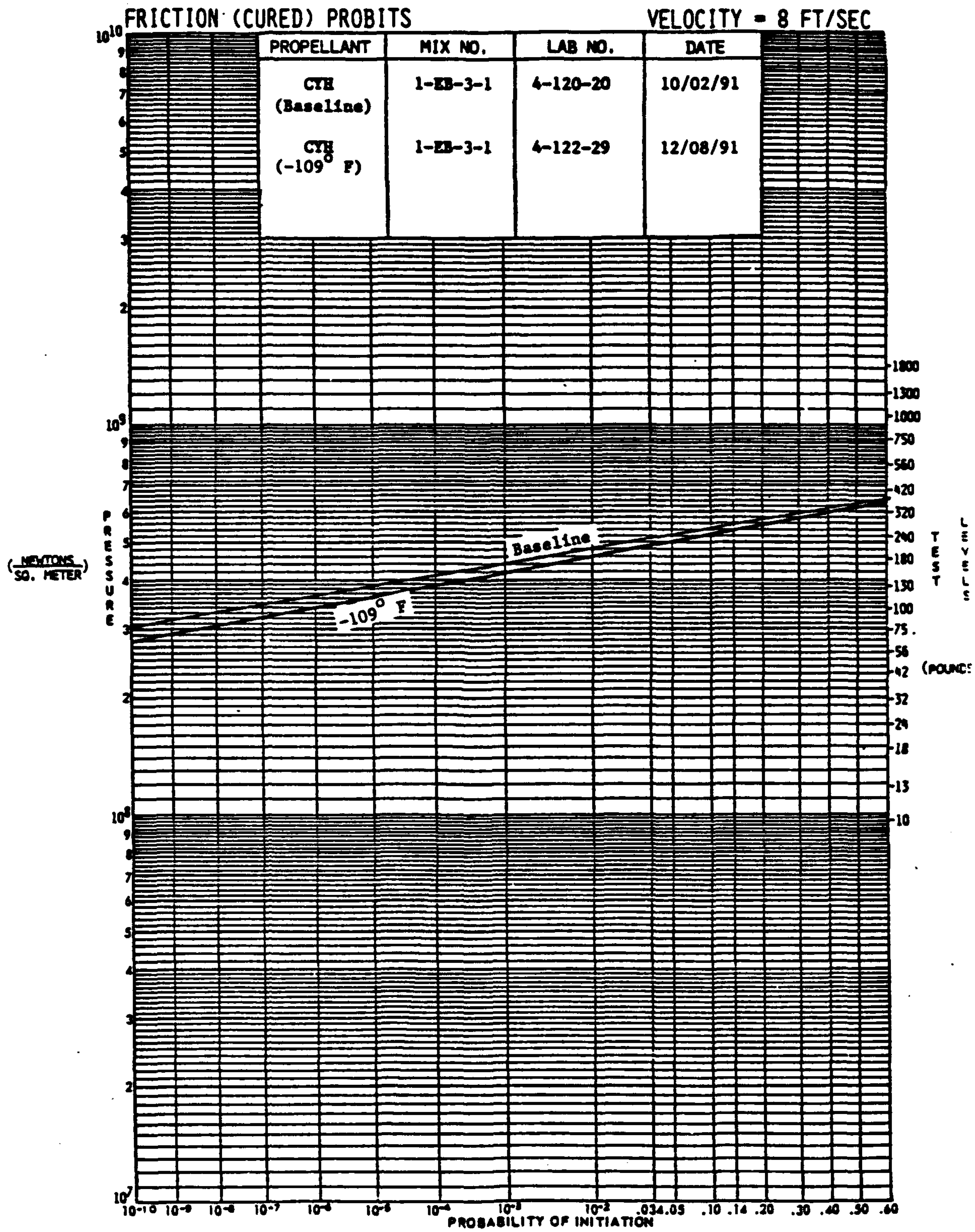


Figure A9. Friction Sensitivity of CMDB Propellant at Ambient and Cryogenic Temperatures

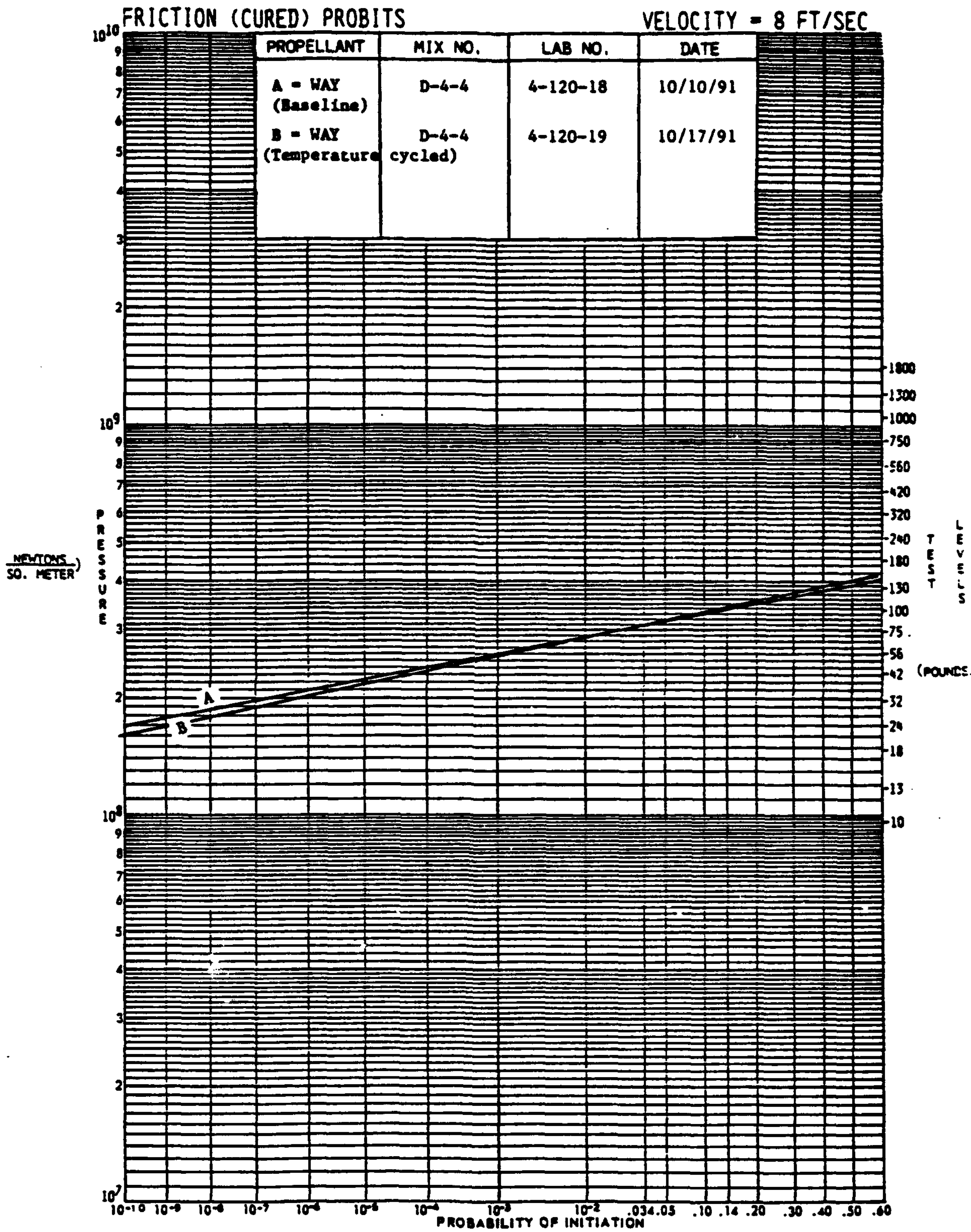


Figure A10. Friction Sensitivity for Temperature Cycled XLDB Propellant

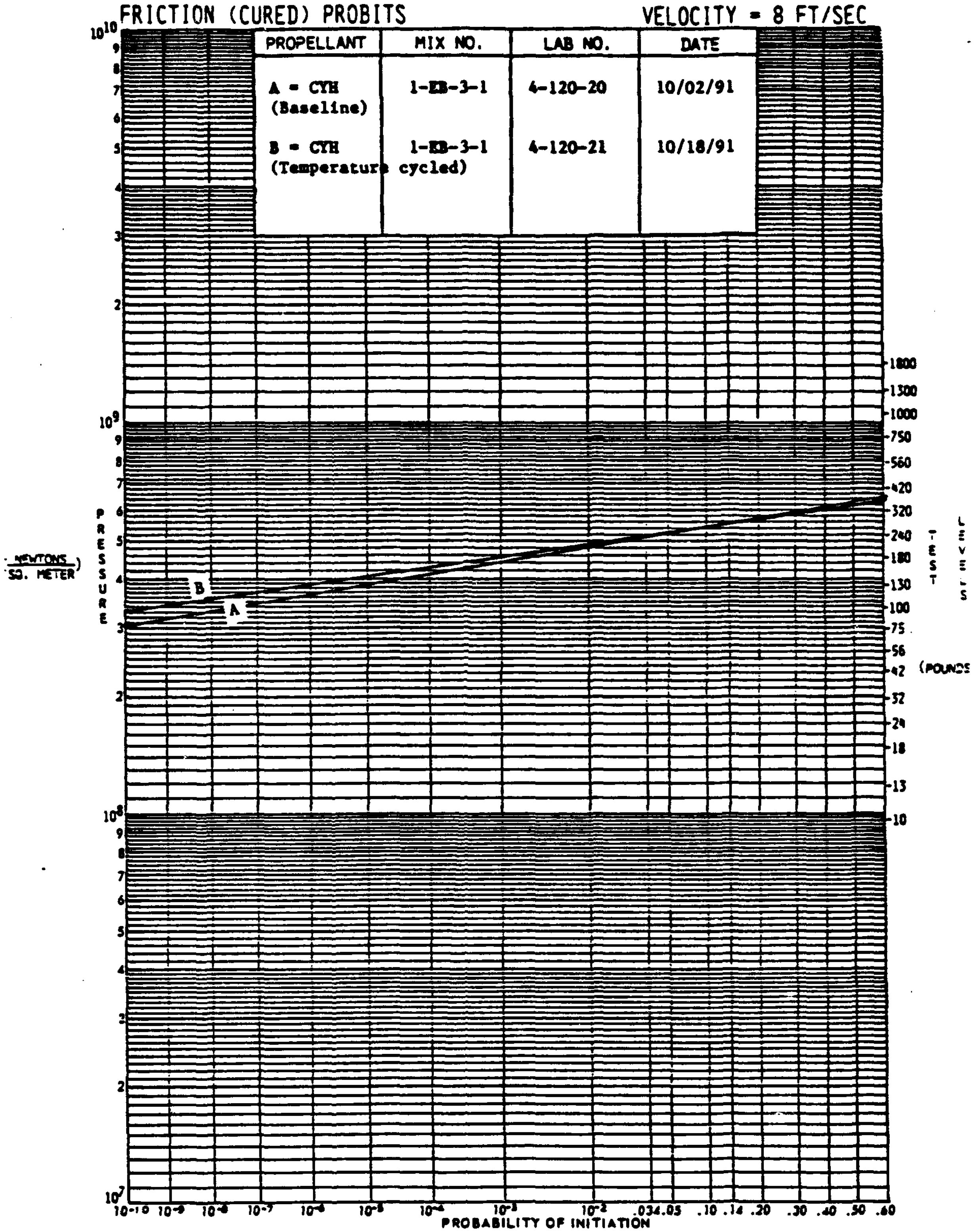


Figure A11. Friction Sensitivity for Temperature Cycled CMBD Propellant

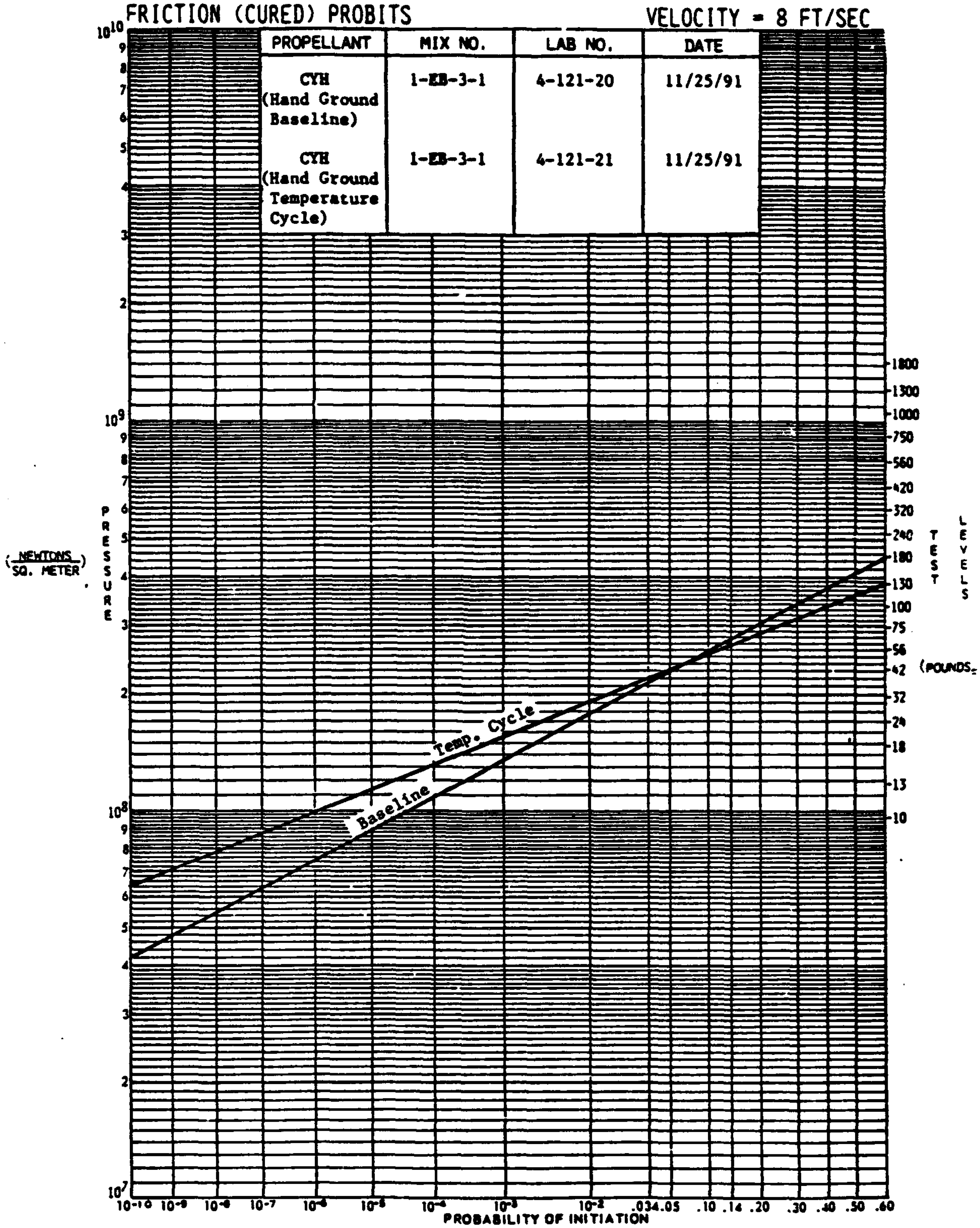
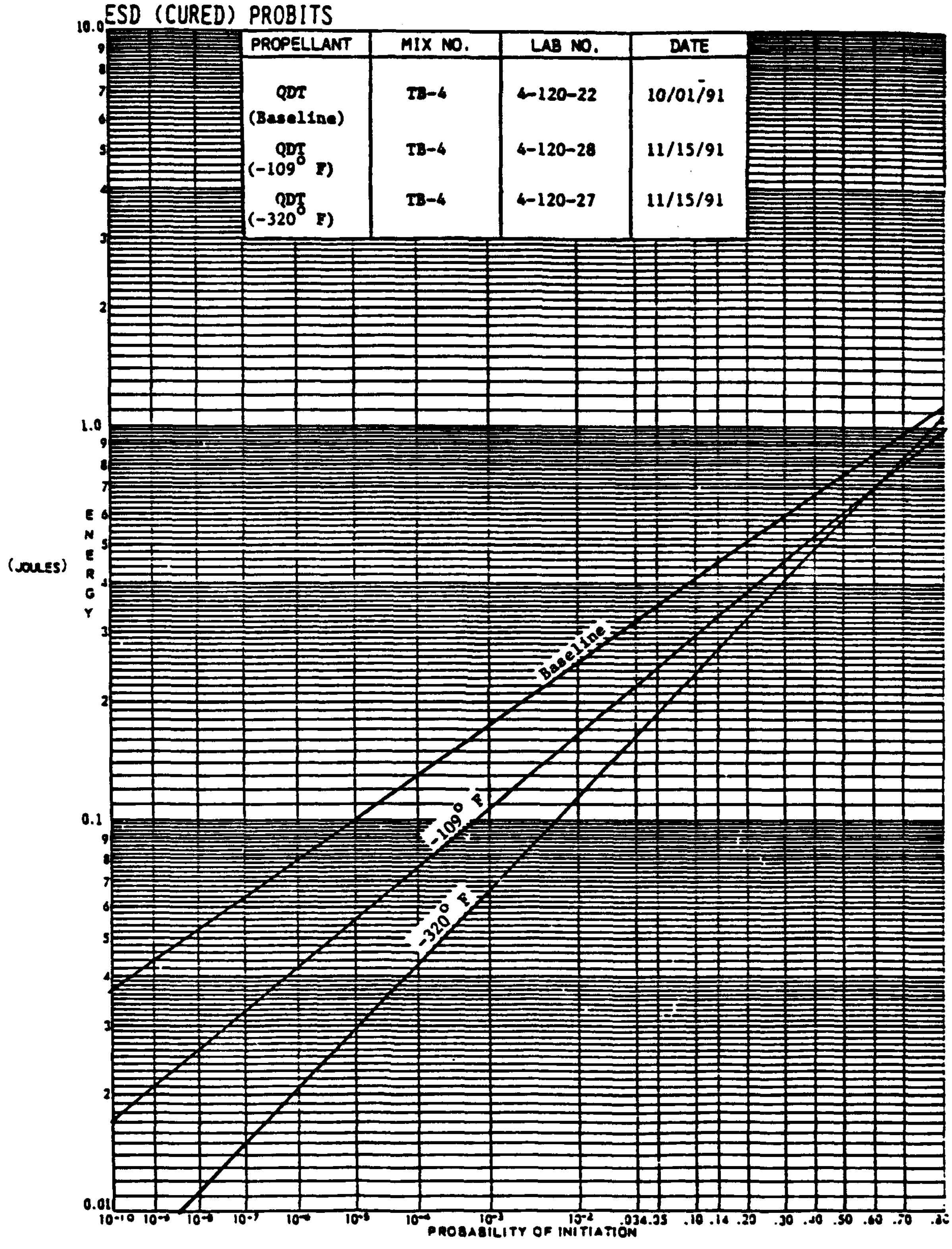


Figure A12. Friction Sensitivity for Hand Ground Temperature Cycled CMDB Propellant



PROPELLANT	MIX NO.	LAB NO.	DATE
QDT (Baseline)	TB-4	4-120-22	10/01/91
QDT (-109° F)	TB-4	4-120-28	11/15/91
QDT (-320° F)	TB-4	4-120-27	11/15/91

Figure A13. Electrostatic Discharge Sensitivity for HTPB Propellant at Ambient and Cryogenic Temperatures

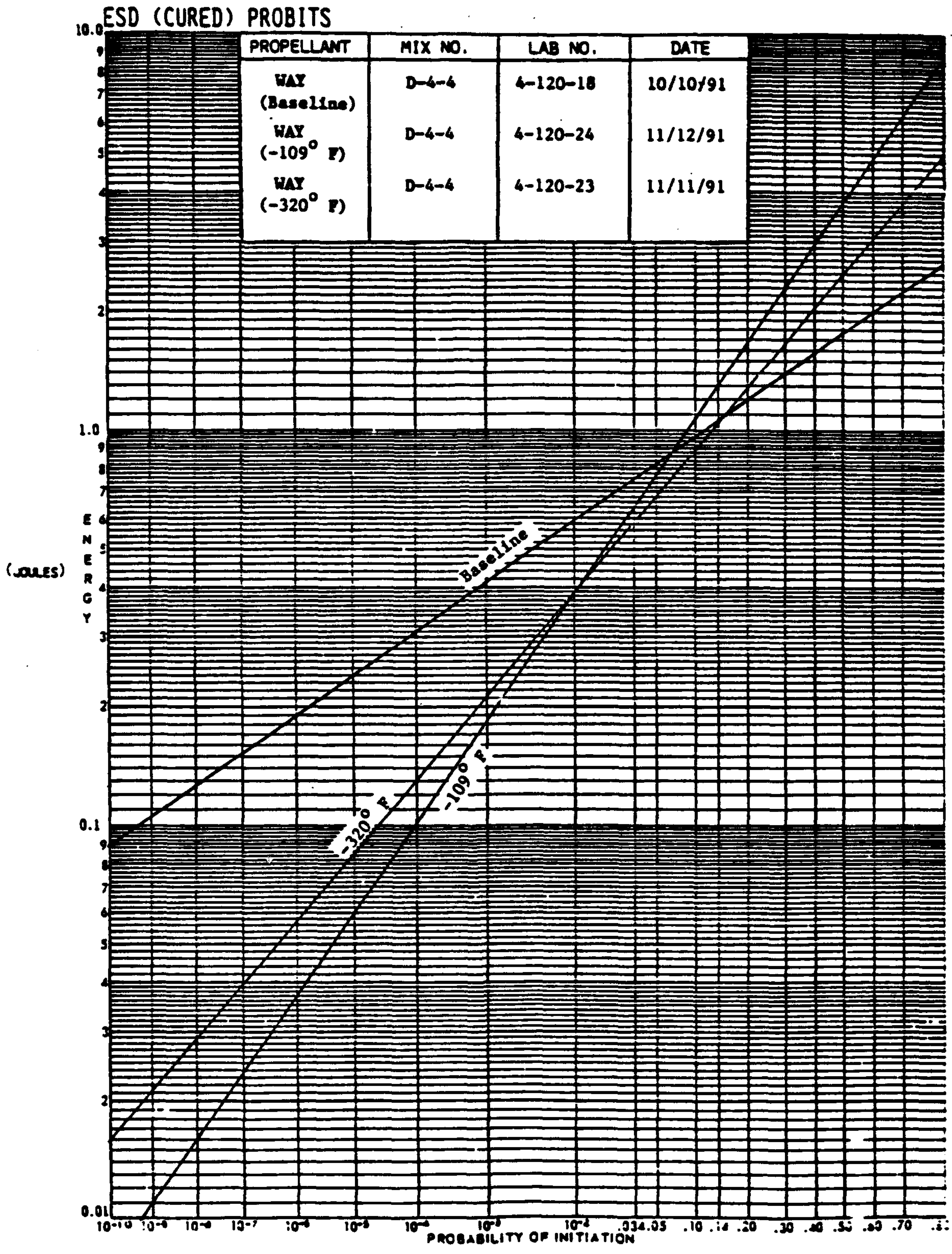


Figure A14. Electrostatic Discharge Sensitivity for XLDB Propellant at Ambient and Cryogenic Temperatures

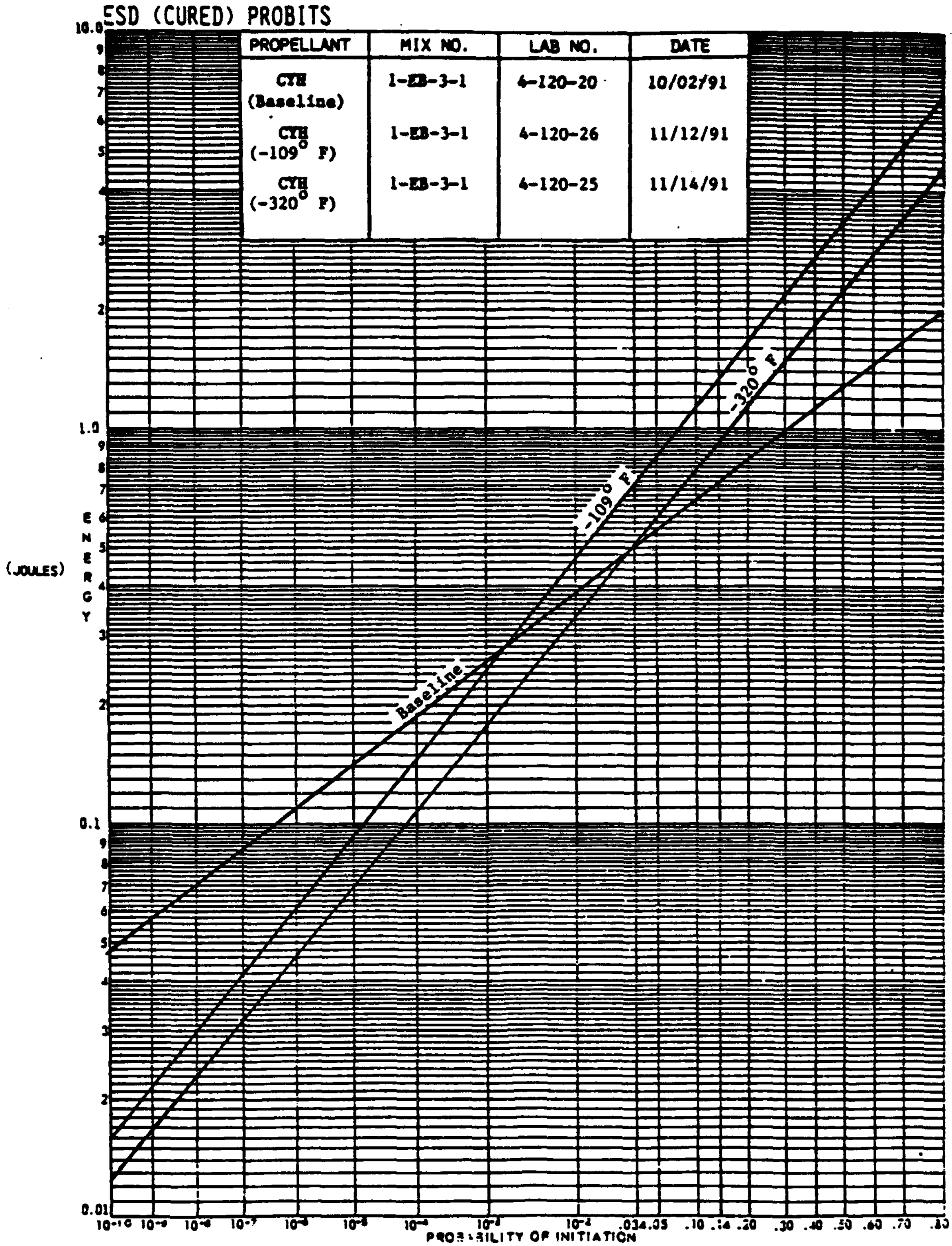


Figure A15. Electrostatic Discharge Sensitivity for CMDB Propellant at Ambient and Cryogenic Temperatures

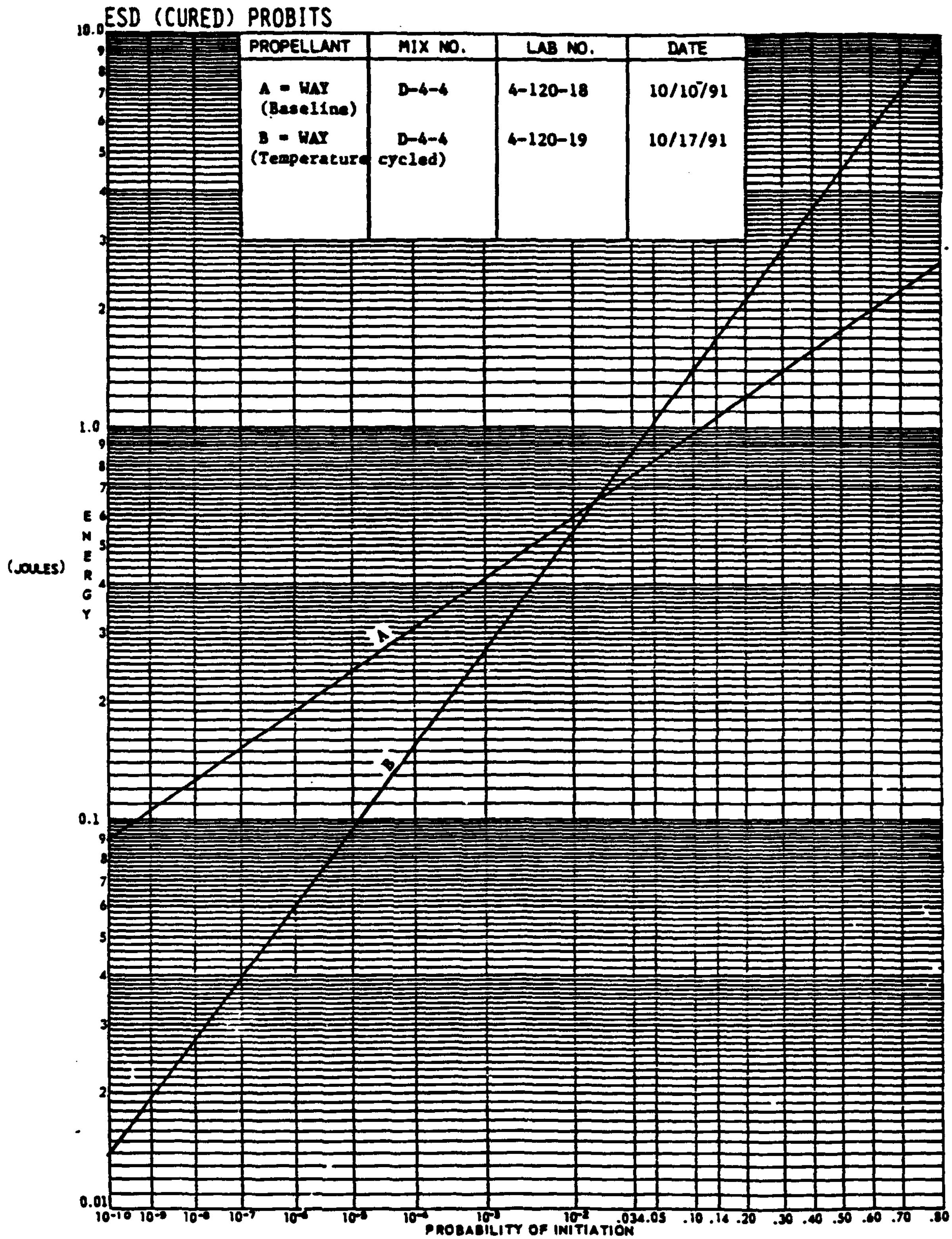


Figure A16. Electrostatic Discharge Sensitivity for Temperature Cycled XLDB Propellant

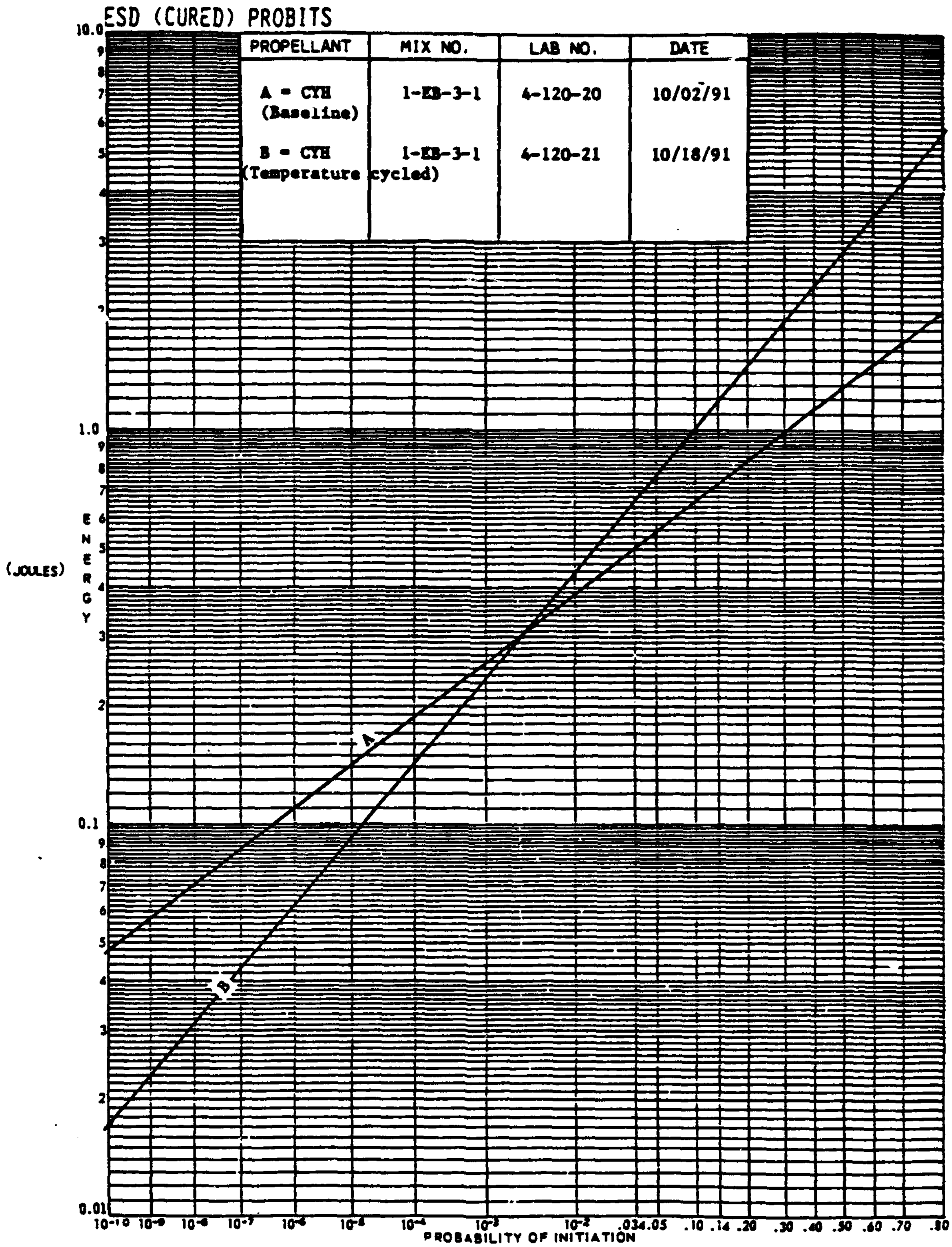


Figure A17. Electrostatic Discharge Sensitivity for Temperature Cycled CMDB Propellant

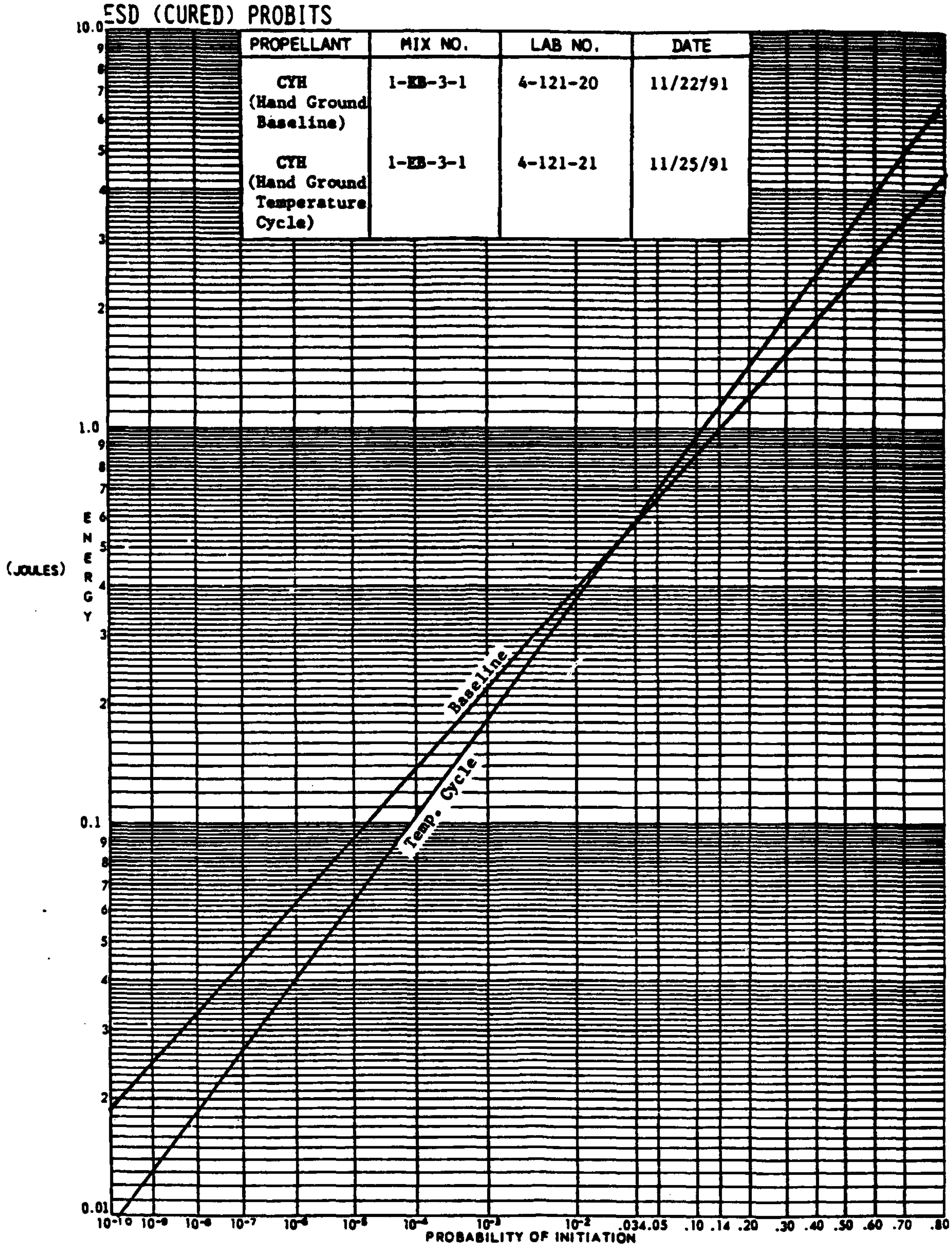


Figure A18. Electrostatic Discharge Sensitivity for Hand Ground Temperature Cycled CMDB Propellant

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APPENDIX B

TASK 1 PROPELLANT SAMPLE PHOTOGRAPHS

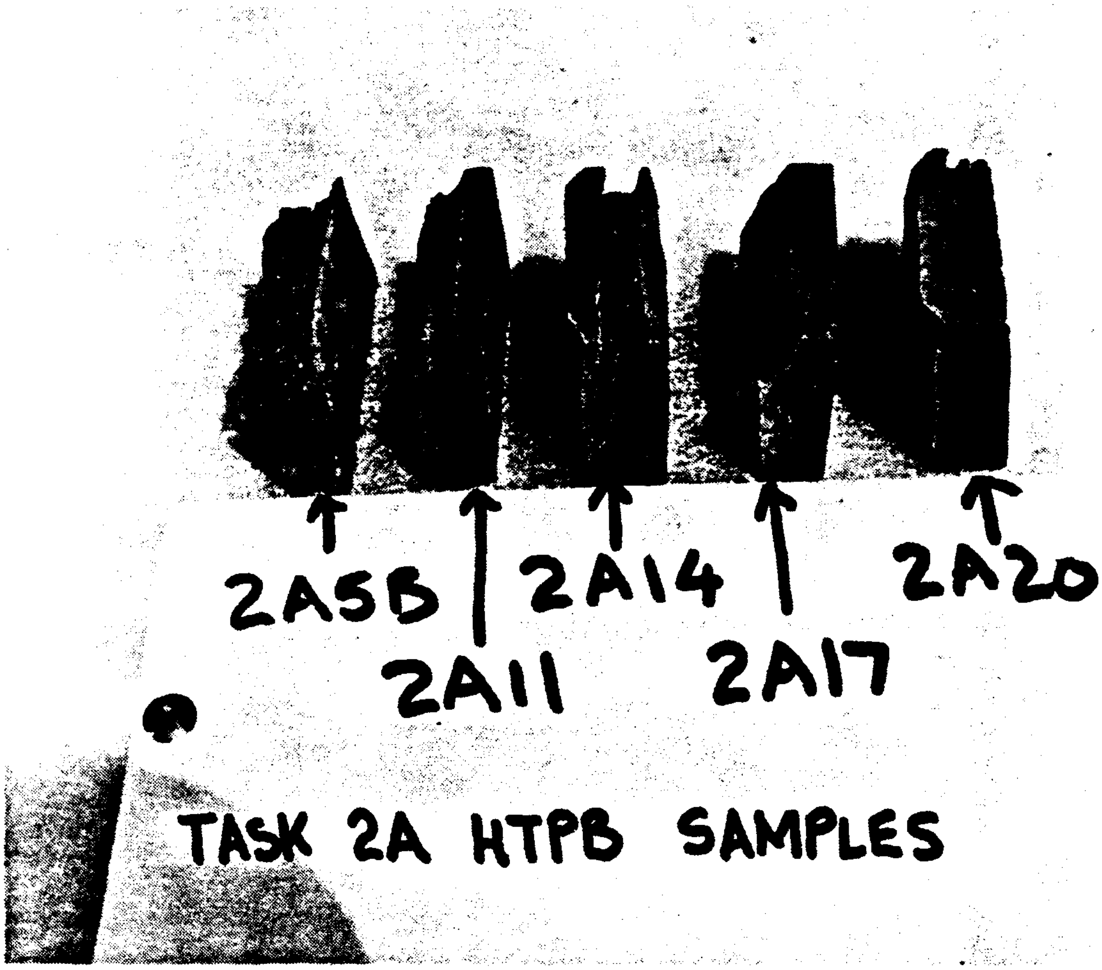

Figure B1. Task 2A HTPB Samples

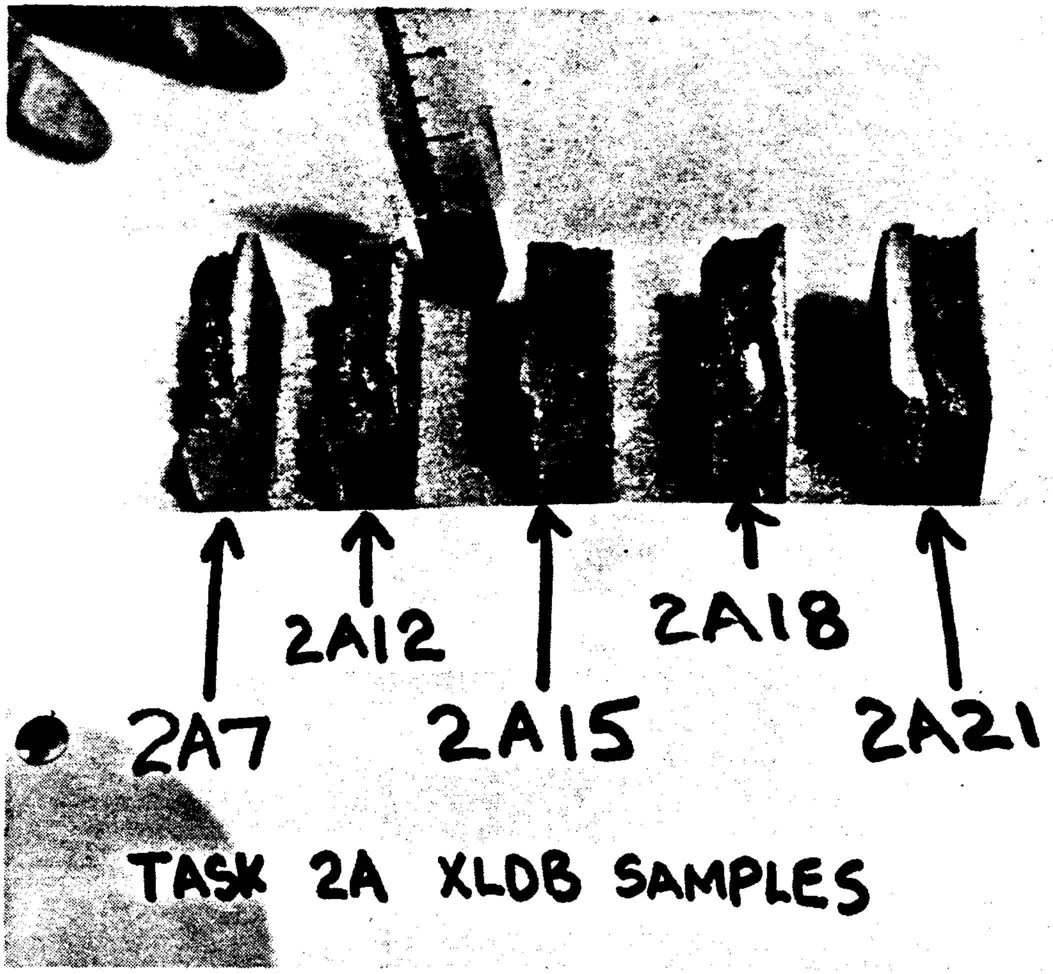

Figure B2. Task 2A XLDB Samples

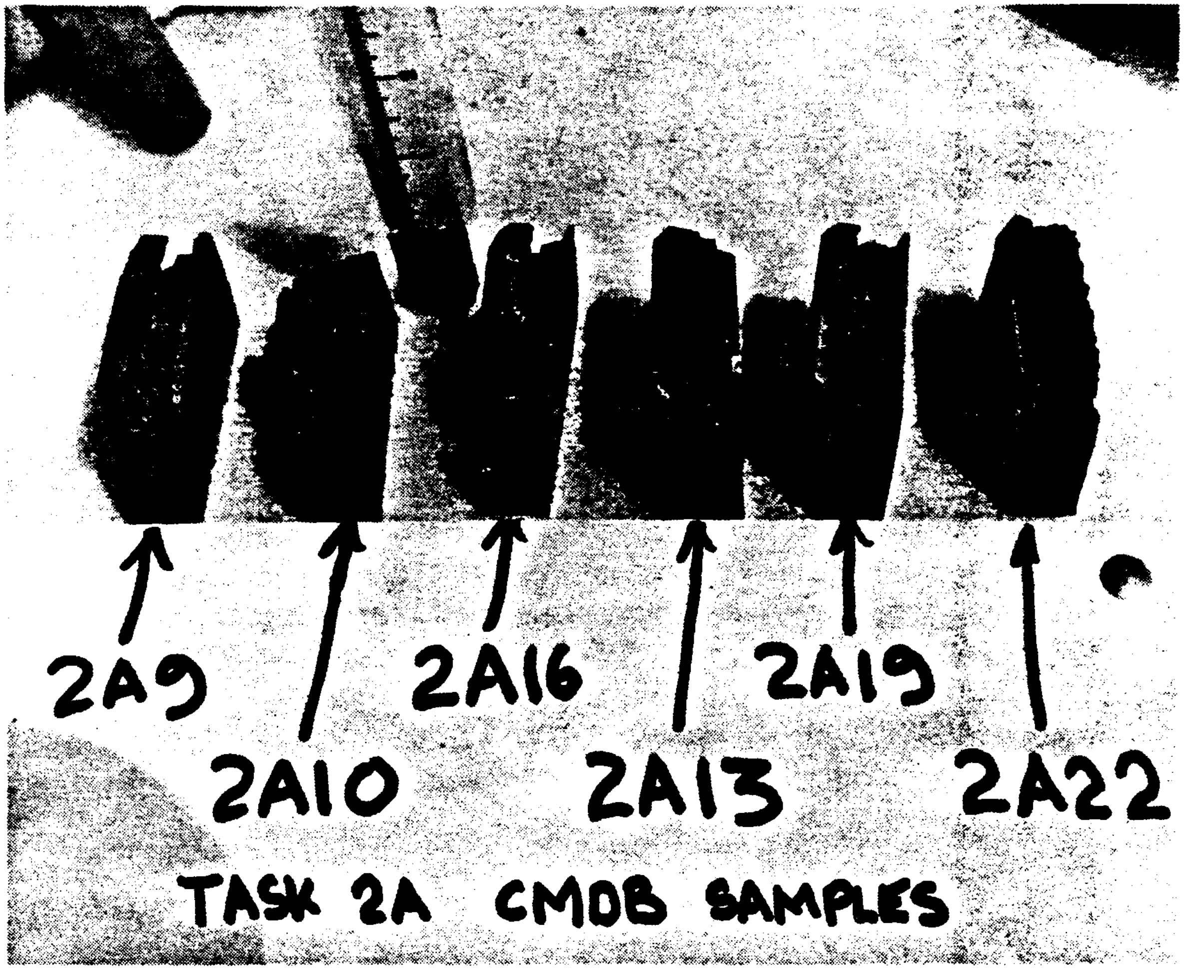

Figure B3. Task 2A CMDB Samples

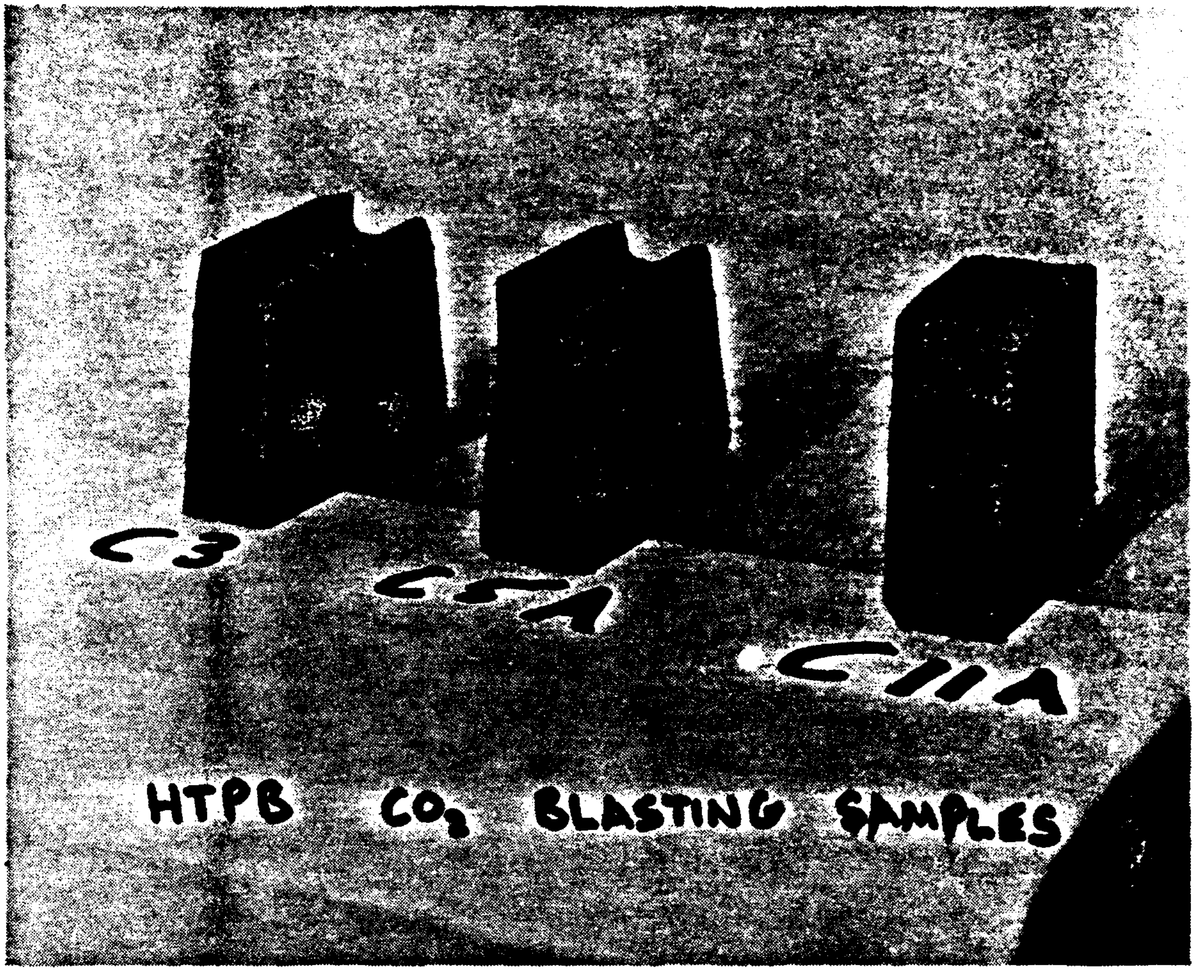

Figure B4. Task 2 HTPB CO_2 Pellet Blasting Samples

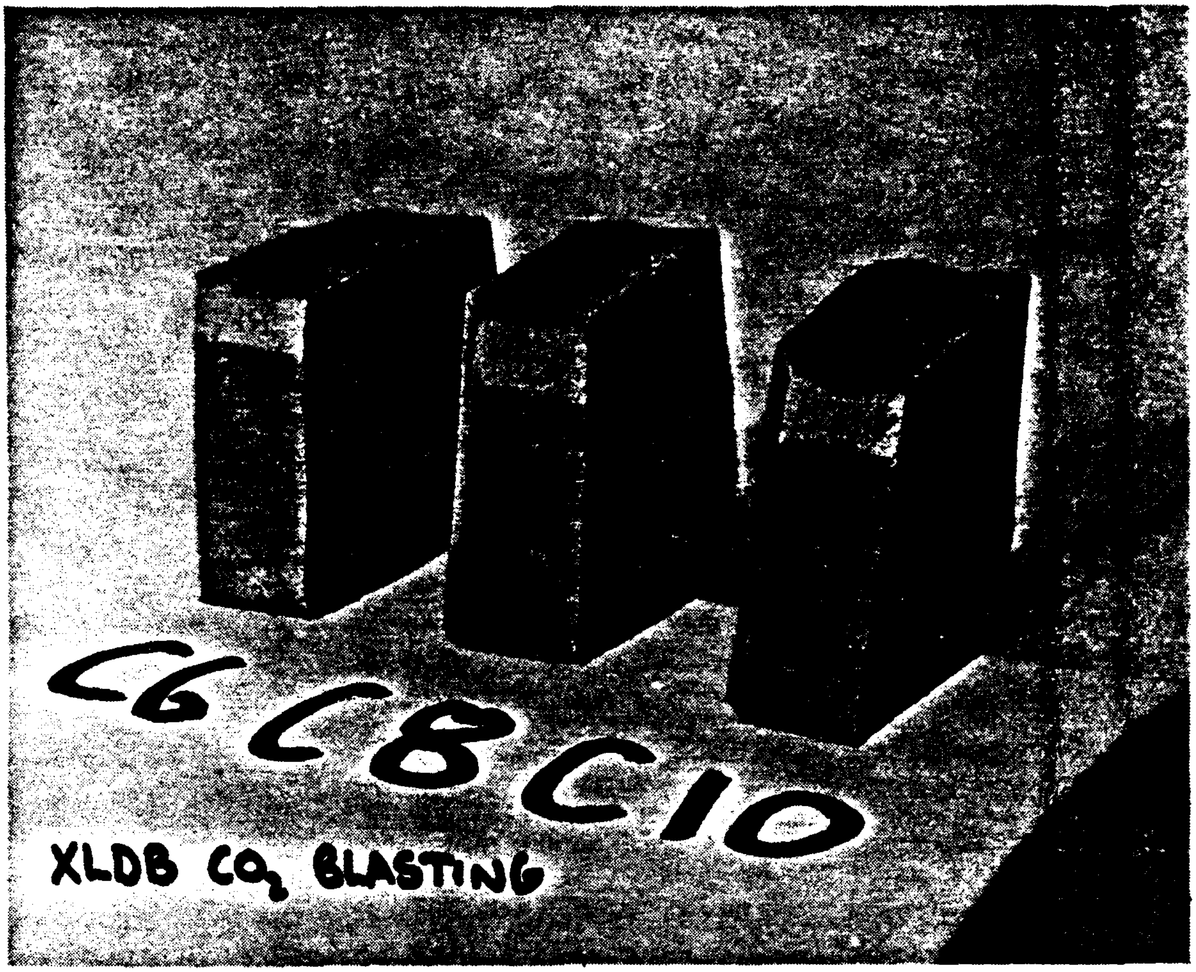

Figure B5. Task 2 XLDB CO_2 Pellet Blasting Samples

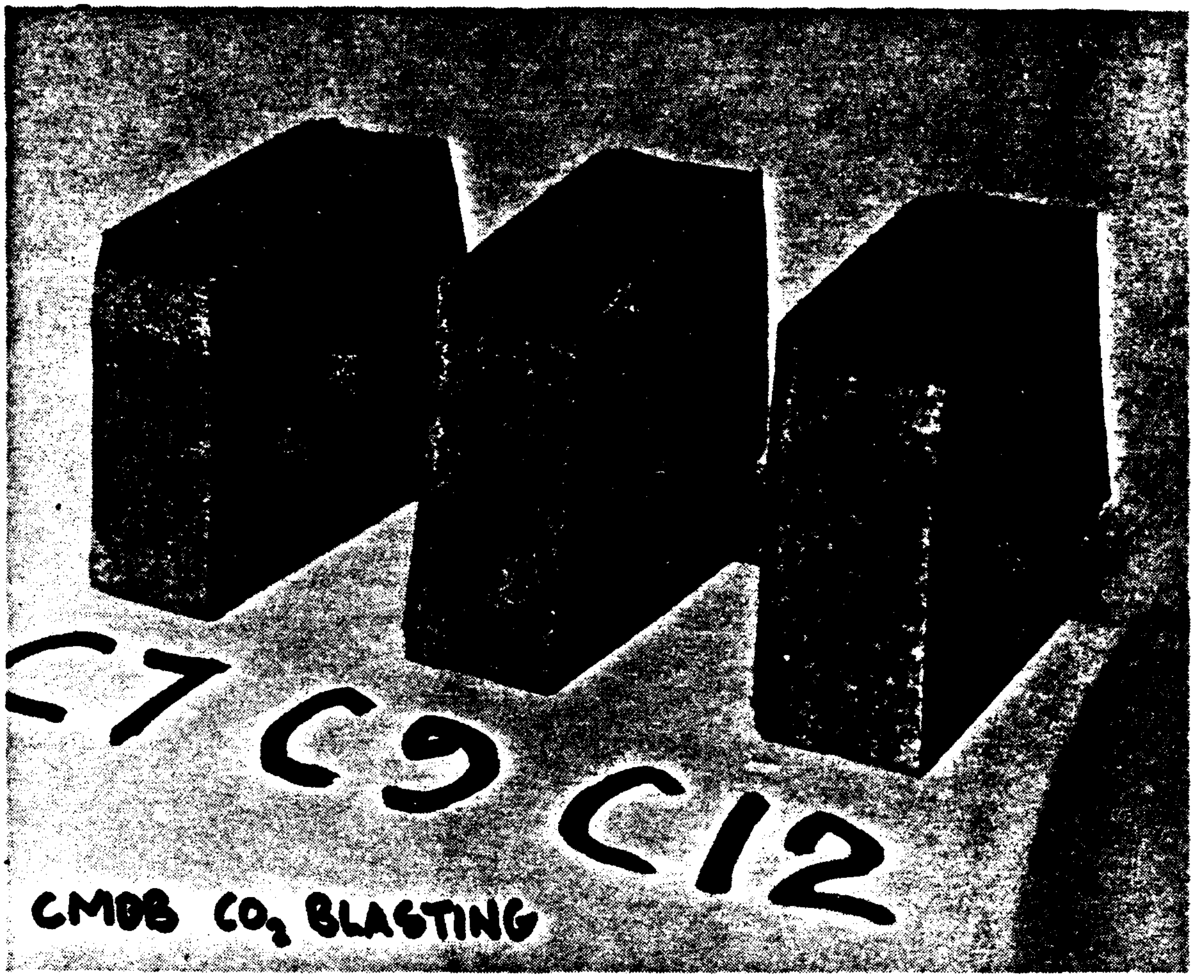

Figure B6. Task 2 CMDB CO_2 Pellet Blasting Samples

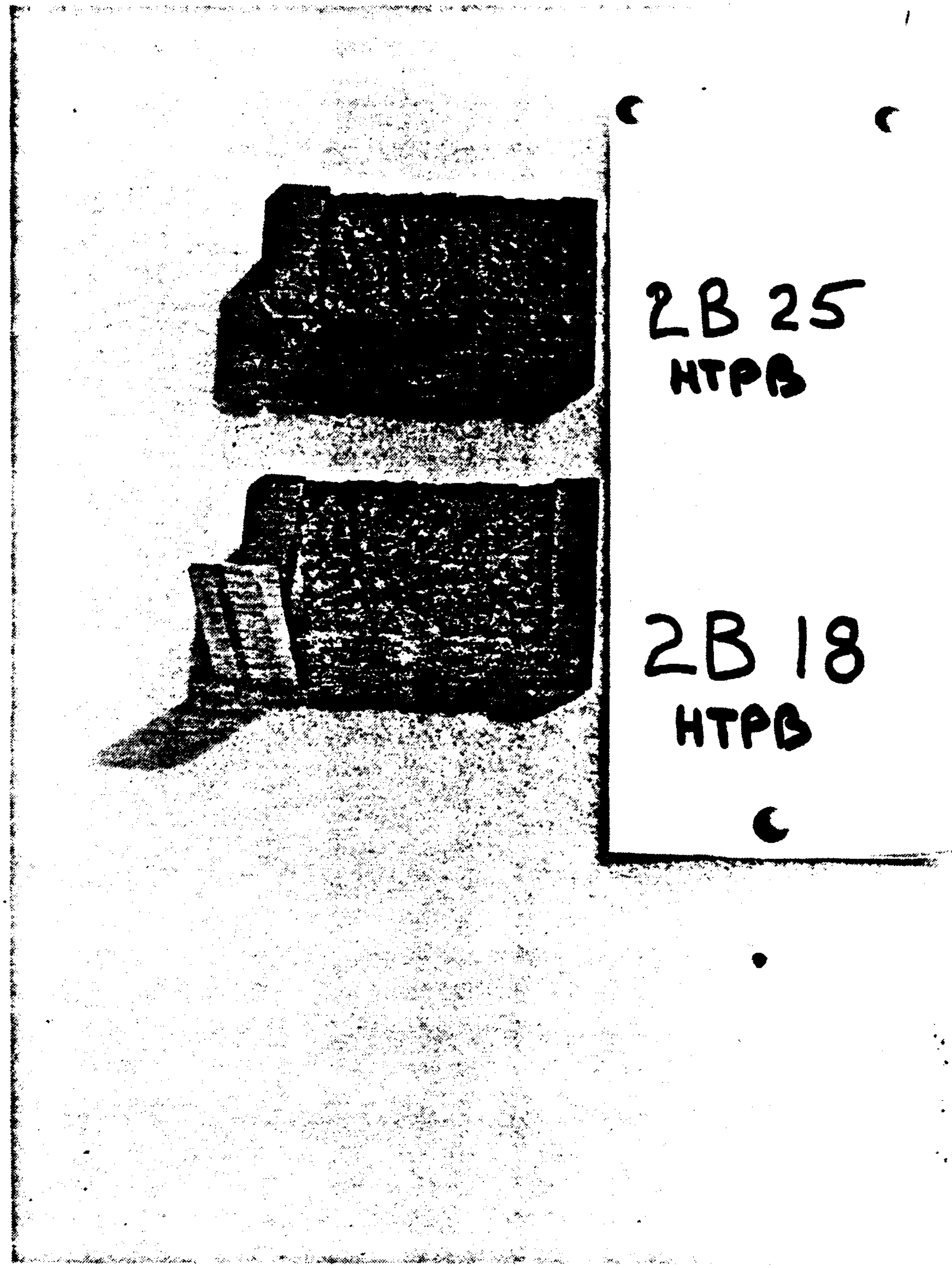

Figure B7. Task 2B HTPB Samples 2B18 and 2B25
(Top view)

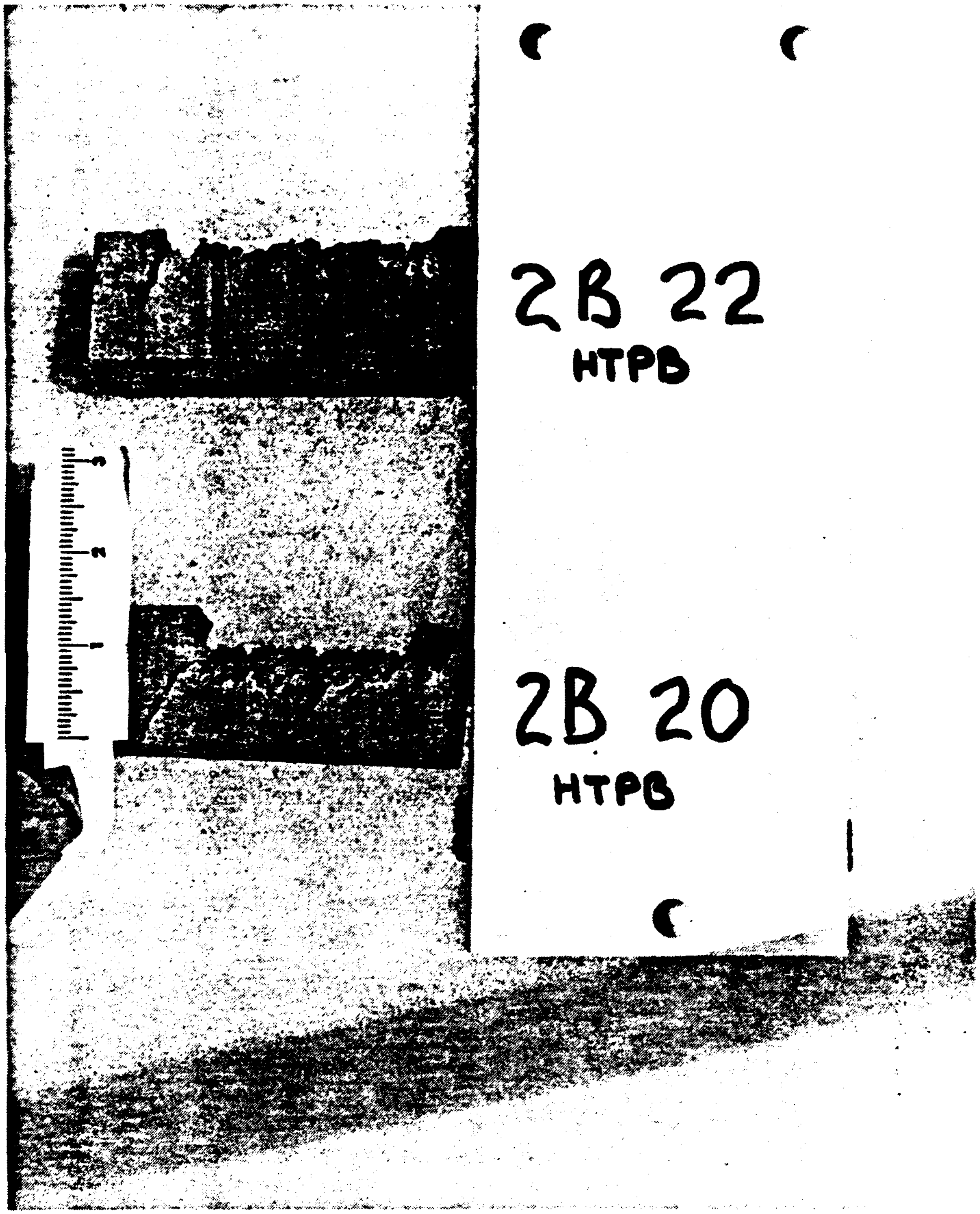

Figure B8. Task 2B HTPB Samples 2B20 and 2B22 (Sectioned)

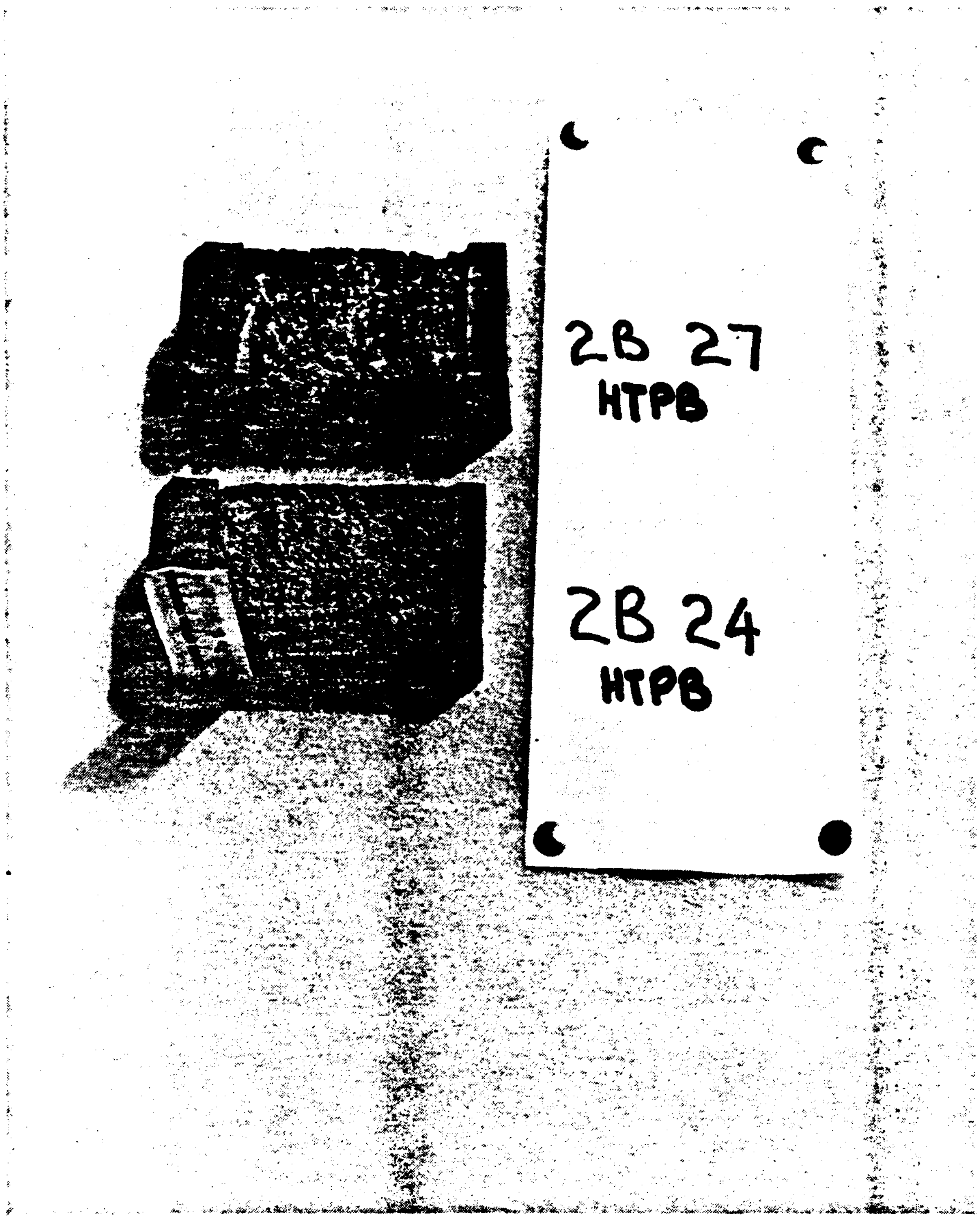

Figure B9. Task 2B HTPB Samples 2B24 and 2B27
(Top view)

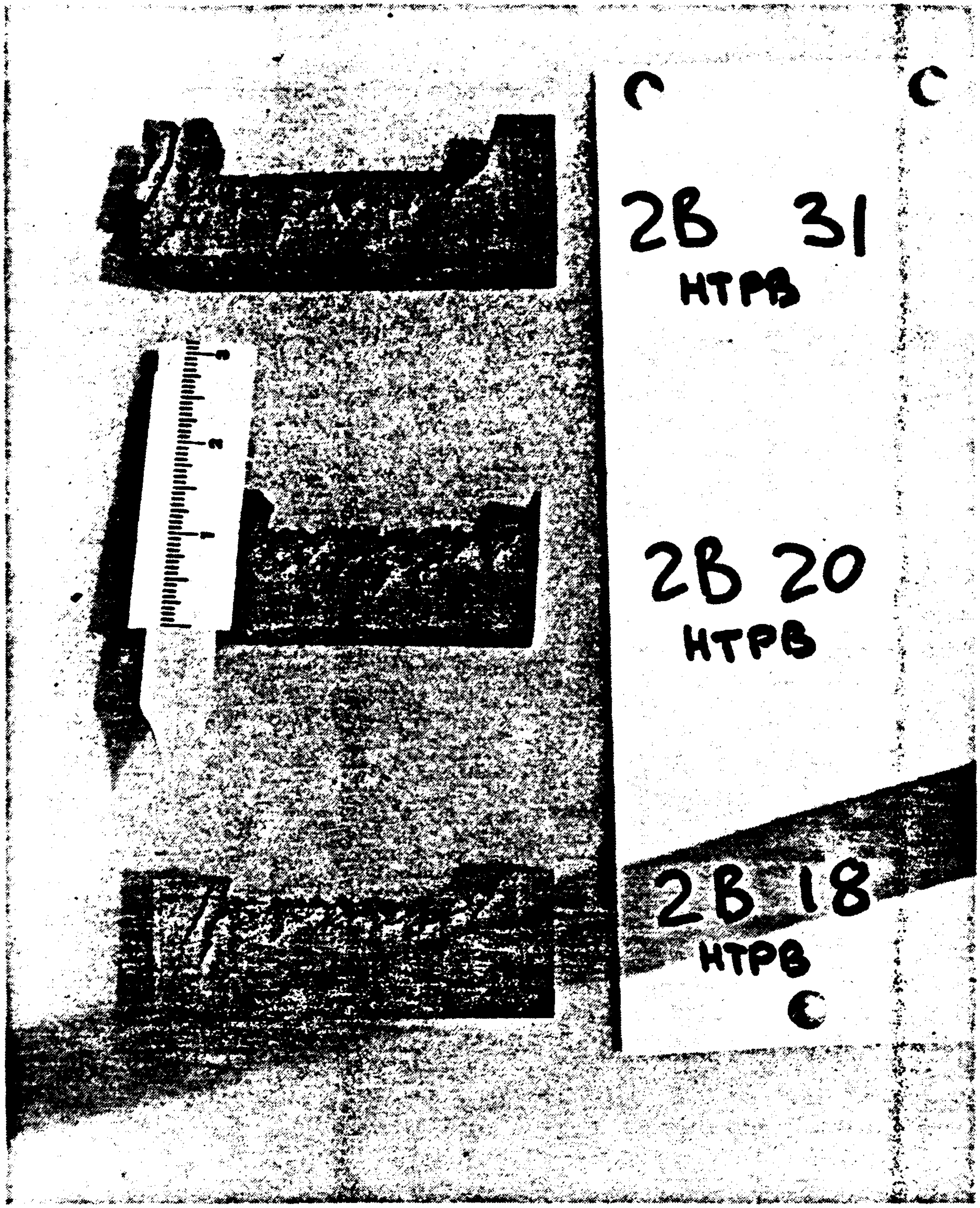

Figure B10. Task 2B HTPB Samples 2B18, 2B20, and 2B31 (Sectioned)

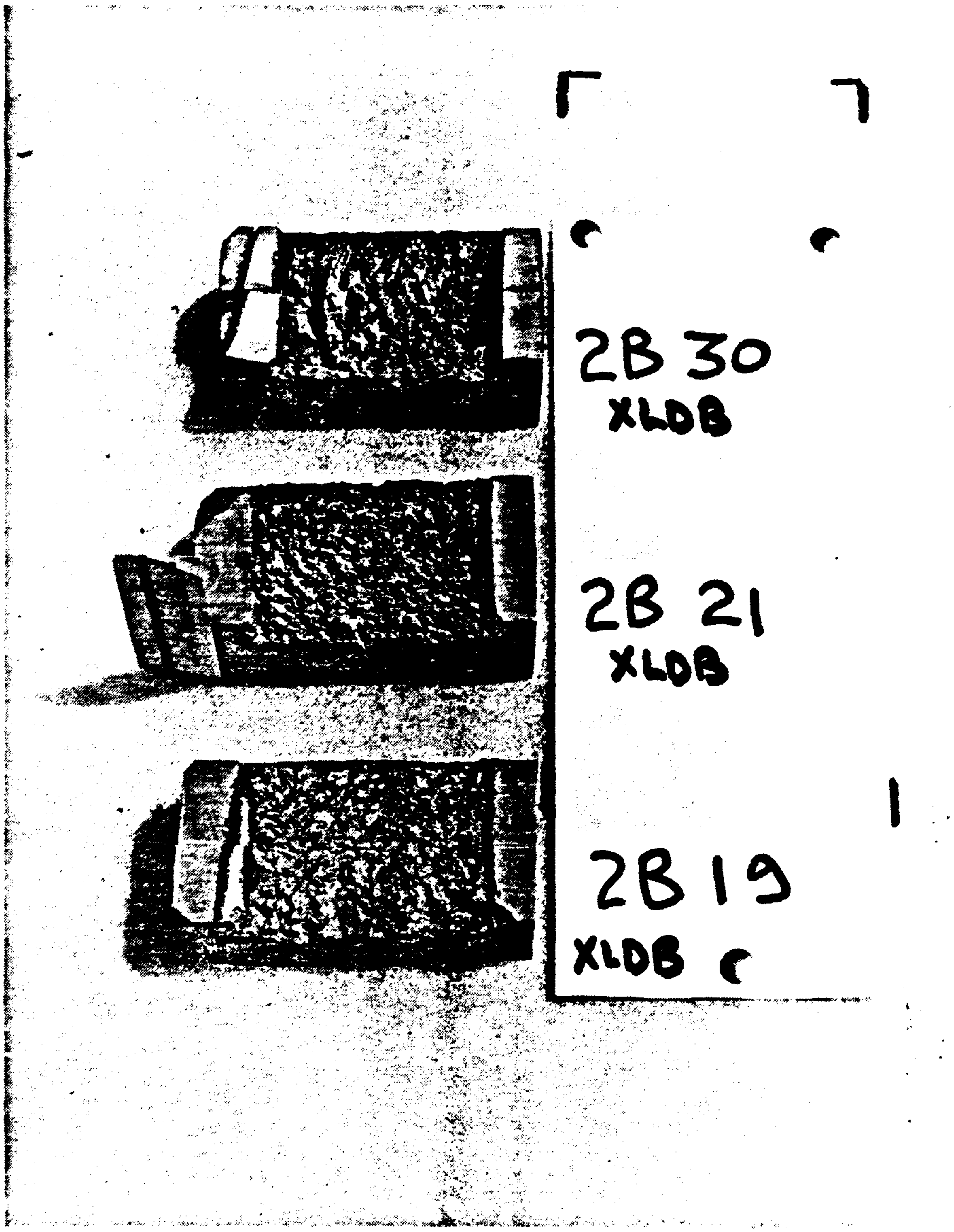

Figure B11. Task 2B XLDB Samples 2B19, 2B21, and 2B30
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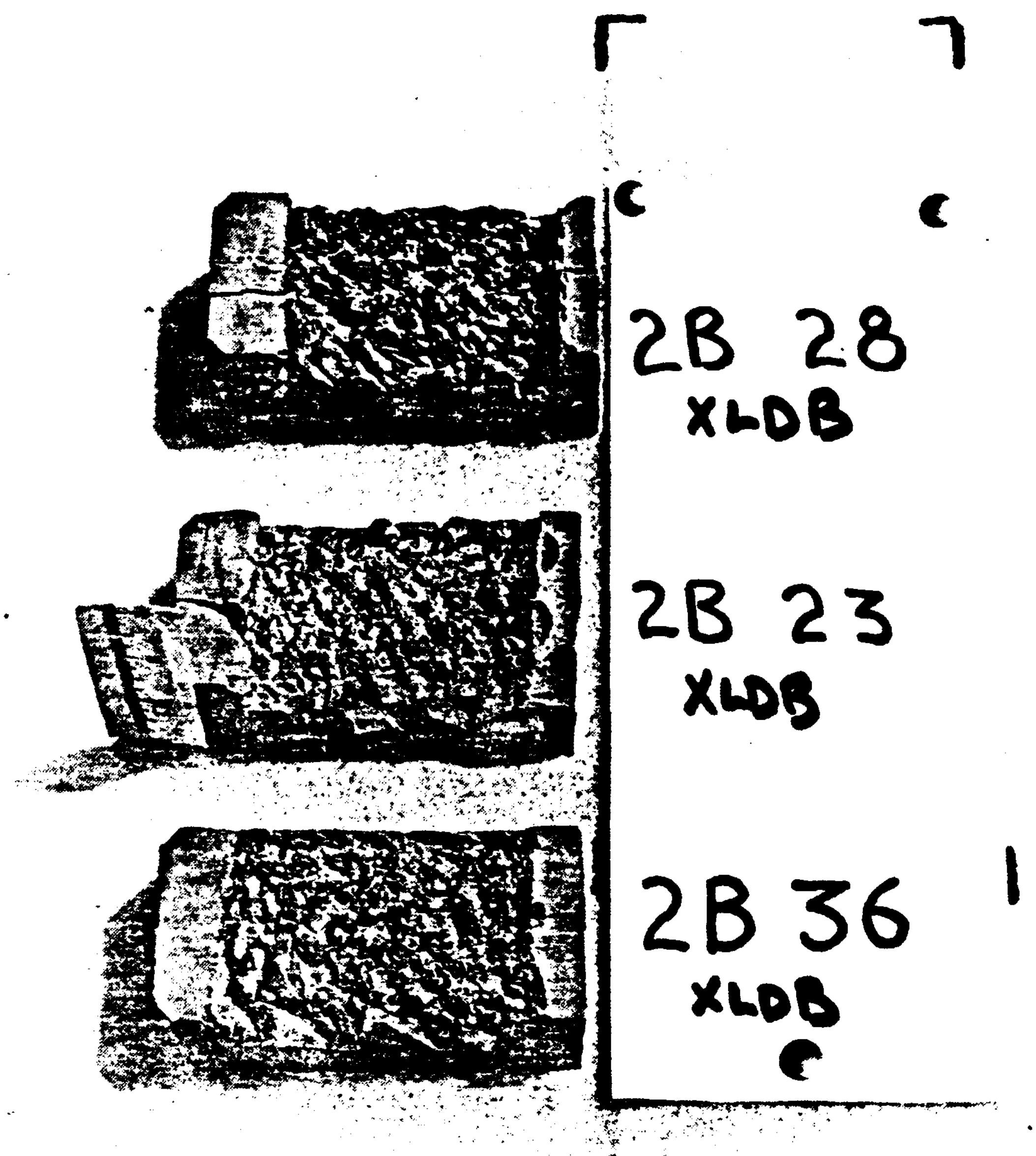

Figure B12. Task 2B XLDB Samples 2B36, 2B23, and 2B28 (Top view)

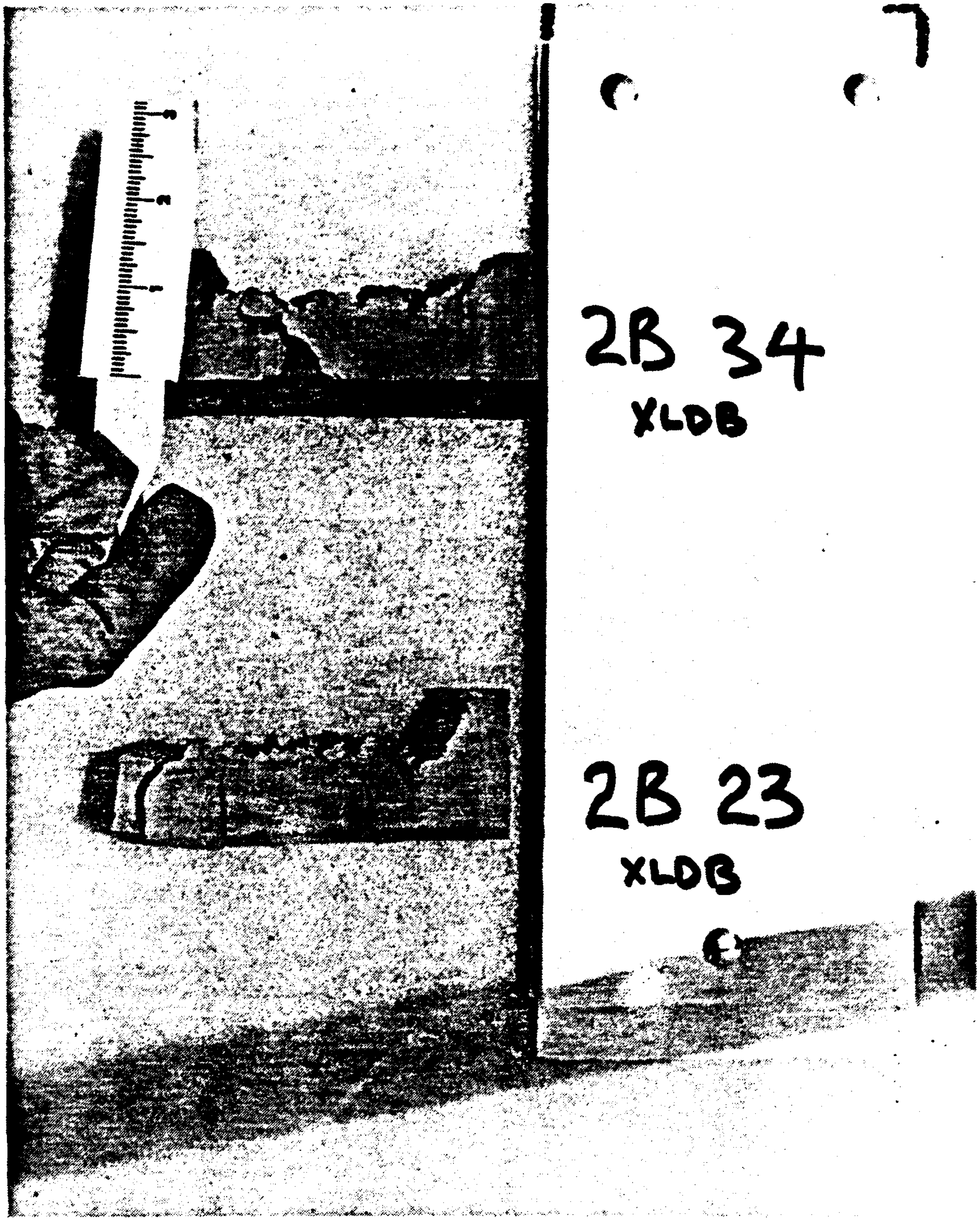

Figure B13. Task 2B XLDB Samples 2B23 and 2B34 (Sectioned)

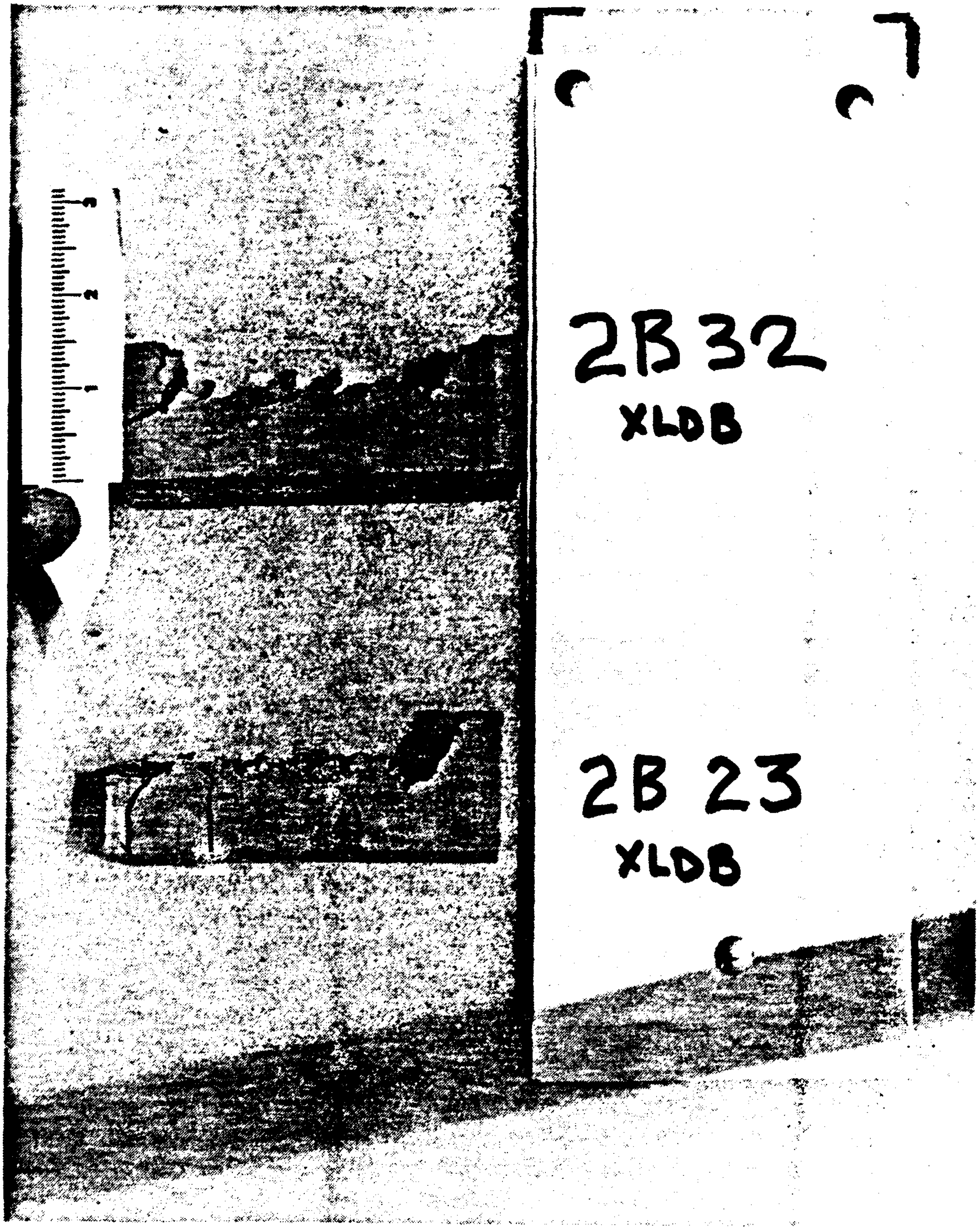

Figure B14. Task 2B XLDB Samples 2B23 and 2B32 (Sectioned)

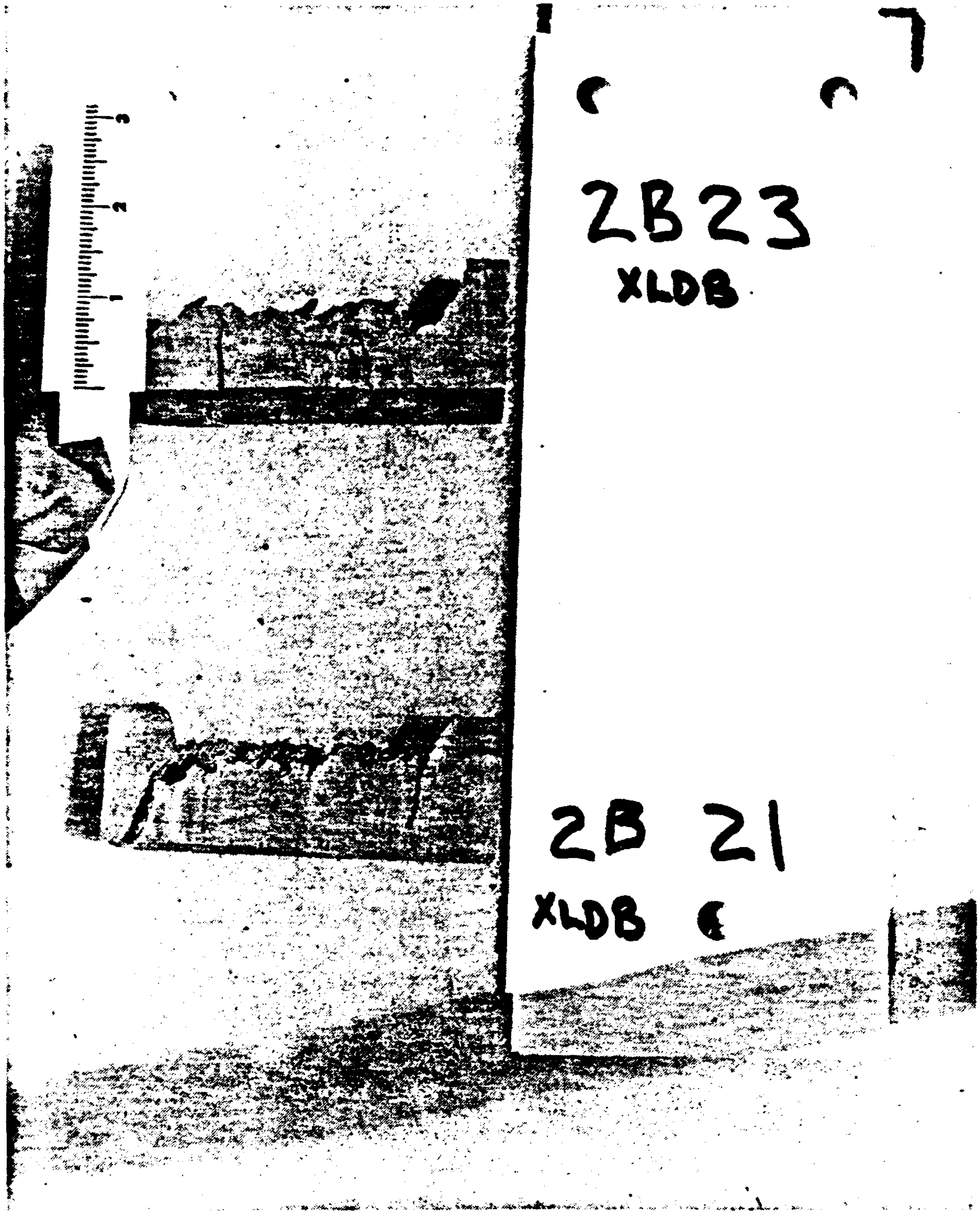

Figure B15. Task 2B XLDB Samples 2B21 and 2B23 (Sectioned)

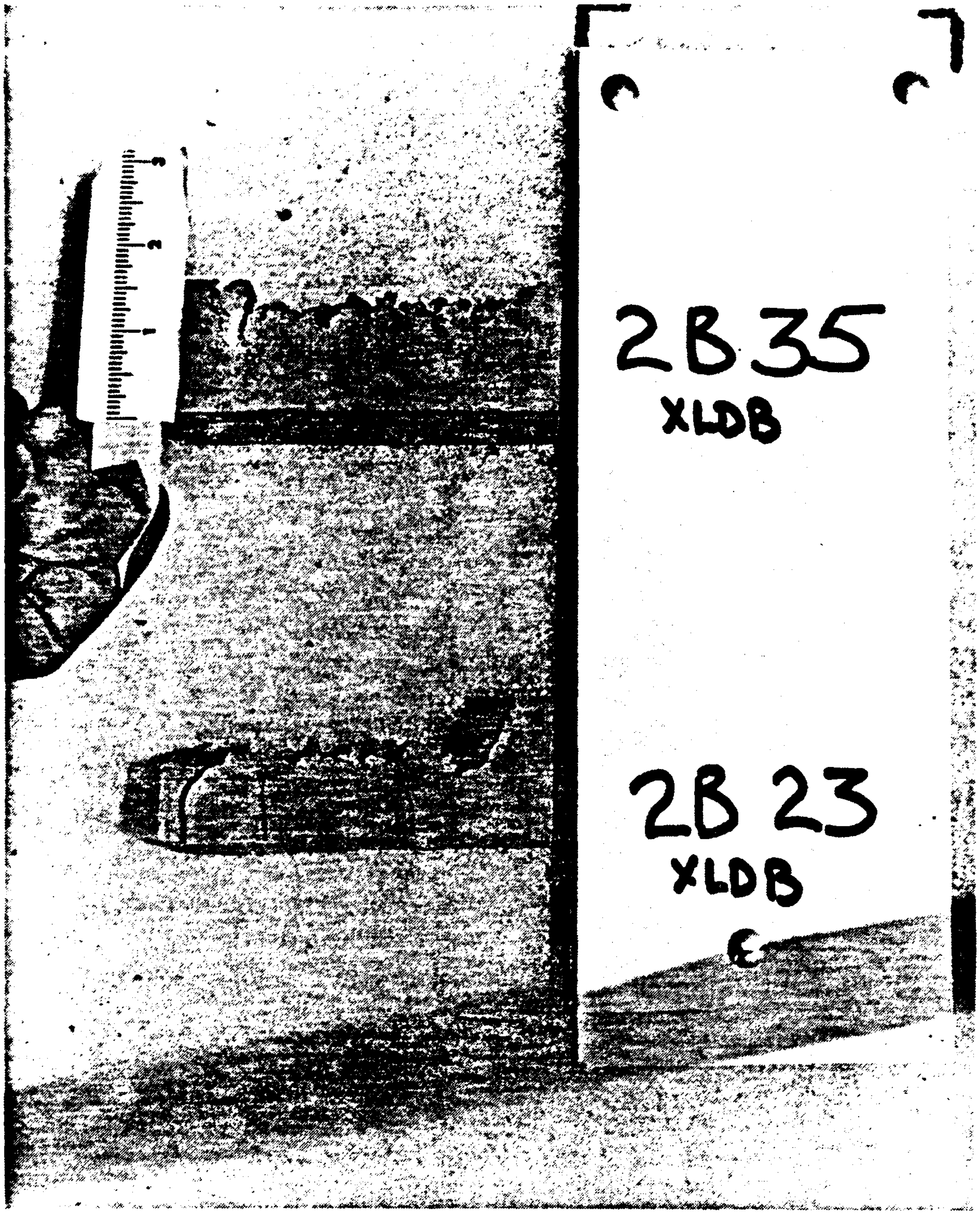

Figure B16. Task 2B XLDB Samples 2B23 and 2B35 (Sectioned)

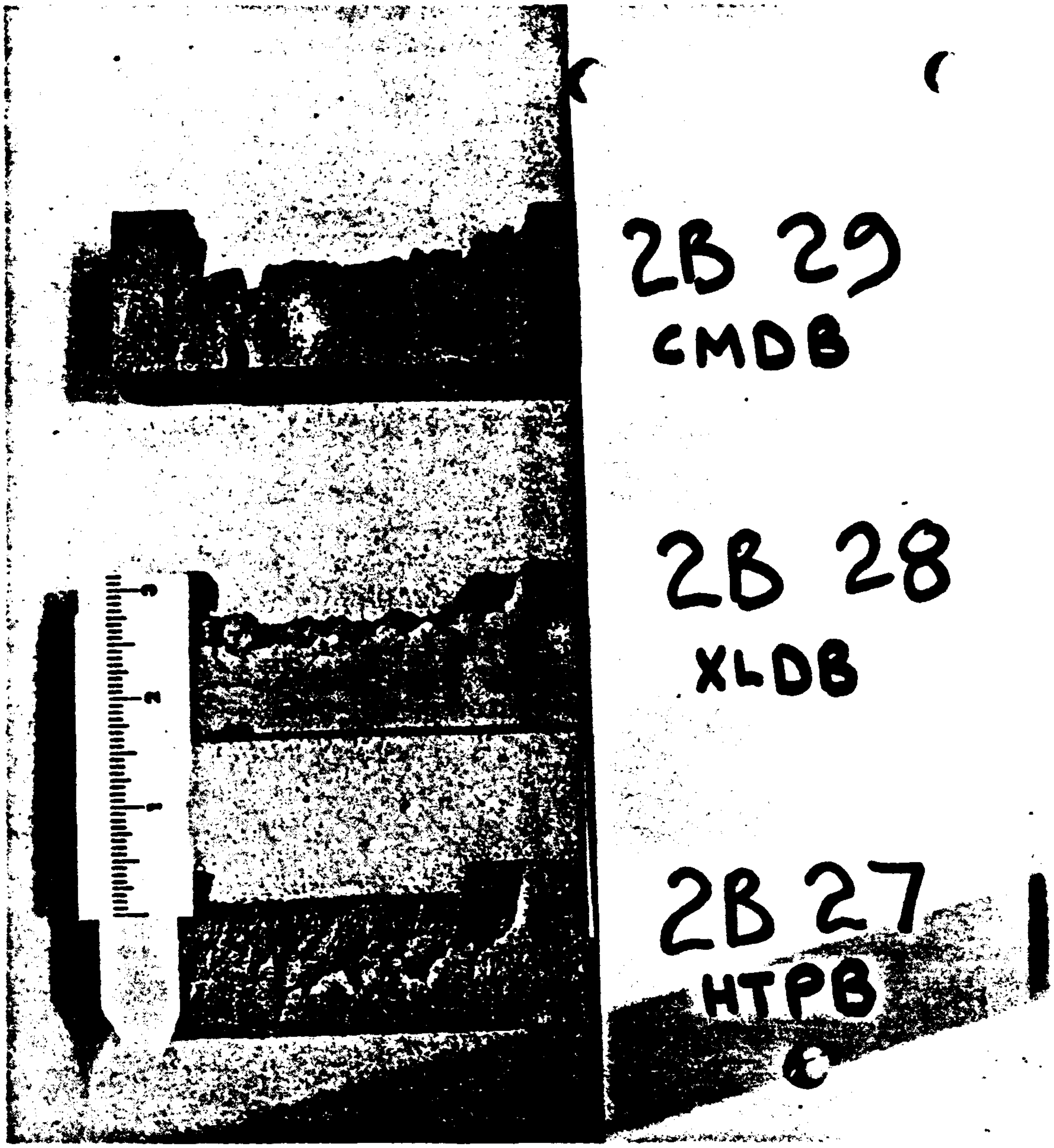

Figure B17. Task 2B Samples 2B27, 2B28, and 2B29 (Sectioned)

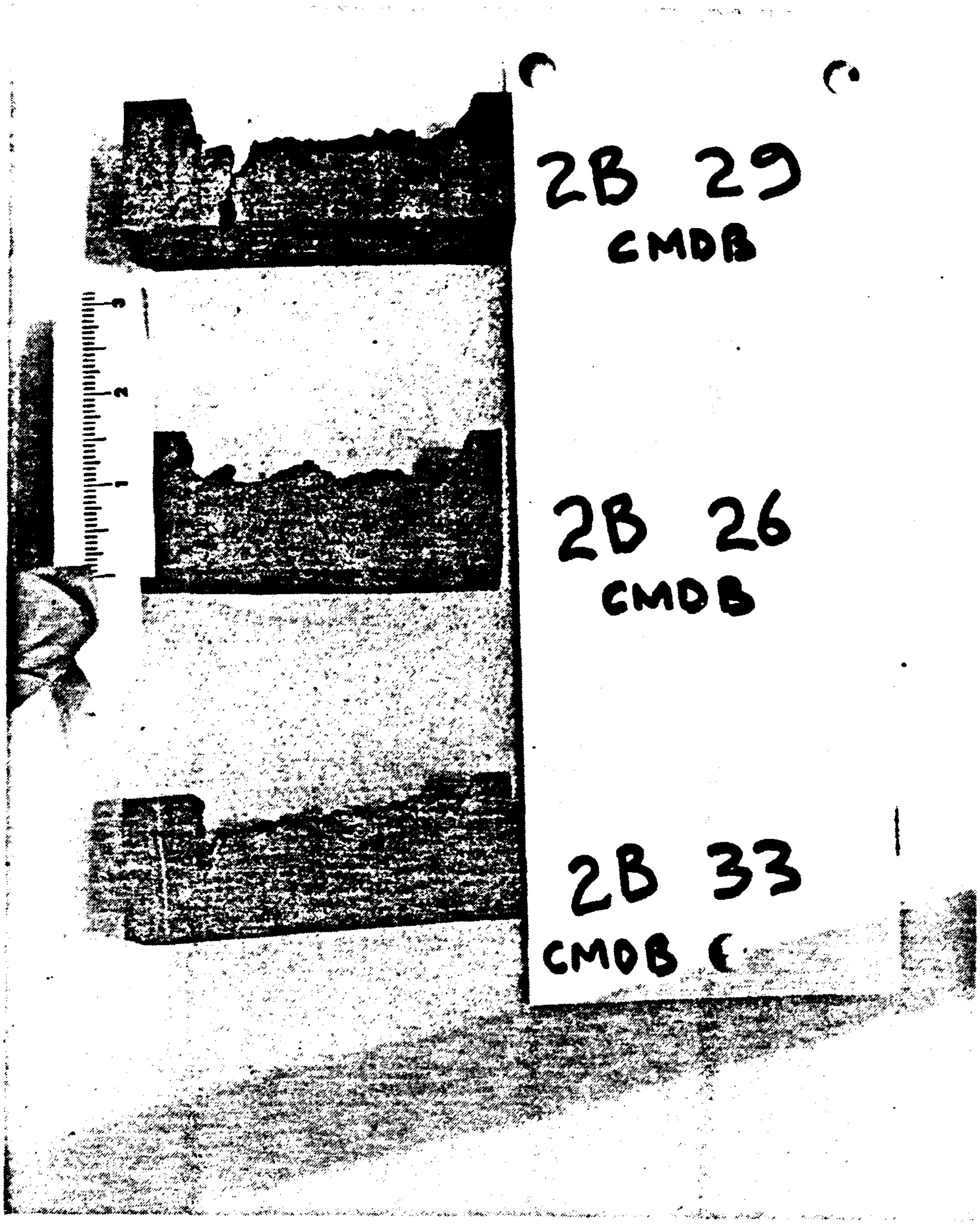

Figure B18. Task 2B CMDB Samples 2B33, 2B26, and 2B29 (Sectioned)

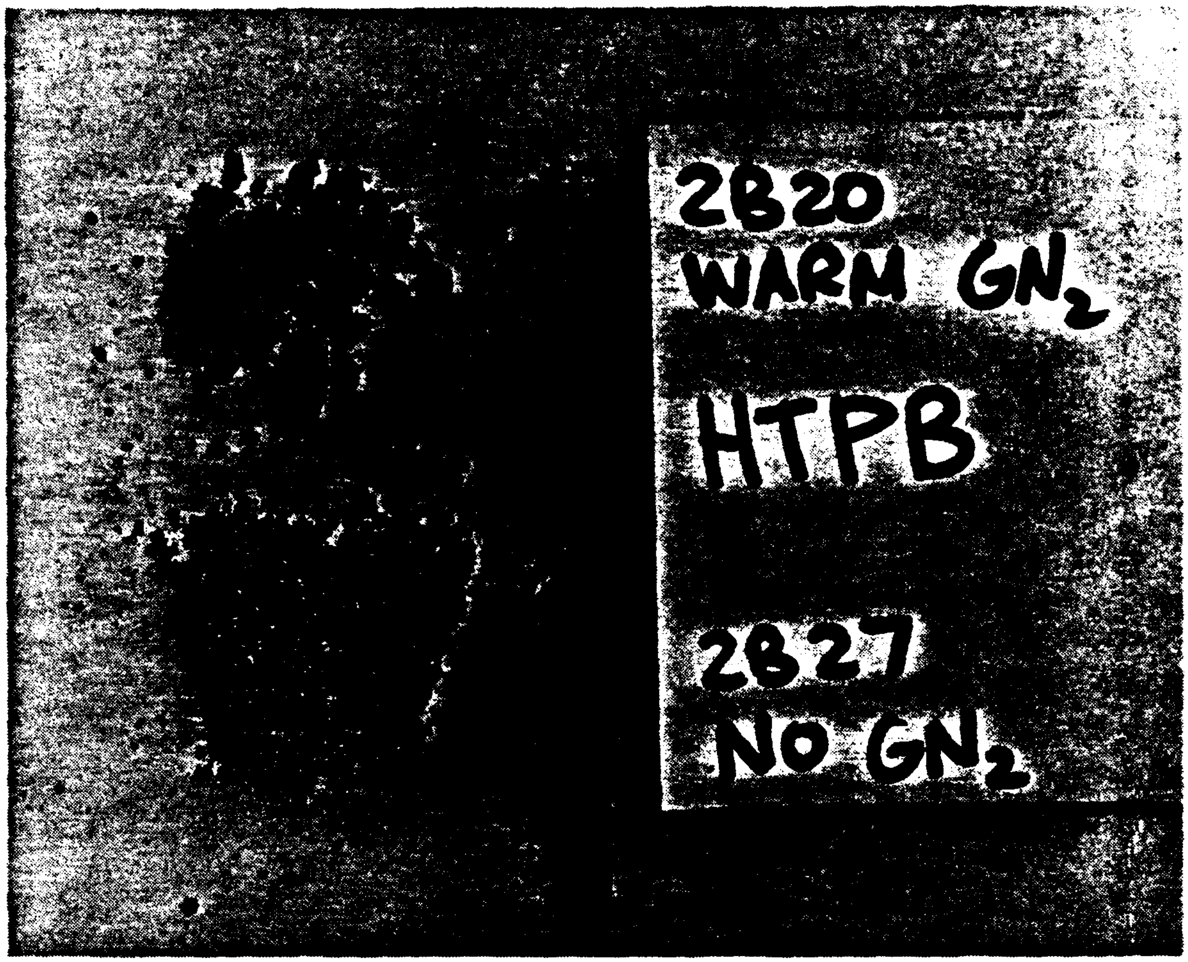

Figure B19. Washed out HTPB Propellant from Task 2B

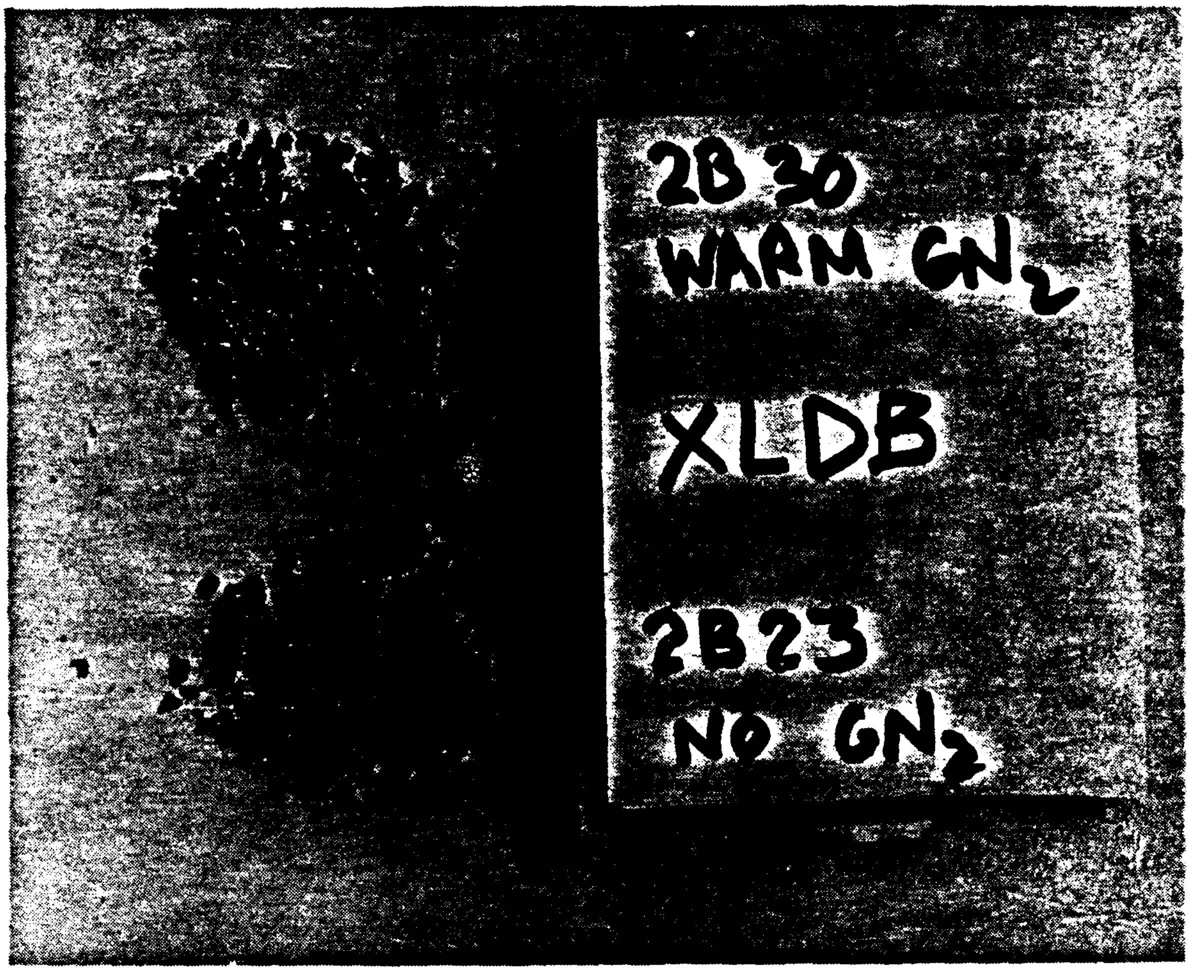

Figure B20. Washed out XLDB Propellant from Task 2B

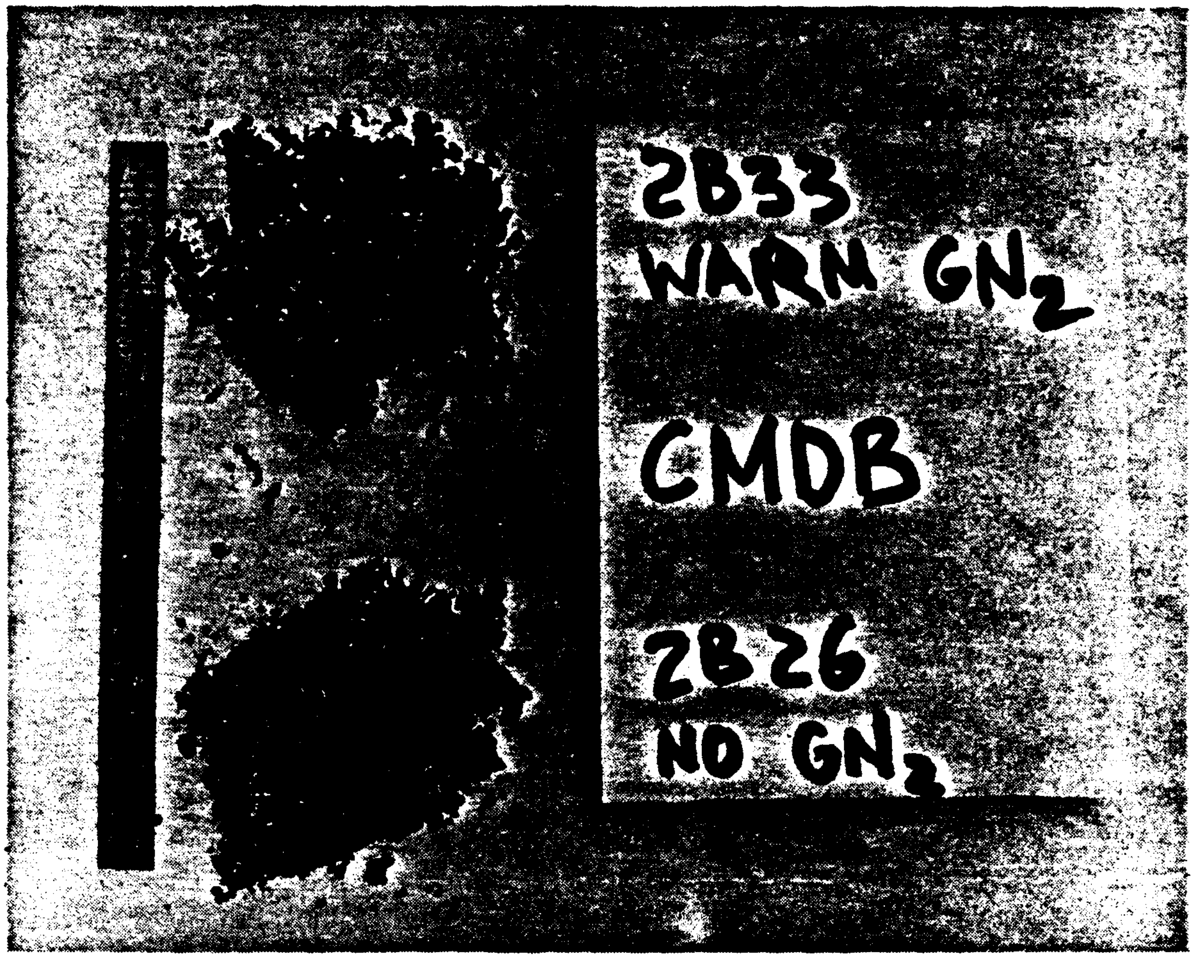

Figure B21. Washed out CMDB Propellant from Task 2B