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by

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1.0 Introduction

This report covers the technical effort on contract 9-X28-7959R-1 through February, 1989. This effort was directed towards the technology associated with the development of a large scale, long pulse DF-CO₂ chemical laser. Optics damage studies performed under Task 1 assessed damage thresholds for diamond-turned salt windows. Task 2 is a multi-faceted task involving the use of PHOCL-50 for laser gain measurements, LTI experiments, and detector testing by LANL personnel. To support these latter tests, PHOCL-50 was upgraded with Boeing funding to incorporate a full aperture outcoupler that increased its energy output by over a factor of 3, to a full kilojoule. The PHOCL-50 carbon block calorimeter was also recalibrated and compared with the LANL Sciencetech meter. Cloud clearing studies under Task 3 initially concentrated on delivering a Boeing built Cloud Simulation Facility to LANL, and currently involves design of a Cold Cloud Simulation Facility. A Boeing IRAD funded theoretical study on cold cloud clearing revealed that ice clouds may be easier to clear than warm clouds. Task 4 involves the theoretical and experimental study of flow system design as related to laser beam quality. Present efforts on this task are concentrating on temperature gradients induced by the gas filling process. General support for the LPCL field effort is listed under Task 5, with heavy emphasis on assuring reliable operation of the Boeing built Large Slide Valve and other device related tests. The modification of the PHOCL-50 system for testing long pulse DF (4 μ m only) chemical laser operation is being done under Task 6.

2.0 NaCl WINDOW DAMAGE STUDIES (TASK 1)

2.1 Objectives

The primary objectives for laser damage measurements during this task were to further assess two specific AR coatings for NaCl windows, and to answer a series of critical questions concerning uncoated NaCl windows. Due to a requirement for high precision, which would provide definitive answers particularly to the questions about bare salt, significant improvements were made in the measurements of both beam spatial profile and energy on target.

Distinguishing features of this unit of work are: (a) the use of 37 μ s long pulses from PHOCL-50 operating as a DF-CO₂ laser, (b) the use of a new target chamber configuration which allowed independent control of the gas species and pressure on the two faces of a test window during irradiation, and (c) the use of diamond-turned NaCl substrates exclusively, for both coated and uncoated samples

The AR coatings tested were two designs which incorporate As₂S₃ as a high-index layer, and one set of samples which use a single quarter-wave layer of NaF.

The specific objectives in this study of uncoated NaCl were as follows:

1. To look for threshold differences between small components (3.7-cm diameter) and large components (28-cm diameter) which might be attributable to fabrication procedures.
2. To determine whether NaCl surfaces which appear clear at the time of fabrication and those which appear hazy at the time of fabrication exhibit different damage threshold.

3. To determine whether humidity-clouded NaCl surfaces exhibit damage thresholds different from those kept dry and clear.
4. To compare thresholds of NaCl diamond-turned by two different vendors.
5. To compare air/air and argon/vacuum environment effects on NaCl window thresholds.
6. To observe the "statistical" scatter of thresholds measured for two or more "identical" samples, and two or more sites on a single component.
7. To compare thresholds for the previously standard Method 1 NaCl and the newer, fast-grown Method 2.
8. To review the absolute values of the new damage threshold measurements and assess the implications as to the reliability of NaCl windows (and their risks) in an application requiring a given fluence.

2.2 Beam Characteristics

The general experimental arrangement is shown in Figure 2-1. The laser pulse time profile is given in Figure 2-2. Spatial profiles were remeasured before the uncoated NaCl tests, using a two-dimensional detector array. Figure 2-3 shows the spatial profile measured in the first layout, where in-air tests were done with 11-inch samples. This arrangement is similar to that of Figure 2-1, but does not include the target chamber. The profile shows a very uniform fluence distribution with an effective area A of 0.379 cm², which is 57% above the previous value of A measured with film burns.

Figure 2-4 similarly shows the profile measured with the array at the gas cell. As in the earlier film burn measurements, this profile exhibited a slight depression at the center. The effective area A of this profile is 0.272 cm², compared to older film burn value of 0.170 cm², representing a 60% increase.

Figure 2-1: Experimental arrangement for the window damage tests.

Figure 2-2: Typical laser pulse time profile.

Figure 2-3: Laser beam spatial profile for in-air tests, $A = 0.38 \text{ cm}^2$.

**Figure 2-4: Laser beam spatial profile for argon/vacuum tests,
 $A = 0.27 \text{ cm}^2$.**

Before the uncoated NaCl tests, the PHOCL-50 carbon block calorimeter was carefully compared with several other calorimeters, including two which were calibrated independently by electrical substitution heating. Among these were two Scientecs, and the CB3 carbon block. The data showed that 100 Joules indicated by the old calibration factor for the PHOCL-50 carbon block, CB1, more accurately corresponds to about 80 Joules as indicated by the Scientecs and CB3. The uncoated NaCl tests reported here take into account the new calibration factor for CB1 (see Sec. 3.4).

2.3 Samples

Table 2-1 is a list of samples for the current phase of this program. Dates received and tested are included as appropriate. LPO designates Laser Power Optics Inc. and JAN denotes Janos Technology Inc.

2.4 Antireflection-coated NaCl

Figure 2-5 shows the exposure schedule and damage recorded for two LPO AR coatings, which used two different materials for the low-index companion to the high-index As_2S_3 . Some details of these coatings are held as proprietary by LOP. "Low 2" clearly provided a superior coating for these tests. The data are reduced to single values of categorized damage in Figure 2-6.

Single-layer AR coating results are given in Figures 2-7 and 2-8. Sample-to-sample uniformity of these specimens is reasonably good, but the measured absolute damage levels were sufficiently low that the quarter-wave design was dropped from further consideration.

It is to be noted that the major interest in these measurements, for near-term application, is in the most severe category of damage, as represented by the solid symbols in Figures 2-5 - 2-8. The recorded microdamage, on the other hand, is a key to understanding the early stages of major damage, which is a critical factor in repetitively-pulsed applications.

TABLE 1. V-Series Optics Damage Samples

Sample	Substrate	Source	Coating	Comments	Received	Tested
V01	NaCl, D.T.	LPO	AR	As ₂ S ₃ /low 2	88-06-01	N.A.
V02	"	"	"	"	"	88-07-20
V03	"	"	"	"	"	88-07-21
V04	"	"	"	"	"	88-07-21
V05	"	"	"	"	"	88-07-21
V06	"	"	"	"	"	.
V07	"	"	"	"	"	.
V08	"	"	"	"	"	.
V09	NaCl, D.T.	LPO	AR	NaF, $\lambda/4$	88-06-01	88-08-08
V10	"	"	"	NaF, $\lambda/4$	"	88-08-08
V11	"	"	"	NaF, $\lambda/4$ buffed	"	.
V12	"	"	"	NaF, $\lambda/4$	"	88-08-09
V13	"	"	"	NaF, $\lambda/4$	"	88-08-09
V14	"	"	"	NaF, $\lambda/4$	"	.
V15	"	"	"	NaF, $\lambda/4$	"	.
V16	"	"	"	NaF, $\lambda/4$	"	.
V18	NaCl, D.T.	Antares: LPO 11" diam	none	S ₁ :(arrow) convex S ₂ : Flat. See boundary	88-07-13	88-09-16
V19	NaCl, D.T.	Antares: JAN 11" diam	none	S ₁ :(arrow) convex S ₂ : Flat. No boundary	88-07-13	88-09-20

TABLE 1. V-Series Optics Damage Samples (Continued)

Sample	Substrate	Source	Coating	Comments	Received	Tested
V21	NaCl, D.T.	JAN	none	Method 1. clear		88-09-28
V22	NaCl, D.T.	"	none	clear		88-09-28
V23	NaCl, D.T.	"	none	clear		-
V24	NaCl, D.T.	"	none	clear		-
V25	NaCl, D.T.	"	none	hazy		88-09-28
V26	NaCl, D.T.	"	none	hazy		88-09-29
V27	NaCl, D.T.	"	none	clear		-
V28	NaCl, D.T.	"	none	clear		-

TABLE 1. V-Series Optics Damage Samples (Continued)

Sample	Substrate	Source	Coating	Comments	Received	Tested
V33	NaCL, D.T.	LPO	none	none	88-08-25	88-09-22
V34	"	"	"	"	"	88-09-22
V35	"	"	"	"	"	88-09-23
V36	"	"	"	"	"	88-09-26
V37	"	"	"	"	"	88-09-27
V38	"	"	"	"	"	88-09-27
V39	"	"	"	"	"	.
V40	"	"	"	"	"	.
V41	NaCL, D.T.	LPO	As ₂ S ₃ /low 2	(second try at V01) no buff	88-08-25	.
V42	"	"	"	no buff	"	.
V43	"	"	"	buffed	"	.
V44	"	"	"	buffed	"	.
V45	NaCL, D.T.	JAN	none	Method 2 (See V21)	88-09-14	88-09-29
V46	"	"	"	"	"	88-09-29
V47	"	"	"	"	"	88-09-29
V48	"	"	"	"	"	.
V49	"	"	"	"	"	.
V50	"	"	"	"	"	.

37 μ s pulse length: Ar/Vac

Figure 2-5: Coated window damage test data.

37 μ s pulse length: Ar/Vac

Figure 2-6: Coated window damage test results.

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37 μ s pulse length: Ar/Vac

Key:

- ▲ Plasma observed
- ▼ $1 \text{ mm} < d_0$
- ▽ $100 \mu\text{m} < d_0 < 1 \text{ mm}$
- ▽ $10 \mu\text{m} < d_0 < 100 \mu\text{m}$
- No damage

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Figure 2-7: Coated window damage test data.

37 μ s pulse length: Ar/Vac

Key:
 $\blacktriangledown$ 1 mm < d_0
 ∇ 100 μ m < d_0 < 1mm
 ∇ 10 μ m < d_0 < 100 μ m
 — No damage

DN9-9-88-3

Figure 2-8: Coated window damage test results.

2.5 Uncoated NaCl

The issues listed in Section 2.1 were addressed with the test matrix shown in Table 2-2. Figure 2-9 gives the measurements made at several sites on large (28 cm diameter) salt wedges, tested in air. They are compared with 3.7 cm diameter samples. These data were reduced to generate the results of Figure 2-10, using the levels of the first occurrence of each category of damage, whether that occurred front, back, or in bulk. A second level of severe damage, "cm damage", was added for this work, and is represented by solid squares. Figure 2-11 and 2-12 similarly present primarily the results of Ar/vacuum measurements for several small-size samples under various conditions.

The results give information on the issues previously listed. Conclusions are drawn here primarily with respect to the major damage category (> 1 cm):

1. The large-diameter wedges exhibit thresholds in air comparable to small-sample thresholds (Sites V18A, V18B, V19A, V19B, V33, and V34).
2. A hazy surface at fabrication time does not necessarily indicate a reduced damage threshold (Sample V18, sites A, B, C, D).
3. Exposure and clouding by humidity did not reduce damage thresholds under our conditions (Samples V37, V38, V35, 36).
4. Diamond turning by two vendors resulted in comparable damage thresholds (Samples V35, V36, V21, V22).
5. An Ar/vacuum window environment gave damage thresholds at least as high as air/air (Samples V33, V34, V35, V36).
6. Duplicate samples and duplicate sites gave results generally in good agreement (Samples V33, V34; V37, V38; V21, V22). Exceptions include Samples V25, V26; V19A, V19B.

7. Fast-growth Method 2 NaCl compared favorably with the older standard Method 1 (Samples V21, V22, V25, V45, V46, V47).

8. The measured damage thresholds and perceived reliability of uncoated diamond-turned NaCl windows are to be preferred over the measured damage thresholds and perceived reliability of AR-coated windows.

2.6 Surface Plasma and Beam Cutoff

The large scale final damage on each of the uncoated NaCl sites (Figures 2-9 to 2-12) was accompanied by a surface plasma. Plasmas may in general occur on both the front and the back face of a window, with the more extended plasma occurring on the front (incident) side.

Plasmas observed in air on the large-diameter samples are shown in Figures 2-13 and 2-14. Figure 2-13 is an open-shutter photograph of the final exposure of Sample 19, Site B (see Figures 2-9 and 2-10). The beam is incident from the left, and the sample surface is seen as the line of symmetry between the plasma to the left, and its image to the right; the image is reflected by the sample surface. Figure 2-14 shows the result of a higher fluence, incident on Site A of the same sample. The form and spatial extent of these plasmas are typical of a fully developed laser-supported detonation wave, whose absorptive leading edge propagates from near the surface back toward the laser at supersonic velocities.

The effect of this event on the transmitted beam is shown in Figure 2-15. Sample V36 (Figures 2-9 and 2-10) was exposed in the gas cell, with argon and vacuum (near 30 mTorr) at the front and back surfaces respectively. The lower trace shows the onset of surface plasma as indicated by visible light to a PIN diode detector. In the upper traces, Ge(Au) detectors show the incident and transmitted laser radiation with cutoff coincident with plasma initiation. Thirty-six percent of the incident pulse energy is intercepted by the plasma. As a point of reference the same fraction, 36%,

was blocked in the air/air test of large Sample V18, Site C, on its final exposure.

The severity of this beam-block threat stems from the nature of the plasmas observed: (1) Since these laser-supported detonation waves propagate at supersonic velocities, an initial point of surface plasma rapidly spreads to block the entire beam; beam cut-off occurs in a time short relative to the 40- μ s laser pulse; (2) the high-temperature plasma is opaque to the beam so that once it is in place, the fraction of the beam leaking through the event is small; (3) once initiated, the plasma does not relax to allow the transmitted beam to recover late in the pulse; during the remainder of the pulse duration the absorptive plasma front is propagating up the beam toward the laser, and continues to hold the transmitted beam fraction near zero. These characteristics result in a beam cutoff which is both fast and complete.

TABLE 2-2. Optics damage test matrix completed in September 1988.

Sample	Surface	Note	Source	Medium
V18A	clear	28 cm	LPO	air
B	•	•	•	•
C	hazy	•	•	•
D	•	•	•	•
V19A	clear	•	JAN	•
B	•	•	•	•
V33	clear	previous standard	LPO	•
V34	•	•	•	•
V35	•	•	•	Ar/Vac
V36	•	•	•	•
V37	exposed	•	•	•
V38	•	•	•	•
V21	clear	Method 1	JAN	•
V22	•	•	•	•
V25	hazy	•	•	•
V26	•	•	•	•
V45	mixed	Method 2	•	•
V46	•	•	•	•
V47	•	•	•	•

Figure 2-9: Diamond-turned NaCl damage test data.

37 μ s pulse length

Figure 2-10: Diamond-turned NaCl damage test results.

Figure 2-11: Diamond-turned NaCl damage test data.

37 μ s pulse length

Key:

- 1 cm < $d_{\bullet}$
- ▼ 1 mm < $d_{\bullet}$ < 1 cm
- ▽ 100 μ m < $d_{\bullet}$ < 1mm
- ▽ 10 μ m < $d_{\bullet}$ < 100 μ m
- No damage

Sample	V37	V38	V21	V22	V25	V26	V45	V46	V47
Surface	Exposed		Clear		Hazy		Mixed		
Note	Previous standard		Method 1				Method 2		
Source	LPO		JAN						
Medium	Ar/Vac								

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Figure 2-12 : Diamond-turned NaCl damage test results.

Figure 2-13: Surface plasma on NaCl, sample V19, site B. Beam is incident from the left.

Figure 2-14: Surface plasma on NaCl, sample V19, site A. Beam is incident from the left. Scale is in cm.

Figure 2-15: Plasma effect on the centerline beam transmission for NaCl, sample V36.

3.0 PHOCL-50 TESTS (TASK 2)

3.1 LTI/LANL Tests

The bulk of the PHOCL-50 schedule through August was devoted to LTI experiments and to detector qualification tests conducted by LANL personnel. The latter tests were resumed in December using the full beam aperture on PHOCL-50 (see discussion below on PHOCL-50 upgrade).

3.2 Gain Measurements

Laser gain measurements were performed on PHOCL-50 during the month of September by G. York and E. Salesky of LANL. Preliminary comparison with earlier data taken on Meteor I showed reasonable agreement between the e-beam and uv initiated gain profiles, for similar gas mixtures. Experiments to determine the initiation level by F₂ disappearance measurements were unsuccessful due to the noise level of LANL He:Cd laser.

3.3 Laser Upgrade & Maintenance

Direct work on Task 2 was not performed during the month of November due to maintenance work on PHOCL-50 that was required to resolve a steadily worsening reactive gas mixture stability problem. The laser gain measurements and optics damage tests were completed in spite of this problem. However, with the anticipated LTI experiments and detector qualification tests, PHOCL-50 needed to be brought up to its historical level of reliability. The PHOCL-50 gas flow meters were checked for accuracy, and actual flow rates were found to be within 10% of their readings. These flow checks eliminated improper gas mixtures as a source of the stability problem. The quartz uv windows were removed, repolished and resealed in their frames. The stability problem appears to have been solved by the re-sealing of the quartz windows.

The 11 inch diameter ZnSe outcoupler for the PHOCL-50 upgrade was also installed during November. The outcoupler has a simple one wavelength

(10.6 μm) coating because optic damages tests of witness samples indicated that the microdamage threshold for the two wavelength coating was too low. We would not expect such a coating to survive under the heavy test schedule planned for PHOCL-50. Based on geometric considerations, the large outcoupler was expected to extract energy from about 43 liters of the PHOCL-50 volume, as opposed to 15 liters from the 6 inch outcoupler used prior to the upgrade. Actual tests show that the energy extracted from the laser with the 11 inch outcoupler is slightly more than 3 times that extracted with the 6 inch outcoupler, using identical gas mixtures and initiation levels. This brings the nominal PHOCL-50 output up to a kilojoule.

3.4 Calorimeter Calibrations

A substantial issue has arisen during this contractual period concerning the calibration of the Boeing carbon block calorimeter (referred to herein as CB1) used to measure the PHOCL-50 laser energy. Measured laser energy has a significant impact on the LANL laser program both when using PHOCL-50 for detector calibrations, laser target interaction experiments and optics damage testing, and when comparing performance of UV and e-beam initiated pulsed chemical lasers .

A careful recalibration of the large calorimeters used by LANL and Boeing has resulted in a change in both the absolute calibration of CB1 as well as the relationship between CB1 and the LANL eight-inch volume-absorbing Scientech (hereafter referred to as S1). The new calibrated responsivity for CB1 is 9.5 $\mu\text{V}/\text{J}$, compared to its old value of 8 $\mu\text{V}/\text{J}$; **all PHOCL-50 laser energies reported before December 13, 1988 must be lowered by 16%.** Even with this new calibration factor, the response of S1 remains 8% lower than the response for CB1. A direct comparison of CB1 and S1 confirmed the 8% difference. We believe this difference may be due to a small hole drilled in the S1 surface, which has created a "dead spot" in the vicinity of the hole. The present calibration of CB1 is, in our opinion, correct to within 5%. The remainder of this section details the experimental methods and data base that the new calibration factors are based on.

Experimental Method:

All calibration tests were conducted with the same basic experimental configuration, as shown in Figure 3-1. The PHOCL-50 laser beam passed through a variable beam attenuator, and was then split by a KCl wedge. The variable attenuation was accomplished with plastic sheets, each of which attenuated the beam by about 20%. The second surface reflection of the wedge was directed (via a focusing mirror and an additional front surface reflection) to a Gentec energy meter that served as an independent energy monitor to normalize the response of the calorimeter under test. The energy transmitted through the wedge was directed through the aperture to the calorimeter under test.

Figure 3-1. Experimental setup for calorimeter calibrations.

For these experiments, the "normalized response" (NR) of a calorimeter is defined by the ratio of the calorimeter output (in Joules) to the mV recorded by the Gentec,

$$NR = \frac{\text{Joules read on calorimeter}}{\text{m V output of Gentec}}.$$

Since both the Gentec signal and the calorimeter output vary linearly with laser energy, the shot-to-shot fluctuations of the PHOCL-50 laser energy do

not affect the measured value of NR. Accounting for the shot-to-shot variations in the laser output by using the Gentec is critical for increasing the accuracy of the calibration measurements. It should be noted that the energy reaching the Gentec is not apertured, hence is independent of the area of the beam aperture. However, the beam into the calorimeter is apertured; thus varying the aperture size results in a different value for NR.

A total of four carbon blocks and three Scientech detectors were tested using three different aperture sizes. They are numbered CB1 through CB4 and S1 through S3; a complete list of the detectors and their calibrated responsivities (both before and after December, 1988) is given in Table 3-3 at the end of this section.

Calibration of the Boeing Detectors:

Six Boeing calorimeters were compared on several occasions in October and November of 1988. The results of this comparison are shown in Figure 3-2, which plots NR for each firing of the laser, relative to the average NR for CB1, using the old pre-December calibrations for all calorimeters. The average relative values of NR are listed in Table 3-1. The results clearly show that four calorimeters (CB3, CB4, S2, and S3) have a normalized response near 80% of CB1 using the old calibration factor, while one calorimeter (CB2) is at 85% of the CB1 value.

Research into the history of Boeing calorimeter calibrations uncovered some pertinent facts about the history of CB1's calibration. CB1 was originally calibrated in 1978 against CB2 at $8 \mu\text{V/J}$. It was recalibrated a year later at $9.5 \mu\text{V/J}$, using both a Marx bank CO_2 laser and PHOCL-50, again with CB2 as a standard. CB1 was then put in storage for several years before it was taken out and recalibrated at $8 \mu\text{V/J}$, that calibration being used from 1984 through the greater part of 1988. No independent beam monitor was available for any of the above calibrations, therefore shot-to-shot variation in PHOCL-50 laser energy was not taken into account. The resulting accuracy in measuring the relative response of the various calorimeters was $\sim 10\%$ for these old calibrations.

Figure 3-2. Normalized response of Boeing calorimeters relative to the average NR for CB1, using the old calibration of $8\mu\text{V}/\text{J}$ for CB1.

Table 3-1. Average Relative Values of NR for Six Boeing Calorimeters.

Calorimeter	Relative NR with respect to CB1 for a given CB1 calibration factor	
	$8\mu\text{V}/\text{J}$	$9.5\mu\text{V}/\text{J}$
CB2	.85	1.01
CB3	.78	.93
CB4	.79	.94
S2	.75	.89
S3	.75	.89
S3*	.78	.93

Additional information was uncovered concerning the calibrations of the other Boeing calorimeters. CB2's calibration, which has not changed, was independently confirmed against an AFWL absorbing glass calorimeter. Previous Boeing experiments using PHOCL-10 indicated that one of our Scientech's response was about 10% low. The previous calibration of CB3 and CB4 against CB2 was not done with as much care as the present experiments, due to a lack of time.

Use of the previous 9.5 $\mu\text{V}/\text{J}$ calibration factor for CB1 results in the second column of Table 1. CB1 and CB2 agree (as they did in the pre-1980 tests), CB3 and 4 are slightly low, and the Scientechs are all low but not extremely so.

Changing the CB1 calibration to the previous value of 9.5 $\mu\text{V}/\text{J}$ seems the most reasonable course of action, particularly since it aligns CB1 with CB2, the only Boeing calorimeter that has been independently calibrated. Since all of the other CB calorimeters were calibrated against CB2, it would appear that all of our previous relative calibrations of CB3, CB4, and CB1 were within about 10% of the new values. The present relative calibrations are more accurate because we have removed the error caused by the shot-to-shot fluctuation in the laser energy.

Linearity was checked using the Fresnel reflection from a NaCl wedge; CB1, CB4, and S3 were all found to be linear from 4% to 100% of the full beam energy of 200 Joules. Schedule constraints did not permit S2, S3*, CB2 or CB3 to be checked for linearity.

S1 & CB1 Comparison:

In an effort to better correlate the results of PHOCL-50 and Meteor I, an experiment was conducted to establish an accurate relative response between CB1 and S1. The tabulated results of the initial experiment to measure their relative response are shown in Table 3-2, using the old calibration factor for CB1 (8 $\mu\text{V}/\text{J}$). If one compares the average laser energy recorded

by S1 with the average laser energy recorded by CB1, the difference in responsivity is apparently 30%. However, by examining column 4 of the table (Gentec readings), one can see that the PHOCL-50 beam energy actually was lower for the shots involving S1, which were taken later in the day than the CB1 shots. When the fluctuation in laser energy level is taken into account, the normalized response for S1 is 76% of that for CB1 (using the old CB1 calibration). When the present calibration of CB1 ($9.5 \mu\text{V/J}$) is used, NR for S1 is 90% of that for CB1. The apparent discrepancy in interpretation of this initial testing data highlights the need to have an independent energy monitor for performing calorimeter calibrations to account for shot-to-shot laser output fluctuations.

Table 3-2. Initial Experimental Results, S1 vs CB1

Shot#	Calorimeter	Joules	Gentec(mV)	NR
100302	CB1	172.9	230	0.752
100303	CB1	169.9	235	0.723
Average		171.4	232.5	0.737
100304	S1	121.7	217	0.561
100305	S1	117.0	209	0.560
Average		119.4	213	0.560
S1/CB1		0.70	0.92	0.76

* Using old calibration factor for CB1 of $8.0 \mu\text{V/J}$

In a follow on set of experiments, we compared CB1 and S1 for a series of shots with varying beam diameters and locations. David Simmons from EG&G independently monitored the tests. The major result of these tests is a new and more accurate calibration ratio between CB1 and S1 that can be used to compare output from PHOCL-50 and METEOR I for a large diameter beam. Evidence was also found that S1 is affected by the hole which was drilled to allow placement of a fast detector.

The first series of tests used a 2.5" diameter aperture; the results for these first eleven shots are shown in Fig. 3-3. The first four shots were into S1 at a location near the fast detector hole; NR averaged 0.106 J/mV. The next three shots were into CB1, and resulted in an average NR of 0.128 J/mV. Two shots followed into a new location on CB1, NR averaged 0.124 J/mV. PHOCL-50 was then fired twice into S1, with the beam located farther from the fast detector hole. The average NR for these two shots was 0.122 J/mV, significantly higher than 0.106 and close to the results obtained for CB1.

Figure 3-3. Normalized response of S1 and CB1 relative to the average NR for CB1, using the new calibration of 9.5 μ V/J for CB1.

Because these results indicated that we should consider the effect of beam position on S1, PHOCL-50 was fired three times in each of three locations on S1, through a 1.5" diameter circular aperture. The results of those shots are plotted on Fig. 3-4, which also shows the locations of the beam for each set of three shots. Clearly the hole has a significant effect on the results, with NR averaging 0.0426 for location 1 (away from the hole), 0.0334 at location 2 (at the hole), and 0.0421 at location 3 (also away from the hole). This is over 20% variance due to location. The above shots were followed by

three shots in CB1, also plotted on Fig. 3-4. The average NR for these three shots was 0.0424. This might indicate that CB1 (using the current calibration, $9.5 \mu\text{V/J}$) and S1 would have an equal response if S1 were not altered by the fast detector hole. However, this conclusion is not certain; there are only 12 thermopiles on S1, and a 1.5" diameter beam may be too small to expect a position-invariant response. In addition, the calibration factor for S1 responsivity, which was accomplished electrically, could have been affected by the presence of the hole. If this were the case, the calibrated responsivity (found to be 1.54 mV/J) would be lower than the actual physical response of the thermopiles. In an actual energy measurement, a given output in mV would indicate a higher energy level than was actually physically present. In that possibility, our findings for NR would be too high for the shots involving S1, which in turn would indicate that the ratio S1/CB1 would also be high. This problem is not easily resolvable, short of comparing S1 to an unaltered 8" volume-absorbing Scientech.

Figure 3-4. Normalized response of S1 and CB1 relative to the average NR for CB1, using the new calibration of $9.5 \mu\text{V/J}$ for CB1 and a 1.5" aperture.

Fortunately, the above discussion does not affect the more important aspect of these experiments, that of establishing a standard for comparing PHOCL-50 and METEOR I laser energies, using CB1 and S1, respectively, for large beam apertures. Fig. 3-5 presents the results from firing PHOCL-50 three times into S1 through a 5" diameter aperture, compared to three shots into CB1 through the same aperture. The 5" aperture was used since normal PHOCL-50 and Meteor I operation to date has used 6" outcouplers with approximately 5" apertures. The ratio S1/CB1 is 92%, which echoes the results of the initial comparison tests between S1 and CB1.

Figure 3-5. Normalized response of S1 and CB1 relative to the average NR for CB1, using the new calibration of 9.5 $\mu\text{V}/\text{J}$ for CB1 and a 5" aperture.

Summary of Calibrations:

Results of cross-calibrations between Boeing calorimeters indicate that we now have a good absolute calibration. Our confidence in the present calibration is reinforced by the fact that rediscovery of the old high value for the CB1 calibration factor yielded close agreement with the independently-calibrated CB2. The January findings of a one-to-one correspondence between S1 and CB1 for a small beam diameter in unaltered regions of S1 give further indication of the absolute accuracy of the present CB1 calibration. This last assertion is not conclusive, however, due to the possible effect of small beam size on S1 response, and the possible effect of the hole on the electrical calibration.

One might argue that the Boeing Scientechs (S2 and S3) are absolutely calibrated and show CB1 as being 10% high. This is not likely to be the case, however, as it would require CB2 being high by the same factor as CB1 (there is nothing to indicate that the calibration of CB2 has changed), as well as S1 being calibrated correctly (the energy defect due to the hole would have to be exactly appropriate to force agreement with the Boeing Scientechs). We find it much more plausible to conclude that CB1 is correct within 5% (and is perhaps high, if anything) while the Boeing Scientechs are within 10% and are perhaps low.

For current (post December, 1988) PHOCL-50/METEOR I comparisons, a CB1 Joule is equal to 92% of an S1 Joule. Prior to December, 1988, a reported CB1 Joule was equivalent to 76% of an S1 Joule.

It would be very helpful to the entire program to involve an independent agency in an absolute calibration of some calorimeter that could be used as a standard to calibrate all others. Since an independent calibration is almost certainly not possible within the scope of the present program, and in view of the importance of maintaining a viable calorimeter calibration, we have initiated the procedure of spot checking our CB1 calibration each month with a different calorimeter. If we notice a discrepancy, we will institute a careful check, in order to continue to report our laser energies as accurately as possible.

Table 3-3: List of Calorimeters Tested.

- CB1.** PHOCL-50 carbon block, previous calibration 8 mV/J. Current calibration is 9.5 μ V/J.
- CB2.** Boeing carbon block, originally used on PHOCL-50. Box is the same size as the PHOCL-50 carbon block, but the actual energy reading surface is 1/2 the size. Calibrated at 6.9 μ V/J. Independently confirmed with AFWL calorimeter.
- CB3.** Carbon block #3 from RPDF. Previously calibrated against CB2 at 9.3 mV/J. Current calibration is 8.7 μ V/J.
- CB4.** Carbon block #4 from RPDF. Calibrated against CB3. Calibration factors the same as CB3; current calibration 8.7 μ V/J.
- S1.** LANL 8-inch volume absorbing Scientech. Output sent directly to the chart recorder; peak value read as 1.54 mV/J.
- S2.** Boeing Scientech #10233788, read in the same manner as S1. The power meter for this Scientech was not working correctly, so we had no choice but to run in this manner. Calibration factor used was 85 mV/Watt. We don't have the factory manual for this Scientech, but we do have two other factory manuals; one gives a calibration of 84.5 mV/W, the other 85.5 mV/W. To obtain the energy, one integrates under the power curve on the chart recorder. After several runs, a calibration of 3.9 mV/J, where the mV reading was the peak voltage on the chart recorder, was shown to be equivalent to the integration technique. New calibration factor for peak voltage is 3.5 mV/J.

Table 3-3: List of Calorimeters Tested (Continued).

S3. Boeing Scientech #10233295, output sent directly to the chart recorder. Factory calibration of 84.5 mV/Watt; also equivalent to 3.9 mV/J (peak). New calibration factor 3.5 mV/J.

S3*. Scientech #10233295. Read with Scientech power meter #06616901. Reads 30 Joules energy, output of 100mv full scale. This output was recorder on the chart recorder, and the peak value was taken as the Joule reading. To align this reading with current Boeing calibrations, multiply the energy reading by 1.08

Independent energy monitor:

Gentec energy detector #06615555, read on an oscilloscope. Nominal calibration of the Gentec is 1.54 V/J, however we did not use this calibration; instead, we use the voltage output of the Gentec as a reference laser power indicator.

4.0 CLOUD CLEARING (TASK 3)

4.1 Operation of the Warm Cloud Simulation Facility

The Cloud Simulation Facility (CSF) was shipped to LANL and assembled in the Meteor I laboratory. Bob Bardon and David Dowling traveled to LANL for delivery and initial setup of the CSF. The cloud chamber is fully functional and is performing as expected based on the earlier testing conducted at Boeing. Operation of the CSF is discussed below.

While appearing quite simple, clouds are complex unstable thermodynamic systems. The creation of a stable laboratory cloud that is representative of some of those found in nature can be extremely difficult (see section 6 of our 1988 Final Report). This fact is underscored by the present lack of any meaningful laser clearing data in representative clouds. The CSF (Cloud Simulation Facility) that we have designed, built, and delivered to LANL can create the conditions we desire, but only with careful attention to the details of the experiment. This means that a dominating concern needs to be placed on eliminating conditions that can subvert the intended operating procedures. Since the early delivery of the CSF to LANL prevented an in-depth characterization of the system's capabilities while it was at Boeing, this memo details background work that we intended to perform.

1. The FSSP (Forward Scattering Spectrometer Probe) should be used to sample the cloud properties from many regions within the test section of the CSF. This is necessary to ensure cloud uniformity. Samples drawn from the sidewall might be significantly different than samples drawn from near the optical axis because of the interaction of the thermal boundary layer of the wall with the cloud droplets. Such an interaction may result in a substantial underestimate of the size distribution (and liquid water content). To protect against this error the size distribution needs to be measured across and along the tunnel axis. The CSF is set up to do this experiment with a series of ports down the length of the tunnel section. These ports are sized to slip-fit PVC water pipe which

will also slip-fit into the FSSP inlet. To do this simple diagnostic experiment, a straight piece of pipe should be attached to the FSSP. The end of the pipe (see Figure 4-1) should be beveled at about 45 degrees and incrementally inserted into the tunnel sample ports (5 cm increments are suggested) while the tunnel is running in equilibrium. Samples should be taken at all three port locations along the axis of the tunnel. Comparisons made between the samples drawn at different locations will almost certainly show some variation but hopefully these variations will be small. A support is required to suspend the FSSP at various insertion depths at the three port locations while keeping the tube length constant. The tunnel flow should be modest during these tests to ensure that impaction losses are very small. We cannot predict the outcome of this experiment; it could be possible that the boundary layer sample point is acceptable. The sampling experiments suggested above should provide the necessary evidence.

Figure 4-1: Preferred mounting of the Forward Scattering Spectrometer Probe.

2. It is likely that the liquid water content measuring system presently in use at LANL is not functional. A PMS (Particle Measuring Systems) technician or engineer should be contacted. A substantial sum was spent to be able to directly measure the liquid water content (LWC) of the cloud. The hot-wire probe is more nearly a first order measurement of liquid water content (no integration with r^3 is required), and an important & necessary check of the FSSP. The importance of using both probes cannot be over-emphasized. Both probes are capable of departures from accurate calibration, but together they can be used with confidence. For the purposes of checking the diagnostics the LWC sensor should be placed as close to the FSSP sample point as possible. This will mean dragging the LWC sensor into the tunnel for checking the two probes against each other. Unfortunately the LWC sensor cannot be permanently left inside the CSF test section because the flow in the CSF downstream of the LWC sensor will be ruined by the suction fan of the LWC sensor. Once it has been decided that both sensors are working properly, it should be OK to put the LWC on the shelf until the next calibration.
3. Using the CSF for cloud clearing requires some attention to the system configuration. The clearing beam should be introduced at the droplet generation end. In order to minimize buoyancy and air flow effects, air should be flowing out slightly (or neutral) at this opening. The outflow can be adjusted by controlling the amount of "make up" air. The tunnel speed should be as low as is practical, i.e. as low as it was for the diagnostic measurements of #1. This approach will minimize the amount of cloud exiting the downstream end as well as the rate at which the cleared path fills in from the sides. Cloud droplet size stability and viewing under these conditions will be improved by putting wet black felt on the interior of the CSF test section.
4. Development of "shutters" at the ends of the test section to halt the flow in the CSF is not recommended. These will prevent the exploitation of some of the unique properties of the CSF. A "static" cloud chamber was rejected in the design phase of this effort as impractical to build and the current CSF is not intended for use as a static system. The current

flowing cloud concept can provide very stable cloud properties, but extension of the current technique to static cloud production will certainly lead to unstable cloud characteristics. The flowing cloud configuration cannot be made perfect, but trying to retrofit the CSF into a static chamber would create bigger problems.

5. After a clearing pulse is sent through the CSF, there are two mechanisms that will cause a subsequent increase in extinction along the cleared beam path: 1) recondensation in the cleared path, and 2) convection of fresh cloud into the cleared path. For several experiments, a high speed movie or video camera should be used in conjunction with a sheet of laser light to image the cleared path during and after the clearing pulse in order to determine the time scales of these mechanisms. If the latter mechanism is dominant, the recorded images will also provide information on the nature of the convective processes.

4.2 Design of The Cold Cloud Simulation Facility:

The Cold Cloud Simulation Facility (CCSF) will be used to simulate natural clouds in the entire temperature range from nearly -40 to +40 °C. There are 5 main groupings of issues in the design of the CCSF: natural ice cloud phenomena, engineering concerns, diagnostics, laboratory & cost constraints, and anticipated experiments. These are all interrelated in the design of the CCSF, but will be discussed separately. This section summarizes how we currently expect to produce a cloud chamber that can be used for the entire temperature range of cloud clearing experiments. Section 6 of our July 1988 final report to LANL provides background for this design study.

Natural Ice Cloud Phenomena:

Ice cloud properties are quite variable¹. As a result it is more reasonable to discuss properties for typical clouds rather than extreme cases. For example, the ice water content varies from about .05 gm/m³ to about 0.50

gm/m³. The particle concentration ranges from less than 5 to more than 500 particles per liter with particle sizes as large as 1000 μ m. The 1/e extinction length for visible radiation in cirrus clouds ranges from below 100 m to above 10 km. Ice clouds exist at temperatures below 0 °C and at humidities near or above 100% relative to ice although cirrus precipitation will survive falling through a great distance of subsaturated air. An important ice cloud parameter, which is not relevant in liquid cloud studies, is the form or "habit" of the ice crystals. The particular crystal habits observed in a natural cloud are determined by the temperature & humidity history of each individual ice crystal. The relationships between crystal habit and history are well documented but not completely understood. A tabulation of natural ice crystal habits is contained in chapter 2 of reference #1, portions of which are found in Section 6 of our July 1988 report. Ice crystals usually form around freezing nuclei, which can be small bits of frozen water or aerosol particles whose surface supports the growth of crystalline ice. If cooled below about -40° C, unnucleated liquid-water cloud droplets will spontaneously freeze. While clouds containing both ice and water are common in nature, our focus in the CCSF will be on clouds composed entirely of ice particles. In nature, cirrus clouds are primarily composed of ice.

Engineering Concerns:

There are several expected difficulties in the complete process of bringing the CCSF "on-line". First of all are the ice cloud issues. We expect that it might take quite a bit of trial and error engineering to get the chamber to produce a stable concentration of acceptable ice crystals. The second major set of concerns are fluid mechanical. There needs to be adequate time for mixing the ice crystals in the surrounding air to insure uniformity of the crystal concentration and air temperature throughout the test section. The turbulence level also needs to be very low in the test section so that unwanted convection of fresh cloud material into the cleared path does not occur. The magnitude of the air velocity everywhere inside the CCSF needs to be low to minimize the impaction losses of ice crystals. All of the interior components of the CCSF will be exposed to subfreezing temperatures which could lead to icing problems. Measurements of optical extinction in the

cloud material at visual wavelengths will require either a long test section or a very good extinction cell.

The CCSF will be a low speed wind tunnel with special equipment for the production of clouds. The most important and necessary feature of the CCSF is complete control of the operating temperature. The current design addresses this with a 26,000 BTU/hr cooling system for sub-ambient temperature operation. Use of the CCSF above ambient temperature, for the study of warm liquid clouds, will also be possible by using an electrical heater. The walls of the CCSF will be made of a "sandwich" of fiberglass/insulation/fiberglass with an insulation rating of R-20. The heater might not be purchased or installed for the initial studies in order to save money.

Because of the extreme difficulty of making a static cloud chamber produce a realistic cloud, we have again chosen a "flowing cloud" design. This has several advantages. The CCSF will functionally resemble the CSF now being used at LANL for liquid cloud clearing experiments. This will make it possible to use the CCSF to confirm the results of LANL's investigations. We have already built one flowing cloud chamber, the CSF, and the experience gained in that process will be put to use in the design & construction of the CCSF. In particular, more attention will be paid to the quality of the flow in the test section and control of the tunnel speed. The anticipated tunnel speeds in the CCSF are far too low to probe the flow quality with traditional hot-wire anemometry techniques, so we will use visual diagnostics to ensure that the background fluid mechanics of the CCSF are "clean" enough to prevent an adverse impact on extinction measurements. The planned minimum working speed in the test section will be about 10 cm per second. This choice will be adjusted as necessary to prevent buoyancy problems at the clearing-beam entrance & exit ports, and thermal gradients within the test section that might drive convection cells or disturb the ice cloud properties. At a test section speed of 10 cm per second we anticipate a 10° C temperature rise between the chiller exit and the end of the test section for a 50° C temperature difference between the laboratory air and the air inside the CCSF just downstream of the chiller. It remains to be determined if a 10° C temperature rise is unacceptable or not.

Ice crystals will be initiated and grown in the CCSF by seeding the flow with a spray of liquid nitrogen or dry ice and providing about 2 minutes of dwell time upstream of the test section. The liquid nitrogen or dry ice injection will create localized regions of the flow in which the temperature is low enough so that water vapor spontaneously freezes out forming tiny ice crystals. These crystals will serve as the freezing nuclei for the ice cloud produced in the CCSF. Ice crystals will grow directly on these nuclei by sublimation. Some fraction of the supercooled droplets will freeze on contact with a nucleus. All of the ice crystals will grow rapidly at the expense of the remaining water droplets. It will not be possible for the ice crystal development time upstream of the test section to exceed about 3 minutes, so the current design attempts to minimize impaction losses in the blower. This might allow ice crystals to survive several circuits of the CCSF and become much larger than "single-cycle" crystals. It may not be possible to use dry ice (carbon dioxide) to seed the cloud since the clearing laser will be a CO₂ laser and extra CO₂ in the air that carries the cloud material may cause unwanted coupling between the clearing beam and the air in the cleared path. We anticipate operating the CCSF at water vapor pressures between saturation over ice and saturation over liquid water. In this regime, the dominate ice crystal habits are plates and columns.

The humidity & ice crystal/water droplet concentration can not be set and maintained independently. In the CCSF they will be jointly regulated by several mechanisms. To raise the humidity & concentration, a variable number of atomizing spray nozzles operating at a variable injection pressure will be installed just downstream of the chiller. The introduction of a controlled amount of ambient room air ("make up" air) will be used to lower the humidity & concentration. It may be necessary to heat each spray nozzle while not in use to prevent it from freezing up. And, as mentioned earlier, the velocity of the tunnel will be controlled by a variable speed fan. This holds the promise of providing some control over the impaction losses of ice crystals (or water droplets). To achieve large supersaturations relative to ice it might be necessary to heat the injected water or even inject steam instead of water droplets.

Figure 4-2: Proposed mixing chamber design for the Cold Cloud Simulator.

The ice crystal and/or water droplets will be dispersed within the flowing volume by placing the injectors at the lip of the inlet duct for the mixing chamber (see Figure 4-2). The large scale turbulent motion set up by the perpendicular filling scheme depicted on Figure 4.2 should uniformly distribute the injected water over the entire cross section of the mixing chamber. It should be noted that this geometry should also minimize thermal gradients. If this mixing geometry proves insufficient, additional baffles and flow obstructions can be easily mounted inside the mixing chamber to increase the dispersion of the injected water. The mixing chamber will be large enough (70" interior diameter) so that simple cloud diagnostics will be able to be performed inside while the CCSF is running. The large diameter will be maintained in the flow direction for as long as possible. The last 90° turn before the test section will have turning vanes to depress large scale motions in the flow. We anticipate the need for 2 perforated plates and a honeycomb to straighten and smooth the flow before it enters the test section. We do not yet know how much effect icing will have on these elements. The diameters of the test section (30") and the clearing-beam entrance & exit ports (8") will be the same as that of the CSF. The downstream end of the test section will have a single perforated plate to

even out the suction produced by the small area outlet which leads to the fan intake. Some turning vanes may also be needed to help the flow make the 90° corner at the end of the test section.

Diagnostics:

The diagnostics described here are the minimum necessary to monitor the performance of the tunnel. Temperature will be measured in 5 places while the CCSF is running, 1) just downstream of the chiller, 2) at the beginning of the test section, 3) at the end of the test section, and 4) at the inlet to the fan, and 5) just upstream of the chiller. Pressure differences will be measured across the chiller, the flow straightening section, and the fan. A He-Ne laser extinction cell will be set up to monitor the optical depth of the cloud produced in the test section. It is not expected that any of the PMS Inc. (Particle Measuring Systems Incorporated) diagnostics will be purchased during the early phases of this work. Our preliminary studies will be done by renting equipment from the University of Washington. Ice crystal habit and size will be documented by direct inspection of ice shapes using Formvar plastic replication². The technique involves coating ice crystals with plastic before they melt to produce a semipermanent record of their shape & size which can be examined with a microscope. The ratio of liquid water to solid water content of the cloud will be estimated by illumination of the cloud particles with a polarized laser and making observations through a polarizer.

Laboratory & Cost Constraints:

Figure 4-3 is a sketch of how we plan to integrate the CCSF into the available laboratory space. The length of the test section (about 11') was chosen primarily by the overall length available in the laboratory and the need for space at both ends to set up the optical diagnostic equipment. The rest of the components of the CCSF were drawn to fit into the remaining space. The exact placement of components will be decided when the various pieces arrive and the CCSF is assembled.

Figure 4-3: Cold Cloud Simulation Facility.

Because of cost constraints we will not be able to modify the existing laboratory walls very much, or purchase new 12" optics for steering and focusing the PHOCL-50 laser beam. The clearing beam path shown on Figure 4.3 can be made with the purchase of only one 12" optical mount and without making any holes in the existing walls.

The mechanical and thermodynamic performance of the CCSF has been given the top priority for the available funding. We anticipate spending most of the available money building, outfitting, trouble shooting, and modifying the CCSF until it produces an acceptable range of natural cloud properties. The remaining money will be spent on the optical diagnostics and clearing experiments.

Anticipated Experiments:

The first series of measurements will be of extinction time-histories at visual wavelengths after the clearing beam is fired. These experiments will be done with a fixed initial optical depth as the temperature in the test section is varied from roughly -40°C to room temperature. These experiments will be done with a laser fluence of about $1/2\text{ joule/cm}^2$ using existing equipment. The fluence level will be increased if the necessary steering & focusing optics for the PHOCL-50 beam can be obtained. Emphasis will be put on measurements in cold clouds.

Additional experiments that might be done in the future are also compatible with the current CCSF design. These include investigations of: 1) the effects of fluence level on extinction in the cleared path, 2) clearing clouds that contain both ice crystal and water droplets, 3) the effects of crystal habit on clearing performance, and 4) the extent to which clearing beam illuminated crystals are melted or evaporated. It is anticipated that varying some or all of the tunnel conditions will produce changes in the habit of the ice crystals. In addition, we will also be in a position to verify LANL liquid-water cloud clearing results as desired.

References (Sec. 4.2):

1. H. R. Pruppacher and J. D. Klett Microphysics of Clouds and Precipitation, D. Reidel Publishing Co. (London, 1979).
2. B.J. Mason The Physics of Clouds, Oxford University Press (Oxford, 1971)

4.3 Enhanced Clearing of Cold Clouds by CO₂ Lasers Pulses

The work reported here has been conducted under Boeing IRAD funding, to support a better understanding of phenomena we expect to encounter in the LANL funded experimental cloud clearing program. It appears to us that a channel cleared in ice particle clouds will be resistant to recondensation (which rapidly obscures the channel in droplet clouds). This result depends on the difference in water vapor saturation concentrations over liquid water and ice.

Some authors have reported partial cloud clearing by lasers at visible wavelengths^{1,2}. Others report that the channel becomes less transparent than the pre-illumination value after the illumination ceases³⁻⁶. Increased extinction in the illuminated channel must be due to the formation of new, smaller water droplets either by shattering the initial droplets or recondensation of water from the evaporated droplets. However, for a range of conditions of practical interest for cloud clearing (laser power levels below 3×10^5 W/cm², wavelength of 10.6 μ m and droplet diameter less than 12 μ m), the droplets do not shatter^{7,8}. Thus the observed decrease in channel transparency must be due to new droplets formed by recondensation. This memo describes a model that predicts the conditions under which recondensation will take place.

Cloud Characteristics:

An ambient fog or cloud consisting of suspended liquid water droplets contains most of its mass in the 3-12 μ m diameter range and the liquid water concentration, ρ_w , is typically 0.05-0.3 gm/m³ except in cumulus clouds with greater than 1 km vertical extent that often have higher water concentrations^{5,9}. The cloud is slightly above 100% relative humidity and the water vapor concentration, ρ_{wv} , approximately doubles for each 10° C temperature increase as shown in Figure 4.4. Cloud particles at temperatures below 0° C can exist either as droplets or as ice crystals. Ice and water have slightly different water vapor concentrations, also as shown

in Figure 4-4. Crystal clouds usually have lower ice concentrations, ρ_i , usually below 0.05 gm/m^3 ; however, high altitude cirrus clouds have not been frequently characterized⁵. Droplets will not freeze without ice nuclei until temperatures are below about -40° C . Clouds containing both ice and water particles are not in equilibrium and will usually have water vapor concentrations above saturation for ice, ρ_{iv} , and below saturation for water, ρ_{wv} . Under these conditions, the water particles evaporate and the vapor deposits onto the ice particles broadening the particle size distribution and increasing the probability of precipitation¹⁰. This conversion of droplets to ice crystals is the key element in commercial "rain making" where ice nuclei such as silver-iodide crystals are added to supercooled clouds.

Figure 4-4: Saturation vapor concentration as a function of temperature for both water and ice¹⁹.

Droplet Evaporation:

The behavior of water droplets under CO₂ laser illumination has been modeled by a number of workers^{3, 11-15}. Their models describe the behavior of water droplets under illumination and include heating, evaporation and conduction. For droplet diameter less than about 12 μm, the droplet absorbs energy from the illuminating laser beam at a rate proportional to the product of the beam intensity times the droplet volume. The absorbed power heats the droplet to a temperature between ambient and 100° C and evaporates liquid water. Thermal conduction from droplet to air is negligible for droplets with diameter larger than a few tenths micrometer¹⁶. The droplet temperature increases rapidly to an equilibrium value and the droplet decreases in volume at a rate proportional to the current volume. The droplet evaporates in this way until conduction to the air becomes an important energy loss mechanism, at which point the temperature decreases and the evaporation rate slows.

Sutton¹⁶ shows that the energy absorbed per volume, V , of the droplet is equal to laser fluence, F , times the bulk water absorption coefficient, K . K has a value of about 840 cm⁻¹. If all the energy absorbed evaporates the liquid at a temperature of 30° C, the latent heat of evaporation, L equals 2550 joules per gram of liquid. Neglecting conduction, the change in volume is given by,

$$dV/V = (K/L) \cdot dF \quad (1)$$

$$V = V_0 e^{-(K/L)F} \quad (2)$$

$$V = V_0 e^{-0.33F} \quad (3)$$

Extinction at visible wavelengths is entirely due to scattering and the scattering extinction coefficient, σ_s , is equal to droplet cross-section per volume of air for particle diameters larger than about 1 μm. Change in extinction as a function of fluence is given by

$$\sigma_s = \sigma_{s0} e^{-0.22F}, \quad (4)$$

and radius, r , decreases as given by

$$r = r_0 e^{-0.11F}. \quad (5)$$

The end product of the process described by these models is a spheroid of warm moist air, probably with the remnant of the initial drop at the location of the starting droplet. The models do not predict recondensation, although Sutton¹⁶ did mention the possibility and Volkovitski⁵ calculated the magnitude of supersaturation of air surrounding the illuminated, evaporating droplet. Note that the model we describe does not predict complete droplet evaporation or channel clearing, only a decrease in particle volume and channel extinction. A more exact model that includes droplet-air conduction would predict a slightly slower decrease in volume, extinction and radius than specified in Eqns. (1)-(5).

Recondensation:

If many new smaller droplets form after illumination of the original droplets ends, optical extinction in the laser illuminated channel may be increased rather than decreased. Volkovitski³, Ivanov⁴ and Fowler⁶, all report that the illuminated channel becomes less transparent after the laser pulse. The mechanism for this must be recondensation of the water from the initial droplets into new smaller droplets. Based on photographs, Ivanov⁴ reported that recondensation takes place in a spherical shell surrounding the original drop.

The water vapor from the evaporated droplet will produce supersaturation (relative humidity above 100%) as water vapor and thermal energy diffuse away from the drop. Air at the interface will be saturated and at drop temperature. Air between drops is at cloud temperature and also saturated. As shown in Figure 4-5, mixing two volumes of saturated air with different initial temperatures produces a volume of air with temperature and water vapor concentration that is a weighted average of the two initial temperatures and vapor concentrations. Supersaturation will always occur when two saturated volumes of air at different

Figure 4-5: Saturation vapor concentration versus temperature for water. The dotted line shows the possible range of temperature and water vapor concentration for a mixture of air parcels with the properties at points "A" and "B". All points along the dotted line are above the saturation vapor concentration.

temperatures are mixed because saturation water vapor concentration is an exponential function of temperature and the mean of the two vapor concentrations will be higher than the saturation value for the mixture temperature. Supersaturation can produce condensation on pre-existing particles or droplets, or can homogeneously nucleate new droplets in particle-free air.

Recondensation and increased extinction is expected after the end of the illumination because:

- 1) The cloud initially contains H_2O in both liquid and vapor forms;

2) The cloud liquid water must be evaporated to clear the cloud, but additional water cannot be retained in the vapor phase without an increase in air temperature. Laser energy is not significantly absorbed by the air, hence a portion of the evaporated water cannot remain in the vapor phase and will recondense.

3) Water can recondense either on the remnant of the original drop to partially restore the original extinction or can form new drops and increase extinction in the channel.

These ideas suggest that the only way to prevent recondensation is to heat the air parcel and increase the capacity of air to retain H_2O molecules that were initially in the particles, in the vapor phase. For a given liquid water concentration in the cloud, the required temperature increase depends on the slope of saturation water vapor concentration versus temperature,

Figure 4-6: The change of saturation water vapor concentration versus change in temperature as a function of temperature.

$\partial\rho_{wv}/\partial T$, shown in Figure 4-6. The fraction of evaporated water molecules that recondense can be calculated assuming that the energy released per gram/m³ of recondensed water heats that same volume of air and enables the remaining fraction of evaporated water molecules to remain in the vapor at increased air temperature. If Ψ = fraction of evaporated molecules that recondense, then $(1 - \Psi)$ is the fraction remaining in vapor. The fraction and amount of water that can remain in vapor is controlled by the temperature change, ΔT , and $\partial\rho_{wv}/\partial T$,

$$(1 - \Psi) \cdot \rho_w = \Delta T \cdot (\partial\rho_{wv}/\partial T). \quad (6)$$

The change in temperature is determined by the ratio of the heat released per gram of condensed water, L , to the heat capacity per m³ of air, S_{air} , as shown below,

$$\Delta T = \Psi \cdot \rho_w \cdot (L/S_{air}). \quad (7)$$

Then substituting Equation (7) into (6),

$$(1 - \Psi) \cdot \rho_w = \Psi \cdot \rho_w \cdot (L/S_{air}) \cdot (\partial\rho_{wv}/\partial T), \quad (8)$$

and the result is independent of ρ_w ,

$$(1 - \Psi) = \Psi \cdot (L/S_{air}) \cdot (\partial\rho_{wv}/\partial T). \quad (9)$$

The value of (L/S_{air}) is nearly independent of temperature and the solution for Ψ is dominated by the strong temperature dependence of $(\partial\rho_{wv}/\partial T)$. Figure 4-7 is a plot of Ψ , the fraction of evaporated water that recondenses, as a function of temperature, assuming that the illuminated droplet evaporates at 30° C. This result shows that as cloud temperature decreases, a larger fraction of evaporated water recondenses because a larger increase in air temperature is required to retain the clouds liquid water in the vapor phase. This is consistent with the experimental reports of recondensation in the laser illuminated channel for laboratory clouds at temperatures below freezing^{3,5,6}.

Figure 4-7: The fraction of water initially in droplets that will recondense after the laser pulse ends, as a function of temperature.

In summary, although definitive experiments have not yet been conducted, the model and experimental results described above are not favorable for laser clearing of droplets clouds and fog, because the CO₂ laser illumination is only absorbed in the condensed water, not in the air. Except for droplet-air conduction, the air surrounding the droplets is not significantly heated without recondensation and the heat delivered by recondensation only allows a fraction of the evaporated water to remain in the vapor phase. Several laser pulses would be necessary to produce a series of evaporation-recondensation cycles to heat the air sufficiently to reach low values of extinction.

Ice Crystal Clouds:

Clouds at temperatures below 0° C can consist of supercooled droplets, a mixture of droplets and ice particles or entirely of ice particles. The fraction containing some or all ice particles increases linearly from zero to 100% over the range 0 to -20° C with significant variability^{5,9}. Without dynamic lifting, a cloud that consists of a mixture of ice and droplets will convert to entirely ice particles in times much shorter than one hour.

A CO₂ laser illuminating an ice cloud would first melt the ice particles to form droplets. Under continued illumination, the droplets would increase in temperature and then evaporate to form a vapor. It would appear that the energy required for clearing an ice particle cloud is the sum of that for droplet clouds of the same condensed water concentration plus the added energy required to melt the crystals. However, the cloud water vapor concentration in an ice particle cloud is at or near saturation for ice and usually below saturation for liquid water. Therefore, with the same vapor concentration that exists in an ice particle cloud, a water droplet cloud is sub-saturated with respect to water vapor.

This critical difference in saturation water vapor concentration allows evaporation of the ice crystals with much lower laser pulse energy requirements than that for droplet clouds. To evaporate the ice particles, the only energy input to the particles is that needed to melt the crystals. The resulting droplets will be surrounded by air below 100% relative humidity and will evaporate without further laser energy input and will not recondense, provided that the surrounding air can accept the added water vapor while providing the required latent heat of evaporation. Figures 4.4 and 4.8 show that ice vapor concentration is below that of water at temperatures less than 0° C. Over the range -2 to -40° C, the difference in saturation vapor concentrations, $\rho_{wv} - \rho_{iv}$, is greater than the maximum 0.05 g/m³ ice concentration in elevated crystal clouds without dynamic lifting, as reported by Pruppacher and Klett⁹ and Volkovitski⁵. In our discussions of ice clouds, we wish to note that detailed measurements of the radiative and microphysical characteristics of clouds are limited. Even

descriptions of the major dynamic forcing mechanisms are actively debated¹⁶.

If the latent heat of evaporation can be supplied by the air, the difference in water minus ice saturation vapor concentrations, shown in Figure 4.8, would allow all the ice crystals at concentrations in typical crystal clouds to evaporate. The limit of this source of heat is set by the decrease in air temperature as the droplets evaporate. Note that this decrease in air temperature will also drop the vapor concentration limit set by saturation over liquid water.

The decrease in air temperature caused by the droplet evaporation is equal to the energy required to evaporate the droplet mass, (about 430 calories per gram of water) divided by the specific heat of air (about 340 calories per m^3 per $^{\circ}\text{C}$). The decrease in air temperature as a function of initial ice concentration is about -0.015°C per 0.01 g/m^3 of ice particles. This decrease in temperature only slightly decreases the water saturation vapor concentration. The maximum concentration of ice particles that will evaporate after melting without further heat input is greater than 0.05 g/m^3 over the temperature range -2 to -40°C and above 0.1 g/m^3 and above 0.1 g/m^3 between -3 and -32°C .

This description assumes droplets evaporate prior to encountering a freezing nuclei. Freezing or ice nuclei are rare (a few per liter), and it is reasonable to assume that in melting the ice crystal to a droplet, the ice nuclei which caused the original droplet to freeze has been destroyed or deactivated. If the original freezing nucleus was an ice crystal fragment as appears to often be the case, the nucleus is destroyed by melting⁹. Also, Mason¹⁷ notes that mineral and organic ice nuclei become much less effective after immersion in liquid water.

Figure 4-8: The difference between water and ice saturation vapor concentration as a function of temperature. This difference is the approximate upper limit in particle concentration for ice cloud evaporation after melting. Note that the difference is above 0.05 g/m³ between -3 and -40° C and above 0.1 g/m³ between -8° and -32° C.

Comparison to Other Reported Measurements of Clearing:

We are reporting the conditions under which recondensation is expected when a droplet or ice particle filled cloud channel is illuminated with a pulsed CO₂ laser. A majority of earlier cloud clearing experiments have detected recondensation and increased extinction. We predict that ice particle clouds will be easy to clear and resist recondensation, in conflict to earlier experimental findings. This prediction requires that the mass concentration of ice particles in the cloud be below the limit 0.05 g/m³. Descriptions of experimental clearing of laboratory fog appear to have given low priority to the physical characteristics of actual clouds. The researchers have usually not measured either the particle size distribution or condensed water concentration. Generally the laboratory fogs have

significant extinction in a short path, typically of order one meter. This indicates that in these experiments, either the particle size is too small or the condensed water concentrations too high to be consistent with reported cloud properties. The ease of clearing ice particle clouds will be demonstrated only if the ice particle mass concentration is less than the limit shown in Figure 4-8. It appears to us that the experiments probably were substantially above this limit and above the concentration of ice particles that actually is present in natural cirrus ice particle clouds. Attempting to clear clouds with excessive particle mass concentration was, with the benefit of hindsight, a significant error in design of prior experiments because high ice particle concentrations will cause both high supersaturation and recondensation, as has been reported. This behavior does not model the actual behavior of low concentration ice clouds when illuminated by pulse CO₂ lasers.

Planned Experiments:

We will conduct fog clearing experiments with careful control of the particle size and concentration in our laboratory fogs at temperatures above and below freezing. We predict that below the concentration limits shown in Figure 4-8, ice particle clouds will require only a fraction of a joule cm⁻² to completely clear the channel rather than several joules cm⁻² required to partially clear a droplet cloud. The exact energy requirements to melt the ice crystals will depend on the ratio of optical absorption at 10.6 μm to particle mass. The laser power level must also be high enough to melt the ice particles, allowing for the better thermal conduction through the high surface to volume ratio characteristic of ice particles. Numerical methods to calculate the optical absorption and thermal conductivity for actual crystal shapes at arbitrary orientations are not available. We hope to explore these questions experimentally in studies of clearing both droplet and crystal clouds at temperatures above and below freezing using particle size distributions and concentrations that mimic those in actual clouds.

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5.0 FLOW SYSTEM DESIGN (TASK4)

5.1 Heat Transfer Model

A heat transfer model has been developed to estimate the bulk temperature difference between the laser gas and the laser wall that occurs during the gas fill processes. This model will be used to determine the effects of fast bulk fill times and D_2 injection on beam quality due to temperature inhomogeneities, as well as provide guidance on how to minimize temperature effects on beam quality. Experiments utilizing a 7 ft x 20 ft vacuum tank were used to confirm the model.

The simplest flow cycle for a pulsed chemical laser consists of filling the evacuated laser canister with the bulk laser gas, injecting & mixing the second reactant, firing the laser, and evacuating the laser canister. This section deals with the mean thermal conditions inside the laser canister during the bulk fill. The beam quality that the laser produces depends critically on the size of the index of refraction fluctuations (i.e. temperature and concentration fluctuations) in the laser gas at the time that the laser is fired. During the bulk fill, compressive heating of the laser gas from the work done during the injection process is eventually transferred to the walls of the laser canister by the resulting motion of the laser gas. What follows here is an attempt to use a simple energy balance to predict the mean temperature of the laser gas, T_g , as a function of time during the bulk fill. A more complete theory that will accurately predict the important aspects of the mean temperature field at any cross section inside of the container awaits the results of the on going experiments.

To make the formulation of the problem realistic and practical several assumptions will be made. First, it will be assumed that the laser cavity is a long cylinder of length L and diameter D , with $L \gg D$. Second, it will be assumed that the injection system for the laser gas is a spray bar consisting of a row of axisymmetric jets placed every third cylinder diameter along one of the inside walls, and pointing toward the axis of the long cylinder. These assumptions allow the problem to be treated as two dimensional in the

plane perpendicular to the axis of the cylinder. Hence, the extensive variables used below are "per-unit-length" quantities. For the accuracy required here, the wall temperature of the laser canister cannot be treated as a constant during the fill process, but will instead be treated as rising linearly during the fill based on a global energy balance. This linearity assumption is valid because the total heat capacity of the laser gas is typically less than 1% of the total heat capacity of the metal cylinder that will contain it.

The solutions that are derived below are only applicable at large times. The reason for this is that the Reynolds number of the flow inside the laser canister will start at nearly zero, and end up at about 10^5 when the fill is complete. An accurate theory of both laminar & turbulent fluid motion that spans that entire range, and yields analytical results is not possible. Each of the three solutions presented below may be "visited" by the real flow during its progression from vacuum conditions to the final pressure of about 1 atm.

Energy conservation for the gas inside the laser canister during the bulk fill is described by the following equation:

$$\frac{d(c_v \dot{m} T_g)}{dt} = -Q_w + \dot{m} c_p T_{oi} \quad (1)$$

where;

c_v = specific heat capacity at constant volume of the gas ,

c_p = specific heat capacity at constant pressure of the gas ,

$\dot{m}$ = mass flow rate per unit length into the volume,

T_g = temperature of the gas inside the laser volume,

Q_w = heat transferred to the cavity walls per unit time & unit length,

T_{oi} = stagnation temperature of the input gas,

The term on the left hand side of this equation is the time rate of change of the internal energy of the gas inside the laser volume. The two terms on the right hand side of the equation are the heat transfer to the walls of the container, and the total enthalpy carried into the laser volume by the injected gas. This conservation equation implicitly assumes that the gas inside the volume is instantly well mixed and quiescent. As a consequence, T_g (and other specific quantities) should be interpreted as a bulk average temperature.

To find a closed form solution to Eqn.(1), several simplifications and assumptions must be made. First, the specific heats of the gas are assumed constant, and the input mass flow rate is taken to be a constant. The stagnation temperature of the input gas may also be taken to be a constant only if the gas source used to fill the volume is isothermal during the fill process. We assume for now that this is not the case and that T_{0i} is a function of time.

The heat transfer term can be expressed in terms of the Nusselt number, Nu ,

$$Q_w = Nu \kappa (T_g - T_w), \quad (2)$$

where T_w is the temperature of the walls of the laser vessel, and κ is the thermal conductivity of the gas. The Nusselt number can be interpreted as the ratio of the actual heat transfer to the amount of heat transfer that would take place by simple conduction without any fluid motion. If Nu is small ($< \text{about } 10^2$), then the relevant heat transfer mechanisms are probably laminar. If Nu is large ($> \text{about } 10^3$), then the transfer of heat is probably driven by turbulent mechanisms. In the overlap region both types of transport could be important. The wall temperature of the container will be assumed to be a simple linear function of time, *i.e.*,

$$T_w = T_w^0 + \frac{t}{\tau_m}, \quad (3)$$

where T_w^0 is the initial wall temperature, and τ_m is a time constant associated with the total heat capacity of the laser container wall material. If Eqn. (1) is divided by T_w^0 , c_v and $\dot{m}$, and a dimensionless temperature difference, $\theta = (T_g - T_w)/T_w^0$, is introduced to replace T_g , the result is;

$$\frac{d(t(\theta + t/\tau_m))}{dt} = -\frac{Nu \kappa \theta}{\dot{m} c_v} + \left(\gamma \frac{T_{oi}}{T_w^0} - 1 \right) \quad (4)$$

where T_{oi} can be a function of time, and γ is equal to c_p/c_v . Equation (4) is a first-order, linear equation in θ provided Nu is only a function of time and does not depend on θ . This condition is satisfied if the buoyant forces produced by temperature differences within the laser gas are small compared to the momentum fluxes in the gas within the laser volume. It is expected that this will be the case while the laser canister is being filled, so the solution of Eqn. (4) can be carried out if a relation for $Nu(t)$ can be found.

To derive an explicit relation for $Nu(t)$, it is necessary to consider the mechanisms of heat transport in this problem. The relevant formulation (without radiative heat transfer) for Q_w is given by:

$$Q_w = -\pi D \kappa \langle (\partial T / \partial n) |_{(at\ the\ wall)} \rangle \quad (5)$$

where the $\langle, \rangle$ brackets denote a spatial average, and n is a coordinate that is perpendicular to the wall. The mean temperature derivative can be replaced by the mean temperature difference, $\Delta T = T_g - T_w$, and an effective thermal boundary layer thickness, δ_T .

$$Q_w = -\pi D \kappa \Delta T / \delta_T \quad (6)$$

If we use Reynold's analogy¹, the assumption that heat and momentum are transferred by similar processes, then δ_T can be estimated from considerations of the mean momentum transfer.

Previous work² has shown that the mean motion inside the laser cavity during the fill process will consist of two large counter rotating vortices. The time for the rotation of these vortices was found to be proportional to a characteristic time, t_c , derived from dimensional considerations of the relevant variables. This characteristic time is given by

$$t_c = \sqrt{\frac{\rho D^3}{J}} , \quad (7)$$

where ρ is the gas density in the laser volume and J is the thrust per unit length of the injection jets. For the case of interest, ρ is given by

$$\rho = \frac{4 \dot{m} t}{\pi D^2} . \quad (8)$$

If we take the injection jet nozzles to be sonic at a pressure P^* , then

$$J = \dot{m} a^* \left\{ 1 + \frac{1}{\gamma} \left(1 - \frac{P_t(t)}{P^*} \right) \right\} , \quad (9)$$

where a^* is the sonic sound speed of the incoming gas, and $P_t(t)$ the time dependent pressure in the volume ($P_t(t) < P^*$ by design). The mean convective velocity of the bulk motion inside the volume is assumed to be given by

$$U = \frac{D}{t_c} . \quad (10)$$

The large vortices will most likely be turbulent since they are produced by an injection process involving many turbulent jets. This mean motion will be driven by the momentum supplied by the injection jets. The rotation of the large vortices will be impeded by the skin friction, τ_w , along the walls of the laser vessel and the mean pressure distribution. In particular, the impact zone on the opposite wall from the injection jets will be at a slightly higher pressure, Δp , when compared to other parts of the laser interior. The scale length of this portion of the wall where the over pressure is

significant will be proportional to the diameter of the vessel. For a quasi-steady state the three forces will balance, which means that:

$$J \approx \pi D \tau_w + f D \Delta p, \quad (11)$$

where f is a dimensionless constant of order unity. If the boundary layer is turbulent, then both the over pressure and the skin friction will be proportional to the dynamic pressure of the flow, i.e.,

$$\Delta p \text{ and } \tau_w \propto \rho U^2, \quad (12)$$

where U is the mean convection velocity of the gas in the large vortices given by Eqn. (10). If the ratio of the pressure term to the wall shear stress term in Eqn. (11) is a constant (independent of the Reynolds number and time) then Eqns. (11), (12), and the momentum transfer equivalent of Eqn. (6),

$$\tau_w = \mu \left\langle \left(\frac{\partial u}{\partial n} \right) \right|_{\text{(at the wall)}} \rangle = \mu U / \delta_M, \quad (13)$$

and the Reynolds analogy, $\delta_T \propto \delta_M$, can be combined to yield the functional dependence of the boundary layer thicknesses on known quantities. The result, ignoring dimensionless constants, is

$$\delta_T \propto \delta_M \propto \mu (D/\rho J)^{1/2}, \quad (14)$$

where μ is the dynamic viscosity of the laser gas. δ_T and δ_M physically correspond to the laminar sub-layer thickness of a turbulent boundary layer. Combining Eqns. (3), (6), (7), (10) and (14) yields

$$Nu \propto \frac{\rho D^2}{\mu t_c} = \frac{\rho U D}{\mu}. \quad (15)$$

Note that this result shows that the Nusselt number is proportional to the Reynolds number ($\rho U D / \mu$) of the bulk fluid motion inside the volume. The

explicit time dependence of Nu is obtained using Eqns. (7) through (10) and (15),

$$Nu \propto \frac{\dot{m}}{\mu} \sqrt{\frac{t}{t_a}}, \quad (16)$$

where t_a is the natural time scale of the problem given by

$$t_a = \frac{\dot{m} D}{J} = \frac{D}{a^*} \left\{ 1 + \frac{1}{\gamma} \left(1 - \frac{P(t)}{P^*} \right) \right\}^{-1}. \quad (17)$$

Note that the Nusselt number of the flow in this case is proportional to $\sqrt{t}$, and that t_a will in general be only weakly dependent on t for $P(t) \ll P^*$.

The governing differential equation can now be rewritten with the primary time dependence of the heat transfer term shown explicitly;

$$\frac{d(t(\theta + t/\tau_m))}{dt} = -c_1 \frac{\gamma \theta}{Pr} \sqrt{\frac{t}{t_a}} + \left(\gamma \frac{T_{oi}(t)}{T_w^o} - 1 \right) \quad (18)$$

where c_1 is a dimensionless constant, $Pr (= \mu c_p / \kappa)$ is the Prandtl number of the gas. Note that Eqn. (18) does not contain the mass flow rate term (i.e., the solution for θ will not depend on $\dot{m}$). The approximations leading to Eqn. (18) are consistent with fully turbulent flow throughout the laser vessel. Hence, the solutions of (18) can not be correct when the Reynolds number is small at the beginning of the fill.

If the boundary layer on the inside wall of the laser cavity is laminar, then the formulation of the Nusselt number is different. The effective boundary layer thickness is given by $\delta_T \propto \sqrt{\mu D / \rho U}$. This, combined with Eqn. (11) without the pressure term and Eqn. (13), results in a Nusselt number given by

$$Nu \propto \left(\frac{\rho U D}{\mu} \right)^{2/3} = \left(\frac{\dot{m}}{\mu} \right)^{2/3} \left(\frac{t}{t_a} \right)^{1/3}. \quad (19)$$

In this case the Nusselt number is proportional to the 2/3rd power of the bulk motion Reynolds number, and the 1/3rd power of time.

The governing equation then becomes

$$\frac{d(t(\theta + t/\tau_m))}{dt} = -c_2 \frac{\gamma \theta}{Pr} \sqrt[3]{\frac{\mu}{\dot{m}} \frac{t}{t_a}} + \left(\gamma \frac{T_{oi}}{T_w^o} - 1 \right), \quad (20)$$

where c_2 is a dimensionless constant. The assumptions leading to Eqn. (20) are consistent with weakly turbulent fluid motion in the interior of the laser volume that is dissipated by a laminar boundary layer on the internal wall.

A third possibility is that the pressure term in Eqn. (11) dominates the force balance, i.e.

$$J \propto \rho U^2 D, \quad (21)$$

and the boundary layer is laminar with the effective boundary layer thickness again given by $\delta_T \propto \sqrt{\mu D / \rho U}$. These two approximations correspond to fully turbulent flow in the interior of the container that is dissipated by turbulent mechanisms outside of the boundary layer. In this case, Eqns. (3), (4), (6) through (10) & (21) can be used to obtain

$$Nu \propto \left(\frac{\rho U D}{\mu} \right)^{1/2} = \left(\frac{\dot{m}}{\mu} \right)^{1/2} \left(\frac{t}{t_a} \right)^{1/4}, \quad (22)$$

and

$$\frac{d(t(\theta + t/\tau_m))}{dt} = -c_3 \frac{\gamma \theta}{Pr} \sqrt[4]{\frac{\mu^2}{\dot{m}^2} \frac{t}{t_a}} + \left(\gamma \frac{T_{oi}}{T_w^o} - 1 \right) \quad (23)$$

where c_3 is a dimensionless constant. The Nusselt number is proportional to the 1/2 power of the bulk motion Reynolds number, and the 1/4th power of time for this case.

Eqs. (18), (20) & (23) are of the form

$$\frac{d(\tau\theta)}{d\tau} = -a\theta\tau^\epsilon + \beta(\tau) \quad (24)$$

where 'a' is a constant, $\beta(\tau)$ is a function that allows T_{oi} to be a function of t , and τ is a dimensionless time given by

$$\tau = \int_0^t \frac{a^*}{D} \left\{ 1 + \frac{1}{\gamma} \left(1 - \frac{P_t(\zeta)}{P^*} \right) \right\} d\zeta, \quad (25)$$

which takes into account the fact that the pressure inside the pressure vessel, P_t , increases during the fill.

The particular solution for $\tau\theta(\tau) = 0$ at $\tau = 0$ is given by

$$\theta = \frac{\exp\left[-\int_0^\tau a\zeta^{\epsilon-1} d\zeta\right]}{\tau} \int_0^\tau \beta(\xi) \exp\left[+\int_0^\xi a\zeta^{\epsilon-1} d\zeta\right] d\xi. \quad (26)$$

The solution for Eqn. (26) for the fully turbulent case, Eqn. (18), is given by $\epsilon = 1/2$, $\beta(\xi) = b + (c - 2d)\xi$, and

$$\theta = \frac{b}{a} \left[\tau^{-1/2} - \frac{3}{2a} \tau^{-1} \{1 - \exp(-2a\tau^{1/2})\} \right] + \frac{c - 2d}{a} \left[\tau^{1/2} - \frac{3}{2a} + \frac{3}{2a^2} \tau^{-1/2} - \frac{3}{4a^3} \tau^{-1} \{1 - \exp(-2a\tau^{1/2})\} \right] \quad (27)$$

where a, b, c, & d are constants. Their definitions for this problem are:

$$a = c_1 \frac{\gamma}{Pr}, \quad b = \frac{\gamma T_{oi}(0)}{T_w^0} - 1, \quad c = \frac{\gamma}{T_w^0} \frac{dT_{oi}}{d\tau}, \quad d = \frac{t_a}{\tau_m}, \quad (28)$$

and their estimated sizes are $.01 < a < 1$, $b \approx .6$, $10^{-6} < c < 10^{-4}$, and $10^{-6} < d < 10^{-4}$. (The expressions for the solution to Eqn.(20) are similar in form to Eqns. (27) and (28), but will not be given here as that case is the least likely to exist in nature.) For $\varepsilon = 1/4$, $\beta(\xi)$ and τ as above, the exact solution of Eqn. (23) is:

$$\theta = \frac{b}{a} \left[\tau^{1/4} - \frac{3}{4a} \tau^{1/2} + \frac{3}{8a^2} \tau^{3/4} - \frac{3}{32a^3} \tau^1 (1 - \exp(-4a\tau^{1/4})) \right] + \frac{c-2d}{a} \left[\tau^{3/4} - \frac{7}{4a} \tau^{1/2} + \frac{21}{8a^2} \tau^{1/4} - \frac{105}{32a^3} + \frac{105}{32a^4} \tau^{1/4} - \frac{315}{128a^5} \tau^{1/2} + \frac{315}{256a^6} \tau^{3/4} - \frac{315}{1024a^7} \tau^1 (1 - \exp(-4a\tau^{1/4})) \right], \quad (29)$$

and redefining 'a' from Eqn. (28) as: $a = c_3(\gamma/Pr)\sqrt{\mu/\dot{m}}$, with a range of value from zero to about 10^4 to 10^6 during a single fill sequence.

The above theoretical model requires the evaluation of one constant for each flow regime. These constants, c_1 , c_2 , and c_3 , must be determined empirically from experiments. Experiments are also required to determine under what flow conditions each regime exists.

References (Sec 5.1):

1. O. Reynolds [1874] "On the extent and action of the heating surface for steam boilers", Proc. Manchester Lit. Phil. Soc. 14, 7-12
2. Breidenthal, R.E., Buonadonna, V.R., and Weisbach, M.F. [1988] "Mixing of jets in confined volumes", submitted to JFM.

5.2 Experiment and Results

Experiments were conducted in a cylindrical pressure vessel shown in Fig. 5-1. The vessel is 2.1 meters in diameter and about 7.3 meters long, made of structural steel (SA 516-70). The wall thickness was 1.3 cm for a total mass of about 5,440 kg. The outside wall was insulated with two 1 cm thick layers of rock wool cloth. Temperature measurements were made with five T-type thermocouples placed in a plane perpendicular to the axis of the cylinder and near the midpoint between the two ends of the vessel (see Fig. 5-1). One of the thermocouples was placed in thermal contact with the inside wall of the pressure vessel. All of the thermocouples utilized electronic thermometers that produced an analog signal (10 mV/°C). These signals were recorded with digital oscilloscopes or a strip chart recorder. Most of the data reported below are from measured temperature differences between the central & wall thermocouples.

The gas used in the experiments was argon. It was injected into the pressure vessel along the bottom through a 2.5 cm ID supply pipe that had ten 3.8 mm diameter orifices with an approximate spacing of 68.5 cm. The pipe was oriented to insure that the turbulent jets emerging from the orifices symmetrically impacted on the far side of the pressure vessel. The pressure difference between the inside of the supply pipe and the inside of the vessel was large enough to insure sonic conditions at each orifice. The source for the injected gas was a farm of 16 standard high pressure cylinders manifolded together. The gas was discharged into the supply pipe through a single-stage dome-loaded regulator which maintained constant pressure in the supply pipe during a run. The bottle farm was charged to 1100 psi before a run from a argon supply trailer. The final pressure inside the large cylindrical pressure vessel was 1 atmosphere. During a run, the pressure in the bottle farm typically dropped by about 500 psi. The pressures in the supply pipe and cylindrical vessel were measured with electronic pressure transducers. The temperature of the gas in the supply pipe was also recorded during a run with a thermocouple to determine the corrections to T_{0i} for isentropic and Joule Thompson cooling. An additional correction for the the Joule-Thompson cooling that takes place across the

orifices was made in the data processing. All of the temperature corrections made to T_{oi} usually amounted to between 2°C and 10°C.

The experiment was run by evacuating the vessel to a fraction of a torr and then filling it with argon to 14.7 psia using the injection system described above. Fill times of 40 to 2000 seconds were possible with this experimental setup. Shorter fill times would have required a higher capacity gas supply system, and longer fill times were not of interest. About a dozen runs were made between these limits. The results were repeatable and all of the thermocouples displayed the same basic behavior.

Fig. 5-2 is a typical oscilloscope trace of the gas temperature and wall temperature measured with thermocouples located on the axis of the cylindrical volume and the inside wall, respectively. Fig. 5-3 shows non dimensionlized data taken for fill times of 1650 sec to 44 sec. Theoretically predicted curves based on the laminar boundary layer model solution, Eqn. (29), are also given for $c_3 = 10.5$. The calculated curves include corrections from measured values of T_{oi} , T_w , T_w^0 , and plotting the results against τ as defined by Eqn. (25), using measured values for P_t .

The model is in excellent agreement with the experiment for fill times longer than ~500 sec. For shorter fill times, the boundary layer is in transition between laminar and fully turbulent flow. Theoretical modeling is very difficult in this transition region. However, the laminar model is conservative in that it over predicts the final gas temperature for fill times between 500 to 44 sec. Data on the post fill temperature equilibration and spatial gradients were also recorded for these runs but have not yet been analyzed nor modeled during this contractual period.

The agreement between the model and experiments show that our modeling of the flow during the fill process is fundamentally correct, and will provide the basis for modeling other aspects of the fill process as related to temperature effects on laser beam quality.

Figure 5-1: Cylindrical pressure vessel and location of thermocouples used for measuring temperature transients.

Figure 5-2: Oscilloscope trace of gas temperature (top trace) and wall temperature (bottom trace) during a 128 sec fill run.

Figure 5-3: Measured gas temperature transients during the filling of a 2.1 meter diameter cylindrical tank from vacuum to 1 atm with argon. Lines are calculated values.

6.0 FIELD TEST SUPPORT (TASK 5)

6.1 General

Much of this support effort concentrated on providing assistance to ensure reliable operation of the large slide valve (see below) and attending LANL workshops on LPCL laser modeling and experiments, and cloud clearing. Notable support was as follows:

V. Buonadonna, B. Bardon and T. Dreiling at LANL for the LPCL program review. Two presentations describing Boeing's work on mixing and PHOCL-50 were given.

M. Weisbach V. Buonadonna, B. Bardon and T. Dreiling at NTS for familiarization with test site operating procedures and LPCL field test location.

L. Radke at the *Cloud Impacts on DOD Operations and Systems 1988 Workshop* held at the Naval Surface Warfare Center in Silver Spring, Maryland. Two papers were presented on the LANL Cloud Simulation Facility and cold cloud clearing theory (see Task 3).

6.2 Large Slide Valve Support

The inflatable seals on the large slide valve were damaged after installation of the valve on the LTV due to an operating error. The LTV was evacuated with the slide in the open position. This resulted in the seals being inflated against the vacuum with 1 atmosphere of pressure since they are exhausted to the ambient air. Subsequent attempts to close the slide resulted in damage to the seals. The seals were fabricated from a fluorsilicon compound that has a very high friction coefficient compared to, e.g., viton.

H.Mann spent 4 days at LANL helping to disassemble the Large Slide Valve and replace the damaged seals. During replacement of the seals, a leak was discovered in the seal stem termination connector and corrected. The suggested seal operating pressure was also reduced to 40 psi to extend the life of the fluorsilicon seals.

Subsequent successful testing of the valve on the LTV using reactive mixtures further revealed that the fluorsilicon seals deteriorated with increased exposure to F₂. This failure of the fluorsilicon seals on the Large Slide Valve due to apparent attack by fluorine prompted us to step up our procurement of viton seals. Fabrication problems by Presray have delayed delivery of a good viton seal until 23 Dec 88. Below is a brief history of our effort to obtain inflatable viton seals for the slide valve.

Inflatable seal procurement history:

During the preliminary design phase of the large slide valve, the inflatable seal was selected as the optimum sealing concept. The three major inflatable seal suppliers, Presray Corp., Kirkhill Rubber and Seal Master Corp., were contacted to determine the availability of seals fabricated from Viton A rubber. A material not normally used for inflatable seals, but required for this application. Of the three suppliers, only Presray Corp. expressed confidence in being able to produce the seal.

Below is a sequence of events following the decision to use inflatable seals in the valve and to procure from the Presray Corp. :

Initial Purchase Order:	21 November 1987
Scheduled ship date:	10 January 1988
Fabrication problems confirmed:	April 1988
Visitation to Presray with Boeing's Rubber expert :	25 April 1988

At this point it was determined that the manufacturing problems associated with fabricating Viton A seals were not going to be solved in time to support the LANL slide valve test schedule. A decision was made to accept a

substitute material, fluorsilicon rubber, for the initial seal order and Presray Corp. agreed to continue their development effort on Viton A seal fabrication.

Revised Purchase Order:	5 May 1988
Received fluorsilicon seals:	2 June 1988
Fluorsilicon seal failure due to operating error:	30 September 1988

Following the seal problems that developed in the valve, Presray was contacted to get the current status on Viton A seal fabrication. Presray reported that they had perfected the fabrication process and had successfully produced Viton A seals of the required configuration for another customer.

Purchase Order:	7 November 1988
Scheduled ship date:	16-23 December 1988
Fabrication problems suspected:	30 November 1988

When coordination with Presray resulted in inconsistent reports, fabrication problems were suspected. It was confirmed that Presray had produced an inflatable Viton A seal for another customer, but with larger cross section and lower pressure than our configuration. The smaller size and higher pressure requirements of our seals contributed to Presray's manufacturing problems.

Visitation:	15 - 16 December 1988
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Presray reported that the fabrication process had been changed from compression molding (used on the initial seal order) to a blow molding process developed for the similar seal fabrication for another customer. This resulted in a requirement for fabrication of a new set of dies and acquisition of a Viton A compound compatible with the blow molding process.

Delays were encountered in the procurement of the Viton A compound (received 28 November 1988) and the extrusion for the seals inner tube (received 12 December 1988). Only normal manufacturing anomalies occurred since 12 December. The first complete seal was removed from the die on 19 December and successfully passed leak test. The seal was then

placed in post cure which was completed on the morning of 21 December, and pressure tested. The seal was shipped 22 December 1988 and received by us the following day. The fabrication of the second seal is proceeding.

6.3 Operation of the LTV Slide Valve

The following is a suggested operating procedure for the large slide valve. The slide valve initially isolates the laser canister from the line-of-sight tube, which contains the optical diagnostics and LTI experiment, so that they may contain different gas mixtures. During the opening motion of the side valve, a variety of flow effects will cause mixing to occur between the reactive laser gas and the inert buffer gas in the line-of-sight tube. These mixing effects will have a direct impact on the laser beam quality due to pressure, density, and refractive index mismatches before (prepulse) and during (intrapulse) the laser pulse. If the refractive indices of the two gases could be perfectly matched, there would be no prepulse effects, and only intrapulse effects due to spatially different heat release would lead to beam quality degradation.

A 1987 Boeing IRAD study examined the effects of the slide valve induced flow disturbances on laser beam quality. The study took into account reasonable estimates of how accurately the refractive index and molecular weight of the laser and buffer gases can be matched, effects of pressure mismatches across the slide valve, growth of the turbulent wakes behind the slide as it is opening, and the effects of buoyancy forces due to molecular weight or temperature mismatches. A copy of the presentation given to LANL concerning the detailed results of this study is attached. This memo summarizes the more important conclusions of the study as pertains to operating and testing the slide valve in conjunction with the LTV.

Molecular Weight and Refractive Index Matching:

It will be necessary to match both the molecular weight and the refractive index of the buffer and laser gas mixtures as precisely as possible. This can only be accomplished by using a 3 component buffer gas mix consisting

of either Ar/He/CO₂ or Ar/O₂/CO₂. The O₂ mix is preferred since the high O₂ concentrations will enhance the laser gas stability at the gas interface and within the slide valve housing (see discussion below under Pressure Matching). For a typical laser gas mixture of

$$F_2/D_2/O_2/CO_2/Ar = 45/15/1/45/654 \text{ torr},$$

the matching buffer gas mix would be

$$Ar/O_2/CO_2 = 691/61/8 \text{ torr}.$$

The accuracy to which the laser gas and buffer gas can be matched is dependent on the the premixing techniques used for both gases. Using a pressure gauge with 0.1% accuracy for mixing by partial pressures in high pressure cylinders (corrections for non-ideal gas law must be applied) and mass flow controllers with accuracies of 1.0% for the laser filling process, it is estimated that the molecular weight and refractive index mismatch errors can be held to 3.5×10^{-3} and 2.5×10^{-3} , respectively. These values were used to determine allowable slide valve operating parameters as they affect beam quality.

Pressure Matching:

The valve is designed so that exact pressure matching can be obtained prior to its opening, by utilizing the internal volume of the valve housing as an equilibration chamber. This housing is vented to the buffer side of the valve and hence is initially filled with the inert buffer gas mix. Pressure matching the laser side to the buffer side to within +1.5 torr before deflating the slide valve seals will allow for exact pressure matching by gas exchange within the valve housing, with less than 10% displacement of buffer gas in the housing. The Δp error should be positive on the laser side to minimize the effects of the displaced buffer gas (i.e., the displaced buffer gas in the housing will squirt back harmlessly into the line-of-sight tube rather than into the laser volume).

Slide Valve Operating Time:

Slide valve operating time is defined as the slide opening time plus the pause time between when the valve is fully open and when the laser is fired. This total slide valve operating time determines the duration for which buoyancy forces can act to degrade beam quality. In addition, the valve opening time (or, equivalently, its velocity) determines the magnitude of wake effects. The beam quality study indicates that, given the ability to match the laser and buffer gases to the accuracies given by Eqn. (1), intrapulse beam quality degradation caused by buoyancy and wake effects will dominate. A slide valve opening time of 2-3 seconds with pause times of 2 seconds or less are recommended to hold beam quality degradation to acceptable levels. If longer operating times are used, or the molecular weight mismatch tolerance significantly exceeds 3.5×10^{-3} , buoyancy effects will severely degrade beam quality.

Operating Sequence:

The following operating sequence is recommended for proper use of the slide valve:

- 1) Slide valve seals inflated.
- 2) Pressurize diagnostic chamber with buffer gas to P_2 .
- 3) Fill laser volume with bulk gas mix and allow for thermalization,
 $P_L = P_1$ slightly less than P_2 .
- 4) Inject D_2 , allow for mixing time (~1 minute).
- 5) Temperature rise induced by D_2 injection will cause slow change in P_L as the gas cools,
- 6) Deflate gate valve seals and equilibrate pressures when $P_L - P_2 \leq +1.5$ torr.
- 7) Open gate valve when $P_L - P_2 < 0.05$ torr.
- 8) Valve fully open in 2 - 3 sec.
- 9) Pause time before firing < 2 sec.

Slide Valve LTV Test Suggestions:

Although we do not expect preignitions to be a problem, they may occur during both opening and closing operations of the slide valve. (The use of O_2 in the buffer gas will minimize any tendency for the slide valve to induce preignitions).

The valve is designed to withstand a 5 atmosphere overpressure in the event of a preignition, providing that the slide valve is fully closed. If a preignition occurs when the slide valve is partially open, damage may occur to the slide. It is therefore suggested that to initially assess the effects of valve operation on preignition, very low concentrations of D_2 be used in order to avoid large overpressures.

Interferometry should be used to assess the optical effects of the slide valve by purposely mismatching the refractive index of the buffer and laser gas mixtures. To evaluate wake effects only, the molecular weights of the buffer gas and laser gas should be matched. To evaluate buoyancy effects, a molecular weight mismatch should be used in conjunction with the index mismatch.

7.0 PHOCL-50 DF MODIFICATION (TASK 6)

In order to perform DF laser performance measurements in PHOCL-50, we plan to procure two outcouplers. One outcoupler will be a ZnSe substrate coated for ~15% transmittance from 3.7 - 4.4 μ m, the other outcoupler will be coated CaF_2 having a transmittance of less than 10% from 3.7 - 4.4 μ m. Since CaF_2 has a significantly higher optical damage threshold than ZnSe, we hope to be able to produce a higher Q cavity in PHOCL-50 using CaF_2 . We are obtaining coated CaF_2 samples from several vendors for damage testing in order to determine the best coating materials.

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