

High-Performance Chemical Oxygen–Iodine Laser Using Nitrogen Diluent for Commercial Applications

D. L. Carroll, D. M. King, L. Fockler, D. Stromberg, W. C. Solomon, L. H. Sentman, and C. H. Fisher

Abstract—A chemical oxygen–iodine laser (COIL), the VertiCOIL device, was transferred from the Air Force Research Laboratory (AFRL) to the University of Illinois at Urbana-Champaign (UIUC) and made operational. The performance of the high-power VertiCOIL laser was measured with nitrogen diluent. New nozzle designs were investigated and implemented to optimize nitrogen performance. Nitrogen diluent chemical efficiencies of 23% were achieved; these are the highest reported chemical efficiencies with room-temperature nitrogen diluent. A long duration, high chemical efficiency test was demonstrated with nitrogen diluent; a chemical efficiency of 18.5% at 30 mmol/s of chlorine was maintained for 45 min. The highest performance was obtained with new iodine injector blocks and a larger throat height. The new iodine injector blocks moved the injectors closer to the throat by 0.7 cm and the throat height was increased from 0.897 to 1.151 cm (0.353 to 0.453 in). The performance enhancements were in qualitative agreement with the system design predictions of the Blaze II chemical laser model. Three-dimensional computational fluid dynamics calculations using the general aerodynamic simulation program code confirmed the principle design change of moving the iodine injectors closer to throat.

Index Terms—Chemical lasers, gas lasers, iodine, laser applications, laser materials-processing applications, lasers, nitrogen, oxygen.

I. INTRODUCTION

LASERS made their debut for materials processing in 1965 [1]. Since then, materials processing with CO₂ and YAG lasers have developed into a mature technology [1]. Other laser technologies still evolving for materials processing applications are CO, excimer, HF/DF, and the chemical oxygen–iodine laser (COIL) [2], [3]. Of these other laser technologies, COIL is of particular interest because of its short fiber deliverable wavelength (1.315 μm), scaleable CW power, and excellent material interaction properties [4]–[6], [43].

Several researchers have suggested that COIL has a significant future as an industrial laser and have identified decommissioning and decontamination (D&D) of nuclear facilities as an important market for COIL [7]–[11]. Entirely new technological methods must be introduced to process and deactivate the large numbers of nuclear reactor power stations now in place

Manuscript received May 3, 1999; revised September 16, 1999. This work was supported by the Air Force Research Laboratory Small Business Technology Transfer Program under Contract F29601-96-C-0149.

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Publisher Item Identifier S 0018-9197(00)00308-0.

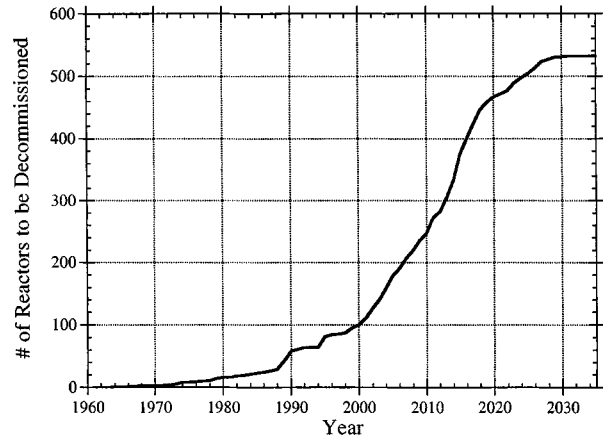


Fig. 1. Estimated total number of reactors to be decommissioned worldwide to the year 2035 (data compiled from [17]). Estimates are based on a 30-year lifespan for each reactor.

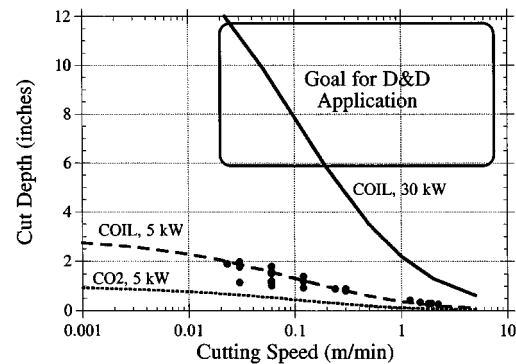


Fig. 2. COIL and CO₂ cutting speed as a function of steel plate thickness and device power (experiments and theory from [5] and [6]). The illustrated COIL cutting data for steel were taken with RADICL. The theoretical curves shown assume a fairly large kerf width (spot diameter) of 1.0 mm and the use of a nitrogen gas assist. A 10–30-kW COIL will be required for cutting 6–12-in steel.

worldwide. Fig. 1 shows the dramatically increasing number of such facilities that will need to be dismantled and replaced in ten to thirty years. Fig. 2 shows experimental COIL cutting results; estimates from a theoretical model [5], [6] determined that a 10–30-kW fiber delivered COIL should meet the needs of the nuclear D&D efforts. Other potential industrial applications for COIL are shipbuilding, automotive manufacturing, heavy machinery manufacturing, and tasks requiring underwater cutting or welding, and there may be useful applications in the oil and gas industry.

II. EFFICIENT NITROGEN NOZZLE DESIGN CALCULATIONS

The highest chemical laser efficiencies of 27% have been demonstrated by the Air Force Research Laboratory (AFRL) [12], [39] using optimized supersonic nozzles and helium as the diluent gas. These efficiencies need to be approached using alternate gases, such as nitrogen, which are more readily available and economically acceptable. Research in Russia has demonstrated chemical efficiencies of 22.4% (798 W) with room-temperature N_2 diluent [13]. In experiments with pre-cooled nitrogen, the Russian group initially demonstrated a chemical efficiency of 22% (200 W) [14] and, more recently, achieved a very high efficiency of 26% (236 W) [15]. The highest power level demonstrated by the Russian group using room-temperature N_2 diluent was 1408 W with a chemical efficiency of 20.7% [13]. The Israeli group has demonstrated chemical efficiencies up to 17% [16] and 18% [17] without any primary diluent at a power level of 177 and 190 W, respectively. A joint Russian and Japanese effort [18] produced a chemical efficiency of 23% (versus 20% at room temperature) and 405 W with pre-cooled nitrogen diluent. Additionally, a novel supersonic injection into a supersonic stream concept was tested by the Russians that yielded 14% chemical efficiency and 130 W [8]. This research shows high promise for an industrial COIL, but until recently had only been performed at a power level of a few hundred watts. While the Japanese have demonstrated a power level of 5 kW using nitrogen diluent, the chemical efficiency was only 15% [19].

Every high power density, high efficiency chemical laser in existence employs a converging–diverging nozzle to bring the primary flow to supersonic velocities. The primary flow typically carries the oxidizer plus a diluent (buffer) gas. A secondary stream carrying the fuel and more diluent is often injected into the primary at some point in the nozzle, either in the subsonic, sonic (or transonic), or supersonic part of the flow (see Fig. 3). In COIL's, injection and mixing into the subsonic region is typically used. For the case of a COIL with nitrogen diluent, it may be preferable to carry out sonic (transonic) or supersonic injection. While the Israelis [17] have experimentally demonstrated 18% chemical efficiency in a COIL using transonic injection, the transonic mode of mixing has not yet been studied in detail.

Quasi- two-dimensional models for supersonic COIL's were independently developed by Carroll at UIUC [21], Barmashenko [22] in Israel, and Yang at Rocketdyne [23]. These models were in reasonable agreement with AFRL data [24]–[26] taken with the RADICL device. While lower dimensional models are extremely useful for preliminary design calculations and parametric studies, the common drawback of both one- and two-dimensional (2-D) models is that they cannot adequately model the nonuniform gain distributions in a three-dimensional (3-D) flowfield. It has been observed by many researchers that complete O_2/I_2 mixing is not achieved [14], [16], [27]. This observation has been confirmed by modeling studies; 3-D computational fluid dynamics (CFD) modeling [28]–[33] clearly shows that the iodine and oxygen densities remain nonuniform across the flow in the resonator region. These irregularities are created in part by the interaction of initially cylindrical iodine jets with the primary cross flow

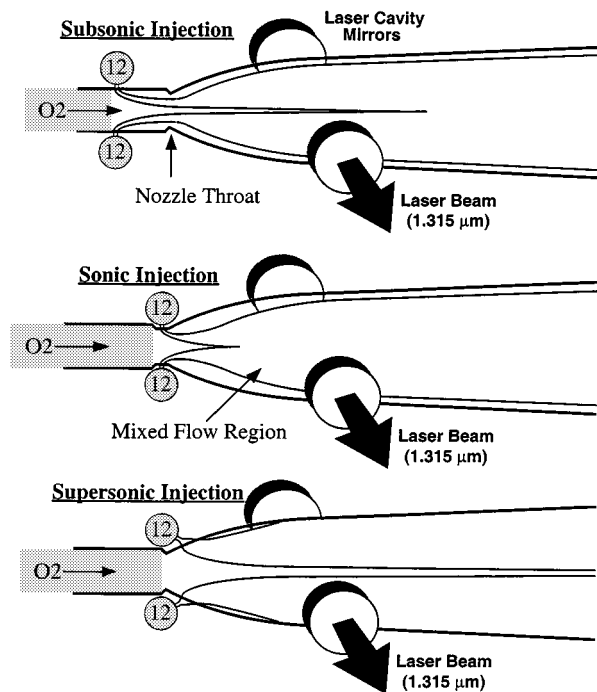


Fig. 3. Subsonic, sonic, and supersonic injection schemes with an illustration of the mixed flow.

that results in the formation of a 3-D horseshoe structure downstream of the injectors [32]. This structure stretches the contact surface between the chemicals and cannot be adequately predicted using 1- or 2-D models. In order to fit the results predicted by lower dimensional models to the experimental data, the laminar diffusion coefficients are modified by an empirical diffusion coefficient multiplier [21]. While this procedure is valid over a narrow range of operating conditions, correct simulation of mixing in COIL devices without any arbitrary assumptions can only be performed using 3-D models.

A. GASP Modeling

Over the past six years, the UIUC has developed refined 3-D modeling capabilities for COIL lasers. Numerous simulations of the AFRL's RADICL device have been performed [29]–[32]. The CFD code used by UIUC is a modified version of a general aerodynamic simulation program (GASP) [34] in partnership with AeroSoft, Inc., which solves the conservative finite-volume formulation of the full Navier–Stokes equations coupled to a nonequilibrium chemistry model and a conservative multicomponent diffusion model. A simulation of the COIL helium diluted flowfield was performed, compared to detailed gain distribution measurements, and accurately reproduced the experimentally measured distributions.

For industrial COIL applications, the use of nitrogen rather than helium diluent is of consequence for economical reasons and the fact that helium is a nonrenewable resource. The heavier molecular weight of nitrogen significantly slows the flow velocity, increasing the residence time of the reactants in the subsonic flow region, and concomitantly shifts the resulting laser gain zone upstream, i.e., the position of the gain zone changes with nitrogen use (see Figs. 4 and 5). Thus,

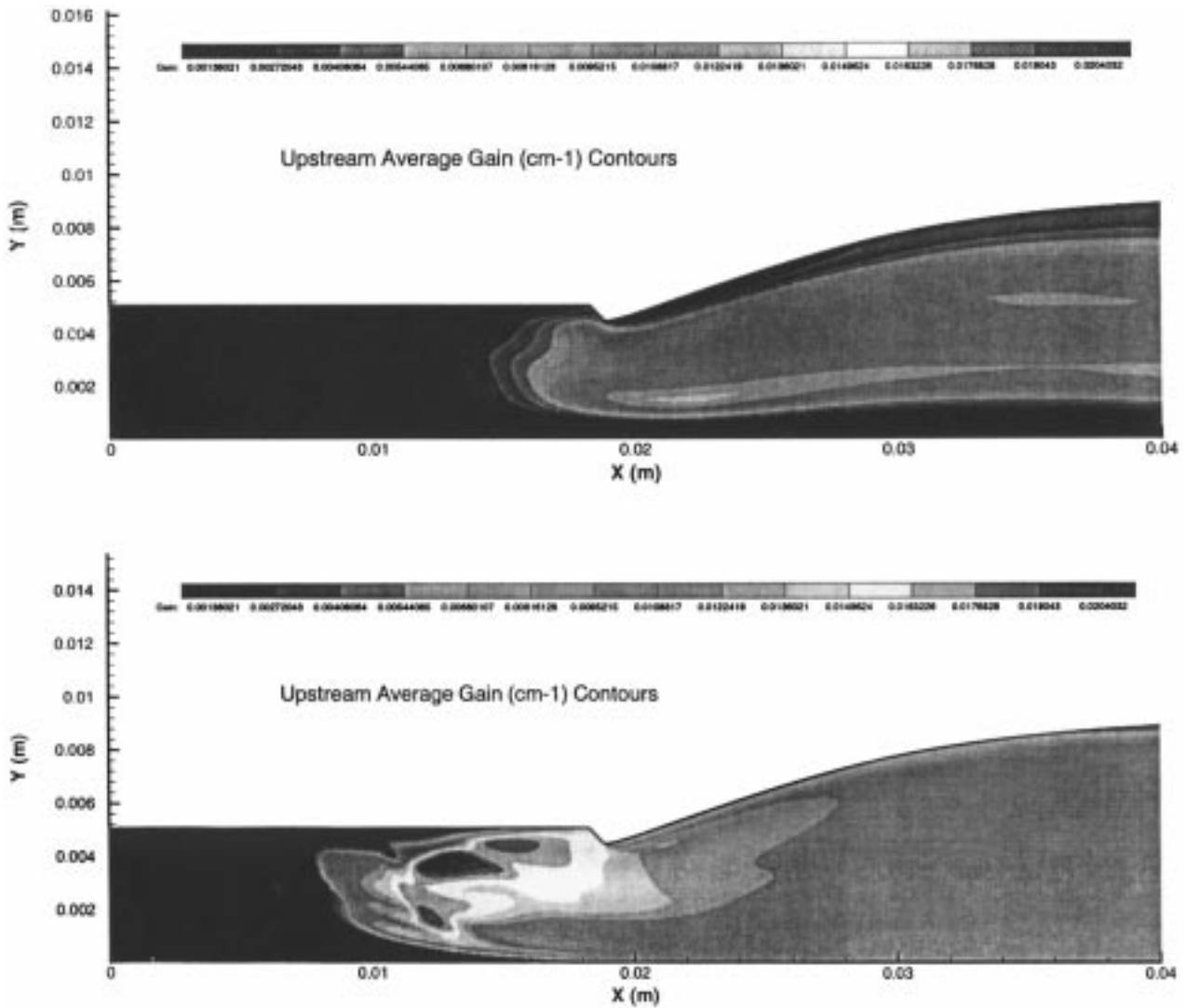


Fig. 4. GASP predictions of average gain for VertiCOIL flow conditions with helium (top) and nitrogen (bottom) diluent. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1.

a nozzle optimized for power with helium diluent (as is the current VertiCOIL nozzle design) is not optimized for use with nitrogen diluent. Note that the GASP calculation for helium diluent is slightly lower than two of the measured data points, but, in general, is in reasonable agreement with gain data taken by AFRL [38].

The GASP computations shown in Figs. 4 and 5 clearly illustrate the need to push the gain region with nitrogen diluent further downstream so that there is higher gain in the optical extraction region (lasing zone). The most straight-forward approach to solving this problem is to inject the iodine further downstream in the flow.

B. Blaze II Design Predictions

To guide our nitrogen nozzle research efforts, the Blaze II model [35] was used to make predictions to improve nozzle design for optimal nitrogen diluent performance. Calculations were previously run to baseline the model to RADICL gain data [36] that were found to overpredict power measurements by an average of 33%; this is a consequence of using a Fabry-Perot

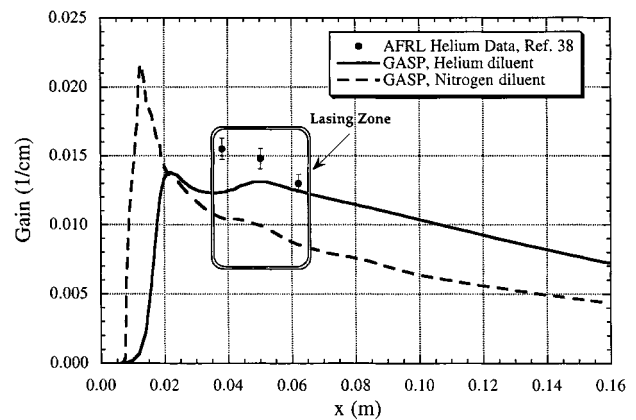


Fig. 5. GASP predictions of the maximum value of the average gain slice as a function of distance for helium and nitrogen diluent. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1.

model to simulate stable resonator data, coupled with some diffractive loss. Since the RADICL nozzle and the baseline VertiCOIL nozzle are identical except for their gain length (10

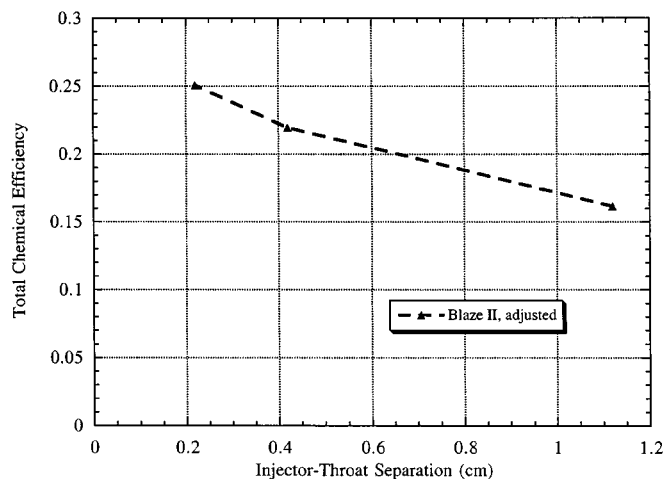


Fig. 6. Predicted VertiCOIL chemical efficiency versus injector-throat spacing with nitrogen diluent and subsonic injection. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1 and a 98% reflective outcoupling mirror.

in for RADICL, 2 in for VertiCOIL), the Blaze II baseline computations for RADICL should be appropriate as a starting point for VertiCOIL. Israeli work [16], [17] indicated reasonable chemical efficiencies with injection at the throat; this led us to perform calculations and experiments as a function of injector location. For injection into the subsonic portion of the nozzle, it was found that moving the injectors incrementally closer to the throat significantly increased the predicted chemical efficiency (defined in [12] and [37], see Fig. 6). This result is consistent with recent Russian experiments [14]. The nominal injector position has the centerline of the large injector 1.12 cm upstream of the throat. Decreasing the separation between injector and throat to 0.42 and 0.22 cm progressively increased the predicted chemical efficiency. An adjusted predicted curve is illustrated because of the previously mentioned Blaze overprediction of power; the adjusted curve is $0.75(=1/1.33)$ the value of the Blaze II predictions and accounts for the 33% overprediction mentioned earlier. Blaze II predicts an increase from 16% to 22% when the injectors are moved from 1.12 to 0.42 cm from the throat.

Injection calculations into the subsonic flow were also made for other parameter variations such as penetration mirror spacing and throat height. A penetration parameter was defined by Helms [25] as

$$\Pi = \frac{\dot{n}_{sec}}{\dot{n}_{pri}} \sqrt{\frac{W_{sec} T_{sec} P_{pri}}{W_{pri} T_{pri} P_{sec}}} \quad (1)$$

where the subscripts pri and sec represent the primary (oxygen, primary diluent, and residual chlorine) and secondary (iodine and secondary diluent) flows, T is the temperature, P is the pressure, W is the average molecular weight, and \dot{n} is the total molar flow rate. Variations in penetration produced no significant improvement in power; increasing the penetration from 0.15 to 0.20 improved the power by 3%. In [12], it was found that $\Pi = 0.156$ was the optimal penetration using helium diluent. Decreasing the distance from the injection point to the start of the lasing region improved the predicted power by 14%. Increasing the throat height from the nominal 0.353 in height up to 0.453 in improved the predicted power by 17% (see

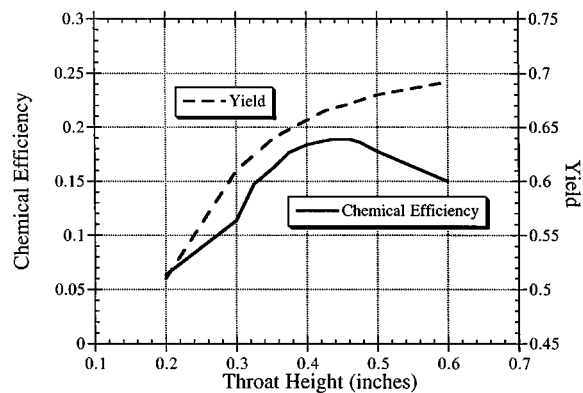


Fig. 7. Predicted VertiCOIL chemical efficiency and yield versus throat height, using nitrogen diluent and subsonic injection. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1 and a 98% reflective outcoupling mirror.

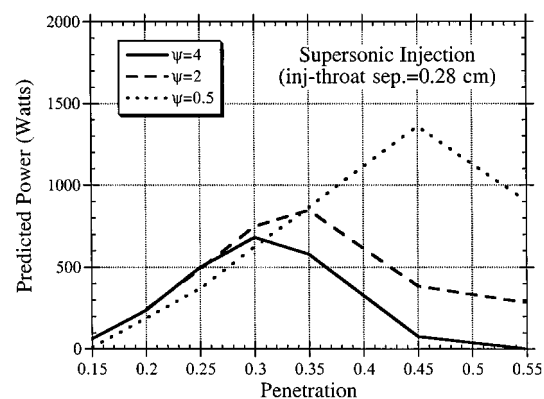


Fig. 8. Predicted VertiCOIL chemical efficiency versus diluent ratio and penetration using nitrogen diluent and sonic injection into a supersonic cross flow. The chlorine flow rate is 70 mmol/s with a 98% reflective outcoupling mirror.

Fig. 7); this increase in performance is primarily a consequence of a lower stagnation pressure which results in an increase in the yield at the I_2 injection point. These variations were tested in conjunction with the movement of the injectors closer to the throat when using N_2 as the diluent.

Calculations were also performed for injection into the supersonic portion of the flow. Immediately, it was found that the power dropped nearly to zero under nominal flow conditions. This was a consequence of the fact that the true penetration (relative momentum of the secondary to the primary stream) of a sonic jet into a supersonic cross flow is not nearly as great as that into a subsonic cross flow. Note that Blaze II is a quasi-2-D model that incorporates penetration due to the momentum ratio into its two-stream mixing model (see [21, eqs. (6)–(10)]. Thus, it is possible for Blaze II to qualitatively simulate the effects of penetration [21]. To obtain significant mixing and penetration into the supersonic flow, two effects were tested. First, the penetration was increased by increasing the secondary diluent, and second, the penetration was increased by decreasing the primary diluent. Fig. 8 illustrates that the best results occurred with high penetration and a very low primary diluent ratio of 0.5. Further decreases in diluent ratio $\Psi(= \text{diluent}/Cl_2)$ produced no significant change. While the maximum chemical efficiency predicted with injection into the supersonic stream is much less (approximately 16%), it also corresponds to

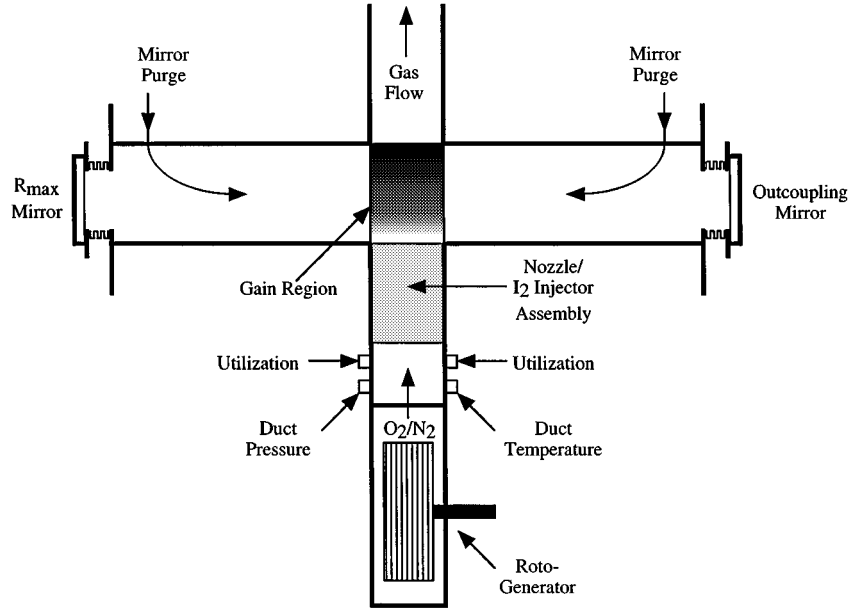


Fig. 9. Schematic of the VertiCOIL experimental setup.

a very low diluent flow rate. The economical tradeoff between higher chemical efficiency with higher diluent flow and lower chemical efficiency with lower diluent flow needs to be examined. The primary inhibitor to performance with supersonic injection appears to be a lack of mixing between the I_2 and the high velocity O_2 stream; this problem can likely be reduced or eliminated by a significant change in nozzle geometry. Further calculations indicated that a marginal performance increase could be obtained by moving the mirrors further downstream, which allows the mixed flow region to increase in size before extracting photons. Interestingly, the trend in these numerical results is very similar to recent Russian work [8], which demonstrated a 14% chemical efficiency with supersonic injection into supersonic primary flow and suggested moving the mirrors further downstream for their injection scheme.

III. EXPERIMENTAL RESULTS

VertiCOIL is a 2-kW class device. For brevity, the device is not described in this paper, but is detailed in a series of papers by the AFRL group [12], [38]–[40]. A schematic of the experimental setup is illustrated in Fig. 9. Several new systems were added to improve operations for the VertiCOIL device. First, a National Instruments LabVIEW data acquisition and control system was introduced. Precision mass flow diagnostics were added to accurately measure the iodine and chlorine flow rates (see Section III-A1). A liquid nitrogen tank with a vaporizer provides all necessary cooling along with all required gaseous diluent flows when using N_2 as the diluent.

A. Calibrations

Calibrations were performed for the various gas flow rates, mirror transmissivities, and to establish basic hydrogen peroxide (BHP) freeze temperatures as a function of the total amount of chlorine run through a batch of BHP.

1) *Gas Flow Calibrations:* Before the device was run, it was necessary to establish flow calibrations for the gases. To accurately establish pressure-orifice calibration curves for flow rates of the diluent and chlorine gases, a precision Micro Motion model CMF025 mass flow meter was used. The flow calibrations were compared with computed mass flow rates based upon choked orifice flow, with the inclusion of a discharge coefficient C_d which was adjusted to match measured flow rates. All of the discharge coefficients for nitrogen diluent ranged between 0.85 and 0.88. For helium diluent, the discharge coefficients ranged between 0.80 and 0.84. The discharge coefficient for chlorine was 0.86. These values of the discharge coefficients are all reasonable for the type of orifice used [0.096–0.253 cm in diameter, 0.051 cm thick (0.038–0.0995 in diameter, 0.020 in thick)]. To be as accurate as possible with the critical chlorine and iodine flow rates, two precision Micro Motion model CMF025 mass flow meters are used.

2) *BHP Freeze Point Curves:* VertiCOIL performance is sensitive to the BHP temperature. The higher the temperature, the more water vapor is present in the flow; as a consequence, the resulting gain and power suffer. As such, it is desirable to run the BHP as cold as possible without freezing it. Thus, care was taken to review old data, to observe new runs carefully for signs of freezing, and to establish curves of the BHP freeze point as a function of BHP batch size and total chlorine run through the batch. Fig. 10 shows the BHP freeze point for both a 38.5-L batch and a 44-L batch as a function of the total chlorine; both batches were 6.6/1.0 HO_2 -/excess H_2O_2 mixtures. These data points were taken over several run days.

To prevent BHP freezing in later runs, the BHP freeze point curve was set in the LabVIEW controller. The total chlorine run through the course of a run day is automatically tallied and is used to control the BHP temperature via LabVIEW. This technique has proven very reliable in preventing freezing while at the same time keeping the BHP temperature as cold as possible to maximize power output.

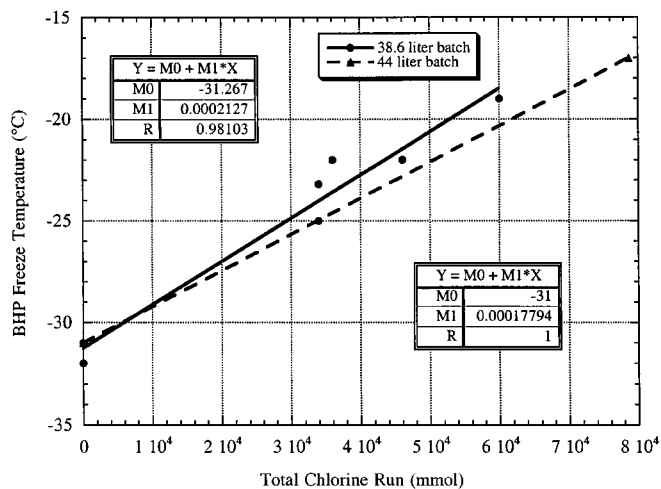


Fig. 10. BHP freeze temperature as a function of the total amount of chlorine run through the mixture and the BHP batch size. The BHP mixture was approximately 6.6/1.0 molar HO_2 -/excess H_2O_2 .

3) *Mirror Measurements*: Eighteen mirrors of varying reflectivities were employed during the course of the small business technology transfer (STTR) program. Eight of the mirrors had been previously used during earlier VertiCOIL testing at AFRL [12], [39], [40]. Transmissivity measurements were made at UIUC on all of the mirrors using a 5–10-W HF overtone beam at approximately $1.35 \mu\text{m}$. The UIUC measurements were typically in rough agreement with the transmissivity measurements made by CVI, Inc., (the mirror manufacturer) with a low-power (mW) beam. Past experience with HF overtone mirrors has given us confidence in our technique of measuring mirror transmissivities and that the use of higher power beams provides a more accurate measurement than do very low-power beams. While the HF overtone wavelength of $1.35 \mu\text{m}$ is slightly different than the COIL wavelength of $1.315 \mu\text{m}$, the transmission curves provided by CVI, Inc., indicated that transmission measurements at these two wavelengths were the same. Since the absorption/scattering losses of these mirrors were not measured, the reflectivity R of the mirrors is approximated as $R \approx 1 - T$, where T is the mirror transmissivity. The reflectivities reported in subsequent data plots are based upon UIUC transmission measurements.

4) *Power and Chemical Efficiency Measurements*: Power transmitted through the outcoupling mirror was measured with an Ophir 5000W-CAL-SH power meter. The power meter calibration was verified using a constant voltage–constant current power source. The total power output through both the outcoupling mirror and the maximum reflector was determined based upon Rigrod’s simple laser theory [44]. Using Rigrod’s [44, eq. (32)], it is possible to show that the intracavity flux is approximately constant throughout a resonator that uses two high-reflectivity mirrors; such is the case when using these high-reflectivity COIL mirrors. Knowing that the intracavity flux is approximately constant through this resonator, it can then be shown that the total transmitted power P_{total} should be

$$P_{\text{total}} \cong P_{\text{out}} \left(\frac{T_{\text{out}} + T_{R \text{ max}}}{T_{\text{out}}} \right) \quad (2)$$

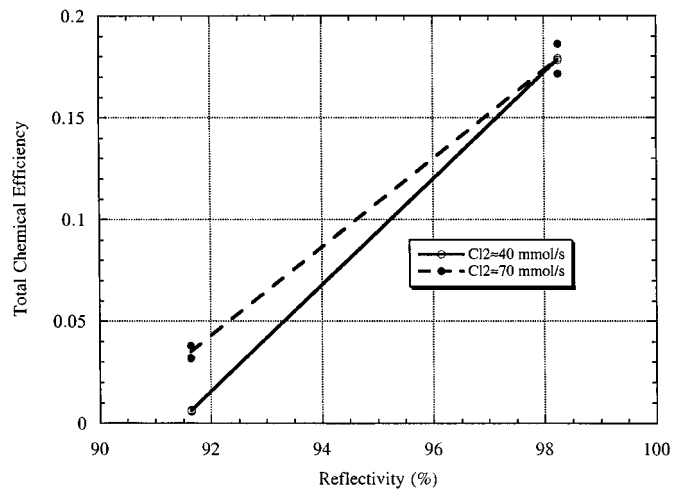


Fig. 11. Chemical efficiency as a function of outcoupler reflectivity using helium diluent and the original VertiCOIL hardware. Old mirrors and a 6.6/1.0 BHP mixture were used. The diluent ratio was 4 : 1.

where

P_{out} measured power transmitted through the outcoupling mirror;

T_{out} transmissivity of the outcoupling mirror;

$T_{R \text{ max}}$ transmissivity of the maximum reflectivity mirror.

This relationship was verified in a couple of experiments by measuring the power transmitted through the outcoupler, followed by a measurement of the power output through the maximum reflector under approximately the same flow conditions.

B. Helium Diluent Data

Helium diluent data taken with VertiCOIL at UIUC achieved 19% chemical efficiency at 40 and 70 mmol/s of chlorine flow (see Fig. 11). This data was significantly lower than the maximum value of 27% measured by AFRL with the same hardware [12]. It is believed that the reason for the decrease in performance is threefold. First, the UIUC data were taken with used mirrors; AFRL reports that efficiencies achieved with used optics are 10%–20% lower than those achieved with new mirrors [12].

Second, the UIUC data were taken with a different BHP mix than used by AFRL. The UIUC BHP mix was obtained by mixing 22 L of 45% KOH and 16.8 L of 50% H_2O_2 , resulting in a 6.6/1.0 HO_2 -/excess H_2O_2 molar batch. The AFRL batch was 7.0 molar [12]. The difference in BHP mixes is a consequence of our desire to use commercially available 50% peroxide, whereas the researchers at AFRL had access to 70% peroxide. The measured utilization of chlorine with our BHP mix was typically around 85%, whereas the experiments at AFRL were yielding 94% utilization [12]. The reduction in utilization with molarity is consistent with data taken by the German group of researchers [41].

Third, it is believed that the optical axis was aligned too far upstream (a consequence of the shipping of VertiCOIL from AFRL to UIUC that resulted in a small unrecognized shift in mirror location). Burn blocks were taken for several flow conditions. The typical measured beam was rectangular in

TABLE I

EXPERIMENTAL VERTICOIL DATA TAKEN WITH NITROGEN DILUENT. DUE TO DROPLET DEPOSITION ON DIAGNOSTIC PORT WINDOWS, THE UTILIZATION DIAGNOSTIC BECAME UNRELIABLE AFTER 30–60 s OF RUN TIME; THE TYPICAL MEASURED UTILIZATION DURING THE EARLY PART OF A RUN WAS $85\% \pm 5\%$ USING NITROGEN DILUENT. THE UTILIZATION WAS ASSUMED TO BE 85% FOR THE CALCULATION OF THE TITRATION RATIO AND χ_{RT}

Run #	980603HF1	980721HF1	980717HF1	980727HF1	980810HF1	980810HF5	980810HF8
Injector-Throat Sep. [cm]	1.12	0.47	0.47	0.47	0.47	0.47	0.47
Throat Height [in]	0.353	0.353	0.353	0.453	0.453	0.453	0.453
Cl ₂ flow rate [mmol/s]	42.8	38.4	27.5	39.3	77.9	23.8	39.1
N ₂ pri. Flow rate [mmol/s]	164.2	158.2	160.8	158.9	105.6	68.6	106.2
N ₂ sec. Flow rate [mmol/s]	36.1	31.4	37.4	47.6	44.0	24.2	34.0
I ₂ flow rate [mmol/s]	0.51	0.56	0.47	0.72	0.76	0.46	0.63
Pressure, Duct [torr]	53.7	49.8	49.3	43.5	41.3	22.0	31.5
Temperature, Duct [°C]	11.5	11.2	6.2	-2.0	25.0	4.9	4.25
Pressure, Secondary [torr]	325.1	209.4	249.3	315.2	261.1	136.8	192.5
Temperature, Secondary [°C]	146.0	142.1	135.9	105.0	91.7	99.5	104.2
Diluent Ratio (N ₂ pri./Cl ₂)	3.84	4.12	5.84	4.05	1.36	2.89	2.71
Titration Ratio (I ₂ /O ₂)	.014	0.017	0.020	0.021	0.011	0.023	0.019
Penetration	0.090	0.101	0.112	0.112	0.111	0.132	0.118
χ_{RT} [Torr-s]	0.0619	0.0529	0.0411	0.0426	0.0800	0.0267	0.0390
Mirrors: T _{out} [%]	1.75	1.58	1.75	1.58	1.56	1.56	1.56
T _{Rmax} [%]	0.159	0.159	0.159	0.097	0.214	0.214	0.214
Measured Power [Watts]	523.5	571.1	462.0	683.6	911.8	431.4	685.1
Total Power [Watts]	571.1	628.6	504.0	725.6	1036.9	490.6	779.1
Total Chemical Efficiency	0.148	0.182	0.204	0.205	0.148	0.229	0.221

shape and approximately 1.613×2.586 cm (0.635 in \times 1.018 in) in size (the second dimension is in the flow direction). Note that this beam length in the flow direction is smaller than the 3.541-cm-long (1.394-in) beam measured by AFRL. Based upon the fact that the measured beam size was smaller than that measured by AFRL, it is believed that the optical axis was aligned too far upstream and that the beam was therefore partially blocked by physical apertures associated with the sideplates. Since the flow rates, pressures, and temperatures all very closely matched those of the AFRL experiments, it is felt to be a combination of used mirrors, optical axis position, and a different BHP mix which inhibited our ability to obtain higher chemical efficiencies with helium diluent. It is believed that, if new mirrors were used and the optical axis position moved downstream, chemical efficiencies with helium diluent would improve up to roughly 25%.

C. Nitrogen Diluent Data

Based upon the GASP and Blaze II modeling studies that were performed, one new set of iodine injector blocks and a new sideplate set were designed by UIUC and fabricated by STI Optonics. The principle change made with the new set of iodine injector blocks was to move the centerline of the row of large injectors from 1.12 cm (0.44 in) upstream of the nozzle throat to a position 0.47 cm (0.185 in) upstream of the nozzle throat. A new set of sideplates were made to test the effect of throat height on performance. While these design changes were not extraordinarily novel, the modeling calculations indicated that these

simple changes would be effective at significantly improving nitrogen diluent chemical efficiencies and at the same time would be cost effective to fabricate and implement experimentally.

1) *Effects of Decreased Injector-Throat Separation:* The measured chemical efficiency increased from 14.8% (571 W at 42.8 mmol/s of Cl₂) to 18.2% (629 W at 38.4 mmol/s of Cl₂) when the injectors were moved from 1.12 to 0.47 cm upstream of the throat (see Table I). Note that AFRL previously obtained a 15.5% chemical efficiency with Verticoil using nitrogen diluent and a 1.12-cm injector-throat spacing [39]. Fig. 12 shows a comparison between the experimental data and the Blaze II model predictions. While Blaze II overpredicted the improvement in performance, it correctly predicted the qualitative trend. As noted in Section II-B, the result of improved performance using nitrogen diluent by moving the injectors closer to the throat is consistent with recent Russian experiments [14]. These results verify that relatively simple design changes to the nozzle section of a COIL designed for helium diluent can significantly improve COIL performance with nitrogen diluent.

2) *Effects of Increased Throat Height:* Chemical efficiency data as a function of reflectivity and throat height for a chlorine flow rate of approximately 40 mmol/s and a diluent ratio of approximately 4:1 are illustrated in Fig. 13. For these flow conditions, the peak chemical efficiency was 18.2% (629 W at 38.4 mmol/s of Cl₂) at a throat height of 0.897 cm (0.353 in) and 20.4% (726 W at 39.3 mmol/s of Cl₂) at a throat height of 1.151 cm (0.453 in) (see Table I). All of the data in Fig. 13 were taken with the new iodine injector blocks having an in-

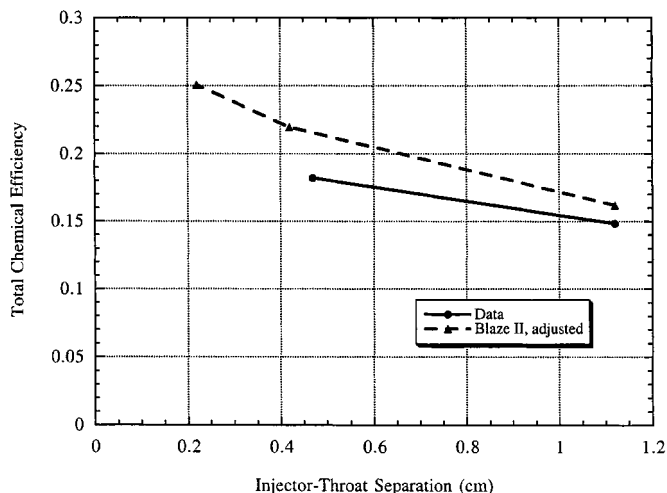


Fig. 12. Predicted and measured VertiCOIL chemical efficiency versus injector-throat spacing with nitrogen diluent and subsonic injection. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1 and a 98% reflective outcoupling mirror.

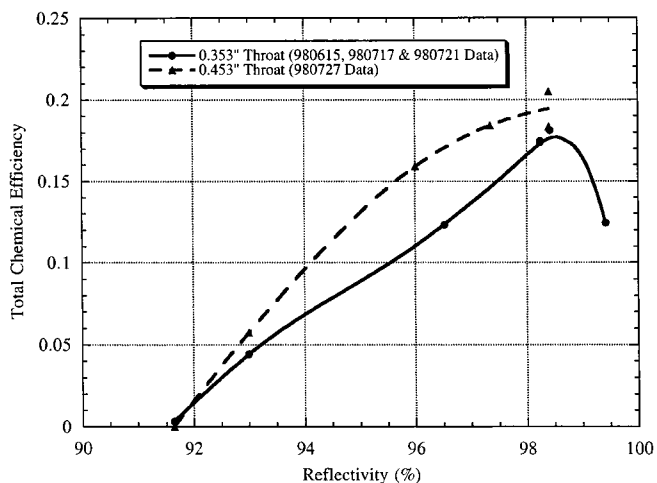


Fig. 13. Chemical efficiency as a function of outcoupler reflectivity and throat height using nitrogen diluent. The chlorine flow rate is 40 mmol/s with a diluent ratio of 4 : 1.

jector-throat separation of 0.47 cm. The peak chemical efficiencies were obtained using a 98.2%–98.4% reflective outcoupler. The chemical efficiency versus reflectivity data clearly illustrate that better performance was obtained with the larger throat. These data verify that the Blaze II model again predicted the correct qualitative trend of better performance with a throat height of 1.151 cm (0.453 in). As mentioned in Section II-B, the improved performance with a larger throat is a consequence of decreased stagnation pressure that leads to a higher yield at the iodine injectors. One data point was obtained with a 99.4% reflective outcoupler before this mirror burned; the chemical efficiency versus reflectivity curve shows the characteristic roll-off in performance as the outcoupling reflectivity approaches unity (100%).

Maximum chemical efficiency data as a function of chlorine flow rate and throat height are shown in Fig. 14. For a throat height of 0.897 cm (0.353 in), the peak chemical efficiency was 20.4% at a Cl₂ flow rate of 27.5 mmol/s, and the total output

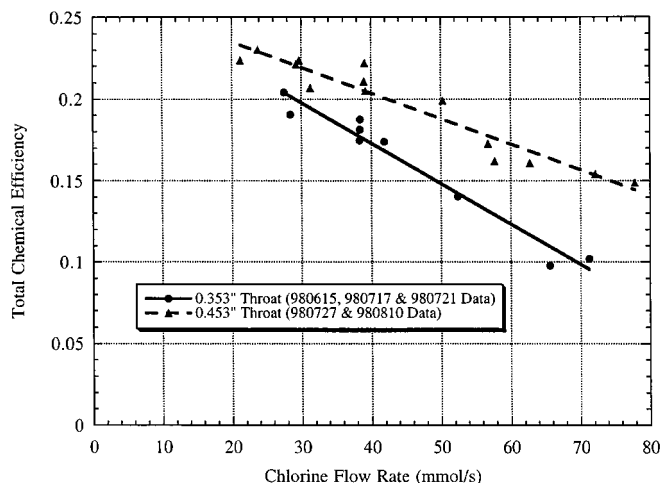


Fig. 14. Chemical efficiency as a function of chlorine flow rate and throat height with nitrogen diluent. These data were taken with the new I₂ injector blocks and an outcoupling mirror with a reflectivity of 98.2%–98.4%.

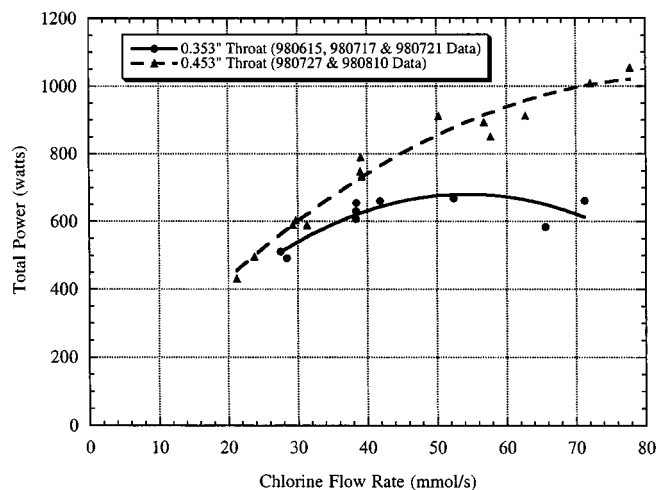


Fig. 15. Power as a function of chlorine flow rate and throat height with nitrogen diluent. These data were taken with the new I₂ injector blocks and an outcoupling mirror with a reflectivity of 98.2%–98.4%.

power was 504 W (see Table I). For a throat height of 1.151 cm (0.453 in), the peak chemical efficiency was 22.9% at a Cl₂ flow rate of 23.8 mmol/s, and the total output power was 491 W (see Table I). All of the data in Fig. 14 were taken with the new iodine injector blocks having an injector-throat separation of 0.47 cm. The peak chemical efficiencies were obtained using a 98.2%–98.4% reflective outcoupler. The chemical efficiency versus Cl₂ flow rate data also clearly illustrate that a better performance was obtained with the larger throat.

Maximum power data as a function of chlorine flow rate and throat height are shown in Fig. 15 (the data points shown in Fig. 15 also correspond to those shown in Fig. 14). For a throat height of 0.897 cm (0.353 in), the peak total power was 669 W at a Cl₂ flow rate of 52.4 mmol/s (chemical efficiency of 14.0%). For a throat height of 1.151 cm (0.453 in) the peak total power was 1037 W at a Cl₂ flow rate of 77.8 mmol/s (chemical efficiency of 14.8%), Table I. All of the data in Fig. 15 were taken with the new iodine injector blocks having an injector-throat separation of 0.47 cm. The peak chemical efficiencies

were obtained using a 98.2%–98.4% reflective outcoupler. The total power versus Cl_2 flow rate data again clearly illustrate that a better performance was obtained with the larger throat.

To obtain the maximum chemical efficiencies and total powers for different chlorine flow rates, it was necessary to alter the diluent ratio. For the 0.897-cm (0.353-in) throat, the diluent ratios (the ratio of the diluent flow rate to the chlorine flow rate) which optimized performance ranged from 3.2:1 to 5.8:1, but showed a slight preference for a higher diluent ratio at a lower chlorine flow (note that the 20.4% chemical efficiency case had a diluent ratio of 5.8:1, Table I). Interestingly, for the larger 1.151-cm (0.453 in) throat, the diluent ratio that produced the highest chemical efficiency at lower Cl_2 flow rates was around 2.9:1, and at the higher chlorine flow rates the diluent ratio had to be reduced to around 1.4:1 (see Table I). The iodine flow rate that maximized performance was typically in the 0.44–0.86-mmol/s range. The titration ratio (the ratio of the iodine flow rate to the product of utilization and chlorine flow rate) which optimized chemical efficiency ranged from 1.0% to 2.7%; typically lower titration ratios were associated with higher chlorine flow rates and higher titration ratios were associated with lower chlorine flow rates. The penetration parameter that maximized performance was in the range 0.10–0.18, but typically was in the range 0.11–0.14; there was a slight preference for higher penetration at lower chlorine flow rates. These titration and penetration values are similar to, but generally slightly lower than, the optimal values determined for VertiCOIL using helium diluent [12], [37]–[39]. The diluent ratio which optimized performance for VertiCOIL with helium diluent was typically 4:1–6:1; this was also the case for nitrogen diluent with the same 0.897-cm (0.353-in) throat with which the helium diluent data were taken. However, when nitrogen was used as the diluent with a larger 1.151-cm (0.453-in) throat, lower diluent ratios typically produced the higher efficiencies. Higher diluent ratios raise the flow stagnation pressure and tend to defeat some of the advantage to increasing the throat height.

In an effort to compare these nitrogen data at different throat heights, a plot of chemical efficiency as a function of $\chi RT (=P\tau)$ was generated and is shown in Fig. 16. This type of plot was first employed by Helms [45]. χ is defined as [12]

$$\chi = \frac{P_{\text{O}_2}\tau}{RT} = \frac{P^2\dot{n}_{\text{O}_2}V}{(\dot{n}_{\text{pri}}RT)^2} \quad (3)$$

where

- P_{O_2} partial pressure of oxygen in the primary flow;
- τ residence time of the flow upstream of iodine injection;
- R universal gas constant;
- T primary flow temperature;
- P primary flow pressure;
- V volume occupied by the primary flow upstream of iodine injection;
- \dot{n}_{O_2} molar flow rate of oxygen;
- \dot{n}_{pri} total molar flow rate of all species in the primary flow.

χ is a measure of $\text{O}_2(1\Delta)$ transport loss; a higher χ value represents higher loss and, hence, a lower yield at the iodine injection point, which typically results in lower laser powers. Fig. 16

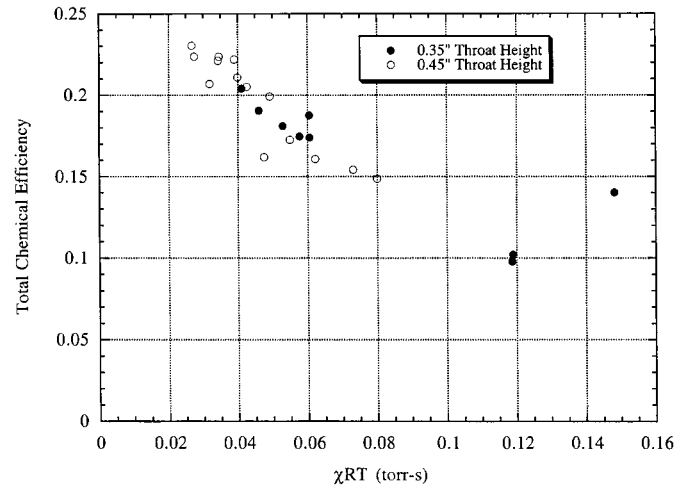


Fig. 16. Chemical efficiency as a function of χRT and throat height for the nitrogen data taken with VertiCOIL.

is presented in terms of χRT for the convenience of the units (torr-s).

Two interesting points can be observed from Fig. 16. First, the nitrogen data for both throat heights fall on top of one another. This indicates that the data sets from different throat heights are consistent with one another in the sense that the chemical efficiency is a function of transport loss, rather than some purely geometrical effect. Second, higher chemical efficiencies were typically obtained with lower values of χRT ; the highest values occurred with the larger 1.151-cm (0.453-in) throat. This is consistent with the physical interpretation that a lower transport loss should result in higher output power and higher chemical efficiency.

Burn blocks were taken for several flow conditions. For the 0.897-cm (0.353-in) throat height, the typical measured beam was rectangular in shape and approximately 1.554×2.868 cm (0.612 in \times 1.129 in) in size (note that the second dimension is in the flow direction). For the 1.151-cm throat height, the typical measured beam was rectangular in shape and approximately 1.971×2.637 cm (0.776 in \times 1.038 in) in size. The burn blocks indicated the expected trend of a narrower and slightly longer beam with the narrower throat height.

Several very important findings were made during this series of tests. Perhaps most importantly, we achieved a chemical efficiency of 23% using room-temperature nitrogen diluent; this is the highest chemical efficiency reported to date with room-temperature nitrogen diluent. Nikolayev *et al.* have recently demonstrated a chemical efficiency of 22.4% with room-temperature N_2 [13] and 26% with pre-cooled nitrogen diluent [15]. Second, we achieved over a kilowatt of power with N_2 diluent and sustained this power level for over a minute. Third, the highest chemical efficiencies and powers were obtained with relatively low diluent ratios; this fact has important implications for commercial COIL's because it means that operating costs can be reduced and pumping requirements may also be reduced, which could significantly reduce the initial capital outlay for a commercial COIL.

3) *Long Duration Runtime Testing:* The concluding experiment for this study was to perform a long-duration high-ef-

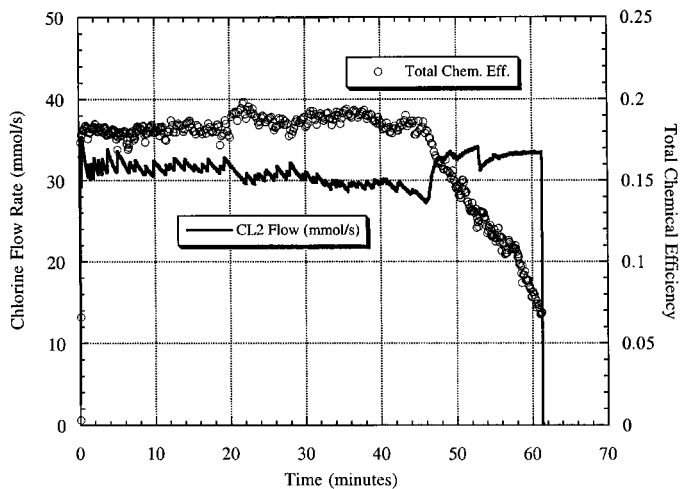


Fig. 17. Chemical efficiency and chlorine flow rate as a function of time for the long-duration run test with nitrogen diluent. These data were taken with the new I_2 injector blocks, the larger throat height of 1.151 cm (0.453 in), a diluent ratio of approximately 2.3 : 1, and an outcoupling mirror with a reflectivity of 98.4%.

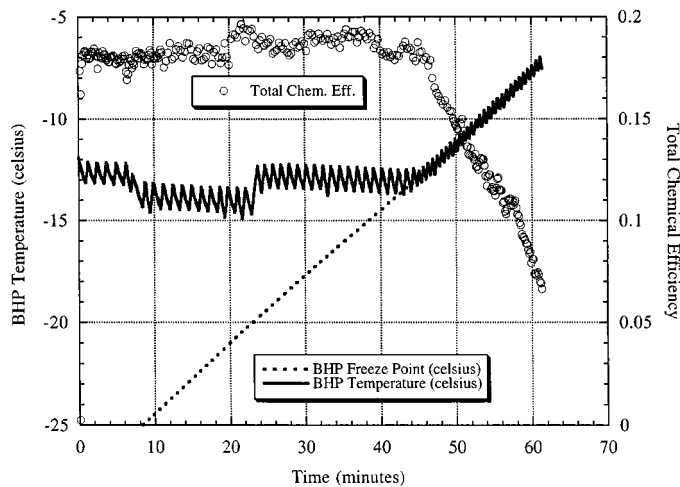


Fig. 18. Chemical efficiency and BHP temperature as a function of time for the long duration run test with nitrogen diluent. These data were taken with the new I_2 injector blocks, the larger throat height of 1.151 cm (0.453 in), a diluent ratio of approximately 2.3 : 1, and an outcoupling mirror with a reflectivity of 98.4%.

efficiency run using nitrogen diluent. The best performing set of hardware (new iodine injector blocks with sideplate set #2, 1.151-cm throat) were chosen for this test. Since run time is essentially limited by the batch size and the chlorine flow rate, a 44-L batch was mixed and a low flow rate of 30 mmol/s of Cl_2 was run. Fig. 17 shows the time history for the Cl_2 flow and the total chemical efficiency. The chlorine flow rate was held relatively constant at around 30 mmol/s; the sawtooth character to the chlorine flow curve is indicative of adjustments made to the flow using the Cl_2 flow control needle valve. Most importantly, the chemical efficiency was held around 18.5% for a period of 45 min; this corresponds to a power level of around 500–525 W. The drop-off in chemical efficiency at roughly the 45-min mark is a direct consequence of the fact that the BHP temperature began warming up to prevent freezing of the mixture, shown in Fig. 18 (recall that the BHP freeze point increases

with chlorine usage, Fig. 10). To eliminate the transient reduction that a progressively warming BHP mixture would have on laser performance, the BHP batch was preset to a warmer than normal temperature of $-12\text{ }^\circ\text{C}$. The BHP freeze point was still monitored and, when the BHP freeze point rose above $-12\text{ }^\circ\text{C}$, the LabVIEW system assumed control of the BHP temperature. Fig. 18 shows that, when the BHP freeze point reached $-12\text{ }^\circ\text{C}$, the LabVIEW system assumed control as planned, the BHP mixture progressively rose in temperature, and the laser performance dropped considerably over the subsequent 17 min of run time. The sawtooth pattern of the BHP temperature curve is a consequence of the simple bang-bang control system, which regulates the BHP temperature. It should be noted that this long duration test began after already having run 17 moles (17 000 mmoles) of chlorine through the fresh BHP batch for the purpose of some other testing. Had this long-duration test started with a completely fresh 44-L batch of BHP, it is likely that the 18.5% chemical efficiency at 30 mmol/s could have been maintained for over an hour.

IV. SUMMARY AND CONCLUDING REMARKS

For the purposes of establishing the economic viability of a commercial COIL device, the performance of the high-power VertiCOIL laser was measured with nitrogen diluent. Several important findings were made during the initial experiments. Perhaps most importantly, a chemical efficiency of 23% using room-temperature nitrogen diluent was achieved, which is the highest chemical efficiency reported to date with room-temperature nitrogen diluent. Second, we achieved over a kilowatt of power with N_2 diluent and sustained this power. Third, the highest chemical efficiencies and powers were obtained with relatively low diluent ratios; this fact has important implications for commercial COIL's because it means that operating costs can be reduced and pumping requirements may also be reduced, which could significantly reduce the initial capital outlay for a commercial COIL. Fourth, a long-duration high-chemical-efficiency test was demonstrated with nitrogen diluent; a chemical efficiency of 18.5% at 30 mmol/s of chlorine was maintained for 45 min.

New nozzle designs were investigated and implemented to optimize nitrogen performance. Nitrogen diluent chemical efficiencies of 22.9% were demonstrated which are the highest reported chemical efficiencies with room-temperature nitrogen diluent. The highest performance was obtained with new iodine injector blocks and a larger throat height. The new iodine injector blocks moved the injectors closer to the throat by 0.65 cm and the throat height was increased from 0.897 cm (0.353 in) to 1.151 cm (0.453 in). The performance enhancements were in qualitative agreement with the system design predictions of the Blaze II chemical laser model. Three-dimensional computational fluid dynamics calculations using the GASP code confirmed that the peak gain region with nitrogen diluent was near the iodine injectors and that a likely design improvement would be to move the injectors closer to the throat.

In summary, we did not exactly replicate AFRL data with helium diluent, but we did achieve the highest reported COIL performance using room-temperature nitrogen diluent. Note that it is believed that the AFRL data could now be nearly matched

using new mirrors and a small shift in the position of the optical axis, although the BHP mixture limits us to approximately 85% utilization. Future recommendations for commercial COIL technology development are the following.

- 1) Nikolayev *et al.* have very recently demonstrated a chemical efficiency of 22.4% with room-temperature N₂ [13] and 26% with pre-cooled nitrogen diluent [15]. This improvement in performance with pre-cooled nitrogen suggests that future experiments should be investigated with pre-cooled nitrogen running through the VertiCOIL SOG.
- 2) New and advanced nozzle concepts can be designed and tested in the calibrated facility. Possible schemes which are suggested are iodine injection at the throat or into the supersonic portion of the nozzle. It is believed that such advanced nozzle schemes could push chemical efficiencies up to around 26%–27%, i.e., comparable to the chemical efficiencies obtained by AFRL using VertiCOIL with helium diluent. These findings should also be evaluated in terms of helium diluent.
- 3) A study of the effect of different BHP mixtures on performance when using nitrogen diluent is suggested.
- 4) Chemical efficiencies fell off significantly with chlorine flow rate when using nitrogen diluent. It is recommended that a new rotating disk generator be designed and optimized specifically for use with nitrogen diluent and higher chlorine flow rates. If such a generator were designed and fabricated, it is believed that it should be possible to obtain 2 kW or higher with the present VertiCOIL nozzle and nitrogen diluent.
- 5) For commercial purposes, it would be useful to demonstrate longer duration runs of several hours. This would likely require some additional equipment for the purpose of regeneration or recycling of the BHP.
- 6) AFRL researchers demonstrated the ability to couple a 7-kW COIL beam into a fiber optic for a short period of time [42]. An excellent complement to this AFRL test would be long-run high-power beam delivery tests through a fiber optic. This would require the design and buildup of a new resonator for higher beam quality than VertiCOIL presently delivers.

While these recommendations will help improve the chemical efficiency and costs associated with operating a commercial COIL, the reality of the matter is that there is no technological barrier that would prevent the assembly and operation of a mobile industrial COIL device. The assembly of a 5–10-kW mobile COIL is expensive but is a relatively straightforward process. The estimated operating costs of a COIL using nitrogen diluent (approximately three to four times that of a CO₂ device per kilowatt-hour) can be reduced if more efficient operating conditions are obtained with next-generation technology. However, the fact that COIL's cut most materials approximately three times faster may make them economically competitive when labor costs are factored into the equation.

ACKNOWLEDGMENT

The authors give many thanks to the personnel of the Gas and Chemical Laser Branch, Directed Energy Directorate at the

AFRL, for all their help and support over the years. Without their assistance this work would not have been possible. The authors would also like thank G. Benavides, T. Cerven, A. Milmoie, C. Sears, M. Sexauer, and M. Sutanto for their work on the project.

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