

PERFORMANCE OF A HIGH POWER CHEMICAL OXYGEN-IODINE LASER USING NITROGEN DILUENT

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Abstract

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 23.0% 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 minutes. 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 0.353" to 0.453". The performance enhancements were in qualitative agreement with the system design predictions of the Blaze II chemical laser model. Three-dimensional computational fluid dynamics (CFD) calculations using the GASP code confirmed the principle design change of moving the iodine injectors closer to throat.

1. Introduction

Lasers made their debut for materials processing in 1965. Since then, materials processing with CO₂ and YAG lasers has evolved 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 continuous wave (cw) power, and excellent material interaction properties [4-6,41].

During the Air Force funded Small Business Technology Transfer (STTR) program to commercialize the COIL, the University of Illinois at Urbana-Champaign (UIUC)/STI Optronics team identified the decommissioning and decontamination (D&D) of nuclear facilities as a primary focus for COIL technology. Other researchers have suggested that COIL has a significant future as an industrial laser and have identified D&D as an important market for COIL [7-10]. The use of a remote fiber delivered COIL cutting/ablation tool in contaminated areas promises to lower risks to workers for the D&D mission. Further, the high cutting speed of COIL will significantly reduce the time required to cut contaminated equipment, reducing costs. COIL is promising for the ablation of material from contaminated surfaces, perhaps to depths thicker than an inch. Laser cutting and ablation minimizes dust and fumes, thus reducing costly waste disposal. Recent experiments [11] have demonstrated the usefulness of short wavelength laser cutting for the D&D mission. The development of a commercial COIL device can provide the basis for a whole new generation of laser cutting and processing tools to government and industry. If successful, this will be the first major advance in high power laser cutting technology since the introduction of the CO₂ laser many years ago.

Entirely new technological methods must be introduced to process and deactivate the large numbers of nuclear reactor power stations now in place world-wide. Figure 1 shows the dramatically increasing number of such facilities which will need to be dismantled and replaced in ten to thirty years. Figure 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 decommissioning and decontamination efforts. A 5 kW COIL prototype followed by a 10 kW COIL laser module are reasonable starting points for the modular construction of a high power industrial COIL laser. Higher laser powers can be produced by adding modules to the laser.

Other potential industrial applications for COIL are shipbuilding, automotive manufacturing, heavy machinery manufacturing, tasks requiring underwater cutting or welding, and there may be useful applications in the oil and gas industry.

It is possible to envision a single high-power COIL feeding many fibers for industrial cutting/welding/processing applications [9]. Fiber delivered underwater applications appear very promising; it may be possible to use a high power, fiber delivered COIL beam to perform cutting/welding underwater and thus save the high cost of dry-docking a ship in need of repair.

In Phase II of the STTR program, the technology developed by the Air Force Research Lab (AFRL) was transferred to the U.S.A. private sector by assembling the VertiCOIL laser [12,35-37], Fig. 3, at UIUC to serve as a testbed for technology developments relevant to industrial use. Since military issues are different than commercial issues, the transfer of the subscale VertiCOIL device to UIUC permits us to perform cost effective commercial technology development experiments; the results and knowledge from this practical experimental approach can then be directly inserted in the development of a large and efficient industrial scale device. Key research sub-topics which must be addressed are: 1) Efficient nitrogen nozzle technologies which will lead to low cost per photon, 2) Optical extraction and fiber delivery which will enable the use of COIL by industry, 3) Supporting technologies which will lead to long duration operation at a relatively constant power level. The principle goal of the UIUC effort for the STTR was to investigate and demonstrate efficient nitrogen nozzle technologies for a commercial COIL device.

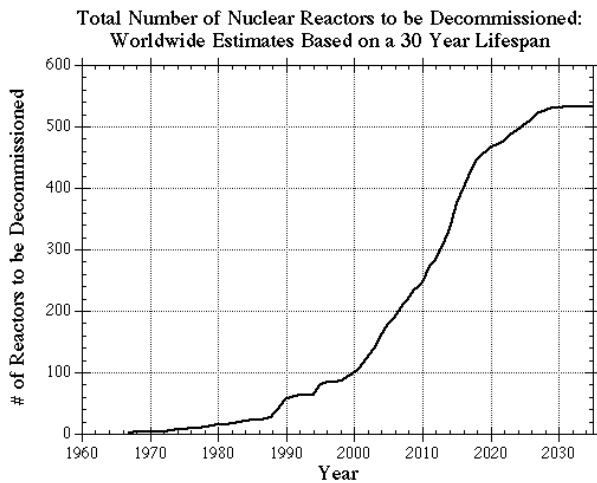


Fig. 1 Estimated number of reactors to be dismantled to the year 2035 (data compiled from Ref 17).

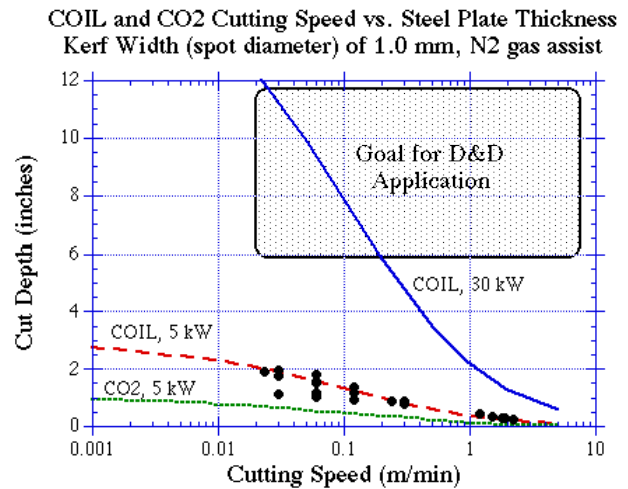


Fig. 2. COIL and CO₂ cutting speed as a function of steel plate thickness and device power. COIL cutting data for steel taken with RADICL are illustrated. A 10-30 kW COIL will be required for cutting 6-12" steel (experiments and theory from Refs. 5 and 6).

2. Efficient Nitrogen Nozzle Design Calculations

Several technological hurdles need to be overcome before a packageable demonstration COIL system can be assembled and tested at a nuclear site. The highest chemical laser efficiencies of 27% have been demonstrated by AFRL [12] using optimized supersonic nozzles and helium as the diluent gas. These efficiencies need to be matched using alternate gases, such as nitrogen, which are more readily available and economically acceptable. Recent research in Russia [13] has demonstrated a chemical efficiency of 22% with pre-cooled nitrogen diluent and 200 Watts. The highest chemical efficiency demonstrated by the Russian group using room temperature N₂ diluent was 16%. The Israeli group [14] has demonstrated chemical efficiencies up to 17% without any primary diluent at a power level of 177 watts. Very recently, a joint Russian and Japanese effort [15] produced a chemical efficiency of 23% (vs. 20% at room temperature) and 405 Watts with pre-cooled nitrogen diluent. Additionally, a novel supersonic injection into a supersonic stream concept was tested by the Russians which yielded 14% chemical efficiency and 130 Watts [8]. This high efficiency research shows very high promise for an industrial COIL, but has 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% [16]. We believe that the potential for high chemical efficiency with nitrogen or no primary diluent needs to be explored in considerable depth at kilowatt power levels. New, highly efficient mixing nozzle concepts are being studied with the VertiCOIL laser, employing nitrogen or no diluent at high power levels more appropriate to a commercial device.

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, Fig. 4. In chemical oxygen-iodine lasers, subsonic injection and mixing 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 [14] have experimentally demonstrated 17% 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 COILs were independently developed by Carroll at UIUC [18], Barmashenko [19] in Israel and Yang at Rocketdyne [20]. These models were in reasonable agreement with AFRL data [21-23] 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 models is that they cannot adequately model the nonuniform gain distributions in a 3D flowfield. It has been observed by many researchers that complete O_2/I_2 mixing is not achieved [13,14,24]. This observation has been confirmed by modeling studies; 3D Computational fluid dynamics (CFD) modeling [25-30] 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 that results in the formation of a three dimensional horseshoe structure downstream of the injectors [29]. This structure stretches the contact surface between the chemicals and cannot be adequately predicted using one or two dimensional 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 (DCM) [18]. 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 three dimensional models.

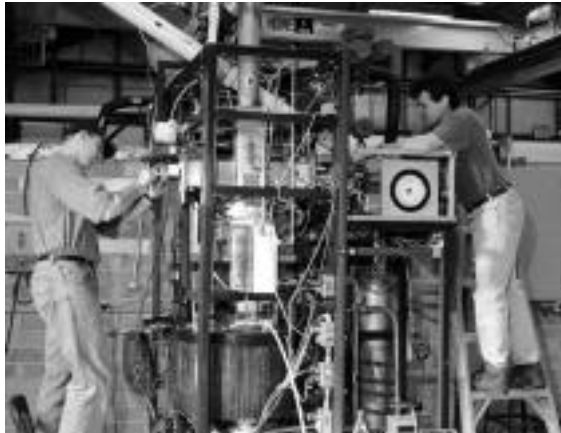


Fig. 3. The 2 kW VertiCOIL device setup at the University of Illinois.

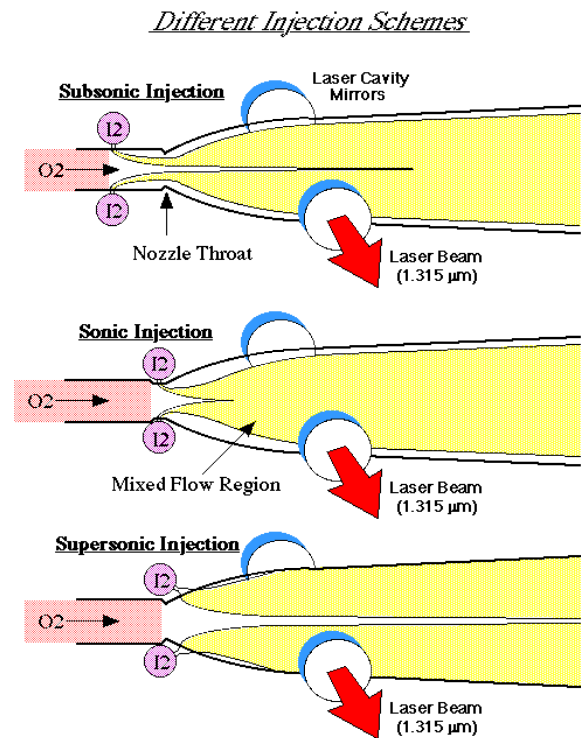


Fig. 4 Subsonic, sonic and supersonic injection schemes with an illustration of the mixed flow.

2.1 GASP Modeling

Over the past five years, the UIUC has developed highly advanced three dimensional COIL modeling capabilities. Numerous simulations of the AFRL's RADICL device have been performed [26-29]. The CFD code used by UIUC is a modified version of GASP [31] 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 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 non-renewable resource. The heavier molecular weight of nitrogen significantly slows down 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, Figs. 5 and 6. Thus, 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 [35].

The GASP computations shown in Figs. 5 and 6 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 straightforward approach to solving this problem is to inject the iodine further downstream in the flow.

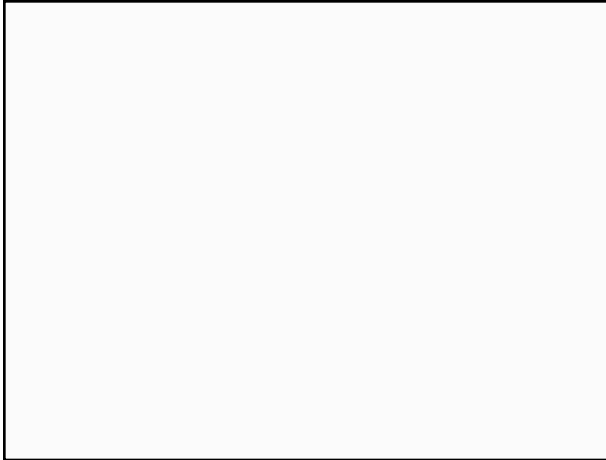


Fig. 5 GASP predictions of average gain for VertiCOIL flow conditions with helium (top) and nitrogen (bottom) diluent.

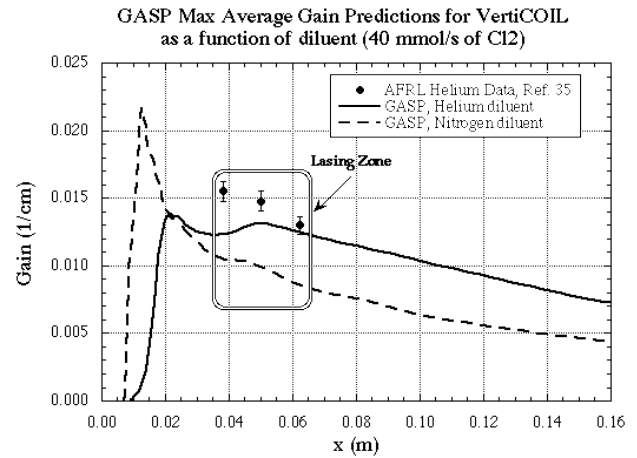


Fig. 6 GASP predictions of the maximum value of the average gain slice as a function of distance for helium and nitrogen diluent.

2.2 Blaze II Design Predictions

To guide our nitrogen nozzle research efforts, the Blaze II model [32] was used to make predictions to improve nozzle design for optimal nitrogen diluent performance. The model which had previously been baselined to RADICL gain data [33] was found to overpredict power measurements by an average of 33%; this is a consequence of using a Fabry-Perot 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" for RADICL, 2" for VertiCOIL), the Blaze II baselining for RADICL should be appropriate as a starting point for VertiCOIL. Israeli work [14] 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 Refs. 12 and 34), Fig. 7. This result is consistent with recent Russian experiments [13]. 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 cm to 0.42 cm from the throat.

Injection calculations into subsonic flow were also made for other parameter variations such as penetration mirror spacing, and throat height. A penetration parameter was defined by Helms [22] as $\beta = (\eta_{\text{sec}}/\eta_{\text{pri}}) * [(MW_{\text{sec}}T_{\text{sec}}P_{\text{pri}})/(MW_{\text{pri}}T_{\text{pri}}P_{\text{sec}})]^{1/2}$. Variations in penetration produced no significant improvement in power; increasing the penetration from 0.15 to 0.20 improved the power by 3%. In Ref. [12] it was found that $\beta = 0.156$ 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" height up to 0.453" improved the predicted power by 17%, Fig. 8; 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.

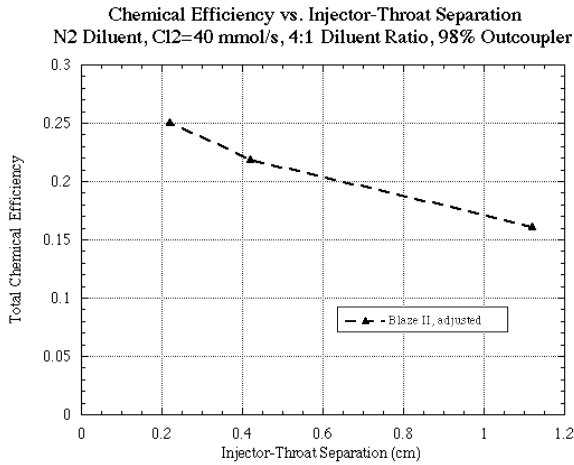


Fig. 7 Predicted VertiCOIL chemical efficiency vs. injector-throat spacing with nitrogen diluent and subsonic injection.

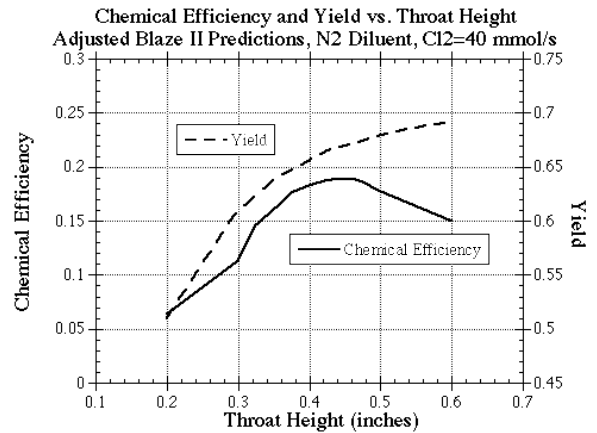


Fig. 8 Predicted VertiCOIL chemical efficiency and yield vs. throat height, using nitrogen diluent and subsonic injection.

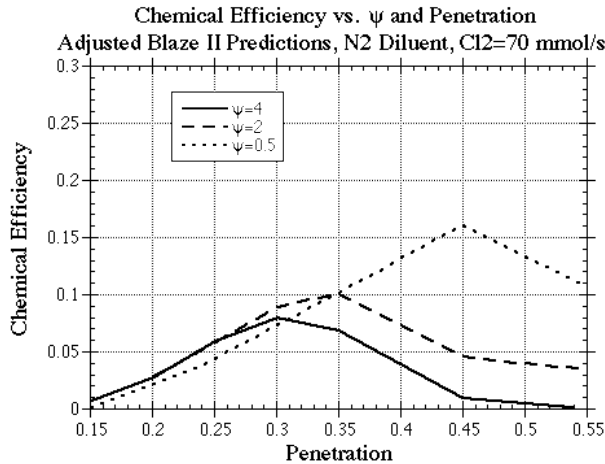


Fig. 9 Predicted VertiCOIL chemical efficiency vs. diluent ratio and penetration using nitrogen diluent and sonic injection into a supersonic cross-flow.

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. 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. Figure 9 illustrates that the best results occurred with high penetration and a very low primary diluent ratio of 0.5. Further decreases in diluent ratio ($=\text{diluent}/Cl_2$) 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 a very low diluent flow rate. The economical trade off 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.

3. 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 [12,35-37]. Several new systems were added to improve operations for the VertiCOIL device. First, a National Instruments LabVIEW data acquisition and control system was introduced. This system has worked extremely well for us and has proven reliable and easy to use. Precision mass flow diagnostics were added to accurately measure the iodine and chlorine flow rates, Section 3.1.1. An LN₂/GN₂ tank provides all necessary cooling along with all required diluent flows when using N₂ as the diluent.

3.1 Calibrations

To have reliable and accurate data it is necessary to have a well calibrated facility. A great deal of care was taken to adequately calibrate flow rates, measure mirror transmissivities, and establish BHP freeze temperatures.

3.1.1 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 (0.038"-0.0995" diameter, 0.020" 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.

3.1.2 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, the resulting gain and power suffer as a consequence. As such, it is desirable to run the BHP as cold as possible without freezing it. As such, care was taken to review old data, to observe new runs carefully for signs of freezing, and establish curves of BHP freeze point as a function of BHP batch size and total chlorine run through the batch. Figure 10 shows the BHP freeze point for both a 38.5 liter batch and a 44 liter batch as a function of the total chlorine; both batches were 6.6/1.0 HO₂-/excess H₂O₂ 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.

3.1.3 Mirror Measurements

Eighteen mirrors of varying reflectivities were tested during the course of the STTR. Eight of the mirrors were provided by AFRL and had been previously used during earlier VertiCOIL testing. Transmissivity measurements were made at UIUC on all of the mirrors using a 5-10 watt HF overtone beam at approximately 1.35 μm . The UIUC measurements were typically in rough agreement with the transmissivity measurements made by CVI 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 μm is slightly different than the COIL wavelength of 1.315 μm , the CVI transmission curves indicated that transmission measurements at these two wavelengths were approximately the same. Since the absorption/scattering (AS) losses of these mirrors were not measured, the reflectivity R of the mirrors is approximated as $R = 1 - T$, where T is the mirror transmissivity. The reflectivities reported in subsequent data plots are based upon UIUC transmission measurements.

3.2 Helium Diluent Data

Helium diluent data taken with VertiCOIL at UIUC achieved 19% chemical efficiency at 40 and 70 mmol/s of chlorine flow, 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 twofold. First, the UIUC data were taken with

used mirrors; AFRL reports that efficiencies with used optics are 10-20% lower than that with new mirrors [12]. Second, the UIUC data were taken with a different basic hydrogen peroxide (BHP) mix than used by AFRL. The UIUC BHP mix was obtained by mixing 22 liters of 45% KOH and 16.8 liters of 50% H₂O₂ resulting in a 6.6/1.0 HO₂⁻/excess H₂O₂ 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 AFRL had access to 70% peroxide. The measured utilization of chlorine with our BHP mix was typically around 85%, whereas AFRL was obtaining 94% utilization [12]. The reduction in utilization with molarity is consistent with data taken by the German DLR group [38]. Since the flow rates, pressures and temperatures all very closely matched those of AFRL, it is felt to be a combination of used mirrors and a different BHP mix which inhibited our ability to obtain higher chemical efficiencies with helium diluent. It is believed that changes made to the operational procedures (mirror alignment, a pre-run KOH rinse of the BHP flow loop, and a larger 44 liter batch of BHP) implemented toward the end of the STTR program would improve the helium chemical efficiencies up to roughly 25% chemical efficiency.

Burn blocks were taken for several flow conditions. The typical measured beam was rectangular in shape and approximately 0.635"x1.018" in size (the second dimension is in the flow direction). Note that this beam length in the flow direction is smaller than the 1.394" long beam measured by AFRL.

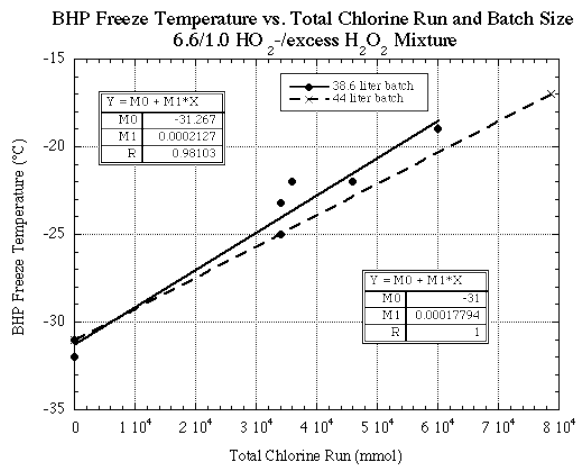


Fig. 10. BHP freeze temperature as a function of the total amount of chlorine run through the mixture and the BHP batch size.

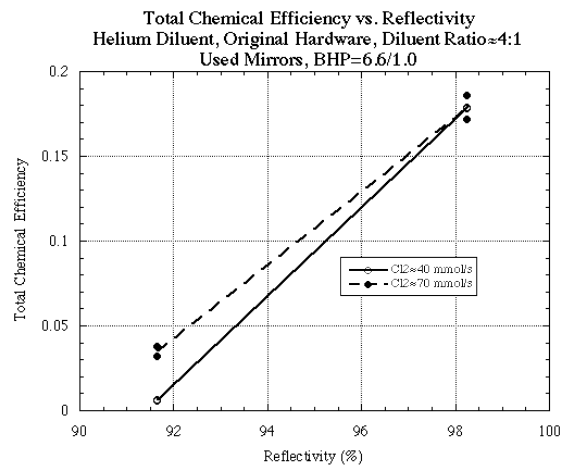


Fig. 11. Chemical efficiency as a function of outcoupler reflectivity using helium diluent. Old mirrors and a 6.6/1.0 BHP mixture were used.

3.3 Nitrogen Diluent Data

Based upon the GASP and Blaze II modeling studies which were performed, one new set of iodine injector blocks and three new sideplate sets were designed by UIUC and fabricated by STI Optronics. 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") upstream of the nozzle throat to a position 0.47 cm (0.185") 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.

3.3.1 Effects of Decreased Injector-Throat Separation

The measured chemical efficiency increased from 15.4% (597 Watts at 42.8 mmol/s of Cl₂) to 18.1% (631 Watts at 38.4 mmol/s of Cl₂) when the injectors were moved from 1.12 cm to 0.47 cm upstream of the throat. Note that AFRL previously obtained a 15.5% chemical efficiency with VertiCOIL using nitrogen diluent and a 1.12 cm injector-throat spacing [36]. Figure 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 2.2, the result of improved performance using nitrogen diluent by moving the injectors closer to the throat is consistent with recent Russian experiments [13]. 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.

3.3.2 Effects of Increased Throat Height

Chemical efficiency (CE) 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 18.1% (631 Watts at 38.4 mmol/s of Cl_2) at a throat height of 0.353" and 20.5% (733 Watts at 39.2 mmol/s of Cl_2) at a throat height of 0.453". All of the data in Fig. 13 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 CE 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 0.453". As mentioned in Section 2.2, the improved performance with a larger throat is a consequence of decreased stagnation pressure which 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 CE versus reflectivity curve shows the characteristic roll-off in performance as the outcoupling reflectivity approaches unity (100%).

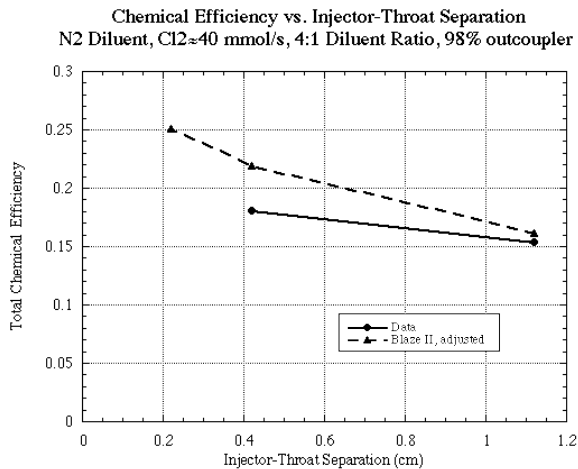


Fig. 12 Predicted and measured VertiCOIL chemical efficiency vs. injector-throat spacing with nitrogen diluent and subsonic injection.

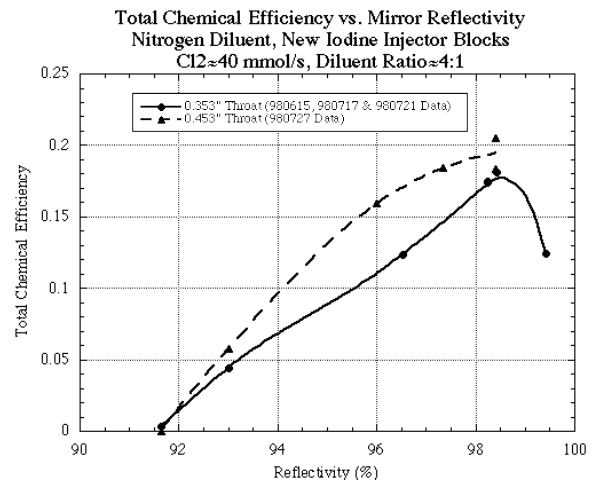


Fig. 13. Chemical efficiency as a function of outcoupler reflectivity and throat height using nitrogen diluent.

Maximum chemical efficiency data as a function of chlorine flow rate and throat height are shown in Fig. 14. For a throat height of 0.353" the peak CE was 20.4% at a Cl_2 flow rate of 27.5 mmol/s; the total output power was 511 watts. For a throat height of 0.453" the peak CE was 23.0% at a Cl_2 flow rate of 23.8 mmol/s; the total output power was 497 watts. 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 CE versus Cl_2 flow rate data also clearly illustrate that 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 0.353" the peak total power was 669 watts at a Cl_2 flow rate of 52.4 mmol/s (CE of 14.0%). For a throat height of 0.453" the peak total power was 1054 watts at a Cl_2 flow rate of 77.8 mmol/s (CE of 14.9%). 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 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 0.353" throat, the diluent ratios which optimized performance ranged from 3.2:1 to 5.8:1 with a slight preference for higher diluent ratio at lower chlorine flow (note that the 20.4% CE case had the diluent ratio of 5.8:1). Interestingly, for the larger 0.453" throat, the diluent ratio which produced the highest CE at lower Cl_2 flow rates was around 2.7:1, and at the higher chlorine flow rates the diluent ratio had to be reduced to around 1.4:1. The iodine flow rate that maximized performance was typically in the 0.44-0.86 mmol/s range. The titration ratio which optimized CE ranged from 1.0-2.7%; 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 which 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 [12,34-36]. 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 0.353" throat with which the helium diluent data were taken. However, when nitrogen was used as the diluent with a larger 0.453" 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.

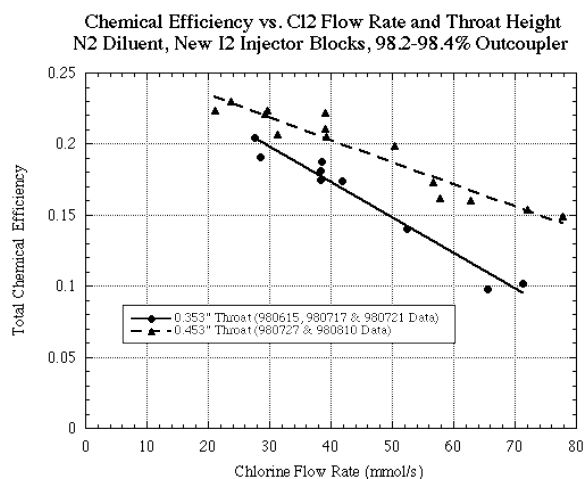


Fig. 14. Chemical efficiency as a function of chlorine flow rate and throat height with nitrogen diluent.

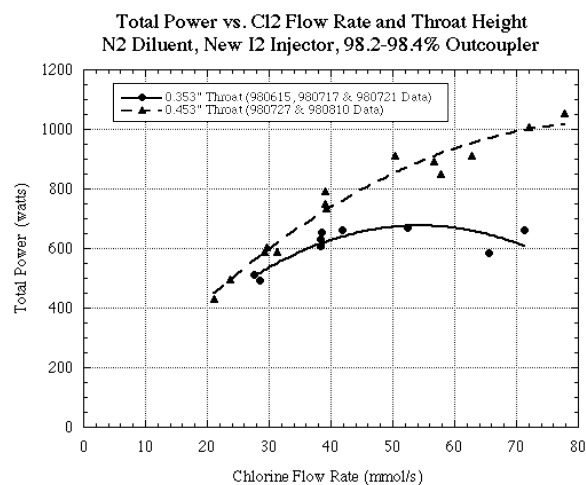


Fig. 15. Power as a function of chlorine flow rate and throat height with nitrogen diluent.

Burn blocks were taken for several flow conditions. For the 0.353" throat height, the typical measured beam was rectangular in shape and approximately 0.612"x1.129" in size (note that the second dimension is in the flow direction). For the 0.453" throat height, the typical measured beam was rectangular in shape and approximately 0.776"x1.038" 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 reported chemical efficiency with room temperature nitrogen diluent. The Russians and Japanese have very recently demonstrated a chemical efficiency of 22% with room temperature N_2 and 24-26% with pre-cooled nitrogen diluent [39]. 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 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.

3.3.3 Long Duration Runtime Testing

The concluding experiment for this study was to perform a long duration, high efficiency run using nitrogen diluent. The best performing set of hardware (new iodine injector blocks with sideplate set #2, 0.453" throat) were chosen for this test. Since run time is essentially limited by the batch size and the chlorine flow rate, a 44-liter batch was mixed and a low flow rate of 30 mmol/s of Cl_2 was run. Figure 16 shows the time history for the Cl_2 flow and the total chemical efficiency. The chlorine flow rate was held relatively steady 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 minutes; this corresponds to a power level of around 500-525 watts. The drop off in chemical efficiency at roughly the 45 minute mark is a direct consequence of the fact that the BHP temperature began warming up to prevent freezing of the mixture, Fig. 17. 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 $-12^\circ C$. The BHP freeze point was still monitored, and when the BHP freeze point rose above $-12^\circ C$, the LabVIEW system would take over control of the BHP temperature. Figure 17 shows that when the BHP freeze point reached $-12^\circ C$, that the LabVIEW system took control as planned, the BHP mixture progressively rose in temperature and the laser performance dropped considerably over the subsequent 17 minutes of runtime. 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-liter batch of BHP, it is likely that the 18.5% chemical efficiency at 30 mmol/s could have been maintained for over an hour.

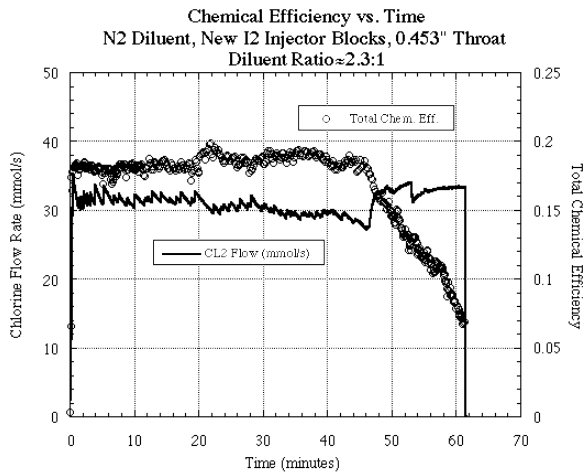


Fig. 16. Chemical efficiency and chlorine flow rate as a function of time for the long duration run test with nitrogen diluent.

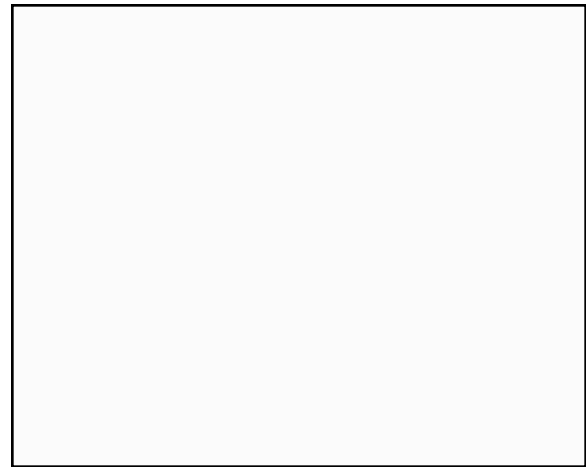


Fig. 17. Chemical efficiency and BHP temperature as a function of time for the long duration run test with nitrogen diluent.

4. Summary and Concluding Remarks

The VertiCOIL device was transferred from the Air Force Research Laboratory (AFRL) to the University of Illinois at Urbana-Champaign (UIUC) and made operational. 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 very important findings were made during the initial experiments. Perhaps most importantly, a chemical efficiency of 23% using room temperature nitrogen diluent was achieved; this is the highest reported chemical efficiency with room temperature nitrogen diluent. 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 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 minutes.

New nozzle designs were investigated and implemented to optimize nitrogen performance. Nitrogen diluent chemical efficiencies of 23.0% were demonstrated; these 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 0.7 cm and the throat height was increased from 0.353" to 0.453". The performance enhancements were in qualitative agreement with the system design predictions of the Blaze II chemical laser model. Three-dimensional computational fluid dynamics (CFD) 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, with the exception of replicating AFRL data with helium diluent, UIUC accomplished all of its goals for the STTR program and achieved 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 more recent operational procedures. Future recommendations for commercial COIL technology development are:

- (1) The Russians and Japanese have very recently demonstrated a chemical efficiency of 22% with room temperature N_2 and 24-26% with pre-cooled nitrogen diluent [39]. 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) Now that VertiCOIL is fully operational at UIUC and the facility is well calibrated, new and highly advanced nozzle concepts can be designed and tested. 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 easily 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 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 device 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 demonstrated the ability to couple a 7 kW COIL beam into a fiber optic for a short period of time [40]. 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 show-stopper 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 a relatively straightforward process. In the low power laser market of <5 kW, there is no question that COIL is uncompetitive with Nd:YAG lasers. The estimated operating costs of a COIL using nitrogen diluent (approximately 3 to 4 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 cuts most materials approximately 3 times faster may make them economically competitive when labor costs are factored into the equation. In the currently non-existent fiber delivered >5 kW laser market, COIL will dominate.

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