AMES LABORATORY

IS-5112
UC-511

Preliminary Design and Estimate of Capital and Operating Costs for a Production Scale Application of Laser Decontamination Technology

Ho-ming Pang and M.C. Edelson
Ames Laboratory
Iowa State University
Ames, IA 50011

Date Transmitted: August 6, 1994

Prepared for Westinghouse Idaho Nuclear Company, Incorporated
Under U.S. Department of Energy Contract W-7405-eng-82

IS-5112
UC-511

Preliminary Design and Estimate of Capital and Operating Costs for a Production Scale Application of Laser Decontamination Technology

Ho-ming Pang and M.C. Edelson
Ames Laboratory
Iowa State University
Ames, IA 50011

Date Transmitted: August 6, 1994

Prepared for Westinghouse Idaho Nuclear Company, Incorporated Under U.S. Department of Energy Contract W-7405-eng-82.

TABLE OF CONTENTS

ABSTRACT

The application of laser ablation technology to the decontamination of radioactive metals, particularly the surfaces of equipment, is discussed. Included is information related to the design, capital and operating costs, and effectiveness of laser ablation technology, based on commercial excimer and Nd:YAG lasers, for the decontamination of production scale equipment.

Introduction

The Ames Laboratory has pursued research in the use of lasers to decontaminate radioactive metals since late in 1990. This work was motivated by the 1989 U.S. Department of Energy (DOE) initiative to remediate contaminated facilities and equipment. The initial announcement of the DOE site restoration program contained two strong imperatives:

1. The remediation of DOE facilities must emphasize recycling. Large quantities of valuable metals were used to construct DOE facilities and decontamination methods could, in principle, allow the recovery of a large percentage of those materials for beneficial reuse. The alternative to decontamination, land burial, is discouraged as both wasteful of resources and environmentally suspect.

2. The remediation of DOE facilities must be accomplished without subjecting workers to health risks due to exposure to hazardous and radioactive materials. This adherence to the ALARA (As Low As Reasonably Achievable) principle in facility remediation suggests that work with radioactive materials be done remotely and with automated equipment whenever possible.

The decontamination of metals that are "surface" contaminated is achieved by ablating material from the surface and capturing the ablated materials before they can redeposit on the treated surface. Work in Ames indicates that laser ablation efficiency is optimized by using fast-pulse lasers (i.e., pulse width <1 μs). Lasers with wavelengths in the near infrared region of the spectrum (1064 nm) and in the ultraviolet region of the spectrum (248 nm) have been shown effective for the laser ablation of metals.

Initial studies in laser decontamination were pursued under funding from the Office of Technology Development (EM-50)[1]. Additional funding was subsequently received from Westinghouse Idaho Nuclear Company, Inc. (WINCO). The success decontaminating small objects in a laboratory setting naturally led to additional questions that are partially addressed

---

[1] H.M. Pang, R.J. Lipert, Y.M. Hamrick, Suna Bayrakal, K. Gaul, B. Davis, D.P. Baldwin, and M.C. Edelson, "Laser Decontamination: A New Strategy for Facility Decontamination," Proc. Int. Topical Meeting Nucl. Haz. Waste Manage. Spectrum '92, Amer. Nuc. Soc., La Grange Park, 1992, Vol. 2, 1335-1341.

in this report. Is laser decontamination technology viable for large objects? Can laser decontamination be performed *in situ* on large objects in restricted access environments? Can the technology be cost competitive with other waste management alternatives? WINCO funding has facilitated studies to address these questions experimentally. This report includes the results of some of those studies.

Preliminary Design

The full-scale demonstration of laser decontamination (i.e., LASDEC) technology has been performed on a surplus tank supplied by WINCO in January 1994. A schematic of that tank is shown in Figure 1.

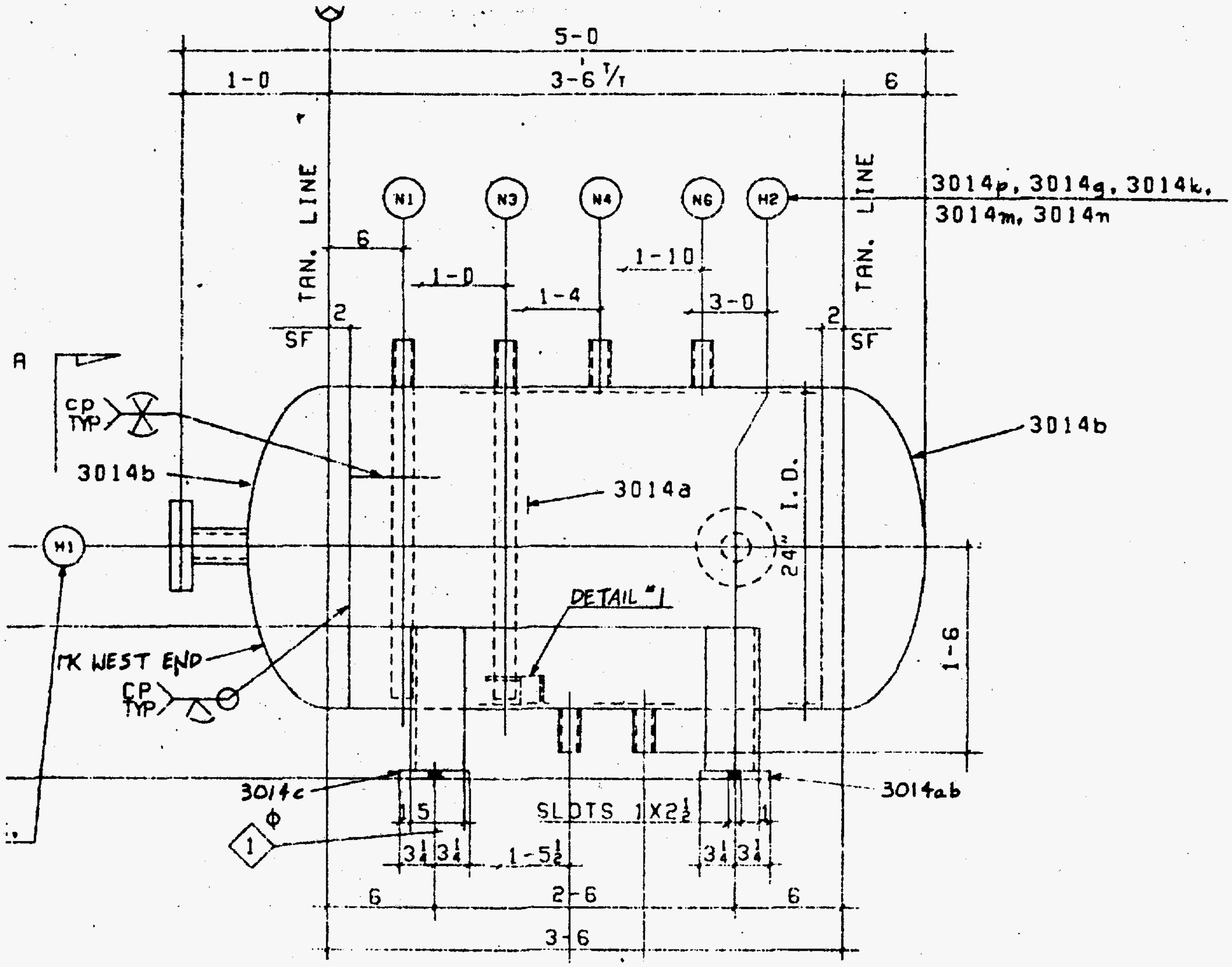

Figure 1. Tank sent to Ames for laser decontamination demonstration.

The preparation of the tank for decontamination of both the external and internal surfaces using an excimer laser requires that the end-cap of the tank be removed to provide access to the tank interior. Since, in a real application, the tank would be located in a restricted environment and manual cutting of the end-cap would be potentially hazardous, a remote cutting method is preferred. The Lumonics Corporation (Industrial Products Division Office, Livonia, MI) offered to demonstrate that the tank could be cut open using a commercial continuous wave (CW) Nd:YAG laser. Furthermore, they would also prove that the CW laser beam could be delivered to the tank by optical fibers positioned around the tank by a robotic arm under computer control to demonstrate that the cutting operation could be performed remotely, with little hazard to workers.

The tank was shipped directly to Lumonics by WINCO and a video tape of the demonstration, which was quite successful, was supplied to us shortly afterwards. As a result of the successful demonstration, we assume that the tank can be prepared for laser decontamination in a remote location.

The preparation steps essentially convert the complex tank into a right circular cylinder that is ~40" long and 24" in diameter with a wall thickness of 0.375." LASDEC is most easily applied to regular geometric shapes such as cylinders and planes; delivery systems employing either fiber optics, for visible and/or near infra-red lasers, or computer controlled mirror/lens assemblies, for excimer lasers, can extend LASDEC to more complex shapes.

The Ames Laboratory Engineering Services Department was asked to help develop an engineering design for the simulated decontamination of the WINCO tank. The design is subject to a major constraint: the assumption that the tank is located in a difficult-to-access environment typical of a hot cell or process cell. The Ames Laboratory LASDEC laboratory was designed with such an application in mind. The excimer laser and computer used to control the rastering of material through the laser beam are located in a "clean" environment outside of a room that contains the "hot" materials needing decontamination. The excimer laser beam is sent through a port in the wall between the hot area and the clean laser facility (Figure 2). Once in the hot area, the laser beam is directed to the material requiring treatment by a mirror or combination of mirrors. The beam is focused onto the material using a simple lens and material ablated from the metal's surface is routed to a HEPA filter for collection.

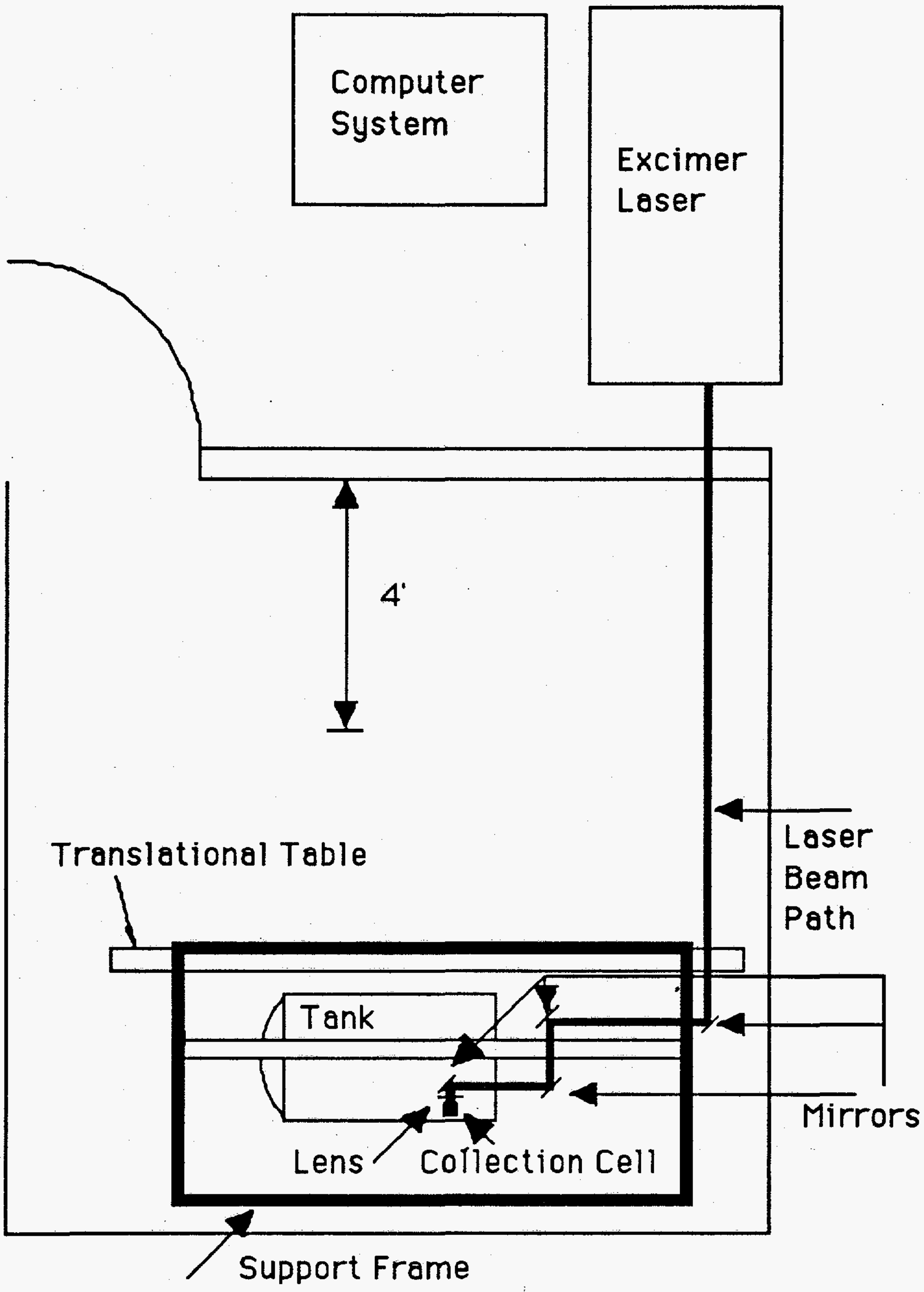

Fig. 2. Schematic diagram of experimental arrangement used to simulate the decontamination of a WINCO tank in a restricted access environment.

The resulting design is based upon the use of a frame that can be constructed over the tank to provide support for translational stages needed to move laser focusing mirrors along the long axis of the tank. The frame does not need to touch the tank and, for a real application, can be made adjustable to fit objects of different sizes and be surface treated to facilitate decontamination. However, to reduce costs, the frame used for the Ames demonstration is fixed in size and is not surface treated. The laser beam is focused onto the tank surface with a cylindrical lens that is fitted into a cell used to collect ablated materials from the surface (see *Figure* 3).

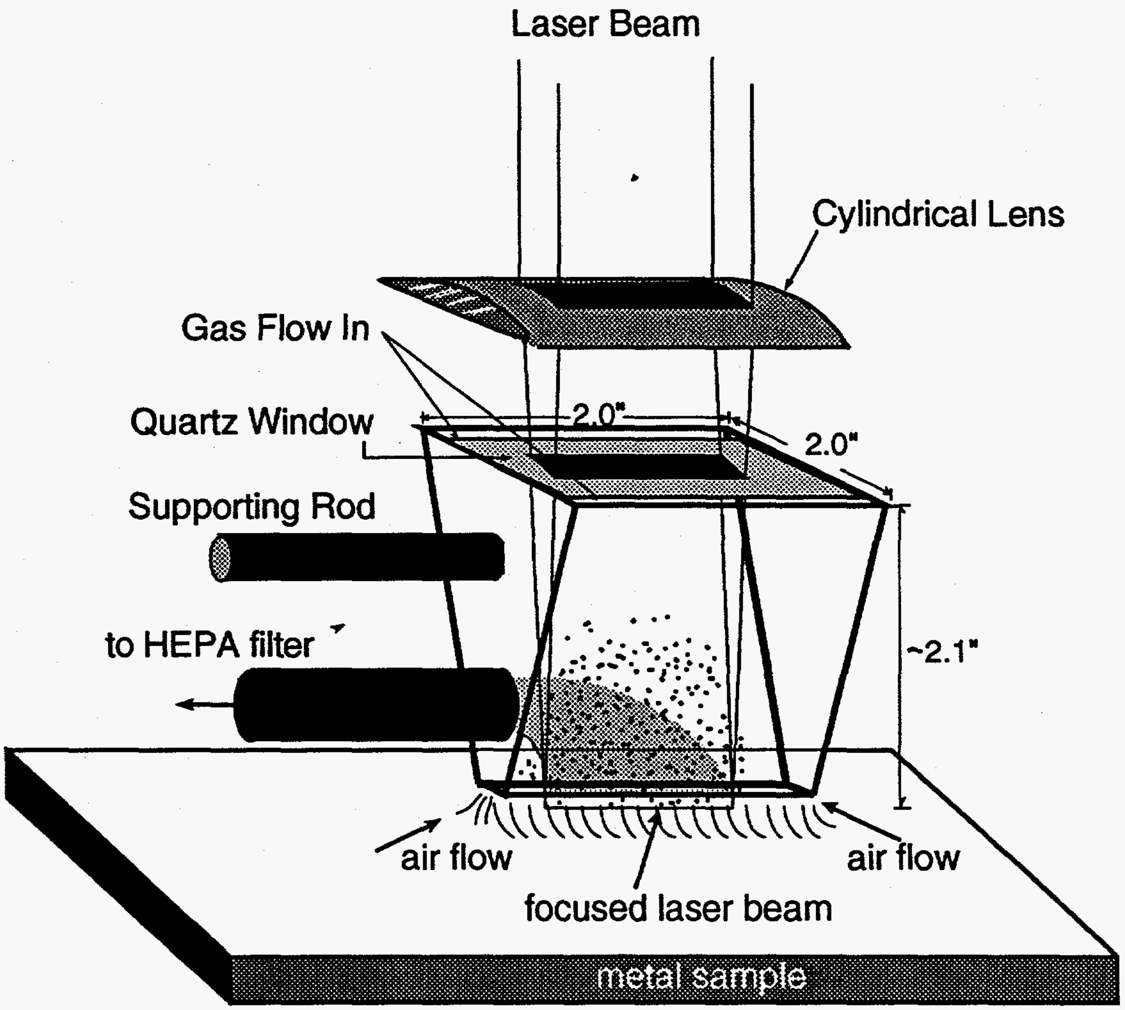

Figure 3. Focusing Lens/Collection Cell apparatus used to deliver laser energy to a surface and capture particulates generated during the laser ablation process.

The work in Ames is accomplished in air at normal pressures; these conditions are chosen to simplify apparatus design and implementation for "real-world" conditions. The laser ablation of metals is most efficient in a helium atmosphere or under reduced pressure[2].

---

[2] Y. Iida, "Effects of atmosphere on laser vaporization and excitation processes of solid samples," Spectrochim. Acta, 45B (1990) 1353 - 1367. The author shows ~90% reduction

The current Ames apparatus uses a photodetector to capture laser light reflected from the surface and automatically adjust the distance between the lens and the surface to maximize ablation efficiency. For the best operation, the direction of the laser beam needs to be perpendicular to the surface being exposed. An apparatus design, featuring a rotational stage under computer control to maintain perpendicularity between the laser beam direction and the surface being treated, emerged as the most appropriate for the LASDEC application in a restricted environment (see Figures 4 & 5). Such a stage is not currently implemented in Ames. Thus the tank was "decontaminated" in sections and it was necessary to periodically manually readjust the tilt of the focusing lens between sections to maintain perpendicularity. These manual adjustments would be very difficult were the tank in a process cell.

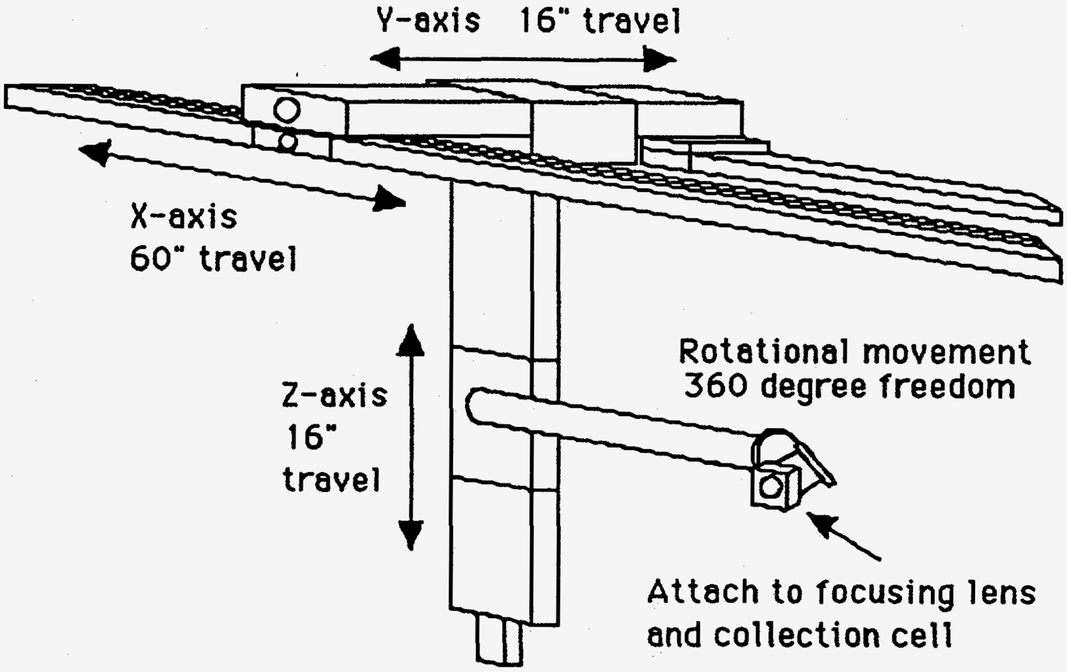

Figure 4. Design of laser positioning apparatus for tank cleaning experiment. This design features a rotational stage, which is not currently implemented in Ames, at the end of the rod that supports the collection cell and focusing lens.

---

in aluminum ablation in argon when the pressure is raised from ~8 torr to 760 torr. The effect is substantially reduced when He is used as a cover gas. Ames results agree with this finding and indicate that air behaves much like argon.

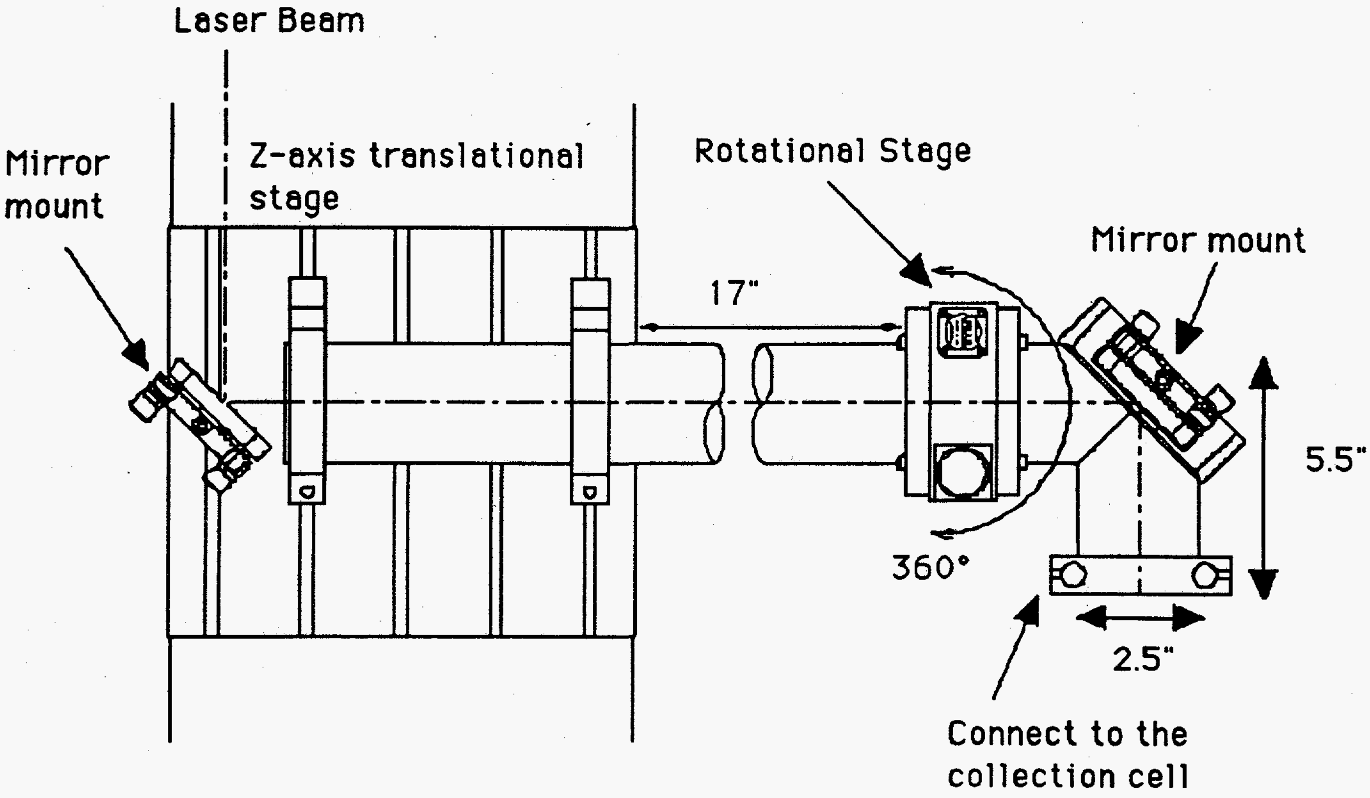

Figure 5. Detail of design shows implementation of rotational cell.

Cost of capital equipment

The cost of capital equipment for a production-scale application of LASDEC technology is estimated from the equipment used for experimentation in Ames, which is listed in Table 1. Both low- and high-value equipment are included in the table. The lasers and optical components used for this work were not originally purchased for an industrial application and may not represent the most suitable choices for a real-world application. The estimated <u>annual</u> cost of capital equipment is calculated according to the formula given in Table 2. This table shows the results of the calculations performed for the Questek laser. We assume a 10-year amortization period for the non-laser components and compute the annual equipment cost as a function of the interest rate and amortization period of the laser (5 to 7 years). A range of interest rates (3 to 11%) yields a range for annualized equipment costs of

1. For an excimer laser (Questek 2460 vβ):	$14,300 to $22,900
2. For a Nd:YAG laser (Continuum YG660)	$8,450 to $13,400
3. For a Nd:YAG laser (Continuum NY82)	$13,250 to $21,500

Table 1. Estimated Capital Equipment Costs for Laser Decontamination Apparatus

Equipment	**Excimer** [Questek 2560vβ]	**Nd:YAG** [Continuum YG660]	**Nd:YAG** [Continuum NY82]
Laser	$60,000	$30,000	$60,000
486-based computer and software	$7,000	$7,000	$7,000
X-Y-Z tables and controller	$6,500	$6,500	$6,500
Rotational stage and controller	$5,200	$5,200	$5,200
Cryogenic gas recirculation system	$5,000	Not required	Not required
Energy meter	$3,000	$3,000	$3,000
Optics (mirrors and cylindrical lens)	$2,100	$1,500	$1,500
Optical table	$2,000	$2,000	$2,000
Gas regulator	$1,900	Not required	Not required
Halogen gas safety cabinet	$1,700	Not required	Not required
Laser displacement sensor	$1,600	$1,600	$1,600
Optical mounts	$1,000	$1,000	$1,000
Particulate collection cell	$1,000	$1,000	$1,000
TV monitor & camera (remote viewing)	$500	$500	$500
Personal safety devices (hearing, eye protection)	$500	$500	$500
Exhaust pump	$300	$300	$300
In-line HEPA filter	$200	$200	$200
Fiber-optic delivery system	N/A	?	?

Table 2. Annualized excimer laser equipment costs for laser decontamination

$$C\_E(i,n) := 60000 \cdot \left[\frac{i \cdot (1+i)^{n}}{(1+i)^{n} - 1} \right] + 39500 \cdot \left[\frac{i \cdot (1+i)^{10}}{(1+i)^{10} - 1} \right]$$

$$n := 1 .. 10$$

C_E(0.03, n)	C_E(0.07, n)	C_E(0.11, n)
$6.643 \cdot 10^{4}$	$6.982 \cdot 10^{4}$	$7.331 \cdot 10^{4}$
$3.599 \cdot 10^{4}$	$3.881 \cdot 10^{4}$	$4.174 \cdot 10^{4}$
$2.584 \cdot 10^{4}$	$2.849 \cdot 10^{4}$	$3.126 \cdot 10^{4}$
$2.077 \cdot 10^{4}$	$2.334 \cdot 10^{4}$	$2.605 \cdot 10^{4}$
$1.773 \cdot 10^{4}$	$2.026 \cdot 10^{4}$	$2.294 \cdot 10^{4}$
$1.571 \cdot 10^{4}$	$1.821 \cdot 10^{4}$	$2.089 \cdot 10^{4}$
$1.426 \cdot 10^{4}$	$1.676 \cdot 10^{4}$	$1.944 \cdot 10^{4}$
$1.318 \cdot 10^{4}$	$1.567 \cdot 10^{4}$	$1.837 \cdot 10^{4}$
$1.234 \cdot 10^{4}$	$1.483 \cdot 10^{4}$	$1.754 \cdot 10^{4}$
$1.166 \cdot 10^{4}$	$1.417 \cdot 10^{4}$	$1.69 \cdot 10^{4}$

i = interest rate, n = amortization period (years). The columns represent the computation of C_E for n=1 to n=10.

Operating costs

These estimated costs are based on an operating schedule of 60 hours/week, 50 weeks/year. The estimates are based either upon extrapolations of our experience or information provided by vendors.

Equipment maintenance costs:

Annual excimer laser maintenance costs are estimated assuming:

1. Replacement of the output coupler (required every two months)	$2500
2. Replacement of rear coupling mirror	$800
3. Replacement of fan assembly (required every two years)	$350
4. Minor supplies (e.g., filters, pump oil, pump diaphragm, etc.)	$500
5. Thyratron (estimated replacement every four years)	$850
Total =	$5000

Annual Nd:YAG laser maintenance costs are estimated* assuming:

1. Replacement of flash lamps	$1,200 (YG660);	$3,600 (NY82)
2. Replacement of cooling water filters	$200 (YG660);	$200 (NY82)
3. YAG rods, mirrors, capacitors, etc.	$1,500 (YG660);	$3,000 (NY82)
Totals =	$2,900 (YG660);	$6,800 (NY82)

(*see discussion on page 10 for vendor's suggestions.)

Consumable supplies:

We assume that the laser apparatuses can be positioned in close proximity to the restricted access area close to items that require decontamination. It is also assumed that electricity and cooling water can be provided at the site at no cost to the decontamination operation.

The Ames excimer laser operation consumes gases and liquid nitrogen (required for the operation of a cryogenic gas purifier). According to one excimer laser vendor (Lumonics) these costs are ~$3.00/hour for a 90W excimer laser used on an industrial basis. The highly automated operation of most modern laser systems permits their use with only minimal supervision and they should be amenable to multi-shift operation. We assume 60 hour/week operation for 50 weeks of the year, which yields an annual gas/liquid nitrogen costs of $9,000.

An excimer laser industry publication[3] detailed recent (1993-1994) improvements in excimer laser performance. It describes a commercial excimer laser system in which the halogen gases and gas delivery system have been replaced by an on-demand pure fluorine gas generator located within the laser tube assembly. This new development in excimer laser technology offers the possibility of year-long industrial operation without any scheduled maintenance or gas replacement.

> Latest advances in material technology comprising new metal alloys and ceramic technology in excimer laser cavity design provided one billion shots hands-off operation of a 50-W deep-UV excimer laser source. [Note that one billion pulses represents approximately thirty-one 60-hour weeks of 150 Hz excimer laser operation].. . Economically operating systems up to 500 W will soon become a reality.

Nd:YAG lasers do not sustain costs for replaceable gases. Flash lamps can be considered a consumable item requiring periodic replacement.

---

[3] "Lambda Highlights," No.44, May 1994, pg. 3.

Representatives of a commercial Nd:YAG laser manufacturer were contacted and asked to comment on the Nd:YAG costs outlined in this report. They stated that[4]:

> We would like a minor modification to be made in the performance and cost area as mentioned in our conversation this morning. 50 Hz repetition rate with 1200 mJ @ 1064 nm in 9 ns is our standard product for over one year (Powerlite 9050). The pricing on this laser is $80,000 with potential for 20 - 25 ns operation for 1064 nm output only.
>
> Annual laser maintenance costs for Nd:YAG as reported should be less due to changes in optical construction and better coating technology incorporated in the new Continuum Powerlite lasers. Greater than 10% of laser cost per year is higher than average of 5 - 8% taking into account 60 hours per week and 50 weeks per year [service]. One operator has [operated at] 24 hours per day for 12 day periods then [shut] down for only 24 - 48 hours and repeats the cycle. This NY82 [laser] has been in operation since 1988 and operates at 80% of rated energy with flashlamp replacement every 50 - 70 million shots. 100 Hz operation with 60W of average power is the new YAG standard for Continuum with a price of $100,000.

Note that 24 hour/day operation at 30 Hz results in ~30 million shots per 12 day period and therefore flashlamps would need to be replaced roughly once per month under these conditions.

An advantage held by Nd:YAG lasers relative to excimer lasers for metal decontamination is the potential for porting Nd:YAG laser beams to remote locations with relatively inexpensive optical fibers. <u>The fibers represent a consumable expense that we have no way to estimate on an annual basis</u>.

<u>Labor costs:</u>

Annual labor costs include two components. First we assume that an employee is trained in the servicing and operation of the laser. We assume that the employee has an undergraduate education with a science major and earns $50,000/year. Overhead and benefits add an additional $50,000 yielding an annual "dedicated" labor cost of $100,000.

An additional labor-related cost component will be added later to cover

---

[4] D. Black, Continuum Lasers, Carmel, IN. Private communication, August 5, 1994.

costs associated with the alignment of laser systems within restricted environments. These costs are related to additional labor that is needed to assist the laser operator during alignment. Since there may be less maintenance associated with the use of a Nd:YAG laser relative to an excimer laser of the type used in Ames it is possible that labor costs would diminish were a laser of this type used. We, however, utilize the same labor costs for each laser in our calculations.

Secondary waste disposal:
A purported advantage of LASDEC over other decontamination methods is related to the minimization of secondary wastes. LASDEC requires no solvents and only a small amount of the total mass of the object is converted to particulates during the ablation process. [If the laser ablation process removed a uniform thickness of 10 µm from the total WINCO tank surface, the weight of material removed would be ~330 grams (this assumes that the material removed has a density of 8 g/cm^3, which approximates the density of stainless steel)]. The ablated material is collected with an in-line HEPA filter and the most significant secondary waste created during laser processing is expected to be the contaminated HEPA filter. No estimated costs for the HEPA filter disposal are included here for two reasons. First, if the object treated is contaminated with high-enriched uranium or plutonium, criticality issues may require the utilization of either a specialized filter (i.e., critically-safe geometry) or the replacement of the filter at frequent intervals. Second, technology development is currently underway to produce a reuseable stainless steel HEPA filter that could be available in the near future.

Tank decontamination

The production scale application considered here is the laser decontamination of a stainless steel WINCO tank. An uncontaminated WINCO tank was shipped to Ames in January 1994 for this demonstration. The use of a laser apparatus for the *in situ* decontamination of this tank was demonstrated by removing a layer of black paint from the outer surface and grease from the inner surface of the tank. The demonstration was conducted with the tank resting on the floor the way it would in a process environment. The demonstration of tank cleaning demonstrated that the laser could reach virtually the entire tank surface, both internal and external (see Figures 6 & 7). The laser could not reach a small portion of the two supports used to balance the tank on the floor.

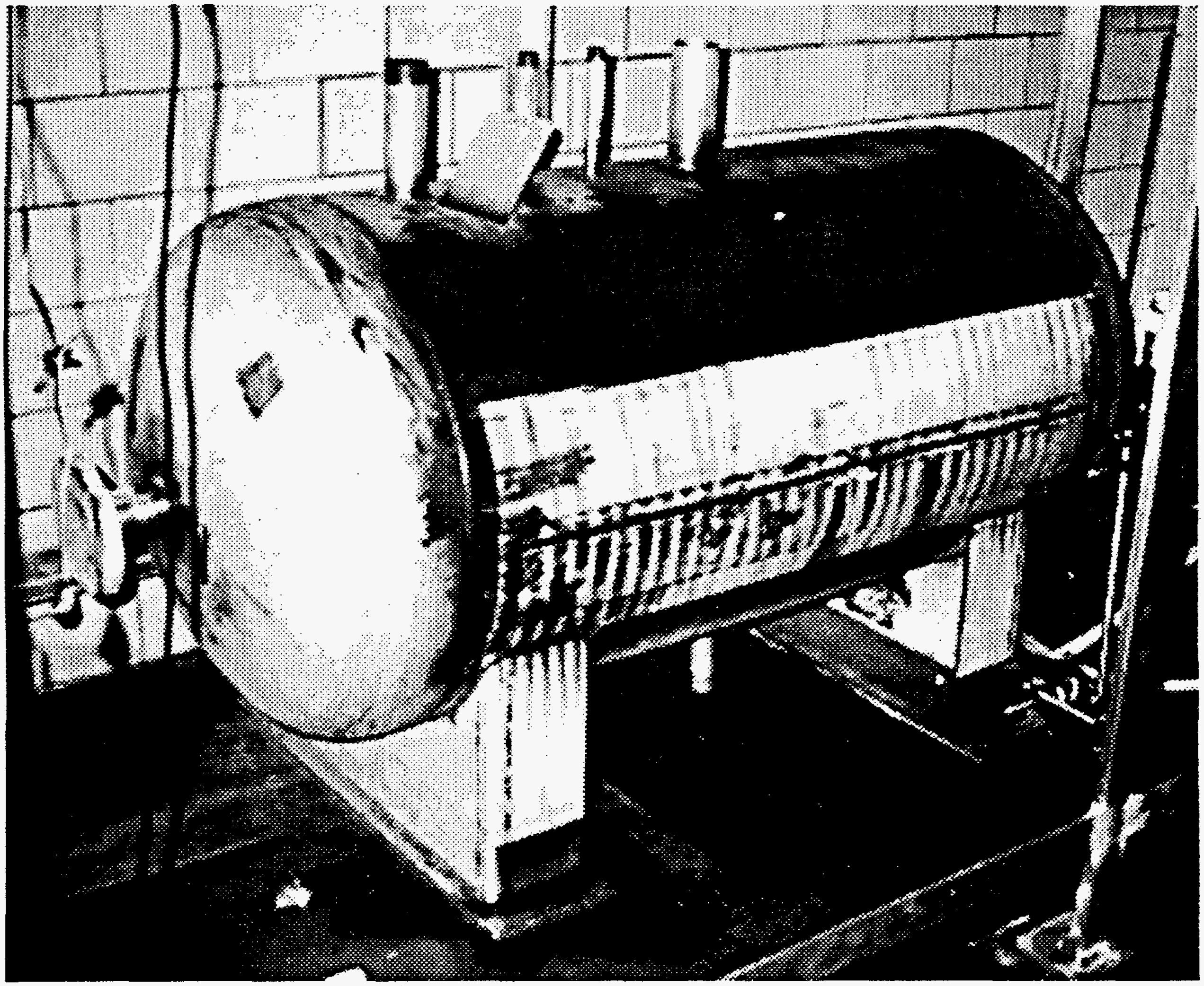

Figure 6. Photograph showing the partial removal of black paint sprayed on the exterior surface of the tank.

To estimate the cost of decontaminating the tank via laser ablation, we need to estimate the cleaning rate. We assume surface corrosion somewhere between that of WINCO SIMCON I and SIMCON II samples, which were laser cleaned as part of another task. Using an excimer laser at ~50W average power (~300 mJ/pulse at 150 Hz), SIMCON I samples were cleaned at a scanning speed of 1.7 mm/s whereas SIMCON II samples were cleaned at 1.25 mm/s. We therefore assume a scanning speed of 1.5 mm/s for the cleaning of the tank surface. This speed translates into an area coverage of 0.16 m^2/h. Since the tank area requiring cleaning has a total surface area (external + internal) of ~4 m^2 the decontamination of the tank should require ~25 hours of laser irradiation. Calculations described in the Appendix suggest that ~12 hours will be necessary.

Similar calculations were performed for three Nd:YAG lasers and the results are given in Table 3. The operative assumption driving the calculations is that a minimum irradiance (joules/s*area = watts/cm^2) of 1E08 W/cm^2 is required for surface cleaning at the excimer laser wavelength of 248 nm whereas 5E08 W/cm^2 is required at the Nd:YAG wavelength of 1064 nm. This assumption is also discussed in the Appendix.

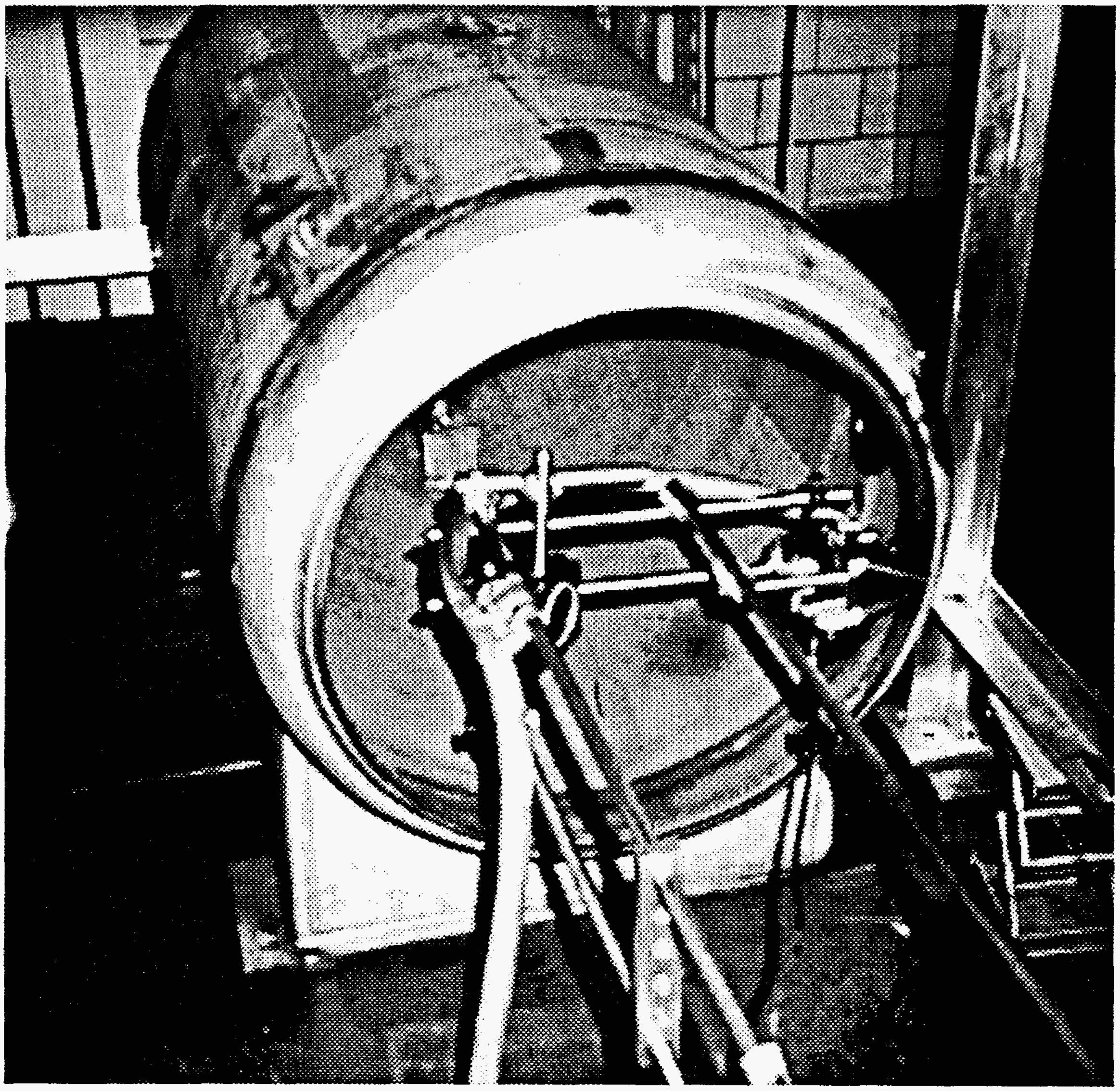

Figure 7. Optics and cleaning cell deployed for interior cell wall cleaning.

Table 3. Relevant Parameters and Estimated Time Required to Decontaminate WINCO Tank Using Excimer and Nd:YAG lasers*.

Laser	Excimer [Questek 2460 vβ]	Nd:YAG [Continuum YG660]	Nd:YAG [Continuum NY82]	Nd:YAG [US Lasers]
Rep. rate	150 Hz	30 Hz	30 Hz	5000 Hz
Pulse energy	250 mJ	150 mJ	700 mJ	50 mJ
Pulse width	25 ns	8 ns	10 ns	150 ns
Focused area	0.1 cm^2	0.037 cm^2	0.14 cm^2	6.7E-4 cm^2
Pulses/area	15	15	15	15
Time	11.4 hours	151.4 hours	40.5 hours	51.1 hours

*Calculations based on 1E08 W/cm^2 irradiance for excimer laser decontamination and 5E08 W/cm^2 for Nd:YAG lasers. This choice is explained in the Appendix.

To minimize maintenance requirements, the Ames group uses its excimer laser at roughly 50% of rated power. The calculations used to compute the excimer laser result in Table 3 assume the use of the excimer laser at roughly 50% of rated average power; values for Nd:YAG parameters are chosen at roughly 100% of rated output power. Currently an excimer laser with an average power in excess of 1000 W is commercially available (SOPRA VEL 1) and another with an average power of roughly 2000 W is under development in Japan.[5] Assuming conservative operation of these devices (50% of maximum power operation) it is likely that the ~12 hour cleaning time could be reduced substantially were one of these lasers used for this task. Assuming that the laser cleaning process can be put under computer control so that only limited attention from site personnel is required, it isn't clear that cost savings would result from the application of very high pulse power lasers to small cleaning projects. However, certain large cleaning projects (e.g., large walls) could be made feasible with the large laser systems.

---

[5] Shunichi Sato, Institute of Research and Innovation, Laser Laboratory, Takada, Kashiwa, Chiba 277, Japan. Private communication during visit to Ames, May 12, 1993.

Tank cleaning costs:
The cost for tank cleaning can be estimated with reference to estimated yearly costs. The annual cost figures need to be prorated against the estimated time needed to clean the tank and additional costs for labor that would be incurred during experimental set-up need to be added. For the sake of this estimate we assume that the worker in charge of the laser will require assistance placing a frame around the tank and aligning the laser system with the tank, which is assumed to be in a hot cell. We assume the set-up to require ~10 person-hours (5 X the time taken in Ames) with the helper's time (5 hours) costed at $50/hour. We assume that each laser is in operation for 3000 hours/year and estimate costs by prorating the time needed to clean the tank against the yearly costs. The laser operator is assumed to spend 7 hours setting up the work and an additional 3 hours observing the work in progress and tearing down the apparatus at the conclusion of the job. The operator's time (10 hours) is compared against a 2000 hour annual work effort (40 hours/week X 50 weeks/year) to arrive at the percentages listed in Tables 4 - 6 below. The other percentages are based on a 3000 hour annual usage and rounded up to the nearest whole percentage. A summary of these costs is provided in Tables 4 - 6. Note that it is very possible that labor costs could be substantially reduced if the laser operator were responsible for more than one laser decontamination apparatus, which, assuming a high degree of computerized operation, is not unreasonable. The estimated costs do not include costs for engineering diagram preparation, safety studies, and dismantlement procedures needed prior to decontamination.

A major uncertainty in the calculation of costs for the Nd:YAG lasers is the cost of the optical fibers needed to port the Nd:YAG laser beams into a restricted area. These should be added, when known, to the supplies portion of the tables. Note that the cost of installing an optical access port onto a hot cell is also omitted from Table 4.

Also note that the lasers used for this comparison are not representative of the current commercial state-of-the-art. Thus these costs should be overestimates of what is currently achievable with both Nd:YAG and excimer laser technologies.

Table 4. Estimated Tank Decontamination Costs (Excimer Laser).

Operation	**Annual cost**	**Duty factor (%)**	**Estimated cost**
Laser operator	$100,000	0.5	$ 500
Capital equip.	$ 17,500	1	$ 175
Maintenance	$ 5,000	1	$ 50
Supplies	$ 9,000	1	$ 90
Set-up labor	N/A	100	$ 300
Contingency		25	$ 235
Total cost			$1350

Table 5. Estimated Tank Decontamination Costs (Continuum YG660).

Operation	**Annual cost**	**Duty factor (%)**	**Estimated Cost**
Laser operator	$100,000	0.5	$ 500
Capital equip.	$ 10,925	5	$ 546
Maintenance	$ 2,900	5	$ 145
Supplies	N/A	-	$ 0
Set-up labor	N/A	100	$ 300
Contingency		25	$ 373
Total cost			$1864

Table 6. Estimated Tank Decontamination Costs (Continuum NY82).

Operation	**Annual cost**	**Duty factor (%)**	**Estimated Cost**
Laser operator	$100,000	0.5	$ 500
Capital equip.	$ 17,375	1	$ 174
Maintenance	$ 6,800	1	$ 68
Supplies	N/A	-	$ 0
Set-up labor	N/A	100	$ 300
Contingency		25	$ 260
Total cost			$1302

Conclusions

This report includes estimates of the capital and operating costs required for the *in situ* laser decontamination of a process tank located within a restricted environment. It is likely that the application of these estimation techniques will require tailoring to individual sites and decontamination projects. These estimations are based upon the performance specifications of research-grade lasers, which are not designed for industrial applications. Both Nd:YAG and excimer lasers are available in industrial models that warrant consideration for WINCO projects. The cost estimates presented earlier in the text (Tables 4 through 6) indicate that equipment costs are a small percentage of total costs. Purchasing a more robust, more easily serviced, laser will not seriously impact the total decontamination cost if the capital equipment can be amortized over a reasonable period of time. Labor costs dominate these projects. Were the laser operator placed in charge of multiple instruments or were additional automation possible, total costs could be reduced significantly.

The tank cleaning cost estimate can be compared with the costs of other waste management alternatives. If the WINCO tank is classed as a low-level waste (LLW) and buried without compaction, the estimated cost for burial (at a LLW burial cost of $100 per cubic foot) will be ~$1200. If the tank needs to be buried as a TRU waste the cost will be substantially greater. No effort has been made here to compare the costs of laser decontamination with those of other decontamination alternatives. This could be done using an expert system available in Ames.[6]

There is great interest in utilizing Nd:YAG lasers, which can be efficiently transported through conventional optical fibers into difficult-to-access areas, for the decontamination of process equipment.[7] The chief impediments to such use are related to wavelength (i.e., ablation of

---

[6] S. Bayrakal, "Analysis of the application of decontamination technologies to radioactive metal waste minimization using expert systems," M.S. Thesis, Iowa State Univ., Civil & Construction Eng. Dept., 1993.

[7] Rod Taylor (Nat. Research Council of Canada) has developed long pulse (~100 ns) excimer lasers for use with optical fibers. He has transmitted 75 W out of 1.5 mm fiber using an 800 Hz excimer laser in "burst mode." Currently fiber lifetime of 100,000 to 1,000,000 shots is difficult to attain. Color center formation limits the lifetime and eventually, the fiber end is eroded by ablation. Research goal is 1E08 shot fiber lifetime.

metals is less efficient at long wavelengths - see Fig. A2), repetition rate (i.e., commercial fast-pulse Nd:YAG lasers currently are only available at ~100 Hz repetition rates whereas excimer lasers are commercially available at >300 Hz repetition rates), and possible damage to optical fibers by high-power fast pulses.

As part of this project, Nd:YAG lasers and optical fibers were evaluated for decontamination. Nd:YAG lasers available in Ames had a maximum repetition rate of 30 Hz and fibers, reputedly capable of transmitting 0.5 J pulses (~10 ns duration), could only reliably carry ~0.04 J at this repetition rate without suffering damage.

The cost estimates presented here which, admittedly, are incomplete (e.g., no estimate of fiber optic costs for Nd:YAG lasers or costs for routing excimer laser beams into a hot cell) suggest that the excimer laser route is most cost-effective, but not by a large margin. The higher repetition rates accessible in excimer lasers do seem to offer significant speed advantages relative to conventional Q-switched Nd:YAG lasers for the decontamination of large area objects. It is, however, quite possible that cleaning problems involving very difficult access can be found that only admit of a solution involving a laser beam carried by an optical fiber. It is clear that, with current optical fiber technology, Nd:YAG laser wavelengths can be more easily transmitted than can any excimer laser wavelength. Testing of an acousto-optically Q-switched Nd:YAG laser that operates at 1064 nm with long pulse widths (~150 ns) and high repetition rates (>1 kHz) will help determine whether this laser type offers good compromise performance that is useful for laser decontamination applications.

Appendix

Calculation of Decontamination Times for Excimer and Nd:YAG Lasers

We presume that there is a minimum irradiance (I_{min}) required to ablate material from a metal surface. This value should be material specific. Walters[8] indicated that 2.7 J/cm^2 is required to "damage" the surface of 316 SS using an laser operating at 266 nm. This "fluence" value, when converted to an "irradiance" value by dividing by Walter's pulse width (~20 ns) is approximately ~1E08 watts/cm^2. Results obtained in our laboratory demonstrated that surface decontamination efficiency increased markedly as the irradiance is increased above I_{min}. These results are shown in Fig A1.

The variation in loss of radioactive contamination, shown in Figure A1, with irradiance appears to be roughly linear.

A recent paper[9] contained evidence that ultraviolet laser pulses are considerably more effective in ablating material from metals than visible or infrared laser pulses. The authors reported that:

> In Fig. 2 [reproduced below as Fig. A2], it is shown that the ablation efficiency, (ablated mass per unit energy per unit surface) as a function of laser fluence is more than one order of magnitude higher (20 times) for a UV laser than for an IR laser or even a visible laser at 200 J cm^{-2}.

---

[8] C.T. Walters, "Short Wavelength/Surface Interaction in Vacuum," Paper AIAA-81-1154, Proceedings of the AIAA 16th Thermophysics Conference, Palo Alto, CA (June 23-25, 1981).

[9] C. Geertsen, A. Briand, F. Chartier, J-L. Lacur, P. Mauchien, S. Sjostrom, and J-M. Mermet, "Comparison Between Infrared and Ultraviolet Laser Ablation at Atmospheric Pressure — Implications for Solid Sampling Inductively Coupled Plasma Spectrometry," J. Anal. Atomic Spectrom., **9** (1994) 17 - 22.

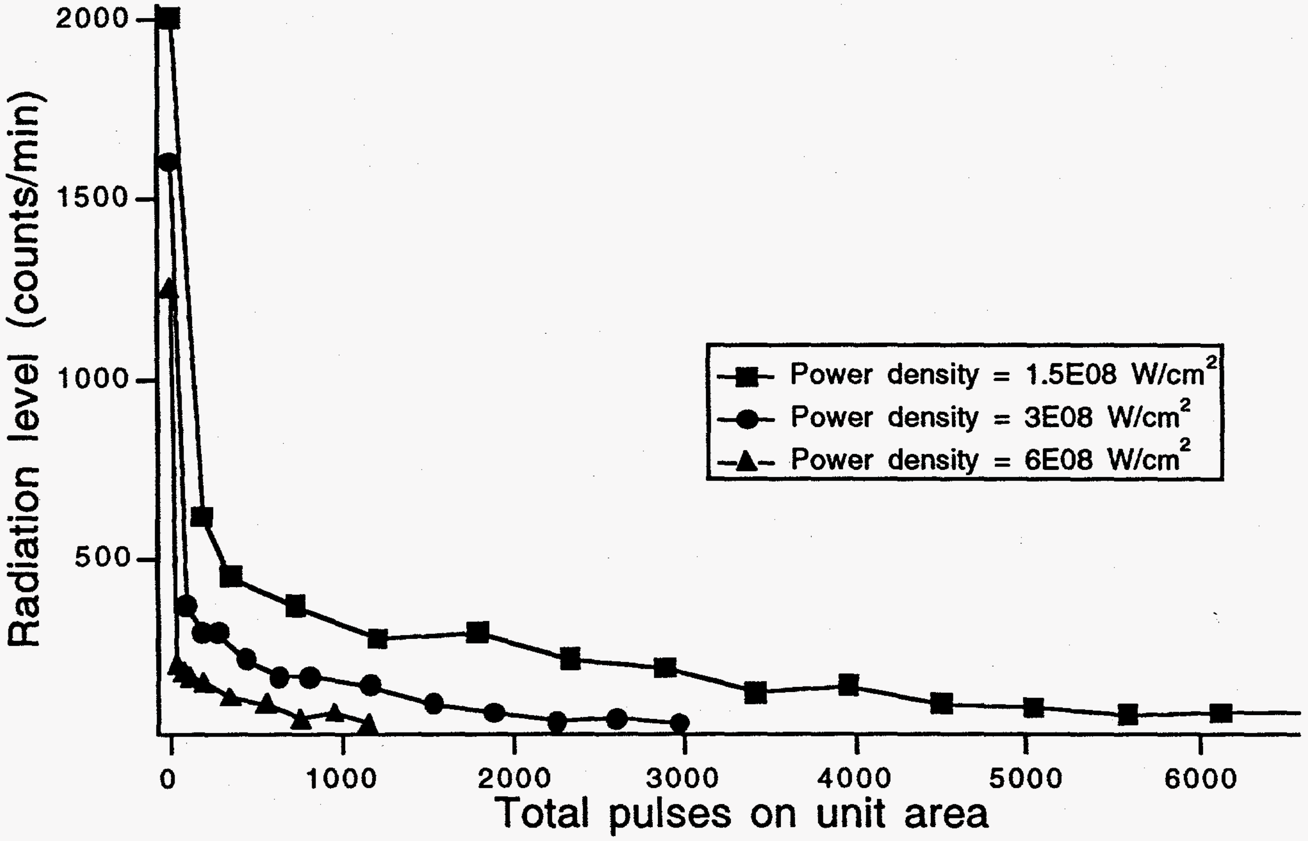

Figure A1. Variation in decontamination rate with power density (i.e.,. irradiance). These data are measured for the decontamination of WINCO SIMCON samples. The irradiance is changed by adjusting the laser spot size while keeping the repetition rate and energy/pulse constant. No correction is made for losses in energy transmission due to reflection from lens surfaces.

Note that the variation of ablated mass with laser fluence, shown in Fig. A2, is approximately linear for all wavelengths. This suggests that the results in Fig. A1 are consistent with removal of radioactive surface contaminants. Also note that there is much more effective surface ablation at lower wavelengths then at the Nd:YAG wavelength.

The fluence used in our experimentation, ~2 J cm^{-2}, is quite a bit lower than those used in the study cited above. Assuming a laser pulse width of ~25 ns for excimer laser pulses, a fluence value of 200 J/cm^2 translates into an irradiance of 8E09 watts/cm^2 where we believe substantial plasma formation will occur. It is likely that surface decontamination efficiency will decline after plasma formation and that there is likely to be an optimum irradiance for decontamination. Such phenomena was reported by Walters.[2]

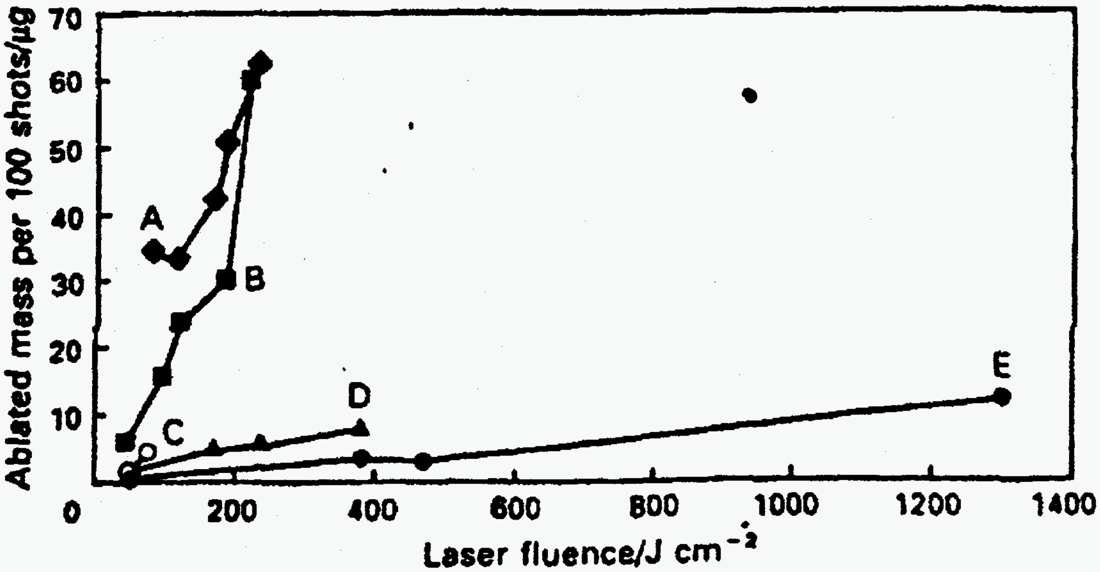

Fig. 2 Ablation efficiency (mass ablated per laser fluence) on a copper target in air buffer gas as a function of laser energy for four different lasers. A, ArF 193 nm; B, XeCl 308 nm; C, Nd: YAG 355 nm; D, Nd:YAG 532 nm; and E, Nd:YAG 1064 nm

Figure A2. Taken from Ref. 9.

We believe that the trend toward higher efficiency at UV wavelengths, shown in Fig. A2, exists at the fluence levels we employ. To be conservative in our comparison of excimer and Nd:YAG lasers, we assume that I_{min} will go from 1E08 W/cm^2 to 5E08 W/cm^2 as we move from 248 nm laser radiation to 1064 nm laser radiation.

Calculation of Decontamination Times:

We begin by calculating the area of the minimum irradiance beam for each laser using the parameters listed in Table 3 and equation A1:

$$Area = E\ (joules)*(Imin)^{-1}*(Dt)^{-1}. \qquad (A1)$$

For 248 nm radiation, I_{min} is assumed to be 1E08 watts/cm^2 whereas it is assumed equal to 5E08 watts/cm^2 for Nd:YAG radiation at 1064 nm.

Next, the time to decontaminate a tank is estimated using equation A2.

$$T = (np*\ A)/(R*a) \qquad (A2)$$

where:

T = time needed for decontamination if lasers used at minimum irradiance,
A = Area of tank = 4.09 m^2 (sum of the interior and exterior surface areas)
R = laser repetition rate
a = area irradiated by a single pulse at minimum irradiance
np = number of pulses needed to decontaminate minimum irradiance area.

In calculations using equ. A2, “np” is set equal to 15. This somewhat arbitrary choice is made because real applications of laser decontamination technology require overlapping pulses onto an elementary area and revisiting areas previously treated to ensure that all contamination is removed. This particular choice is consistent with experimental work in our laboratory that shows effective decontamination at an irradiance close to the estimated minimum at 248 nm. Since our experimental evidence suggests that raising the irradiance above the minimum value increases the amount of material ablated (see Figs. A1 and A2) in a roughly linear fashion, we can modify equation A2 to

$$T = [(np*\ A)/(R*a)]*[I/Imin] \qquad (A3)$$

accommodate these facts (A3).

LIST OF FIGURES

LIST OF TABLES

DISTRIBUTION LIST

1. Mr. Russell Ferguson
Westinghouse Idaho Nuclear Co., Inc.
1950 Freemont Ave.
Idaho Falls, ID 83403-4218

2. Mr. Rick Demmer
Westinghouse Idaho Nuclear Co., Inc.
1950 Freemont Ave.
Idaho Falls, ID 83403-4218

3. Mr. Keith Kibbe
Martin Marietta Energy Systems
PO Box 2003
Oak Ridge, TN 37831-7325

4. Mr. Jerry Hyde, EM-551
U.S. Department of Energy
Trevion II, EM-551
12800 Middlebrook Rd.
Germantown, MD 20874

5. Dr. James C. Corones
Technical Program Manager
Ames Laboratory
Ames, IA 50011

6. Dr. Craig T. Walters
Craig Walters Associates
2353 Cambridge Blvd.
Columbus, OH 43221

7. Dr. Adam Habayeb
Ontario Hydro - Research Division
800 Kipling Avenue
Toronto, Ontario M8Z 5S4
Canada

8. Mr. Patrick Appelhans
EG&G Rocky Flats
PO Box 464
Golden, CO 80402-0464

9. USDOE-TIC
Oak Ridge National Laboratory
PO Box 62
Oak Ridge, TN 37830

10. Patent Office, USDOE
Chicago Operations Office
9800 S. Cass Avenue
Argonne, IL 60439

11. Mr. Thomas Kugler
Manager, Applications Lab.
Lumonics Corporation
19776 Haggerty Road
Livonia, MI 48152-1016

12. Dr. Kevin Carney
Argonne Nat. Laboratory
PO Box 2528
Idaho Falls, ID 83403

13. Dr. Paul Denney
ARL Pennsylvania State Univ.
PO Box 30
State College, PA 16804

14. Mr. Dann Flesher
Westinghouse Hanford Corp.
PO Box 1970 MS R2-07
Richland, WA 99352

15. Mr. Brad Frazee
Westinghouse Idaho Nuclear Co., Inc.
1955 Freemont Ave., MS 5217
PO Box 4000
Idaho Falls, ID 83403

16. Mr. Joel Haugen
Technical Program Officer
US Department of Energy
Chicago Operations Office
9800 S. Cass Avenue
Argonne, IL 60439

17. Mr. Wayne Hayden
Oak Ridge National Laboratory
Engineering Materials Section
Oak Ridge, TN 37831

18. Dr. Takeshi Ishikura
Manager, Decommissioning Group
Nuclear Power Eng. Corp.
Shuwa Kamiyacho Bldg.
Tokyo, Japan 105

19. Dr. Kaneharu Kato
Japan Atomic Energy Research Inst.
Tokai Research Establishment
Tokai-Mura, Naka-Gun
Ibaraki-Ken, 319-11
Japan

20. Mr. Judson Lilly
US Department of Energy
Trevion II, EM-423
12800 Middlebrook Rd.
Germantown, MD 20874

20. Mr. Lowell Mathison
ES&H Group
Ames Laboratory
Ames, IA 50011

21. Dr. Ho-ming Pang
Ames Laboratory
Ames, IA 50011

22. Dr. Martin C. Edelson
Ames Laboratory
Ames. IA 50011

23. Mr. Paul Malik
PMX Co.
209 Main St.
Northport, NY 11768

24. Dr. Leonard Reed
Chairman of the Board
InTA
2281 Calle de Luna
Santa Clara, CA

25. Mr. Pete Sanford
EG&G Rocky Flats
PO Box 464
Golden, CO 80402-0464

25. Dr. Marc Sentis
IMFM VM 34 CNRS
1 rue Honorat
Marseilles 13003
France

25. Dr. G. Dan Smith
Chief, Planning & Technology
US Department of Energy
Office of Safeguards & Security
SA-134
Washington, DC 20585

26. Dr. Rod Taylor
National Research Council of Canada
Montreal Rd.
Ottawa, Ontario
Canada

27. Mr. Karl Trauttmansdorff
Kleiber & Schulz, Inc.
2017 New Highway
Farmingdale, NY 11735

28. Mr. William Schutte
US Department of Energy
Trevion II, EM-50
12800 Middlebrook Rd.
Germantown, MD 20874