Report No. 4090-001

FEASIBILITY OF USING LASERS AND INFRARED HEATERS AS UNREP ICING COUNTERMEASURES

Final Report

December 1989

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Prepared for

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Encl: (1) NKF Report No. 4090-001, "Feasibility of Using Lasers and Infrared Heaters as UNREP Icing Countermeasures," Dec 89

1. David Taylor Research Center (DTRC), under the Northern Latitude Logistic Support Task of the 6.2 Logistics Block Program, has conducted research on developing and assessing concepts to improve Underway Replenishment (UNREP) operations in cold weather environments. Earlier work, described in reference (a), identified solutions that focused on the prevention and removal of ice buildup on UNREP deck areas and equipment. Potential solutions were categorized as either conventional, unconventional, or high technology for both anti-icing and de-icing applications. Conventional systems were evaluated and those with potentially high payoff were recommended for inclusion in shipboard cold weather kits currently in formulation. Additional top priority anti-icing/de-icing concepts were identified for further feasibility study. These concepts are lasers, infrared heaters, and a two-phase chemical pellet system. The 6.2 work for the lasers and infrared heaters has been concluded. The evaluation of the two-phase chemical pellet system is continuing.

2. Enclosure (1) presents the results of the feasibility evaluation for laser and infrared heating technology for the UNREP anti-icing/de-icing application. It was concluded that laser de-icing is physically and technically feasible, but is not practical. Design constraints incorporated due to safety requirements limit the de-icing capability of the laser system. In addition, a laser de-icing system would be cost prohibitive and is not recommended for shipboard use. In comparison, a water lance system would provide superior de-icing capability with fewer safety and operational concerns at a reduced cost.

3. It was also concluded that infrared heating technology is feasible and is very well suited for the UNREP application. The primary mode of operation would be anti-icing UNREP deck working areas with additional benefits of personnel warming and de-icing if needed. Infrared heaters are appropriate for retrofit where

an anti-icing capability is required on existing ships and may also be incorporated into new ship designs. A heating load of approximately 150 watts/ft^2 is required to maintain an ice-free deck under the design conditions of -20°F and 60 knot winds. Electric powered infrared heaters can provide this anti-icing capability at mounting heights of 8 feet. Under less extreme conditions, anti-icing and personnel warming can be provided at mounting heights over 12 feet.

4. Hardware for a prototype infrared heater anti-icing system was sized and selected for a 20 x 5 foot deck area on a combatant Fueling-At-Sea station. The system consists of six two-element quartz lamp overhead mounted infrared heaters rated at 3000 watts per element. A variable voltage power controller is included to allow adjustable power levels. All hardware is available off-the-shelf with a system cost of about $13,000.

5. It is strongly recommended that this infrared heater anti-icing system be demonstrated and evaluated in a shipboard test. The upcoming Ship Icing Test provides an excellent testing opportunity for demonstration of the system. DTRC will provide follow-on test support of the infrared heater system if requested. Test support should include development of test plans, ship installation plans, hardware procurement, shipboard testing, and final test report.

6. Point of contact at DTRC is Joe Mackes, Code 1250, AUTOVON 281-2261 or Commercial (301)267-2261.

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This report summarizes the results of a study directed toward determining the feasibility of applying laser technology to UNREP deicing, and infrared heating technology to UNREP anti-icing and deicing. The shipboard applicability of lasers for use as an UNREP deicing tool was determined to be technically feasible, with the laser system operating in either a melting mode or a shattering mode. Design approaches were developed for overcoming concerns related to the ability of the laser to remove ice without damaging the underlying painted surface, and the ability to use the system without risk of injury to the operator or to other members of the deicing team. The resulting design constraints have a significant impact on the applicability of the system, however. Based on a comparison with a high pressure water jet

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system, the laser system was determined to be economically unpractical. The water lance was estimated to have greater capability at a fraction of the cost without the operational and safety complications of the laser system. In the case of the infrared heating UNREP anti-icing and deicing system, the system continues to have promise, preferably when used in the anti-icing mode and primarily for retrofit applications, but possibly also for new construction. A prototype demonstration system was designed for the immediate work area of a surface combatant refueling station. Recommendations are made for shipboard applications tests and performance tests of the infrared anti-icing system.

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1. SUMMARY

The nation's Maritime Strategy requires that the U.S. Navy be prepared to operate its surface ships at northern latitudes with more frequent exposure to extreme conditions of low temperature and topside icing. The nature of these operations includes underway replenishment. The purpose of the first phase of this study was to conceptually identify solutions to low temperature and icing problems associated with northern latitude underway replenishment. Among the top priority candidate systems identified for countering UNREP cold weather and icing problems selected for possible further evaluation in the program were the use of a laser gun for deicing; the use of infrared heaters for anti-icing, deicing, and on-deck personnel heating; the use of sea calming oil, or storm oil, to moderate the local sea conditions and reduce the amount of topside spray; the use of electric contact heaters, or strip heaters, primarily for anti-icing, and secondarily for deicing; the use of flexible waterproof tarpaulin-type equipment covers for anti-icing; and the use of heat guns for deicing. Of these top priority systems, the laser and infrared systems were selected for further feasibility assessment in this second phase of the program. This report summarizes the work performed in the second phase of the program.

The objectives of this phase of the program were to evaluate the feasibility of applying laser technology to UNREP deicing, and to evaluate the feasibility of applying infrared heating technology to UNREP anti-icing and deicing. The intent of the program was to definitely establish the shipboard practicality or non-practicality of the two systems.

For both the laser and infrared systems, the general approach to assessing feasibility was to develop performance estimates of deicing and anti-icing, assess personnel and other safety hazards associated with the use of the equipment, and identify candidate applications for the systems If the systems continued to look promising for this application, prototype hardware would be selected, and a test outline developed for use in the further evaluation of the systems. Due to the significant differences in the level of development and application of laser technology and infrared heating technology, the feasibility assessment of the laser deicing system was anticipated to be more oriented toward an analytical approach based on engineering fundamentals, while the assessment of the infrared anti-icing and deicing system was anticipated to be more applications engineering oriented.

1.1 Laser Deicing

Lasers are generally classified into four groups, gas, solid-state, semiconductor, and liquid. Within each of these families there can be differences in the method of excitation, wavelength, output power, type of transition, and output pulse characteristics.

Four specific types of lasers were considered for possible use as an UNREP deicing system. In order of increasing wavelength from visible red to near infrared, these lasers are designated as helium-neon, ruby, neodymium-glass or neodymium-YAG, and carbon dioxide. The first and last are gas lasers, while the others are solid-state lasers. Semiconductor lasers were not considered to be appropriate candidates for the deicing application because of their low power output and wide beam divergence. Liquid lasers were judged inappropriate because they do not possess the mechanical durability, ease of operation, and ease of maintenance required for shipboard use. Of the four types investigated in some detail in this study, the helium-neon laser, which operates in the visible portion of the spectrum, does not produce enough output power to be useful in deicing. The ruby laser also operates in the visible spectrum, and can produce high output power levels. In recent years, however, ruby lasers have lost favor to neodymium lasers, which have a higher efficiency and a faster pulse repetition rate. This, combined with the fact that saline ice readily absorbs infrared radiation while reflecting a good portion of the radiation in the visible portion of the spectrum, leads to the conclusion that infrared lasers are better suited to the UNREP deicing task.

Both the neodymium and the carbon dioxide lasers operate in the infrared portion of the spectrum, and are readily available in a range of commercial power levels. Of these two laser types, the neodymium laser was selected for further consideration because fiber optic cables can be used as a beam delivery system with neodymium lasers while they cannot be used with carbon dioxide lasers, and because the greater durability of the neodymium laser over the carbon dioxide laser was considered to be of major importance in the shipboard application. The neodymium laser operating at a wavelength of 1.06 μm was therefore selected as the most appropriate laser for use in the UNREP deicing application. Relative to all of the laser systems available, neodymium lasers are durable lasers, require little maintenance, use simple fresh water cooling systems, require no cryogenic materials, are commercially available in a broad range of power levels including high power models used for the welding of metals, are compatible with fiber optic delivery systems, and produce infrared radiation which is readily absorbed by ice.

There are many safety issues associated with the shipboard application of lasers to deicing. These issues include the effect of laser radiation on the eyes, the effect of laser radiation on the skin, the danger of electrical shock, the danger of contact with cryogenic materials, noise, fire, and explosion. The most controversial hazard by far has been radiation damage to the eye, since even moderately high radiation intensities can result in irreversible ocular injuries. The federal government has grouped all lasers into four broad categories for safety purposes, depending on their radiation emission levels and the relative hazard to personal safety. The neodymium laser, and any laser of sufficient power to be useful in deicing, is in Class 4, the highest, or most potentially hazardous, class.

The best protection against laser radiation is the erection of shields and enclosures between the operator and the laser beam path. This form of protection has proven to be more effective than the use of protective eye goggles from the standpoint of eye safety because there is a common reluctance on the part of laser users to wear the protective goggles. In the case of the UNREP deicing situation, however, since the deicing laser, or the fiberoptic beam delivery system, is required to be portable, permanent shielding is not practical, and eye protection must be provided by protective eyewear. Such protective eyewear should be selected to afford the wearer with protection against the maximum anticipated exposure while still allowing the largest amount of visible light to enter the eye. The guidelines suggested for the maximum permissible exposure (MPE) for radiation entering the eye varies with the wavelength of the incident radiation, and its intensity and duration. Protective eyewear is available having the capability to attenuate the incoming laser radiation to the MPE level. Personnel safety considerations related to both eye protection and skin protection have a major impact on the design of a laser deicing system. The remaining hazards mentioned above can be minimized through proper selection of laser type for the application, and the establishment of an active laser safety and training program under the direction of a designated laser safety officer incorporating routine medical surveillance.

Two approaches were investigated for using lasers for shipboard deicing. One approach involves melting the ice with heat supplied with a high-power laser through a moderate intensity beam of light. The second approach is to use a focused high intensity beam from a low-power laser to produce mechanical chipping and shattering of the ice. This approach relies on the phenomenon of a normally transparent material becoming an absorbing material once the incident laser radiation increases above some threshold intensity. It is important to emphasize that in both cases the objective is not to melt or shatter all of the ice, rather the approach is to melt or cut grooves in the ice leaving slabs of ice of a few square feet in area that could then be pried off manually in the traditional manner. In application, therefore, the use of a laser deicing system would parallel the use of a steam lance or high pressure water lance deicing system which would also be used primarily to slot the ice such that the ice can then be removed from the surface in slabs.

The deicing by melting laser system postulated a typical high-powered neodymium laser similar to the types commercially available for manufacturing processes. The laser beam was sized to melt the ice as quickly as possible without causing damage to the underlying painted surface. The laser was estimated to be capable of melting a groove through glaze ice at a rate of about 1 cm^2/sec, so a 1 cm deep slot could be made with the laser beam scanning at a rate of 1 cm/sec (0.4 in/sec). For the deicing by shattering laser system, a much smaller powered neodymium laser can be used with focused intensities of light on the order of 10^8 to 10^9 W/cm^2 to produce fractures 0.1 to 2 cm long in the ice. Ice removal was projected to occur at a rate of 2 cm/sec for grooves up to 2 cm in depth, or a performance level of about twice the beam velocity of the melting laser system. At this point in the study, the deicing by shattering laser system looks most promising, however, neither the requirements for personnel safety nor the cost of such a system have as yet been considered.

Both of the neodymium lasers discussed above are classified as Class 4 lasers, presenting definite safety hazards for personnel. These lasers present a hazard not only from direct or specular reflections, but also from diffuse reflections. One approach to the selection of eye protection is to match the skin maximum permissible exposure (MPE), and the ocular MPE limit with eye protection. The next step is to determine safe working ranges, or the nominal hazard distance (NHD), for the laser operator and for people working in the vicinity of the laser. For the high powered deicing by melting laser, the output power intensity and the estimated reflected power intensity are well above the skin MPE limit. One possible approach for solving this problem is to introduce a large divergence to the laser beam through the placement of a convex lens as the exiting optics at the end of the fiber optic delivery tube. The operator then directs the laser beam exactly where needed with a hand held tube which contains the optics. This design feature, required for personnel safety, unfortunately eliminates the usefulness of the laser for anything other than melting ice in very close proximity. For example, an operator could not stand on the deck and lase the ice off of a remote boom. The laser beam has enough intensity at the exit of the hand held tube to melt ice at that point, but beyond that point the beam diverges rapidly in order to reduce the beam intensity for personnel safety. In the case of the deicing by shattering laser system, the severity of the problem is somewhat less, but a similar beam divergence system is also required for personnel safety. These considerations do not, however, totally eliminate the safety concerns associated with the use of laser deicing systems. Safety hazards remain even with the diverging beam systems, however, the hazard zone is defined, and should be controllable. In terms of defining the hazard zone, the NHD for people without eye protection is about 27 feet for the deicing by melting system, and 13.5 feet for the deicing by shattering system. With proper training, a laser deicing system is judged to be no more dangerous than an operating chain saw. It would also be required to install a deadman's switch on the hand held tube that would automatically shut down the beam if the operator were to slip and fall on the icy deck.

A search of manufacturers of lasers revealed the availability of a wide assortment of low powered lasers typically used for medical applications and in the manufacturing of electrical components, and a wide assortment of high powered lasers typically used in heavy manufacturing for cutting, welding, and drilling holes in metals. The selection of middle range lasers is relatively limited, apparently because of the limited number of applications for such systems. Three commercially available neodymium lasers potentially suitable for use in deicing by shattering systems were identified. Unfortunately, the purchase price of the lasers alone ranges from $42,000 to $67,500. A fiber optic coupling and a suitable length of fiber optic cable was estimated to add about $10,000 more to the cost of a system. The total cost of a laser deicing by shattering system was therefore estimated to be in the range of $60,000 to $70,000. In order to put this cost into some sort of perspective, the laser system was roughly compared with the performance and cost of a portable high pressure water jet system. Although a direct performance comparison was not possible, the conclusion was made that a deicing water jet is capable of removing much larger quantities of icing material because of its ability to direct the stream at the interface between the ice and the underlying surface, thus removing substantial sections of ice in slabs. In terms of cost, commercial units having the proper output pressure and capacity are available for about $5,000 to $10,000, with the more rugged units suitable for shipboard applications at the upper end of the price range. It was therefore concluded that a portable high pressure water lance would likely provide superior deicing performance, with far fewer safety and operational concerns, at about 10% to 20% of the cost of a laser deicing system. It was therefore recommended that no further assessment of the laser deicing system be undertaken.

This study of the use of lasers for removing accreted topside ice from shipboard UNREP stations therefore results in the following conclusions:

1. Lasers can be used as deicing tools to make grooves in accreted ice, such that slabs of the ice can be subsequently pried off the surface, either by melting slots in the ice or by shattering slots through the ice. Design limitations which significantly impact the performance of the system are imposed due to the requirement to remove ice without damaging the underlying painted steel or aluminum surface. This analysis indicates that the shattering mode offers the promise of higher performance levels than the melting mode.

2. Laser deicing systems can be engineered to minimize the risk of damage to personnel and objects through the incorporation of optics which provide a rapidly diverging beam, but, again, with some significant penalty in the applicability or usefulness of the system. Even with design features dedicated to the safety of the system, a significant training effort would be required to assure that the laser deicing system would be operated at an acceptable level of safety.

3. The cost of a laser deicing system, including a fiber optic cable beam delivery system, was estimated to be in the range of $60,000 to $70,000.

4. On the basis of a rough comparison with a high pressure water lance deicing system, it was estimated that the water lance system would deliver superior deicing performance with substantially fewer safety and operational concerns at about 10% to 20% of the cost of a laser deicing system. Some of the anticipated operational advantages of the laser system, such as the ability to remove accreted ice from booms, masts, and lines at great distances with the laser beam, had to be designed out of the system for safety reasons. Other advantages, such as the ability to remove ice without the use of steam or water which have the potential of adding to the icing problem, remain, but are of relatively minor importance in view of the cost and operational complications of the system.

5. It is therefore recommended that laser deicing systems be dropped from further consideration at the present time. If at some future time lasers are considered for use on ships for other purposes, such as for the removal of paint, their use for deicing should again be considered as a supplementary application.

1.2 Infrared Heating Anti-icing and Deicing

Heat is transferred by three different mechanisms, conduction, convection, and radiation. The uniqueness of radiation heat transfer is that heat is transferred directly from the source to the receiver without the necessity of heating some intermediate body or fluid, that is, the medium through which the heat flow takes place does not become heated. Infrared radiation, being part of the electromagnetic spectrum of radiation, is the same type of wave motion as are radio waves, x-rays, and light waves, differing only in the wavelength. Radiant energy is governed by the same laws of geometric optics as light in that it travels in straight lines, obeys the laws of reflection, suffers refraction, and may be polarized. Two of the key characteristics of infrared radiant heat transfer are that the energy provided by an infrared heater varies as the fourth power of the emitter temperature, and that the infrared energy diffuses as a function of the square of the distance as it travels outward from a point heat source. The result of such diffusion of the radiant energy is that the energy intensity or density varies inversely as the square of the distance from the point heat source.

For the purposes of evaluating the applicability of infrared heating to the anti-icing of shipboard UNREP stations, a rather severe but justifiable design condition was established of maintaining a deck and equipment surface temperature of 35°F in an ambient temperature of -20°F and a relative wind of 60 knots. The relative wind of 60 knots results from the worst case of combining a true wind of 40 knots and a ship speed of 20 knots into the wind. The objective of the heating system is to keep the deck and equipment warm enough so as to prevent the freezing of sea spray and atmospheric precipitation on the deck and equipment. In the anti-icing scenario, the system is energized throughout the icing event, thereby preventing the formation of ice. In the deicing scenario, the system is not energized until after the icing event, at which point the heating load can be the same as that associated with the anti-icing scenario, plus the additional load associated with both raising the temperature of the ice to the melting point, and melting the ice. The heating requirement for anti-icing is to provide a power density at the deck in the range of 150 to 200 Watts/ft^2, in the mixed units conventionally used in the industry. The deicing capabilities of such a system, for a zero heat loss case of all of the heat going into warming the ice to the melting point and melting the ice, with no heat lost to the cold wind, are to melt 3 inches of ice in about 4.6 hours and 5 inches of ice in about 7.6 hours. Such deicing rates, even with the substantial reduction that would be associated with a significant heat loss, appear reasonable. Because of the time required to deice, anti-icing would be the preferred operational approach, while deicing with the heaters remains a fairly practical alternative.

Infrared heaters can be oil-fired, gas-fired, or electrically powered. The 150 to 200 Watts/ft^2 power level required at the deck is quite high, and pushes the upper limits of the capacity of infrared heaters. In general, the output capacities of electrical units are greater than those of gas-fired and oil-fired units, therefore, the selection of heater type is directed toward electrical heaters on the basis of capacity alone. In addition, gas-fired units can be eliminated from consideration since propane is not allowed on Navy surface ships for safety reasons. In addition to having capacity limitations, oil-fired units would require the installation of a much more complex and costly fuel distribution system. For all practical purposes, the electrical capacity is generally available, and the distribution system is in place. Of the various types of electrical infrared heaters, the quartz tube type, consisting of a coiled tungston element housed in an inert gas filled and sealed quartz rod envelope is most appropriate for the anti-icing application. This type of infrared heater has the highest emitter temperature of 4050°F, the highest radiant efficiency, and excellent resistance to thermal shock, wind, and moisture.

A search for manufacturers of infrared heating equipment revealed that the manufacturers can be grouped into two categories, those serving process heating needs, such as print drying and curing coatings onto various substrates, and those serving space heating needs. In process heating applications, infrared heaters are generally used in very close proximity to the heated material, typically measured in inches. The reaction of process heating equipment manufacturers to the requirement for mounting the heaters some 8 to 50 feet away from the surface to be heated was generally one of panic. The greatest interest in this application was therefore shown by the space heating equipment manufacturers. The manufacturer displaying the most capability and demonstrating the most interest was Fostoria Industries.

Fostoria has had considerable experience in the application of infrared heaters to snow and ice control problems at building entrances and parking garage ramps in severe northern climates. These applications are as close as one can get to the shipboard anti-icing application. Shipboard anti-icing systems can then be designed on the basis of Fostoria's snow and ice control design guidelines, coupled with a consideration of the likely justification for the guidelines on the basis of a knowledge of the fundamental principles of radiant heat transfer.

Several concerns related to the safety of using infrared heaters for shipboard anti-icing and deicing were raised in the concept development phase of the study. Concerns of a radiation hazard to personnel were without justification. Concerns that the heating element might shatter when hit with cold sea spray were also found to be without justification. The quartz lamp heating elements can withstand being sprayed with ice water when operating at full capacity without shattering. Concerns related to the possible degradation of performance due to sea spray deposits on the heater and reflector were also rejected by the manufacturers on the basis that the deposits would melt or vaporize off. Concerns related to the corrosion resistance of the heater fixtures resulted in the recommendation that stainless steel fixtures be used. These are commonly used in swimming pool applications. Concerns related to the possibility of the overheating of personnel if personnel were working on deck while the heaters are energized can be handled by including a variable output SCR control system for the infrared heaters. The one major concern that could not be satisfactorily resolved is the concern of an explosion hazard due to the presence of fuel fumes in the atmosphere surrounding the envelope of the high temperature heating elements. The nearly unanimous informal opinion is that this should not be a problem in the open exposed deck application, however, because of liability concerns no one was willing to offer a formal opinion without thoroughly evaluating the situation. Before a prototype system is operated in the presence of fuel fumes, it is recommended that the system be submitted for a Preliminary Systems Safety Review by NAVSEA 55X21, the Ship Systems Safety Branch of the Damage Control and Safety Division of the Naval Sea Systems Command. A prototype system can, of course, be fully evaluated for anti-icing and deicing capability without such a review with the firm restriction that the system not be energized during refueling operations.

In terms of shipboard applications, it is generally agreed that the applicability of infrared anti-icing heating systems would primarily be to retrofit rather than new construction. This in no way lessens the level of interest in the system, however, since the first concern associated with expanded levels of northern latitude operations is to significantly improve the capabilities of the existing fleet. The more direct approach for anti-icing heating in the case of new construction would be to mount permanent contact heaters or strip heaters on the underside of the deck. Depending on the results of prototype testing, however, infrared anti-icing systems may be a stronger contender for use in new construction in competition with contact heaters than was initially apparent due to the fact that, even in the case of new construction, the installation costs of an infrared system could be substantially less, the weight could be substantially less, and the infrared system provides equipment and personnel heating which is not inherently provided by the contact heater system.

The scope of the UNREP icing countermeasure problem encompasses virtually every ship in the fleet. Representative shipboard applications of an infrared anti-icing heating system were reviewed, and one specific application selected for the design of a prototype system which can be field tested for further evaluation of the system. The application selected for prototyping is an exposed but sheltered deck area (that is, there is a deck overhead) in the immediate vicinity of a refueling station, taken to be a deck area of about 20 feet long by 5 feet wide. An infrared heating anti-icing system for this application was designed which will provide a power density at the deck of about 211 Watts/ft^2, essentially at the upper limit of the design condition of 200 Watts/ft^2. The system consists of six Fostoria stainless steel fixtures containing twelve quartz lamp elements rated at 3000 Watts each, mounted in red Vycor sleeves to reduce the intensity of illumination. The fixtures are attached to the 8 foot high overhead, and are fitted with stainless steel wire grid lamp guards. The heaters are controlled by an infinitely variable SCR controller. The catalogue price of the system is $13,100. The actual negotiated price of the hardware for a prototype system should be significantly less. It is recommended that the prototype system be purchased and installed on a ship scheduled for a northern latitude deployment. The system can then be further evaluated under field conditions, but should not be activated during fueling operations until a System Safety Review is completed. Recommendations are made in the report for tests intended to answer questions related to the shipboard applicability of the system, and for quantitative performance testing in the case where an icing event is experienced, and in the case in which no icing events are experienced.

This study of the use of infrared heaters for preventing the formation of topside ice at shipboard UNREP stations, and for removing accreted topside ice from shipboard UNREP stations, therefore results in the following conclusions:

1. Infrared heating systems can be used to provide both anti-icing and deicing capability at UNREP stations, with anti-icing being the preferred mode of application. The system is particularly applicable to retrofit situations where an anti-icing heating capability is required on existing ships. Depending on the results of the recommended prototype performance tests, infrared anti-icing systems could also compete favorably with, or be used in conjunction with, underdeck-mounted strip heater anti-icing systems in some applications on new construction. The major limitation in the application of infrared heating systems for

anti-icing is that they must be mounted in relatively close proximity to the surface being heated, making their application to large expanses of open deck difficult.

2. The heating capacity required to maintain the deck and equipment surfaces at an UNREP station at a temperature somewhat above the freezing point of sea spray and atmospheric precipitation under severe northern latitude conditions is quite high, requiring the use of infrared heaters which have the highest output capacity and the highest operating efficiency. For these reasons, the type of infrared heater selected for UNREP anti-icing is the electric quartz lamp type, fitted with red Vycor sleeves to reduce the otherwise very high levels of illumination provided by these heaters.

3. It is recommended that the infrared heating anti-icing system be demonstrated and further evaluated through the shipboard testing of a prototype system. The hardware for a prototype infrared anti-icing system sized for a roughly 20 foot by 5 foot immediate work area of a surface combatant refueling station has been selected. The catalogue price of the hardware, including an SCR controller which provides infinitely variable heater output capability, is $13,100. The negotiated price of a prototype system should be significantly less.

4. Completion of the shipboard applications tests and performance tests recommended for the prototype system will provide the additional information necessary for making a decision as to the fleet-wide applicability of infrared heater UNREP anti-icing systems.

2. INTRODUCTION

2.1 Background

On the basis of two 1983 Chief of Naval Operations Instructions, S3470.5a entitled "U.S. Navy Policy Regarding Arctic Polar Region" and S3470.6 entitled "U.S. Navy Arctic Warfare Program", the U.S. Navy is preparing to operate its surface ships in cold weather conditions at high latitudes on a routine basis in support of the nation's Maritime Strategy. In addressing these operating requirements, the U.S. Navy's David Taylor Research Center established a Northern Latitude Logistic Support Task under the Replenishment Project of the 6.2 Logistics Block, which is funded by the Office of Naval Technology. The purpose of the task is to develop a technology base to enhance the operability and sustainability of Navy and merchant support ships in the resupply of our combat forces with fuel, ordnance, and cargo when operating under extreme northern latitude environmental conditions. The areas of concern are Underway Replenishment (UNREP) and Logistics Over-the-Shore (LOTS) operations. The major environmental threats associated with high latitude operations are cold weather, or low air temperature and low sea water temperature, topside icing, floating ice, and heavy seas. Icing and low temperature problems associated with UNREP operations have been identified as critical problems, and have been selected as the focus for the current efforts.

By way of further background, the U.S. Navy defines UNREP as a transfer of liquid and/or solid cargo between two ships while underway. This underway logistic support of a fleet unit allows the unit to operate at sea for prolonged periods of time. Two methods of transfer between the ships are employed, horizontal transfer via connected replenishment rigs (CONREP), and vertical transfer, or vertical replenishment (VERTREP), via helicopter. It is further stated that the goal of an UNREP is the safe delivery of the maximum amount of cargo in the minimum amount of time. An UNREP should be accomplished in such a manner that it does not interfere with the primary mission of the support force.

In the first phase of this program, completed in July 1988 [1], the effort was directed towards the conceptual identification of solutions to icing and low temperature problems associated with northern latitude underway replenishment. In that study it was determined that all of the work related to countering the shipboard topside icing problem performed thus far indicates that no universal solution to the problem exists, rather a combination of approaches and techniques will be required to obtain a satisfactory level of response. Several recently completed studies identified what might be termed conventional approaches for countering shipboard topside icing. The intent of the first phase of the program was to use this prior work on conventional approaches as a starting point for broadening the treatment of the conventional approaches themselves, for expanding the range of possible approaches considered through the identification of potential unconventional solutions, and for expanding the range of possible approaches still further through the identification and order-of-magnitude assessment of potential high-tech solutions. The categories of conventional, unconventional, and high-tech were broadly conceptual in nature, and not at all rigidly defined for the purposes of this study. A systematic brainstorming approach was used in an effort to identify as many potential approaches for response as possible. The final assessment of the most promising approaches was based upon a consideration of all three categories of response. While the emphasis of the study was on anti-icing and deicing approaches, some consideration was also given to protective work stations, UNREP-specific personal gear, and deck traction.

Upon the completion of the brainstorming sessions, an initial assessment and screening process was completed, the preferred systems were identified in terms of specific type of application as related to UNREP operations, and the systems were ranked in order of preference. The results, incorporating both the conclusions of the study and the recommendations for further work, are presented in Table 1. As indicated in the table, the approaches listed as conventional were judged suitable for immediate application. The approaches listed as unconventional were recommended for further engineering evaluation. The level of evaluation generally envisioned for the unconventional approaches was of an applications engineering nature without the need for additional research. The approaches listed under the classification of high-tech were generally anticipated to require a more research and development oriented process of further engineering development and feasibility evaluation. The infrared heaters were judged to be somewhat of an exception to this, possibly only requiring the applications engineering approach, since they represent well established technology currently employed in somewhat similar applications.

As shown in the table, among the top priority candidate systems identified for countering UNREP cold weather and icing problems selected for further evaluation in the program are the use of a laser gun for deicing; the use of infrared heaters for anti-icing, deicing, and personnel heating; the use of sea calming oil, or storm oil, to moderate the local sea conditions and reduce the amount of topside spray; the use of electric contact heaters primarily for anti-icing, and secondarily for deicing; the use of flexible waterproof tarpaulin-type equipment covers for anti-icing; and the use of heat guns for deicing. Of these top priority systems, the laser and infrared systems were selected for further feasibility assessment in the second phase of the program. This report summarizes the work performed in the second phase of the program.

Table 1
Preferred Systems for Countering
UNREP Low Temperature & Icing Problems

SYSTEM	APPLICATION
Anti-Icing Approaches	
Conventional - For Immediate Application	
Electric Contact Heaters	Hatches, doors, panel covers, freeing ports, deck work areas, enclosed machinery
Waterproof Covers	Deck machinery, limit switches, control panels
Low Friction Paints	Bulkheads, kingposts, M-frames, ram tensioners; particularly inaccessible areas
Water Flooding	Deck work areas, but not during operations
Unconventional - For Further Engineering Evaluation	
Bow Flare, Greater Freeboard, Solid Bulwarks, & Side Flare	New construction - general spray control
Sea Calming Oil	General spray control
Lead Ship Sea Moderation	General spray control - operational procedure
Mechanical Sail	Mostly new construction - general spray control
Portable Physical Barriers	Work station shielding
Air Curtain	Local work station shielding
Heated Deck Mat	Work station deck area
Warm Air Ventilation Exhaust	Shielded work station area
Spray Collection Streamers	General 'tween-ship spray control, on phone/distance line
High-Tech - For Further Development & Feasibility Evaluation	
Infrared Heaters	Work station area, machinery, personnel; not spray heating

NOTE: Recommended systems are listed in prioritized order for each category (Conventional, Unconventional, High-Tech).

Table 1 (Continued)
Preferred Systems for Countering
UNREP Low Temperature & Icing Problems

SYSTEM	APPLICATION
Deicing Approaches	
Conventional - For Immediate Application	
Mechanical Removal Devices (baseball bats, ax handles, pry bars, etc.)	General application
Portable Heat Guns	Spot application
Water Lance	General application
Steam Lance	General application
Contact Heaters	General application, but better applied to anti-icing
Water Flooding	Deck work areas, but not during operations
Unconventional - For Further Engineering Evaluation	
Pneumatic Pulse	Work station decks and bulkheads, equipment housings
Heated Deck Mat	Work station deck areas, but better applied to anti-icing
Whip Sander/Needle Gun	Very localized hand work
Electro-Expulsive Boot	Inaccessible areas
High-Tech - For Further Development & Feasibility Evaluation	
Two-phase Chemical Pellet	Deck work areas, very low storage/material requirement
Laser Gun	Inaccessible areas, masts and stays, connecting lines, decks
Infrared Heaters	Work station area and machinery, but secondary to anti-icing
Ultrasonics	Accessible surfaces and equipment
Panel Vibrator	Work station deck areas
Highline Vibrator	Highline

2.2 Objectives

The objectives of this task are to evaluate the feasibility of applying laser technology to UNREP deicing, and to evaluate the feasibility of applying infrared heating technology to UNREP anti-icing and deicing. The intent of the program is to definitely establish the shipboard practicality or non-practicality of the two systems.

2.3 Scope

For both the laser and the infrared systems, the general approach to assessing feasibility was to develop performance estimates of deicing and anti-icing, assess personnel and other safety hazards associated with the use of the equipment, identify candidate applications for the systems, and if the system continued to look promising, select prototype hardware for testing, and, finally, to outline a test plan for use in further evaluation of the system. Due to the significant differences in the level of development and application of laser technology and infrared heating technology, the feasibility assessment of the laser deicing system was anticipated to be more oriented toward an analytical approach based on engineering fundamentals, while the assessment of the infrared heating anti-icing and deicing system was anticipated to be more applications engineering oriented. For example, in the case of the laser deicing system, the assessment of the suitability of the various types of lasers for the deicing application, and the development of laser deicing performance estimates for different distances, deicing rates, and energy levels could only be based on the use of fundamental scientific and engineering analysis. In the case of the infrared heating anti-icing and deicing system, the estimates of heating requirements, infrared heating system performance, and modifications to standard infrared heating systems for exposed shipboard applications were of a more straightforward applications engineering nature. It was further anticipated that if both systems continued to be viewed as having promise at the end of this study, the next step in the evaluation process would likely be the conduct of laboratory feasibility tests for verification of the performance projections in the case of the laser deicing system, and shipboard field trials of a prototype installation in the case of the infrared anti-icing and deicing system. Further developmental work was therefore anticipated in the case of the laser deicing system, while it was expected that the infrared anti-icing and deicing system would be transitioned out of the research phase and into applications assessments.

The next section of this report addresses the optical properties of sea ice in general terms, since this information applies to both the laser and the infrared heating portions of the study. Following this, the work performed in the study related to the laser system is presented. This work starts with a practical summary of laser technology, addresses the safety concerns associated with laser deicing, summarizes the limited experience reported on the use of lasers in ice, presents estimates of the performance of a laser deicing system, addresses applications issues, discusses hardware selection considerations, and presents conclusions related to the use of lasers for shipboard deicing. Suggestions are also given relative to any future testing of lasers for this application.

The infrared anti-icing and deicing evaluation is then addressed, also starting with a practical summary of the relevant technology. Following this, experience in the use of infrared heating for anti-icing and deicing is discussed, performance estimates are developed, and safety concerns are investigated. An applications analysis is then presented, followed by the selection of hardware for a prototype shipboard system, and an outline of field testing considerations. The conclusions and recommendations of the study are then summarized in the final section of the report.

3. OPTICAL PROPERTIES OF SEA ICE

The application of either lasers or infrared heaters to the problem of removing, or stopping the formation of, icing material on a ship at sea through heating is really a radiation heat transfer problem. As such, the capability of ice to absorb light and other forms of electromagnetic radiation is a key element in determining the feasibility of any radiation based deicing/anti-icing method. High-power laser radiation has also been found to cause damage to normally transparent materials, and to ice, but much of the physical processes involved have yet to be understood. Little is known directly about the optical properties of ice formed during a topside icing event, but in the vast majority of cases (89%), the icing material comes from ship generated ocean spray [2]. Minor sources of shipboard icing include fresh water spray, fog, rain, drizzle, and snow. Therefore, the optical properties of topside spray ice should be somewhat similar to those of young sea ice. Since the type of ice formed during a topside icing event varies with wind velocity, temperature, sea state, etc., and can appear as a clear, hard, homogeneous glaze, or a white, opaque, granular, soft rime [2, 3], the optical properties can also be expected to vary. This section outlines what is known about the optical properties of sea ice, with particular emphasis on the visible and near-infrared regions of the spectrum.*

When radiation of a particular wavelength (e.g. light) is incident upon a material which is perfectly transparent at that wavelength, the radiation is split into two components; a reflected portion and transmitted portion [4]. Since the material is transparent, none of the radiant energy is absorbed into the material, and the reflectance, r, plus the transmittance, t, totals 100%. If a material is opaque, on the other hand, very little, if any, of the incident radiation can pass through, and the radiation is either reflected or absorbed. The non-reflected portion of the radiation intensity, or irradiance, is exponentially attenuated with depth into the material, and for a homogeneous material can be described by

$$I(\lambda,z) = (1 - r(\lambda))\cdot I_0(\lambda)\cdot \exp(-a(\lambda)\cdot z) \qquad (1)$$

where I_0 is the initial radiation intensity (W/m^2 or similar dimensions), z is the depth, and a is the absorption or attenuation coefficient. Quantities which are functions of the wavelength are indicated by λ.

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* Approximate limits for this portion of the electromagnetic spectrum are:

Visible Light	400 nm	-	780 nm
Near Infrared	780 nm	-	10 µm
Far Infrared	10 µm	-	1 mm

This explains why even opaque materials such as metals can become partially transparent if thin enough (mirrored sunglasses, for instance). The amount of radiation absorbed into the material, and converted into heat, is equal to the incident radiation intensity minus the reflected and transmitted intensities.

Equation 1 emphasizes the wavelength dependance of the absorption coefficient. In fact, the values associated with the reflection, transmission, and absorption coefficients are all wavelength dependent and vary from material to material. In translucent materials, such as the earth's atmosphere or ice, a fourth parameter is needed to describe the eventual distribution of incident radiation. This is the scattering coefficient, s, and when present, Equation 1 is modified as follows:

$$I(\lambda,z) = (1 - r(\lambda))\cdot I_0(\lambda)\cdot \exp(-[a(\lambda)+s(\lambda)]\cdot z) \qquad (2)$$

Figure 1 shows a schematic representation for all four processes occurring in a homogeneous layer. If the optical properties vary with depth, the material can be divided into a number of layers, and a series of equations like (1) or (2) applied to each layer.

Measurements of the electro-optical properties of ice, particularly sea ice, only began in earnest during the 1970's. It quickly became apparent that the absorption coefficient of ice versus wavelength could not be inferred from similar graphs for bulk water. In addition, the absorption coefficient was found to be heavily dependent upon salinity as small amounts of salt were introduced into the ice [5, 6]. Some of the most extensive early investigations involving sea ice were carried out by Grenfell and co-workers [7, 8, 9] with the reported results being primarily in the visible light spectrum. Detailed results are reported by Grenfell and Perovich [10] for the absorption coefficient in bubble free pure polycrystalline ice between wavelengths of 400 nm to 1400 nm which covers the visible and near-infrared spectrum. This type of fresh water ice contained no bubbles and was filtered to remove dust so that scattering was only possible at boundaries between ice crystal grains. The absorption coefficients were calculated assuming a purely absorbing media.

The latest work by Perovich and Grenfell [11], and Grenfell [12] returns to sea ice with the development of a theoretical model describing optical properties over the visible and near-infrared range, and compares the predicted results to measured data. The model takes into account physical properties of the ice such as ice thickness, density, growth rate, and warming and cooling, and considers ice below its eutectic point (about -21°C for NaCl). Vapor bubble and brine inclusions are related to the physical properties, since these tend to be the prime internal scatterers in the visible light spectrum and give sea ice its white opaque appearance.

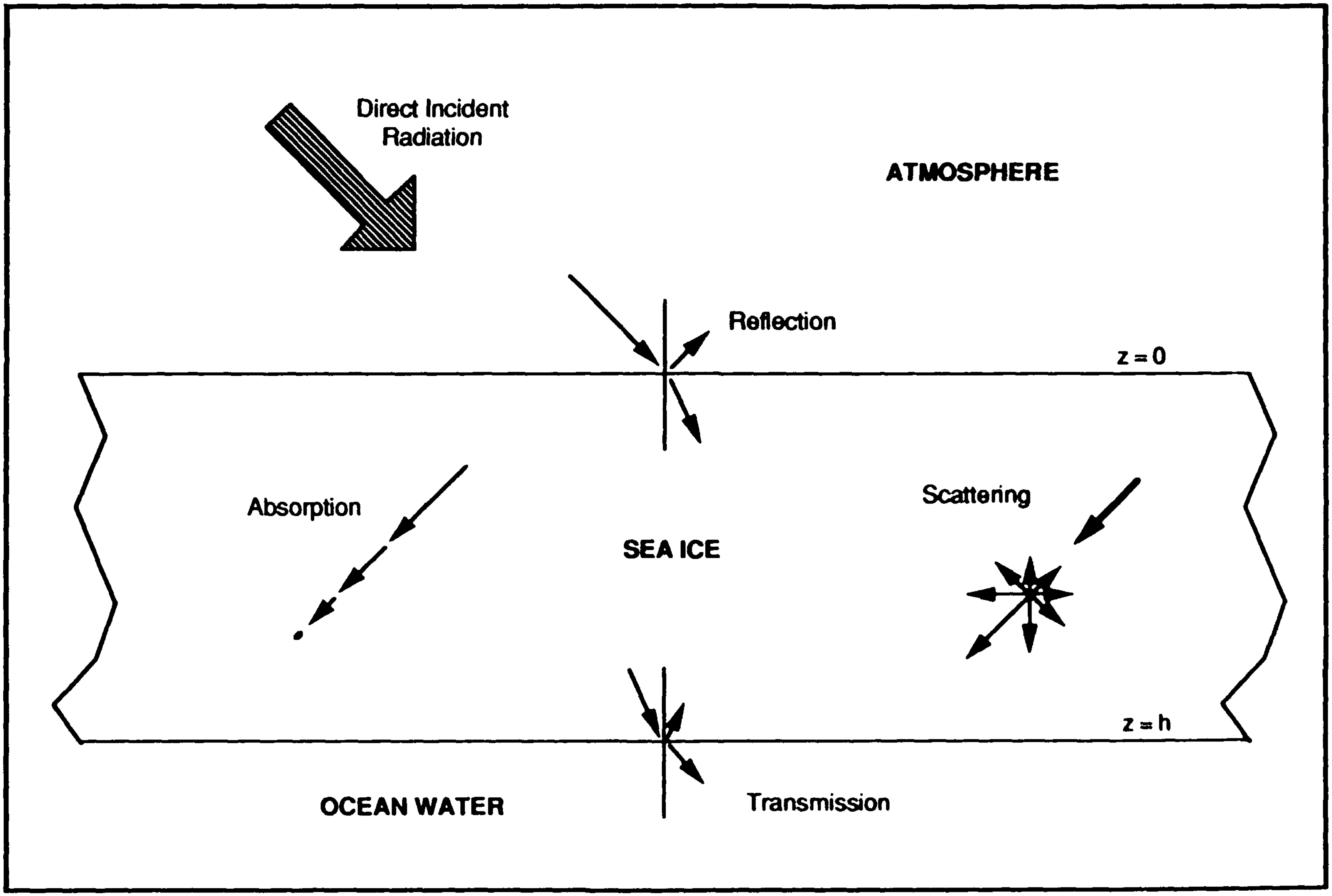


Figure 1 - Radiative Transfer Mechanisms Occurring in a Layer of Sea Ice

Grenfell [12] points out that the model is limited to a single homogeneous layer of ice, thus the amount of measured data available for comparison was severely reduced. The comparisons appear to be in good agreement, however, and the constraint for a single homogeneous layer does not affect application of the results to topside icing glaze ice or rime.

Most of the investigations of the optical properties of sea ice are concerned with solar radiation striking floating ice sheets, and hence, the ratio of the amount of reflected electromagnetic radiation from a body to the amount of incident radiation is referred to as its albedo instead of reflectance. The total or bulk albedo is related to the albedos for each wavelength through

$$\alpha_{bulk} = \int \alpha(\lambda)\cdot I_0(\lambda)\, d\lambda / \int I_0(\lambda)\, d\lambda \qquad (3)$$

where the integration is over all wavelengths. Therefore, for the case of monochromatic light from a laser, the bulk albedo is equal to the spectral albedo at the laser's particular wavelength.

Because of the difficulty in separating the effects of absorption and scattering in ice, the absorption and scattering coefficients are usually combined into an "extinction" coefficient, κ. The bulk extinction coefficient at any depth into the ice is determined in a manner similar to the bulk albedo:

$$\kappa_{bulk}(z) = \int \kappa(\lambda)\cdot I(\lambda,z)\, d\lambda / \int I(\lambda,z)\, d\lambda \qquad (4)$$

where the intensity remaining at any given depth is

$$I(\lambda,z) = (1 - \alpha(\lambda))\cdot I_0(\lambda)\cdot \exp(-\kappa(\lambda)\cdot z) \qquad (5)$$

Finally, the ratio of the amount of electromagnetic radiation emerging from the bottom of the layer of ice to the amount of incident radiation, or transmittance, is computed from

$$\tau(\lambda,h) = I(\lambda,h)/I_0(\lambda)$$

$$\tau(\lambda,h) = (1 - \alpha(\lambda))\cdot \exp(-\kappa(\lambda)\cdot h) \qquad (6)$$

where h is the thickness of the ice sheet.

The following set of three figures shows some of the results for sea ice from Grenfell [12]. Figure 2a gives the albedo versus ice thickness for young sea ice. The only changes in albedo occur in the visible light range, and show the transition from a gray-black surface for thin ice to a gray-white highly reflective surface characteristic of thicker ice. There is no change in albedo in the infrared range with the amount of radiation reflected being less than 10%. At the same time, the extinction coefficient (Figure 2b) increases dramatically with wavelength. Grenfell points out that in the visible range, K is about two orders of magnitude greater than that for pure ice or water, but there is almost no change in the infrared portion of the spectrum. This is because scattering from vapor bubble and brine inclusions dominates over absorption for visible light. The characteristic size associated with the scattering inclusions is appropriate for causing diffraction and interference patterns with wavelengths in the visible spectrum. However, the longer wavelengths of the infrared radiation undergo less interference from the inclusions. Hence, absorption dominates over scattering in the infrared.

Figures 3a & 3b show the effect of ice density on the albedo and extinction coefficients. Again, the only real changes with density occur in the visible light range. As the density of the ice decreases, more and more vapor bubbles are trapped in the ice causing greater scattering. Notice that at 470 nm, the albedo doubles as the density is decreased giving a "whiter" appearance to the ice. With reference to the types of ice found during icing, glaze ice has a density of around 0.7 to 0.9 gm/cm^3, and hard rime from 0.1 to 0.6 gm/cm^3 [2]. Soft rime ranges from 0.01 to 0.08 gm/cm^3, but this type of ice is delicate in structure and only loosely bonded. Thus, the optical properties of hard glaze ice should be comparable to the denser "bubble-free" sea ice, while hard rime can be expected to have an albedo of about 90% at 470 nm as indicated by the trend with density in Figure 3a. If only radiation in the infrared region is considered, density has very little effect on albedo and extinction.

Finally, Figures 4a & 4b show the variation of optical properties with the growth rate of bubble free sea ice. Growth rate affects the number of brine inclusions trapped in the structure of the ice, and faster ice growth results in a greater number of brine pockets. These brine pockets act as scattering inclusions in the visible portion of the spectrum, and Figure 4a shows an increase in albedo over this range as expected. Again, there is no appreciable affect from growth rate on the optical properties in the infrared.

The results presented so far for the optical properties of sea ice combine the absorption coefficient and the scattering coefficient into one parameter called the extinction coefficient ($K = a + s$). Only the absorption coefficient can be used to quantify the amount of the incident irradiance that is retained in the ice and converted to thermal energy. Few attempts have been made to measure the portion of the extinction coefficient attributable to absorption as a function of wavelength. A new experimental technique has recently been reported (1987) [13], but the complete results and their application to ice physics has yet to be published. None the less, it is well know that scattering is the predominant extinction mechanism in the visible light spectrum, while absorption dominates in the infrared.

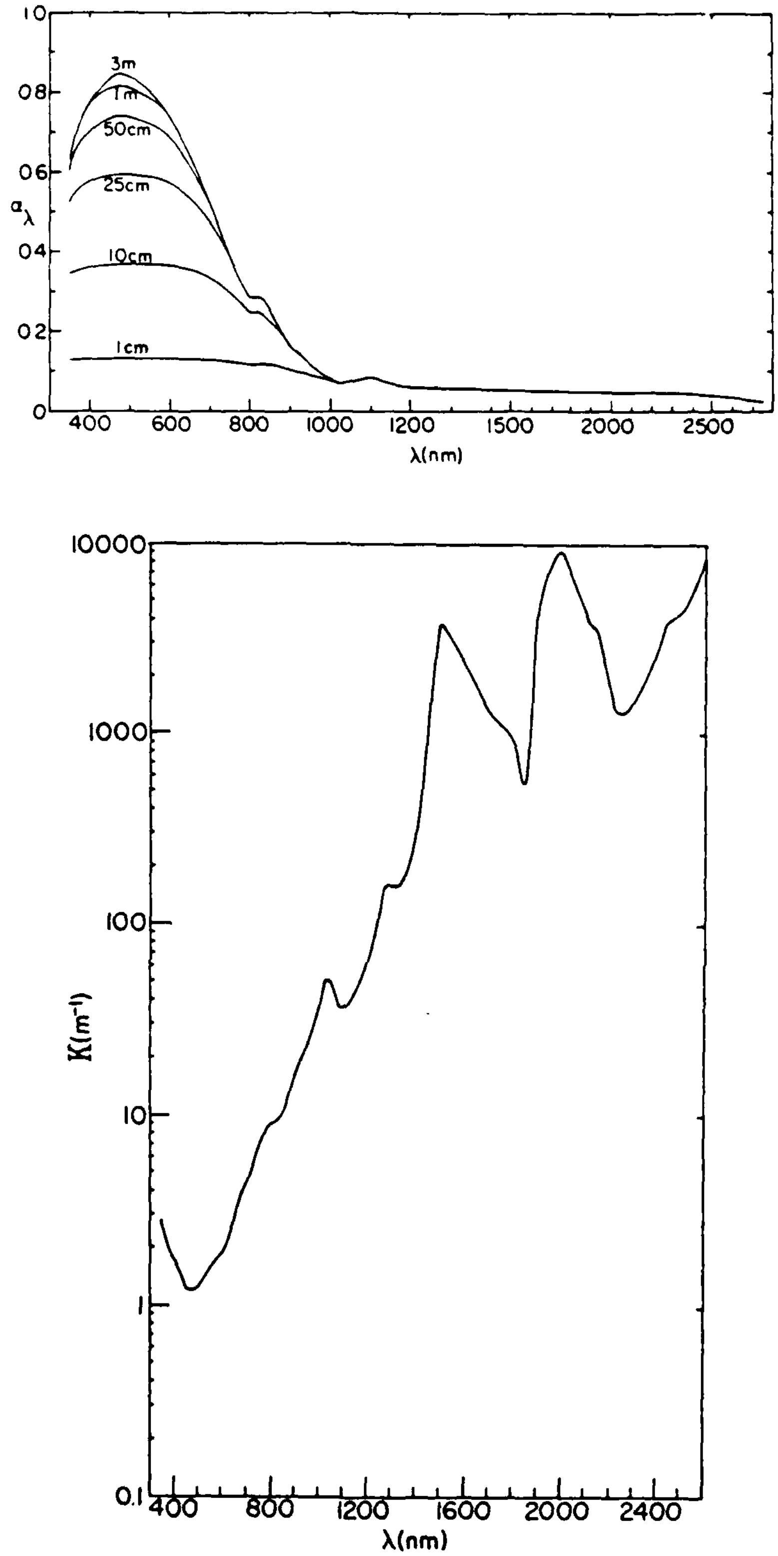


Figure 2 - (a) Spectral albedos versus ice thickness for young sea ice. Salinity = 11 ppt., Vgr = 8 × 10^{-5} cm/sec, T = -2.8°C, ρ = 0.88 gm/cm^3; $\alpha(\lambda)$ is plotted versus wavelength (λ) in nanometers. **(b)** Asymptotic extinction coefficient versus wavelength for young sea ice. Ice parameters are the same as for Figure 2a. [12]

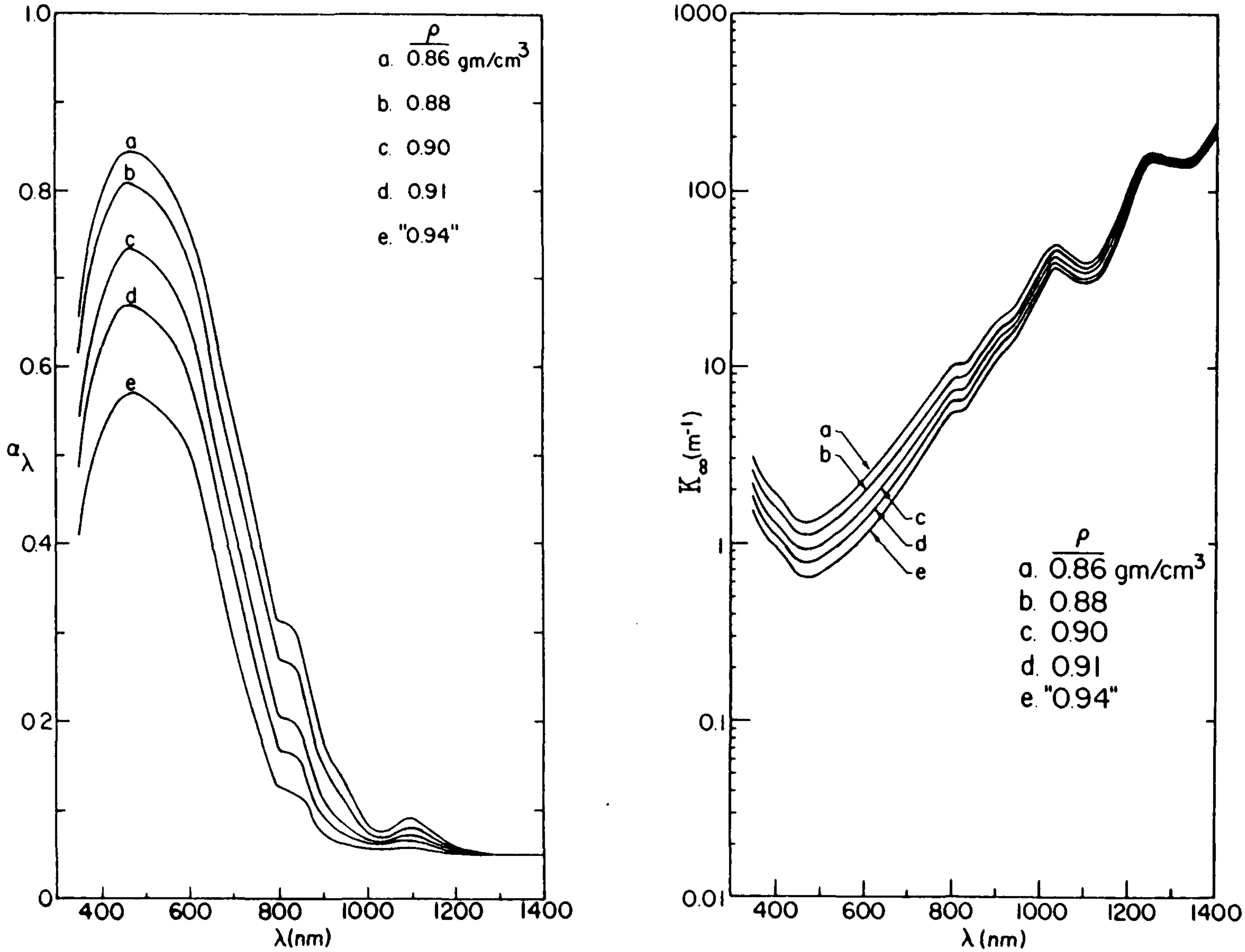


Figure 3 - **(a)** Density dependence of spectral albedo, from bubble-free ice ($\rho = 0.94$) to $\rho = 0.86$ gm/cm^3. Other ice parameters are the same as for Figure 2a. **(b)** Density dependence of asymptotic extinction coefficient, from bubble-free ice ($\rho = 0.94$) to $\rho = 0.86$ gm/cm^3. Other ice parameters are the same as for Figure 2a. [12]

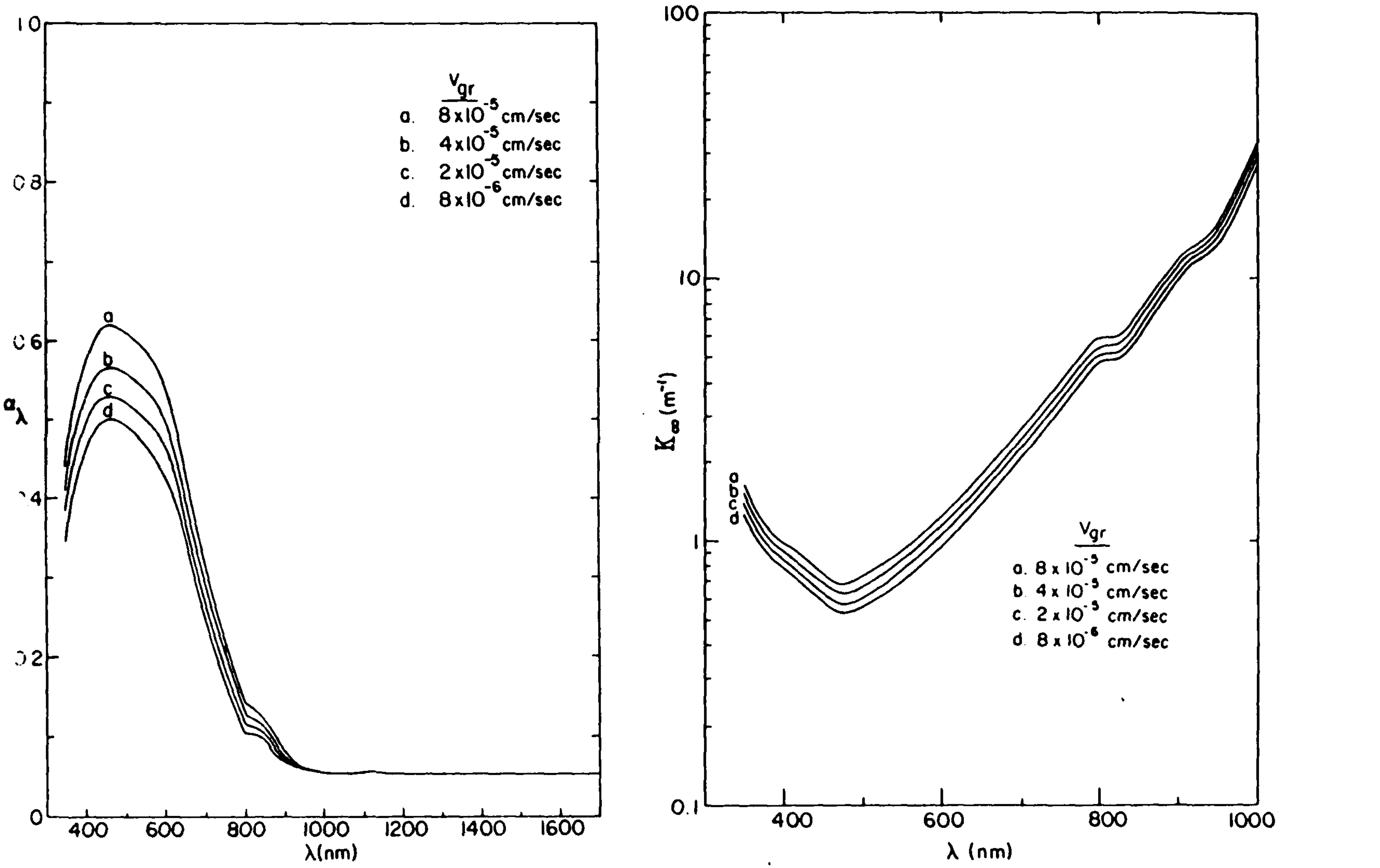


Figure 4 - (a) Dependence of spectral albedo on growth rate in cm/sec. Other ice parameters are the same as for Figure 2a. **(b)** Dependence of asymptotic extinction coefficient on growth rate. Other ice parameters are the same as for Figure 2a. The wavel(b) th range is restricted from 400 to 1000 nm. [12]

4. LASER UNREP DEICING

4.1 Practical Summary of Laser Technology

A wide variety of different devices can be called lasers, but they all use some physical process to produce "light amplification by the stimulated emission of radiation." This section will review some of the processes and terminology common to all lasers, and give a brief description of the general types of lasers. This is followed by a more detailed discussion of several specific types of lasers (He-Ne, Ruby, Neodymium, & CO_2) that merit consideration as candidates for future shipboard deicing equipment. No attempt will be made here to give more than just the highlights since detailed descriptions are readily available elsewhere. While much has been written about lasers, the books tend to fall into two camps; those which are introductions to lasers and really too simple to be of any technical use, and those devoted to the theory of quantum electronics (laser physics). Two excellent sources intended to bridge this gap and provide technical, practical information for scientists and engineers who are non-laser specialists are given as References 14 and 15.

4.1.1 General Types and Characteristics of Lasers

Lasers are quantum mechanical devices that use the discrete nature of energy and its interaction with matter to produce high-intensity, non-divergent beams of coherent, monochromatic electromagnetic radiation. (If you understand that last sentence, please skip on to the next section.) Basically, to comprehend the operation of a laser only a rudimentary understanding of the interaction between light and matter is necessary. Laser specialists tend to use the term "light" to include ultraviolet and infrared electromagnetic radiation as well as visible light. Photons of light contain a specific amount of energy which is easily related to the frequency of the light. The relationship is

$$E = h \cdot \nu \tag{7}$$

where E is the energy associated with the photon, h is Planck's constant, and ν is the frequency of the light. Thus, beams made up of photons of different energies will appear to have different wavelengths.

The atoms, molecules, or ions which make up the active laser material, on the other hand, contain definite, descrete energy levels. There are several ways this energy can be stored, but it is customary to describe the process in terms of a simple atom. The electrons bounded to the atom have well defined accessible energy levels, and an electron changing from a higher to a lower energy state emits the extra energy in the form of a photon. This is described by

$$E_2 - E_1 = h \cdot \nu_{21} \qquad (8)$$

Likewise, if a photon contains just enough energy to move an electron from a lower to a higher energy state, it can be absorbed upon striking the atom.

Lasers use three basic types of transitions between energy levels. The movements of electrons within an atom or molecule are classified as electronic transitions. The energies associated with this transition, as normally used in lasers, give light with wavelengths in the ultraviolet, visible, and near-infrared. Other wavelengths are possible, but these are less favorable for laser action. The second type of transition possible is vibrational. Atoms within a molecule can vibrate in several different degrees of freedom. These modes are quantized giving discrete energy levels, and a change from one state to another involves absorbing or emitting light in the infrared range. Finally, quantized rotational energy levels are possible with the rotation of a molecule yielding light in the far-infrared.

Photons can be given off from an atom or molecule through either stimulated or spontaneous emission. When a species (atoms or molecules) is in an excited state, it will naturally decay into a lower energy state and give off energy in the form of photons. This is called spontaneous emission and the natural decay time is a small fraction of a second. Stimulated emission, on the other hand, occurs when a photon of the right energy level interacts with an already excited atom or molecule. The photon can not be absorbed and a second photon of the same energy is released. In addition, the photons are in phase, and therefore coherent. If enough of the species are in the excited energy state, and a few photons are available to cause stimulated emission, then more photons are released which cause more stimulated emission and more photons. The resulting "cascade" of photons forms a coherent monochromatic light.

Laser action relies on a cascade of photons through stimulated emission. There must be a greater number of photons produced than are absorbed into the active laser species. This means there must be a larger population of excited atoms or molecules compared to the lower energy level population in order for a net gain in photons to take place. This situation seldom occurs in nature, since spontaneous emission tends to return a species to the lowest energy state possible. Lasers use some external means of excitation to produce and maintain an excited population, such as absorption of photons from other light sources, collisions between electrons and the active medium, or chemical reactions. In addition, species with relatively long spontaneous decay times make better laser materials, since a greater population inversion is possible.

Once the generation of laser light is possible through stimulated emission, it has to be amplified and directed. This is frequently achieved in a resonant cavity that generates a collimated beam. Simple cavities are made from two mirrors positioned at opposite sides of the laser material. Spontaneous emission generates a few photons, most of which are lost out the sides of the cavity. Some, however, strike the mirror at one end and are reflected back through the laser material generating more photons through stimulated emission. The oscillation continues and the number of coherent monochromatic photons increases with each pass through the cavity as long as a population inversion is maintained. Various mechanisms are used to release the beam of light, such as using a partially transparent mirror at one end which allows a known percentage of the light to escape.

Lasers can be operated in several different modes, with the most common being continuous operation, pulsed operation, and Q-switching. Continuous laser light can be produced if the excitation process can sustain a net population inversion sufficient for the active medium to lase through stimulated emission. In many cases continuous operation is not possible because a population inversion cannot be maintained above the laser threshold, the high power needed for excitation has to be collected and discharged intermittently, or heat build-up changes the emission characteristics of the active medium or can cause damage to the laser itself. In these situations, a pulsed operation is used. Usually the pulse repetition rate can be selected within operational limits, and this affects the energy delivered per pulse and the peak power of the pulse. The average power of a laser operated in the pulsed mode is the energy delivered in one pulse divided by the cycle time. Q-switching is a means of producing short, intense bursts of laser light. The term "Q factor" is used to describe the energy gain or loss of the system, and Q-switching modifies the gain in a laser cavity. Initially, some energy is allowed to escape, keeping the laser medium below the threshold of laser oscillation and building up energy in the form of a higher than normal population inversion. Then the energy loss is removed (high Q), and stimulated emission occurs, producing a high intensity beam. Q-switching relies on the ability of the active medium to store energy in its excited state which requires a relatively long spontaneous emission lifetime. Therefore, Q-switching is not possible with all lasers.

The classification of lasers into various categories proves to be a useful means of describing how specific families of lasers operate. Generally, four groups are used: gas, solid-state, semiconductor, and liquid lasers. Within each of these families there can be differences in the method of excitation, wavelength, output power, type of transition, and output pulse characteristics.

Gas Lasers: Gas lasers are many and varied, and are relatively easy to produce. All that is needed is a sealed tube containing the gas, mirrors at each end of the tube to contain the laser oscillation, and some means to excite the gas into higher energy states. Gas laser developers have the flexibility to alter the proportions and pressure of the gas mixture with ease to find the optimum operating condition for their apparatus. (This is much easier than determining the best crystal structure to be used in a solid-state laser.) Gas lasers really have to be subdivided into the types of excitation used. The most common is electrical discharge excitation. An electric current is passed through the active medium, and the electrons transfer energy to the gas during collisions. In some cases, an electron-beam particle accelerator is used to fire high energy electrons into the gas. This transfers energy quite quickly, but the apparatus is expensive and bulky. Ion beams can also be used to excite the gas, but this equipment is even more cumbersome. Optical pumping has been used with gases that are strongly state-selective with closely spaced energy levels. This method allows different laser wavelengths to be selected, but the overall efficiency is very low.

One very special type of gas laser is the chemical laser. Since chemical reactions can produce large amounts of energy, extreme high power laser action is possible. A chemical laser uses the reaction energy to produce a population of inverted, excited species to generate the lasing action. One popular reaction involves hydrogen and fluorine to produce HF molecules in vibrationally excited states. Most chemical lasers produce species which lase from transitions from infrared vibrational states of diatomic molecules. One experimental chemical laser for the military is reported to produce continuous powers of a couple hundred kilowatts [14]. Chemical lasers rely on high volume gas flow through the optical cavity to produce light while the reaction is in progress. Needless to say, large amounts of cryogenic material are consumed with the process. A variation on the chemical laser is the gas-dynamic laser. These use the expansion of hot, high pressure gas into a vacuum to achieve a population inversion in an excited species. Like the chemical laser, rapid gas flow is essential since the population inversion only lasts until equilibrium is achieved.

Solid-state Lasers: Solid-state lasers use a crystalline or glass host material to hold impurities of about 1 percent. The material is usually excited optically for an external light source to produce a population inversion in the impurity. The rod is typically mounted between two mirrors to provide the optical feedback needed for laser action. One major advantage over most gas lasers for the generation of high-power laser light is the much higher density of excited laser species possible within the solid host lattice. Solid-state lasers are versatile devices which can emit light in either a pulsed or continuous mode, and are generally more durable than gas lasers. As used in the laser world, the term solid-state does not include the semiconductor lasers.

Semiconductor Lasers: These lasers, also called semiconductor diode lasers, emit light throughout the infrared portion of the spectrum, and sometimes just into the visible red. This type of laser is very similar to regular p-n junction diodes where free electrons and "holes" move in opposite directions across the junction. When the current flow ceases, the electrons and holes recombine, and energy is released. Most of the energy is in the form of heat, but in semiconductor lasers, light is emitted. (Light emitting diodes, LED's, are related devices, but emit incoherent light.) The active layer in a semiconductor diode laser has polished, reflective sides to provide laser oscillation and stimulated emission. Power output can range up to about 10 milliwatts in continuous or pulsed mode. In addition to the low output power, semiconductor lasers have the disadvantage of large beam divergence which can be as much as 40°. The primary use for these lasers has been with "information handling" by providing the coupling to fiber-optic communication networks, and has recently expanded with the growth in popularity of compact-disc players.

Liquid Lasers: The only laser which fits in this category is the tunable dye laser. This laser has found many applications in scientific research because of its flexibility. A dye can be selected which produces light over a continuum of specific wavelengths. The typical wavelengths can be from the near-ultraviolet to the near-infrared, but different dyes have to be used in different ranges. The dye is a fluorescent organic compound which is dissolved in a liquid solvent (usually not water) and excited by intense lighting from another laser or a flashlamp. Because of the complexity of the dye molecules, they can absorb and emit light over a range of wavelengths using a wide collection of electronic, vibrational, and rotational energy states. Adjustable, and sometimes elaborate, optics are used to select the desired wavelength. Another complexity is the dye itself. This is the major consumable in dye lasers, and is susceptible to thermal and photochemical degradation. However, some dyes are capable of long lifetimes.

4.1.2 Description of Potential Lasers for Deicing Systems

Four specific types of lasers were considered for possible use with high-technology deicing systems. They are, in order of increasing wavelength from visible red to the near-infrared: Helium-Neon (He-Ne, 632.8 nm), Ruby (694.3 nm), Neodymium Glass or Neodymium-YAG (1.06 μm), and Carbon Dioxide (CO_2, 10.6 μm). The He-Ne laser typically has very low output power, but was included here because it is one of the most common lasers, and could be used in conjunction with an infrared laser as a means of visualizing and aiming the invisible infrared beam. The other lasers are commercially available, and are in common use in manufacturing and material processing. Semiconductor lasers were not considered for deicing applications because of their low power output and large beam divergence. In addition, the tunable dye laser, and other lasers designed primarily for scientific research or laser development, were not considered appropriate candidates for deicing systems. Generally speaking, these lasers would not possess the mechanical durability, ease of operation, and ease of maintenance required for shipboard use.

4.1.2.a He-Ne Laser

This is the most common and inexpensive laser around. It is frequently used in classrooms and for laboratory demonstrations, and can be found scanning packages at supermarket check-out counters. He-Ne can be made to lase in the infrared part of the spectrum, and quite recently, a weak green line is possible, but the most common wavelength is at 632.8 nm in red visible light. Since this is a gas laser, the density of the population inversion is much less than that possible for lasers with a solid active medium (about 10^{21} He atoms/m^3 compared to approximately 6-10^{25} Nd atoms/m^3 in a Nd:YAG laser). As a consequence, higher power He-Ne lasers of several meters in length are rare. The typical output power for He-Ne lasers operating at 632.8 nm is a continuous beam from a few tenths of a milliwatt to 60 mW. Output at other wavelengths is less.

The active medium of helium and neon gases in the cavity is a mixture with about five times more helium than neon. The excitation of the gas is carried out by an electric current with the anode and cathode at opposite ends of the tube shaped glass cavity container. Only a few milliamperes are required to pass through the gas in order to maintain a continuous beam, but an initial voltage of around 10 kV is needed to start laser operation. The electric current produces collisions between the electrons and the helium and neon atoms. The energy transfer which occurs during the collision raises the atoms to an excited state with most of the collisions taking place with the more numerous helium atoms.

Figure 5 shows the energy levels of both atoms. It can be seen that the helium 2^1S and 2^3S atomic states are quite close to the energy levels of the neon atom's 3S and 2S states. Collisions now take place between the excited helium atoms and the neon atoms. While the energy levels between the two is not exact, most of the energy transfer yields excited neon atoms with kinetic energy accounting for the energy difference. The figure indicates the various paths by which the neon atom returns to the ground state, and the wavelengths that are important laser transitions. The optics and operating conditions of the tube dictate the wavelength of the light emitted.

The continuous output laser beam can be modulated electronically up to 1 MHz. The lasers are generally not operated in the pulsed mode. The beam diameter is usually around 1 mm, and tends to increase with increased power levels. Beam divergence is about 1 milliradian (mrad) and decreases with larger beam diameters.

Most He-Ne lasers operate off of 110 Volt house current, with 220 V being an option. The overall efficiency is quite low, being in the range of 0.01 to 0.1 percent. Operating temperatures can be from -20°C to +50°C. The rated operating lifetime is typically from 10,000 to 20,000 hours with a shelf life of 10 years.

Nearly all He-Ne laser tubes are completely sealed so that the amount of gas escaping is almost nil, and contamination from water vapor is insignificant. Therefore, no consumables are usually considered as a part of He-Ne operation. They are largely maintenance free, and can be manufactured with a high degree of durability. In general, a complete laser can be anywhere from a foot to about a yard in length, and weigh less than ten pounds.

Mass-produced He-Ne lasers cost from $100 for the lowest powers, up to about $2,000 for lasers with powers over 10 mW. At 50 mW, the price can be over $10,000.

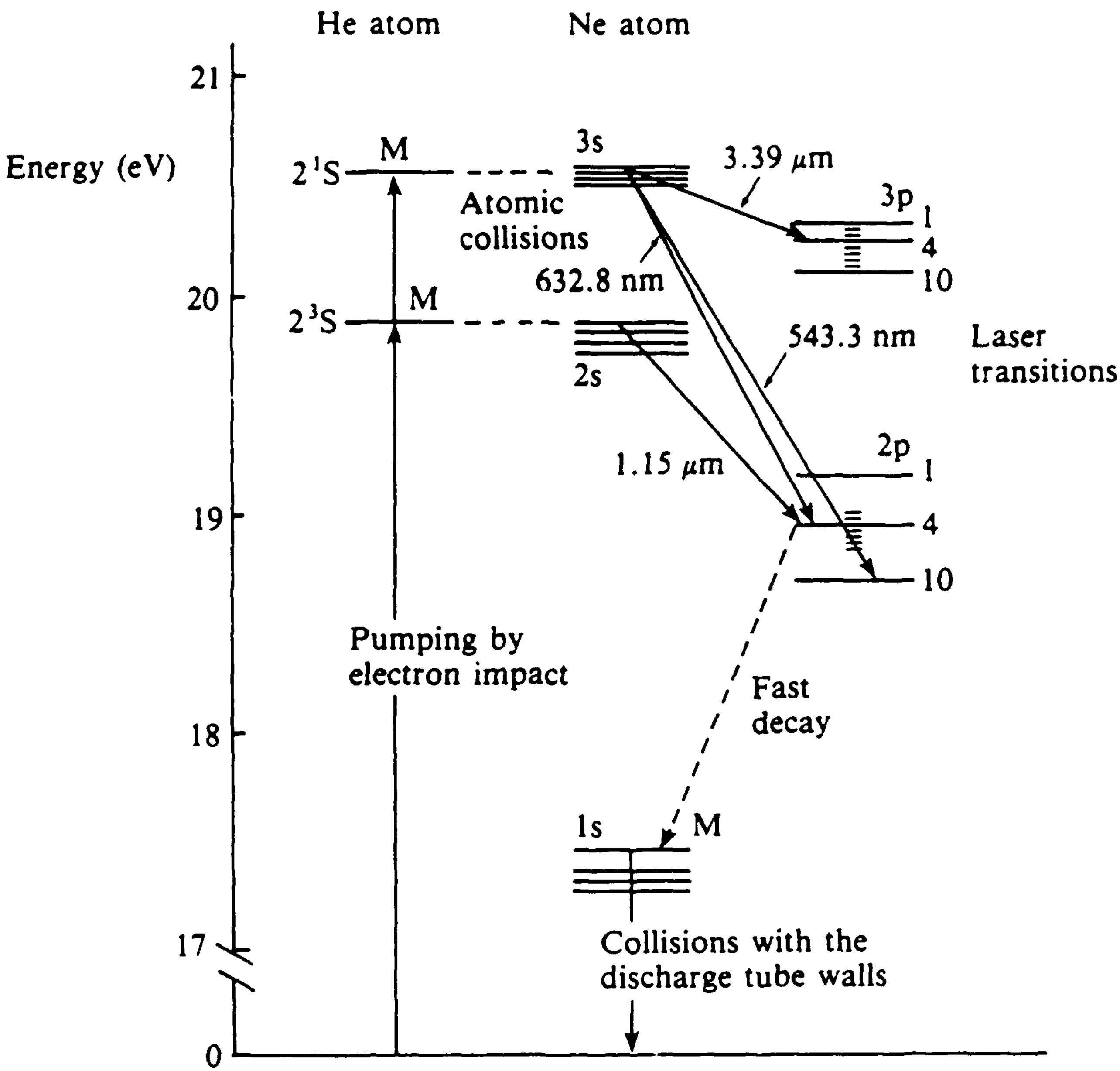


Figure 5 - Energy levels relevant to the operation of the He-Ne laser. M indicates a metastable state. [15]

4.1.2.b Ruby Laser

Ruby lasers were the first true lasers developed. They were also the first lasers to be used in materials processing, but have been largely replaced by other lasers, particularly Neodymium and CO_2. They are classified with the solid-state lasers. The active medium is a synthetically grown sapphire crystal which has been doped with a small quantity of chromium; the ruby rod. As the crystal is grown from aluminum oxide (Al_2O_3), chromium (Cr) is added, and since chromium and aluminum have the same number of valence electrons, the aluminum can be replaced by the chromium at some points in the crystal. The weight concentration of chromium is only about 0.01 to 0.5 percent, which is around 10^{19} atoms per cubic centimeter. This is what gives the rod its pink or red color. The output beam is in the deep red with a wavelength of 694.3 nm.

Ruby rods typically range from an eighth of an inch to one inch in diameter, and up to about 8 inches in length. The usual laser cavity has a mirror at one end and a partially reflective mirror at the opposite end. The light passing through the second mirror is the laser output. The chromium atoms (actually Cr^{3+} ions) in the ruby crystal are the source of the laser light. They are excited by flash pumping; large bursts of incoherent light directed on the ruby rod in order to transfer photon energy to the Cr. Figure 6 shows several types of arrangements for coupling the flash lamp to the rod. There are two cavities in this type of system: the laser cavity consisting of the rod itself, and the pump cavity surrounding the rod. The elliptical cavities shown in the figure are more efficient because most of the pump light can be focused upon the ruby rod. If cooling of the laser is necessary, pure water flows through the pump cavity. One disadvantage of ruby lasers is that the light at the laser wavelength is strongly absorbed in the unpumped section of the rod. Thus the whole rod must be illuminated as much as possible. Figure 7 shows the energy states for the chromium ions. Pump light with wavelengths of around 400 nm or 550 nm raises the energy in the atoms to the $^4T_1$ or $^4T_2$ level. Chromium rapidly decays in about 100 nanoseconds to the ^2E levels. These energy levels are fairly stable with a spontaneous emission lifetime of around 3 milliseconds. The long lifetime allows a population inversion in preparation for stimulated emission. The lower energy 694.3 nm transition dominates.

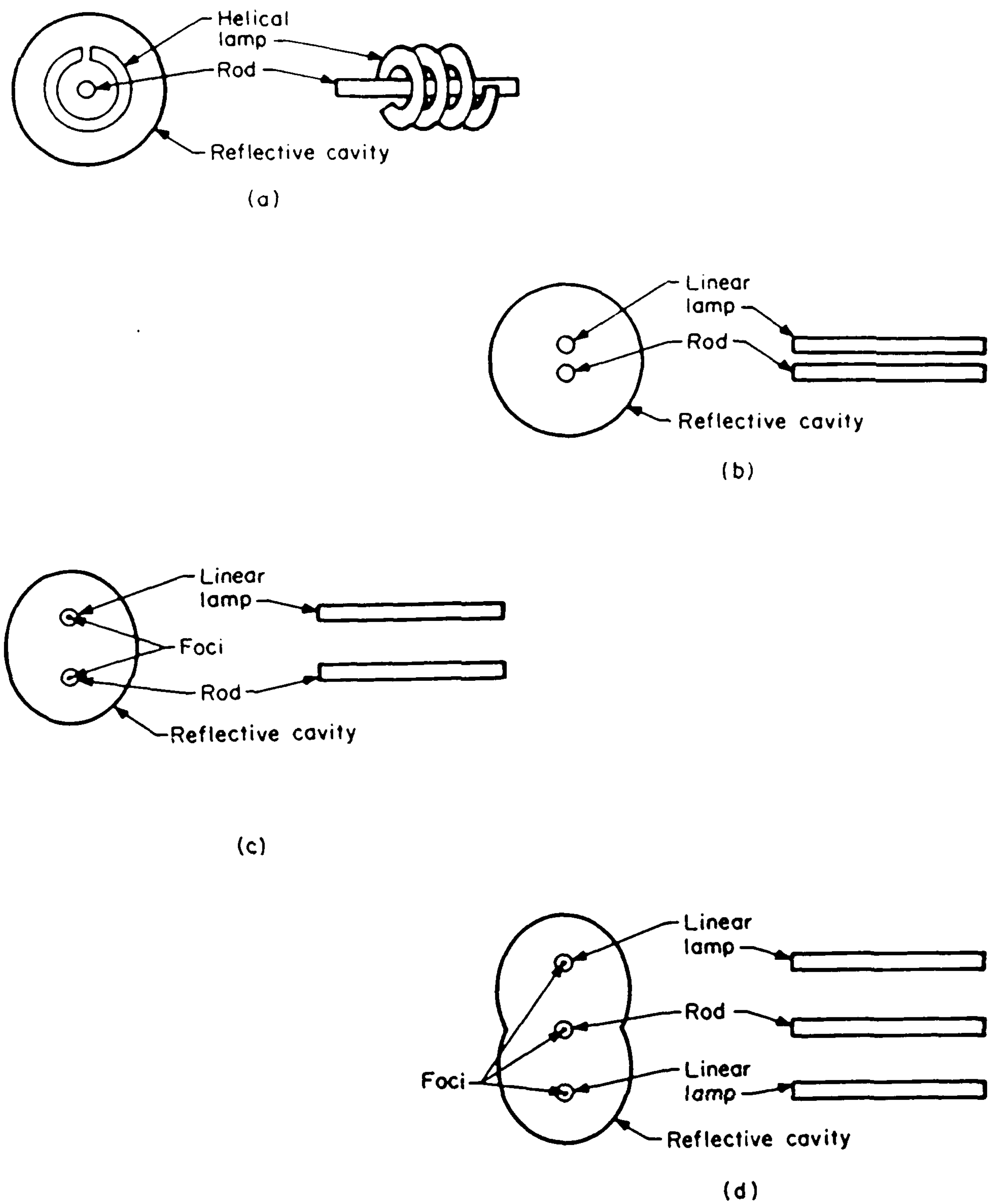


Figure 6 - Representative pump cavity configurations. (a) Helical lamp, (b) closely coupled lamp, (c) elliptical cavity, (d) dual elliptical cavity. [14]

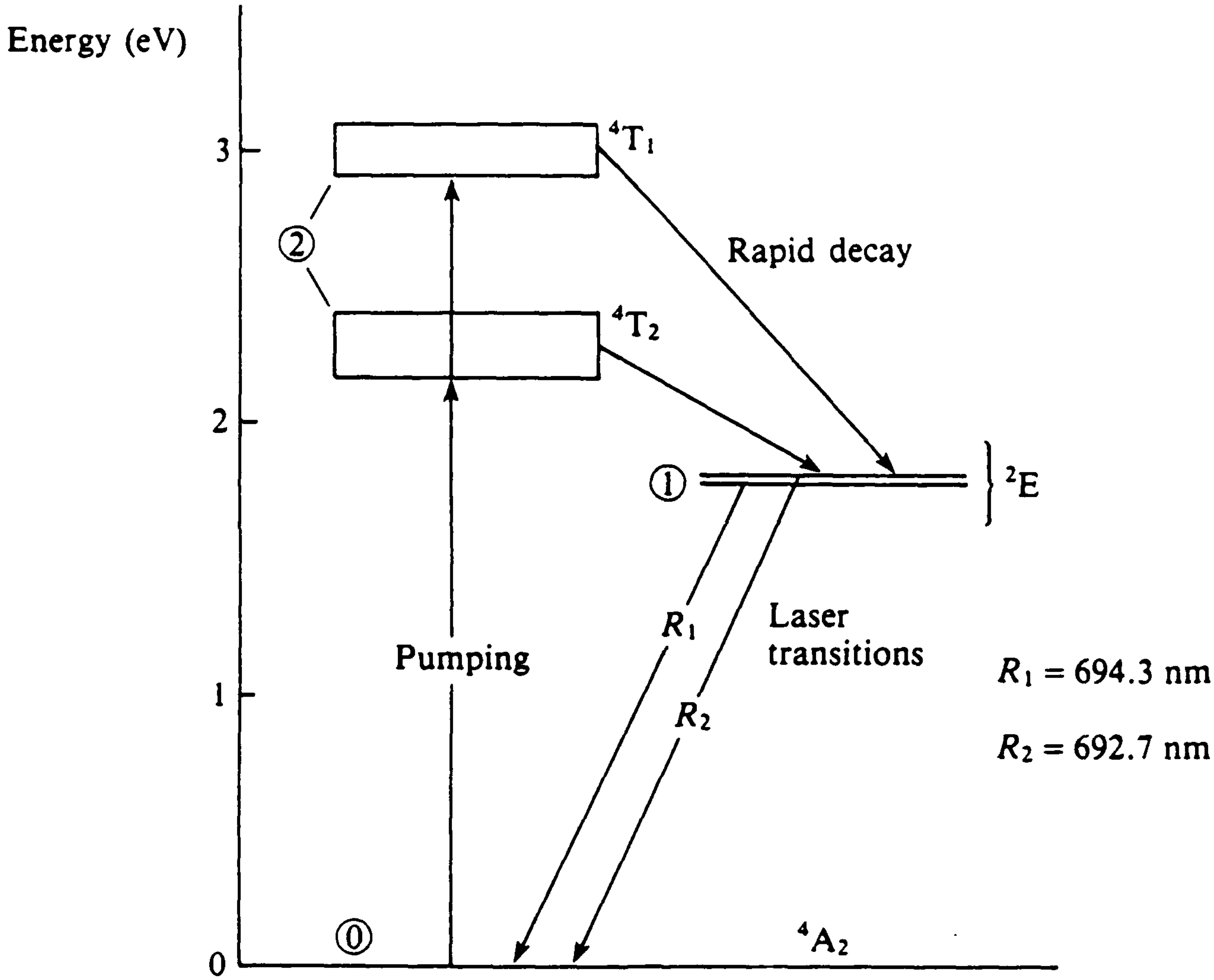


Figure 7 - The three-level system of the ruby laser. Pumping is due to the Cr^{3+} ions absorbing blue (excitation to $^4T_1$ levels) and green (excitation to $^4T_2$ levels) light. The wavelengths of the R_1 and R_2 laser lines are temperature dependent; the values given are typical. [15]

All commercial ruby lasers are pulsed because of high flash lamp pumping power requirements, but a wide variation of output characteristics exists. With a pulse length of a millisecond, output energy per pulse ranges from 50 to 100 J. The average power is low because of a low pulse repetition rate of only a few Hertz. A maximum average power of 100 W is possible, but careful water cooling is required. Ruby lasers can be operated in a Q-switched mode. This limits the pulse energy and decreases average power, but can raise the peak energy per shot to the 100 MW range. In general, the beam diameter for ruby lasers can range from 1 to 25 mm, with divergences from 0.25 to 7 mrad.

Most Ruby lasers operate off of 110 Volt house current, but some use 220 V-ac. The overall efficiency is quite low, being in the range of 0.1 to 1 percent. Some form of active cooling is required for ruby lasers. This is usually accomplished by flowing deionized water over the laser rod and flashlamp. Flashlamps must be replaced after about 1 million shots, but because the pulse repetition rate is low, this can be a long time. High power lasers require a high degree of cleanliness, since dust and other contaminates on the surface of the rod or optical components can cause damage in the form of pitting to the surface. In some cases, lenses are considered to be consumable for this reason. Other consumables include water filters and deionizer cartridges for closed-cycle lasers.

Ruby lasers are generally reliable when given the proper care. Most of the damage to high power models stems from a lack of cleanliness. With time, some realignment may be necessary between the flash cavity and laser rod. Also, silvered mirror coatings inside of flash cavities need occasional polishing to maintain peak efficiency. Even though ruby rods are fairly short, high power lasers sometimes use several rods to amplify the light in stages. The laser head can be from 3 to 7 feet long, and the power supply and controls are typically contained in a console 4 to 5 feet high.

Commercial lasers cost from $14,000 up to about $200,000 for the most specialized models. In many situations, such as military range finders, ruby lasers are being replaced with Nd:YAG lasers because of their higher efficiency and faster repetition rate.

4.1.2.c Neodymium Laser

Neodymium lasers are very similar to Ruby lasers in that they are both solid-state lasers. In fact, some manufacturers produce combination Ruby/Neodymium lasers where the active medium, crystal rod can be swapped out of the same optical cavity with only slight modifications to the resonator optics. Neodymium lasers are the most common member of the family of solid-state lasers with many diverse applications in both scientific research and industrial materials processing. Their output can be in the continuous mode up to about 100 mW, or in the pulsed mode of many megawatts. The wavelength of Neodymium lasers is in the near-infrared at around 1.06 µm.

The active medium for these lasers consists of tripled ionized neodymium atoms imbedded at impurity-level concentrations, about 1% by weight, in a crystalline or glass material. This amounts to approximately 10^{20} atoms per cubic centimeter. The most common host material by far is yttrium aluminum garnet (YAG) which has the chemical formula $Y_3Al_5O_{12}$. The crystal growth of this material is quite difficult, and Nd:YAG rods have a maximum length of about 10 cm, with a diameter of around 6 to 9 mm. Nd:YAG rods have the most desirable optical, mechanical, and thermal properties found to date. Other materials include yttrium lithium fluoride (YLF), and yttrium aluminate with the chemical make up $YAlO_3$ (hence referred to as YALO). Collectively, neodymium lasers made from materials other than YAG are called Nd-glass lasers. They are usually fabricated more easily and cheaply, and can receive higher concentrations of impurities. However, their lower thermal conductivity precludes continuous mode operations and lowers the pulse repetition rate for pulsed mode models. Glass rods can be up to 1 meter in length, with a diameter of several centimeters.

Neodymium lasers are excited by flash pumping or a continuous light source, and use the same optical cavities as ruby lasers (see Figure 6). Figure 8 shows a simplified energy level diagram for Nd^{3+} ions. While the excitation lamp source will tend to emit light over a range of wavelengths, the neodymium ions absorb the energy best at wavelengths of around 0.7 to 0.8 µm. Once excited, the ions undergo a quick nonradiative decay to the metastable $^4F_{3/2}$ level where there is a population inversion between this and lower energy states. Then stimulated emission can take place producing the laser light. Because of size limitations inherent in Nd:YAG rods and the natural decay lifetimes associated with the energy levels, the amount of energy that can be stored in the rod at any one time is limited to around 500 millijoules. This limitation is overcome by arranging a series of rods in an "oscillator-amplifier" configuration. The first rod is the regular laser oscillator (active medium with mirrors at each end). The pulsed beam from the oscillator is directed into a second optical cavity, called an amplifier, which contains another Nd:YAG rod flashpumped into an excited state with the necessary population inversion.

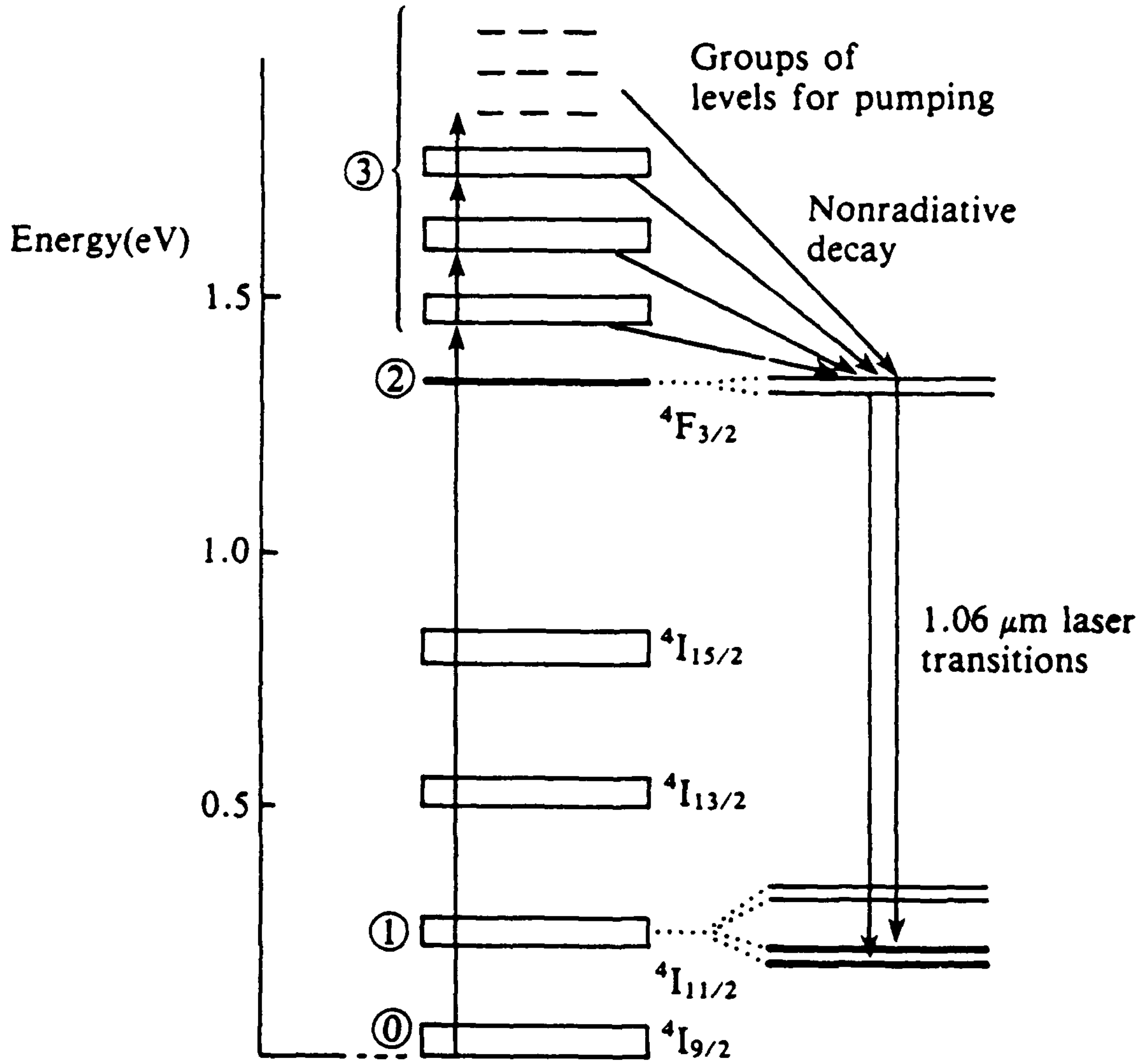


Figure 8 - Simplified energy-level diagram for the neodymium ion in YAG showing the principal laser transitions. Laser emission also results from transitions between the $^4F_{3/2}$ levels and the $^4I_{15/2}$ and $^4I_{13/2}$ levels, but at only one tenth of the intensity of the transitions shown. [15]

There are no resonator mirrors at the ends of the second cavity except to keep the light from being reflected backwards along its path. The laser beam causes stimulated emission in the second cavity resulting in a combined, amplified beam of light. Several of these amplifiers can be linked together in the higher power neodymium lasers.

Neodymium lasers are very adaptable with many accessories available to alter the output beam. Q-switched neodymium lasers are quite common for increasing the peak pulse power. Non-linear crystals are also used to change the output wavelength through harmonic generation. Coherent light passing through one or more of these crystals has its frequency increased by an integer amount, resulting in fractional reductions in the fundamental wavelength. The second, third, and fourth harmonics correspond to wavelengths of 0.532, 0.335, and 0.226 μm in the visible and ultraviolet portions of the spectrum. Output power is greatly reduced by this process, however.

The nominal wavelength for neodymium lasers is 1.06 μm, but this can vary depending on the type of host material, weak energy transitions near the main transition line, and harmonic generation. The actual wavelength for the main line in Nd:YAG is 1.064 μm. Higher power lasers usually cannot be operated in the continuous mode. Beam diameter for Nd:YAG models is usually 1 to 10 mm. Glass lasers typically have larger diameters because of their larger cross-section rod size. Beam divergence is a fraction of a milliradian (mrad) to about 10 mrad.

Input power can come from regular single-phase 110 V-ac for small neodymium lasers, and up to 220 V three-phase for high power models. The overall efficiency is similar to Ruby lasers, and is in the range of 0.1 to 1 percent. Low power, portable neodymium lasers can operate with only conductive cooling (or resort to low pulse repetition rates), but for larger lasers, tap water is used for cooling. A typical, low power 1 W laser uses about a gallon of tap water per minute, while a 400 W laser needs approximately 15 gallons per minute. The lifetime of neodymium lasers can be a decade or more, with some components replaced as a part of a regular maintenance schedule. Generally, the pump lamp needs replacement most frequently, and has a lifetime of a few hundred hours of operation for continuous output lamps, or every tens of millions of shots for a flashlamp.

As with ruby lasers, neodymium lasers are generally reliable when given the proper care. Most of the damage to high power models stems from a lack of cleanliness. Dirt on exposed optical surfaces can cause excess radiation absorption resulting in damage. Periodically, some realignment may be necessary between the flash cavity and laser rod. Also, silvered mirror coatings inside of flash cavities need occasional polishing to maintain peak efficiency. For small lasers, the entire unit can weigh about 6 pounds, but for high power varieties, the laser head is separate from the power supply and controls. In some cases, the laser head can be the size of a desktop, while the power supply and cooling system fills a room.

Low power neodymium lasers can cost as little as $3000, but prices increase quickly with output power, accessories, and performance requirements. A typical high power laser for materials processing would cost about $200,000.

4.1.2.d CO_2 Laser

Carbon Dioxide lasers are very versatile gas lasers much in use for materials processing. The radiation emitted can range from 9 to 11 μm as a tunable line chosen by the user, but the strongest wavelengths occur at 9.6 and 10.6 μm. These lasers also have a wide range of continuous or pulsed output power levels from 1 W up to many kilowatts.

The lasing transitions of the CO_2 laser come from energy levels associated with the quantization of the vibrational and rotational energy of the CO_2 molecule. As with the He-Ne laser, other gases are present with the CO_2 active medium, usually nitrogen and helium. The nitrogen molecules help excite the CO_2 molecules to an asymmetric stretching mode in the same way that helium atoms transfer energy to neon atoms through collisions in He-Ne lasers. The high energy CO_2 molecules have two main decay paths. A transition from the asymmetric stretching mode to the bending mode produces a 9.6 μm photon, while transition to the symmetric stretching mode yields a 10.6 μm photon. Changes in the molecules' rotational states around these two transitions give rise to families of laser lines. If helium gas is present with the CO_2, its purpose is to bring CO_2 molecules from the lower energy states after lasing back to the ground state in order to maintain a population inversion. Figure 9 shows a simplified energy level diagram for carbon dioxide laser operation.

CO_2 lasers come in several different configurations with slightly different methods for exciting the CO_2 gas molecules. The first is the "sealed-tube" configuration which is much like the He-Ne laser. The gas is contained in a closed tube with mirrors at each end to form the laser cavity. An electrical current passes through the tube from one end to the other to excite the gas. Unfortunately, the electricity breaks down the CO_2 molecules unless hydrogen or water is added to the gas mixture to cause CO_2 regeneration. Output power from sealed-tube lasers is limited to around the 100 W range because the process can only produce about 50 W per meter of tube length.

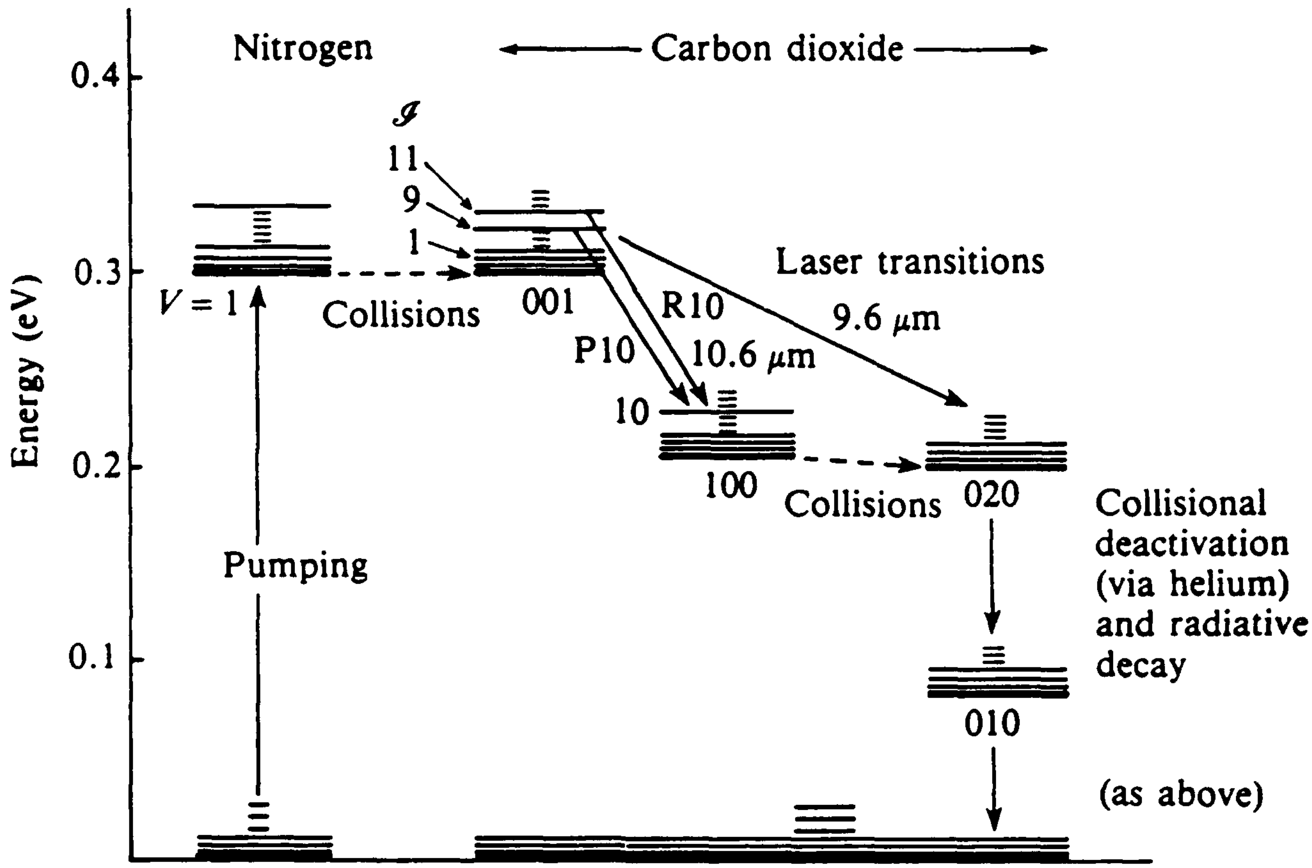


Figure 9 - Simplified energy level diagram for the carbon dioxide laser. Each vibrational level has many rotational levels associated with it. [15]

"Axial flowing gas" lasers solve part of the CO_2 breakdown problem by recirculating the gas along the length of the tube. This increases power output to around 700 W/m of tube length, and high power lasers are possible by doubling the tube back upon itself several times. There is also a "transverse-flow" laser which removes the excess heat and dissociation products more efficiently. The gas moves sideways across the laser cavity, and proper flow is important to output efficiency. Output power for these lasers can reach 10.0 kW/m of active tube length. Some systems identify wind tunnels as key components. Another high power configuration is the "gas-dynamic" laser where hot gas is forced to expand in a low pressure chamber after passing through a nozzle. Rapid cooling of the gas causes a population inversion over a short distance downstream of the nozzle. These lasers are being investigated for military applications since output power can reach 100 kW or more. Other types of configurations are possible for special applications.

There is one major drawback inherent with CO_2 lasers. Most optical materials, chiefly glass and quartz, are not transparent around the 10 µm wavelength of CO_2 operation. Materials have been developed which are transparent in the infrared spectrum, but these exotic materials also tend to be highly toxic or hygroscopic; that is, they absorb water from the atmosphere and slowly dissolve. Typically, these materials are not transparent in the visible spectrum. Figure 10 shows a list of optical materials and the windows over which they are suitably transparent. One implication is that a CO_2 laser's 10.6 µm wavelength light can not be used with fiber-optic cables, while Nd:YAG lasers (1.06 µm) can. Metals tend to be highly reflective at the CO_2 wavelength, and so optical mirrors are used instead of lenses wherever possible. In medical applications, CO_2 laser beams are passed down the center of a series of articulated metal tubes with a mirror at each elbow.

CO_2 lasers can be operated in either the continuous or pulsed mode, however the pulsed mode is quite common because of thermal build up during operation. The wavelength for these lasers is usually written as 10.6 µm, but this should be considered a nominal value. The principal spectrum lines occur at 9.6 and 10.6 µm, with many closely spaced rotational transitions superimposed on the vibrational transitions yielding about 100 distinct emission wavelengths. Optical diffraction gratings, or other tuning elements can be used to select a particular wavelength, but higher power is available if tuning is unnecessary. For the sealed-tube and axial-flowing gas lasers, the beam diameter can range from 3 mm to 70 mm, and tends to increase with increased power levels. Beam divergence is about 1 to 3 milliradian (mrad).

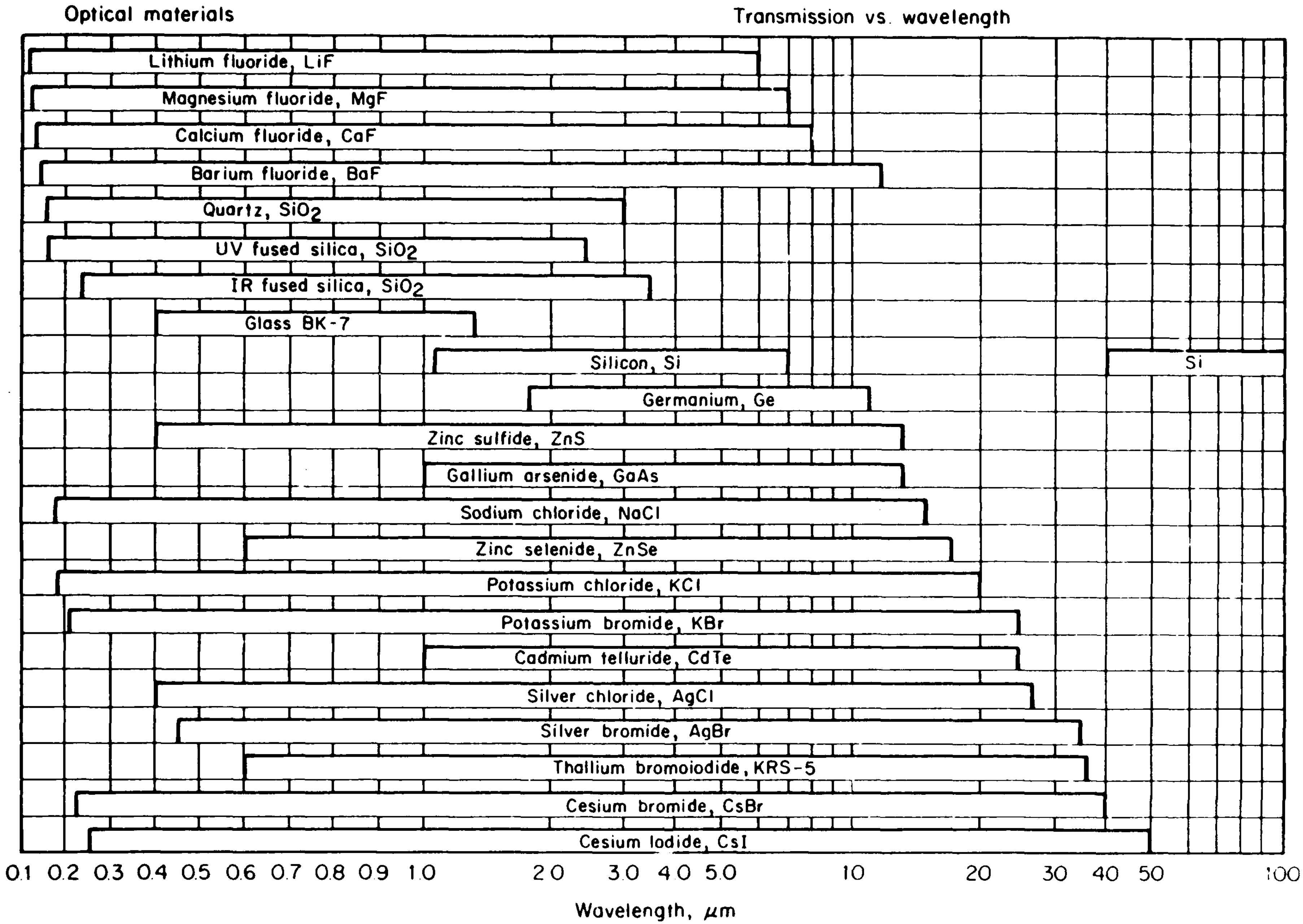


Figure 10 - **Spectral regions at which selected optical materials transmit adequately for optical applications. Note that different forms of silica, including quartz and optical glass, have different transmissions - a consequence of different levels of impurities. [14]**

Just as there are many configurations for CO_2 lasers, the power requirements are just as varied. Continuous wave flowing-gas lasers use about 10 to 20 times their optical output power for running vacuum pumps, cooling equipment, and accessories as well as the laser itself. Input power can come from regular single-phase 110 V-ac up to 440 V three-phase. The efficiencies of CO_2 lasers are quite good by laser standards, typically running between 5 to 20 percent. Forced air cooling is used for smaller lasers, while water cooling is necessary for the higher powered models. The operating lifetime for sealed-tube lasers is a few thousand hours before gas replacement, and is usually not specified for flowing gas lasers.

The main consumable for CO_2 lasers is the gas. For flowing-gas models, continuous replenishment is necessary, with higher powered lasers requiring proportionally more gas each hour. Some maintenance is also required for these lasers. In addition to gas replacement, degraded optics and high voltage parts have to be replaced, and vacuum pumps need occasional lubrication. In general, these lasers are designed for use in a fixed location and can not withstand extensive vibrations and shock, hence they are probably not suitable for shipboard use. A few have been designed for field use as military range finders, however.

As with their other characteristics, the pricing for CO_2 lasers varies widely. The sealed-tube variety can range from $5,000 to $35,000, while flowing-gas types go from about $20,000 to a cool million. The more expensive models are built specifically for materials processing and come with expensive options.

4.1.2.e Conclusion

Helium-Neon, Ruby, Neodymium, and Carbon Dioxide lasers were discussed in greater detail in the preceding sections with an eye towards selecting the most appropriate laser to consider for a possible laser deicing system for surface ships. Some of the pertinent characteristics of these lasers are summarized in Table 2. The summary table also notes various features or characteristics which would be considered desirable for the UNREP deicing application.

The He-Ne lasers (the first column of the table) do not produce enough output power to be useful for deicing, but they are relatively inexpensive and are frequently used to direct the radiation of infrared lasers which is not visible to the human eye. In addition, the wavelength is in the visible spectrum so a large fraction of the radiation would be reflected off of an icy surface. Therefore, it can be concluded that the He-Ne laser is unsuitable for deicing except that it may still have a role as a visible means of directing an infrared wavelength laser's beam.

Ruby lasers also operate in the visible spectrum and can produce high output powers. However, in recent years they have lost favor to neodymium lasers which have a higher efficiency and a faster pulse repetition rate. This, combined with the fact that saline ice readily absorbs infrared radiation and reflects a good portion of visible light, suggests that infrared lasers would be better suited to the UNREP deicing task.

Both the neodymium and CO_2 lasers operate in the infrared part of the spectrum and are readily available in a range of power levels through commercial sources. It turns out, however, that fiber optic cable cannot be used by CO_2 lasers because common optical materials, suitable for visible wavelengths, are opaque in the far infrared portion of the spectrum. Fiber optic cable is readily used by neodymium lasers as a beam delivery system. All CO_2 lasers require gas replenishment from time to time, but for some higher-powered models, a constant supply of fresh gas is needed. This is the only laser of the four types considered that has a major consumable requirement, other than for electric power and perhaps a water cooling system. In addition, CO_2 lasers operate best at room temperatures, which may present a problem for their use on shipboard. Finally, the greater durability of neodymium lasers over CO_2 lasers leads to the conclusion that if lasers are to be used for deicing at sea, neodymium lasers operating at the 1.06 μm wavelength are the way to go.

Table 2
Summary of Laser Characteristics for Helium-Neon, Ruby, Neodymium, and Carbon Dioxide Laser Types

	He-Ne	Ruby	Nd	CO_2
Spectrum	Visible	Visible	Near-IR*	IR*
Wavelength	632.8 nm	694.3 nm	1.06 µm*	10.6 µm*
Laser Type	Gas	Solid-State*	Solid-State*	Gas
Operating Modes	CW	Pulsed Q-switched	CW Pulsed Q-switched	CW Pulsed Q-switched
Pulse Repetition Rate	CW Modulated up to 1 MHz	Low, ~1 Hz†	0 - 500 Hz	0 - 300 Hz
Excitation Means	Elec. Current	Flash Lamp	Contin. Lamp Flash Lamp	Elec. Current
Beam Diameter	~1 mm	1 - 25 mm	1 - 10+ mm	3 - 70 mm
Beam Divergence	~1 mrad	0.25 - 7 mrad	0.3 - 10 mrad	1 - 3 mrad
Fiber Optic Capability	Yes*	Yes*	Yes*	No†
Output Power Level	< 60 mW†	< 100 W	< 400 W*	400 - 800 W/m
Output Energy/Pulse		< 100 J	< 100 J	< 100 J
Power Requirements	110 - 220 V	110 - 220 V	110 - 220 V	110 - 440 V
Efficiency	0.01 to 0.1%	0.1 to 1%	0.1 to 1%	5 to 20%
Approximate Cost	$100 up to $10K	$14K up to $200K	$3K up to $200K	$5K up to $100K
Durable	If Desired	Yes*	Yes*	No†
Operating Lifetime	20,000 hrs	1 Million Pulses	10 Million Pulses	Few 1,000 hrs for Gas
Operating Temperature	-20 to +50°C	Wide Range*	Wide Range*	Room Temp.†
Consumable Materials	None	Water Cooling	Water Cooling	Gas†, Water Cooling
Typical Usage	Education, Alignment, Medicine, Communication	Holography, Range Finders	Materials Processing*, Medicine, Range Finders	Materials Processing*, Medicine

* Desirable feature or characteristic for UNREP deicing application.
† Undesirable feature or characteristic.

4.2 Safety Concerns Associated with Laser Deicing

There are many safety hazards associated with the use of lasers: laser radiation on the eyes or skin, electric shock, contact with hazardous cryogenic materials, noise, and fires, just to name a few of the most important. The most controversial hazard by far has been radiation damage to the eye since even moderately high radiation intensities can result in irreversible ocular injuries. Radiation damage to human skin can also be substantial, but this is usually given secondary consideration. While the radiation hazard is perhaps the most critical safety consideration, no known deaths have ever been caused by a laser beam. The danger due to electric shock, however, has proven to be far more deadly [14] and cannot be ignored.

Since safety and safety training are such important considerations to the appropriate use of lasers, information on the biological effects of laser radiation and associated laser hazards is readily available and can be found in varying degrees of depth depending upon need. The most complete reference book detailing the medical hazards associated with lasers is by Sliney and Wolbarsht [16], but there are several excellent handbooks designed to be used by the designated "laser safety officer" (LSO) of any laser equipped facility. (See for instance the "Laser Safety Handbook" [17].) Finally, there are brochures and pamphlets intended to be distributed by the LSO to laser operators for safety training [18, 19]. The U.S. Food and Drug Administration has issued regulations for the performance standards for laser products required to be met by all laser manufacturers [20]. These regulations are intended to protect the user by the elimination or containment of radiation which is not a part of the direct laser beam, require warning labels and instructions on the laser to alert the user to the level of the emitted radiation hazard, and establish a classification system for laser products based on their relative radiation hazard. Additional voluntary standards for the safe use of lasers have been issued by the American National Standards Institute (ANSI) [21]. While the federal regulations are intended for manufacturers in the production of safe and properly classified laser products, the ANSI Standards apply to laser safety in the workplace by providing a means to compute human exposure limits to radiation from installed lasers.

4.2.1 Radiation Safety

No discussion of laser safety hazards is complete without at least a brief description of the human eye because potential eye damage from radiation can occur to several different parts of the eye structure depending upon which area absorbs the most radiant energy per volume of tissue. A sketch of the eye is given in Figure 11. The inner layer of the eyeball is called the retina and contains the nerve cells for light perception. The macula of the retina has a small region called the fovea which lies at the focal point of the cornea-lens optical system. Because of the focusing ability of the cornea-lens system, the intensity of incoming light striking the fovea can be up to 100,000 times greater than the intensity of light at the *cornea*. Needless to say, since the magnitude of laser radiation intensity is so much greater than normal light, this focusing effect can quickly result in ocular injury.

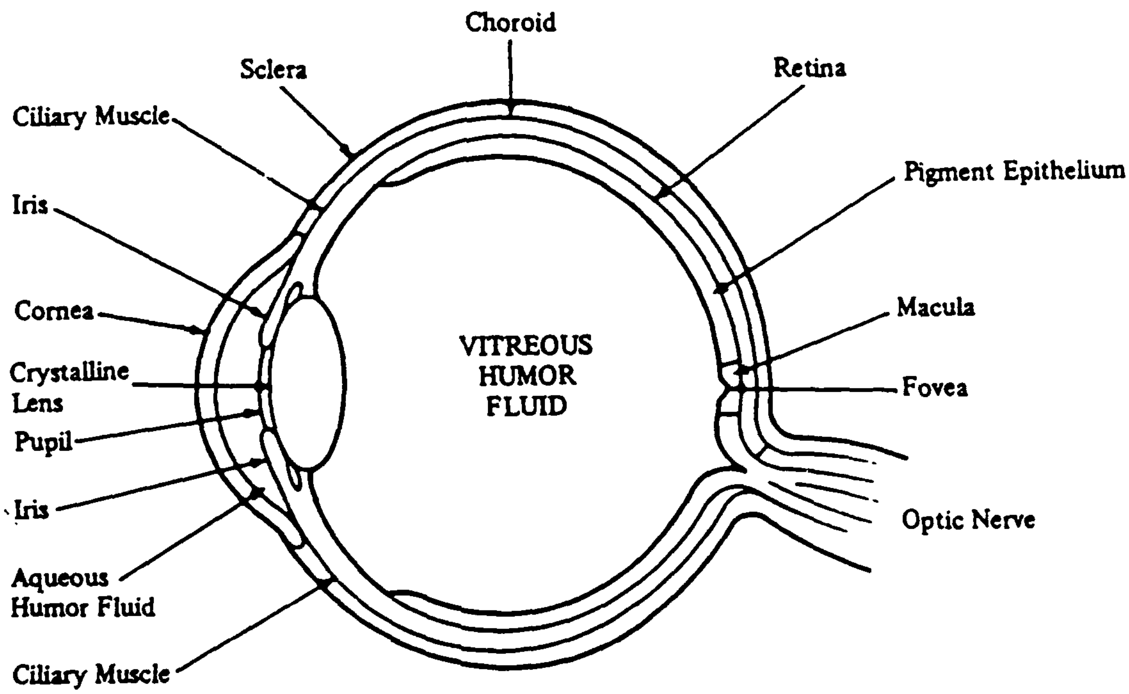


Figure 11 - Schematic Diagram of the human eye. Parallel rays of light can be focussed to a very small area on the retina when the eye is relaxed, i.e. focussed at infinity. [17]

Just as for other materials, the various tissues and fluids contained in the eye absorb, reflect and transmit radiation depending upon the incident wavelength. In the visible and near-infrared (400 to 1,400 nm), light is transmitted through the cornea, aqueous humor, crystalline lens, and vitreous humor, and is absorbed by the retina and choroid. This is the retinal hazard region. For wavelengths in the far-infrared from 1,400 nm to 1,900 nm, the cornea and aueous humor become almost total absorbers, and above 1,900 nm, the cornea is the only absorber. On the other side of the visible light spectrum, near-ultraviolet radiation (315 to 400 nm) is mainly absorbed by the crystalline lens with only a slight amount of radiation reaching the retina. Figure 12 gives a summary of the various parts of the eye which absorb radiation at different wavelengths along with a brief description of the biological injuries possible. A graph of absorption versus wavelength for the retina and choroid is shown in Figure 13, and clearly shows the retinal hazard region.

Several mechanisms have been identified as contributing to tissue damage from laser radiation. The principal form of damage comes from thermal heat absorbed at the site. The better the absorption properties of the tissue the greater the chance for injury. Also, a larger irradiated area is more likely to suffer injury than a smaller area because the surrounding tissue is less able to conduct heat away. Thermal effects range from no effect, to simple tissue reddening, steam generation, and charring. Explosive tearing or ripping may even be possible when very high radiation exposure levels occur. Photochemical effects are not completely understood, but ultraviolet absorption by the corneal epithelium may suffer damage from denaturization of proteins and other molecules. Acoustic transients are generated when laser pulses striking tissues convert part of their energy into mechanical compression (an acoustic wave) which is capable of ripping or tearing tissue. Chronic exposure to radiation, such as the link between ultraviolet radiation and certain skin cancers, and eye damage are areas which require further study. The near-infrared radiation emitted from foundries and glass furnaces are believed to be responsible for cataracts [17].

Radiation damage to skin is usually considered to be of secondary importance to the eye hazard because skin damage is more readily repairable. However, with the increased use of higher powered lasers and ultraviolet lasers, the chances for greater degrees of damage deserves attention. Human skin is made up of two major layers: the epidermis on top, and the dermis below. The epidermis contains no blood vessels, but its lower layers have some nerve endings. Also, the lower epidermis layers contain the pigment called melanin which controls the skin color.

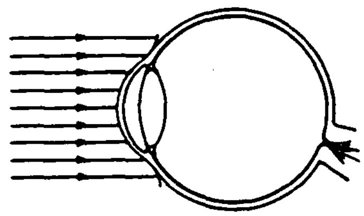
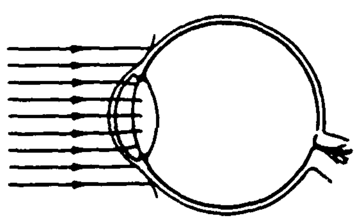
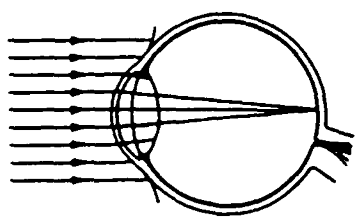
Spectral Region	Absorption Area	Eye Schematic Representation	Specific Biological Effects	Comments
Far-Infrared (IR-B and IR-C) (1.4–1000 μm)	Cornea		• Minimal corneal lesion. • Loss of transparency of cornea or "glassworkers or furnaceman's" cataract. • Increased irradiance can cause more serious damage.	A minimal corneal lesion is a small white area solely on the corneal epithelium, with the surface neither swollen nor elevated. It appears within 10 minutes after exposure and heals within 48 hours without visible scars.
Short-Ultraviolet (UV-B and UV-C) (100–315 nm)	Cornea		• Excessive ultraviolet exposure can produce: – Redness – Tears – Secretion of mucus from the eyeball (conjunctival discharge) – Peeling or stripping off of the surface layer of cells from the cornea or connective tissue (stromal haze). • Damage to corneal epithelium by photochemical denaturization of proteins or other molecules (i.e., DNA, RNA, etc.).	Damage to the corneal epithelium is probably of photochemical rather than thermal origin.
Near-Ultraviolet (UV-A) (315–400 nm)	Primarily Lens		• Lens can flouresce. • Very high doses can cause corneal and lenticular opacities.	
Light (400–700 nm) Near-Infrared (IR-A) (700–1,400 nm)	Retina and Choroid		• Mildest reaction may be simple reddening. • Minimal or threshold retinal lesion. • Increased retinal irradiance can cause large lesions, charring, hemorrhage, as well as gas formation, disruption of the retina and physical alteration of the eye structure.	A minimal retinal lesion is the smallest visible change in the retina viewed with an ophthalmoscope. It occurs within a full day after exposure and is a small white patch (likely coagulation).

Figure 12 - Summary of Specific Biological Effects on the Eye. [17]

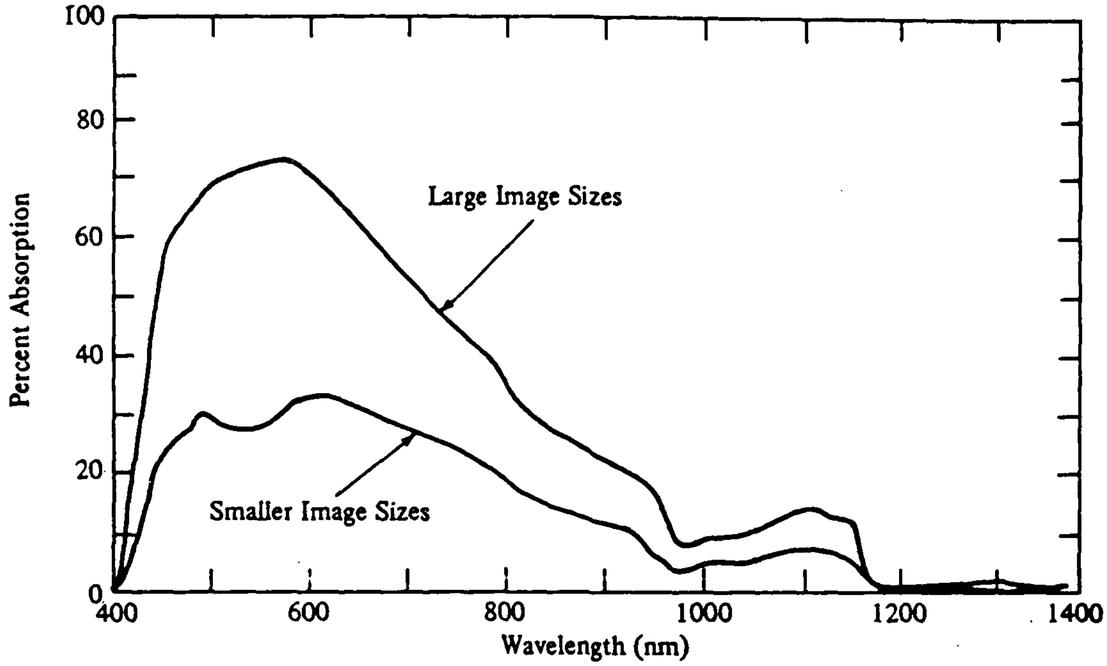


Figure 13 - Spectral absorbed dose in retina and choroid relative to spectral corneal exposure as a function of wavelength. [17]

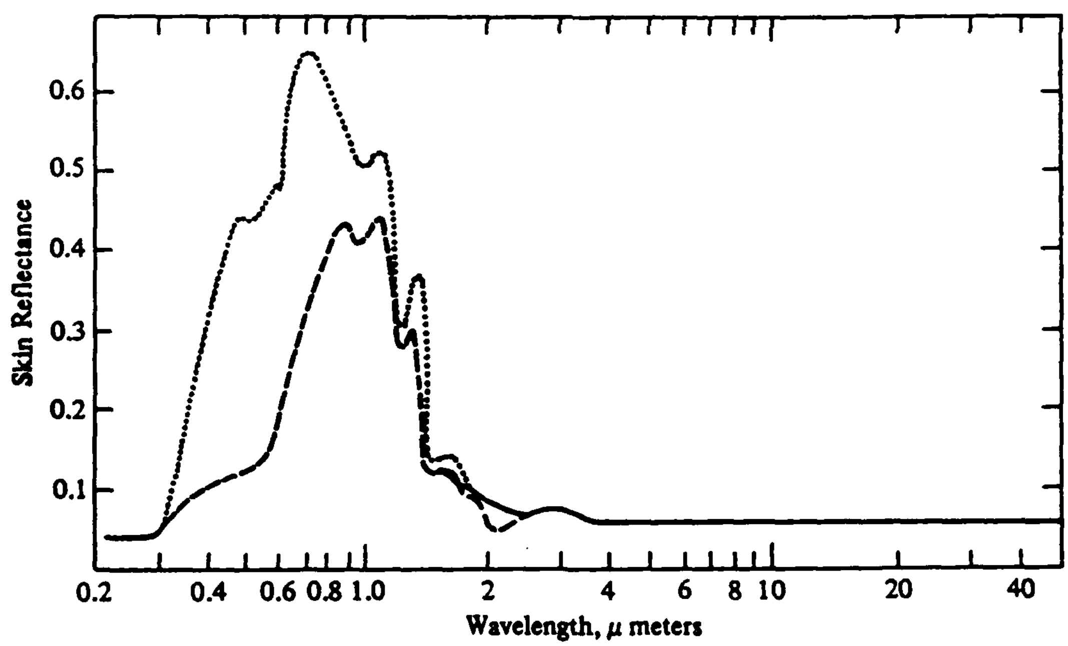


Figure 14 - Spectral reflectance of human skin. Dotted and dashed lines are data from individuals having a very fair complexion and for individuals having heavily pigmented skin. Spectral reflectance for skin in the ultraviolet and infrared regions is shown by a solid line. [17]

Since skin is comprised largely of water it is relatively transparent to most wavelengths of laser light up to the layer of melanin pigmentation. The pigmentation is the principal absorber of radiation in the skin. In addition, fair skinned people reflect more light from their skin than dark skinned people. This is shown over a range of wavelengths in Figure 14. Therefore, persons with dark complexions are more prone to radiation injuries. Absorption of high intensity radiation on the skin results in damage ranging from elevated temperatures, reddening of the skin (sun burn), blistering, charring, and finally, actual burned-out portions of the body tissue. In addition, some forms of ultraviolet radiation have been found to accelerate skin aging, and are believed to cause several types of skin cancers.

Just as for eye tissues, irradiation over a smaller area of skin allows a greater portion of the absorbed heat to be conducted away from the site than large area irradiation, so skin damage is either less likely or less severe. For example, a CO_2 laser at the 10.6 μm wavelength will give the sensation of warmth to human skin at 0.1 W/cm^2 for a 1 cm diameter spot, however, it requires only 0.01 W/cm^2 over the entire body to provide the same degree of warmth. For a similar example related to the eye, the threshold for retinal injury during a moderate exposure duration is 1 kW/cm^2 for a 20 μm spot, while only 1 to 10 W/cm^2 is needed for a 1000 μm image [17].

The best protection against laser radiation is the erection of shields and enclosures between the operator and the laser beam path. This form of protection has proven to be more effective than eye goggles from the standpoint of eye safety because there is a common reluctance on the part of laser users to wear the glasses. This attitude can be attributed to the lack of light weight eyewear, reduced field of vision, and/or reduced ability to see in the workplace due to the absorption of visible light. It has been found that these situations can allow users to convince themselves that their safety is improved by removing the protection. In general, the application of lasers to the task of deicing at sea would require the use of protective eyewear because the deicing laser would be a portable device and not mounted behind permanent shields.

Laser eye protection should be selected to afford the wearer with protection against the maximum anticipated exposure while still allowing the user the largest amount of light to enter the eye. The maximum permissible exposure (MPE) suggested for radiation entering the eye varies with the wavelength of the incident radiation, and its intensity and duration. Properly selected protective eyewear will attenuate the incoming laser radiation to the MPE level. The quantity which describes the amount of attenuation at a particular wavelength is called the optical density (OD or $D\lambda$) and is defined as the logarithm to the base ten of the reciprocal of the transmittance, and can be computed from the ratio of the incident intensity to transmitted intensity:

$$D_\lambda = \log_{10}(I_i/I_t) = -\log_{10}(1/\tau_\lambda) \quad (9)$$

where τ_λ is the transmittance. Therefore, the desired optical density for the selection of proper eyewear is the minimum optical density required to attenuate the maximum radiation intensity expected down to the maximum permissible exposure (MPE) limit.

$$D_\lambda = \log_{10}(I_i/MPE) \quad (10)$$

Appendix A gives a listing of some laser eye protection eyewear currently available along with a partial listing of manufacturers and suppliers. For each model of eye protection given, the optical density is noted over a range of wavelengths. The appendix also gives the daylight visible transmittance to provide an indication of how much of the user's vision might be impaired in the workplace.

Other factors to consider in the selection of proper eye protection include: field of view, ventilation ports to prevent fogging in goggles, effect on color vision, night vision transmittance, impact resistance, and availability of prescription lenses or sufficient goggle frame size to permit wearing eyeglasses inside the goggle.

4.2.2 Radiation Exposure Limits for Personnel

The federal government has grouped all lasers into four broad categories depending upon their radiation emission levels and relative hazard to personnel safety [20]. This classification system allows general safety regulations and precautions to be promulgated in a simple manner to cover each class of laser. In addition to the four classes, voluntary standards for the safe use of lasers have been issued by the American National Standards Institute (ANSI) [21]. The ANSI Standards establish limits on the maximum permissible exposure (MPE) depending upon the radiation wavelength, intensity and duration, and depending upon whether the radiation strikes the skin or enters the eye.

The laser classification system uses four basic levels to denote the relative hazard to personnel safety; the higher the number, the greater the danger. The four categories and related subcategories are as follows [18].

Class 1 denotes exempt lasers or laser systems that cannot, under normal operating conditions, produce a hazard.

Class 2a denotes low power visible lasers or laser systems that are not intended for prolonged viewing, and under normal operating conditions will not produce a hazard if viewed directly for periods not exceeding 1000 seconds.

Class 2 denotes low power visible lasers or laser systems which, because of the normal human aversion responses, do not normally present a hazard, but may present some potential for hazard if viewed directly for extended periods of time (like many conventional light sources).

Class 3a denotes lasers or laser systems that normally would not produce a hazard if viewed for only momentary periods with the unaided eye. They may present a hazard if viewed using collecting optics.

Class 3b denotes lasers or laser systems that can produce a hazard if viewed directly. This includes intrabeam viewing of specular reflections. Except for the higher power Class 3b lasers, this class laser will not produce a hazardous diffuse reflection.

Class 4 denotes lasers or laser systems that can produce a hazard not only from direct or specular reflections, but also from a diffuse reflection. In addition, such lasers may produce fire hazards and skin hazards.

For both continuous wave and pulsed mode lasers in the visible and infrared portions of the spectrum, including the Nd:YAG wavelength of 1.06 μm, a time-averaged emitted power of greater than 0.5 W is considered a Class 4 laser. As such, any laser with sufficient power to be efficient for deicing will also be in the Class 4 category.

The ANSI Standards [21] provide a criteria for exposure of the eye and skin to laser radiation such that hazardous levels of radiation are not exceeded. These recommended levels for the maximum permissible exposure are based on the best information currently available from experimental studies. Since the Nd:YAG laser was determined to be the most appropriate laser for deicing at sea, only the exposure limits pertinent to the 1.06 μm infrared wavelength will be noted here. Reference 21 should be consulted for detailed information at other wavelengths. Considering the case of skin exposure first, the maximum permissible exposure in both the visible and near-infrared portions of the spectrum is given as a function of exposure duration:

$$
\begin{array}{llll}
MPE = 2 \cdot C_A \cdot 10^{-2} & J/cm^2 & \text{for } t = 10^{-9} \text{ to } 10^{-7} \text{ sec} & \\
MPE = 1.1 \cdot C_A \cdot t^{0.25} & J/cm^2 & \text{for } t = 10^{-7} \text{ to } 10 \text{ sec} & (11) \\
MPE = 0.2 \cdot C_A & W/cm^2 & \text{for } t = 10 \text{ to } 3\times10^{4} \text{ sec} &
\end{array}
$$

where

$$
\begin{array}{lll}
C_A = 1 & \text{for } \lambda = 0.400 \text{ to } 0.700\ \mu m \\
C_A = 10^{2.0(\lambda-0.700)} & \text{for } \lambda = 0.700 \text{ to } 1.050\ \mu m \\
C_A = 5 & \text{for } \lambda = 1.050 \text{ to } 1.400\ \mu m
\end{array}
$$

Therefore, for relatively long exposure times (greater than 10 seconds) the maximum permissible exposure would be 1 W/cm^2. This is the worst case situation, but it is probably the most appropriate choice for a laser operator assigned the task of deicing large regions of a ship's surface at an UNREP station. For shorter durations, the MPE energy density in J/cm^2 for a single laser pulse is used. This can be converted to intensity by dividing by the pulse duration.

For direct ocular exposure, which includes viewing the laser beam directly or by non-diffuse reflection, the maximum permissible exposure for the near-infrared wavelengths is:

$$
\begin{array}{llll}
MPE = 5 \cdot 10^{-6} & J/cm^2 & \text{for } t = 10^{-9} \text{ to } 5\times10^{-5} \text{ sec} & \\
MPE = 9 \cdot t^{0.75} \cdot 10^{-3} & J/cm^2 & \text{for } t = 5\times10^{-5} \text{ to } 10^{3} \text{ sec} & (12) \\
MPE = 1.6 \cdot 10^{-3} & W/cm^2 & \text{for } t = 10^{3} \text{ to } 3\times10^{4} \text{ sec} &
\end{array}
$$

In this case, the most hazardous scenario would yield an ocular MPE of 1.6 mW/cm^2. This is for an exposure duration of over 1000 seconds (17 minutes), however, which is akin to staring directly into the laser beam. Therefore, a shorter exposure duration is probably justified in determining the ocular MPE for a deicing laser operator. Figure 15 gives a graphical representation of the ocular MPE limits for the near-infrared and other laser wavelengths. The ANSI Standards also consider other situations, such as an extended emitting source where the eye aperture cannot view the whole object and not all the radiation enters the eye directly. This situation would occur when viewing a diffuse reflection close up, and need not be considered for deicing operations where the laser user is some distance away from the reflected beam.

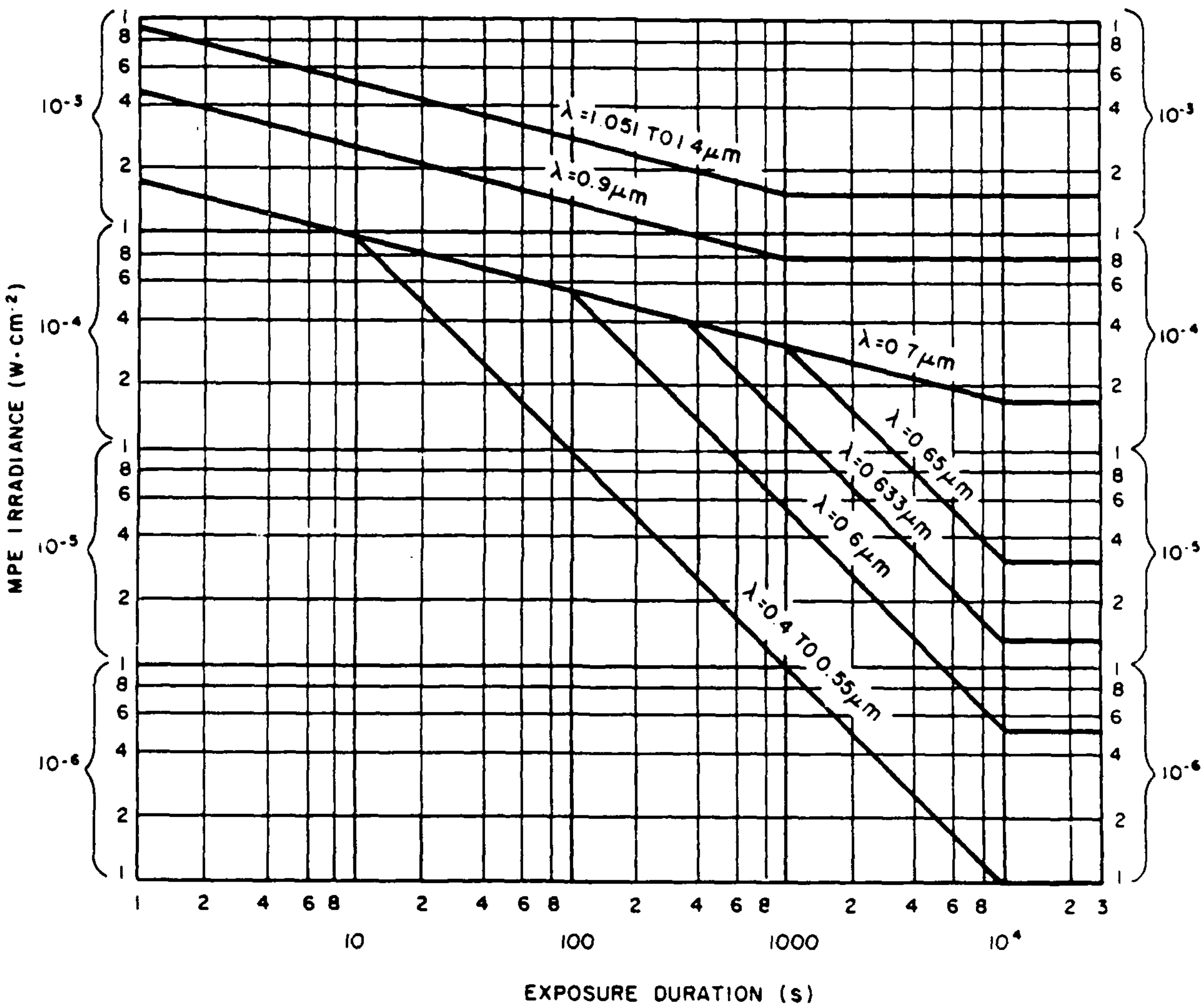


Figure 15 - Ocular MPE for intrabeam viewing as a function of exposure duration and wavelength. [21]

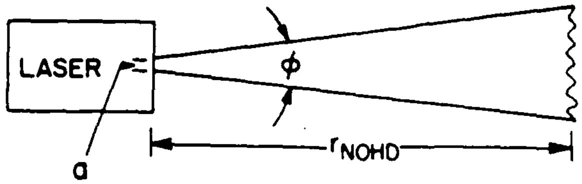
The ocular MPE is combined with the selected laser's beam characteristics through Equation 10 to determine the required optical density of protective eyewear. The most likely hazardous viewing scenario is used in determining the intensity of the laser beam reaching the person's eyes. Figure 16 shows several configurations for the laser beam path along with the related equations for determining the range under which the MPE is exceeded. Φ is the total radiant power output of a continuous wave laser, or the time-averaged radiant power of a repetitively pulsed laser.

4.2.3 Other Safety Considerations

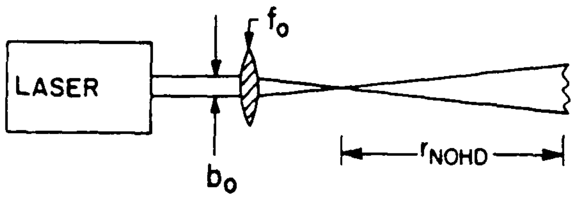
While personnel contact with the laser beam is the single most important hazard associated with laser operation, there are several other safety hazards that must be considered. Among these are:

- Electrical
- Airborne contaminants
- Cryogenic liquids
- Noise
- Ionizing Radiation
- Non-laser beam optical radiation
- Explosions
- Fire

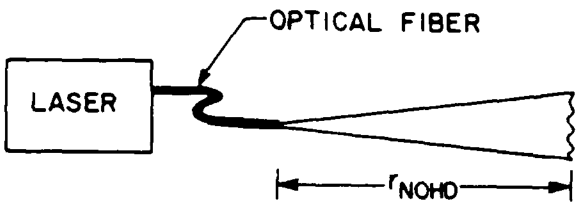
Electrical. Electrical accidents stemming from the use of lasers occur with greater frequency than eye and skin injuries from direct and reflected laser beams. In fact, there have been several documented cases of electrocutions in the United States. The main factor influencing the degree of injury due to electric shock is the current level. Other factors include the body resistance, current pathway through the body, duration of electric shock, voltage, current frequency, and phase of the heart beat. With generally increasing levels of current through the body, the victim can experience the following physiological effects: slight tingling sensation at the threshold level of experience; pain and muscle soreness possibly with temporary ringing in the ears and flashes and spots before the eyes; muscle contractions from alternating current (the victim may be unable to let-go of the conductor ("frozen") at higher current levels); rapid increase in blood pressure as a result of the strong muscle contractions; stupor and/or collapse, unconsciousness; paralysis of the breathing muscles; ventricular fibrilation (this can occur even for moderate current levels); burns in the body tissues; severe hemorrhages of the brain, nervous system and other organs; heart standstill requiring artificial resuscitation within a few minutes for survival; fatal damage to the central nervous system; and at very high currents, rapid increase in the body temperature resulting in almost instant death.



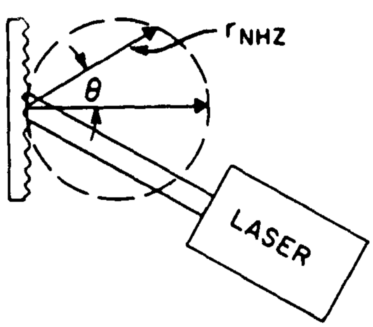
$$r_{NOHD} = \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi \cdot MPE}\right)^{1/2} - a\right]$$



$$r_{NOHD} = \left(\frac{f_o}{b_o}\right)\left(\frac{4\Phi}{\pi \cdot MPE}\right)^{1/2}$$



$$r_{NOHD} = \begin{cases} \dfrac{1.7}{NA}\left[\dfrac{\Phi}{\pi \cdot MPE}\right]^{1/2} & \text{(MULTIMODE)} \\ \dfrac{\omega_o}{\lambda}\left[\dfrac{\Phi}{MPE}\right]^{1/2} & \text{(SINGLEMODE)} \end{cases}$$



$$r_{NHZ} = \left(\frac{\rho\Phi\cos\theta}{\pi \cdot MPE}\right)^{1/2}$$

Figure 16 - Examples of use of laser range equation for determining Nominal Hazard Distance. Bottom figure shows the Nominal Hazard Zone for a diffuse reflection. [21]

Airborne contaminants Depending on the type of laser used and its application, different types of airborne contaminants can be hazardous if inhaled in quantity. The contaminating material can come from the active laser medium, such as carbon dioxide and carbon monoxide escaping from a gas laser or ozone produced by flash lamps, or be produced as a result of some material processing application. In the latter case, a metal target can give rise to iron oxide fumes or paint fumes. The Occupational Safety and Health Administration (OSHA) has issued some regulations regarding the exposure level allowed for some common laser generated airborne contaminants [22]. Airborne contaminants should not present much of a problem on the deck of a windy ship.

Cryogenic liquids Cryogenic liquids such as liquid nitrogen, hydrogen or helium are used to cool some high powered lasers. These lasers are generally found in research and development laboratories. The hazards associated with cryogenic liquids are: high pressure as the liquid expands rapidly into a gas; flammability; burns to the body from contact; asphyxiation; toxicity; and improper material usage such as storage containers which turn brittle at low temperatures. In most cases, Nd:YAG lasers use water for cooling.

Noise Discharging capacitors used in some high energy pulsed lasers can generate hazardous noise levels.

Ionizing Radiation Power supply tubes which generate voltages in excess of 15 kV can produce X-ray radiation. Most lasers use voltages under 8,000 volts.

Non-laser beam optical radiation Ultraviolet radiation is possible from some optical flash lamps. Flash lamps are generally contained within secure enclosures to prevent this from becoming a hazard, however.

Explosions Explosions are possible from faulty flash lamps and capacitor banks of high powered lasers. Any laser designed for commercial use should be designed to prevent this from becoming a hazard. Some target materials are known to explode when a laser beam strikes them. For instance, a high power laser beam passing through a glass window may cause the window to shatter.

Fire Laser related fires can be caused either from a faulty electrical circuit in the power supply, or from heating a target material with an intense beam until it bursts into combustion. A concern here with a laser used for deicing would be starting fires by playing the laser beam directly on painted surfaces, combustible material, or fuel lines.

As mentioned earlier, the federal government has grouped all lasers into four broad categories depending upon their radiation emission levels and relative hazard to personnel safety [20]. The classification system allows general safety regulations and precautions to be promulgated for each class of laser. The ANSI Standards [21] incorporate and extend the safety procedures using the same classification system. A key element for the safe use of lasers in any organization is the establishment of a sound laser safety program. Not only does this include an active laser safety training program, but also designating a laser safety officer (LSO) and ensuring that adequate medical surveillance takes place. Guidelines for the organization of a laser safety program are discussed in the Laser Safety Handbook [17]. Table 3 outlines the safety control measures covered by ANSI for each laser class with reference to where detailed information can be found in the Standards.

Table 3
Control Measures for the Four Laser Classes [21]

Controls	Classification	1	2a	2	3a	3b	4
ENGINEERING	Protective Housing (4.3.1)	X	X	X	X	X	X
	Without Protective Housing (4.3.1.1)	LSO shall establish Alternate Controls					
	Interlocks on Protective Housing (4.3.2)	Δ	Δ	Δ	X	X	X
	Service Access Panel (4.3.3)	▽	▽	▽	▽	▽	X
	Key Switch Master (4.3.4)	—	—	—	—	•	X
	Viewing Portals (4.3.5.1)	—	—	□	□	□	□
	Collecting Optics (4.3.5.2)	—	—	□	□	□	□
	Totally Open Beam Path (4.3.6.1)	—	—	—	—	X	X
	Limited Open Beam Path (4.3.6.2)	—	—	—	—	X	X
	Remote Interlock Connector (4.3.7)	—	—	—	—	•	X
	Beam Stop or Attenuator (4.3.8)	—	—	—	•	•	X
	Activation Warning Systems (4.3.9)	—	—	—	—	•	X
	Emission Delay (4.3.9.1)	—	—	—	—	—	•
	Class 3b Laser Controlled Area (4.3.10.1)	—	—	—	—	X	—
	Class 4 Laser Controlled Area (4.3.10.2)	—	—	—	—	—	X
	Laser Outdoor Controls (4.3.11)	—	—	—	—	X	X
	Temporary Laser Controlled Area* (4.3.12)	▽	▽	▽	▽	—	—
	Remote Firing & Monitoring (4.3.13)	—	—	—	—	—	•
	Labels (4.3.14)	—	X	X	X	X	X
	Area Posting (4.3.15)	—	—	•	•	X	X
ADMINISTRATIVE & PROCEDURAL	Administrative & Procedural Controls (4.4)	—	X	X	X	X	X
	Standard Operating Procedures (4.4.1)	—	—	—	—	•	X
	Output Emission Limitations (4.4.2)	—	—	—	LSO Determination		
	Education and Training (4.4.3)	—	—	•	X	X	X
	Authorized Personnel (4.4.4)	—	—	—	—	X	X
	Alignment Procedures (4.4.5)	—	—	X	X	X	X
	Eye Protection (4.4.6)	—	—	—	—	•	X
	Spectator Control (4.4.7)	—	—	—	—	•	X
	Service Personnel (4.4.8)	▽	▽	▽	▽	X	X
	Laser Demonstration (4.5.1)	·	—	X	X	X	X
	Laser Fiber Optics (4.5.2)	—	—	X	X	X	X

LEGEND X - Shall, • - Should, — No requirement, ▽ - Shall if Embedded Class 3b or Class 4, □ - Shall if MPE is exceeded, Δ - Shall if embedded Class 3a, Class 3b, Class 4, * During Service Only

4.3 Experience in the Use of Lasers on Ice

While some information has been found on experience with the use of high powered lasers on ice, no information could be located on the routine use of these lasers for ice removal or melting. Many other studies have been carried out on lasers in ice (most of these have been mentioned or referred to in the section on Optical Properties of Sea Ice), but the investigators generally used low power lasers to observe the optical properties of ice in response to a particular wavelength of radiation without the experimental uncertainty introduced by melting ice.

One very interesting experiment was reported out by Clark, et al. [23], in 1973. Their investigation concerned the feasibility of using lasers to assist icebreakers by cutting a path ahead of the icebreaker. They determined that melting a channel through the ice in front of the ship as wide as the ship's beam took unwarranted amounts of energy. Instead they concentrated on the idea of cutting two slits in the ice separated by a distance equal to the beam so that the ship could clear out a channel with greatly reduced horsepower. In the laboratory a 50 W continuous wave CO_2 laser operating in the 10.6 µm infrared wavelength was used to obtain performance measurements. The laser beam was focussed to a power density of 500 W/cm^2 and played across the 0 °C freshwater ice at different velocities. Measurements were taken of the depth of cut, width of cut, and beam cutting velocity. With the ice slab mounted vertically, the laser beam was able to drill holes at a rate of about 1 cm/sec. For an ice sheet translating through the laser beam at speeds from 0.3 cm/sec to 1.2 cm/sec, the product of the depth of cut times the cutting velocity was close to a constant 0.4 cm^2/sec. The average slot was 0.3 cm in width. Melting rate calculations performed after the experiment revealed that about 80% of the beam's laser power was absorbed by the ice. This is remarkably close to the results presented in Section 3 which indicated approximately 90% absorption in sea ice for radiation of this wavelength. The increased absorption can be attributed to the increased salinity of sea ice [6].

Clark, et al., also conducted experiments on horizontally mounted ice sheets and found the cutting performance to be about half as that achieved for the vertical case for a 0.5 cm cut if the water formed was allowed to collect in the slot. The performance became even worse for deeper cuts. They noted that the pooled water was very warm to the touch and helped to melt ice at the edges of the cut slot. Also, water at the point of impact boiled violently and generated steam. The cutting performance was the same as for the vertical case if the water was allowed to run out.

One set of interesting experiments directly related to deicing with high-power laser radiation was reported by Lane and Marshall in 1976 [24]. The thrust of their investigation centered on the observation that certain materials, normally transparent to a particular wavelength of light, began tc absorb the radiation once a threshold value of intensity was reached. Below the threshold, the beam passes through the material with no effect, but above the threshold, absorption begins with material removal from the surface, melting, vaporization, production of internal voids, and in some cases violent shattering [25]. The phenomenon was first observed in the early days of laser development. As higher and higher laser output power was sought, it was discovered that transparent optical lenses in the high intensity beam's path became damaged on a regular basis. In fact, for the operation of some high-power pulsed lasers, lens systems are considered one of the consumables [14].

Lane and Marshall used a Ruby laser operating at 6943 Å and a Nd:Glass laser at 1.06 μm to carry out their study on several types of ice attached to different substrates. In general, they found that focussed intensities on the order of 10^8 to 10^9 W/cm^2 produced fractures 0.1 to 2 cm long in ice. (This is roughly the same intensity as the threshold level found to produce damage in glass [25].) Depending on the type of ice used, the damage occurred with greatest frequency on the surface, in the bulk of the ice, or at the substrate interface. However, for sea ice the damage was found only at the surface. The sea ice damage took the form of chipping, holes mechanically removed from the ice, and melting from which the investigators concluded that the technique could be applied to deicing if a suitable focusing system could be developed. A single pulse of optical energy of 1 to 5 Joules at 1.06 μm and focused to a point diameter less than 0.2 cm was sufficient to cause damage about one fifth of the time. The type of substrate was found to have no bearing on the initial crack formation in the ice, but would determine the ease with which the remaining ice could be removed from the surface.

The Lane and Marshall investigation concentrated on the type and frequency of high intensity damage caused by single pulses of laser light. As such, they gave no performance estimates on the rate of ice removal. A relatively low-powered laser operating in pulsed mode and focused at the ice surface, as they recommend, should be capable of chipping out a trench in the ice about 1 cm wide, but it is impossible to establish the effective beam velocity needed to accomplish this due to the nature of their investigation.

Discussions were also held with individuals of the Laser Group of the Naval Undersea Systems Command (NUSC) who have had some experience with using lasers in ice [26]. Basically, they are using various lasers to probe into an ice sheet and measure the electro-optical properties of the transmitted and reflected light. In general, however, the lasers used by the Group were not of sufficient power or intensity to cause melting in the ice, although they are becoming interested in determining how a puddle of melt water on the surface of an ice sheet affects the electro-optical properties of the laser radiation.

4.4 Performance Estimates for Laser Deicing

A judgement on the practicality of using lasers for UNREP deicing must consider two possible alternatives because two physical means of ice removal appear to be feasible. As discussed in the previous section, one means of deicing involves melting the ice with heat supplied with a high-power laser through a moderate intensity beam of light, while the second method uses a focused high intensity beam from a low-power laser to produce mechanical chipping and shattering of the ice. For both processes, the probable method of application to deicing on ships would be to use the laser to cut (or melt) a slot in the ice leaving a section of attached ice of a few square feet. This would then be pried off in the traditional manner, but with greatly reduced effort. Thus the laser application would be much the same in operation as using a steam lance or high pressure water jet to slot the ice.

For simplicity in discussing the two physical methods of deicing, the high-power laser with a moderate intensity light beam is referred to as a melting scenario, while the low-power laser with a focused high intensity beam is called the ice shattering scenario. Both methods will be discussed in this section and performance estimates will be established for the melting case. While ice shattering looks quite promising, no performance estimates can be established since the actual physical mechanisms for shattering transparent materials with high intensity light are little understood [25], and experiments with ice sheets concentrated on types of single laser pulse damage rather than the measurements of the speed of ice removal [24]. If the overall engineering requirements can be satisfied by laser deicing systems, then the personnel safety aspects of using high-powered lasers on shipboard will be addressed to determine if safe operation can be achieved.

4.4.1 Design Conditions for Melting

A determination of the practicality of using lasers to melt ice can be made on the basis of first estimating the heating requirements for representative deicing conditions, and assessing the ability of an infrared laser to meet those heating requirements. Once established, the performance estimates for the melting scenario can be compared with estimated ice removal rates achieved by other ice removal systems.

For the application of lasers to aid in deicing it is assumed that no action is taken during the icing event itself, rather, upon completion of the icing event the task of removing the accreted ice begins. The initial temperature of the ice can be quite variable depending upon the ambient air temperature. In a study concerned with the new design of conventional major surface combatants for cold weather operations, Schultz [27] determined that a minimum air temperature of -20 °F (-29 °C) roughly corresponded with the boundary for the 50% concentration of floating ice. This was recommended as the low temperature design requirement for the Marginal Ice Zone capable ship defined in the study. In addition, there is a lower limit to the air temperature at which topside icing can occur. At some point, the sea spray droplets will freeze while traveling through the air and strike the ship without adhering in any quantity. Minsk [2] reports that shipboard observers have witnessed icing at temperatures as low as -29 °C, but that the majority of reported icing incidents have occurred between −4 and −10 °C. Therefore −29°C can be taken as the lowest reasonable air temperature limit at which icing will be experienced. Since the melting process caused by heat supplied from laser radiation is expected to occur fairly quickly, the bulk or average temperature of the icing material is needed. In general, the bulk ice temperature will be the same as the ambient air temperature for ice attached to exposed topside equipment, and can be estimated to be the average of the air temperature and 0 °C for poorly insulated regions of the superstructure.

The upper limit temperature to which the laser energy warms the ice is assumed to be 50 °C. This value is selected since laboratory experiments with lasers melting slots in ice reported both steam generation and the presence of warm water [23]. For the operation of deicing at sea, it is envisioned that wind will not hinder the efficiency of melting the ice with lasers. First off, almost all of the energy contained in the laser beam will reach the ice surface since the wind is expected to remove the steam away from the working site. (Water molecules in the atmosphere represent a prime absorber of infrared radiation.) Secondly, the melting process is expected to occur quickly enough so that the convective heat transfer associated with the wind removing heat from the working site can be neglected.

Glaze ice has a density ranging from 0.7 to 0.9 gm/cm^3, hard rime from 0.1 to 0.6 gm/cm^3, and soft rime from 0.01 to 0.08 gm/cm^3 [2]. The average density value for glaze ice was considered the most appropriate to use in this evaluation since glaze ice is well bonded to the substrate and its removal by standard mechanical means would be greatly enhanced by an efficient method of slotting the ice into smaller sectional areas. Soft rime has a granular delicate structure which is very loosely bonded, while the less dense forms of hard rime fall away easily to light blows. Therefore, icing material with a density of about 800 kg/m^3, presents the typical most difficult case for ice removal. As shown in the section on the optical properties of sea ice (chiefly Figure 3), the albedo associated with infrared radiation on sea ice is approximately 7%, and remains almost unchanged with changes in density. A value of 10% for the reflectance will be used for the calculations presented here to allow for some energy losses.

The actual thickness of accreted ice need not be established for design considerations at this point since the ice removal performance estimated will be presented in terms of the rate of beam traversing velocity times the depth of the slot (units of $Length^2/Time$). That is, if the beam velocity is cut in half, the depth of cut will be doubled.

Finally, the characteristics of the laser to be applied to the deicing by melting task should be noted. It was concluded at the end of Section 4.1 that neodymium lasers represented the best possible choice for UNREP deicing. They are durable lasers requiring little maintenance, use simple fresh water cooling systems, and require no cryogenic materials, which makes them suitable for shipboard use. In addition, they are commercially available in many different power levels, including the high-power models used in material processing applications such as welding. Finally, the 1.06 μm wavelength infrared radiation emitted by the neodymium laser is readily absorbed by ice, while still allowing the use of fiber optic cables and lenses associated with visible wavelength radiation. A typical commercially available neodymium laser at the high end, as far as output power is concerned, has the following beam characteristics:

Wavelength	1.06	μm
Average Power	400	W
Maximum Pulse Energy	55	J
Pulse Width	0.5	msec to Continuous
Pulse Repetition Rate	0.2	to 500 Hz
Beam Diameter	1	mm

A laser with these characteristics would provide the greatest amount of output power reasonably available through commercial sources. Higher power levels would currently require specially designed systems at a much greater cost, thus the laser described here represents the upper limit of practicality.

4.4.2 Heating Load for Deicing

The statement of the heat transfer problem for using a neodymium laser to melt and/or vaporize icing material from the surface of a ship is pretty well described in the previous section. There is one additional constraint to the problem, however. The laser beam should not be of sufficient intensity so as to damage the underlying material to which the ice is attached. For a ship, the superstructure is either steel or aluminum, and coated with gray paint. Therefore, holding the laser beam steady upon the ice covered surface should not result in damage to either the metal, nor the paint. From a practical point of view, any operational laser based deicing system should not damage these surfaces even when they are not covered with ice.

The amount of heat absorbed by an opaque surface depends upon the amount of radiation reflected by the surface. Figure 17 shows the reflectance for several polished metals over the visible and near-infrared wavelengths. The curve for carbon steel indicates that the amount of radiation reflected from a CO_2 laser (10.6 μm) is greater than that reflected for a neodymium laser (1.06 μm), which implies that the amount of radiation actually absorbed into the metal over time is less for the CO_2 laser. The same is true to a lesser extent for aluminum. Thus it appears that CO_2 lasers have an advantage over neodymium when it comes to melting ice from metal surfaces; the longer wavelength is more readily absorbed by the ice, and a greater amount is reflected back into the ice by the metal. Unfortunately, metal reflectance decreases with increased surface temperature, and once melting begins at the metal's surface, the percent of absorbed radiation is over 90% for both laser wavelengths. This phenomena is shown in Figure 18. The high reflectance of CO_2 laser wavelengths from metals such as brass, copper and aluminum, which also have high thermal conductivities, has been a disadvantage of this type of laser for materials processing. In these metals, most of the radiation is reflected from the material initially, and what heat does penetrate the surface is rapidly conducted away. Manufacturers desiring to use CO_2 lasers for welding and metal etching have overcome this difficulty by first coating the surface of the metal with a thin layer of another highly absorptive substance. This reduces the metal's natural reflectance and allows the surface temperature to raise quickly to the melting point. It turns out that gray paint is an excellent choice for this application.

For the three materials under consideration, paint, steel and aluminum, the one with the lowest melting point determines the highest steady-state temperature that the painted metal should be allowed to reach without damage occurring. The Handbook of Materials Science [28] reports that common, highly durable enamels have a melting point below 1050 °F (565 °C), which suggests that 500 °C is an appropriate limiting temperature for paint. The melting point for aluminum is 660 °C, and for mild steel, about 1430 °C. Hence, dried paint will begin to melt, and probably burst into flame, before either of the underlying metals is affected.

For very long heating times, a source of heat energy which is uniformly distributed over a circular area of radius r will reach some limiting temperature because the heat absorbed into the material is allowed to diffuse sideways as well as into the material. The steady-state solution (very long heating times) for the increase in temperature with depth below the center of the heated area is given by [15]

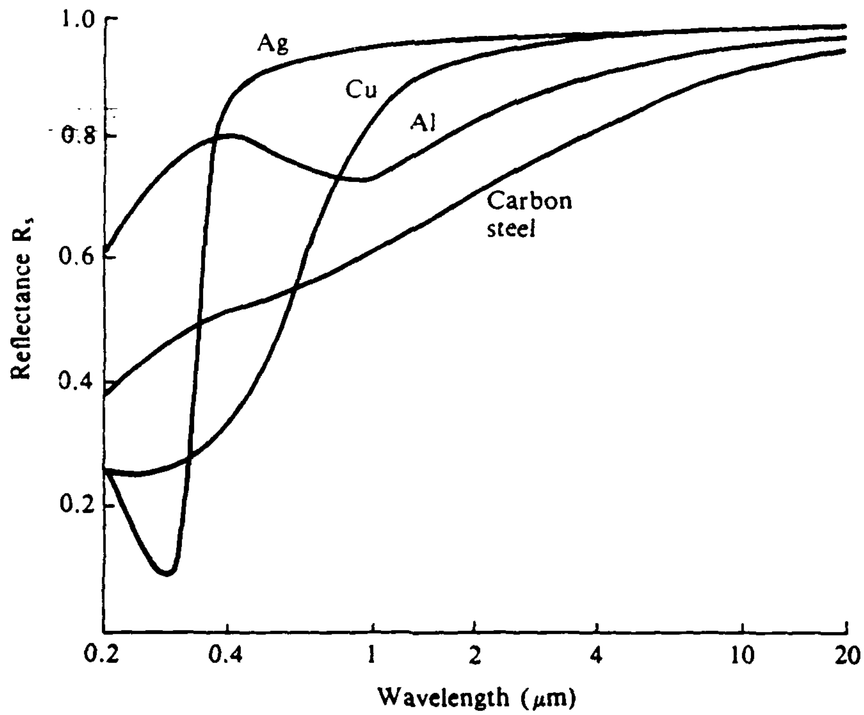


Figure 17 - Reflectance versus wavelength for various polished metal surfaces at room temperature. [15]

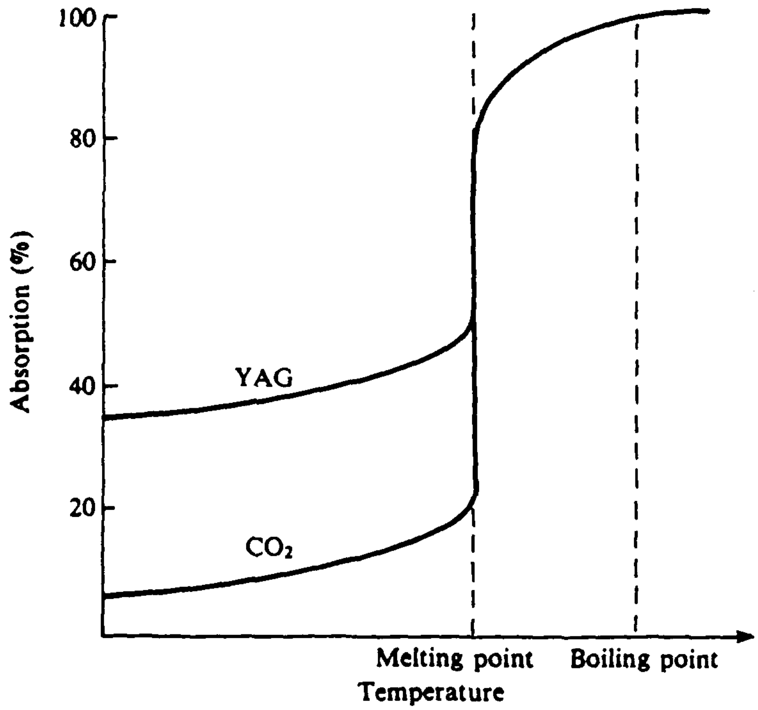


Figure 18 - Schematic variation of absorption with temperature for a typical metal surface for both the Nd:YAG and CO_2 laser wavelengths. [15]

$$\Delta T(z, t=\infty) = (q''/k)\cdot(\sqrt{z^2 + r^2} - z) \quad (13)$$

where
ΔT = amount of temperature increase
q'' = heat flux, or rate of heat flow per unit area
k = thermal conductivity
z = depth below the surface

The highest temperature which can be achieved is at the surface at the center of the heated area. In this case, Equation 13 reduces to

$$\Delta T(z=0, t=\infty) = q''\cdot r/k \quad (14)$$

The thermal conductivity for aluminum is 238 W/m°K, and for mild steel 45 W/m°K (at 300 °K). Thus, for a given heat flux, steel results in the highest temperature at the center of the heated spot. Since both metals are assumed to be coated with gray paint, they have the same absorption properties, and a given laser beam held in a steady manner on either surface would generate the same heat flux.

The reflectance of daylight light from Navy Gray paint (Federal Color #16187) is 14%, and for Deep Navy Gray paint (Federal Color #16081) is 7% [28]. Thus it is reasonable to assume a 90% absorption coefficient, $a(\lambda)$, for the amount of heat energy absorbed by the painted surface. Thus

$$q'' = I_0(\lambda)\cdot a(\lambda) = P\cdot a(\lambda)/\pi\cdot r^2 \quad (15)$$

where P is the time-averaged laser power. Substituting this expression for the heat flux into Equation 14, and using 400 Watts for the power supplied by the laser beam, the laser beam radius necessary to just warm the painted surface up to 500 °C is 5.1 mm, or about one-fifth of an inch. Although the typical high-powered laser characteristics given above suggest a beam diameter of only 1 mm, this is easily altered with neodymium lasers by placing a beam expander in the beam path. The resulting incident beam intensity for the 5.1 mm beam radius is 490 W/cm^2.

Recapping some of the results thus far— A typical high-powered neodymium laser, which would be reasonably available through commercial sources, was sized so that its output beam would not damage a steel surface painted with gray paint, even if the laser was pointed towards one location on the surface for long periods of time. The resulting beam diameter is just under a half an inch, which would provide a slot or groove through an ice sheet of sufficient width for prying off small sections of icing material with fingers or pry bars depending upon the bonding strength between the ice and the paint. The beam size would also be suitable for melting ice from covered valve handles, wire rope block and tackle sets, and other movable apparatus that must be freed before UNREP operations can commence. The analysis so far does not take into account the requirements for personnel safety, nor does it address the cost of such a laser system. These issues will be discussed in later sections.

The next consideration for the neodymium laser system described herein, is to establish its performance with regards to melting icing material. The full-blown expression for the amount of heat required to bring a frozen material, in this case sea ice, through the liquid phase and into vaporization is

$$Q = \pi \cdot r^2 \cdot z \cdot \rho_{ice} \cdot [Cp_{ice}(T_{melt} - T_i) + L_{fus} + Cp_{water}(T_{vap} - T_{melt}) + L_{vap}] \quad (16)$$

where

Q	=	amount of heat required, J	
r	=	laser beam radius, m	
z	=	thickness of ice, m	
ρ_{ice}	=	density of the icing material	$= 800\ kg/m^3$
Cp_{ice}	=	heat capacity of the ice	$= 2113\ J/kg \cdot {}_8C$
Cp_{water}	=	heat capacity of the water	$= 4226\ J/kg \cdot {}_8C$
L_{fus}	=	latent heat of fusion	$= 3.33 \times 10^5\ J/kg$
L_{vap}	=	latent heat of vaporization	$= 2.459 \times 10^6\ J/kg$

This can be simplified by using the concept of "specific energy," or the amount of heat required to raise a unit volume from one temperature to another.

$$Q = \pi \cdot r^2 \cdot h \cdot E_s \quad (17)$$

where E_s = specific energy, J/m^3

By taking the time derivative of Equation 17 and dividing through by the beam spot area, the heat flux can be related to the rate at which the surface material is removed (either by melting or vaporization depending upon where the specific energy is evaluated).

$$q'' = v_s \cdot E_s \quad (18)$$

where v_s = surface velocity or drilling speed, m/sec

Once again, this heat flux is related to the time-averaged intensity of the incident laser beam through Equation 15. As discussed in the section on the optical properties of sea ice, light at the 1.06 μm wavelength is readily absorbed with only about 10% being reflected, therefore an absorption coefficient of 90% can be used.

An estimate for the cutting rate executed by the laser beam can be related to the surface removal velocity. Let v_b be the beam scanning velocity and r the beam radius, then the beam will transverse a distance equal to the diameter of the beam in a time t equal to $2 \cdot r/v_b$. In the same period of time, the depth of the material removed is z and is equal to $v_s \cdot t$, so z equals $v_s \cdot 2 \cdot r/v_b$. Therefore, the beam scanning velocity resulting in a cut of depth z is given by

$$v_b = 2 \cdot r \cdot v_s / z \tag{19}$$

This expression is used to relate the depth of cut to the beam velocity in the laser material processing industry [15]. Substituting this result into Equation 18, and equating the heat flux to the laser's beam characteristics via Equation 15, the result is

$$q'' = I_0(\lambda) \cdot a(\lambda) = [v_b \cdot z/(2 \cdot r)] \cdot E_s \tag{20}$$

An estimate of the material removal performance for the laser melting the icing material is given by the product of the depth of cut times the cutting velocity (units of $Length^2/Time$). This makes sense from the point of view that if the beam velocity is cut in half, the depth of cut will be doubled. In this manner, the deicing by melting laser system can be compared with other ice cutting methods. Table 4 gives performance estimates for a range of different initial ice temperatures. It can be seen that there is not a great deal of difference in cutting performance with different starting temperatures. This is because the heat capacity for water is twice that for ice. The laser cutting process would be much more efficient if the icing material could be raised just to the melting temperature and the water instantly removed, but the heating process at the surface occurs so quickly that water and steam will be generated.

It should be noted that Table 4 was based on ice with a density of 800 kg/m^3 typical of glaze ice. If the density were cut in half to 400 kg/m^3, which is representative of hard rime, the cutting performance would be doubled to just under 1 in/sec. Reducing the density even further, Clark, et al., observed that covering an ice sheet with snow had almost no effect on the cutting performance of their laser system [23].

Table 4
Melting Speeds for 400 Watt Neodymium Laser

Temperature Initial °C	Temperature Final °C	Specific Energy E_s J/m³	Cutting Performance $v_b \cdot z$ m²/sec	Cutting Performance $v_b \cdot z$ cm²/sec	Beam Vel., v_b for z = 1 cm cm/sec	Beam Vel., v_b for z = 1 cm in/sec
-29	50	4.88E+08	9.21E-05	0.921	0.92	0.36
-25	50	4.81E+08	9.34E-05	0.934	0.93	0.37
-20	50	4.73E+08	9.51E-05	0.951	0.95	0.37
-15	50	4.64E+08	9.68E-05	0.968	0.97	0.38
-10	50	4.56E+08	9.86E-05	0.986	0.99	0.39
-5	50	4.47E+08	1.00E-04	1.005	1.00	0.40

4.4.3 Comparison of Laser Melting Performance with Other Deicing Methods

The only information with which to compare the cutting performance of the deicing by melting laser system is the empirical work reported by Clark, et al. [23]. Their CO_2 laser operating on freshwater ice produced slots an average of 0.3 cm in width. The product of the depth of cut times the cutting velocity was close to a constant 0.4 cm²/sec. This cutting performance is about half of the computed results given in Table 4 above, even though both laser systems generate an incident radiation intensity of about 500 W/cm². Part of the difference comes about from the different types of ice used. In particular, freshwater ice is more dense than the saline icing material, causing longer cutting times for a given volume of ice. Most of the cutting performance difference, however, is a result of the different laser beam radii. Equation 19 shows that the cutting performance, $v_b \cdot z$, is directly proportional to the laser beam radius. A larger beam, of the same intensity and moving with the same beam velocity, is incident upon a single point location for a longer period of time, producing a deeper cut.

Portable high pressure water lances have been used successfully in deicing applications on fishing vessels, supply boats, and offshore platforms. Their relatively small size and weight, their portability, their nominal ship interface requirements, and their versatility make their consideration important in the development of any shipboard deicing system. It should be pointed out, however, that water lances are not an universal solution to the shipboard deicing problem. Their use under sustained severe low temperature conditions could result in the rapid freezing of the runoff, thereby intensifying the problem rather than solving it. It is also possible that under sustained severe low temperature conditions the fluid lines and the pump of the exposed pressurized lance equipment could freeze-up, resulting in overload of the drive motor, bearing failure, or possible bursting of pipes, hoses, and housing due to the expansion of the freezing water. These problems can be minimized, but not eliminated, by the selection of a hot high pressure water lance or steam lance system. For deicing operations, the water jet is used to drill a hole through the thickness of the ice, at which time the jet is directed at the interface between the ice and the underlying surface with the objective of breaking the bond at the interface.

While water lances and steam lances are fairly prevalent, no hard engineering performance data are available for deicing performance estimates which allow direct comparison with laser deicing by melting. Performance estimates are available for cleaning and paint or rust removal since these are the primary applications for water and steam lances. The usual performance parameter is given in terms of area cleaned per unit time, but this bears no relationship to the method of deicing by water lance.

One experiment was performed for the U.S. Navy using a pulsed water jet for deicing a FFG-7 class frigate at sea [29]. The water jet operated at a 3000 psi pump pressure and had a flow rate of 2 GPM. The pulsed mode of operation was believed to offer enhanced erosivity over continuous stream water jets. In any event, the system was found to remove 2.3 pounds of seawater ice from a painted steel panel for each pound of water ejected from the nozzle. In terms of volume, the amount of icing material removed was approximately 2.5 times the volume of water used. At the 2 GPM flow rate, this amounts to a volumetric removal rate of 1.136 m^3/hr or 315 cm^3/sec. This result should not be construed as implying that a 1 cm wide water jet would cut a 1 cm deep trough with a jet transverse velocity of 315 cm/sec. Rather this is the volume of ice removed from the superstructure by erosion, melting, and separation of chunks of ice. Removal by separation is the predominate mechanism. As such no direct comparison exists between this performance result for a pulsed water lance and the high-powered laser melting speed given in Table 4. It does indicate, however, the superior performance of water lances when it comes to removing large sections of material from wide flat surfaces. Unless the melting laser can direct heat from a cut slot into the interface between the ice and the underlying surface and separate chunks of ice with the same efficiency as the water lance eroding ice at the interface (unlikely), there can be no doubt as to which system removes the greatest amount of ice in a given period of time.

4.4.4 High Intensity Laser Radiation for Ice Removal

The previous section dealt with the application of a high-power laser generating a "moderate" intensity light beam to melt a path through a sheet of icing material so that smaller sections of ice could be pried free with ease and disposed of over the side of a ship at sea (the deicing by melting scenario). It has been demonstrated by Lane and Marshall [24] that much lower powered lasers with a highly focused beam of light can result in mechanical damage to ice sheets. This is referred to as the deicing by ice shattering scenario. A summary of their experimental results is given in Section 4.3 of this report. Basically, they found that focused intensities of laser light on the order of 10^8 to 10^9 W/cm^2 produced fractures 0.1 to 2 cm long in ice. In their conclusions, they recommended a 1.06 µm laser (neodymium) producing single pulses of optical energy at 1 to 5 Joules and focused to a point diameter less than 0.2 cm. With this configuration damage was generated about 20% of the time. Specifically, with the laser beam focused at the surface of sea ice, observed damage took the form of removed chips, holes blasted through the ice (up to 2 cm), and melting. Based on these conclusions, deicing by the ice shattering method looks quite promising. Unfortunately, no performance estimates can be firmly established since the investigation concentrated on the amount and type of damage resulting from single pulses of laser radiation rather than measurements of the speed of ice removal.

The physical mechanisms by which absorption of a particular wavelength radiation begins in normally transparent solid materials are not completely understood. Below some threshold intensity, the level of which depends primarily upon the material, the beam passes through the material with no effect, but above the threshold, absorption begins with material removal from the surface, melting, vaporization, production of internal voids, and in some cases violent shattering. Ready's book on the effects of high-power laser radiation [25] goes into some detail on the phenomena with many references to published experiments, observations, and theories. The primary emphasis, however, is on transparent materials used in laser rods and optics. The following is a brief description of the various proposed damage mechanisms mentioned by Ready. One or several of the mechanisms may be present in a damage event.

Hypersonic Waves Hypersonic waves, or coherent acoustic phonons, are generated in the transparent material by a stimulated Brillouin process. Brillouin scattering involves an interaction between an optical/electrical field and an acoustic field. The incident laser radiation has an electric field associated with it. This field produces electrostrictive strain in the material, which in turn exerts pressure and drives an acoustic pulse. In order to damage ice by Brillouin scattering alone, the acoustic wave pressure has to be on the order of the tensile strength of ice.

Multiphoton Absorption Multiphoton absorption is the harmonic production and subsequent absorption of the frequency-doubled light. Imagine two photons of light at a frequency ν (energy $h\nu$) passing through a material. One photon is absorbed by an atom or molecule and then re-emitted, but re-emitted in such a way that it combines with the second photon. The new photon has an energy of $2h\nu$ and is twice the frequency. If the higher energy light is absorbed into the material, electron ionization can occur. As further electrons are produced, an absorbing plasma is formed resulting in large heat build-up and damage to the material.

Intraband Absorption Intraband optical absorption is similar to multiphoton absorption in the production of an electron plasma, which leads to heat build-up and material damage.

Absorption at Defects Structural inhomogeneities, such as microcracks, present in an otherwise transparent material result in increased absorption of the light at the inhomogeneities. It is uncertain how damage to the material is caused, but it is speculated that the hypersonic pressures or thermal stresses lead to expansion of the original microcracks.

Microplasmas-High Temperatures A high temperature plasma is formed near the focal point of laser light. The heating leads to vaporization, and in some cases ionization, inside the material. Pressure is exerted by the vaporized material on the surrounding region. If the pressure in the solid material exceeds its yield strength, further damage will occur.

Superposition of Stress Waves The superposition of stress waves assumes that some radiation is absorbed even in nominally transparent materials. It is postulated that, under some conditions, low level stress waves are formed which are superimposed in some region of the material. This can lead to a very high stress state and possible damage.

Surface Damage It has been observed that surface damage can occur at lower levels of intensity than volume damage.

In many cases, a theoretical analysis using one of the above postulated damage mechanisms predicts much higher threshold intensity than the threshold intensities measured in laboratory experiments. A large part of the discrepancy may be due to the phenomenon of self-trapping or self-focusing of the laser beam. The high intensity associated with the beam alters the index of refraction within the transparent material. Instead of diverging in the medium, the beam focuses itself and creates its own waveguide. In this situation, intensities can be generated which are higher than those computed from the beam characteristics and and associated optics.

The laser used in the Lane and Marshall study [24] was a much smaller unit (and undoubtedly less expensive) than the one postulated for the melting scenario. The laser had interchangeable rods to allow for both ruby and neodymium wavelength operation, but in the neodymium configuration, it had the following beam characteristics.

	Normal Pulsed Mode	Q-switch Mode
Pulse Width	0.8 to 2 msec	30 to 50 nsec
Maximum Pulse Energy	5 J	0.9 J

In general, the investigators found the Q-switched mode to be more efficient in producing fractures. Even though the pulse energy is lower in this mode, the delivered power, energy divided by pulse width, can be much higher over the duration of the pulse. This should not be confused with the time-averaged power (pulse energy divided by the pulse repetition period).

All lasers which operate in the pulsed or Q-switched mode have a performance envelope which describes the available combinations of output energy and pulse width verses the pulse repetition rate (PRT). Specifics were not given for the Lane and Marshall laser, but typical values for a continuous excitation neodymium laser operated in the Q-switched mode are a pulse repetition rate of 0 to 100 kHz, with a pulse duration of 100 to 700 nsec. Nd:Glass lasers can be built with larger rods than Nd:YAG and are therefore capable of higher energy pulses. Unfortunately, the Nd:Glass rod suffers from thermal problems which limit its average power to less than that of the YAG. These lasers are only available with pulsed lamp excitation which solves the heating problem, but also limits the pulse repetition rate. Typical performance envelope values would be a pulse repetition rate of 0 to 200 Hz (lamp limited) and a pulse duration of 3 to 30 nsec [14]. However, in order to achieve high pulse energies, the pulse repetition rate must drop. The usual value encountered for a Q-switched pulse energy of 1 J is only 10 Hz (unless the high-powered lasers from the previous section are again considered).

We are now in a position to speculate upon the performance of a moderately low-powered neodymium laser focused to a high intensity spot on the surface of an ice sheet. Let the selected laser be a commercially available, Q-switched laser capable of producing pulses of 1 J and a modest 10 Hz pulse repetition rate. Next, assume that mechanical damage is achieved with a 20% frequency as observed by Lane and Marshall. Typical fractures were reported as being distributed between 0.1 to 2 cm in diameter, but assume that the average damage size is only 0.5 cm in diameter and that the distance between damaged locations is 1 cm. With these characteristics the laser generates 2 points of damage per second, or, ideally, a groove through the ice at a rate of 2 cm/sec (about 1 inch/second). This velocity is two times higher than that achieved by the deicing by melting method, and does not even account for the fact that 90% of the laser energy which is not involved in producing mechanical damage (the other 4 out of 5 pulses) is absorbed by the saline ice in the form of heat. In actual performance tests, it may turn out that once a point of fracture has been initiated in the ice, a faster beam velocity is realized. Laboratory tests are needed to determine the real performance characteristics of the deicing method.

All enthusiasm aside, one problem with deicing by shattering is the fact that the focused laser beam must be accurately positioned on the surface of the ice sheet. It is envisioned that the deicing laser system would start with a fiber optic cable coming from the neodymium laser for ease of handling. At the business end of the cable, a hand held wand or tube would send the laser light from the fiber optic cable, through a carefully positioned convex lens, and on to the lens focal point just outside the opposite end of the tube. In operation, the discharge end of the tube would be placed flat against the ice surface which would also allow the high intensity light at the lens focal point to be positioned right at the ice surface. With this simple arrangement it would be difficult to damage unintentionally other surfaces or equipment because the location of the highly focused part of the beam is known, however, it would also be impossible to break away ice located inside a groove or pit. As mechanical damage occurs and a slot or groove is started, it becomes harder to remove more ice from inside the groove. Thus, the beam scanning velocity looks better for deicing by ice shattering than by ice melting (if 2 in/sec could be achieved, this would probably be a reasonably efficient deicing tool), but the depth of the cleared groove remains a question.

Another concern with the Q-switched laser described for the chipping application is the damage that it can do to other surfaces. Although the laser itself is much less powerful than the deicing by melting laser, the focused beam of light has an extremely high intensity at the focal point. This should not be a problem, however, unless the deicing wand is intentionally held against a surface because the beam diverges after the focal point which reduces the radiant intensity with distance from the wand. The laser described here has a time-averaged output power of 10 Watts (1 Joule divided by 0.1 sec pulse repetition period).

4.4.5 Conclusions

Two types of deicing laser mechanisms have been described; one uses a moderately intense laser beam to remove ice from an ice covered surface by melting alone, the other process uses a relatively low-powered laser with a highly focused beam of light to remove ice by mechanical means such as chipping, blasting holes, and violent shattering. The latter case relies on the phenomenon of a normally transparent material becoming an absorbing material once incident laser radiation passes above some threshold intensity.

The deicing by melting laser system postulated a typical high-powered neodymium laser similar to the types commercially available for manufacturing processes. The laser beam was sized to melt the ice as quickly as possible without causing damage to the underlying painted surface. The computed performance for the laser to melt a groove through glaze ice was about 1 cm^2/sec, so a one centimeter deep slot could be made with the laser beam scanning at a rate of 1 cm/sec (0.4 in/sec). It was assumed that any steam generated would be blown away and that melt water would run-off quickly so that the efficiency of the laser systems would not be reduced further. These were felt to be reasonable assumptions for ice covered vertical surfaces on a wind swept ship at sea. The primary culprit in the low performance estimate is the high heat capacity of water. The cutting speed would improve greatly if the ice could be brought just to the melting point and the water instantly removed, unfortunately, hot water and steam have been observed to be by-products in other laser/ice experiments.

The discussion of deicing by ice shattering relied heavily upon the experimental results reported by Lane and Marshall [24] where they used a much smaller neodymium laser with focused intensities of laser light on the order of 10^8 to 10^9 W/cm^2 to produce fractures 0.1 to 2 cm long in ice. They concluded that the method was feasible and reasonably efficient for the deicing application. However, no performance estimates were established since the investigation concentrated on the amount and type of damage resulting from single pulses of laser radiation rather than measurements of the speed of ice removal. Some rough estimates were attempted here which suggest ice removal at a rate of 2 cm/sec (1 inch/second) for grooves up to 2 cm in depth. This performance guess is about twice the beam velocity for the melting laser system. Analytic performance estimates are not possible at the present time because the physical mechanisms behind the mechanical damage process are not completely understood, or even identified. As such, a laboratory test is probably the only means to develop accurate performance estimates for this deicing method.

Based on these conclusions, the deicing by ice shattering method looks quite promising, unfortunately, the question of its actual ice removal rate remains unanswered. The analysis so far does not take into account the requirements for personnel safety, nor does it address the costs of either laser system. These issues will be discussed in later sections.

4.5 Applications Analysis

Both of the neodymium lasers postulated in the previous section for deicing by melting or deicing by ice shattering produce sufficient radiation to be classified as Class 4 lasers. Lasers of this class are definite safety hazards for personnel. These lasers produce a hazard not only from direct or specular reflections, but also from diffuse reflections. In addition, such lasers may produce fire hazards and skin hazards. For both continuous wave and pulsed mode lasers in the visible and infrared portions of the spectrum, including the Nd:YAG wavelength of 1.06 μm, a time-averaged emitted power of greater than 0.5 W is considered a Class 4 laser.

In Section 4.2.2 on laser safety, the maximum permissible exposure, MPE, for human skin at the neodymium laser's 1.06 μm wavelength was determined to be 1 W/cm^2 over long exposure times. This represents the worst case situation, and is probably the most appropriate choice for the crewmember assigned to operate the deicing laser. For direct ocular exposure, the maximum permissible exposure is 1.6 mW/cm^2 for an exposure duration of over 1000 seconds (17 minutes). This is the most hazardous scenario and is akin to staring into the laser beam. The 1.6 mW/cm^2 is the intensity of the radiation reaching the eye, therefore a crewmember is considered safe from ocular radiation danger if eye protection is worn which reduces the intensity to the ocular MPE level or less.

One approach to the selection of eye protection with adequate optical density is to match the skin MPE and ocular MPE. That is, the relative radiation hazard striking the body is the same for both the eyes and the skin. In Section 4.2.1 it was pointed out that the desired optical density for eyewear is the minimum optical density required to attenuate the maximum expected radiation intensity down to the ocular MPE limit. The optical density was defined in Equation 10.

$$D_\lambda = \log_{10}(I_i/MPE) \tag{10}$$

Greater optical density does reduce the intensity reaching the eye below the MPE, but it also reduces the individual's ability to see; also a safety hazard. If the radiation reaching the safety glasses is the same as the skin MPE, then for the 1.06 μm neodymium laser

$$D_\lambda = \log_{10}(MPE_{Skin}/MPE_{Eye})$$

$$= \log_{10}(1\ W/cm^2 \div 1.6\ mW/cm^2)$$

$$= 2.79$$

Table A-1 in Appendix A lists some types of laser eye protection by manufacturer. For each model, the optical density is given versus wavelength. The table shows that several models exist which offer a optical density of greater than 3 at the 1 06 µm wavelength, while still possessing a daylight transmittance of around 80%.

The next step in the applications analysis is to determine the safe working ranges, the nominal hazard distances (NHD), for people in the vicinity of the laser or the laser operator. Two ranges will be considered depending upon whether an individual is wearing safety glasses or not. If the individual is wearing safety glasses as described above, the NHD is that distance where the incident intensity is equal to 1 W/cm². Without glasses, the eyes determine the safe intensity level, and the NHD is set where the incident intensity is 1.6 mW/cm².

Starting with the high-powered deicing by melting laser, the time-averaged power output was given as 400 W with a beam radius of 5.1 mm in order to avoid melting or burning the paint covering the metal parts of the superstructure. This results in an intensity of 490 W/cm² which is way above the skin MPE limit. Even if the laser beam is directed to the ice and only 10% of the radiation is reflected, the reflected intensity would be 50 times too high for skin exposure. One solution to this problem is to introduce a large divergence to the beam through a convex lens mounted at the end of the fiber optic delivery cable, although this approach eliminates the possibility of deicing at remote distances using the laser. It is envisioned that the laser deicing apparatus would be set up as follows: a laser power supply permanently installed at some safe, dry location in the interior of the ship; the actual laser would be permanently mounted near the power supply with its beam of light coupled to a long fiber optic cable; the laser deicing operator would be at the other end of the cable directing the laser beam where needed with a hand held tube. The fiber optic cable is attached to one end of the tube which serves to hold the light exiting optics and provides a safe means for the operator to direct the light. Figure 19 shows a sketch of the arrangement.

The question remains, what beam divergence angle is necessary to make this arrangement safe for operating personnel and passers-by? The upper part of Figure 16 gives an equation to determine the range necessary at which the radiation is equal to the safe MPE. The equation was derived using small angle approximations, so the complete equation for the range to the nominal hazard distance (NHD) is

$$r_{NHD} = [\sqrt{P/(\pi \cdot MPE)} - r/2]/\sin(\varphi/2) \qquad (21)$$

If the ocular MPE is used, then the result is the range to the nominal hazard ocular distance (NOHD).

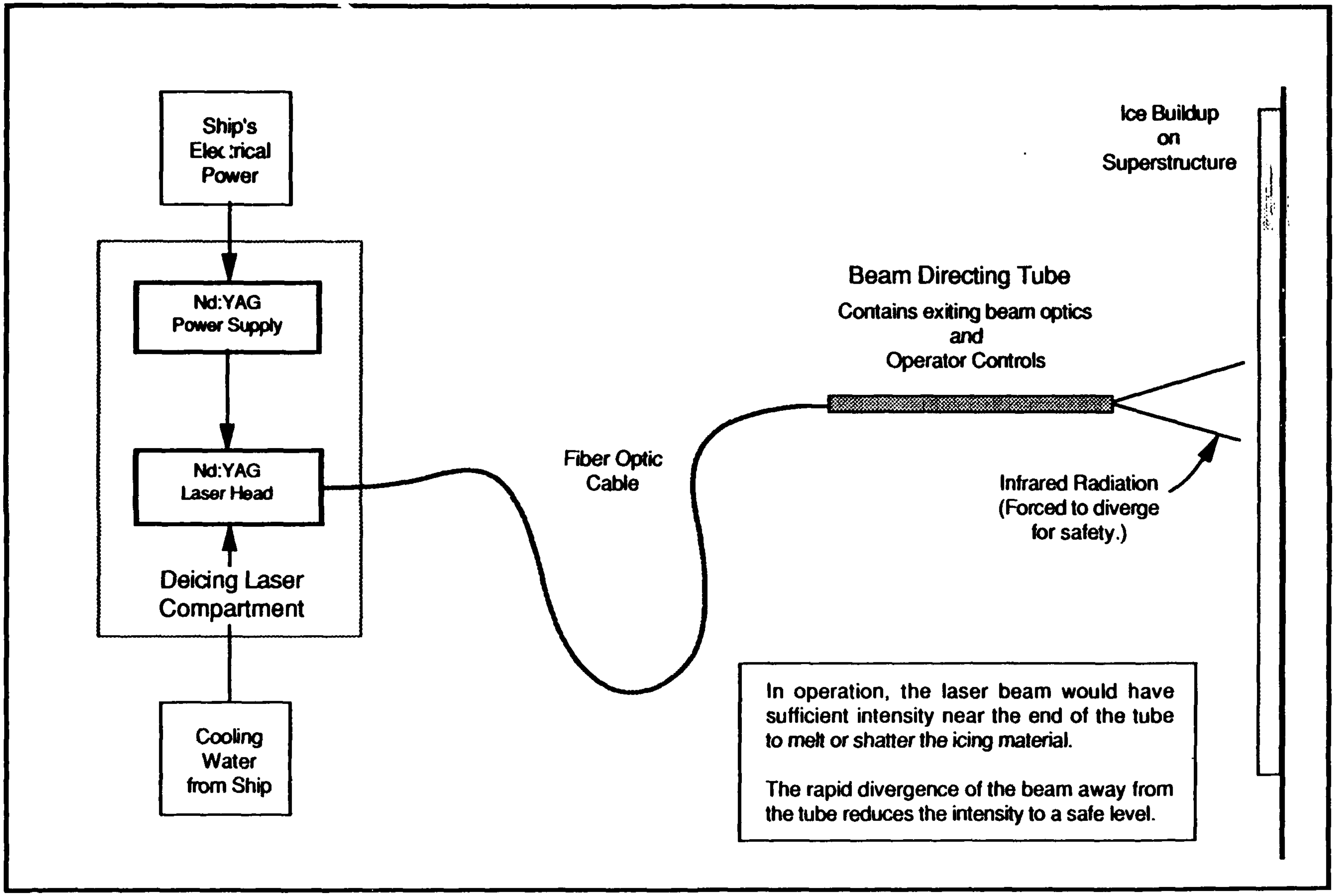


Figure 19 - Basic Concept for a Deicing Laser System
Using a Fiber Optic Beam Delivery System

Table 5 shows the computed NHD for a high-powered laser with 400 W average power being emitted. The laser beam would still have enough intensity at the hand-held tube exit to melt the ice, but the beam diverges after this point in order to reduce the radiant intensity for personnel safety. For example, for a divergence of 40°, about the same as that of a common flashlight, the laser operator and other members of the deicing team would be considered safe at a distance of 1 foot from the tube exit if they were wearing the proper safety glasses. A passer-by without safety glasses would be safe at a range of 27 feet. Since approximately 90% of the radiation is absorbed by the ice, the reflected light beam is much less intense.

The diverging beam greatly reduces the radiation hazard range. Unfortunately, the 27 ft hazard distance for passers-by may prove unacceptable on a navy vessel with many sailors out on deck trying to remove accreted ice as quickly as possible. A similar computation for a 10 W average power deicing by ice shattering laser is given in Table 6. In this case a divergence of only 7.5° would yield approximately the same NMD ranges as before. A divergence of 12.5° gives a deicing team safe range of about a half a foot, and a 13.5 ft safe range for a passer-by. Higher divergences may be difficult to achieve with this laser configuration since the beam would have to be focused to a tight point close to the lens for the very high intensities required before the beam diverges beyond the focus. Since low pulse repetition rates are involved here, this calculation should also be performed based on the energy delivered in each pulse in addition to the intensity (J/cm^2 instead of W/cm^2) depending upon the pulse duration of the laser used.

There are still safety hazards associated with a deicing system using a diverging beam, however the hazard zone is now known and controllable. With proper training, a laser deicing system could be no more dangerous than an operating chainsaw. One important hazard still exists, however. Suppose the laser operator slips on the icy deck and falls on the hand-held tube. Severe medical injuries would result, and at the very least, a dead man's switch should be incorporated into the beam directing tube's design. At least with the use of a fiber optic delivery system, the problem of electric shock from the laser's power supply is eliminated.

Table 5
Nominal Hazard Distances for High-Powered Deicing by Melting Laser With and Without Eye Protection

Average Power	400	W
Beam Radius	5.1	mm
	0.51	cm
Beam Intensity	489.52	W/cm^2

Divergence	Range NHD MPE = 1 W/cm^2		Range NOHD MPE=1.6 mW/cm^2	
φ (°)	cm	ft	cm	ft
0.1	12346	405.05	322672	10586.37
1	1235	40.51	32268	1058.65
2	617	20.25	16134	529.35
3	412	13.50	10757	352.92
4	309	10.13	8068	264.71
5	247	8.10	6455	211.79
7.5	165	5.40	4305	141.25
10	124	4.06	3231	106.00
12.5	99	3.25	2587	84.86
15	83	2.71	2157	70.78
20	62	2.04	1622	53.20
25	50	1.63	1301	42.68
30	42	1.37	1088	35.69
35	36	1.18	936	30.72
40	32	1.03	823	27.01
45	28	0.92	736	24.14
50	25	0.84	666	21.86
55	23	0.77	610	20.01

Table 6
Nominal Hazard Distances for Deicing by Ice Shattering Laser With and Without Eye Protection

Average Power	10	W	(in Q-switch mode)
Beam Radius	0.25	mm	
	0.025	cm	
Beam Intensity	5092.96	W/cm^2	

Divergence	Range NHD MPE = 1 W/cm^2		Range NOHD MPE=1.6 mW/cm^2	
φ (°)	cm	ft	cm	ft
0.1	2016	66.14	51083	1675.94
1	202	6.61	5108	167.60
2	101	3.31	2554	83.80
3	67	2.20	1703	55.87
4	50	1.65	1277	41.91
5	40	1.32	1022	33.53
7.5	27	0.88	682	22.36
10	20	0.66	511	16.78
12.5	16	0.53	409	13.43
15	13	0.44	342	11.20
20	10	0.33	257	8.42
25	8	0.27	206	6.76
30	7	0.22	172	5.65
35	6	0.19	148	4.86
40	5	0.17	130	4.28
45	5	0.15	116	3.82
50	4	0.14	105	3.46
55	4	0.12	97	3.17

4.6 Prototype Hardware Selection

Earlier conclusions indicated that a moderately powerful neodymium laser, with a highly focused beam to shatter icing material, was probably more efficient and certainly less expensive than using a high-powered laser to melt through the ice. This conclusion was based on the successful experiments conducted by Lane and Marshall [24]. Both laser configurations can be designed so that a reasonable level of personnel safety from laser radiation can be achieved. The next question to address is the costs associated with using a neodymium laser system for deicing. With many laser systems, the costs would be divided into the purchase price and operating costs, but neodymium lasers in general have very low operating costs. Most of the lasers investigated could be powered from a 220 volt electrical circuit, and generally use plain water for cooling. They are also among the more durable of lasers, and so are better able to withstand the tossing and pitching of a ship at sea. Therefore, routine maintenance and safety training would be the main operating costs.

The purchase price for any sophisticated laser system, however, turns out to be considerable. Appendix B gives a listing of all laser manufacturers (most of them neodymium laser manufacturers) contacted for information in the course of this study. Table 7 below lists specific neodymium laser systems and their estimated purchase price for a range of output power levels. The laser systems given are ordered in terms of increasing cost.

In general, the table shows a rapid increase in purchase price with increased output power capability. In all cases, the option for Q-switching from a pulsed laser is extra. The laser systems given here can be divided into three broad categories by operating principle and cost. At the low-power end, the neodymium lasers tend to operate in the CW mode. If Q-switching is desired, the laser can be turned on and off rapidly in phase with the required Q-switch cycle frequency. These low-power lasers are used for medical applications and in manufacturing electronics components. This power level is too low for them to be used for either the deicing by melting or deicing by ice chipping systems.

Table 7
Approximate Costs for Neodymium Laser Systems

Model & Manufacturer	Operating Mode	Average Power	Pulse Energy	Pulse Repetition Rate	Approx. Cost, $
Model 775M Lee Laser	CW Q-switched	75 W	 15 mJ	 <50 kHz	17,325 23,300
M0060-0101 MY32-10 Laser Photonics	Pulsed	2.5 W	225 mJ	10 Hz	27,500
M0060-0102 MY32-20 Laser Photonics	Pulsed	2.5 W	225 mJ	20 Hz	28,900
Model 9430 Laser Metrics	Pulsed Q-switch option		3 J 450 mJ	10 Hz	21,500 29,480
M0060-3761 MY33-10 Laser Photonics	Pulsed	4.5 W	400 mJ	10 Hz	30,000
M0060-0341 MY34-10 Laser Photonics	Q-switched	8 W	700 mJ	10 Hz	32,500
M0060-0342 MY34-20 Laser Photonics	Q-switched	8.5 W	700 mJ	20 Hz	37,500
300 Watt Model U.S. Laser Corp.	Pulsed	300 W		<100 Hz	38,000
M0060-3771 MY35-10 Laser Photonics	Q-switched	11 W	1 J	10 Hz	42,000
Model 936Y3H-3 Laser Metrics	Pulsed Q-switch option		30 J 2 J	1 Hz	39,400 51,100
Antares Model 76 YLF Coherent Laser Products	CW	22 W			58,000
KLS016 LASAG Corp.	Pulsed Q-switch option	30 W	26 J 200 mJ	<20 Hz	58,000
Model SS484 Raytheon	Pulsed	100 W			60,000

Table 7 (Continued)
Approximate Costs for Neodymium Laser Systems

Model & Manufacturer	Operating Mode	Average Power	Pulse Energy	Pulse Repetition Rate	Approx. Cost, $
Model 94100	Pulsed		10 J	10 Hz	55,800
Laser Metrics	Q-switch option		1 J		67,500
Model JK702	Pulsed	250 W	2.2 J	@100 Hz	69,875
Lumonics				Plus 7,000 for optics	
Antares YAG	CW	24 W			
Coherent Laser Products	Q-switched	13 W	4 mJ	<20 kHz	76,000
Model SS550	Pulsed	400 W	3.5 J	@100 Hz	115,000
Raytheon					
450 Watt Model	Pulsed	450 W	50 J	<300 Hz	150,000
LASAG Corp.					

At the high-powered end, generally over 100 Watts average power in pulsed mode, are the heavy manufacturing lasers which are used for cutting, welding and drilling holes in metal. These lasers operate in the pulsed mode rather than continuous mode to avoid overheating the neodymium rod. In general, they can be modified to operate with Q-switching with a greatly reduced average output power (peak power is increased substantially, however). In the pulsed mode, the pulse width is usually about 1 to 10 msec wide. This provides heat energy stretched out over a "long" period of time in order to melt and flow material without vaporization during welding. In the Q-switch mode, however, the pulse width is on the order of a few nanoseconds. This is used during drilling holes to remove material quickly through vaporization. As a general rule, in order to produce higher peak power levels in either mode, a given laser needs a longer cycle time; i.e., shorter pulse repetition rate. These lasers would be suitable for the deicing by melting application, but note that they cost between $60,000 and $150,000.

The neodymium lasers between these two groups, moderately powered lasers up to 100 Watts average power while operating in the pulsed mode, have similar characteristics to the laser used for the Lane and Marshall investigation. In this regard, any neodymium laser capable of producing about 5 Joules per pulse in normal pulsed mode, or 1 Joule per pulse in Q-switch mode, which is focused to sufficient intensity will generate mechanical failure in ice. The laser used in their study, a Hadron/TRG Model 104A laser system, is no longer being produced. In fact, Hadron Inc. is no longer in the business of manufacturing lasers. However, three similar lasers were found that achieve these performance requirements in one mode or the other. These are given in Table 8.

Table 8
Neodymium Laser Systems Suitable for Deicing by Ice Shattering Tests

Model & Manufacturer	Operating Mode	Average Power	Pulse Energy	Pulse Repetition Rate	Approx. Cost, $
M0060-3771 MY35-10 Laser Photonics	Q-switched	11 W	1 J	10 Hz	42,000
KLS016 LASAG Corp.	Pulsed Q-switch option	30 W	26 J 200 mJ	<20 Hz	58,000
Model 94100 Laser Metrics	Pulsed Q-switch option		10 J 1 J	10 Hz	55,800 67,500

It can be seen that the pulse repetition rate necessary for the energy levels stated is around 10 Hz. Also, the purchase price averages about $50,000 to $60,000. A fiber optic delivery system is available for each laser at an additional cost. For instance, a fiber optic cable for the Laser Metrics Model 94100 has a 600 µm optical diameter and costs about $1200 for the optical coupling and $1200 for each 5 meters of cable length. Care must be taken in choosing the proper fiber optic cable in these lasers because the high energy per pulse translates into very high light intensities traveling through the cable. This is particularly true with the Q-switched option since the pulse energy is crammed into very short time periods giving a peak power that is usually higher in this mode than the normal pulsed mode. After all, the concept of shattering ice with high intensity radiation originally came from documented cases of high intensity mechanical damage to glass and optical components, and the intensity levels needed to generate this damage is about the same for glass and ice. When such damage occurs to a fiber optic cable, this is referred to as "blowing out a cable."

Of the three models given, only the third listed meets the output energy levels used by Lane & Marshall in both the pulsed and Q-switched mode. Since the mid-range lasers are considerably less expensive than the high-powered manufacturing lasers, require less space for their power supplies and associated equipment, and their feasibility for ice removal by mechanical damage has been established, future investigations into laser deicing should concentrate on these types. It turns out that lasers in this middle ground, between the low-powered, light industry lasers and the high-powered, heavy manufacturing lasers, are not as common on the market place because of a limited number of applications. Appendix B contains more detailed information describing the features of each of the three lasers.

In Section 4.4.3 a comparison was made between laser deicing and using a portable high pressure water jet for deicing. Although a direct performance comparison was not possible, the conclusion was made that a deicing water jet is capable of removing much larger quantities of icing material because of its ability to direct the water stream into the interface between the ice and the underlying surface, thus removing substantial sections of ice in slabs. A comparison should also be made of the costs associated with the two deicing methods. Schultz conducted a survey of commercially available high pressure water jets suitable for deicing [30]. In general, it was reported that most water lances actually used for ice removal used a jet pressure of around 3,000 to 4,000 psi. (Pressures on the order of 20,000 psi are needed to remove paint from steel.) An additional requirement of the investigation was that the units be of a size that could be handled manually with the intent of using them aboard U.S. Navy surface ships for deicing. The typical price range for units meeting the criteria ranged from $5,000 to $10,000, with the more rugged units pushing the top of the price range.

Therefore, even the more expensive high pressure water lances cost only 10 to 20% of what a moderate powered neodymium laser suitable for deicing by ice chipping with additional fiber optic beam delivery system would cost. In addition, training the crew for deicing operating techniques and safety would be minimal for the water lance. It is conceivable that routine maintenance expenses would be roughly comparable between the two systems, but replacement of major components is certainly more expensive for the laser system. Also, in the event of a breakdown which renders the water lance system out of commission, it is likely that the ship's machine shop could fabricate the necessary parts for temporary repair. No such back up, short of maintaining a ready supply of spare parts, exists for the laser deicing system.

4.7 Conclusions on the Use of Lasers for Deicing and Some Suggestions for Future Laboratory Tests

It has become clear in the course of this investigation that the world is not yet ready for laser deicing of surface ships after a topside icing event. It has been shown that it is physically possible for lasers to remove icing material from painted metal either by melting or by producing mechanical damage within the ice. Ice melting can be accomplished without damaging the underlying material if the proper wavelength laser is selected so that the energy is absorbed into the ice while the radiation intensity is kept to low enough levels to avoid burning the paint. In the case of ice removal by mechanical damage, a lower powered laser than the deicing by melting laser can be used if the laser beam is focused to an extremely high intensity. This is technically feasible and the theory has been verified by previous laboratory tests.

Once it was determined that laser deicing was physically possible, an investigation was conducted into the safety aspects of the problem. While radiation and electrical safety are major concerns, it is felt that laser deicing systems could be engineered that afford a reasonable level of safety to the laser operator and other topside personnel. The question of safety does, however, limit the range of applications for the laser deicing system. The need for a rapidly diverging beam, for instance, precludes using the laser to remove ice some distance from the operator.

Thirdly, a search was conducted of current laser manufacturers to determine if commercially available lasers exist which could be adapted to the problem of removing icing material. Several suitable, durable neodymium lasers were located, and purchase price information was obtained. Average prices ranged around $50,000 to $60,000 before inclusion of special features such as a fiber optic delivery system.

Finally, a comparison was made between a prototype laser deicing system and high pressure water lance deicing systems. Unfortunately for the laser, the water jet turned out to possess greater capability for removing large quantities of ice while costing about one tenth to one fifth as much. In addition, the water lance is simpler to maintain and does not have the same level of safety concerns as the laser system.

Therefore, the concept of using a laser for deicing is both physically and technically feasible, however the comparison with a high pressure water lance demonstrates that simpler, safer, cheaper, and more efficient methods exist for attacking the problem of removing ice prior to conducting UNREP operations aboard U.S. Navy surface ships operating in the high latitudes of the world.

While the prospect of using lasers for deicing does not look promising at the present time, the situation could change if additional uses for the laser are found. For instance, it was shown in the course of this study that the intensity of infrared radiation produced by neodymium lasers would be limited by the melting and/or burning point of Navy Gray paint. The lasers considered here could be adapted to the task of routine paint removal by a simple adjustment to beam optics and using a pulsed mode of operation.

If it becomes desirable to conduct laboratory tests on laser deicing at some point in the future, the following comments and suggestions might prove helpful. Previous laboratory tests demonstrated the feasibility of using moderately powered lasers to produce mechanical damage to the surface of sea ice [24], however, no practical performance estimates were reported since the focus of the experiment was to determine if mechanical damage did indeed occur. Future laboratory tests should use a similar laser with both normal pulsed and Q-switched modes of operation for a comparison of the results. The Q-switched configuration appears to be the more effective in generating mechanical damage, but it is also an expensive option that may not be needed if the purchase of several units is contemplated. Performance estimates to be obtained as a result of the experiment include measurements of the rate at which a slot can be cut through ice sheets of various thicknesses. Saline ice should be used instead of fresh water ice, and, if possible, ice of different densities should be grown.

In addition, a simple test should be conducted to determine the total volume of ice removed by melting a hole through the ice, directing the laser beam at the interface and separating chunks of ice from the substrate. This would provide a comparison with the method of using a water lance for deicing. The experiment should also determine if a laser beam which is pointed at a single location, melts a hole through the ice, and uses the thermal conductivity of the metal to melt more ice along the interface between the ice and metal, and around the melted hole, is an effective laser deicing technique.

5. INFRARED UNREP ANTI-ICING AND DEICING

5.1 Practical Summary of Infrared Heating Technology

5.1.1 Fundamentals of Radiant Heat Transfer

Heat is transferred by three different mechanisms, conduction, convection, and radiation [31]. The common features of these mechanisms are that temperature differences must exist in order for heat to be transferred, and that heat is always transferred in the direction of decreasing temperature, or from the higher temperature to the lower temperature. These mechanisms differ entirely, however, in the physical process which occurs, and the laws by which they are governed. Heat conduction is due to the property of matter which allows the passage of heat energy through the matter, even if a physical body is impermeable to any kind of radiation and its parts are not in motion relative to one another. Heat convection is due to the faculty of moving matter to carry heat energy in the manner of transporting a load from one place to another. Heat radiation is due to the property of matter to emit and to absorb different wavelengths of radiation from the electromagnetic spectrum. Empty space is perfectly permeable to this radiation, and many types of material are more or less transparent to the passage of this radiation.

By way of example, if one end of a metal rod is placed in a flame while the other is held in the hand, that part of the rod that is being held will become hotter and hotter although it is not itself in direct contact with the flame. Heat reaches the cooler end of the rod by conduction along or through the material of the rod. The term convection is applied to the transfer of heat from one place to another by the actual motion of hot material. Examples are a hot air furnace and a hot water heating system. If the heated material is forced to move by a blower or pump, the process is called forced convection. If the material flows due to differences in density, the process is called natural or free convection. Radiant heat transfer consists of the transfer of energy by invisible electromagnetic waves. Two common examples of radiant heat transfer are the heat of the sun and heat from a fireplace.

The term radiation refers to the continual emission of energy from the surface of all bodies. This energy is called radiant energy and is in the form of electromagnetic waves. These waves travel with the velocity of light, and are transmitted through a vacuum as well as through air. This characteristic of radiation heat transfer, i.e. the fact that it does not depend on an intermediate material as a carrier of energy as do conduction and convection, is one of the primary attributes of interest in the application of infrared heating to the topside icing problem. When the electromagnetic waves fall on a body which is transparent to them, such as one's face or the deck, they are absorbed and their energy is converted into heat. The radiant energy emitted by a surface depends on the nature of the surface and on its temperature [32]. At low temperatures the rate of radiation is small and the radiant energy is chiefly of relatively long wavelength. As the temperature is increased the rate of radiation increases very rapidly, in proportion to the fourth power of the absolute temperature. At each temperature, the radiant energy emitted is a mixture of waves of different wavelengths following a distribution curve. A rough idea of the spectral energy distribution from a black surface can be obtained from the fact that about 25% of the energy is radiated at wavelengths shorter than the wavelength of maximum emissive power, while about 75% is radiated at wavelengths longer than the wavelength of maximum emissive power [33]. At a temperature of 300 °C (572 °F), practically all of the radiant energy emitted by a body is carried by waves longer than those corresponding to red light, hence, the name infrared, or beyond the red. At a temperature of 800 °C (1472 °F), a body emits enough visible radiant energy to be self-luminous and appears to be "red hot". By far the larger part of the energy emitted, however, is still carried by infrared waves. At 3000 °C (5432 °F), which is approaching the temperature of an incandescent lamp filament, the radiant energy contains enough of the shorter wavelengths so that the body appears nearly "white hot" [32]. The infrared portion of the electromagnetic spectrum includes those wavelengths which will produce heat upon being absorbed by an object, and covers the range of wavelengths from 0.72 to 1000 microns. The range of useful wavelengths for industrial applications is from 1 to 10 microns. A chart of the electromagnetic spectrum is shown as Figure 20 [32]. An expanded presentation of the infrared portion of the electromagnetic spectrum is presented as Figure 21 [34].

The rate of emission of radiant energy from the surface of a body is expressed by the Stefan-Boltzmann Law:

$$q = \epsilon \sigma A T^4 \qquad (22)$$

where:

- q = rate of emission of radiant energy, or the rate of heat flow, BTU/hr
- ϵ = emissivity of the surface, lying between 0 and 1, depending on the emitter material, the nature or condition of the surface, and the temperature
- σ = Stefan-Boltzmann constant, independent of both surface and temperature, 1.73 x 10-9 BTU/ft^2-hr-R^4
- A = area of the surface, ft^2
- T = absolute temperature, ° Rankine.

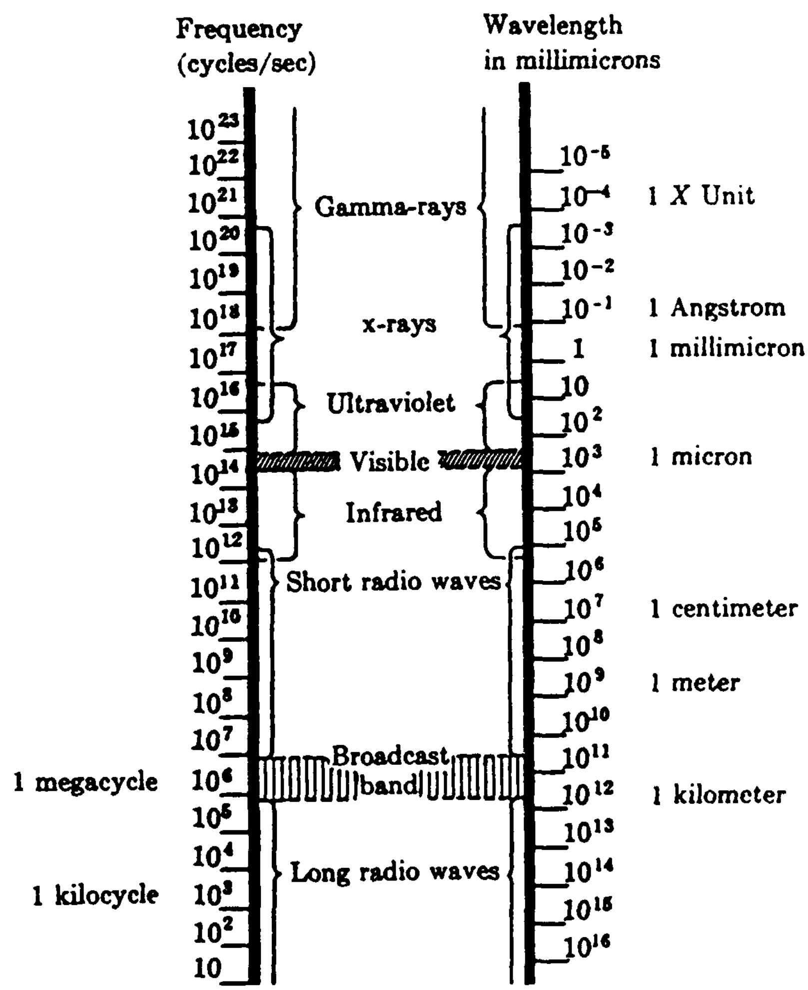
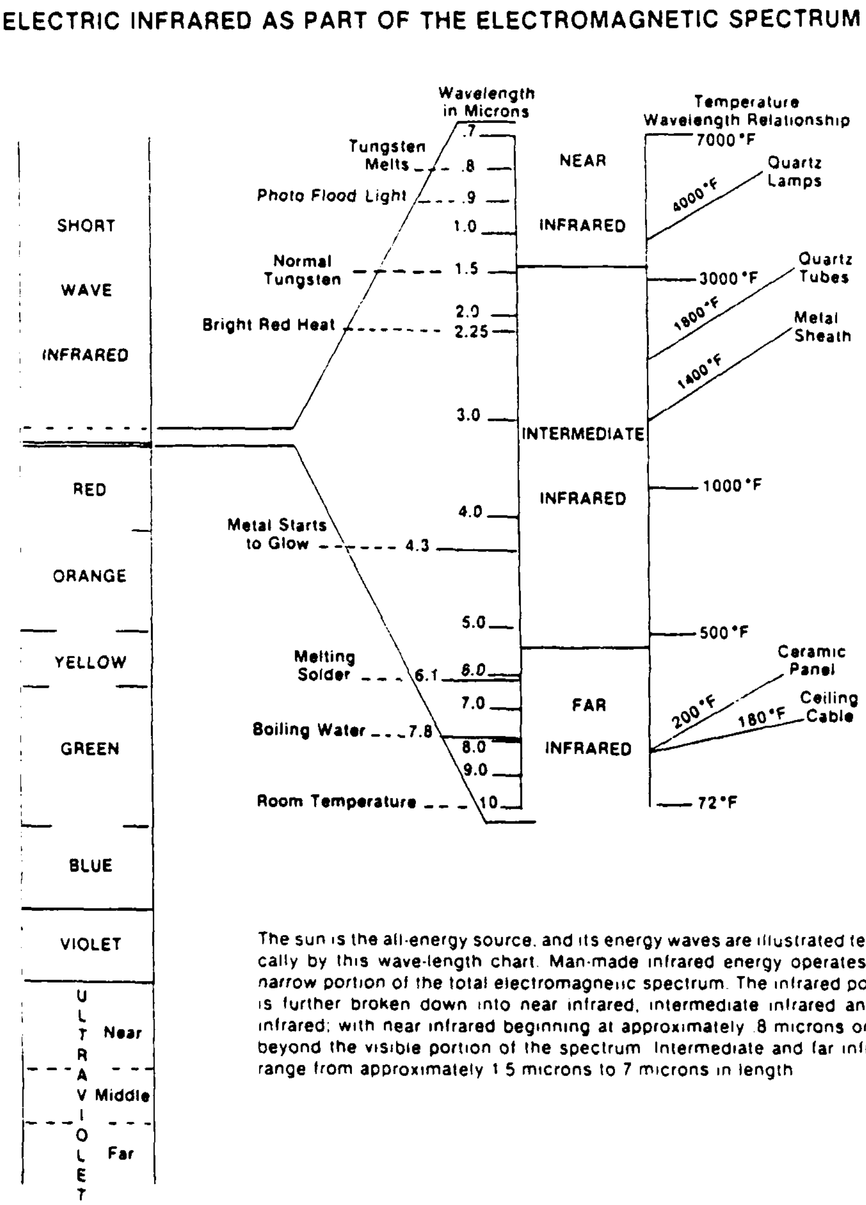


Figure 20 - A Chart of the Electromagnetic Spectrum [32]



The sun is the all-energy source, and its energy waves are illustrated technically by this wave-length chart. Man-made infrared energy operates in a narrow portion of the total electromagnetic spectrum. The infrared portion is further broken down into near infrared, intermediate infrared and far infrared; with near infrared beginning at approximately .8 microns or just beyond the visible portion of the spectrum. Intermediate and far infrared range from approximately 1.5 microns to 7 microns in length.

Figure 21 - Expansion of the Infrared Portion of the Electromagnetic Spectrum [34]

A good emitter is also a good absorber, and a poor emitter is also a poor absorber. Also, since every body must either absorb or reflect the radiant energy reaching it, a poor absorber must also be a good reflector. Hence a good reflector is a poor emitter. Any surface which absorbs all of the incident energy and reflects no radiant energy is called an ideally black surface, or a blackbody. The emissivity, ϵ, of an ideally black surface is equal to unity. For all real surfaces, termed nonblack, it is less than one. If the emissivity is not dependent on the wavelength, the surface is called gray. Gray surface characteristics are often assumed in calculations.

Radiant heat transfer differs from heat flow by conduction or convection in that the medium through which the heat flow takes place does not become heated. The mechanism of energy transfer by radiation is composed of three distinct components: first, the conversion of the thermal energy of the hot source into electromagnetic wave motion; second, the passage of the wave motion through the intervening space, and third, the reconversion of the wave motion energy into thermal energy by absorption at the cold body [31].

Infrared radiant energy is the same type of wave motion as radio waves, x-rays, and light waves except for the wavelength. Radiant energy is governed by the same laws of geometric optics as light: it travels in straight lines, obeys the laws of reflection, suffers refraction, may be polarized, and is weakened with the inverse square of the radial distance from a point source of radiation. When radiant energy falls on a body, part may be absorbed, part reflected, and the remainder transmitted through the body. In mathematical form:

$$\alpha + \rho + \tau = 1 \qquad (23)$$

where:

- α = absorptivity, or the fraction of the total energy absorbed
- ρ = reflectivity, or the fraction of the total energy reflected
- τ = transmissivity, or the fraction of the total energy transmitted through the body.

If the material is opaque to infrared, as are most solids including glass, the transmissivity is zero. Absorptivities of different nonmetallic solid materials at ordinary temperatures are given in Table 9, extracted from Jakob [35]. As pointed out by Jakob, there are some surprises in the table. All of the absorptivities given lie in the range of 0.85 and 1.00, and there are no great differences due to the roughness or the color of the surface. For instance, polished light gray marble does not absorb

Table 9

Absorptivity of Some Non-metallic Surfaces at Ordinary Temperatures [35]

Material	State of Surface	Absorptivity
Hoarfrost, white	....	0.985
Ice at -9.6 °C	Transparent	0.965
Lampblack-waterglass (heavy coat)	....	0.965
Asbestos slate	Rough	0.960
Water	....	0.950
Lampblack-waterglass (thin coating)	....	0.945
Rubber, hard black	Glossy	0.945
Paper, thin, on black lacquered iron	....	0.940
Glass	Smooth	0.935
Marble, light gray	Polished	0.930
Brick, red	Rough, but without great irregularities	0.930
Quartz, fused	Rough	0.930
Porcelain	Glazed	0.925
Lacquer, white, on copper, heavy coat	....	0.925
Paper, thin, on tinned iron sheet	....	0.920
Enamel lacquer, snow white	....	0.910
Roofing paper	....	0.910
Gypsum	....	0.900
Oak wood	Planed	0.895
Rubber, soft, gray	....	0.860
Lacquer, black or white on copper, thin coat	....	0.850

less than rough red brick or smooth glass. Of particular interest to this study is the fact that the absorptivity of transparent fresh water ice is the same as that of lampblack, equal to 0.965, and the fact that the absorptivity of hoarfrost, although entirely white to the eye, is 0.985, and therefore comes closest to the absolute black body of all substances investigated as yet. Figures 2, 3, and 4, presented earlier in Section 3 of this report, showed the wavelength dependency of the reflectance of sea ice. The key point here is that these values of absorptivity are for radiation at ordinary temperatures, or long wave radiation consisting primarily of wavelengths in the infrared portion of the spectrum, as opposed to short wave radiation such as that of the sun. If high temperature, short wave radiation, such as that of the sun (10,000°F) strikes ice or a white surface, the absorptivity is much less than when it hits a black surface. The good reflection of sunlight by ice or white fabrics is well known. It is less well known that the reflection of the same bodies is very small for long-wave radiation.

Lambert's Law states that the emissive power of radiant energy over a hemispherical surface above the emitting surface varies as the cosine of the angle between the normal to the radiating surface and the line joining the radiating surface to the point of the hemispherical surface. Such radiation is called diffuse radiation [33]. This Lambert emissive power variation is equivalent to assuming that radiation from a surface in a direction other than normal occurs as if it came from an equivalent area with the same emissive power per unit area as the original surface. The equivalent area is obtained by projecting the original area onto a plane normal to the direction of radiation. Black surfaces obey Lambert's Law exactly. The law is approximately true for many actual radiation and reflection processes, especially those involving rough surfaces and nonmetallic materials. Most radiation analyses are based on the assumption of gray-diffuse radiation and reflection.

The distribution of radiation from a surface to the surface it irradiates is determined by a quantity variously called an interception, view, configuration, angle, or shape factor. In terms of two surfaces, i and j, the shape factor from surface i to surface j is defined as the fraction of diffuse radiant energy leaving surface i which falls directly upon surface j. The shape factor, F_{12}, between two surfaces is given by [33]:

$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \Phi_1 \cos \Phi_2}{\pi r^2} \, dA_1 \, dA_2 \qquad (24)$$

where:

F_{12} = the shape factor between the two surfaces
A_1, A_2 = the area of the two surfaces
r = the distance between dA_1 and dA_2
Φ_1, Φ_2 = the angles between the respective normals to dA_1 and dA_2 and the connecting line r
dA_1, dA_2 = the elemental areas of the two surfaces.

Numerical values of the shape factor for common geometries are given in texts on radiation heat transfer [35]. For the purposes of this discussion, the key point is that the radiant energy received varies inversely as the square of the distance between the emitter and the receiver. The radiant heat exchange between two large black surfaces, where area A_1 is the warmer surface, is then given by:

$$q_{12} = \sigma A_1 F_{12} (T_1^4 - T_2^4) \qquad (25)$$

where:

q_{12} = net heat transferred
A_1 = area of the warmer surface
F_{12} = a shape factor which accounts for the geometrical arrangement of the two surfaces based on the area A_1, and is less than 1.

As a final thought, it is helpful to note that elementary gases such as oxygen, nitrogen, hydrogen, and helium are essentially transparent to thermal radiation. Their absorption and emission bands are confined mainly to the ultraviolet region of the spectrum. The gaseous vapors of most compounds, however, have absorption bands in the infrared region. Carbon monoxide, carbon dioxide, water vapor, sulfur dioxide, ammonia, acid vapors, and organic vapors absorb and emit significant amounts of energy. Also, it should be mentioned that radiation exchange by opaque solids is considered a surface phenomenon. Radiant energy does, however, penetrate the surface of all materials. The rate of exponential attenuation of the energy is given by the absorption coefficient. Metals have large absorption coefficients, and radiant energy penetrates only a few hundred angstroms at most. Absorption coefficients for nonmetals are lower. It is therefore safe to consider radiation heat transfer as a surface phenomenon unless the material is transparent to infrared.

Summarizing some of the key characteristics of infrared radiant heating for the purposes of this study, infrared energy is not absorbed by the air, and does not create heat until it is absorbed by an infrared opaque object. The energy provided by an infrared heater varies as the fourth power of the emitter temperature.

Infrared energy diffuses as a function of the square of the distance as it travels outward from a point heat source. The intensity, therefore, decreases in a proportional manner. For example, at a distance of 20 feet from the heat source, the energy pattern of radiant heat will cover four times the area covered at a distance of 10 feet. Conversely, at 20 feet from the heat source, the intensity of the energy is one-quarter of the intensity developed at 10 feet. A properly engineered system, therefore, consists of a proper mix of heat source power levels, the number of units, the mounting distance, the mounting spacing, and the reflector beam pattern. Reflectors have been designed for asymmetric, symmetric, or offset patterns.

5.1.2 Infrared Heating Equipment

Infrared heaters are generally characterized as compact, self-contained, high intensity direct heating devices. They are commonly used for heating in hangers, factories, warehouses, foundries, and gymnasiums, and for areas such as loading docks, racetrack stands, under marquees, outdoor restaurants, and around swimming pools. They are also used for snow melting, control of condensation, and industrial process heating [36]. Some high-intensity infrared heaters emit a significant amount of visible light and have been used for the combined purposes of heating and illumination. Infrared heating units may be electric powered, gas-fired, or oil-fired. They consist of an infrared source or generator operating in a temperature range of from 500°F to 5000°F. Reflectors are used to control the distribution of the radiation into specific patterns.

5.1.2.a Gas- and Oil-fired Infrared Heaters

Modern gas-fired and oil-fired infrared radiation heaters use the burning gas or oil to heat a specific radiating surface, generally a ceramic refractory material, to an incandescence either by direct flame contact or with the combustion gases. Typically only 10% to 20% of the energy produced by the combustion of a gaseous fuel is delivered as infrared radiant energy. Gas infrared heaters have been categorized into four types by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) as discussed below. The distinguishing characteristics of each type are illustrated in Figure 22, extracted from the ASHRAE Handbook [36].

Type 1. Indirect infrared radiation units which are internally fired and have the radiating surface between the hot gases and the load. Combustion takes place within the radiating elements, which may be ceramic or metallic, tubes or panels, and which operate with surface temperatures up to 1200°F. The tube type generally consists of an aluminized steel tube emitter with a gas burner at the inlet end. The burner discharges into the tube where the hot products of combustion move through the tube, and discharge out a vent to the outside. Typical ratings for individual tube type

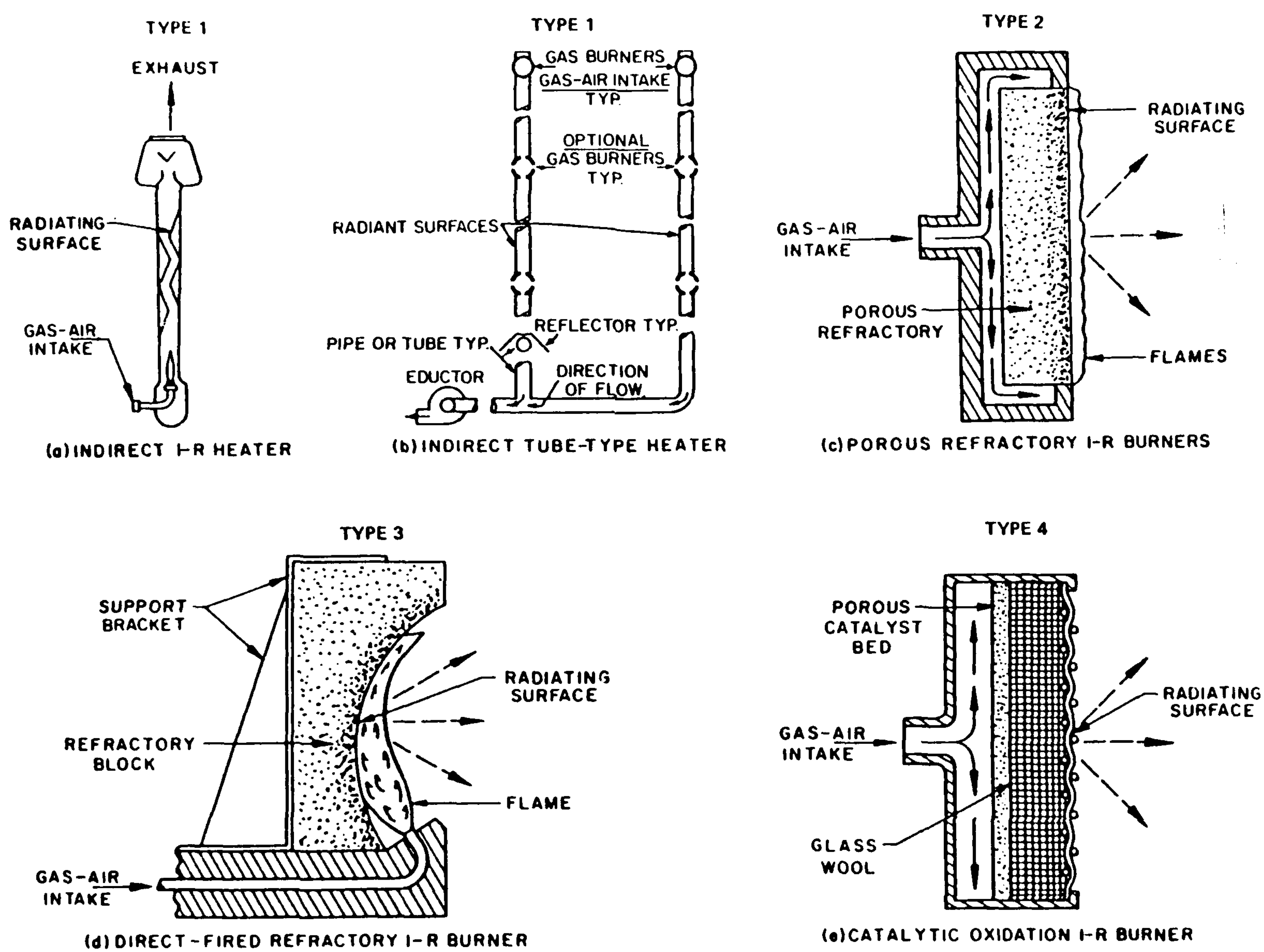


Figure 22 - Characteristics of Gas-fired Infrared Heaters [36]

units are from 20,000 to 120,000 BTU/hr. Oil-fired infrared radiation heaters are similar to the gas-fired Type 1 units.

Type 2. Porous refractory infrared units. In this type of gas-fired infrared heater, the refractory material may be porous ceramic, drilled port ceramic, perforated stainless steel, or a metallic screen. A combustible gas-air mixture enters the enclosure, flows through the refractory material to the exposed face, and is evenly distributed because of the porous nature of the refractory. Combustion occurs evenly on the exposed surface, heating it to produce radiant energy to add to that produced by the flame itself. Surface temperatures up to 1650°F for atmospheric burners, and 1800°F for power burners, are achievable.

Type 3. Direct fired refractory infrared radiation units. In this type of unit the flame or hot gas impinges on the radiating side of an open refractory surface. Surface temperatures of 1650°F to 2800°F are achievable.

Type 4. Catalytic oxidation infrared radiation units. This type of unit is similar to the Type 2 heater in construction, appearance, and operation, but the refractory material is usually glass wool and the radiating surface is a porous catalyst bed that causes oxidation to proceed without visible flames.

These and other characteristics of typical gas-fired infrared heaters are summarized in Table 10. Key information presented in the table for the purposes of this study includes the fact that the maximum operating temperature that can be realized from gas-fired infrared heaters is relatively low, at about 2800°F, and that the radiation generating ratio, defined as the ratio of radiant output to fuel energy input, is in the range of only 35% to 60%.

5.1.2.b Electric Infrared Heaters

Electric infrared heaters use heat produced by current flowing in a high resistance wire or ribbon. There are a wide variety of types available with the main differences being in the way the wire or ribbon is supported, and the way the heat is transferred. As was the case for the gas-fired units, ASHRAE has categorized electric infrared radiant heaters into four types as discussed below. The features of each type are illustrated in Figure 23, extracted from the ASHRAE Handbook [36].

Table 10

Characteristics of Typical Gas-fired Infrared Heaters [36]

Characteristic	Type 1	Type 2	Type 3	Type 4
Operating temperature, °F	to 1200	1600 - 1800	1650 - 2800	650
Relative heat intensity (1) BTU/hr sf	Low to 7,500	Medium to 32,000	High to 62,000	Low to 3,000
Response time, sec	180	60	60	300
Radiation gen. ratio (2)	0.35 - 0.55	0.35 - 0.60	0.35 - 0.50	No data
Thermal shock resistance	Excellent	Excellent	Excellent	Excellent
Vibration resistance	Excellent	Excellent	Excellent	Excellent
Color blindness (3)	Excellent	Very Good	Good	Excellent
Luminosity	To Dull Red	Yellow Red	To White	None
Mounting height, ft	7 to 50	7 to 50	No data	To 10
Wind resistance	Good	Fair	Fair	Very Good
Venting	Optional	Nonvented	Nonvented	Nonvented
Flexibility	Good	Excellent	Excellent	Limited

Notes:

1. Relative heat intensity is measured at the burner surface.
2. Radiation generating ratio is the ratio of radiant output to fuel energy input.
3. Color blindness refers to absorptivity by various loads of energy emitted by the different sources.

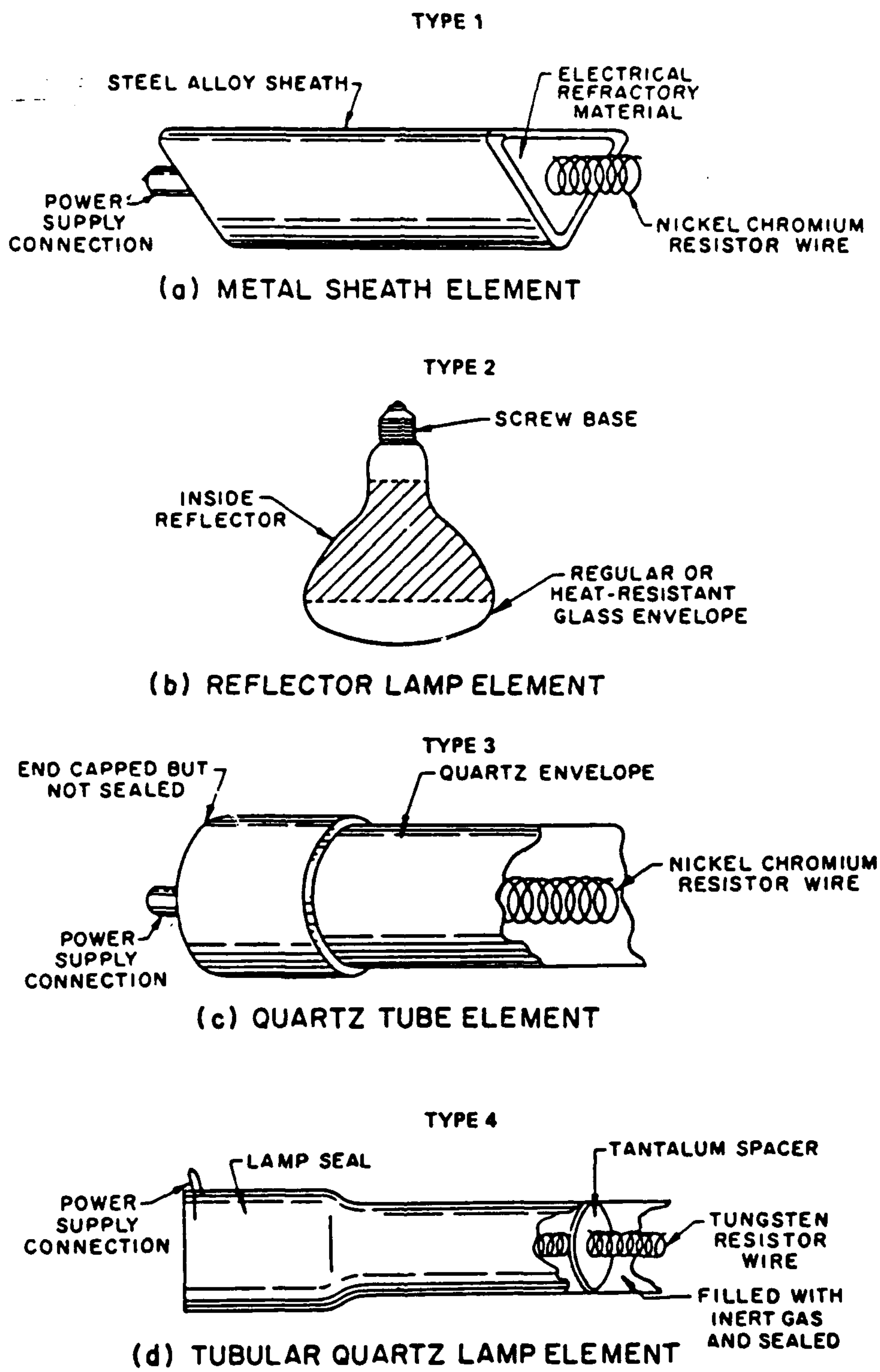


Figure 23 - Characteristics of Electric Infrared Heaters [36]

Type 1. Metal sheath infrared radiation elements. These elements are composed of a coiled nickel-chromium heating wire that is embedded in an electrical insulating refractory of magnesium-oxide powder encased by a metal inconel tube. These elements are the most rugged of the four types, having excellent resistance to thermal shock, vibration, and impact. In addition, they can be mounted in any position. Metal sheath elements attain a sheath surface temperature of from 1200°F to 1800°F. These elements are generally mounted in a fixture incorporating a reflector which aids in directing radiation to the load. They have the poorest radiant efficiency and the slowest heat up and cool down times of the electric units. A variation of the metal rod radiant heating element is the ceramic infrared radiant heating element. In this type of element, the nickel chrome resistance wire is cast within a glazed ceramic surface. The glazed ceramic surface protects the element from the effects of atmospheric oxidation and corrosion.

Type 2. Reflector lamp infrared radiation units. These units have a coiled tungsten filament which approximates a point source radiator. The filament is enclosed in a heat-resistant, clear, frosted, or red glass envelope which is partially silvered inside to form an efficient reflector. The temperature of the element is normally 4050°F. These units, more commonly known as heat lamps or sun lamps, can be screwed into an ordinary 120 volt light socket, but have very limited output capacity.

Type 3. Quartz tube infrared radiation unit. This type of unit has a coiled nickel-chromium wire lying unsupported within an unevacuated fused quartz tube, which is capped, but not sealed, by porcelain or metal terminal blocks. Translucent fused quartz provides the highest infrared transmission capability of any material available. These units are easily damaged by impact and vibration, but stand up well to thermal shock and splashing. They must be mounted in a horizontal position to minimize problems of coil sag, and are usually used in a fixture that contains a reflector which aids in directing radiation to the load. Normal operating temperatures range from 1300°F to 1800°F for the coil, and about 1200°F for the tube. Visually they have a bright orange glow. They are intermediate of the large capacity electric types in radiant efficiency, heat up and cool down time, moisture resistance, and mechanical ruggedness.

Type 4. Quartz lamp infrared radiation unit. A typical quartz lamp element consists of a 0.38 inch diameter fused quartz tube containing an inert gas and a coiled tungsten filament that is held in a straight line and away from the tube by tantalum spacers. Filament ends are embedded in the envelope end sealing material. Common lamps must be mounted horizontally, or nearly so, in order to minimize filament sag and overheating of the sealed ends. Specialized lamps with supported elements are available for vertical mounting. Quartz lamp filaments generally operate at 4050°F, while the envelope generally operates at about 1100°F. Visually, they have a high brightness. The envelope material can be clear, translucent, or frosted quartz, and can be provided with an integral red filter if it is necessary to reduce the visual brightness. Their radiant efficiency is substantially higher than that of the other industrial types. In addition, they have the fastest heat up and cool down time, the highest moisture resistance, but the lowest mechanical ruggedness. They are the only type of electrical radiant heater recommended for outdoor use, and they are specifically identified as the only type of element to be used for all snow and ice control applications.

These and other characteristics of electric infrared radiant heaters are summarized in Table 11. For industrial applications, the straight metal rods are recommended only for unique applications with an extremely high vibration environment, in all other cases, a quartz tube is recommended as a better choice.

Table 11

Characteristics of Electric Radiant Heating Elements [36]

Characteristic	Type 1 Metal Sheath	Type 2 Reflector Lamp	Type 3 Quartz Tube	Type 4 Quartz Lamp
Element	Nickel chrome	Tungston	Nickel chrome	Tungston
Heat intensity Watts/inch	Medium 60	High 125-375/spot	Medium to High 75	High 100
Resistor temp,°F	1750	4050	1700	4050
Envelope temp,°F	1550	525-575	1200	1100
Radiation gen ratio (1)	0.58	0.86	0.61	0.86
Response time,sec	180	Few	60	Few
Luminosity	Low dull red	High	Low orange glow	High
Thermal shock resis	Excellent	Excellent	Excellent	Excellent
Vibration resistance	Excellent	Medium	Medium	Medium
Impact resistance	Excellent	Medium	Poor	Poor
Moisture resistance	Lowest	Medium	High	Highest
Available power, W	300-4500	125-375	450-3200	500-3650
Wind resistance	Poor	Excellent	Medium	Excellent
Mounting position (2)	Any	Any	Horizontal	Horizontal
Envelope material	Steel alloy	Glass	Quartz	Quartz
Color blindness (3)	Very good	Fair	Very good	Fair
Flexibility	Good	Limited	Excellent	Limited
Life Expectancy, hr	Over 5000	5000	5000	5000
Applications	Indoor spot and area heating with high vibration	Indoor spot heating	Indoor spot and area heating	Outdoor and indoor, all snow/ice control

Table 11 (Cont)

Characteristics of Electric Radiant Heating Elements [36]

Notes:

1. Radiation generating ratio is defined as the ratio of radiant output to Watt input.
2. Quartz tube and quartz lamp elements can be provided with special internal supports for other than horizontal use.
3. Color blindness refers to absorptivity by various loads of energy emitted by the different sources.

5.2 Performance Requirements for Infrared Anti-Icing and Deicing

A judgement of the practicality of using infrared heating for UNREP anti-icing and deicing can be made on the basis of first estimating the heating requirements for selected representative anti-icing and deicing scenarios, and then assessing the ability of an infrared system to meet those heating requirements. If the gross engineering requirements can be satisfied by infrared systems, then the practicality of installing hardware in shipboard applications can be determined and the feasibility determined. In the first phase of this program [1], infrared heaters were identified as having potential application for both anti-icing and deicing. In the anti-icing application the objective is to keep the surface or equipment of interest slightly above the freezing point of both sea water and fresh water, say at about 35°F, so that neither the sea spray nor precipitation will freeze to the surface. In the deicing application, the assumption made is that no action is taken during the icing event itself, rather, upon completion of the icing event action is taken to remove the accreted ice.

5.2.1 Design Conditions

The first task in assessing the ability of infrared systems to meet the anti-icing and deicing heating requirements is to select appropriate design ambient conditions, primarily the air temperature and the wind speed, and the thickness of the accreted ice in the deicing situation. The General Specifications for Ships of the United States Navy [37] requires that, for normal operations, exposed equipment and machinery be designed for a minimum air temperature of -20°F at a wind speed of 40 knots. For cold weather operations, exposed equipment and machinery are specified to be designed to a minimum air temperature of -40°F and a wind speed of 70 knots. The fact that a typical Top Level Requirement [38] for the design of a major surface combatant specifies the upper limit of capability for underway replenishment and strikedown to be at sea state 5, with a corresponding mean wind speed of 24.5 knots, is irrelevant, at least in the case of the anti-icing scenario. In this study the concern is not with the worst conditions under which UNREP would take place, but rather, the worst conditions under which the anti-icing system must prevent the formation of spray ice on the deck and equipment.

As reported by Minsk [2], it is generally agreed that there is a minimum temperature below which topside icing is no longer of concern, but unfortunately, there is not agreement on the value of that limiting temperature. The rationale for believing in the existence of a limit is sound, being based on the fact that at some low temperature all the sea spray freezes before striking the ship, therefore, the material striking the ship consists of small and dry ice crystals which do not adhere to the ship or equipment surfaces. Minsk reports that a number of Russian sources claim that this temperature is around 0°F. Again as reported by Minsk, the Russians show data on icing incidence for Soviet ships operating in both the northern Atlantic and Pacific Oceans which show that most icing incidents occur when the air temperature is in the range of +32°F to +5°F, with a sharply reduced number of occurrences when the air temperature is in the lower range of +5°F to -5°F. Whether this results from the mechanism previously described, or whether it simply reflects a possible lower incidence of operations in the more extreme low temperatures is not resolved. Minsk also states, however, that actual shipboard observers have reported that icing can occur at temperatures as low as -20°F. Even this value, however, is not established by Minsk as a lower limit. Therefore, while there is no firm basis for setting a lower limit of temperature for the occurrence of topside icing, based on the present state of knowledge it seems reasonable for the purposes of this study to establish -20°F as a practical lower limit of air temperature for the occurrence of topside icing.

As a further consideration, in a study concerned with the new design of conventional major surface combatants for cold weather operations, Schultz [27] determined that a minimum air temperature of -20°F roughly corresponded with the boundary for the 50% concentration of floating ice, the ice condition recommended as the limiting condition for a Marginal Ice Zone (MIZ) Augmented ship defined in that study. The concern for the lower cold weather design temperature of -40°F was associated with in-port periods rather than at-sea periods, and therefore is felt to be not as applicable to UNREP considerations. For this study, therefore, in view of all of these considerations, a design condition of a minimum air temperature of -20°F was selected for the analysis of infrared icing countermeasure systems.

The most appropriate wind speed to be used in the analysis is also not obvious. The wind speed normally associated with the temperature limit of -20°F is 40 knots. However, the speed of importance to the heat transfer process is not the true wind speed, but rather the wind speed relative to the ship. Major surface combatants typically operate in Battle Groups at a speed of around 20 knots. UNREP typically takes place at speeds of 12 to 15 knots. Top speeds are typically in excess of 30 knots. A 40 knot wind, however, corresponds to sea state 6, with wave heights of 13.1 to 19.7 feet. It is doubtful that under normal conditions a major surface combatant would be operated in sea state 6 at anywhere near top speed, and probably not even at the typical Battle Group speed of 20 knots. It would therefore seem safe to assume that a reasonable upper limit on relative wind speed would be 60 knots, the true wind of 40 knots plus the ship speed of 20 knots dead into the wind.

The design conditions for the heat transfer analysis of topside icing are therefore established for this study as a minimum air temperature of -20°F and a relative wind speed of 60 knots. For the thickness of accreted ice in the case of the deicing situation, in the study previously referred to concerned with the new design of conventional major surface combatants for cold weather operations, Schultz [27] recommended that the design thickness of accreted ice be increased from the current value of about 1.75 inches, established by the General Specifications [37], to 3 to 5 inches. This range of the thickness of accreted spray ice can be used for further analysis.

5.2.2 Heating Load for Anti-icing

The statement of the heat transfer problem for an anti-icing situation is to maintain the surface of the portion of the working deck area of interest at a temperature of 35°F under conditions of an ambient air temperature of -20°F and a relative wind of 60 knots along the deck. The heat transferred from the deck to the air, which in turn must be supplied to the deck surface by the infrared heating system, can be estimated by using the following relation from Jakob [35] for forced heat convection in turbulent flow parallel to a plane plate at uniform temperature:

$$q_0' = 0.0366\ \rho\ c_p\ v_0\ \theta_0\ L\ [\nu/(v_0\ L)]^{1/5} \qquad (26)$$

where:

q_0' = rate of heat flow per unit width from a surface of length L in the flow direction, BTU/hr ft

ρ = density of air, lbm/ft^3

c_p = specific heat at constant pressure, BTU/lbm °F

v_0 = velocity, ft/hr

θ_0 = temperature differential, °F

L = length, ft

ν = kinematic viscosity, ft^2/hr.

For air at -20°F and atmospheric pressure, the values of the physical properties needed are:

ρ = 0.0903 lbm/ft^3

c_p = 0.2397 BTU/lbm °F

ν = 0.421 ft^2/hr.

For a temperature differential of -20°F to 35°F, or 55°F, and a velocity of 60 knots, equivalent to 364,800 ft/hr, Equation 26 becomes:

$$q_0' = 1032\ L^{4/5} \text{ BTU/hr per foot of width.} \qquad (27)$$

A feeling for the power density required at the deck can then be obtained by considering two specific situations. First, for a refueling station deck area taken as 100 feet long by 5 feet wide, the heat transferred from the deck to the air is 205,425 BTU/hr, or about 60 kW. The power density required to be delivered to the deck by infrared heating is, therefore, in the mixed units commonly used by the infrared heating industry, about 120 Watts/ft^2. For a second situation, taken as a 20 foot by 25 foot UNREP deck work area, the rate of heat transfer from the deck to the air as determined by Equation 27 is 283,425 BTU/hr, or about 83 kW. The power density required to be delivered to the deck by infrared heating for this situation is therefore about 166 Watts/ft^2.

5.2.3 Heating Load for Deicing

For the deicing situation, it is assumed that the icing event proceeds to completion, and some significant period of time on the order of hours elapses before the deicing activity gets underway. In this worst case scenario, the heat load for the deicing task consists of the heat load associated with the melting of the accreted ice, the heat load associated with raising the temperature of the ice up to the melting point from the ambient temperature of -20°F, plus the anti-icing heat load discussed in the preceding section since the heat transferred from the warmed ice to the cold high velocity air would be essentially the same as that transferred from the warmed deck to the air. The energy requirements of the deicing scenario are therefore substantially greater than those associated with the anti-icing scenario. As a result, it is clear that if an infrared heating system were installed on board ship it should be used as an anti-icing system rather than a deicing system. In order to get some feel for the magnitude of the numbers, the additional heating beyond that required for anti-icing in order to warm the ice up to the melting point, and then to melt the ice is given by:

$$Q'' = w\, h\, (c_p\, \theta + h_f) \tag{28}$$

where:

Q'' = heat required per unit area, BTU/ft^2

w = specific weight of the ice, lb/ft^3

h = thickness of accreted ice, feet

c_p = specific heat of the ice, BTU/lb °F

θ = temperature difference, °F

h_f = heat of fusion of the ice, BTU/lb.

For the temperature difference of -20°F to 28°F, or 48°F, and the following representative property values for the accreted sea spray ice selected from the tabular data provided by Minsk [2]:

$$w = 50 \text{ lb/ft}^3$$

$$c_p = 0.581 \text{ BTU/lb °F}$$

$$h_f = 160 \text{ BTU/lb,}$$

the heat required per unit area is given by:

$$Q'' = 9379.4 \text{ BTU/ft}^2 \text{ per foot of thickness of accreted ice.} \quad (29)$$

For the ice thicknesses discussed previously of 1.75, 3, and 5 inches, the heat required per unit area is, then, 1368, 2345, or 3908 BTU/ft². If it is assumed, for the sake of discussion, that the energy lost to the air is zero, that is, all the energy provided goes into raising the temperature of the ice up to the melting point and melting the ice, then the same order of power density determined above for the anti-icing application of about 150 Watts/ft² (512 BTU/hr ft²) would result in melting the 1.75 inches of ice in 2.7 hours, melting the 3 inches of ice in 4.6 hours, and melting the 5 inches of ice in 7.6 hours. These zero heat loss melt times give an indication of the deicing capabilities of the infrared heating systems. These deicing times are reasonable, but, again, it is emphasized that the preferred approach is to use the infrared heating system for anti-icing rather than deicing.

5.2.4 Design Heating Load

Based on the requirements established for the two anti-icing scenarios, and recognizing that anti-icing rather than deicing is the preferred approach having the less demanding energy requirements, it is concluded that the design heating load for the heat energy required from the infrared heaters at the deck should be based on the more severe anti-icing requirement of about 166 Watts/ft². For the purpose of selecting hardware for a prototype system, the nominal heating capacity should be in or near the range of 150 to 200 Watts/ft². If the more practical system hardware tends toward the lower limit, or even falls somewhat below the limit, prototype equipment can still be sized for further evaluation since, in most occurrences, the rather severe design conditions assumed provide for a significant margin in capability. On the other hand, it is always advisable to be conservative in the sizing of equipment for a prototype system and provide for a significant level of capacity margin, recognizing that system capacity can be reduced in the final design if operating experience with the prototype system indicates that such is possible.

5.3 Selection of Heater Type

The first step in selecting an infrared heater for application to shipboard UNREP anti-icing applications is to choose from among the gas-fired, oil-fired, and electric types. The design condition defined in the previous section of this report, consisting of a heating requirement of 150 to 200 Watts/sf at the deck, is a very demanding requirement for any type of heater, even for the case of strip heaters mounted on the underside of the deck. Based on the discussion of infrared heating fundamentals presented in Section 5.1, the selection is quickly directed to a heater with the highest emitter temperature, since the heat output varies as temperature to the fourth, and a heater with the highest radiation generating ratio. Both of these major considerations favor the selection of electric heaters over gas-fired or oil-fired heaters. As shown in Tables 10 and 11, the operating temperature of oil-fired infrared heaters, comparable to the Type 1 gas-fired units, is typically in the neighborhood of 1200°F, while gas-fired units are available with operating temperatures up to 2800°F, and the quartz lamp electric units with tungston filaments operate at 4050°F. Also as indicated in the tables, the radiation generating ratio of oil-fired and gas-fired units is in the range of 0.35 to 0.60, while for the quartz lamp electric type the ratio is 0.86. For the high energy levels required for this application, therefore, the quartz lamp type of electric infrared heater, Type 4, has very fundamental and significant technical advantages over the other types of infrared heaters. Further, as indicated in Table 11, in comparison to the other types of electric infrared heaters, the quartz lamp heater has the advantages of an excellent resistance to thermal shock, excellent resistance to wind, and the highest moisture resistance. Also, as previously discussed, the electric quartz lamp heater is the only type of infrared heater recommended by the manufacturers for outdoor use, and for all snow and ice control applications.

While the selection of the quartz lamp electric infrared heater can be justified on the above considerations alone, practical shipboard applicatior considerations further support this selection. Gas-fired units are not appropriate for shipboard use since propane is not allowed on Navy surface ships for safety reasons. Further, if it were necessary to proceed with gas-fired units, their use would require introduction of an entirely new item into the supply system. Gas-fired infrared heaters are therefore clearly inappropriate for shipboard use. While the installation of oil-fired units on board ship would be possible, in comparison to the installation of electric units, an oil-fired installation is judged to be orders of magnitude greater in complexity and cost. For all practical purposes, the electrical capacity is generally available, and the electrical distribution system is in place and available for use, whereas the distribution system for an oil-fired system is not. Practical installation considerations, therefore, totally eliminate the gas-fired infrared heaters from consideration, and strongly favor the selection of electric infrared heating over oil-fired systems for the shipboard UNREP anti-icing application.

5.4 Search of Manufacturers of Infrared Heating Equipment

A search for manufacturers of infrared heating equipment was conducted based primarily on the use of the Thomas Register [39] and the Product Specification File of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) [40]. The results of the search are summarized in Table 12. For the purposes of this study, the manufacturers can be grouped into two categories, manufacturers of infrared process heating equipment, and manufacturers of infrared space heating (more accurately people heating in open spaces) equipment. In general, the manufacturers oriented toward space heating were much more interested in discussing the anti-icing application than were the manufacturers oriented toward process heating. In process heating applications, infrared heaters are generally used in very close proximity to the heated material, typically measured in inches. Examples of process heating applications include plastic forming, print ink drying, drying and curing adhesives and coatings on various substrates, laminating, drying of textiles, and curing of rubber products. The reaction of process infrared heating people to the requirement for mounting the heaters some 8 to 50 feet from the surface to be heated generally was one of panic. Only one of the many process heating oriented manufacturers, The Thermal Devices Division of John J. Fannon Co., Inc., was interested in seriously considering the application.

The manufacturers of infrared space heating equipment could be further subdivided into those oriented toward industrial applications and those producing what are termed architectural infrared heating panels. The latter products are low temperature, low capacity units represented by the drop-in heated ceiling panels for suspended office or commercial ceilings that are sometimes used around the interior perimeter of a building to supplement the main heating system near high heat loss window walls. Such units are clearly not applicable to the shipboard UNREP anti-icing application. Manufacturers of industrial space heating equipment expressed the most interest in this application. In addition, it appears that the number of suppliers of infrared heating equipment is substantially greater than the number of actual manufacturers; that is, in an effort to offer a more complete line of heating equipment, a supplier will simply relabel and repackage a heater manufactured by another company as its own.

Of particular interest when the search was begun were those manufacturers who stated that they had snow and ice control experience, and those offering a broad based, comprehensive line of heating equipment of all types. In the case of those suppliers offering a comprehensive line of all types of heating equipment, such as Chromalox and Wellman, an initial enthusiastic expression of interest ultimately gave way to an election of not pursuing the application. The identification of manufacturers having snow and ice control experience was felt to be of great importance on two counts. First, the vast majority of infrared heating applications are for building interiors where the heaters have no exposure to the elements. The snow and ice control applications generally have at least partial, if not total, exposure to the elements. Second, the use of infrared heaters for snow and ice control on sidewalks, driveways, and parking garage ramps was felt to be as close to the UNREP anti-icing application as could be achieved.

As indicated in Table 12, the suppliers advertising snow and ice control experience include Aitken Products, Fostoria, Markel, and Tempco. Of these, Fostoria emerged as the clear front runner in snow and ice control experience by a very substantial margin. Markel quickly stated that their infrared units were manufactured by Fostoria and referred the inquiry to Fostoria. Tempco representatives seemed surprised to learn that snow and ice control was listed in their catalogue as an application for infrared heating. Fostoria also demonstrated the greatest interest in the shipboard UNREP anti-icing application by a very substantial margin. Fostoria was therefore selected as the recommended hardware supplier for the prototype shipboard infrared UNREP deicing system.

Table 12

Manufacturers of Infrared Heating Equipment

Aitken Products, Inc.	Geneva, OH	216-466-5711
Snow melting experience; limited line of quartz lamp heaters		
American Infra-Red	Detroit, MI	313-824-0841
Gas fired infrared; 20,000 to 100,000 BTU/hr input		
Aztec	Albuquerque, NM	505-884-1818
Low temperature radiant ceiling panels for offices; 250 to 1500 w/panel		
Baume Corp.	Cinnaminson, NJ	609-786-1444
Custom manufacturer of quartz infrared elements, not heaters		
Chromalox	Pittsburgh, PA	412-967-3800
Limited line of radiant heaters		
Delta T Products, Inc.	Butler, NJ	201-492-1533
Custom industrial infrared heating systems		
Detroit Re-Verber-Ray	Warren, MI	800-222-1100
Gas fired portable and commercial units; 16,000 to 160,000 BTU/hr		
Drypoll Inc.	Flushing, NY	718-353-3426
Only ceramic heaters, only for process use		
Fannon Thermal Devices	Mt. Clements, MI	313-263-8850
Gas and electric infrared industrial processing ovens		
Fostoria	Fostoria, OH	419-435-9201
Broad range of commercial and industrial infrared heaters of all types; snow and ice control experience; 300 to 3650 W (1000 to 12,500 BTU/hr)		
Grainger	Chicago, IL	312-647-8900
Portable electric and LPG infrared heaters		
Markel	Buffalo, NY	716-691-3001
Advertised snow and ice control experience; units manufactured by Fostoria; referred to Fostoria		
Marsden	Pennsauken, NJ	609-663-2227
Gas fired radiant strip process heaters		
Oal Associates, Inc.	Escondido, CA	619-743-7143
Process and laboratory infrared ovens		
Protherm	So. St. Paul, MN	612-450-4702
Electric industrial process infrared heaters		
Radiant Heat	Coventry, RI	401-822-0360
Electric infrared industrial process heaters, primarily textile industry		
Radiation Systems, Inc,	Wyckoff, NJ	201-891-7515
Industrial infrared heat processing equipment		

Table 12 (Cont)

Manufacturers of Infrared Heating Equipment

Research, Inc.	Eden Prairie, MN	612-829-7481
Process and laboratory heaters		
Roberts-Gordon	Buffalo, NY	800-828-7450
Low intensity commercial gas-fired infrared heaters; 20,000 to 150,000 BTU/hr		
Tempco Electric Heater Corp.	Wood Dale, IL	312-350-2252
Limited line of infrared heaters for process baking applications, but snow and ice control experience listed		
Therma-Tech	S. Paterson, NJ	201-345-0076
Electric infrared panel heaters for process systems		
Wellman	Shelbyville, IN	317-392-5329
Metal sheath, quartz lamp, and quartz tube; limited line and apparently limited experience with infrared applications		

5.5 Infrared Snow and Ice Control Experience

In discussing this application with manufacturers of infrared heating equipment, a common response was that the problems of engineering an infrared heating application were associated with the height, the "throw" or radiant energy distribution, and how to control it. A great deal of misinformation exists in the field, with rigid requirements stated on the basis of what was required in some previous application to make the system work properly, while the original engineering justification was totally lost in the process. For example, the vast majority of the process heating manufacturers simply stated that infrared would not be suitable for this application because of the "tremendous" height of 8 feet at which the heater would have to be mounted in one application configuration. Another manufacturer was even more extreme, stating that the 8 foot mounting height was far too great a distance from which to heat the deck, and too little a distance for safe personnel clearance. In applying infrared heating to the shipboard UNREP anti-icing application, therefore, it is essential to keep the engineering fundamentals of infrared heating in mind for interpreting and evaluating the applicability of the various "absolute truths" stated by the various manufacturers either informally or in official applications guides.

As indicated in the previous section of this report, several manufacturers of electric infrared heating equipment listed snow and ice control as an appropriate application for the equipment. Only one manufacturer, however, Fostoria Industries of Fostoria, Ohio, went beyond the listing in their literature to present actual guidelines for snow and ice control applications, and to give an example. Fostoria's guidelines for the application of infrared heaters to snow and ice control are presented in their entirety on page 21 of their Electric Infrared Heating Manual [34]. This page of the Manual is reproduced as Figure 24. As is typical for the industry, the guidelines are presented in engineering handbook fashion as a series of rules stated without explanation. The first "principle" states that only the quartz lamp type of infrared heater should be used for snow and ice control applications. The unstated reasons for this are assumed to be that relatively high outputs are typically required for snow and ice control applications, and the fact that the quartz lamp heater has the greatest moisture resistance. The second "principle" simply states that of the various types of Fostoria infrared heating fixtures, only the Mul-T-Mount fixture series is suitable for completely exposed outdoor installation. The third "principle", suggesting the use of the most focused reflectors, is assumed to again result from the typically relatively high heating requirement, and the desire to minimize the diffusion of the energy. The fourth "principle" suggests mounting heights of 8 to 10 feet, and states that the units should never be mounted above 14 feet. This requirement again reflects the high heat load expected in general, and, more importantly, the tie-in to the power density requirements given in Table B of Figure 24 in

SNOW AND ICE CONTROL

Principles:

1) **ALWAYS** use clear quartz lamps as proper element selection. **NEVER** use any other element.

2) **ALWAYS** use the Mul-T-Mount series. The Mul-T-Mount units are UL approved for both semi-exposed and completely exposed areas.

3) For BEST results use the 30° symmetric or asymmetric units (30, A30, A31). SATISFACTORY results can be obtained when using 60° symmetric or 60° asymmetric patterns in semi-protected or shielded areas. If 60° heat pattern is required for exposed areas, consult factory for watt density. **NEVER** use 90° pattern for snow and ice control.

4) Table B shows watt densities needed when units are mounted at 8′ - 10′. For best results strive for this 8′ - 10′ level. Consult factory for densities required when mounting above 10′. **NEVER** mount above 14′.

5) Strive for blanket coverage.

Snow Control Factors

To determine the watt density of infrared required for any area, see Table 4 (located at the back of the manual) to obtain outside design temperature (I) and annual snowfall (II). From Table A, obtain the value for each factor, and add Factor I and Factor II together. Refer to Table B to obtain watt density based on the **total** value.

Table A

Factor I		Factor II	
Outside Design Temp. °F	**Value**	**Annual Snowfall**	**Value**
−20° to −60°	4	80″ to 115″	4
−10° to −19°	3	50″ to 79″	3
0° to −9°	2	20″ to 49″	2
+19° to +1°	1	10″ to 19″	1
+40° to +18°	0	0″ to 9″	0

Table B

	Watt Densities per Square Foot		
Total Value	***Exposed**	***Semi-Protected**	***Protected**
8	200	185	160
7	175	160	145
6	125	110	100
5	110	100	90
4	100	90	85
3	95	80	75
2	90	70	65

*Exposed = Totally open area
*Semi-Protected = One side closed plus roof or overhang
*Protected = Three sides closed plus roof or overhang

Example: Albany, New York has an outside design temperature of −6° or a Factor I value of 2. The yearly mean snowfall is 65.7 inches or a Factor II value of 3. The total value is 5; therefore the watt density needed for an exposed area is 110 watts per square foot.

Figure 24 - Snow and Ice Control Guidelines as Presented by Fostoria [34].

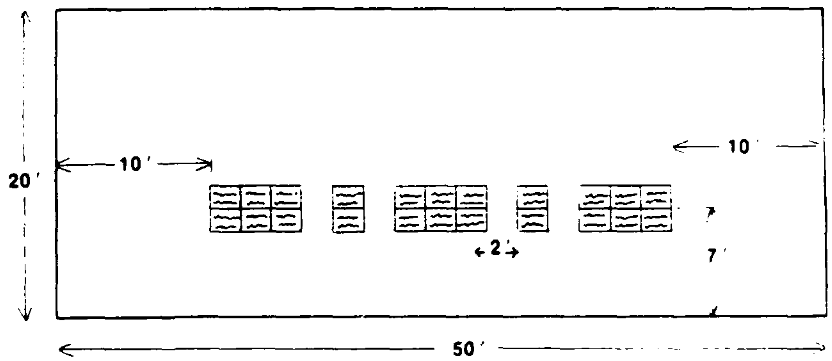
particular. This "principle" could be more accurately stated as never mount above 14 feet if Tables A and B of Figure 24 are to be used for guidance in the design of the system. The final "principle" stated, that of striving for blanket coverage, again reflects the expected high heating loads associated with snow and ice control applications. While the detailed handbook design process given in Figure 24, which is based on outside design temperatures and annual snowfall data for specific geographic locations, does not directly apply to the shipboard UNREP anti-icing application, it is of interest that the unit power densities presented in Fostoria's Table B do extend to as much as 200 Watts/ft^2.

As an example of a snow and ice control application Fostoria presents a flier on Case History 72, incorporated here as the two page Figure 25. Paired asymmetric fixtures are mounted at a height of 18 feet (in violation of Principle No. 4) to heat an area of 50 feet by somewhat greater than 20 feet under the main entrance canopy of a condominium. The second page of the case history flier shows the use of infrared heaters for snow and ice control at the entrance and exit ramp of the condo's underground parking garage. In the open area of the entrance, the heaters are mast-mounted at a height of 12 feet in specially designed T-bar frames. In the covered part of the ramp area, the units are angle mounted at a height of 6 feet. These applications illustrate several points. First, the units can be mounted at reasonably high elevations and the power density increased by ganging multiple units together. A limit is achieved for any given elevation when the maximum output units are used, and mounted directly in contact with each other. Second, the mast mounted arrangement brings to mind the possibility of ship-mounted mast or catwalk configurations of infrared heaters. Third, concerns of mounting the heaters as close as eight feet from people were clearly overcome in the six foot application cited. In addition, this application brings to mind the installation of corner mounted units on an exposed bulkhead where there is no overhead on which to mount the standard suspended units, such as at a refueling station on an exposed and unsheltered weather deck. All of these points will be discussed further in the applications analysis section of this report.

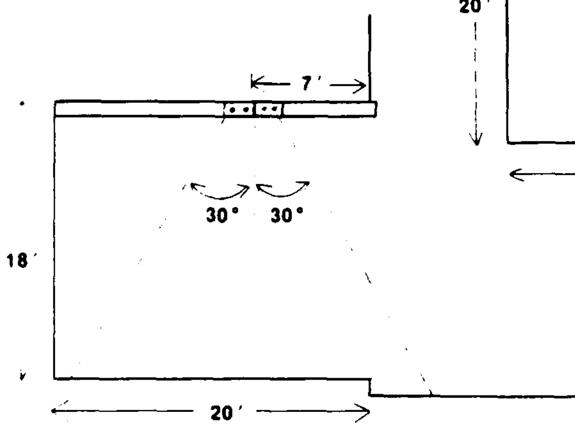
Harbor Point Condominium • 155 Harbor Drive • Chicago, IL

Located just off Lakeshore Drive in the heart of Chicago, this installation is a showpiece for snow/ice control and people comfort. Harbor Point, with its park and lakefront setting, became a beautiful addition to Chicago's skyline when construction was completed in 1974.

Mounted under the main entrance canopy are 22 units of Model 222-A30-TH Mul-T-Mount, with clear quartz lamps. The heaters are mounted at 18', covering an area 50' wide by 20' in depth. Heaters are recess mounted in a specially designed black canopy to match the existing architecture.



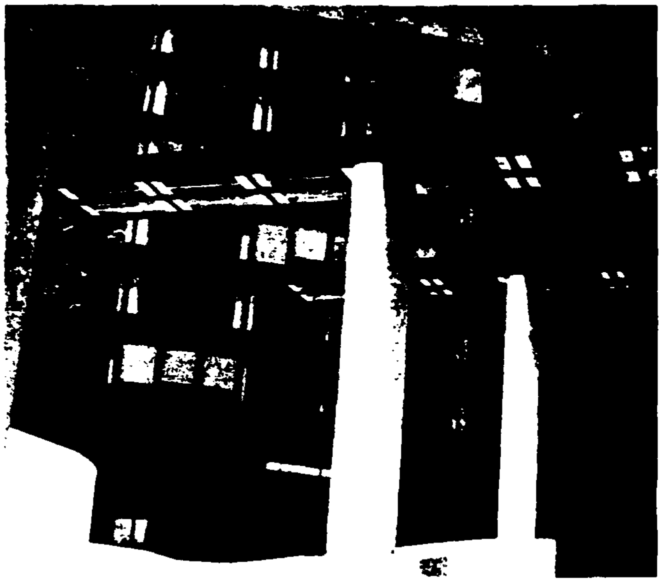
Underview Main Entrance Canopy



End View

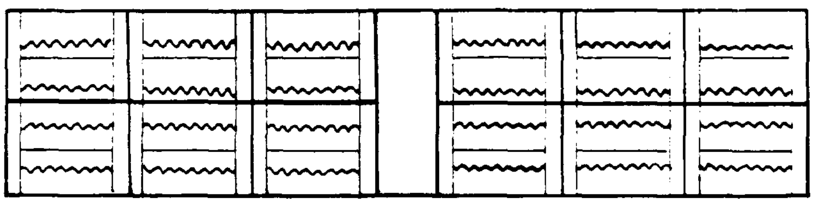
Infrared heat gives warmth and comfort for people entering or exiting the building or waiting under the canopy. The heat pattern also extends beyond the front of the canopy to keep exposed pick-up area free of ice/snow and moisture. This helps avoid an accumulation of slush which would normally be tracked into the building.

Figure 25 - Fostoria Snow and Ice Control Case History

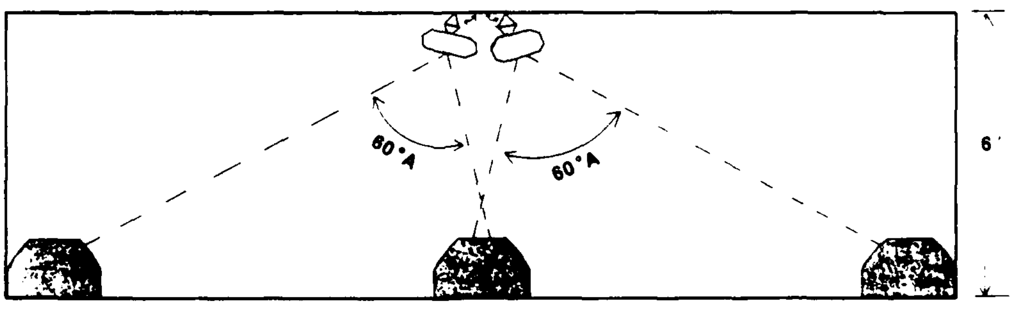


The up-down ramp leading to an underground parking garage for the condominium presented a critical snow/ice control problem due to the degree of incline. Specially designed T-bar frames were built to house 12 each 222-A30-TH Mul-T-Mount heaters equipped with clear quartz lamps. These are mounted at a 12′ height from the ramp surface. The asymmetric 30° fixtures were mounted in two rows back to back to provide a combined heat pattern of 60° yet utilizing the high efficiency 30° reflector.

The last photo displays the continuation of the ramp going underground. This semi-exposed snow/ice control area utilizes 28 of Model 222-A60-TH mounted at the center of the ramp at a 6′ distance from the surface. Using Fostoria's CHB2AX, the units are tilted 15° toward the ramps.



Underside View of T-BAR
1 of 3 T-BAR Frames 18′ Apart



End View — Ramp Going Underground

Figure 25 - Fostoria Snow and Ice Control Case History (Cont.)

5.6 Safety and Operational Concerns Associated with Infrared Anti-icing and Deicing

Several concerns related to the personal and operational safety of using infrared heaters for shipboard anti-icing and deicing were raised in the concept development phase of this study of northern latitude UNREP. Each of these concerns is addressed individually in the following sections of the report.

5.6.1 Radiation Hazard

The only conceivable hazard to personnel associated with infrared heat is the normal risk of working in close proximity to any heat source, the risk of being overheated. Personnel will readily detect any overheating and can then take simple corrective action such as moving out of the direct path of the infrared radiation, or reducing the output of the heaters. There is no long term exposure concern associated with infrared electromagnetic radiation, as there would be, for example, in the x-ray portion of the spectrum. In addition, there are no ultraviolet components in electric infrared radiation as there are in sunlight. The ultraviolet radiation in sunlight is the source of tanning and skin cancer concerns. Infrared heating, therefore, presents no radiation safety hazards to personnel.

5.6.2 Sea Spray Induced Element Shattering

As discussed earlier, the quartz lamp infrared heating element consists of a coiled tungston filament housed within a 3/8 inch diameter clear quartz envelope. The tungston element has a normal operating temperature of 4050 °F. The quartz envelope, while some 97% transparent to infrared, never the less reportedly heats up to anywhere from 1100°F to 2000°F, depending on the source quoted. The question was raised as to whether or not the quartz envelope would shatter due to thermal shock when struck by cold sea water spray. All suppliers of complete heating units that were contacted expressed concern over this issue, but had little direct experience upon which to base a judgement. A major manufacturer of the quartz lamp elements, however, insisted that anyone who said this would be a problem was just plain wrong. The element manufacturer insisted that the man-made quartz envelopes will not crack when sprayed with cold sea water. The quartz envelopes have a very high temperature rating and an extremely low coefficient of thermal expansion, such that ice water can be poured on an operating element with no damage to the element. This was subsequently confirmed by some others who relayed the story of demonstrating the ice water spray test at trade shows. It is therefore concluded that the quartz lamp infrared heating elements will not shatter or crack when sprayed with cold sea water.

5.6.3 Explosion Hazard

The presence of fuel fumes in the vicinity of the infrared heaters during refueling operations raised the question of whether or not there is any significant danger of igniting JP-5 or DFM fuel fumes with the infrared heaters. Both of these fuels have a flash point of 140°F. The concern is associated with both the high temperature element envelope, typically operating at a surface temperature of 1100°F to 2000°F, and the 4050°F element itself in the event the envelope is somehow broken.

A definitive resolution of this issue could not be obtained from manufacturers who were concerned over potential liability problems, however, the unanimous informal opinion was that there should be no explosion hazard due to routine operations in this exposed application. It was pointed out that these heaters are commonly used in severe northern climates at gasoline stations with no problems. They are also commonly used in process industries for drying and curing in the presence of flammable solvents and drying agents. One manufacturer did, however, point out that for severe highly explosive environments, the infrared units are enclosed and vented with a ducted blower system which maintains a slightly positive pressure of fresh ventilation air in the heater housing, thereby maintaining a safe atmosphere in the presence of the heater elements. Another consideration pointed out by the infrared heater manufacturers is the fact that common electric light bulbs also use a tungston filament. It would appear, therefore, that it would be adequate to parallel the explosion hazard precautions taken with incandescent lighting systems when dealing with infrared heaters.

In an effort to gain further insight into this issue, informal discussions were held with representatives of the Naval Sea Systems Command concerned with specifications and standards, fuel systems, fuels, firefighting, electrical systems, and damage control and safety. Again, the results were not conclusive. The Navy classifies JP-5 as a non-explosive fuel, as opposed to gasoline, for example, which is classified as an explosive fuel. However, the low flash point of JP-5, combined with the very high envelope and element temperatures of the infrared heating element, always raises concern. It would also seem to be equally of concern in the case of conventional incandescent light bulbs. Again drawing a parallel between the infrared heating elements and incandescent light bulbs, it is felt that one of the most relevant pieces of information obtained in this part of the investigation is the fact that incandescent lighting fixtures are not required to be explosion proof when mounted topside on Navy ships, even in the aircraft refueling area and at ship refueling stations. The use of explosion proof lighting is, however, required on Navy ships in any closed compartment in which fuel fumes may be present. The opinion was therefore expressed by a member of the electrical group that the infrared heaters would similarly not need to be explosion proof for this topside, exposed application.

Navy firefighting experts questioned the need for having the heaters operating during the refueling operation itself, assuming that the major anti-icing concern was one of prevention during the icing event, and prior to any refueling operation. This is not necessarily the case, in that while personnel would not be likely to be out on deck conducting refueling operations during the severe design conditions selected for sizing the heaters, it is likely that there will be many other occasions when refueling will occur under conditions less severe than the design conditions which will still result in icing. In addition, the secondary advantage of using the heaters for personnel heating during cold weather operations is lost. While recognizing these points, the suggestion was made that, at least for the prototype test installation, the heaters not be used during the refueling operation itself. In the event that the results of the prototype testing are favorable, it was suggested that a meeting then be held of representatives of all interested NAVSEA Codes, including those identified above, to discuss, evaluate, and finally decide this issue.

A very similar response was obtained when the problem was described to damage control and safety personnel. It was unofficially felt that the use of infrared heaters out in the open and at very low air temperatures could probably be allowed in their standard configuration, even with the 1100°F to 2000°F temperature of the exposed quartz lamp envelope, but the safety issues associated with their use in the presence of fuel fumes are marginal enough that a definitive answer could not be given without full consideration and review of all relevant factors. It was suggested that if a decision is made to proceed with the testing of a prototype system, the system should first be submitted for a Preliminary Systems Safety Review by NAVSEA 55X21, the Ship Systems Safety Branch of the Damage Control and Safety Division. If this preliminary safety assessment is favorable, and the prototype test results are favorable, then the full 55X21 System Safety Review would be completed as a prerequisite to making the system available to the fleet. An issue of this level of importance, concerned with the basic safety of the ship, must be given full consideration well beyond the scope of this study.

It should also be pointed out that a variety of potential solutions to the hazard problem exist, depending on the degree of severity of the problem. These potential solutions range from the use of a protective infrared transparent window or lens over the face of the heater, to the use of completely sealed heater housings, to the extreme case of venting the heater housings with a positive pressure of ducted fresh air in order to prevent any contact between the heating element and the fuel fumes. These various approaches to solving the hazard problem would clearly have a wide range of impact on the economics of installing such anti-icing systems.

5.6.4 Performance Degradation due to Salt Spray Deposits

Another concern regarding the performance of shipboard anti-icing infrared heaters was the potential degradation of the performance of the infrared heating system due to deposits of salt from sea water spray on the element envelope or the reflector. The design approach taken for infrared heaters is to direct the energy to the heated object with a focusing, highly polished reflector. If the reflector gets dirty, the infrared reflectivity of the reflector is substantially degraded. In this event, two things happen. First, the energy directed to the heated object is substantially reduced. Second, the energy absorbed by the reflector and the heater housing increases substantially, possibly to the point of causing damage to the heater unit itself. The more experienced applications engineers contacted felt, however, that at the very high operating temperature of the quartz lamp elements the salt residue would not stick to the more critical surfaces. Further, if this were identified as a major problem, it could be countered with periodic maintenance to clean the elements and reflectors, or minimized in terms of the element itself or the reflector by placing a window or lens of infrared transparent material over the heater in the manner of placing a cover on a fluorescent light fixture in a suspended office ceiling. If such a window or lens is required, high temperature glass is available which is relatively transparent to infrared. Tempered Vycor and the neoserans such as pyroseran were suggested. This issue was therefore judged to be of such a nature that it could be satisfactorily handled. The need for a protective lens for the heater, which would add significantly to the cost of a heater, can be further evaluated during the prototype testing phase of the program.

5.6.5 Corrosion Resistance of Heater to Salt Water Spray

It was generally agreed by most manufacturers that the salt spray corrosion resistance of standard infrared heater housings would not be adequate, however, most manufacturers offer a stainless steel housing at additional cost that would be suitable for the shipboard application.

5.6.6 Personnel Overheating

A final concern developed when it was determined that the design heating requirement was quite substantial. The question was raised as to whether or not operating the heaters at the design condition would be dangerous to, or unbearably uncomfortable for, personnel working on deck. In view of the relatively close proximity of the heaters to personnel on deck in some conceivable applications, such as the 8 foot deck to overhead clearance on a sheltered deck, it was generally agreed that it would be advisable to install a variable output control system for use with the infrared heaters. Variable output is typically achieved by varying the supply voltage with a phase-fired SCR. The need for such a control system, which does add substantially to the cost of a system, can be further evaluated during the prototype testing phase of the program.

5.7 Applications Analysis

5.7.1 General Applicability of Infrared Anti-icing Systems

Before looking into specific shipboard applications of UNREP infrared anti-icing systems, it is appropriate to briefly discuss the general applicability of infrared anti-icing systems, and their potential role in the complete approach to UNREP icing countermeasures. In Phase I of this study of northern latitude UNREP [1], several conventional, unconventional, and high-tech approaches for countering UNREP icing problems were identified as preferred systems in both the anti-icing and deicing categories. In the case of anti-icing, the preferred conventional approaches were identified as electric contact heaters, waterproof covers, low friction paints, and water flooding. The preferred unconventional approaches included hull form design features for spray control, sea calming oil, lead ship sea moderation, mechanical sails, portable physical barriers, air curtains, heated deck mats, warm air ventilation exhaust, and spray collection streamers. Infrared heaters were identified as the loosely defined high-tech approach to anti-icing. In the case of deicing, the preferred conventional approaches were identified as mechanical removal devices (baseball bats, etc), portable heat guns, water lances, steam lances, contact heaters, and water flooding. The preferred unconventional approaches included the pneumatic pulse system, heated deck mats, whip sanders, needle guns, and the electro-expulsive boot. The preferred high-tech approaches were defined as infrared heaters, laser guns, ultrasonics, panel vibrators, and highline vibrators. The point of reviewing all of this material is to emphasize that both of the icing countermeasures investigated in this study, the infrared anti-icing system and the laser deicing system, were identified as two of many approaches worthy of further consideration. Neither system was judged as likely to be the universal icing countermeasure, nor even necessarily the primary icing countermeasure. Further, in the case of the infrared anti-icing system in which the approach is to heat the deck surfaces at the UNREP stations to a temperature somewhat above the freezing point such that sea water spray and atmospheric precipitation will not freeze to the deck and equipment, other methods of heating in addition to infrared were recommended for consideration. In fact, the use of electric contact heaters, or strip heaters, for anti-icing was ranked as the highest priority approach. A similar recommended approach based on achieving anti-icing through heating is the use of heated deck mats. Each of these systems also has applicability as a deicing system. In practice, however, each system also has a unique set of advantages and disadvantages.

It is generally agreed on first consideration that in the case of new construction the preferred method of warming deck work areas to the point at which spray and precipitation would not freeze on the deck is through the installation of permanent strip heaters, more accurately designated as metal sheath, mineral insulated contact heaters, on the underside of the deck. This approach has already been successfully demonstrated on the helicopter pads of some Canadian and European icebreakers. Retrofitting such an installation of permanent contact heaters has generally, but not universally, been regarded as impractical. It is therefore in the case of retrofitting an anti-icing system to an existing ship that the use of both infrared heaters and heated deck mats appear to have a major advantage over the use of contact heaters. Infrared heaters offer the additional advantage of warming deck equipment and machinery in addition to the deck itself, and the advantage of warming personnel working on deck, resulting in a great improvement of the working environment under severe cold weather conditions. The main concerns expressed regarding the use of heated deck mats have been associated with their ability to stand up to the harsh use that would be required of them at an UNREP station, and the fact that no suitable mats currently exist. Several manufacturers have expressed confidence, however, in the fact that the technology currently exists for the production of adequately rugged heated deck mats that could be permanently cemented in place on the deck surface.

It is, therefore, generally agreed that the applicability of infrared anti-icing heating systems is primarily for retrofit rather than new construction. This in no way lessens the level of interest in the system, however, since the first concern associated with expanded levels of northern latitude operations is to significantly improve the capabilities of the existing fleet for such operations. In addition, depending on the results of prototype testing, infrared anti-icing systems may be a stronger contender for use in new construction in competition with contact heaters than is initially apparent due to the fact that, even in the case of new construction, the installation costs of an infrared system could be substantially less than that of a contact heater system, the weight of an infrared system could be substantially less than that of a contact heater system, and the infrared system provides equipment and personnel heating which is not inherently provided by the contact heater system. No decision on the use of contact heater systems in comparison to infrared heater systems for anti-icing in new construction should be made until shipboard experience has been gained with a prototype infrared system, and a ship impact and cost trade-off analysis has been completed for the two systems.

5.7.2 Representative Shipboard Applications

The scope of the UNREP icing countermeasure problem can be somewhat overwhelming in that it encompasses virtually every ship in the fleet. For the purpose of this study, some representative shipboard applications will be discussed with the objective of outlining the scope of the problem and selecting a representative application for prototype evaluation.

The UNREP anti-icing problem encompasses both the replenishment, or delivery ship, and the supported, or receiving ship. The problem encompasses the transfer of fuel, ordnance, stores, and provisions. An UNREP deck work area is defined as any area where personnel are handling lines, hoses, stores, ammunition, and so forth. The UNREP station work area can be relatively small and have convenient mounting surfaces for infrared heaters on bulkheads and overheads as shown for the refueling station on board the USS YORKTOWN, CG 48, in Figure 26, or there can be no convenient heater mounting surfaces as shown for the YORKTOWN's forward VERTREP station identified by the white square on the deck in Figure 27. The UNREP station work area can also be a major portion of the deck area as in the case of a tanker or a multipurpose supply ship. A view of the deck of the replenishment oiler USS SAVANNAH, AOR 4, is shown in Figure 28, while the deck area of the replenishment oiler USS WACCAMAW, TAO 109, is shown in Figure 29. In both cases, one can perhaps envision the mounting of a bank of infrared anti-icing heaters on the underside of the trusswork connecting the kingposts, or perhaps on the kingposts themselves. The feasibility of projecting infrared heat at the required power density from such heights will be assessed in the next section of the report.

In applying anti-icing systems to a receiving ship, it is suggested that selected UNREP stations be equipped for anti-icing and be designated as the cold weather UNREP stations. In the case of a multipurpose supply ship or a replenishment tanker capable of resupplying a ship on each side simultaneously, it may or may not be necessary to equip all UNREP work areas with anti-icing capability.

5.7.3 Applications Considerations

In applying infrared heaters to the anti-icing application, the applications engineering task consists of selecting the heat source power level, the number of heating units, the mounting distance, the spacing of the heater units, and the reflector beam pattern. Recall from the previous discussions that the radiant energy received at a target from a point source varies inversely as the square of the distance between the emitter and the receiver. Also recall that the radiant energy diffuses as a function of the square of the distance as it travels outward from a point source emitter. As has also been discussed previously, recall that the heat load of a power density at the deck of 150 to 200 Watts/ft^2 is a reasonably severe requirement. In view of the thoughts on possible applications contained in the previous section, and the applications guidelines presented by Fostoria as reproduced in Section 5.5, one immediately becomes concerned with the ability to obtain the required power density at the deck with anything more than the bare minimum heater elevation due to the diffusion of the infrared radiation. The following discussion is an effort to quantify these concerns based primarily on

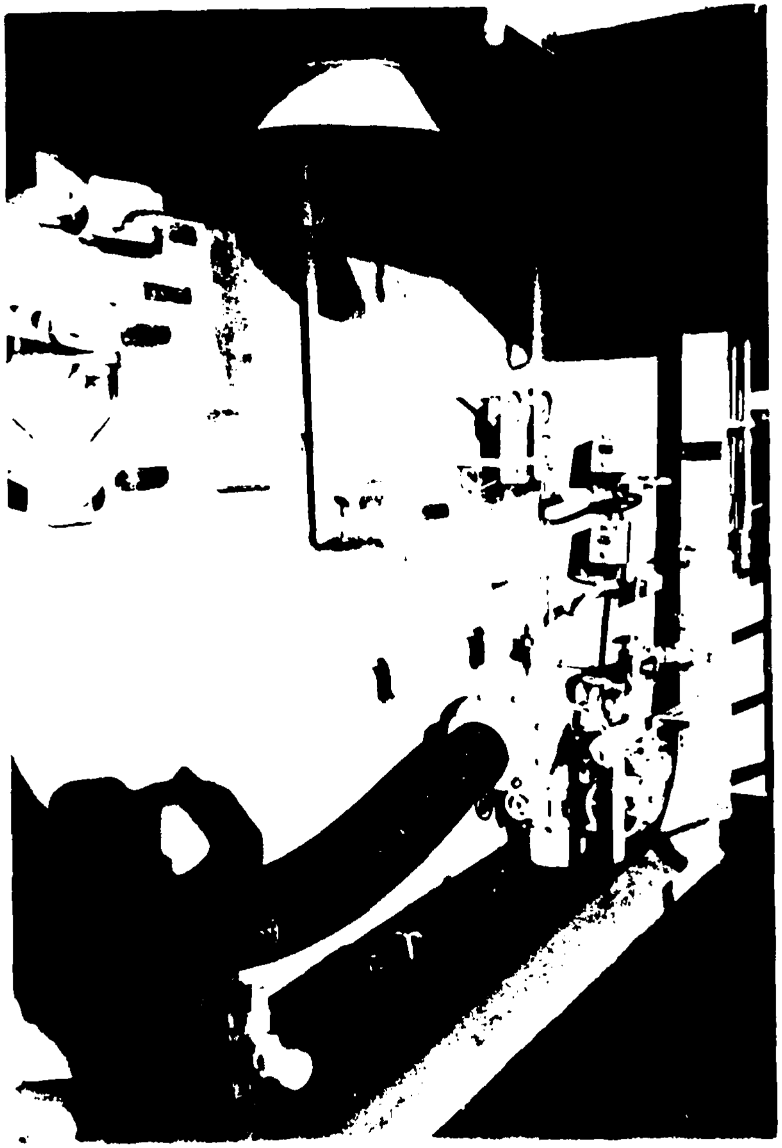


Figure 26 - Photo of Refueling Station on the USS YORKTOWN

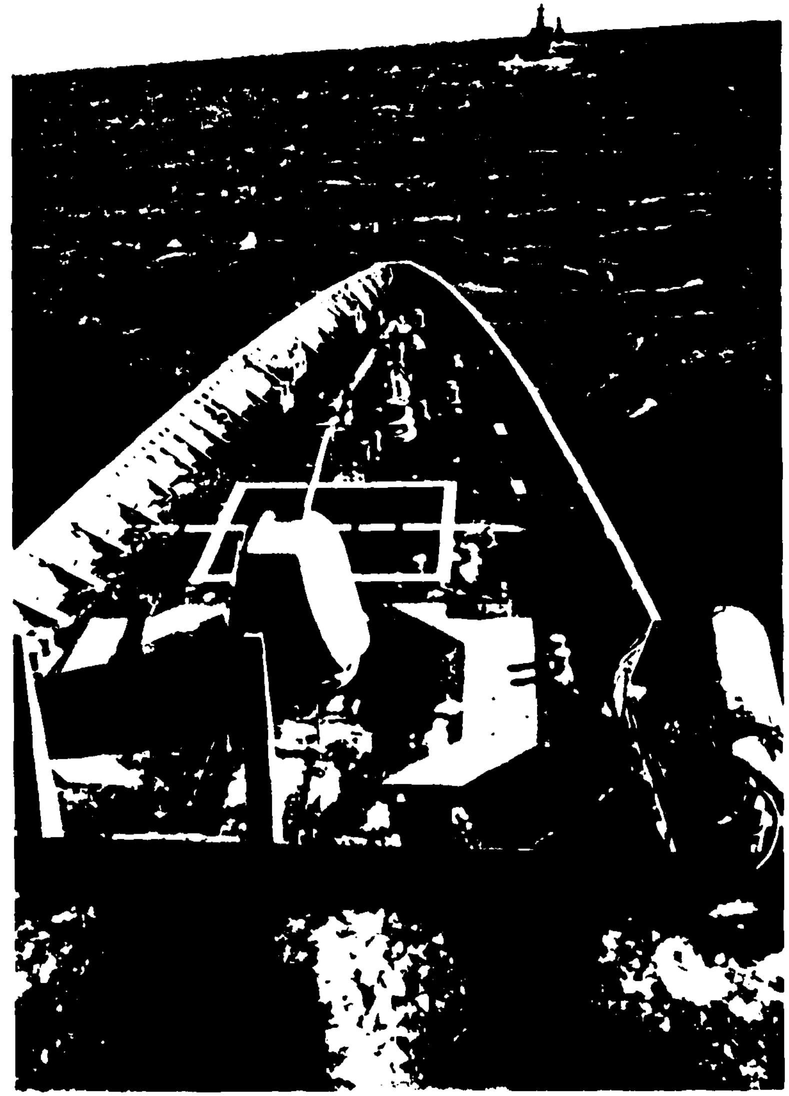


Figure 27 - Photo of Forward VERTREP Station on the USS YORKTOWN

Figure 28 - Photo of the Working Deck Area of the USS SAVANNAH

Figure 29 - Photo of the Working Deck Area of the USS WACCAMAW

information contained in the Fostoria Electric Infrared Heating Manual [34].

The highest capacity quartz lamp infrared heating element available from Fostoria is rated for an input power of 3650 Watts. This element, however, is built without internal supports for the tungston coil, and is specified for horizontal installation only. This element is, therefore, unsuitable for shipboard applications. The highest capacity element constructed with internal coil supports, designated as suitable for vertical installations, is rated for an input power of 3000 Watts. These elements are nominally 4 feet in length, requiring the use of Fostoria's 462 Series Mul-T-Mount fixture, which is the largest available and is UL listed for both indoor and totally exposed outdoor areas. In addition, this fixture series mounts two elements in each fixture, for a total input rating of 6000 Watts per fixture.

In Table 5 of the Fostoria Manual, reproduced in Appendix C as part of the product information on infrared heaters, reflector and heat distribution patterns are presented for each of Fostoria's fixtures. For the largest and most focused Mul-T-Mount fixture, the narrow beam 462-30-TH having a 30° symmetric beam, the length of the heated region, the width of the heated region, and the area of the heated region are restated for different mounting heights in Table 13. The heated length, width, and area are then presented graphically as a function of mounting height in Figures 30, 31, and 32 respectively. The length and width are seen to vary linearly with mounting height, and the area varies generally as the square of the mounting height. The plots are extrapolated well beyond the 20 foot mounting height given in the Fostoria catalogue to a mounting height of 60 feet for purposes of illustration.

Table 13

Heated Length, Width, and Area for Different Mounting Heights for the Fostoria 462-30-TH Fixture [34]

Mounting Height ft	Heated Length ft	Heated Width ft	Heated Area ft^2
2	4.0	1.0	4.00
4	5.0	2.0	10.00
6	6.0	3.0	18.00
8	7.0	4.0	28.00
10	8.5	5.5	46.75
12	9.5	6.5	61.75
14	10.5	7.5	78.75
16	11.5	8.5	97.75
18	12.5	9.5	118.75
20	13.5	10.5	141.75

FIGURE 30

HEATED LENGTH AS A FUNCTION OF MOUNTING HEIGHT

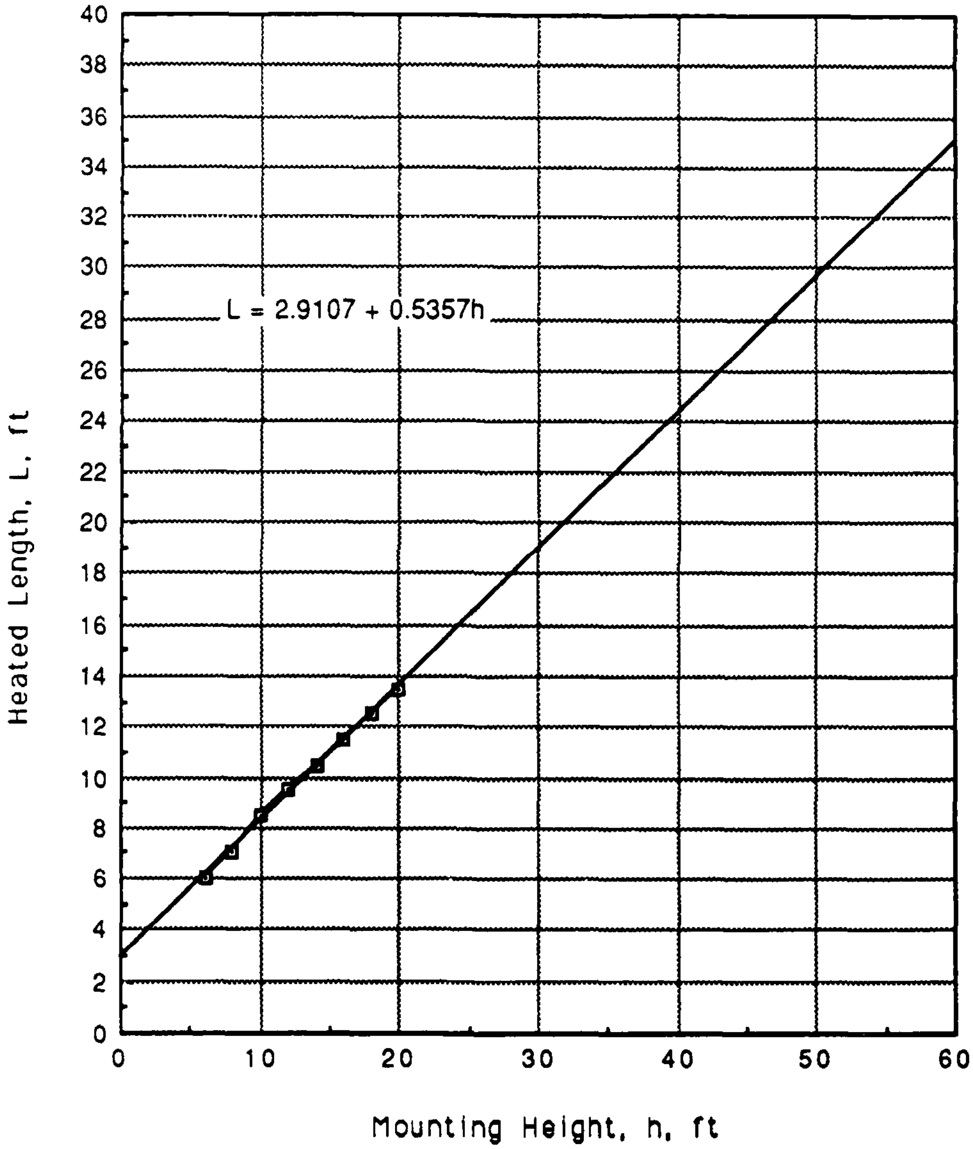


FIGURE 31

HEATED WIDTH AS A FUNCTION OF MOUNTING HEIGHT

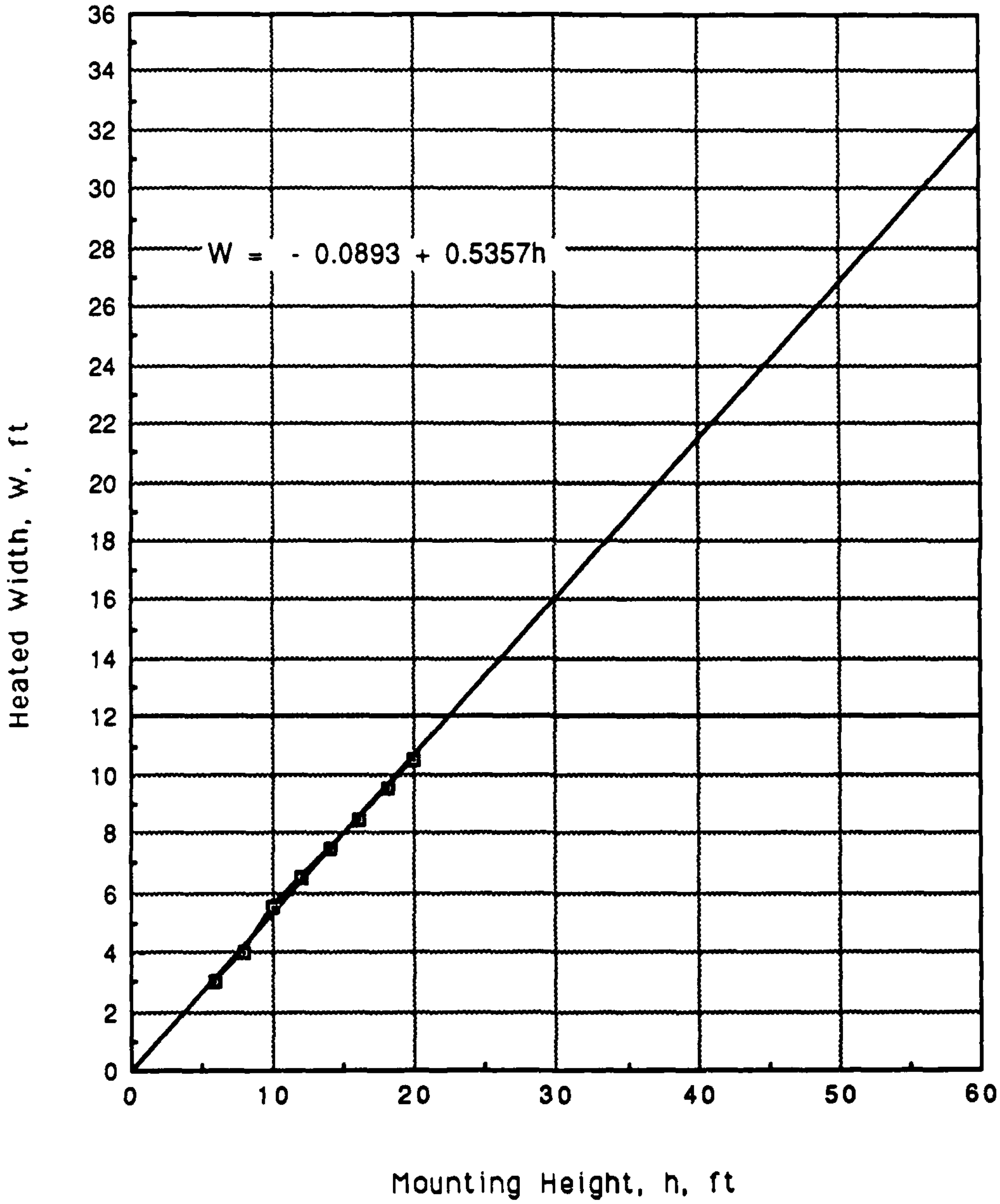
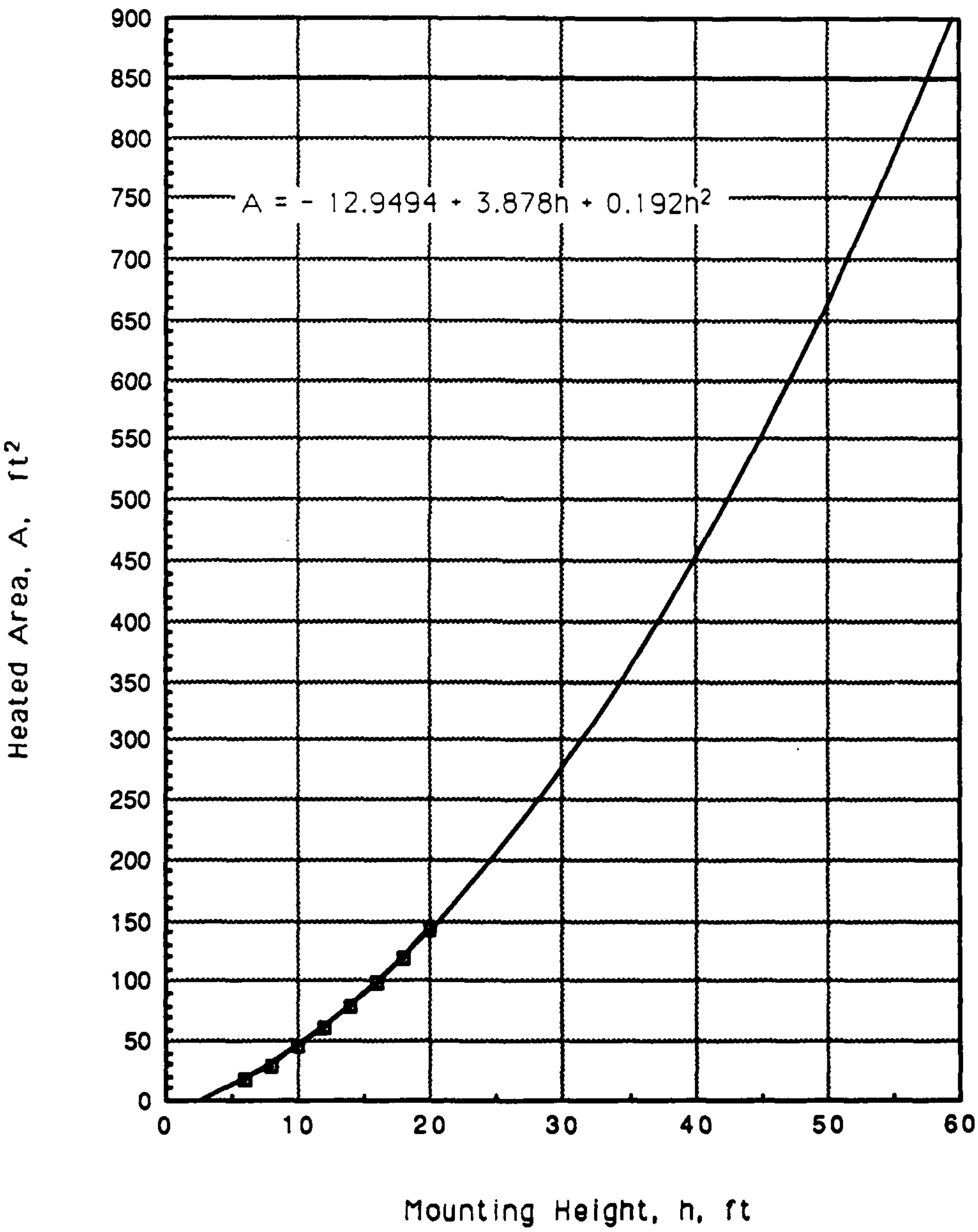


FIGURE 32

HEATED AREA AS A FUNCTION OF MOUNTING HEIGHT



Fostoria defines the mounting height as the distance from the infrared element source to the receiving surface. The intercepts of the linear regressions of the heated length and width data shown by the straight lines plotted in Figures 30 and 31 are indicative of the heated length and width of a single nominal 4 foot quartz lamp element. This element has an actual overall length of 41 11/16 inches, and a heated length of 38 inches. The diameter of the quartz tube enclosing the element is 3/8 inch. The second order heated area curve regressed in Figure 32 shows that the heated area varies from about 47 ft^2 for a mounting height of 10 feet to about 660 feet at a mounting height of 50 feet. For example, if this were a 100% efficient, 6000 Watt total, dual element heater, the power density at the receiver for a 10 foot mounting height would be about 128 Watts/ft^2. For a 50 foot mounting height, the power density from this single fixture would only be about 9 Watts/ft^2.

Looking at the limits of infrared heating capacity using the Fostoria 462 Series fixtures in another way, the catalogued dimensions of the fixture are 46 inches in length by 15 inches in width. The average maximum power density for the fixture at the face of the fixture can be calculated on the basis of the fixture face area of about 5 ft^2. Again, for a 100% efficient, 6000 Watt total, dual element heater, the maximum power density at the heater would nominally be 1200 Watts/ft^2. This approach is useful in determining the maximum power outputs achievable by ganging fixtures together in direct contact with one another as was done in the Fostoria snow and ice control case history shown previously in Figure 25.

At this point, it is appropriate to discuss the fact that while the efficiency of quartz lamp infrared heaters is quite good and approaches 100% under normal design conditions, for various reasons it will be less than the 100% used in the above discussion for the shipboard application. Three major factors will reduce the overall heating efficiency of the heaters, the convection heating loss of the heater element as quantified by the radiation generating ratio, the difference between the rated and the shipboard supply voltage, and the likely necessity of reducing the very high visual brightness of the heater element with the use of a red Vycor sleeve. The Fostoria Manual lists the radiant efficiency of their clear quartz lamp radiant heaters as 96%. This efficiency defines the amount of input power given off as infrared radiation by the heater, with the remainder lost to convection heating. The convection heating loss is a true heat loss for the shipboard application, in contrast to an enclosed space heating application, since the convection heating of the heater is lost to the atmosphere.

The voltage at which the heaters are rated is 480 volts, while the voltage of the standard shipboard power supply is 450 volts. The ratio of actual to rated voltage is then 0.9375. From Graph D of the Fostoria Manual (Appendix C of this report), the power supplied is then only 88% of rated power. The reduced voltage also results in a reduction of the color temperature of the heating element, which lowers the radiant efficiency. From Graph E (Appendix C) of the Fostoria Manual, the reduced voltage results in a slight reduction of the radiant efficiency to 95%.

It is judged likely that the visible glare of the infrared heating elements will be quite objectionable during night operations. When the visible glare of quartz lamp infrared heating elements is objectionable, it is recommended that ruby red Vycor sleeves be fitted over the elements. These sleeves eliminate about 96% of the visible light output, but at a cost of reducing the infrared heat output by about 4%. The visual effect provided by the red sleeves is that of a "warm red glow".

Combining the effect of all of these considerations for the shipboard application, the ratio of output power to input power is (0.88)(0.95)(0.96) = 0.80256, or about 80%. The actual radiant heat output of a 6000 Watt fixture will therefore be about 4800 Watts. The corresponding maximum output power density at the face of the fixture is then about 960 Watts/ft^2. The power density at the receiver for one 6000 Watt input fixture housing two 3000 Watt quartz lamp elements for different mounting heights is then as presented in Table 14, which also repeats the heated length, width, and area data presented in Table 13. The data are shown graphically in Figures 33 and 34. The plot of power density as a function of mounting height in Figure 33 illustrates the rapid reduction of power density with increasing mounting height, and its asymptotic approach to zero. The plot of power density as a function of the inverse of the mounting height squared in Figure 34 illustrates the fact that the power density varies as the inverse square of the mounting height. The non-zero intercept reflects the fact that the heating element has a finite length and width, rather than being a true point source of radiation.

Table 14

Power Density at Receiver for Different Mounting Heights for the 6000 Watt Input Fostoria 462-30-TH Fixture

Mounting Height ft	Heated Length ft	Heated Width ft	Heated Area ft^2	Power Density at Receiver Watts/ft^2
2	4.0	1.0	4.00	1200
4	5.0	2.0	10.00	480
6	6.0	3.0	18.00	267
8	7.0	4.0	28.00	171
10	8.5	5.5	46.75	103
12	9.5	6.5	61.75	78
14	10.5	7.5	78.75	61
16	11.5	8.5	97.75	49
18	12.5	9.5	118.75	40
20	13.5	10.5	141.75	34

FIGURE 33

POWER DENSITY AT THE RECEIVER AS A FUNCTION OF MOUNTING HEIGHT

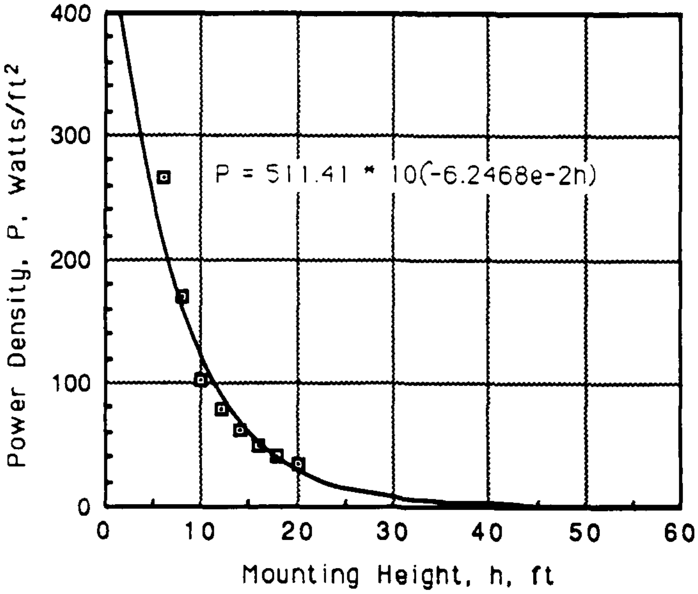
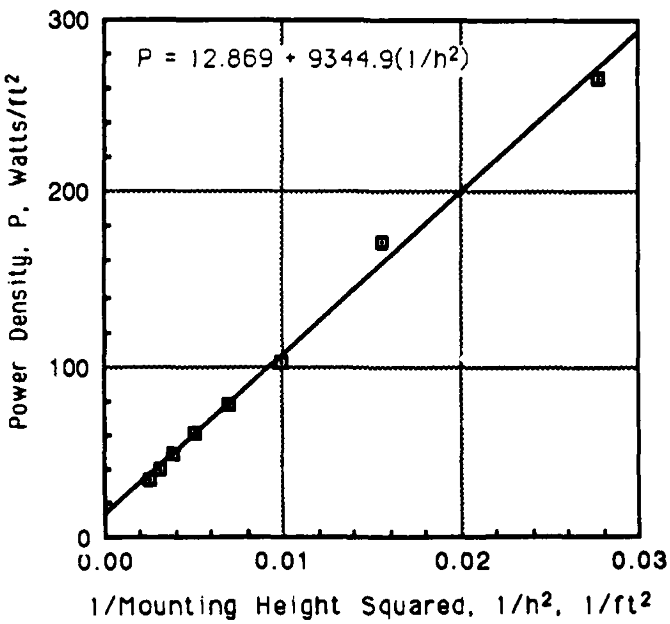


FIGURE 34

POWER DENSITY AT THE RECEIVER AS A FUNCTION OF INVERSE MOUNTING HEIGHT SQUARED



5.7.4 Large Area Anti-icing

Looking back at the photo of the working deck of the USS SAVANNAH, presented earlier as Figure 28, it would not appear to be practical to attempt to maintain the entire length and beam of the working deck in a ready condition under severe icing conditions with banks of infrared heaters. Estimating the length of the working deck as about half the 659 foot length of the vessel, and taking the full 96 foot beam of the vessel, the area to be heated would then be 31,632, or roughly 32,000, ft^2 of deck area. Heating this much deck with a power density of 200 Watts/ft^2 at an overall efficiency of 80% would require the entire 8000 kW electrical power generating capacity of the ship. This is clearly not a practical situation.

Backing off to a somewhat less demanding approach, and again thinking in terms of designating one of the UNREP stations as the cold weather station, the deck area to be heated could be reduced to a length of about 110 feet for the full 96 foot beam, resulting in an area to be heated of about 10,000 ft^2. Going further with the designated cold weather UNREP station approach, perhaps this heated area could be halved again by only having a cold weather station on one side of the ship. For this half beam case, the 5000 ft^2 deck area to be heated at a power density of 200 Watts/ft^2 at an overall heating efficiency of 80% requires a total power input of 1250 kW, still a substantial load, but probably not unreasonable for the limited operations possible under the cold weather conditions.

Again based on the use of 6000 Watt Fostoria 462-30-TH heaters, a total of about 200 heaters would be required. At 5 ft^2 per heater, the face area of the 200 heater fixtures would be 1000 ft^2, or about one-tenth the heated area. For a fixture length to width ratio of about 3, a closely packed platform of heaters would measure about 55 by 18 feet. The installation of such a bank of infrared heater fixtures over one of the fully exposed UNREP stations shown in the photo presented previously as Figure 28 is probably not practical. For the station immediately aft of the forward house, or immediately forward of the after house, where it may be possible to mount at least some of the heating fixtures on the bulkhead and make use of the 30° asymmetric fixtures which direct the infrared radiation out 30° from a perpendicular to the deck, the concept may be reasonable. For prototype testing, however, it is clearly preferable to consider applications of a much lesser scale.

5.7.5 Local Area Anti-icing

A very practical application for the prototyping of an UNREP infrared heating anti-icing installation is a refueling station on a major surface combatant. As an example, consider the refueling station on the USS YORKTOWN shown previously in Figure 26. Infrared heating fixtures could be installed on the overhead to maintain the deck ice free. Infrared heating could also be partially directed toward the bulkhead of the refueling station to provide anti-icing for that area. The deck area associated with an underway refueling operation at a single station is estimated to be about 100 feet long and 5 feet wide. The 100 foot length includes both the length of the refueling station itself and the length of the portion of the deck required by the line handlers. For the purpose of prototype testing, however, it is recommended that only the portion of the deck in the immediate vicinity of the refueling station be heated with infrared anti-icing heaters. This length is taken as about 20 feet. For the testing and demonstration of a prototype system, therefore, the deck area to be heated is taken as 20 feet by 5 feet, for a total of 100 ft^2. Hardware selection for this application will be discussed in the following section of this report.

5.8 Prototype Hardware Selection

Hardware will be sized and selected for anti-icing a 20 by 5 foot section of deck at a refueling station with the use of overhead mounted electric quartz lamp infrared heaters. The rather severe design condition requires the provision of a heating capacity at the deck of 200 Watts/ft^2. As discussed above, a Fostoria Mul-T-Mount 462-30-TH dual element fixture rated at 6000 Watts input will provide an output of 4800 Watts in the shipboard application.

With a deck to overhead height of 8 feet, and allowing a 3 inch standoff for mounting the fixture and 6 inches for the depth from the element to the top of the fixture (that is, the element is about 1 inch back from the face of the 7 inch deep fixture), the mounting height of the element from the deck is 7.25 feet. From Figures 30 and 31, the length and width of the portion of the deck heated by the fixture is about 6.5 by 3.5 feet. For this mounting height, then, the power density at the deck is about 211 Watts/ft^2, or for all practical purposes, at the design condition. Taking the conservative arrangement of the heaters and placing them in the overhead oriented athwartships, that is, orienting the 6.5 ft length of coverage with the 5 ft width of the deck, six fixtures (20/3.5 = 5.7) are required to provide anti-icing capability over the 20 foot length of the refueling station. The hardware selection and the catalogue prices from the Fostoria price list dated 1 October 1989 are summarized in Table 15. Fostoria has indicated a willingness to significantly discount the catalogue prices for a prototype system.

Table 15

Hardware Selection and Cost for Prototype Refueling Station Infrared Anti-icing System

Item	Unit Cost $	Quantity	Total Cost $
Mul-T-Mount 462-30-TH Fixture in Stainless Steel	900	6	5,400
GF-3857V 3000 Watt, Vertical Mount Quartz Lamp Element	113	12	1,356
31-941 Ruby Red Vycor Sleeve	52	12	624
CHWG-462 Lamp Guards in Stainless Steel	75	6	450
SCR Variable Voltage Output Power Controller	5,270	1	5,270
System Hardware Catalogue Total Price			$ 13,100

5.9 Prototype Testing Considerations

5.9.1 Purpose

While electric infrared heating is in common usage for particular applications, most notably manufacturing process heating and direct people heating in large structures such as high bay factories and hangers where the cost of heating the entire volume of air in the space is prohibitive, the application of the system to shipboard anti-icing is new. As with any new application of existing technology, a number of questions arise as to the practicality of the system for the application, and the actual quantitative performance of the system in the application. While quantitative performance can best be measured in laboratory tests conducted under controlled conditions, system suitability for a particular application can best be determined through prototype testing in the field. In this case of the adaptation of existing technology, the performance of the system can be predicted with a relatively high degree of confidence, and the confirmation of the quantitative performance of the system can likely be adequately based on measurements taken during prototype testing without the necessity of undertaking a laboratory test program. It is therefore recommended that concerns related both to the applicability of the system and the quantitative performance of the system be addressed in a prototype test program. Under this prototype test program, the prototype hardware identified in the previous section of this report would be purchased and installed on board a ship that, preferably, is scheduled for a deployment in cold regions. The information to be gathered in the prototype test program is outlined in the following sections.

5.9.2 Applications Considerations

During the course of this study a number of questions arose regarding the suitability of electric quartz lamp infrared heating for the UNREP anti-icing application. Some of these questions could be answered with a relatively high level of confidence during the study, while others could not. The prototype testing phase of the program offers the opportunity to definitively answer all of the questions on the basis of operating experience under actual field conditions. A list of the major questions and concerns to be answered through the conduct of the prototype test program follows:

1. Are the standard vertical-rated quartz lamp infrared heating elements rugged enough for shipboard use?

2. Are the stainless steel Fostoria Mul-T-Mount infrared heater fixtures rugged enough for shipboard use? If not, should they be redesigned or simply enclosed in a rugged standard Navy-type housing?

3. Do the operating quartz lamp heaters break when hit with cold sea water spray?

4. Does the salt residue from the sea spray build up on the reflector or quartz lamp when the heater is operating and cause heating performance degradation or fixture overheating? If a unit is well coated with the residue of sea spray while switched off, does the residue melt or vaporize off when the heater is energized? If sea spray residue is a problem, a possible solution is to install standard heating fixtures (stainless steel units would probably no longer be necessary) in an enclosure (which could be stainless steel) having a lens or window of clear Vycor quartz sheet as is used by Process Thermal Dynamics Inc. in their Protherm process heaters (Appendix C).

5. Do the ruby red Vycor sleeves adequately eliminate the visible glare produced by the heaters, particularly during night operations?

6. It is likely to be uncomfortably hot for personnel working under the heaters when they are operated at full output. Under what ambient conditions is it necessary to reduce the output of the heaters for personnel comfort, and to what level must the heater voltage be reduced?

5.9.3 Performance Considerations

While it is not envisaged that the opportunity will be available to conduct fully instrumented tests of the prototype infrared anti-icing system, it would be advisable to collect as much performance data on the system as is possible. The ideal situation would result from having the ship on which the prototype system is installed experience a significant icing event. Even if an icing event is not encountered, however, a significant verification of the performance of the system can be realized with a relatively limited amount of data collected with normal shipboard instrumentation supplemented by hand-held instrumentation. The hand-held instrumentation required consists of a surface pyrometer, or a non-contact hand-held infrared thermometer as described at the end of Appendix C, for measuring surface temperature, and an anemometer for measuring local wind speed. This instrumentation could be supplemented with the use of a power density meter for measuring the infrared radiation energy level at the deck if such a meter were available. The meter would be used to measure the areal power density distribution in the same manner that the surface thermometer would be used to map the surface temperature. Recommendations for collecting data related to the quantitative performance of the prototype infrared anti-icing system for each of these situations are outlined below.

5.9.3.a Performance During an Icing Event

The primary data to be collected in connection with an icing event are as follows:

1. General environmental data:

    a. Air temperature
    b. Ship's speed and direction
    c. Relative wind speed and direction
    d. True wind speed and direction
    e. Local relative wind speed at the heated deck
    f. Wave height
    g. Description of spray wetting volume and frequency at the heated refueling station
    h. Sea water temperature

2. Ice data:

    a. If possible, periodically measure or estimate the accreted ice thickness during the icing event
    b. Measure the area of the deck effectively covered by the heaters
    c. At the completion of the icing event, measure the profile of the ice thickness over areas adjacent to the heated area, and over the heated area itself if ice forms
    d. Using a surface pyrometer, measure the surface temperature of the deck or the ice in the heated area, and the surface temperature of the ice in adjacent areas
    e. If any ice had formed over the heated portion of the deck, record the time required to melt it at full heating output
    f. If no ice formed over the heated area, try to remove a slab of ice from an adjacent area, measure it's area and thickness, position it in the heated area and measure the time required to melt the ice
    g. (Optional) Measure the weight and volume of a sample of the ice for determining its density

5.9.3.b *Performance in Cold Weather Without Icing*

In the event of a cold weather deployment where no icing is encountered, some quantitative assessment of the performance of the infrared anti-icing system can be obtained by measuring the result of heating the deck, preferably under low temperature conditions. In this case, the primary data to be collected are as follows:

1. General environmental data:

    a. Air temperature
    b. Ship's speed and direction
    c. Relative wind speed and direction
    d. True wind speed and direction
    e. Local relative wind speed at the heated deck
    f. Wave height
    g. Description of spray wetting volume and frequency at the heated refueling station if any
    h. Sea water temperature

2. Infrared heating system performance data:

    a. Map the temperature profile of the deck in the heated area to determine the area covered by the heaters and the temperature variation due to heater spacing
    b. Measure the temperature of adjacent unheated deck areas
    c. Adjust the heater output in steps to 80%, 60%, and 40% of maximum output and, after allowing steady state conditions to be reestablished, repeat the above measurements

6. CONCLUSIONS AND RECOMMENDATIONS

As a result of this feasibility study of applying laser technology to UNREP deicing, and applying infrared heating technology to UNREP anti-icing and deicing, the infrared system continues to look promising, while the laser system does not.

The shipboard applicability of lasers for use as an UNREP deicing tool, either in the ice melting mode or in the ice fracturing mode, is technically feasible. Approaches for overcoming several of the concerns associated with the practical application of lasers to shipboard deicing were developed, while maintaining laser power levels that provided a reasonable level of deicing operating capability. These concerns included the ability to use the laser to melt ice without damaging the underlying material (paint or metal), and the ability to use the laser for removing ice without risk of injury to the operator or to other members of the deicing team. The design constraints imposed in the interest of safety do, however, limit the range of applications suitable for the use of the laser deicing system. The laser deicing system was, therefore, judged to be both physically and technically feasible, but economically unpractical. On the basis of a performance and cost comparison with a high pressure water lance deicing system, it was determined that the water lance has a greater capability to remove ice at a cost of about one-fifth to one-tenth of the cost of the laser deicing system. The price of a representative laser system, including a fiber optic delivery system, is in the range of $60,000 to $70,000.

More specifically, this study of the use of lasers for removing accreted topside ice from shipboard UNREP stations results in the following conclusions:

1. Lasers can be used as deicing tools to make grooves in accreted ice, such that slabs of the ice can be subsequently pried off the surface, either by melting slots in the ice or by shattering slots in the ice. Design limitations which significantly impact the performance of the system are imposed due to the requirement to remove ice without damaging the underlying painted steel or aluminum surface. This analysis indicates that the shattering mode offers the promise of higher performance levels than the melting mode.

2. Laser deicing systems can be engineered to minimize the risk of damage to personnel through the incorporation of optics which provide a rapidly diverging beam, but, again, with some significant penalty in the applicability or usefulness of the system. Even with design features dedicated to the safety of the system, a significant training effort would be required to assure that the laser deicing system would be operated at an acceptable level of safety.

3. The cost of a laser deicing system, including a fiber optic cable beam delivery system, was estimated to be in the range of $60,000 to $70,000.

4. On the basis of a rough comparison with a high pressure water lance deicing system, it was estimated that the water lance system would deliver superior deicing performance with substantially fewer safety and operational concerns at about 10% to 20% of the cost of a laser deicing system. Some of the anticipated operational advantages of the laser system, such as the ability to remove accreted ice from booms, masts, and lines at great distances with the laser beam, had to be designed out of the system for safety reasons. Other advantages of the laser system, such as the ability to remove ice without the use of steam or water which have the potential of adding to the icing problem, remain, but are of relatively minor importance in view of the cost and operational complications of the system.

5. It is therefore concluded that laser deicing systems should be dropped from further consideration at the present time. If at some future time lasers are considered for use on ships for other purposes, such as for the removal of paint, their use for deicing should again be considered as a supplementary application.

The practical shipboard applicability of infrared heating systems for use in UNREP anti-icing and deicing continues to look promising. In general, the preferred application is to use infrared heaters in the anti-icing mode, that is, to keep the UNREP station at a temperature high enough so as to prevent the formation of ice during an icing event. Feasibility assessment calculations also indicate, however, that the use of infrared heaters for deicing will provide reasonable results. The most obvious applicability of an infrared heating anti-icing and deicing system is as a retrofit on existing ships. It is also possible, however, that the system could compete favorably with the installation of underdeck strip or contact heaters in the case of new construction.

More specifically, this study of the use of infrared heaters for preventing the formation of topside ice at shipboard UNREP stations, and for removing accreted topside ice from shipboard UNREP stations, results in the following conclusions:

1. Infrared heating systems can be used to provide both anti-icing and deicing capability at UNREP stations, with anti-icing being the preferred mode of application. The system is particularly applicable to retrofit situations where an anti-icing heating capability is required on existing ships. Depending on the results of the recommended prototype performance tests, infrared anti-icing systems could also compete favorably with, or be used in conjunction with, underdeck-mounted strip heater anti-icing systems in some applications on new construction. The major limitation in the application of infrared heating systems for anti-icing is that they must be mounted in relatively close

proximity to the surface being heated, making their application to large expanses of open deck difficult.

2. The heating capacity required to maintain the deck and equipment surfaces at an UNREP station at a temperature somewhat above the freezing point of sea spray and atmospheric precipitation under severe northern latitude low temperature and high wind conditions is quite high, requiring the use of infrared heaters which have the highest output capacity and the highest operating efficiency. For these reasons, the type of infrared heater selected for UNREP anti-icing is the electric quartz lamp type, fitted with red Vycor sleeves to reduce the otherwise very high levels of illumination provided by these heaters.

3. It is concluded that the infrared heating anti-icing system should be demonstrated and further evaluated through the shipboard testing of a prototype system. The hardware for a prototype infrared anti-icing system sized for a roughly 20 foot by 5 foot immediate work area of a surface combatant refueling station has been selected. The catalogue price of the hardware, including an SCR controller which provides infinitely variable heater output capability, is $13,100. The negotiated price of a prototype system should be significantly less.

4. Completion of the shipboard applications tests and performance tests outlined for the prototype system will provide the additional information necessary for making a decision as to the fleet-wide applicability of infrared heater UNREP anti-icing systems.

The following specific recommendations are made on the basis of this feasibility study of applying laser technology to UNREP deicing, and applying infrared heating technology to UNREP anti-icing and deicing:

1. While the assessment of the economic practicality of the laser deicing system was unfavorable in this study, the advent of additional uses for lasers of this type aboard ship would warrant the reconsideration of the laser deicing application. For example, it was shown in this study that the intensity of the deicing laser had to be limited in order to not burn the underlying paint. The lasers identified in this study could be adapted to the task of routine paint removal by a simple adjustment of the laser beam optics and switching to a pulsed mode of operation. If it is determined that it may be useful to pursue the laser deicing concept at some future time, recommendations related to the laboratory testing of lasers for deicing applications are provided in the report.

2. It is recommended that a prototype infrared anti-icing and deicing system of limited scope be installed as a demonstration and test unit aboard a surface ship scheduled for a northern latitude deployment, and tested during the deployment. A prototype system suitable for use at a sheltered (overhead mounted

heaters) refuelin: UNREP sta:ion has en design:ed and priced in this study. Recommendation. for te ng of the system have been developed in terms of the suitabili of the system for general application, and in terms of obtaining performance data both during an icing event, and in the case of a deployment which experiences cold weather, but not icing, cond

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Appendix A

PRODUCT INFORMATION
ON
LASER EYE PROTECTION

Table A-1 gives a listing of some laser eye protection eyewear currently available (Reference: Guide for the Selection of Laser Eye Protection). For each model of eye protection, the optical density (OD or D_λ) is noted over a range of wavelengths. The optical density of a filter at a particular wavelength is defined as the logarithm to the base ten of the reciprocal of the transmittance, and can be computed from the ratio of the incident intensity to transmitted intensity:

$$D_\lambda = \log_{10}(I_i/I_t) = -\log_{10}(1/\tau_\lambda)$$

where τ_λ is the transmittance. In general, the desired optical density for the selection of proper eyewear is the minimum optical density required to attenuate the maximum radiation intensity expected to the maximum permissible exposure (MPE) limit.

$$D_\lambda = \log_{10}(I_i/MPE)$$

The last column of the table gives the daylight visible transmittance which provides an indication of how much the user's vision might be impared in the workplace.

Table A-2 gives a listing of manufacturers or suppliers of protective eyewear for laser safety.

Table A-1
Optical Density of Standard Laser Eye Protection [19]
(Wavelength in nm)

	Ar F₂ 193	Kr F₂ 249	XeCl₂ 308	HeCd₂ 325	N₂/Ne 337	Xe F₂ 351	He Cd 441	Ar 488	Ar 515	He Ne 633	Kr 647	Ruby 694	Ga As 840	Nd 1060	Er 1730	HF 2700	DF 3600	CO 5000	CO₂ 10,600	% T
AMERICAN OPTICAL																				
581G	>2	>2	>2	>2	>2	>2	<1	<1	<1	4.1	4	6.1	5	2						10
584G	>2	>2	>2	>2	>2	>2	<1	<1	<1	1	1	4.4	11.2	9.5						30
585G	>2	>2	>2	>2	>2	>2	<1	<1	<1	3	3	7.1	17.4	14.7		<1	>3	>3	>3	25
588S	>2	>2	>2	>2	>2	>2	<1	<1	<1	2.2	3	6.0	14.8	12.5	1.5	<1				35
598S	>2	>2	>2	>2	>2	>2	17	13.5	9.1	<1	<1	<1	<1	<1						25
599G	>2	>2	>2	>2	>2	>2	14	8.6	5.5	<1	<1	<1	<1	<1						25
680G	>2	>2	>2	>2	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	15	15	90
698G	>2	>2	>2	>2	>2	>2	12	10	8	<1	<1	>4	>10	7.4						5
BAUSCH & LOMB																				
54						30	17	14	12	<1										4.3
55							7	3	<1	<1	<1	<1	<1	<1						57
56				>8	>8	8	1	<1	<1	13	14	15	5							6.2
57							1	<1	<1	4	5	7	11							3
58							1	1	1	1	1	2	4	8						3
EALING CORP																				
25-2478										5		10		30						
FISH-SCHURMAN CORP																				
AL515	>10	>10	>10	>10	>10	>10	>10	>10	7	<1	<1	<1	<1	<1						46
AL565	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1						15
AL633-4	>5	>5	>5	>5	>5	5	<1	<1	<1	4	7	>7	>7	>7						13
AL694	>5	>5	>5	>5	>5	5	<1	<1	<1	5	8	12	16	16						26
AL-1060-9				<1	<1	<1	<1	<1	<1	<1	<1	<1	2	9						63
AL-1060-11				<1	<1	<1	<1	<1	<1	<1	>1	<1	5	11						50
AL-10600				<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1						92
GLENDALE OPTICAL																				
Laser- N,H				>16	16	16	<1	<1	<1	<1	<1	<1	<1	<1						70
Gard HeNe				>10	>10	>10	1	<1	<1	6	5	2	<1	<1						17
Ar				20	19	18	14	15	11	<1	<1	<1	<1	<1						45
Ruby				8	9	9	<1	<1	<1	6	4	6	<1	<1						19
Ar/Nd						20		15	11					14						45
Nd/Ga As				25	24	22	7	1	1	1	1	3	14	16						45
CO₂																			12	30
Broad Band A				25	20		<1	<1	<1	<1	1	6	20	20						20
Broad Band B	25	25	25	25	25	25	14	11	7	<1	<1	<1	4	4						45
PHASE - R																				
Blue								>1	>2	>5	5	>1	1							
Red				5	5	5	<5	>4	>4	1	<1									
FRED REED OPTICAL, INC.																				
GG9	>5	>5	>5	>5	>5	>5	1.5	1	<1	<1	<1	<1	<1	<1	<1	.1	.15	>2.3	>2.3	85
GG420	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	<1	<1	<1	.05	.1	1.4	>2.3	>2.3	80
GG455	>5	>5	>5	>5	>5	>5	1	<1	<1	<1	<1	<1	<1	<1	.05	.09	1.4	>2.3	>2.3	70
GG475	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	<1	<1	.05	.08	1.3	>2.3	>2.3	60
OG515	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	<1	.04	.09	1.3	>2.3	>2.3	55
OG530	>5	>5	>5	>5	>5	>5	>5	>5	5	<1	<1	<1	<1	<1	.05	.09	1.3	>2.3	>2.3	60
OG550	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	.05	.09	1.3	>2.3	>2.3	50
OG570	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	.05	.09	1.3	>2.3	>2.3	40
OG590	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	.05	.1	1.4	>2.3	>2.3	30
RG610	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	.05	.09	1.3	>2.3	>2.3	40
RG630	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1	.05	.09	1.3	>2.3	>2.3	20
RG665	>5	>5	>5	>5	>5	>5	>5	>5	>5	>5	4	<1	<1	<1	.04	.09	1.3	>2.3	>2.3	10

Table A-1 (Continued)
Optical Density of Standard Laser Eye Protection [19]
(Wavelength in nm)

	ArF_2 193	KrF_2 249	$XeCl_2$ 308	$HeCd_2$ 325	N_2/Ne 337	XeF_2 351	He Cd 441	Ar 488	Ar 515	He Ne 633	Kr 647	Ruby 694	Ga As 840	Nd 1060	Er 1730	HF 2700	DF 3600	CO 5000	CO_2 10,600	% T
FRED REED OPTICAL, INC., con't																				
KG-3	>5	>5	1.5	<1	<1	<1	<1	<1	<1	<1	<1	<1	2	4.5	>3	>2.3	>2.3	>2.3	>2.3	85
KG-5	>5	>5	>5	2	<1	<1	<1	<1	<1	<1	<1	<1	3	6	>3	>2.3	>2.3	>2.3	>2.3	85
UV-400				>3	>3	<1	<1	<1	<1	<1	<1	<1	<1	<1						90
BG 1	>5	>5	<1	<1	<1	<1	<1	<1	4	6	5	4	<1	<1	1.4	.26	1.1	>2.3	>2.3	20
BG 18	>5	>5	>5	>5	1.7	1	<1	<1	<1	1.5	3	5	>5	>5	1.3	.6	>2.3	>2.3	>2.3	45
BG 39	>5	>5	>5	3	<1	<1	<1	<1	<1	1.5	2	>5	>5	>5	.91	.49	>2.3	>2.3	>2.3	60
BG 40	>5	>5	>5	4	<1	<1	<1	<1	<1	<1	1	2.5	>5	>5	.51	.57	>2.3	>2.3	>2.3	70
ROCKWELL ASSOCIATES, INC.																				
Ar-LEPD-11				>5	>5	>5	>5	>5	>5	<1	<1	<1	<1	<1						>40
UV/FIR-LEPD-22				>5	>5	>5	<1	<1	<1	<1	<1	<1	<1	<1						>40
SPECTRA - OPTICS																				
UV-1	>6	>6	>6	>6	>6	>6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	>3	>10	>80
UV-2	>6	>6	>6	>6	>6	>6	>6	>1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	>3	>10	>80
Argon-1	>15	>15	>15	>15	>15	>15	>15	>15	>15	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	>3	>10	>50
Argon-2	>15	>15	>15	>15	>15	>15	>15	>15	>15	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	>10	>10	>25
Krypton-1	>10	>10	>10	>10	>10	>10	>10	>10	>10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	>3	>10	>10
He/Ne-1	>5	>5	>3	>2	>5	>5	<1	<1	>5			>3	<1	<1	<1	<1	<1	>10	>10	60
He/Ne-2	>10	>10	>3	>2	<1	<1	<1	<1	<1	>5	>6	>9	>12	>13	<1	<1	<1	>3	>10	>30
Ruby-1	>5	>5	>3	>2	<1	<1	<1	<1	<1	>3	>5	>5	<1	<1	<1	<1	<1	>3	>10	>60
Ruby-2	>10	>10	>3	>2	<1	<1	<1	<1	<1	>4	>5	>9	>12	>13	<1	<1	<1	>3	>10	>30
Nd/YAG	>10	>10	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	>5.5	>4	>4	>4	>4	>10	>70
Nd-1	>10	>10	<1	<1	<1	<1	<1	<1	<1	>1	>2	>4	>12	>13	<1	<1	<1	>3	>10	>30
Nd 12-1	>15	>15	>15	>15	>15	>15	>15	>15	>6	<1	<1	<1	<2	>5.5	>4	>4	>4	>4	>10	>40
Nd 12-2	>15	>15	>15	>15	>15	>15	>15	>15	>6	>1	>2	>4	>12	>13	<1	<1	<1	>3	>10	>20
CO_2 -1	>10	>15	>4	>1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	>6	>20	>85
Spectro-Gard	>15	>15	>15	>15	>15	>15	>15	>15	>5	>5	>6	>9	>12	>13	<1	<1	<1	>3	>20	>7.0
U.S. LASER CORP.																				
1075-1				<1	<1	<1	<1	<1	<1	<1	<1	<1	1.5	6	>5	>5	>5	>5	>5	80
1075-1a				<1	<1	<1	<1	<1	<1	<1	<1	<1	2.5	10	>5	>5	>5	>5	>5	70
1075-2						<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	>6	>10	90
1075-3	>5	>5	>5	>5	>5	5	<1	<1	<1	1.5	1.5	>6	>10	>10			>3	>3	>3	70
1075-4	>5	>5	>5	>5	>5	>5	>5	>6	>6	<1	<1	<1	<1	<1				>3	>3	50
1075-6	>5	>5	5	1	<1	<1	<1	1	4	>7	>6	2	<1	<1	4			>3	>3	35
1075-7	>5	>5	>5	>5	>5	>5	>5	>5	>5	<1	<1	<1	1.5	>6						45

NOTE: Another characteristic of these goggles which should be considered in the selection of laser eye protective eyewear is the maximum irradiance before damage of filter plate or plastic.

Table A-2
Partial List of Laser Protective Eyewear Suppliers

American Optical Company Safety Products Group 14 Mechanics Street Southbridge, MA 01550	(508) 765-9711
Ealing Electro-Optics, Inc. New Englander Industrial Park Holliston, MA 01746	(508) 429-8370
Edmund Scientific Edmund Building, Publications Department Barrington, NJ 08007	(609) 547-3488
Energy Technology, Inc. P.O. Box 1038 San Luis Obispo, CA 93406	(805) 544-7770
Fish-Schurman Corp. P.O. Box 319 New Rochelle, NY 10802	(914) 636-1300
General Scientific Equipment Co. 525 Spring Garden Philadelphia, PA 19123	(215) 922-5710
Gle dale Protective Technologies 130 Crossways Park Drive Woodbury, NY 11797	(516) 921-5800
Omicron Eye Safety Corp. 73 Main Street Brattleboro, VT 05301	(802) 257-7363
Phase-R Co. Box G-2 New Durham, NH 03855	(603) 859-3800
Fred Reed Optical P.O. Box 27010 Albuquerque, NM 87125	(505) 265-3531
Rockwell Associates, Inc. P.O. Box 43018 Cincinnati, OH 45243	(513) 271-1568

Table A-2 (Continued)
Partial List of Laser Protective Eyewear Suppliers

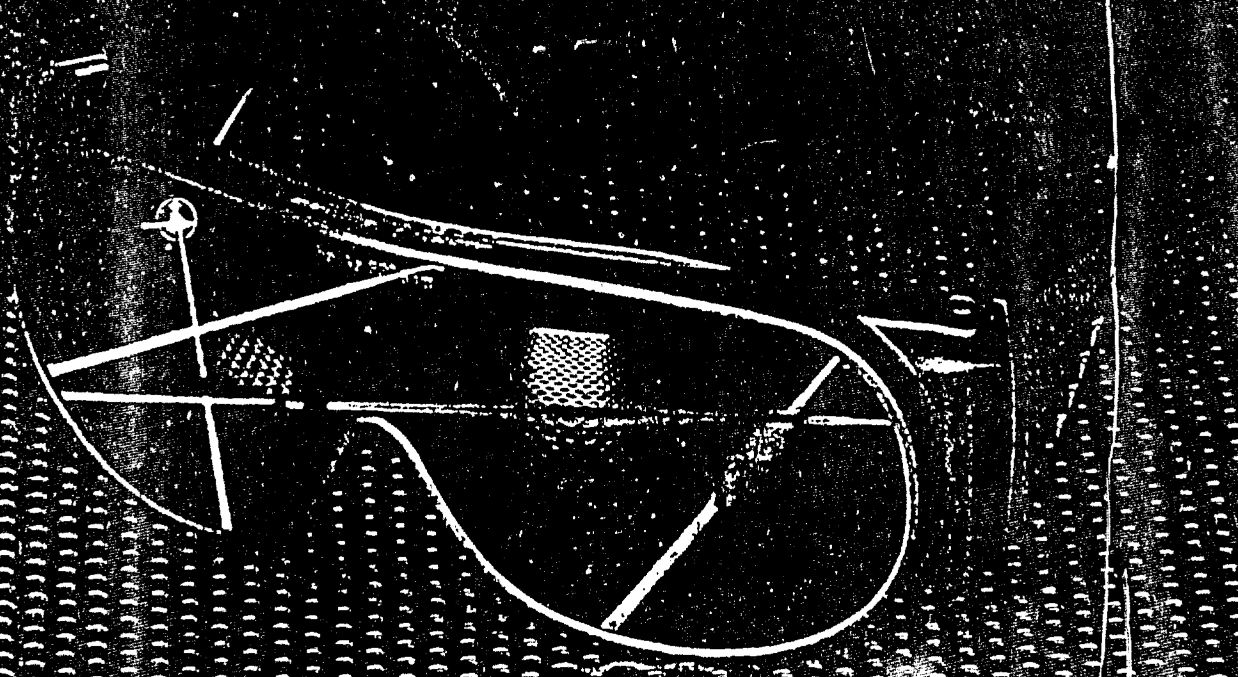
U.S. Laser Corp. P.O. Box 609 825 Windham, Ct. N. Wychoff, NJ 07481	(201) 848-9200
U.V.P., Inc. P.O. Box 1501 San Gabriel, CA 91778	(818) 285-3123
UVEX Winter Optical, Inc. 10 Thurber Blvd. Smithfield, RI 02917	(401) 232-1200
Yamamoto Kogaku Co., Ltd. Safety and Health Care Division 1-2 Chodo-3 Higashiosaka City, Osaka 577, Japan	(06) 783-1104

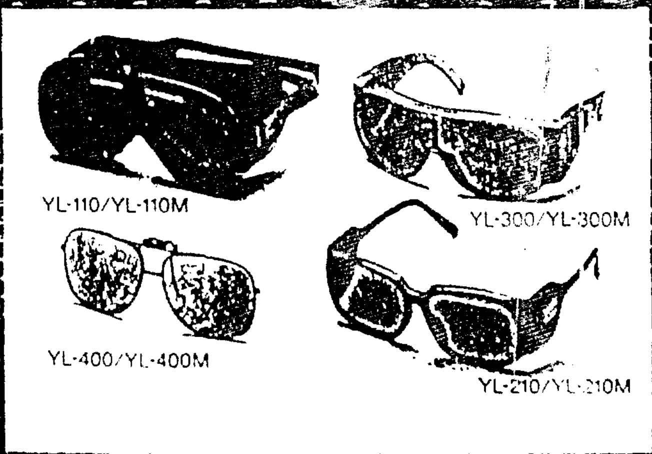
LASER EYE PROTECTOR
WE COVER ANY LASERS!

Available for laser of any wavelength from U.V. laser to I.R. laser.
A variety of laser protective eyewear is available in order to meet any demand.

The material of lenses used on our laser protective eyewear is polycarbonate on which hard coating is treated.
Lenses are highly impact resistant except for small portion of our line.

There are two types; one is a completely absorbing laser which has a high optical density and another is a partially absorbing laser which is used in cace of alignment of visible laser.





yamamoto
SAFETY & HEALTH-CARE DIV.

YAMAMOTO KOGAKU CO.LTD
1-2, CHODO-3, HIGASHIOSAKA CITY, OSAKA 577, JAPAN TEL:(06)783-1104 TELEFAX:(06)781-7320

CIRCLE NO. 86

Appendix B

PRODUCT INFORMATION
ON
LASERS

Table B-1
Laser & Laser Products Manufacturers Contacted for Information

Amoco Laser Co. 1251 Frontenac Road Naperville, IL 60540	(312) 369-4190	Micro Lasers & Low Power Nd:YAG
Balzers Optical Corporation 170 Locke Drive Marlborough, MA 01752	(508) 481-9860	Optical coatings.
Coherent General 1 Piker Road Sturbridge, MA 01566	(617) 347-2681	High powered CO2 laser systems and large inductrial machine tools.
Coherent Laser Products 3210 Porter Drive P.O. Box 10321 Palo Alto, CA 94303	(800) 527-3786	Low Power Nd:YLF
Coherent Optics Division 2301 Lindbergh St. Auburn, CA 95603	(916) 889-5230	Optics applications & technical support.
CVI Laser Corporation 200 Dorado Place, SE P.O. Box 11308 Albuquerque, NM 87192	(505) 296-9541	Optics & fiber optics products.
Directed Energy 2382-T Morse Ave. Irvine, CA 92714	(714) 553-1225, Ext 17	CO2 laser systems; 20 to 250 W.
Edmund Scientific Edmund Building, Publications Dept. Barrington, NJ 08007	(609) 547-3488	Optics supplies. Low Power lasers for classroom and small laboratories; mostly He-Ne & CO2.
ESCO Precision Optics 171 Oak Ridge Road Oak Ridge, NJ 07438	(201) 697-3700	Optical windows.
Galileo Electro-Optics Corp. P.O. Box 550 Sturbridge, MA 01566	(508) 347-9191/(800) 648-1800	Optics & fiber optics products.

Table B-1 (Continued)
Laser & Laser Products Manufacturers Contacted for Information

Hadron Inc. 9990-T Lee Highway Fairfax, VA 22030	(703) 359-6100 Manufacturer for the laser system used in the Lane & Marshall CRREL Deicing report. Unfortunately, no longer making lasers.
II-VI Incorporated Saxonburg, PA 16056	(412) 352-1504 IR optics products.
Jodon 62 Enterprise Drive Ann Arbor, Michigan 48103	(313) 761-4044 General Lasers & Supplies. Industrial He-Ne lasers featuring an integral beam pointing mechanism.
LASAG Corp. 702 West Algonquin Road Arlington Heights, IL 60005	(312) 593-3021 Medium powered Neodymium lasers available.
Laser Applications, Inc. Division of Laser Metrics, Inc. 12722 Research Parkway Orlando, Flordia 32826	(407) 380-3200 Medium powered Neodymium lasers available.
Laser Photonics 12351 Research Parkway Orlando, Florida 32826	(407) 281-4103/(800)624-3628 All types of lasers. Technical support & advise. Medium powered Neodymium lasers available.
Laser Resale, Inc. Sudbury, MA	(617) 443-8484 A used laser broker.
Lee Laser, Inc. 3718 Vineland Road Orlando, Florida 32811	(407) 422-2476 Low powered CW Nd:YAG

Table B-1 (Continued)
Laser & Laser Products Manufacturers
Contacted for Information

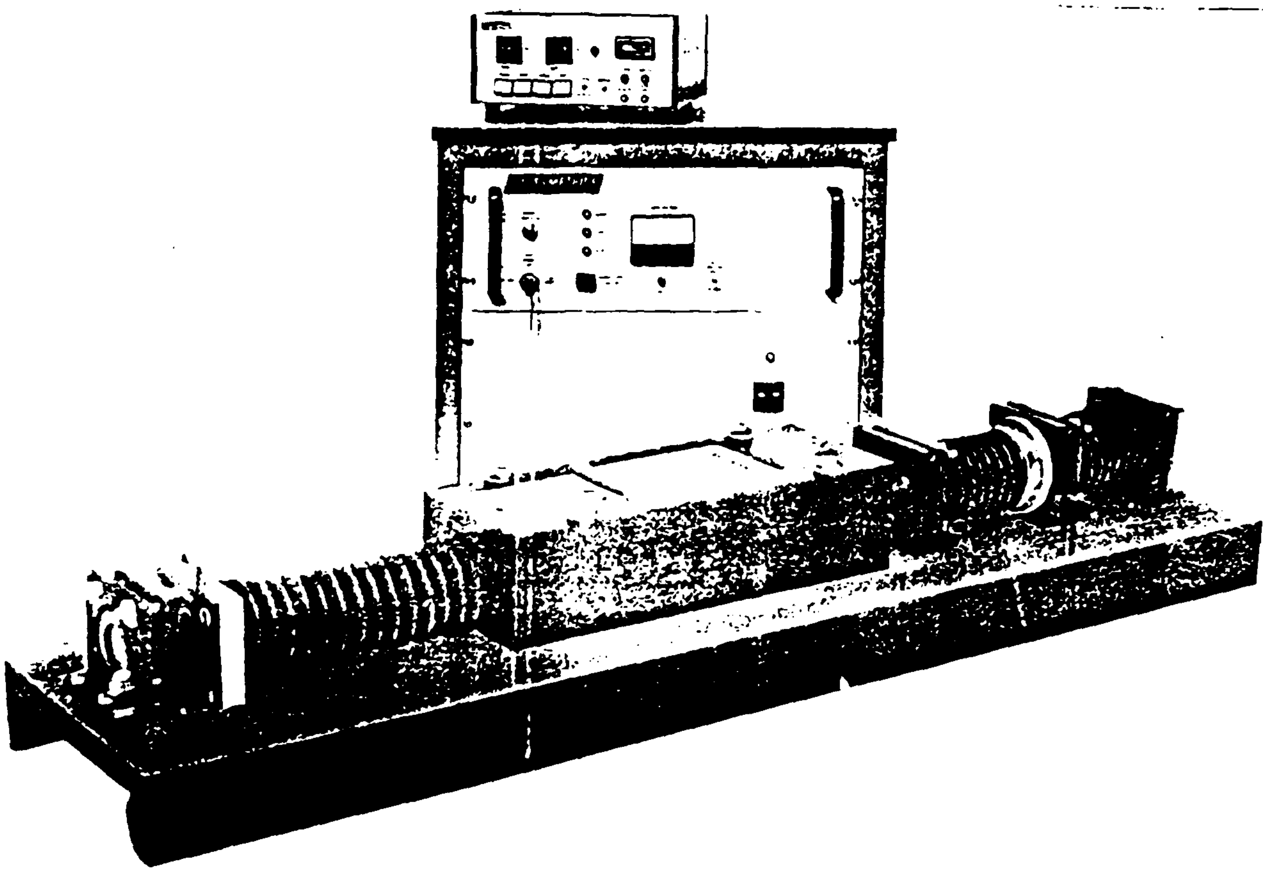
Lumonics Material Processing Corp. 12163 Globe Road Livonia, MI 48150	(800) 423-1542 High powered CO2 lasers. Pulsed Nd:YAG lasers for cutting, drilling and welding. Fiber optic beam delivery to 100 m from source; 100 to 400 W.
Mitsubishi Cable America, Inc. Diaguide Products Division 520 Madison Ave. New York, NY 10022	(212) 888-2270/(800)262-6200 Fiber Optics
NEC Electronics, Inc. 401 Ellis Street Mountain View, CA 94039	(800) 632-3531 Nd:YAG & Fiber Optics
Quantronix 49 Wireless Blvd. P.O. Box 9014 Smithtown, NY 11787	(516) 273-6900 Nd:YLF
Raytheon Co. P.O. Box 5300 465 Centre Street Quincy, MA 02269	(617) 479-5300 High powered Nd:YAG & CO2 lasers for industrial material processing.
Reynard Enterprises, Inc. 26098 Getty Drive Laguna Niguel, CA 92677	(714) 831-6026 Optical components.
Rofin-Sinar 3333 North First Street San Jose, CA 95134	(408) 432-6133/(800) 227-1921 World's largest producer of industrial CO2 lasers; 80 to 6000 W.
Rolyn Optics 706 Arrow Grand Circle Covina, CA 91722	(818) 915-5707 Optics catalog
SPAWR Optical Research, Inc. P.O. Box 1899 Corona, CA 91718	(714) 735-0433 Power Meters

Table B-1 (Continued)
Laser & Laser Products Manufacturers Contacted for Information

Spectra-Physics 1250 West Middlefield Road P.O. Box 7013 Mountain View, CA 94039	(415) 961-2550/(800) 227-8054 A leading supplier for over 25 years; high powered lasers 500 to 5000 W.
Spectron Laser Systems 21 Paynes Lane Rugby, Warwickshire CV21 2UH England US Distr.: Quantum Electronic Instruments	(0788) 544694 (508) 369-8081 Nd:YAG
U. S. Laser Corporation 825-T Windham Court North P.O. Box 609 Wyckoff, NJ 07481	(201) 848-9200 Nd:YAG laser systems. Medium powered Neodymium lasers available.
3M Fiber Optic Products, Inc. 420 Frontage Road West Haven, CT 06516	(201) 544-9119 Large core fiber optics

HIGH POWER, HIGH REPETITION RATE YAG LASERS

9400 SERIES



* MODULAR DESIGN
* SOLID-STATE POWER SUPPLY
* OPTICAL RAIL MOUNTING
* SIMMERED FLASH LAMP
* SAFETY INTERLOCKS
* INTRACAVITY SPACE
* EASY CHANGE PUMP LAMP
* ACCESSORIES FOR Q-SWITCHING, HARMONIC GENERATION, MODE-LOCKING AND CAVITY DUMPING

LASERMETRICS

Laser Applications Division

3500 Aloma Avenue, Winter Park, Florida 32792

Fax: (407) 679-0180 Telex: 80-8881 Telephone (407) 678-8995

TECHNICAL SPECIFICATIONS
Pulsed Nd:YAG LASERS
SERIES 9400

	9403	9430	94100
Wavelength (micrometers):*	1.06	1.06	1.06
Beam Diameter (millimeters):	4	6	9
Laser rod size (dia. x length - mm):	4x54	6.3x79	9.5x108
Beam Divergence (milliradians):	2	3	5
Average Power Output (Watts):	3	30	100
Pulse Repetition Rate (Hertz):*	20	10	10
Pulse Energy (Joules):	.150	3	10
Pulse width (microseconds):*	270	700	800
Peak Power (kilowatts):	.5	4.2	12.5
Output Stability (% RMS):	3	3	5
Polarization:*	random	random	random
Type of Flashlamp:	xenon	xenon	xenon
Number of Flashlamps:	1	1	2
Ave. Lamp Life (million pulses):	10	10	1
Electrical Input (volts):	115	220	208
(Hertz):	50/60	50/60	50/60
(# of phases):	1	1	3
(Amps):	10	40	75
Water Cooling (@ 25deg C):	self	5 GFM 35 PSI	5 GPM 35 PSI
Dimensions (WxHxD inches)			
Optical Head:	6x8x24	6x8x36	6x8x40
Power Supply	23x31x30	23x41x38	27x41x57

Series 9400 - Specifications

Q-SWITCH OPTION (-Q)

Pulse width (nanoseconds):	20	20	20
Pulse Energy (millijoules)	30	450	1,000
Peak Power (megawatts):	1.5	22.5	50
Polarization:	vert	vert	vert

CAVITY DUMPED OPTION (-CD)

Pulse width (nanoseconds):	5	5	na
Pulse Energy (millijoules)	10	100	na
Peak Power (megawatts):	2	20	na
Polarization:	vert	vert	na

*** OPTIONS at extra cost**

Operation at 1.319 micrometers available. Energy output is about 30% of that at 1.064 micrometers.

Longer pulse widths available in normal mode. They are:

Model 9403	up to 500 microseconds
Model 9430	up to 1,200 microseconds
Model 94100	up to 5,000 microseconds

Longer pulse widths not needed for Q-Switch or Cavity-Dumped option.

Customer may specify up to 5 selective pulse widths.

Horizontal polarization for Q-Switch or Cavity-Dumped option available at no extra cost.

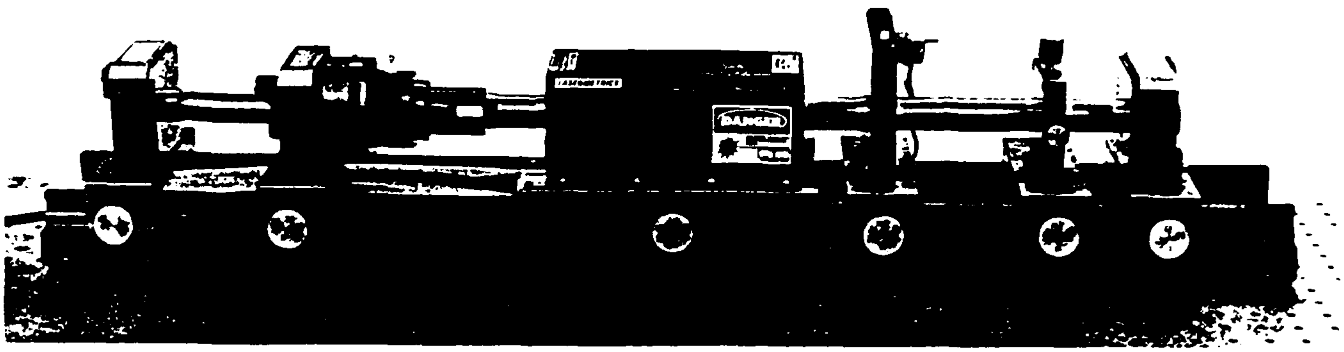
Horizontal or vertical polarization for normal mode operation is available.

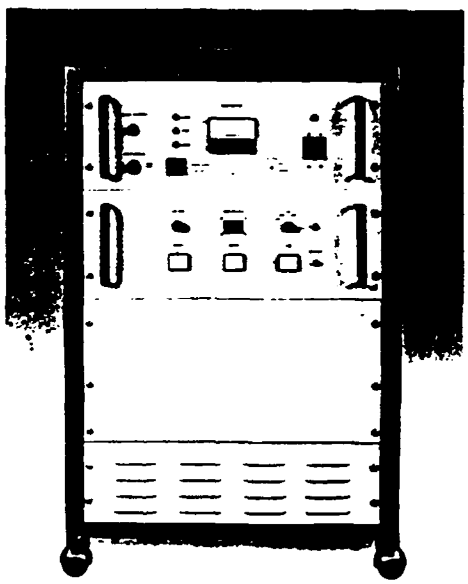
Single Transverse Mode (TEMoo) option available. Energy output is about 5 to 10% of that specified above (Q-Switch/Cavity-Dumped maximum is 25 millijoules).

Higher repetition rates are available at reduced outputs.
up to 200 Hertz for Model 9403
up to 50 Hertz for Model 9430
up to 20 Hertz for Model 94100

High-Power Lasers and Systems

9000 Series





Lasermetrics offers a complete line of pulsed, high power lasers and integrated systems for industrial and scientific applications. The modular laser components and accessories are designed for convenience, ease of alignment, and reliability. Modules may be combined to obtain a variety of performance characteristics including high power amplification, mode locking, Q-switching, pulse shaping, single or multiple pulse gating and harmonic generation. These functions can be optimized for any particular application.

SERIES 9000 RANGE OF PERFORMANCE	
Wavelengths, µm:	1.34, 1.06, 1.05, 0.69, 0.67, 0.53, 0.353, 0.345, 0.265
Pulse Energy:	Conventional Mode — up to 100 joules Q-switched — up to 15 joules
Laser Materials:	YAG, Ruby, Glass
Peak Power:	Up to 1 GW

APPLICATIONS

Holography
Non-destructive Interferometry
Lidar & Ranging
Welding & Cutting
Drilling
Dynamic Balancing
Photochemistry
Fluorescence Spectroscopy
Schlieren Photography
Plasma Diagnostics
Non-Linear Effects
Scattering Experiments

NEW NUMBERS
~~PHONE: (407) 678-8995~~
FAX: (407) 679-0180

LASERMETRICS

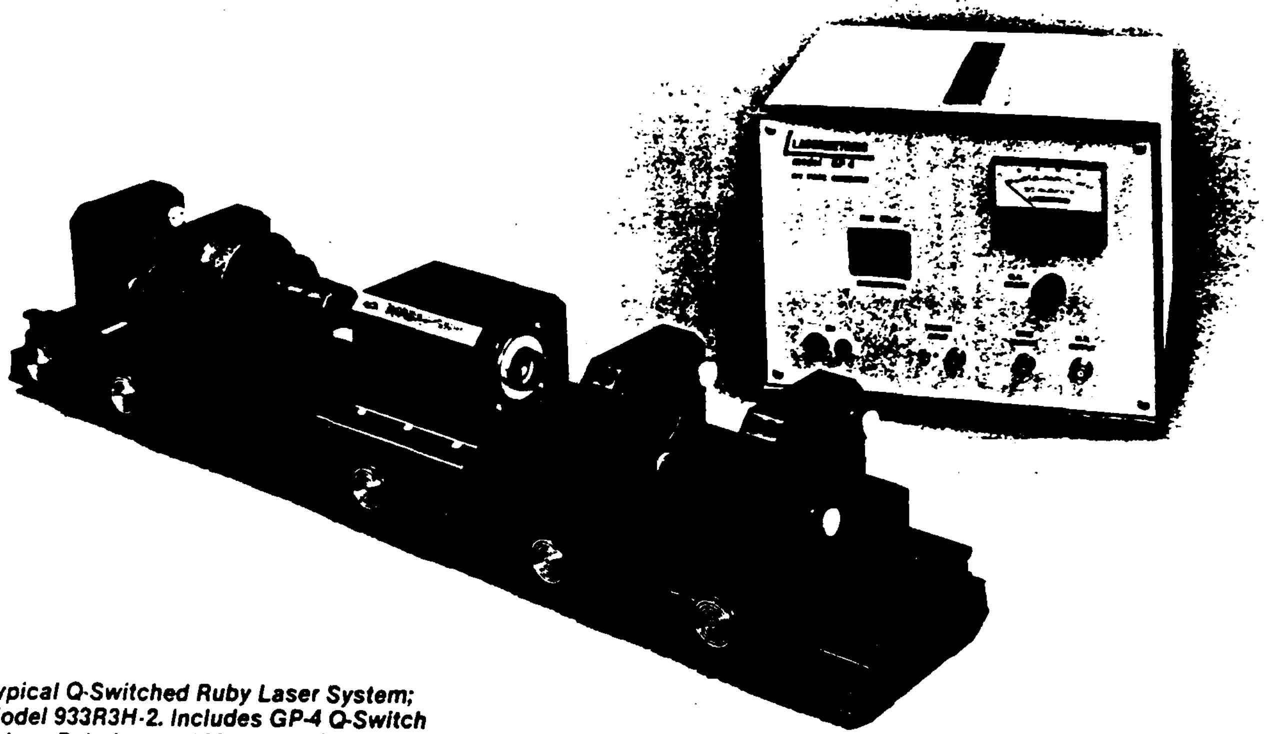
Laser Applications Division

3500 Aloma Avenue, Winter Park, Florida 32792
Fax (305) 679-0180 Telex 80-8881 Telephone (305) 678-8995

Lasermetrics is a unique source of lasers and laser systems. Established in 1965, the company specializes in the growth of electro-optic and non-linear crystals and has developed an extensive product line of laser pulse control components and ultra-fast switching systems. These products include:

- Pockels Cell Q-Switches
- Amplitude Modulators
- Phase/Frequency Modulators
- Picosecond Shutters
- Polarizers
- Optical Harmonic Generators
- Picosecond Detectors
- Laser Pulse Shapers & Slicers
- Gimbals & Positioning Devices
- Holographic Components

Our experience and knowhow in these fields benefit customers by identification of the techniques and components needed to produce reliable laser systems which meet the specifications and requirements of the user.



Typical Q-Switched Ruby Laser System; Model 933R3H-2. Includes GP-4 Q-Switch Driver, Polarizer and Mounting Gimbals.

9330 SERIES — 3 Inch Laser System, Ruby, Nd: YAG, Nd: Glass, Conventional Mode -Q-Switched High Rep-Rate (60PPM) and Low Rep-Rate (6PPM)

NOMINAL SPECIFICATIONS

MODEL	LASER ROD	OUTPUT ENERGY	PULSE WIDTH	PEAK POWER	BEAM DIVERGENCE	P.R.F.
933R3L-1	Ruby 3" x 3/8"	0-10J	0.75ms	NA	3mr	6PPM
933R3H-1	Ruby 3" x 3/8"	0-10J	0.75ms	NA	3-5mr	60PPM
933R3H-2	Ruby 3" x 3/8"	0-1.5J	12-15ns	100MW min.	3-5mr	60PPM
933R3L-2	Ruby 3" x 3/8"	0-1.5J	12-15ns	100MW min.	3mr	6PPM
933G3L-1	Nd: Glass 3" x 3/8"	0-10J	0.75ms	NA	3mr	6PPM
933G3L-3	Nd: Glass 3" x 3/8"	0-1.5J	12-15ns	100MW min.	3mr	6PPM
933Y3L-1	Nd: YAG 3" x 3/8"	0-10J	0.75ms	NA	3mr	6PPM
933Y3H-1	Nd: YAG 3" x 3/8"	0-10J	0.75ms	NA	3-5mr	60PPM
933Y3H-3	Nd: YAG 3" x 3/8"	0-0.75J	12-15ns	50MW min	3-5mr	60PPM
933Y3L-3	Nd: YAG 3" x 3/8"	0-1.0J	12-15ns	67MW min.	3mr	6PPM

Specifications subject to change without notice.

9360 SERIES – 6 Inch Laser System, Ruby, Nd YAG, Nd Glass, Conventional Mode – Q-Switched High Rep-Rate (60PPM) and Low Rep-Rate (6PPM)

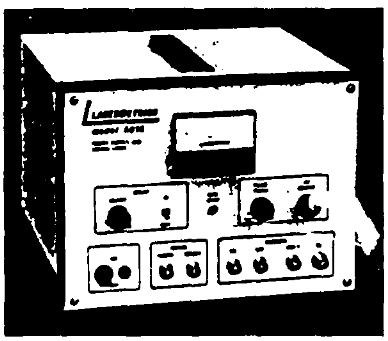
NOMINAL SPECIFICATIONS

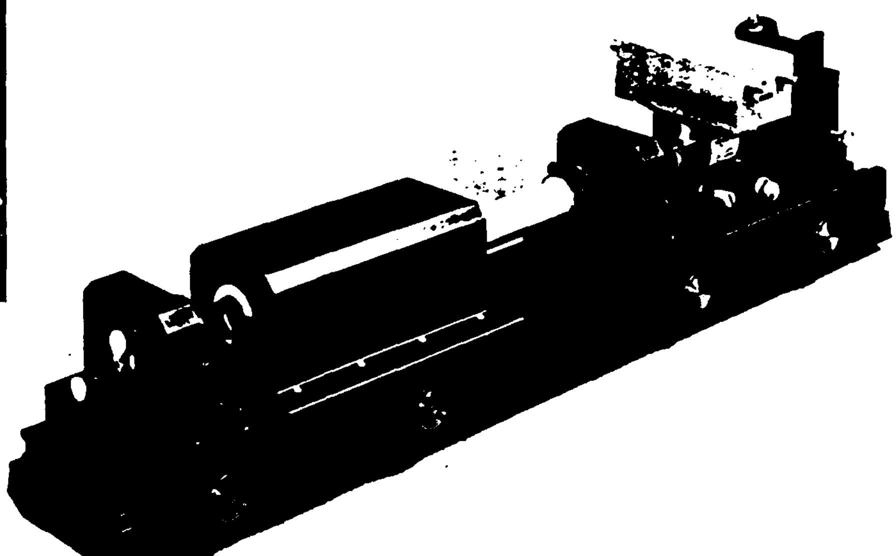
MODEL*	LASER ROD	OUTPUT ENERGY	PULSE WIDTH	PEAK POWER	BEAM DIVERGENCE	P.R.F.
936R3L-1	Ruby 6" x 3/8"	0-30J	0.75ms	NA	3mr	6PPM
936R3H-1	Ruby 6" x 3/8"	0-20J	0.75ms	NA	3-5mr	60PPM
936R3L-2	Ruby 6" x 3/8"	0-2.0J	12-15ns	133MW min.	3mr	6PPM
936R3H-2	Ruby 6" x 3/8"	0-2.0J	12-15ns	133MW min.	3-5mr	60PPM
936G3L-1	Nd: Glass 6" x 3/8"	0-30J	0.75ms	NA	3mr	6PPM
936G3L-3	Nd: Glass 6" x 3/8"	0-2.0J	12-15ns	133MW min.	3mr	6PPM
936Y3L-1	Nd: YAG 6" x 3/8"	0-30J	0.75ms	NA	3mr	6PPM
936Y3H-1	Nd: YAG 6" x 3/8"	0-30J	0.75ms	NA	3-5mr	60PPM
936Y3L-3	Nd: YAG 6" x 3/8"	0-2J	12-15ns	133MW min	3mr	6PPM
936Y3H-3	Nd: YAG 6" x 3/8"	0-2J	12-15ns	133MW min.	3-5mr	60PPM

*NOTE All 936 models are available with ½-inch-diameter laser rods for increased output specifications. To order, change digit #5 in part number from 3 to 4.

9380 SERIES — Oscillator, Oscillator-Amplifier Systems, Ruby, Nd: Glass, Conventional Mode and Q-Switched

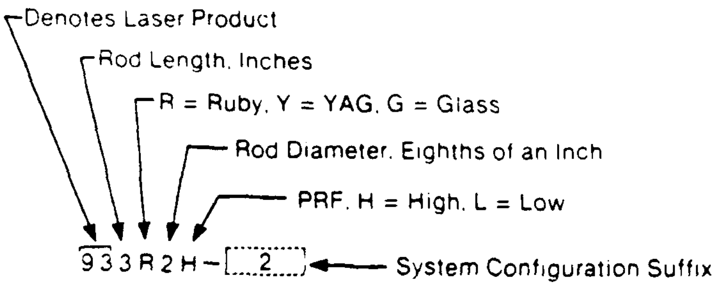
MODEL	LASER ROD	OUTPUT ENERGY	PULSE WIDTH	PEAK POWER	BEAM DIVERGENCE	P.R.F.
938R6L-1	Ruby 8" x 3/4"	0-100J	1.5ms	NA	3-5mr	4PPM
938R3R4L-4	Amp. Ruby 8" x 3/4" and Osc. Ruby 3" x 1/2"	0-7.5J	15ns	500MW	3mr	4PPM
938R6R4L-4	Amp. Ruby 8" x 3/4" and Osc. Ruby 6" x 1/2"	0-15J	15ns	1000MW	3mr	4PPM
938G6L-1	Nd: Glass 8" x 3/4"	0-100J	1.5ms	NA	5mr	4PPM
938G3G4L-6	Amp. Nd: Glass 8" x 3/4" and Osc. Nd: Glass 3" x 1/2"	0-7.5J	15ns	500MW	3mr	4PPM
938G4G4L-6	Amp. Nd: Glass 8" x 3/4" and Osc. Nd: Glass 6" x 1/2"	0-15J	15ns	1000MW	3mr	4PPM





Model 936R3H-1 Ruby Amplifier with an Upcollimator and Model 5016 Pulse Slicing and Shaping System.

MODEL NUMBERING SYSTEM

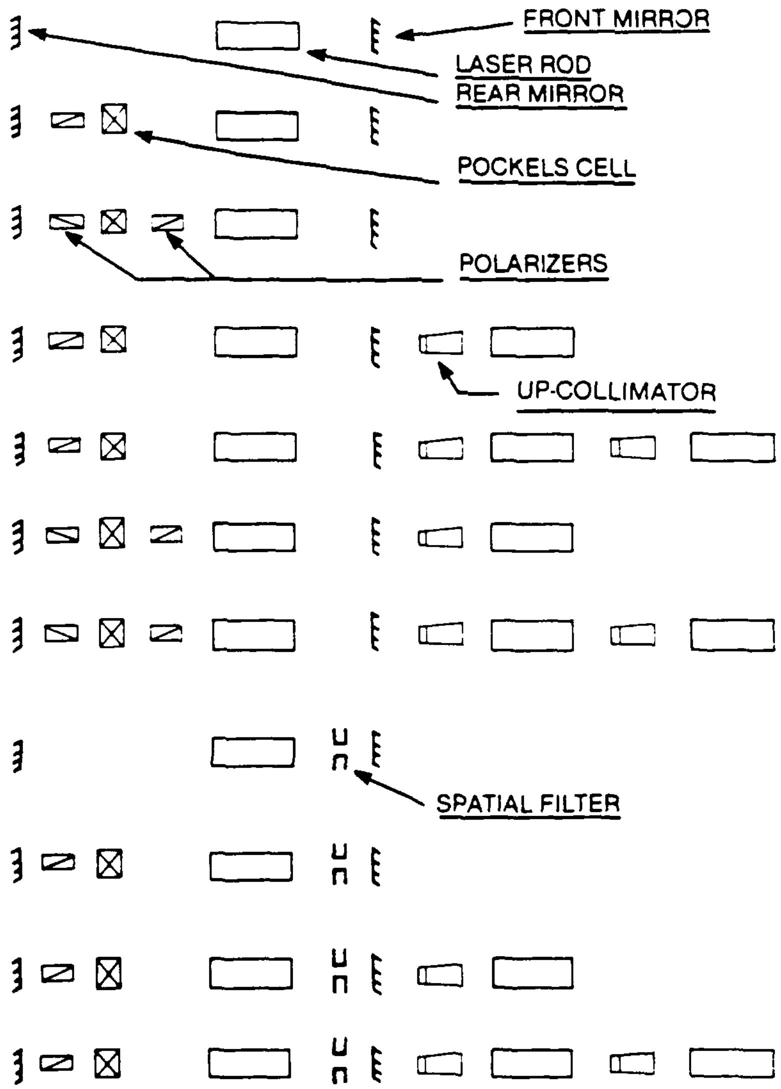


Example above is a ¼" diameter x 3" long ruby, Q-Switched system.

Example: 938G6G4L-6 is a Q-Switched Nd: Glass Oscillator-Amplifier with upcollimator, two polarizers and a GP-4 Q-Switched Driver.

Mode-Locked Lasers: Contact our Sales Department for Specifications on our Mode-Locked Laser Systems

SYSTEM CONFIGURATIONS



SUFFIX	
(-1)	RUBY, Nd YAG, Nd GLASS CONVENTIONAL MODE
(-2)	RUBY Q-SWITCH OSCILLATOR
(-3)	Nd YAG, Nd GLASS Q-SWITCH OSCILLATOR
(-4)	RUBY Q-SWITCH OSC. — AMPLIFIER
(-5)	RUBY Q-SW. — AMP. — AMP.
(-6)	Nd YAG, Nd GLASS Q-SW. OSC. — AMP.
(-7)	Nd YAG, Nd GLASS Q-SW. OSC. — AMP — AMP
(-8)	RUBY, Nd YAG, Nd GLASS CONV. MODE — SPATIALLY FILTERED OSCILLATOR
(-9)	RUBY Q-SW — HOLOGRAPHIC OSC.
(-10)	RUBY Q-SW. — HOLOGRAPHIC OSC. — AMP
(-11)	RUBY Q-SW — HOLOGRAPHIC OSC. OSC. — AMP — AMP

FEATURES

LASER HEAD Compact, Treated Aluminum Laser Head

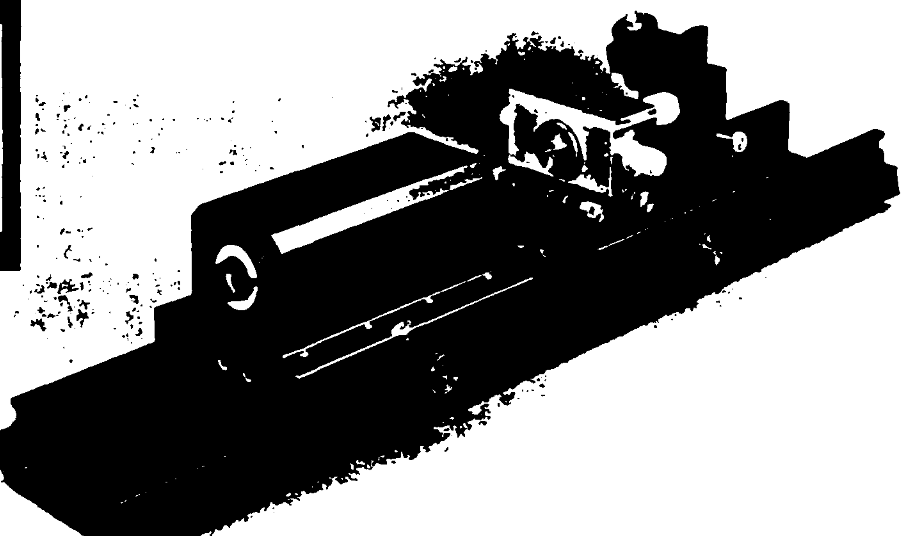
- Utilizes de-ionized laminar flow water cooling — no need for corrosive or expensive coolants
- Laser rod is protected from solarization
- Corrosion free materials used throughout
- Interchangeable laser rods, o-ring sealed
- Floating flash lamp 1 000,000 shot capability
- Efficient, inexpensive laser head lamp reflector
- Completely compatible with all Lasermetrics' peripheral equipment

OPTICAL RAIL — Modular Optical Components Mounted to Stable U Channel Optical Rail

- Building block approach for simplicity and convenient configuration changes
- Optically stable, 3 point contact mirror and gimbal mounts used throughout for long term stability
- Invar side rails and reinforced optical rails available for extreme stability
- User replaceable optical components
- Variety of optical carriages available for specialized applications
- Total system alignment time less than 15 min.

POWER SUPPLY & HEAT EXCHANGER — 1980's Integrated Laser Power Supply and Heat Exchanger

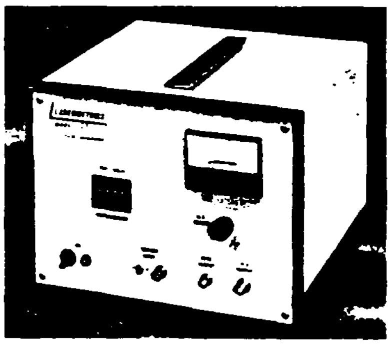
- Integrated circuits and printed circuit boards with easy access and servicing kept in mind
- All components overdesigned for high reliability
- Safety features a top priority. Meets all B.R.H. safety standards including overvoltage protection circuitry, all access sides interlocked, laboratory door and "Laser" room light interlocks, laser coolant, temperature and pressure interlocks on primary and secondary systems. Automatic optical rail shutters for laser cavity and alignment autocollimator.
- Efficient single or three-phase 50-60Hz charging circuit using constant monitoring and regulation of pulse forming network voltage for shot-to-shot repeatability
- Remote control convenience — external computer programming available for all control functions
- Remote controllers can be used in master/slave configurations for multiple laser head configurations such as Oscillator/Amplifier systems
- Remote controller and power supply indicators, show system status at all times
- Built-In Auto-Fire and rep-rate generators available for all models
- Line frequency locked circuitry for accurate rep-rate timing. Easily changed for either 50Hz or 60Hz operation
- Front panel connector for external PFN
- Straightforward controls for ease of operation
- Intermediate water temperature shut down point at 85°F (30°C) on external coolant models. Convenient standby mode for fast temperature correction in case of temporary secondary coolant failure.

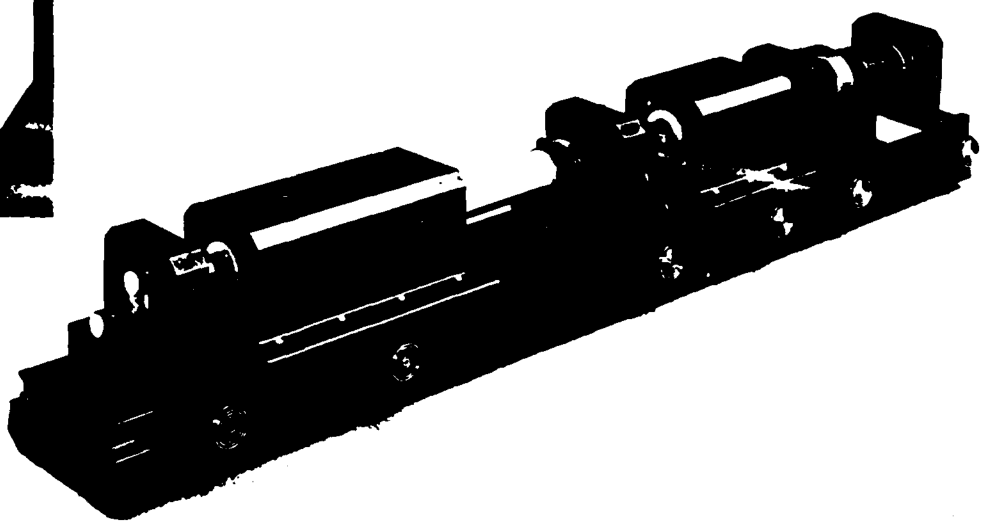


Model 938R6L-1 Ruby Amplifier with a 5020 Mode Locked Pulse Extraction and Pulse Shaping System. (8601 Driver)

ACCESSORIES

- Q-Switch modules and pulse drivers
- Pulse slicing systems (150 P.S. 1.5ns Pulse Widths)
- All systems have harmonic generation add-on feature
- Mode-locked extraction systems
- Up/Down collimators
- Integrated HeNe alignment lasers and autocollimators
- Pulse counting totalizer
- Preset pulse counter, to allow the user to set predetermined number of pulses and repetition rate for automatic operation
- Laser pulse monitor, energy and power meters
- Laser pulse regulator — actively adjusts bank voltage each shot to help maintain a constant output
- Optical scanning systems
- X-Y table options, including programmable systems to accommodate various work functions
- Complete holographic systems, including beam splitters, lens and film plate holders, incorporating single and multi-pulse bursts
- Multiple head and frequency doubling crystals available for harmonic wavelength experiments and applications
- Character generator for marking systems
- Electronic interfacing for single or multiple bus control
- Laser safety eye protectors available directly from Lasermetrics
- Totally enclosed systems for factory environments, including purging for "dusty" areas
- Complete gaseous atmosphere at work area for various applications
- T.V. or film monitoring of work surface
- X-Y position read out for repeatability at work surface
- Complete line of view optics, shutters and displays



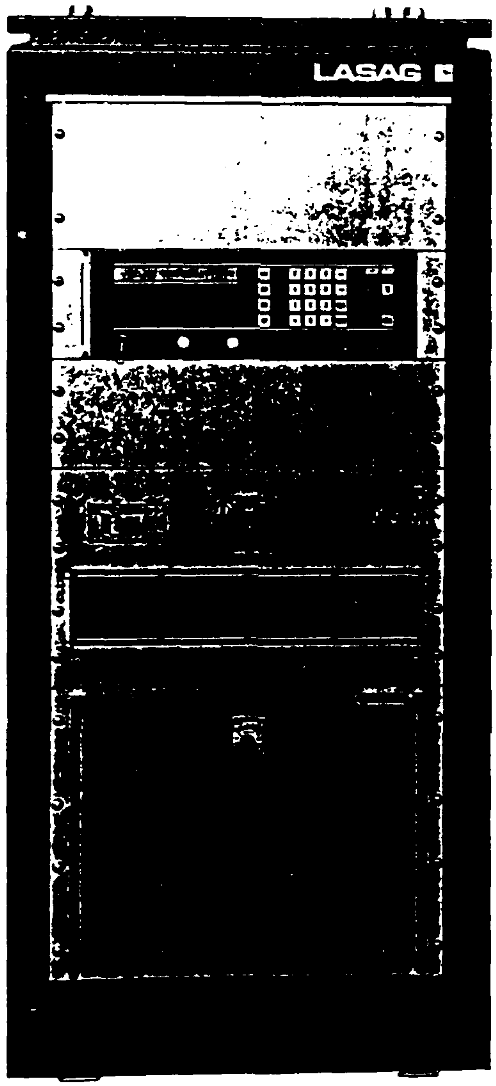


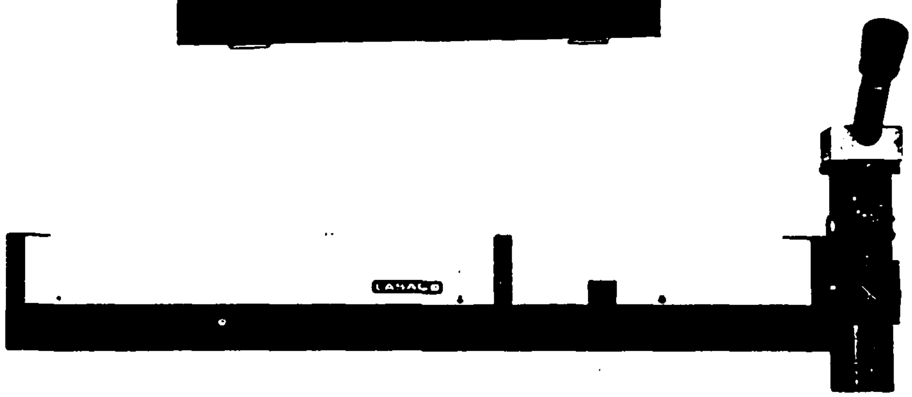
Model 938G3G4L 6 Q-Switched Nd: Glass Oscillator — Amplifier with GP-4 Q-Switch Driver, Polarizers, Upcollimator and Mounting Gimbals.

U.S. Bureau of Radiological Health (BRH) warning logotypes, similar to that shown here appear on each laser to indicate the BRH classification and to certify that the output power of the laser will not exceed the power level printed on the logotype which is approximately 50% greater than the rated output power, shown in table.

LA-HPLB-8701
Printed USA 2.5M

Lasag-Laser KLS 016





L A S A G

Compact Laser System KLS 016

[illegible]
[illegible] following features:

- wide range of achievable parameters
- extended monitoring possibilities
- easy operation
- smooth and effective integration possibilities into production systems
- complying with international safety regulations
- wide range of standard accessories

Range of Applications

The KLS 016 laser is a spot welding source allowing to achieve welding depths up to 1 mm (.04") and spot diameters up to 1.2 mm (.047"). By using a laser beam deflection or a fibre optic system it is possible to extend and adapt the system to the respective application.

Services

Lasag guarantees competent consultation on matters relating to applications. An intensive training of customers on operation and maintenance and after sales sèrvice operating worldwide.

The Technology

The compact design of the laser head allows convenient mounting possibilities and easy maintenance. The attachment of a resonator extension, if desired with HeNe positioning laser, is possible.

The standard laser head is equipped with a monocular viewing optic with adjustable cross-hair. As an option it can be replaced with a binocular or trinocular viewing system with a closed circuit TV monitor.

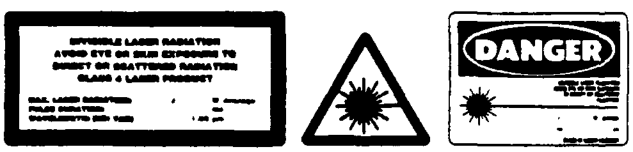
A state-of-the-art laser control system incorporates three microprocessors for demanding real time operations and allows a continuous adjustment of all important laser parameters including the pulse energy. The input data is entered via the keyboard or the user interface. Ramping and burst parameters are also programmable. Full safety interlocks and comprehensive fault diagnostics are also provided within the control system. The operating panel is located on the power supply cabinet. As an option it can be delivered mounted in a remote control cabinet with a cable length of 5 metres (over 16 ft long).

Optional Laser Beam Deflection System

By using a beam deflection system up to a maximum of 50 spotwelds can be lased on a non-moving work piece. The deflection of the laser beam is done by moving mirrors, and the positioning of the spotwelds on the work piece is freely programmable by means of a diode pin matrix.

Optional Fibre Optics

Instead of a standard laser head it is possible to connect fibre optic modules for 1 or 3 fibres to the laser. This option extends the flexibility of the system and allows in particular to use it together with production robots.



USA label

[illegible]

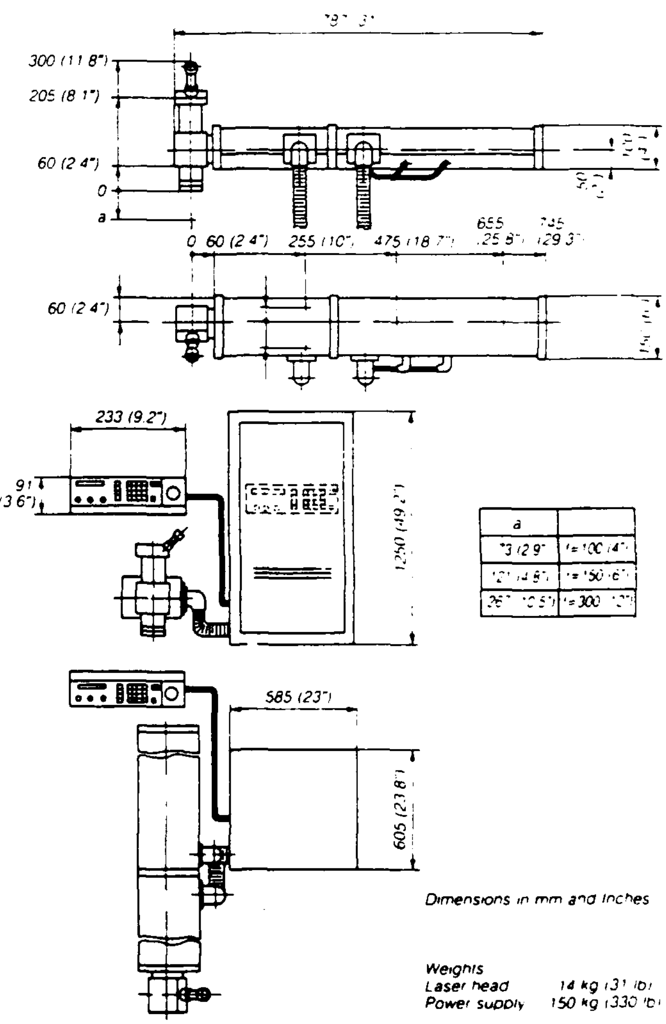
Laser type	KLS 016
Wave length	1.06 µm
Beam diameter	6 mm (.24")
Pulse duration	0.2 to 10 ms (optional 0.2 to 20 ms)*
Pulse frequency	20 Hz (optional 50 Hz)*
Pulse power	4 kW
Pulse energy	26 J
Average Power up to	30 W
	* both options together not possible

Services

Electrical	
Main voltage	220 V ± 10% (P+N+E) single-phase
Main frequency	50 Hz (USA 60 Hz)
Power	2 kVA
Max. Phase current (eff.)	10 A
Recommanded Fuses	10 A

Water Cooling	
Water Inlet	2-10 bar 18 °C (64 °F)
Water Outlet	back pressure free
Water Consumption	5 l/min (1.3 US Gallons/min)

Dimensions and Weights



Dimensions in mm and inches

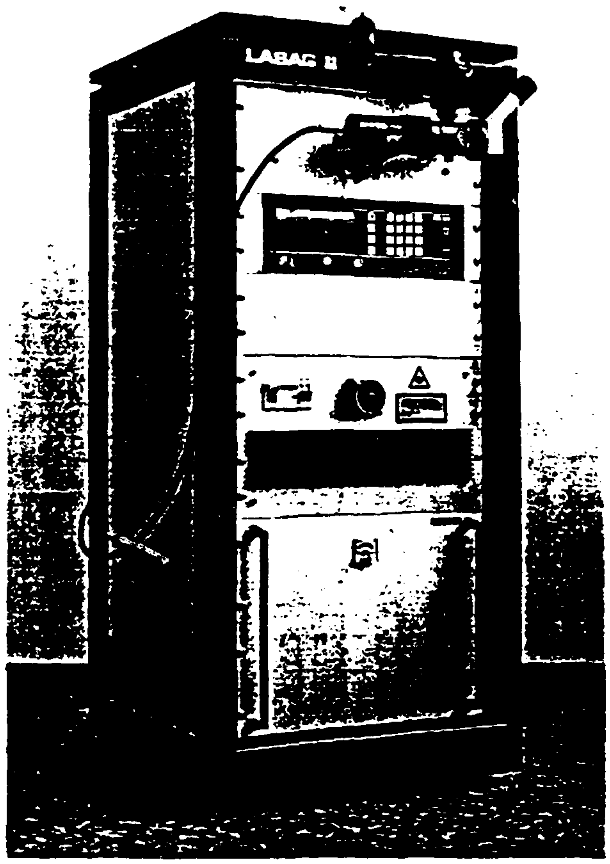
Weights	
Laser head	14 kg (31 lb)
Power supply	150 kg (330 lb)

subject to change

Lasag AG, Steffisburgstrasse 1, CH-3600 Thun (Switzerland)
Tel. 033 224522, Telex 921171 lasa ch, FAX 033 224173

L A S A G

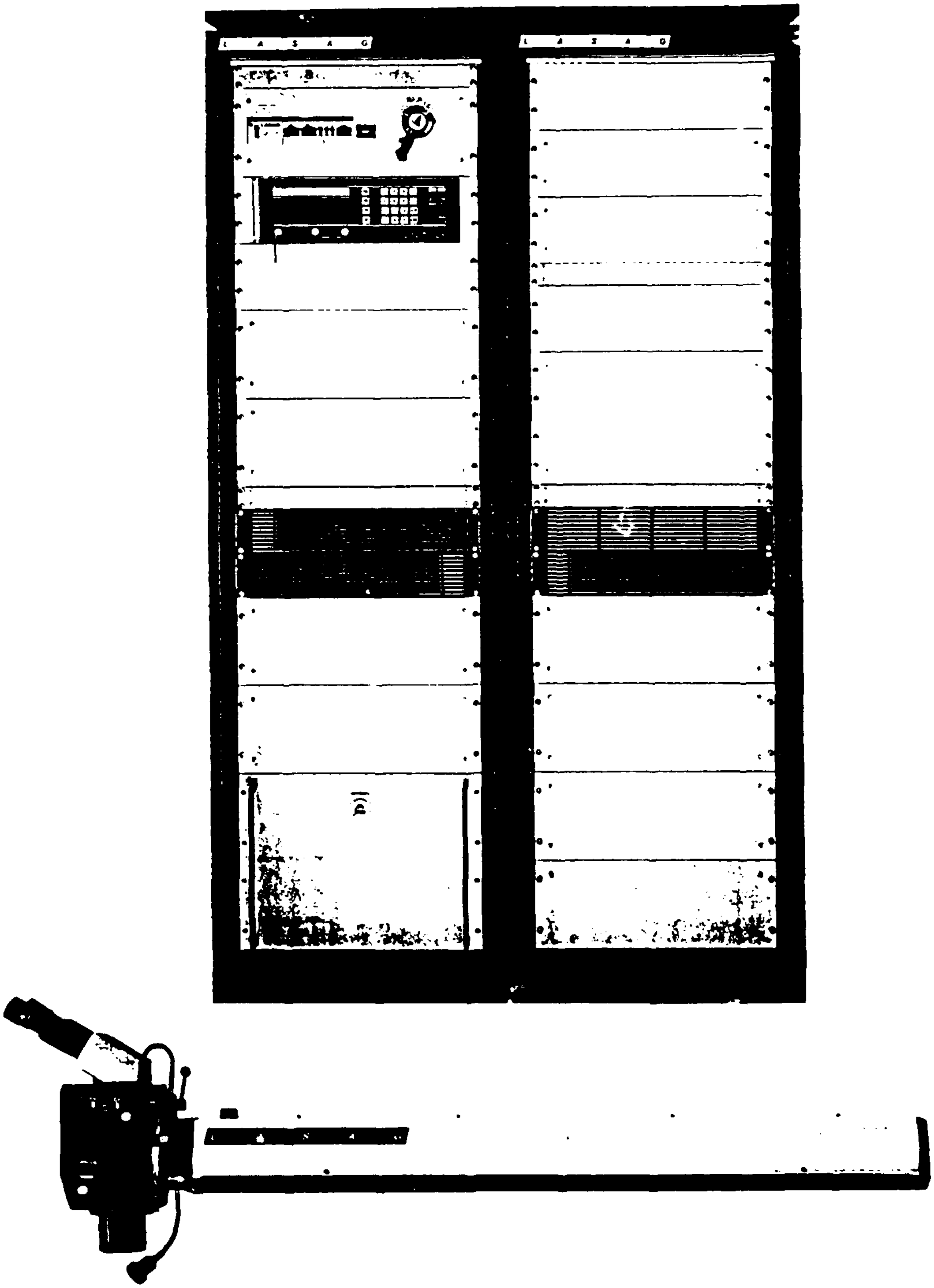
Lasag Laser System SLS



Specifications (nominal values)

Laser type	SLS
Wave length	1.06 µm
Beam diameter	6 mm (.24")
Pulse duration	0.2 - 10 ms
Pulse frequency	20 Hz
Pulse power	4 kW
Pulse energy	~~26 J~~ 20 J
Average power up to	~~30 W~~ 20 W
Services:	
Main voltage	220 V ± 10 % (P+N+E) single-phase
Main frequency	50 Hz
Power	2 kVA
Max. phase current (eff.)	10 A
Recommended fuses	10 A
Water inlet	2 - 10 bar, 18 °C (64 °F)
Water outlet	back pressure free
Water consumption	5 l/min. (1.3 US Gallons/min.)
Dimensions:	585 x 605 x 1'305 mm
Weight:	170 kg, approx. net weight

LASAG-Laser KLS 112, 322, 522



Advantages of LASAG Nd: YAG-Lasers

Versatility

Highest processing flexibility and optimal setting of focal point guarantees perfect results in cutting, welding, and drilling.

- *No thermal distortion in material*
- *No contact or tool wear*
- *Processing in magnetic field or under tension*
- *No vacuum chamber needed*

Economy

- *Powerful optimized laser processing*
- *User friendly operation*
- *Quick interchangeability of adapter units*

Controlling the Laser Process

The thyrister controlled power supply with laser pulse average power nearing 20 kW is necessary for high quality cuts and holes. In addition, this is just as important for welding highly reflective material such as precious metals.
Simple control of the working process through a constant pulse form eliminates time consuming setting-up

User friendly

LASAG lasers are for user friendly applications in industrial applications.
Main characteristics:

- *Short training time*
- *Quick interchangeability with few adjustments*
- *Simple lamp exchange due to flip out cavity*
- *Magnetic protection glass holder*
- *External resonator adjustment*

Simple use because of:

- *Remote control by CNC, computer, etc.*
- *HeNe aiming beam*
- *Protection and cutting gas solenoid*
- *Easily adjustable focal point position*

Reliability

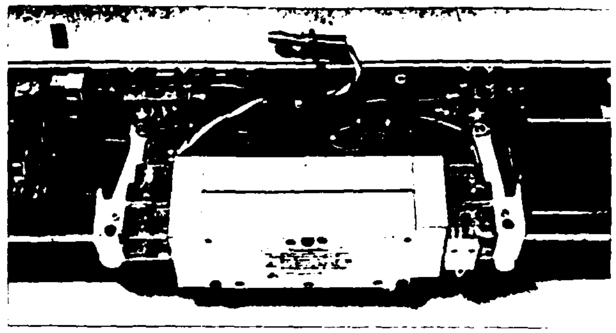
Strict quality control and testing guarantee reliability even for 24-hour operation.

Safety

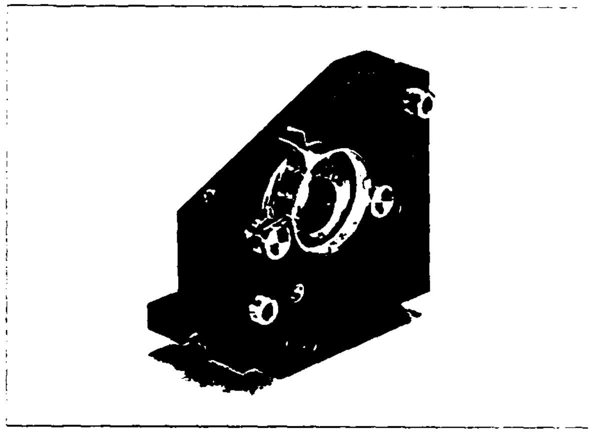
All LASAG lasers conform to European and U.S. safety standards.
Safety class IP 54/NeMA 12.

Integratability

Its compact design makes it easy for integration into many processing systems. Well conceived over mechanical, optical, and electrical interfacing.



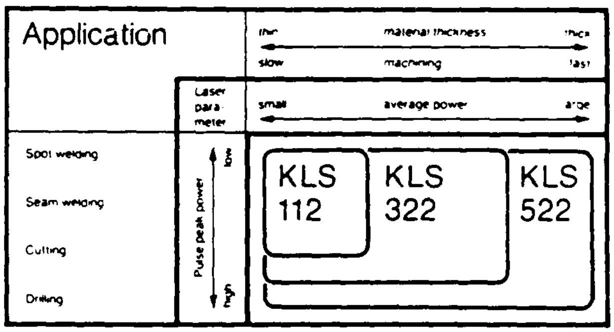
Flip out cavity reduces down time



Mirror holder for fast easy exchangeability

The correct Laser Source for a particular Machining Task

Various laser sources have been designed for different machining tasks. This is shown in the following diagram:



Applications

Spot Welding

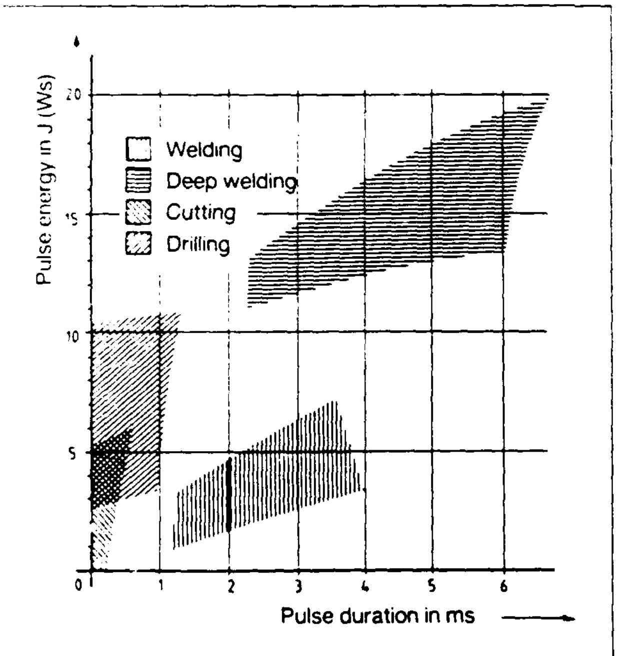
Lasers can be used for spot welding to depths up to 1.5 mm (0.06"). Their high pulse power makes it even possible to weld high thermal conductivity materials like copper, gold, and silver.

Seam Welding

Welding depth to a penetration of 1.5 mm (0.06") is possible at relatively high speeds and excellent quality. This is achieved through high pulse repetition rates up to 300 Hz and high average output power.

Cutting and Drilling

With the wide range and excellent control of pulse parameters available, it is possible to achieve precise cutting and drilling. Material thicknesses can range from thin foils to 6 mm (0.24"). Short pulse durations (0.2 ms) and high peak powers (20 kW for KLS 522) combine to achieve outstanding machinability especially in hardened materials.



Range of applications for LASAG laser KLS 322

Service

- *Competent consultation for any application is provided by our staff*
- *Intensive training on operation and maintenance of our systems is available through our Customer Service Department*
- *World-wide after sales service is provided by our network of local representatives*
- *Production of preliminary batches*

Technique

Laser Head

Mounting flexibility is achieved due to its long slender compact design. Stability is obtained through its 3 point mounting with a ribbed base construction.

All optics and beams are enclosed in a dust-free environment. The mechanical interface allows for quick and precise change to different adaptation units (trepan, fiber optics, etc.). Also utilizing a new flip out design of the cavity, lamp replacement becomes quick and easy with no re-alignment necessary.

A built in HeNe aiming laser used in alignment enables positioning of the workpiece. A simple resonator design with motorized beam expander makes adjustment simple for different processing applications.

The rear end mirror is mounted in a way that at different positions it can always be adjusted externally, without removing a cover. High beam stability is achieved through thermal insulation of the cavity.

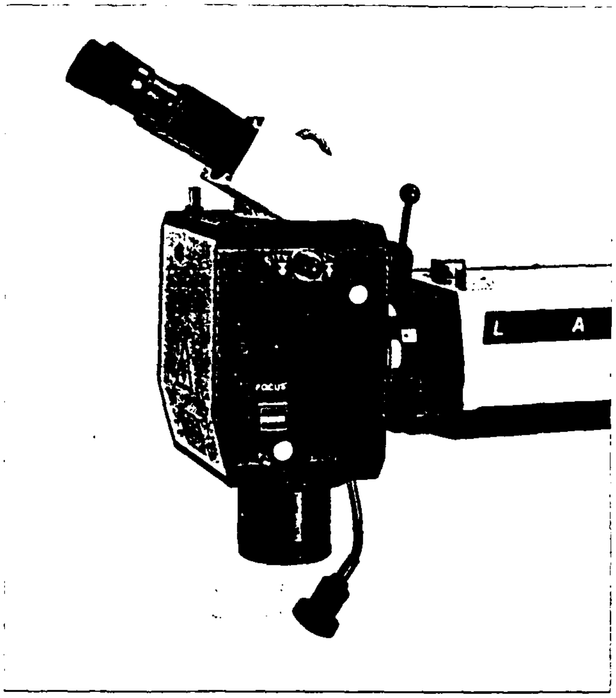
For flexible access to the workpiece the processing head can be tilted +/- 100°. Three different focal lengths are offered – standard 100 mm (4"), 150 mm (6"), and 300 mm (12") – with a rapid change protection glass. The focal point is positionable within 10 mm (0.4") by fine toothed gears with a mechanical readout.

A solenoid for protection- or cutting-gas is also integrated. For positioning and viewing the beam, the processing heads come standard with a monocular and cross hair. Eye protection is made possible by a built in filter. Finally, to illuminate the viewing area, an integrated halogen lamp with fiber optic is used.

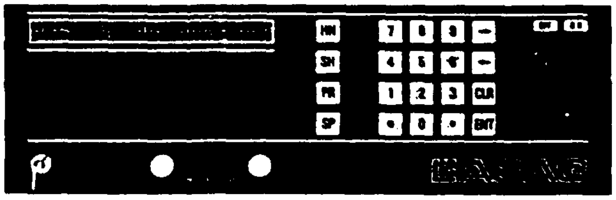
Power Supply

The cabinet is of modular design allowing for quick and simple maintenance. It is equipped with an infinitely variable pulse duration featuring high pulse output.

These are important criteria for cutting and drilling applications. Careful design ensures delivery of the full nominal output power over the entire energy range.



Processing head with binocular and built in CCTV camera



Operator control panel

Control Unit

As standard equipment, the LASAG lasers contain a state of the art control system. Three microprocessors are utilized for real time operations including special functions. This unit also prevents the selecting of improper laser parameters which are harmful to the flash lamps or produce stress on the internal components.

Primary Control Parameters

The LASAG real time control unit monitors the overall safety circuit and the laser system functions. It also offers the following adjustments:

- Laser parameters (energy, pulse duration, frequency)
- Energy regulation
- Multi shot
- Ramping (up or down)
- Single shot

Programmable system parameters:

- Limiting values
- Laser application mode
- Charging voltage and energy tolerance
- Energy calibration factor

The limits of the different functions are controlled:

- Absolute values for charging voltage, frequency, and pulse length
- Proportional (pulse length for given frequency)
- Pulse energy
- Average power
- Commutating current

A high regulating and measuring accuracy featured by this control unit results in high stability and repeatability of the work piece.

Over the interface control signals as follows are transmitted:

- Remote control, RS 232 interface
- Multi shot (single and series)
- Ramping

Further user friendly features are:

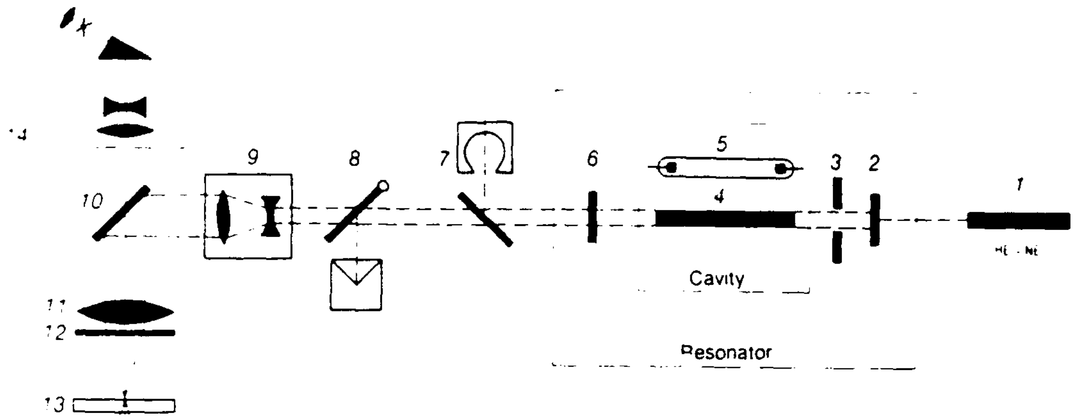
- Energy readout and regulation
- Resettable pulse counter, self diagnostic.

Also, this control unit allows for interfacing of additional power supplies for oscillator/amplifier combinations.

Accessories

- Binocular viewing
- CCTV camera
- Connection for LASAG-fiber-optic-system utilizing 1 or 3 fiber-optic cables instead of processing head. Therefore, flexibility of the KLS laser is obtained for integration into robot production systems. Different length cables and attachments depending upon application.
- Various beam paths (i. e. beam splitter)
- Remote operator control panel
- External energy monitor
- Special selected laser rod for drilling applications

Optical Schematic for LASAG Nd: YAG-Lasers

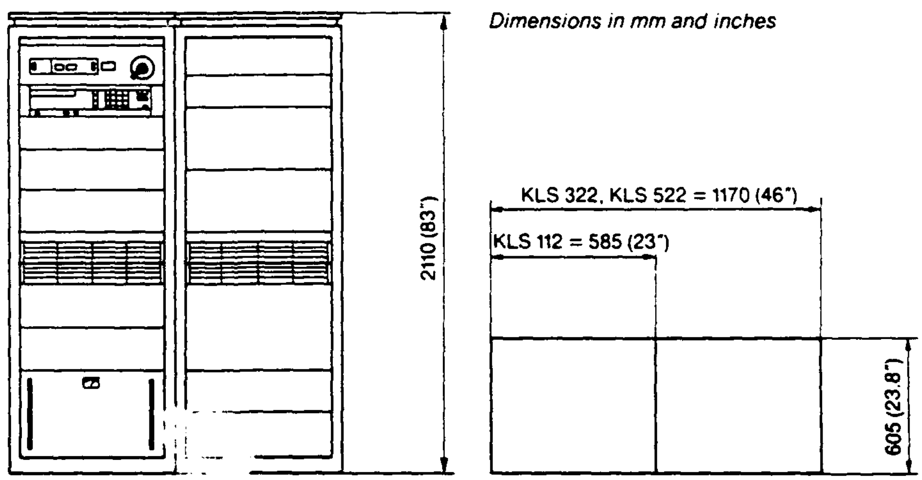


1 HeNe positioning laser
2 Rear end mirror (100% reflective, HR)
3 Diaphragm
4 Nd. YAG crystal
5 Flash lamp
6 Front end mirror (partial reflective, DC)
7 Beam detector
8 Shutter and beam dump
9 Beam expander
10 Beam bender
11 Output lens
12 Protection glass
13 Working surface
14 Viewing optic

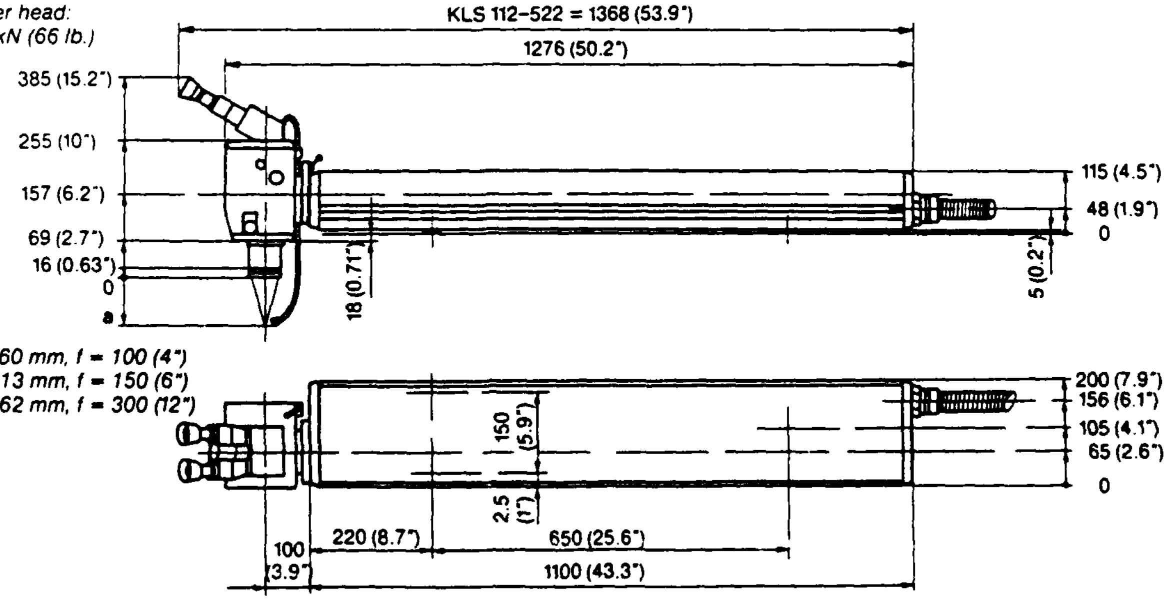
Dimensions and Weights

Power supply
KLS 112 = 3.5 kN (770 lb.)
KLS 322 = 7.0 kN (1540 lb.)
KLS 522 = 7.0 kN (1540 lb.)

Dimensions in mm and inches



Laser head:
0.3 kN (66 lb.)



a: 60 mm, f = 100 (4")
113 mm, f = 150 (6")
262 mm, f = 300 (12")

Standard Specifications

Nd: YAG-Laser-Type	KLS 112	KLS 322	KLS 522
Wavelength	1.06 µm	1.06 µm	1.06 µm
Beam diameter	6 mm	6 mm	9 mm
Pulse duration	0.1–20 ms	0.1–20 ms	0.1–20 ms
Pulse repetition rate	300 Hz	300 Hz	300 Hz
Pulse peak power	4.5 kW	12 kW	20 kW
Pulse energy	35 J	50 J	50 J
Pulse average power	100 W	300 W	450 W

Values apply only to compact resonator

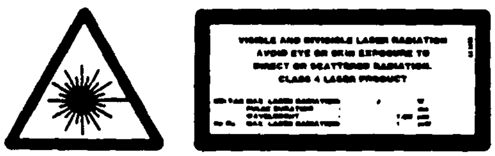
Requirements

Electrical	KLS 112	KLS 322	KLS 522
Mains voltage	3x380 V/220 V ± 10% For other voltages or 3 phase without neutral, an external transformer is required		
Mains frequency	50 Hz	50 Hz	50 Hz
Power consumption	11 kVA	16 kVA	20 kVA
Max. phase current (eff)	16 A	25 A	30 A
Recommended fuses	20 A	40 A	40 A

Water	KLS 112	KLS 322	KLS 522
Input	30–150 psi, max. 64 °F for all lasers		
Output	no back pressure	no back pressure	no back pressure
Consumption (depends on load)	0.5–2.5 g/min.	0.5–4.7 g/min.	0.5–4.7 g/min.

Subject to engineering changes

Presented by:



Warning labels (except USA)

USA label

LASAG AG, Steffisburgstrasse 1, CH-3600 Thun, Switzerland, Telephone 033-22 45 22, Telex 921171 lasa ch, FAX 033-22 41 73
An enterprise of SMH
US-Subsidiary: LASAG Corporation, 702 West Algonquin Road, Arlington Heights, Illinois 60005, Telephone 312-593 3021, Telex 023-494 1019 LASAG, FAX 312-593 5062

LASAG-Fiber-Optic-System

Advantages of LASAG-Fiber-Optic-Technology

Small Investment Costs
Beam sharing to more than one work station over long distances

Time Savings
Multiple processing at various stations at the same time

Multiple Applications
Flexibility in most work stations with interfacing connections for robotics

Same Advantages as in Laser Processing
Non-contact manufacturing, small heat affected zone, high production speeds and excellent process quality.

Modular Design

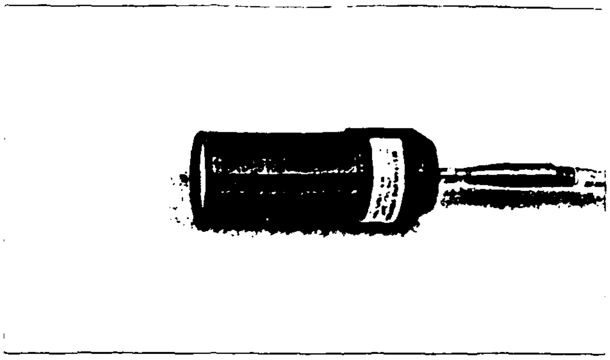
Included in this modular design are:

- *Standard LASAG laser source*
- *Fixed working heads or multiple beam delivery systems*
- *Fiber-optic cables*
- *Compact profile of the processing heads*

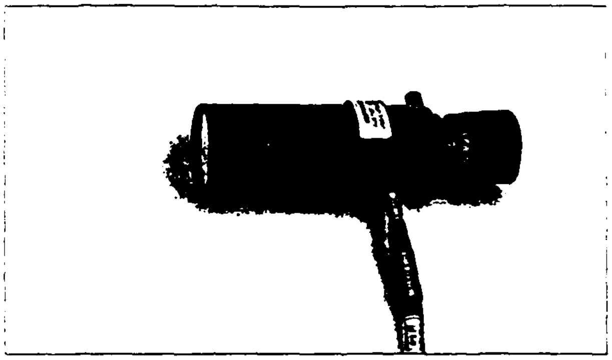
Areas of Application

Laser processing with fiber-optics include installations where:

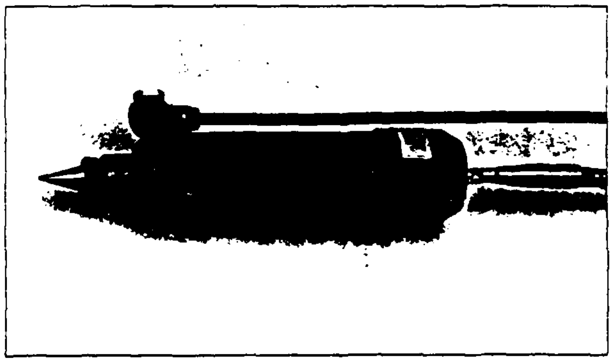
- *you need simultaneous seam or spot welds*
- *you have limited space where a complete processing head will not fit*
- *you need beam delivery to more than one work station simultaneously or one after another on the same and/or similar processing function*
- *you need laser processing done in inaccessible areas*
- *you need laser processing in a severe working environment.*



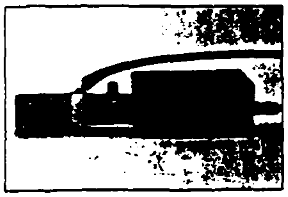
Processing head for welding



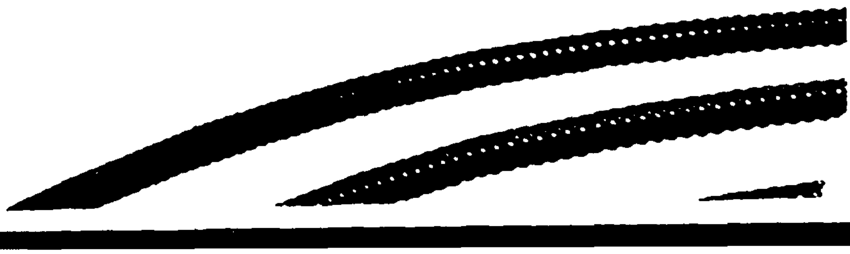
Processing head with eye piece for welding



Processing head with cutting nozzle and gas assist



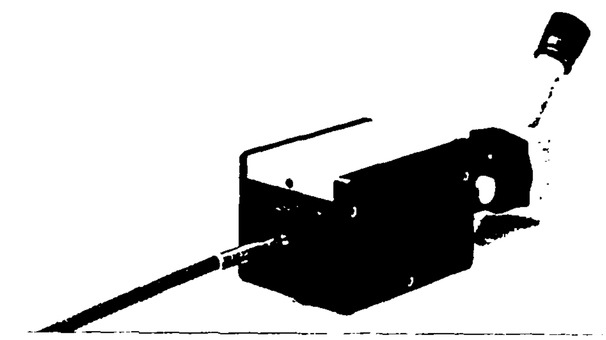
Accessory: Processing head for welding with closed circuit TV camera



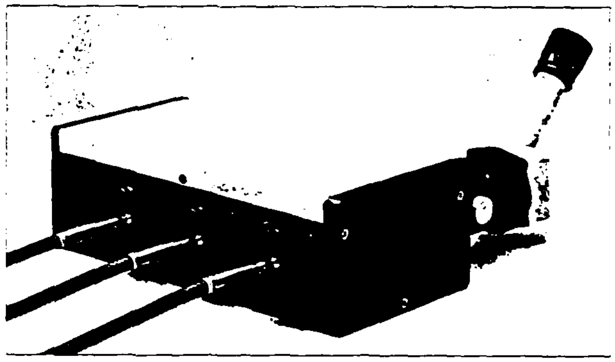
Cutting
Possible up to 2 mm (0.08") thickness

Spot Welding
Possible up to 1 mm (0.04") depth.

Seam Welding
For seams up to 1 mm (0.04") depth and 0.3 mm (0.01") to 2 mm (0.08") width, high processing speed and outstanding processing quality is achieved. This is due to high frequency and an average power of 200 Watt which can be transmitted through a processing head.



Single connection module with positioning eye piece and fiber-optic



Triple connection module with positioning eye piece and fiber-optic

Technique

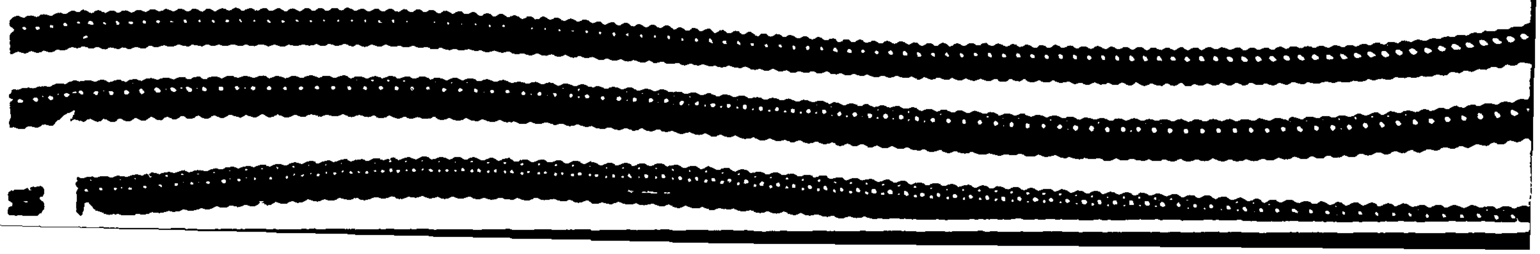
Processing Heads
For the fiber-optic-system different processing heads are offered.
Versatile mounting is achieved through its small dimensions and light weight which allows for flexible applicability.
Obtainable working distances of 43 mm (1.7") and 97 mm (3.8") can be ordered.
Processing heads for welding applications can be fitted with eye pieces used in viewing and positioning the working point. Also for viewing purposes, a closed circuit TV camera can be attached.

Connection Module
The standard program covers different versions as follows:

- Manual control of single connector module
- Manual control of triple connector module with 1/3 laser power per fiber (parallel beam sharing)
- Electrical control of triple connector module using remote control with full laser power per fiber (series time sharing)
- Special versions with up to six connections are possible.

The manually switchable connection module is used mainly for specific mass production purposes.
The remote control switchable connection module is used where time sharing of the laser beam can be delivered. Usually to different work stations where the same or similar processing function is required.

Fiber-Optic Cable
The fiber-optic cable is used to transmit laser energy and is protected by a metal jacket and vinyl coated. Therefore, the cable is protected against mechanical, chemical and other hazardous environments.



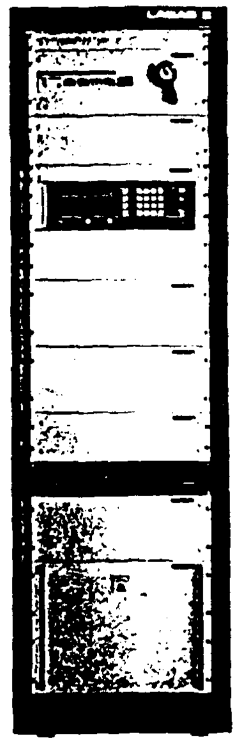
Service

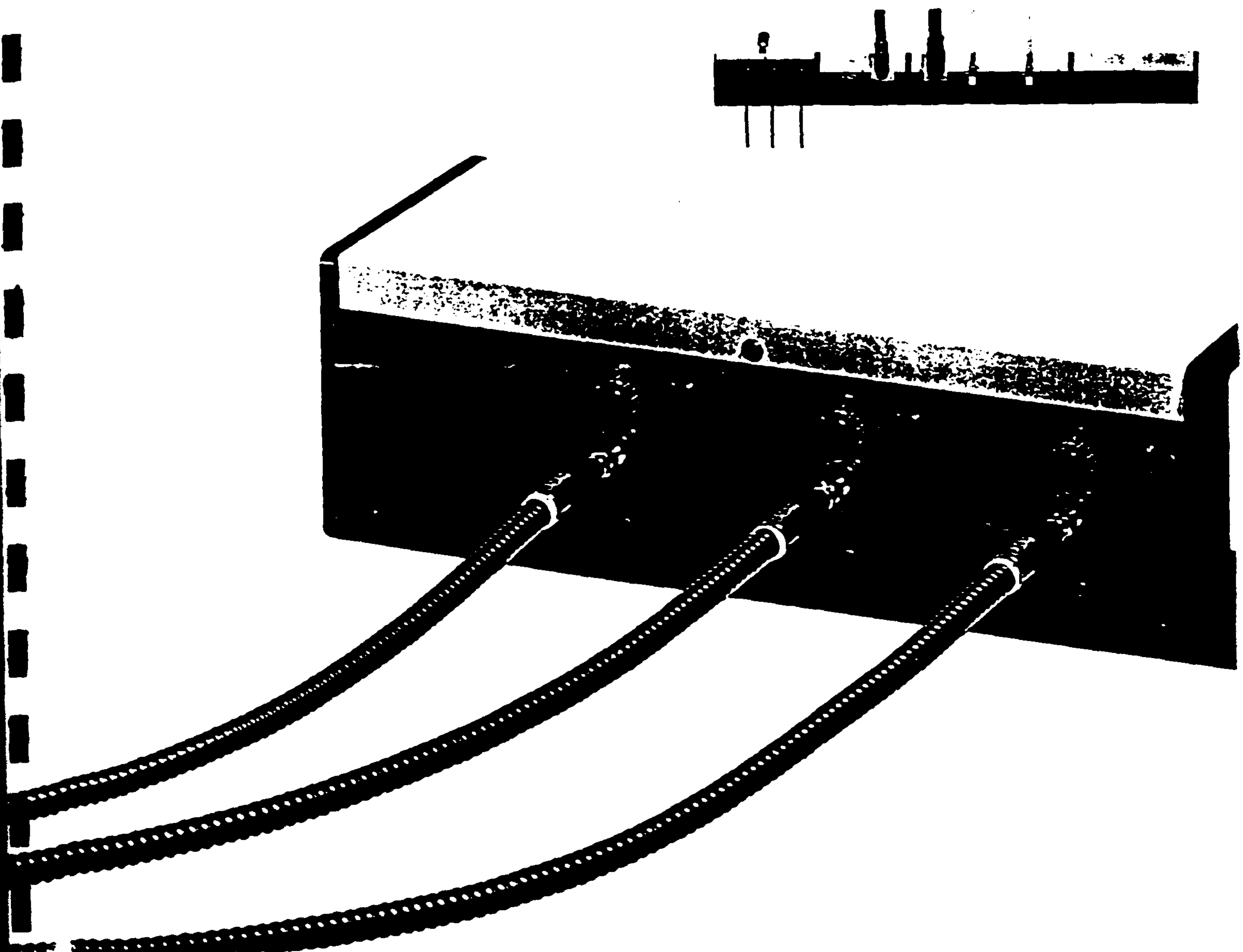
Assistance
Competent advice on all questions by our specialists.

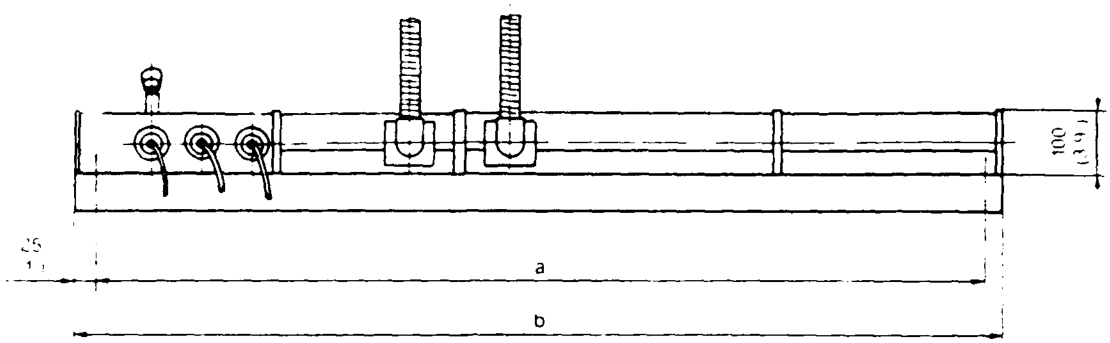
Training
Thorough training of customers in use and maintenance of the laser system.

Customer Service
Worldwide service through LASAG or local representatives.

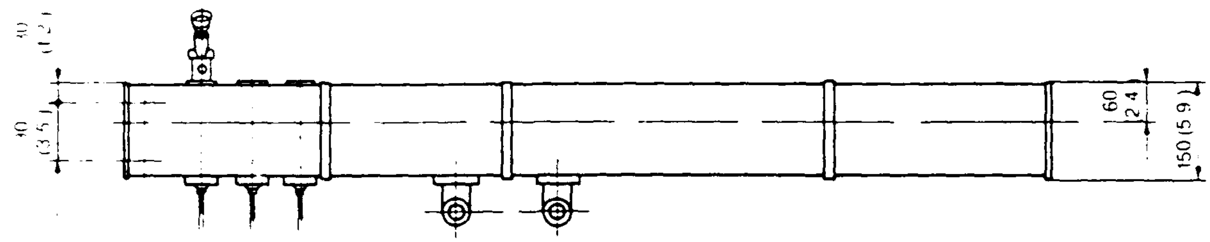
Laser-Processing
Possibilities of sample work for feasibility studies.

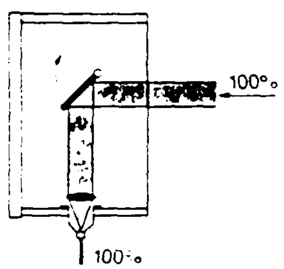




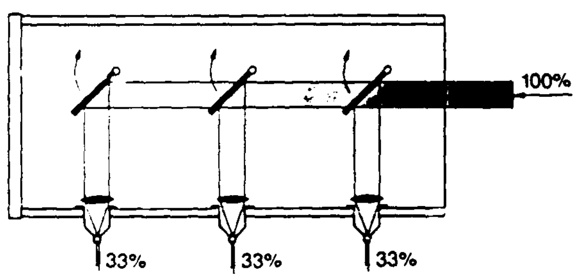


Single Connection Module	a	b	Triple Connection Module	a	b
with KLS 016.111	1126 (44.3")	1176 (46.3")	with KLS 016.111	1336 (52.6")	1386 (54.6")
with KLS 321	1201 (47.3")	1251 (49.3")	with KLS 321	1411 (55.5")	1461 (57.5")

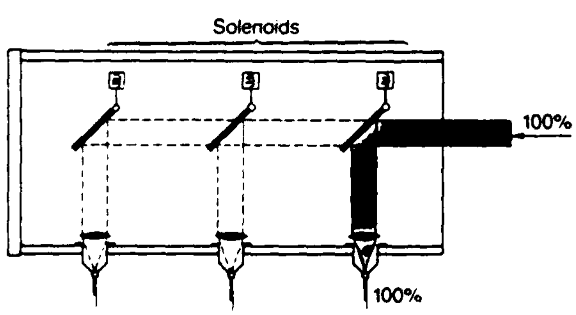




Manual Single Connection Module

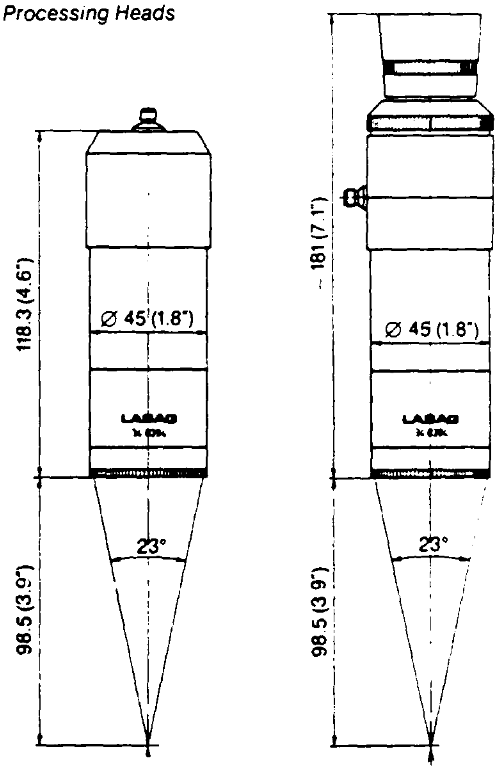


Manual Triple Connection Module



Remote Control Triple Connection Module

Processing Heads



Dimensions in mm and inches

LASAG-Fiber-Optic-Program

Connection Modules

Manual control

- 1 Fiber-optic connector
- 3 Fiber-optic connectors using 1/3 the laser energy per connector

Electric control

- 3 Fiber-optic connectors switchable by remote control at 1 Hz, with beam sharing of 3 × 100 % of laser power

Other energy splitting percentages upon request, up to two connection modules in series possible

Fiber-Optic Cables

Standard lengths for 3, 5 and 10 m. (approx. 10', 16' and 33')

- 200μ Fiber-optic, max. 7 Joule or 40 Watt average power
- 400μ Fiber-optic, max. 15 Joule or 100 Watt average power
- 600μ Fiber-optic, max. 30 Joule or 200 Watt average power

Processing Heads

- Without eye piece, ⌀ 45 mm (1.8") with 97 mm (3.8") working distance, 1:1 representation
- Without eye piece, ⌀ 45 mm (1.8") with 43 mm (1.7") working distance, 1:0.5 representation
- With eye piece, ⌀ 45 mm (1.8") with 97 mm (3.8") working distance, 1:1 representation
- With eye piece, ⌀ 45 mm (1.8") with 43 mm (1.7") working distance, 1:0.5 representation

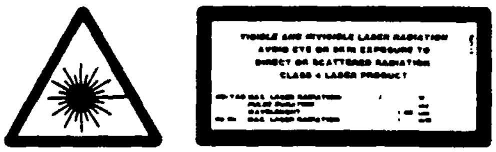
All heads with ⌀ 45 mm (1.8") come with easily exchangeable protection glass.

Options

- Closed circuit TV viewing with 1:1 representation
- Cutting nozzle with gas connection

Subject to engineering changes

Presented by:

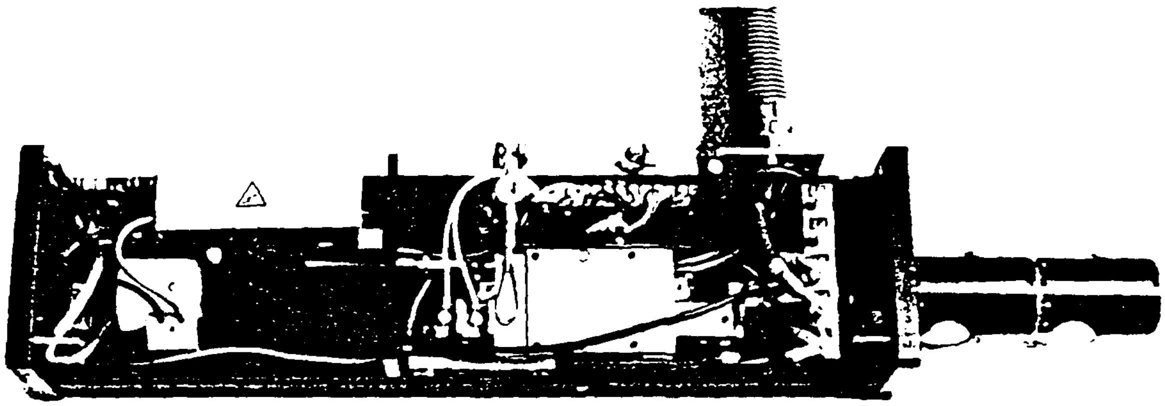


Warning labels (except USA)

USA label

LASAG AG, Steffisburgstrasse 1, CH-3600 Thun, Switzerland, Telephone 033-22 45 22, Telex 921171 lasa ch, FAX 033-22 41 73
An enterprise of SMH
US-Subsidiary: LASAG Corporation, 702 West Algonquin Road, Arlington Heights, Illinois 60005, Telephone 312-593 3021,
Telex 023-494 1019 LASAG, FAX 312-593 5062

Q-SWITCHED LASERSYSTEMS



In LASAG's modular optic system is also a Q-switch model available. It is built into a resonator extension and contains:

- Pockels cell
- Polariser
- High voltage PC-driver

The model can directly be attached to the standard laserheads (LaK 101 and LaK 301)

Technical Specifications

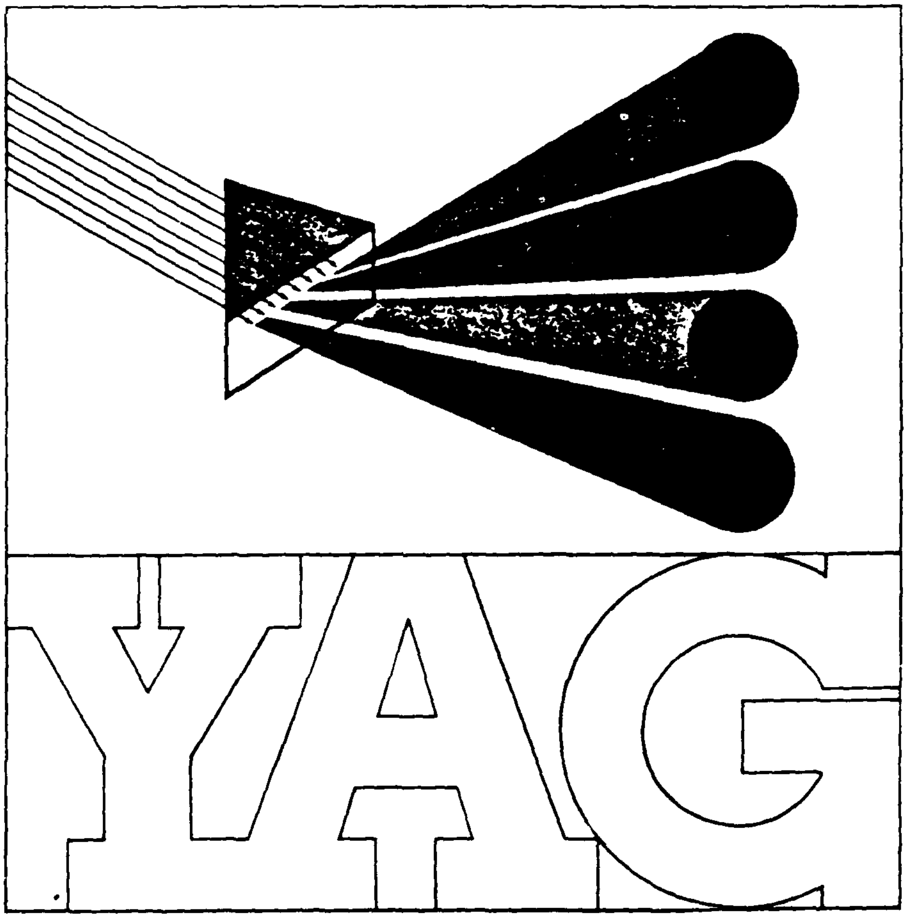
Wavelength	1.06 µm *
Free running pulse (variable)	200 µsec
Q-switched pulse	15 - 20 nsec
Pulse rate	1 - 50 Hz depending on model
Beamdiameter	apprx 5 mm
Polarisation	linear
Divergences	typically 2 - 3 mrad
Energy variation (electrically)	1:8

* Frequency doubling available

Output energy - relatively to pulse length in Wsec

Pulse length	1 µs	5 µs	10 µs	50 µs	10 µs
Oscillator	0.015	0.75	0.15	0.75	1.5
Osc. + 1 ampl.	0.10	0.40	0.70	2.0	4.0
Osc. + 2 ampl.	0.50	0.85	1.50	4.0	6.0

Nd: YAG Lasers



A Dedication to Reliability and Performance

Molectron background

Molectron Corporation embarked on a program to develop a pulsed Nd YAG laser in 1976. As the leading supplier of tunable pulsed dye lasers pumped by nitrogen lasers, Molectron viewed the YAG laser as a new high power pump source for dye lasers, and one that would allow an extension of the tuning range in the UV and the infrared through stimulated Raman scattering and frequency mixing techniques not possible with nitrogen lasers. Thus the objective was to provide a YAG Dye system with both higher pulse energy and broader tuning range than N_2 Dye systems.

The task of developing a high power and high quality Nd YAG laser which sells at a reasonable price was not an easy one. Customers wanted "turn-key" operation and a laser that would work for thousands of hours without realignment and without major failure. To meet this objective a team of four engineers and designers experienced in pulsed Nd YAG lasers was hired. (Their combined experience is almost 40 years!) This team also worked on another Molectron Nd YAG product, a CW laser system for medical applications.

The Molectron tradition of a dedication to reliability and performance was quickly assimilated by this team. The result of their efforts was a new optical design which combines excellent near-Gaussian beam quality with maximum pulse energy in a convenient, easy to use system. This laser also promises to be even more reliable than Molectron's well-known nitrogen lasers which have set industry standards for pulsed laser reliability.

Types of Nd:YAG lasers

The Nd YAG laser was among the earliest developed, having been operated both in the pulsed and CW or continuous wave modes in 1964. The early versions produced a pulse 100 microseconds in duration which was actually a group of much shorter pulses. Control of the cavity "Q" or "Q-switching" was added later and resulted in shorter pulses of 10-30 nanoseconds duration but with extremely high peak power. Nearly all pulsed YAG lasers today are Q-switched to produce megawatts of peak power output.

TEM_{00} Cavity

Until recently the standard optical configuration was the TEM_{00} cavity shown in Figure 1a. This design produced an output beam with a Gaussian profile and low divergence. The Gaussian TEM_{00} or "fundamental mode" as this beam is called is the optimum beam profile because it is the only one which never changes as it propagates ("once a Gaussian, always a Gaussian"), and it is the most uniform beam profile. A great deal of effort is spent in laser design to produce a Gaussian beam.

Unfortunately the TEM_{00} cavity is limited in the amount of energy that can be extracted from the YAG rod. While a standard 6.3mm diameter by 75mm long rod can store 400-500mJ, only 10-30mJ can be delivered in the TEM_{00} mode because to produce such a mode the beam must be restricted by an aperture to a diameter much smaller than the rod. Thus the TEM_{00} mode operates only in the small central region of the rod.

If the aperture in a TEM_{00} cavity is enlarged, the output energy increases but higher order modes appear. By the time the aperture is the size of the rod, approximately 250mJ can be produced but the beam divergence has increased to 8-10 milliradians. This "multimode" output is not useful in applications requiring either uniform beam quality or low divergence.

The only way to achieve both high pulse energy and low divergence with the TEM_{00} oscillator approach is to add amplifier stages. A typical configuration uses three amplifier stages to produce 350mJ at 1064nm in a Gaussian beam. Unfortunately such a system is both complex and expensive.

Diffraction-coupled unstable resonators

The term "unstable" in resonator design refers to the optical configuration and does not imply a mechanical or operational instability. An unstable resonator is basically one in which there is no closed ray path. That is, all rays eventually leave the cavity, often around one of the mirrors.

The unstable resonator shown in Figure 1b was introduced in 1976 as an alternative to the multiple amplifier TEM_{00} system. This resonator is known as "diffraction-coupled" because the beam exits and diffracts around a small total reflecting output mirror. The term "positive unstable" refers to the positive curvature of the output mirror.

This type of resonator produces both high pulse energy (250mJ) and low divergence (0.5mrad) in a beam which has essentially a planar or uniform phase wavefront. Pulse duration depends on both cavity length and pump energy, and is typically 8ns for a 60cm cavity. The beam profile is that of a donut in the near field because the output mirror occludes the central region. Fresnel rings also appear in the intermediate field as a modulation to the donut profile. These rings are caused by diffraction from the edges of the Nd YAG rod and fade away in the far field.

One of the characteristics of this design is that the donut does not persist. Because the beam is diffracted sharply around the output mirror the beam profile constantly changes as a function of distance from the laser. In the intermediate field (1-5 meters) a small central spot appears which has extremely high power density, up to four times that of the donut, and is potentially damaging to optical components. This spot, called both the "Poisson spot" and the "spot of Arago", causes a discontinuity in the refractive index of transmitting materials and leads to self-focussing and potential materials damage. In the far field, approximately 10 meters from the laser, the beam profile is the classical Airy pattern with 60-80% of the energy in the central lobe.

Figure 1c shows the optical schematic of a "negative" unstable resonator, so termed because of the concave output mirror. The optical and mechanical tolerances in this design are less stringent than those for the positive versions. As a result this design is well suited for military lasers and has been used for several years by military equipment contractors. For mirror curvatures identical to the positive counterpart, the cavity is twice as long and produces a longer pulse, 15ns for a 120cm cavity. Otherwise the output is identical to the positive version.

Polarization-coupled stable resonator

Late in 1977 a stable resonator using polarization output coupling was introduced. Shown in Figure 1d, this design employs two factors different from previous designs. First, it uses polarization techniques to couple the beam out of the cavity; and second it uses the oscillator rod as an amplifier to increase the output energy.

The basic resonator is a TEM_{00} configuration formed by the concave rear mirror and partially reflective front surface of the quarter-wave plate. The aperture restricts the oscillator to the center of the rod and the resulting beam, polarized horizontally, is low in energy. This beam exits the cavity through the $\lambda/4$ plate which converts the beam to circular polarization. When reflected off the convex mirror and passed back through the λ/4 plate the expanded and diverging beam is polarized vertically, then amplified in the YAG rod and coupled out by the polarizer. A lens then recollimates the beam.

While the oscillator output is TEM_{00} the beam exiting the polarizer is not. The oscillator has depleted the gain at the rod center so the output beam has a prominent "dip" in the center. Fresnel rings also are present and are more severe than in the diffraction coupled unstable design because the beam is diverging as it re-enters the rod for amplification.

Note that this design depends on converting all of the horizontally polarized oscillator beam to vertical polarization for coupling out of the cavity. In fact, thermal birefringence in the YAG rod converts some of the amplified beam to horizontal polarization. At high pump energies this unwanted feedback upsets cavity oscillations and limits the energy and quality of the output beam. A standard 6.3mm diameter by 75mm long rod can deliver only 150mJ with this design, but larger rods can deliver more energy.

Molectron approach

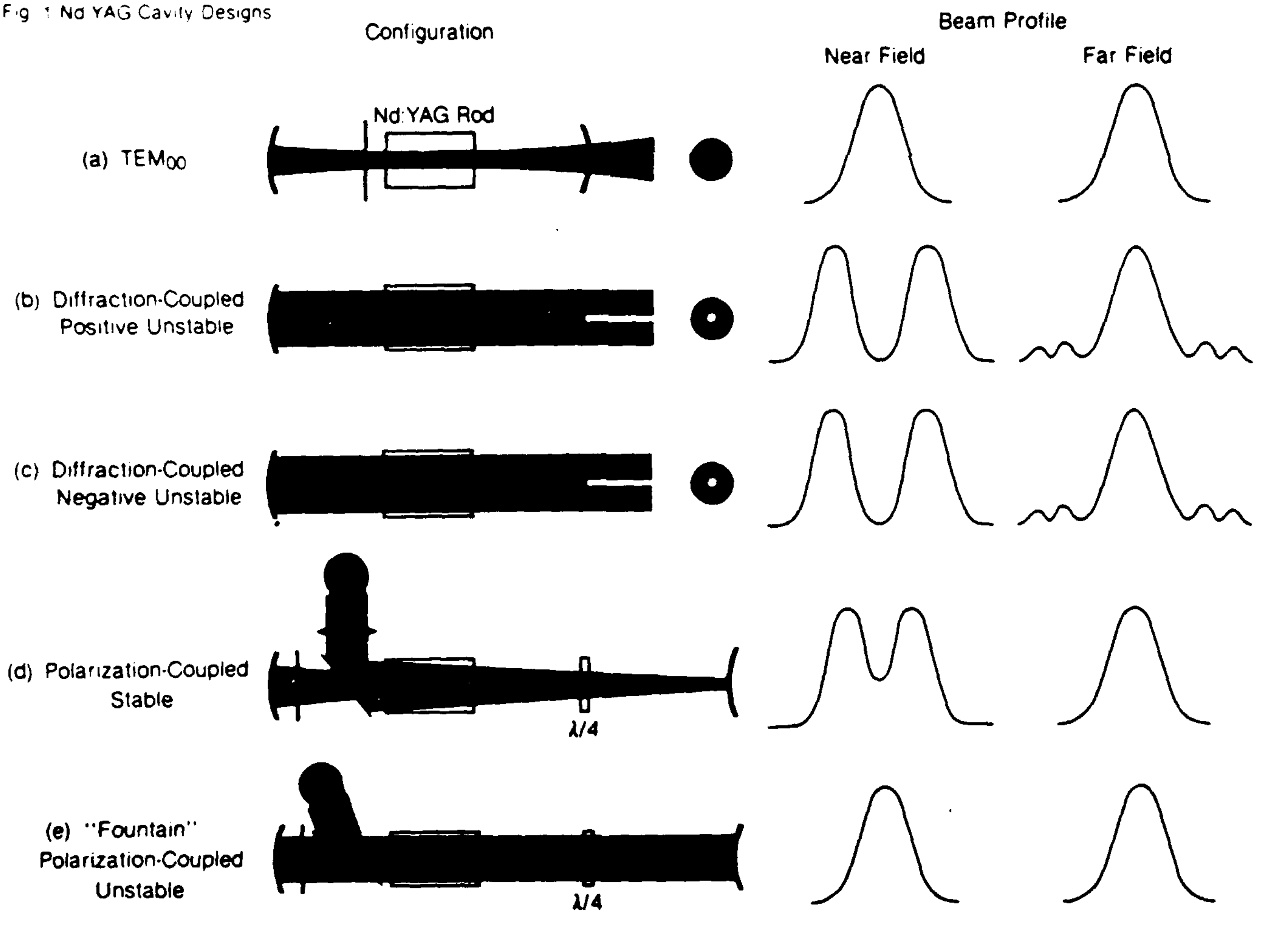
In 1977 Molectron selected the negative unstable resonator with diffraction-coupled output (Figure 1c) as the best choice for a commercial product. Only the unstable resonator could provide high pulse energy in a low divergence beam, although the resulting donut beam was recognized as less than ideal for most applications.

After proving the negative unstable design, Molectron engineers began an exploratory investigation of polarization output coupling. This type of output coupling had the potential of overcoming the deficiencies of the "donut" beam. Rather than apply polarization coupling to a stable resonator, Molectron engineers chose the unstable resonator.

The results at first were disappointing. Although the early designs delivered high energy in a low divergence beam, the beam profile in the near field was far from satisfactory, resembling concentric rings. Further improvements reduced the ring modulation considerably until late in 1978, a design was found which had no modulation on the beam and whose intensity decreased monotonically away from the beam center. Quantitative beam profiles indicated a beam close to Gaussian in shape at all positions away from the laser (Figure 1e).

This design is now available in the MY-Series Pulsed Nd YAG Lasers described in this brochure. It is the only design which provides near-Gaussian beam quality while maintaining both high pulse energy and low divergence. This "Fountain" design is named after its developer William D. Fountain.

Fig. 1 Nd YAG Cavity Designs



The optical schematic for the MY-Series Nd:YAG lasers is shown below. The oscillator for all models is the same except for rod size. Although the schematic looks similar to the polarization-coupled stable resonator, the operation is in fact quite different because the Fountain design is a true unstable resonator.

How it works

Mirrors M_1 and M_2 form the optical cavity. In the region to the left of the intracavity polarizer the beam is polarized horizontally. In passing through the quarter-wave plate the beam becomes elliptically polarized. After reflecting off mirror M_2 and passing back through the wave plate, the beam is polarized approximately 75% in the vertical plane and 25% in the horizontal plane. The vertical component is coupled out of the cavity by the polarizer, while the horizontal component remains in the cavity as the "feedback" component.

Note three distinct differences from the polarization-coupled stable resonator. First, the quarter-wave plate does not act as a mirror and is not set with its axis at 45° which would couple essentially 100% of the beam out of the cavity. Second, thermal birefringence in the Nd:YAG rod has no adverse effect on performance because the wave plate axis is adjusted for optimum output coupling which then includes the effects of thermal birefringence. Third, the output beam is collimated, requiring no lens and producing no Fresnel rings.

The horizontal component of the beam which remains in the cavity must pass through an aperture before reaching mirror M_1. This aperture acts as the loss mechanism for the cavity. That is, just as in the diffraction coupled unstable resonator the beam "walks" its way out of the cavity around the front mirror, in the Fountain design the beam walks its way out of the cavity and strikes the aperture. However the energy lost at the aperture is very small.

The exceptional near-Gaussian beam quality of this design is produced by a subtle solution subset of the unstable resonator problem. An obvious means of achieving such beam quality is to restrict the aperture, just as in a TEM_{00} stable resonator. But pulse energy is sacrificed, as in the TEM_{00} case. A not so obvious solution is to magnify the concentric rings produced in the early designs so that the rings are eclipsed by the aperture leaving only the uniform central spot. This is the principle behind the Fountain oscillator.

Outside the oscillator

After the beam exits the cavity it is incident on a second polarizer which is used to improve the polarization ratio before amplification. Two turning mirrors then direct the beam along the rear beam line of the laser.

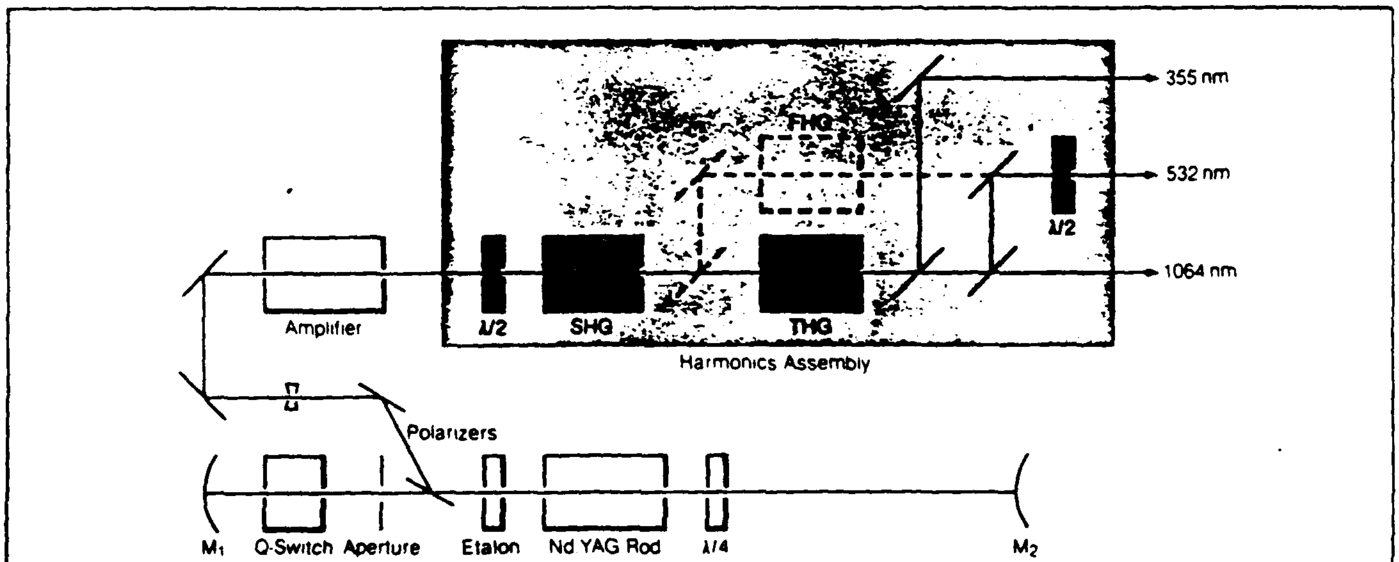
In an oscillator-alone configuration, a beam-reducing telescope is used to increase the power density on the harmonic crystals. A complementary beam-expanding telescope on the output brings the beam back to its original size and also permits adjustment of the output divergence.

In an oscillator/amplifier configuration, the amplifier stage replaces the beam-reducing telescope which is not needed. A negative lens is installed before the amplifier to expand the oscillator beam and to compensate for the positive thermal lensing of the amplifier rod.

In both configurations the beam then enters a sealed "harmonics box" where the 2nd, 3rd and 4th harmonics are generated (SHG, THG and FHG respectively). Each harmonic crystal is in a hermetically sealed cell and kept at an elevated temperature stable to 0.05°C to improve long-term stability. The crystals are angle tuned with thumbwheels accessible from outside the laser.

Before the SHG crystal, a half-wave plate rotates the polarization of the 1064nm beam to an axis appropriate to the type of SHG crystal used, either Type I or Type II. Following the crystals, dichroic beamsplitter pairs separate sequentially the shortest wavelength from the combined beam. These mirrors are high reflectors for the shortest wavelength and high transmitters for the longer wavelengths. Following the dichroics, half-wave plates may be inserted to produce any desired polarization axis.

The dichroics and wave plates are mounted on interchangeable "chess pieces" to permit any combination of these beams of different wavelengths to be directed out the three exit ports of the laser. The center beam line pumps the dye laser directly, the rear beam line is used for mixing with the dye laser output or for experiments such as CARS which require a second wavelength, and the front beam line is reserved for the residual fundamental beam. A water-cooled beam dump is included with the harmonics assembly to contain the 1064nm beam safely inside the laser.



Optical Schematic MY-Series Pulsed Nd:YAG Laser

Beam quality

The output beam of the MY-Series lasers has a near Gaussian profile in the near intermediate and far fields. The scanned array profile below of the near field pattern shows the departure from Gaussian to be very small, less than 20% at any point on the profile.

In the near field the outer regions of the beam appear to be somewhat square. That is, a low intensity burn pattern would be slightly square in appearance. However, scanned array profiles along either 45° diagonal shows this distortion to be very weak, again less than 20% departure from Gaussian.

Variable pulse duration

The intracavity quarter-wave plate is rotated to vary the output coupling for maximum energy at 1064nm. This position corresponds to the shortest pulse duration, 15ns. By rotating the waveplate slightly from optimum, the pulse duration increases to approximately 30ns. Of course the harmonic efficiencies fall because the peak power density has decreased.

Amplitude stability

The MY-Series lasers employ a number of techniques to maximize amplitude stability.

1. Simmered flashlamps—a small "keep alive" current maintains an arc down the center of each flashlamp so the main discharge has a well-defined path to follow. Simmered flashlamps also have higher efficiencies and much longer lifetimes than unsimmered lamps.

2. Small bore flashlamps—there is a tendency to use a large bore flashlamp to increase lamp life, but stability is sacrificed because the arc "wanders around" the bore from pulse to pulse. The MY-Series lasers use small lamps, the bores of which are entirely filled by each pulse. Flashlamp life is maintained by the low pulse energy of the discharge and normally exceeds 30 million pulses.

3. Voltage-regulated power supply—the flashlamp charging supply is voltage regulated to 0.1%. Thus the stored energy for the flashlamp is stable to approximately 0.2%, which with the simmer and small bore design produce a very stable rod gain from pulse-to-pulse.

The histogram below shows the energy distribution of pulses at 1064nm over a time period of ten minutes. The data was collected using the IR Monitor signal, an LP20 Laser Photometer (boxcar) in a sample-and-hold mode, and the DL240 Laser Scan Control based on an HP9825A Desk Calculator. The results show a stability for 90% of the pulses of ±1.25% while 100% of the pulses occurred within a ±2% envelope. Similar data for the harmonic wavelengths has led to the specifications shown on page 15.

Long-term stability measurements show that the mean value of the histogram is stable to ±5% over a 2 hour period and ±8% over a 4 hour period.

Temporal pulse shape

Without the MY-SAM Single Axial Mode accessory, all MY-Series oscillators operate over several axial modes. The temporal waveform then displays several prominent beats, as shown by the photo below. The separation between the beats is the cavity round-trip transit time, 7ns.

The photo recorded approximately 1200 pulses during a two minute exposure and reveals both peak power stability and low jitter from the Q-switch "sync" which was used to externally trigger the oscilloscope.

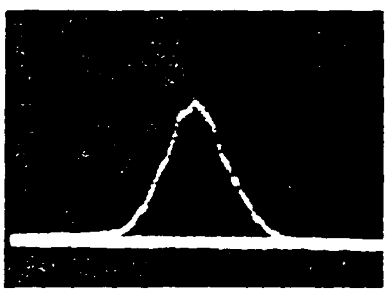
An interesting feature of these beats is that their position relative to the Q-switch trigger is fixed. A change in the flashlamp energy moves the envelope of the waveform, but each beat remains stationary. Thus when the flashlamp energy is changed, the temporal waveform changes continuously as the adjacent beat becomes more or less dominant. The waveform shown is the extreme case of one dominant beat, the other extreme is the case of two equal beats.

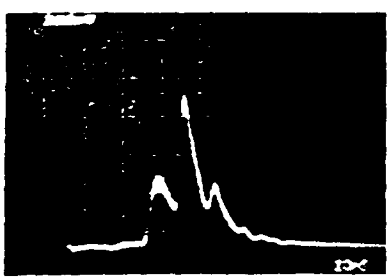
The temporal profile remains constant for hours at a time due to excellent gain stability.

Timing sequence

The sequence shown in the figure contains the important timing information. The Q-switch high voltage supply is triggered first at t=0 so the voltage corresponding to $\lambda/4$ retardation is achieved before there is any gain in the oscillator. Next the flashlamps fire at approximately t=200μs accompanied by the flashlamp "sync" output. The Q-switch trigger is adjusted to occur at maximum gain approximately 175μs after the flashlamp "sync". The laser output occurs approximately 100ns later.

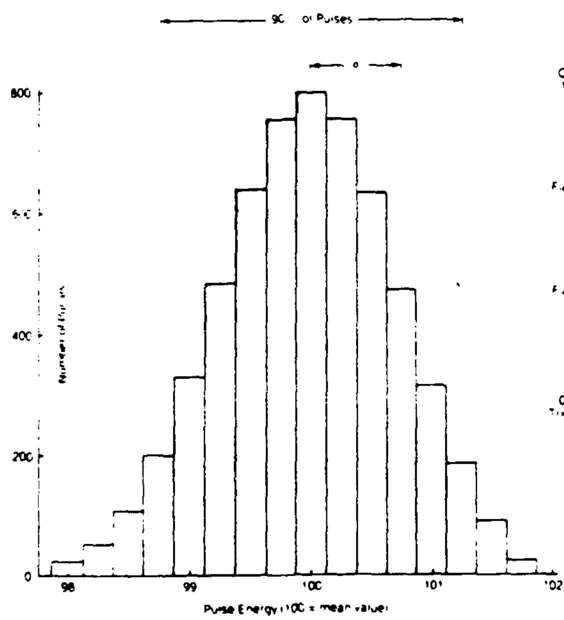
Reticon Array Profile of Output Beam



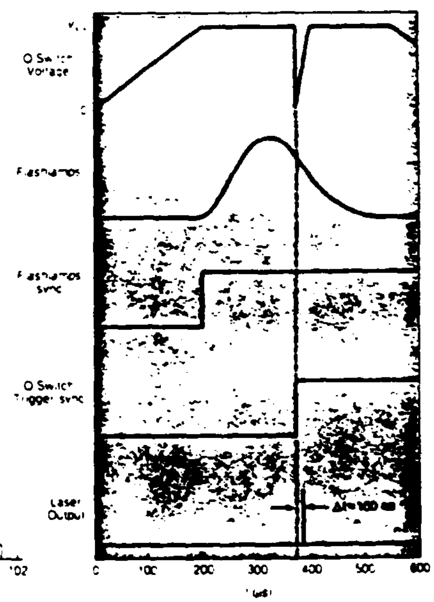


Temporal Profile of Output Beam

Stability Histogram (6000 pulses)



Timing Sequence



Models MY32, MY33, MY34 and MY35

FEATURES

- High efficiency, high reliability design
- Modular for later upgrading
- Optimum beam profile: near-Gaussian
- Variable pulse duration 15-30 ns
- Low jitter, stable temporal profile
- *Excellent pulse-to-pulse energy and peak power stability*
- Programmed Q-switch power supply

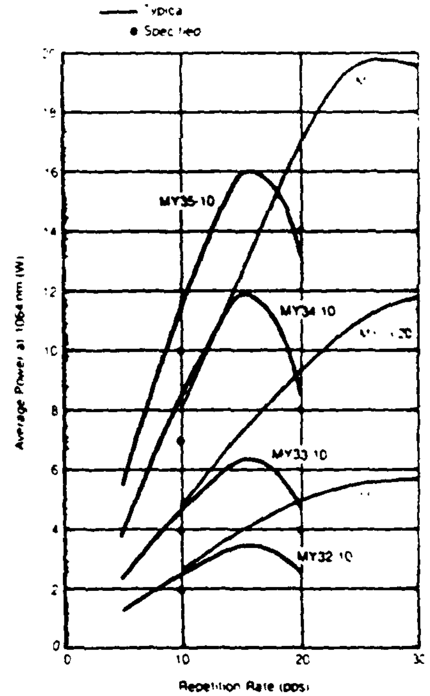
MY32 and MY34. Based on a 6.3mm diameter oscillator rod and 8.5mm diameter amplifier. The MY32 can be upgraded in the field to an MY34. Both models are available in 10 and 20 pps versions.

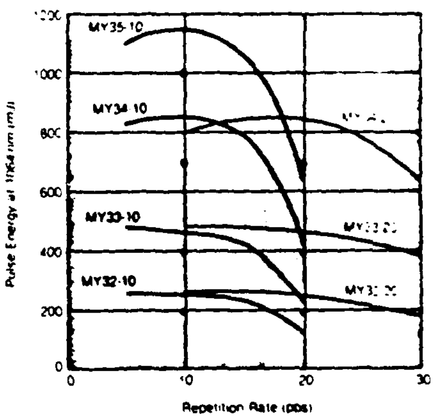
MY33 and MY35. Based on 8.5mm diameter oscillator and *amplifier rods.* The MY33 can be upgraded in the field to an MY35. The MY33 is available in 10 and 20pps versions; the MY35 is available only at 10 pps.

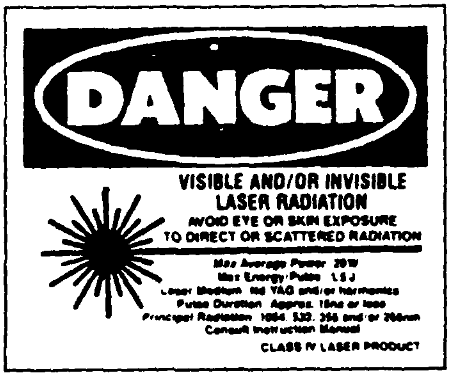
10 and 20 pps Versions
Because thermal lensing of the oscillator rod varies with repetition rate, only the design rate of 10 or 20 pps gives a collimated output beam. At lower rates the beam diverges to as much as twice the minimum value. At higher rates the beam converges weakly to a focus in the far field. The *diameter at focus may be* only slightly less than the original beam diameter.

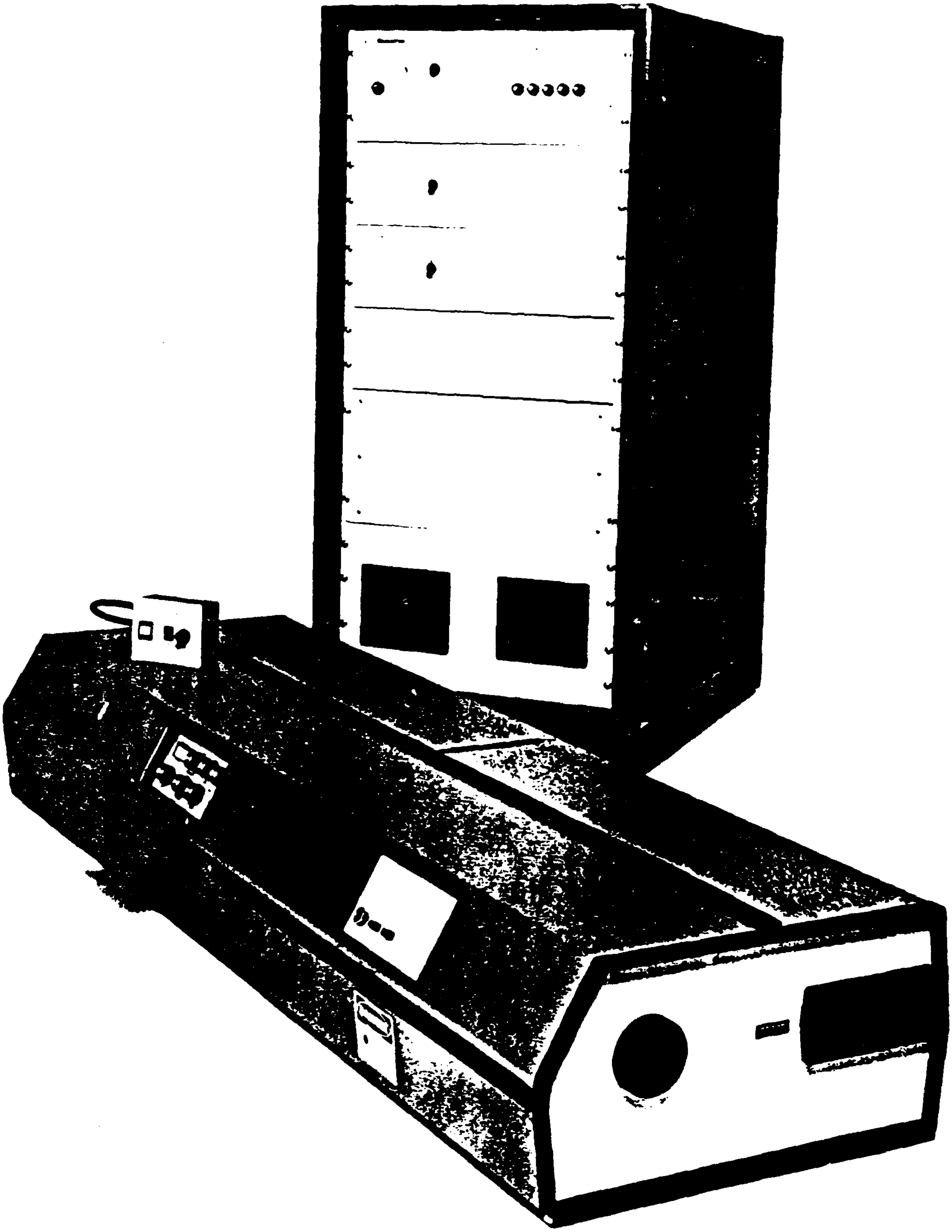
The pulse energy output at 1064 nm is relatively constant over a wide range of repetition rates, subject to power supply limitations. However, the pulse energy in each of the harmonics peaks at or near the design rate because the harmonic efficiency is sensitive to beam divergence.

To designate repetition rate, each model has an appropriate suffix −10 or −20 as shown in the figures at the right.









Reliability

Invar Resonator. The two cavity mirrors (and only these mirrors) are mounted to the rugged Invar resonator structure which is kinematically mounted to the baseplate. This stable and isolated structure insures long term alignment stability.

Rigid Baseplate. The heavy aluminum plate is strengthened by U-shaped stiffeners under each beam line and a vertical support fin on top. The plate is kinematically mounted to the end bezels to insure isolation from the main supporting frame.

Sealed Beam Line. The entire beam line is enclosed either in tubes or in protective boxes to protect the optical components from dirt and potential damage.

Conservative Electrical Design. All components are operated at or below 75% of ratings for long life.

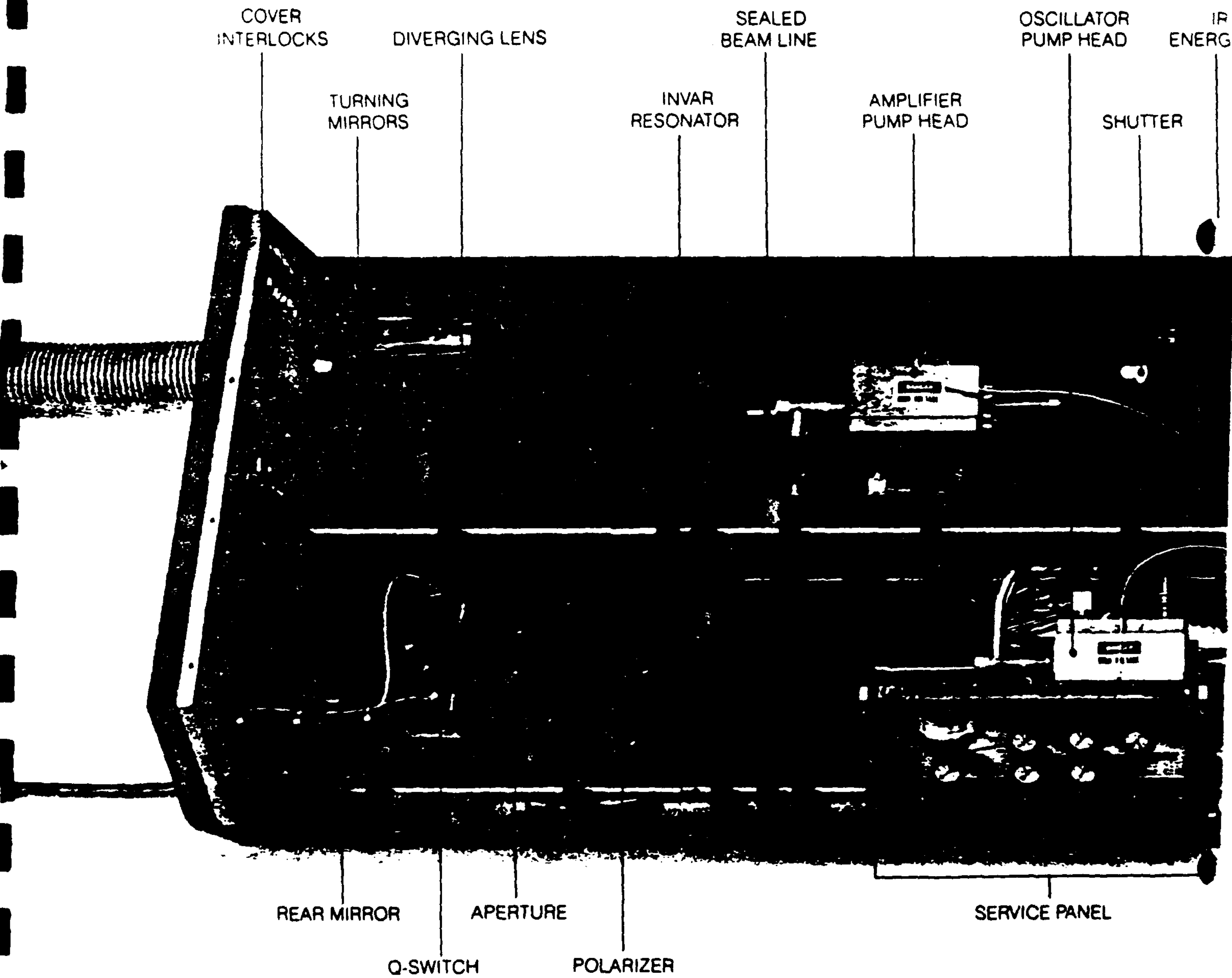
Conservative Optical Design. Power densities are kept below 100MW/cm². All optics are tested for damage resistance prior to installation in the laser.

Flexibility

Modular Design. Add the amplifier later if you prefer, or convert from 10 pps to 20 pps. All accessories can be added in the field.

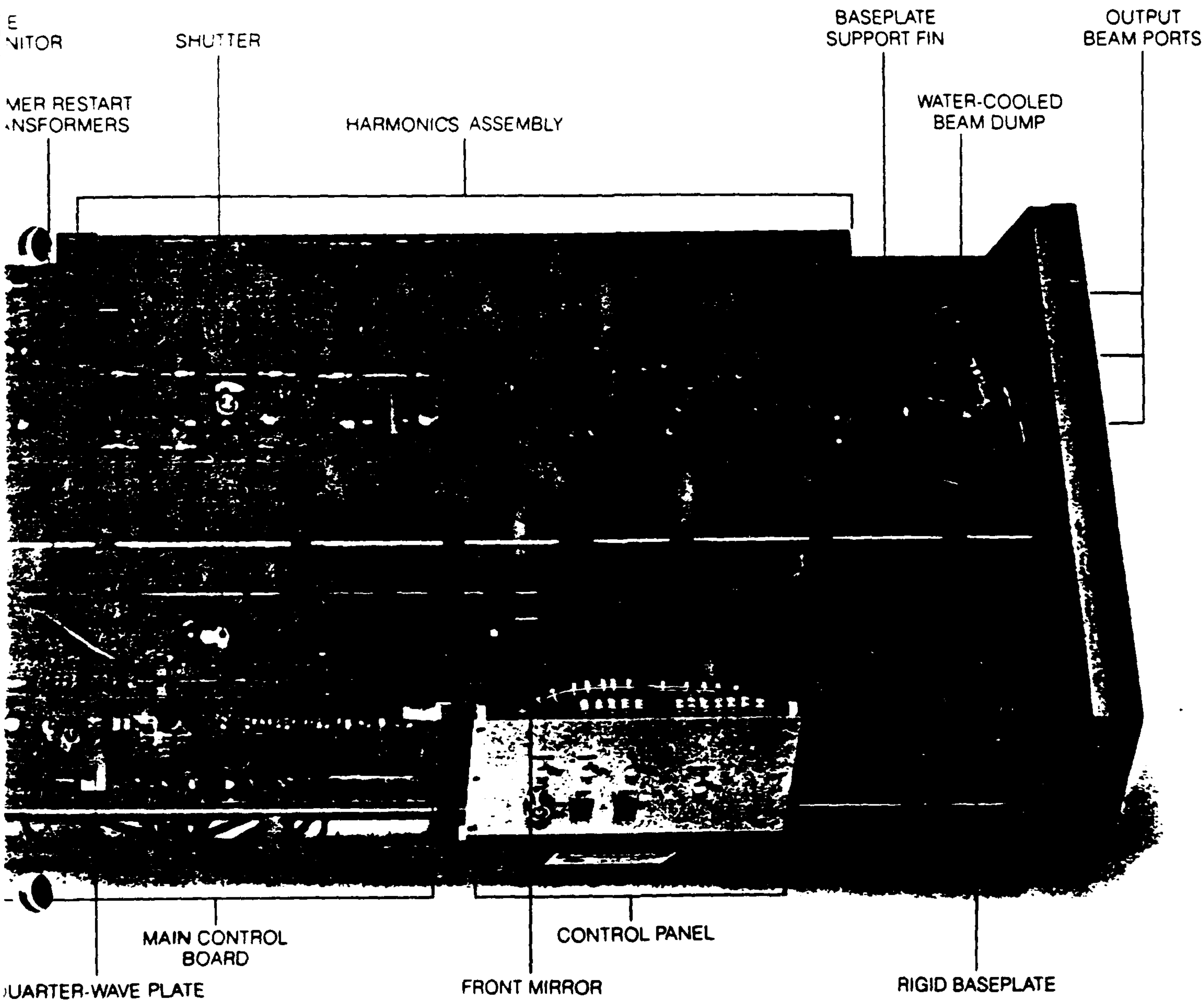
Multiple Beam Ports. Three output beam ports can accommodate any of the output wavelengths. Change from one wavelength to another in minutes.

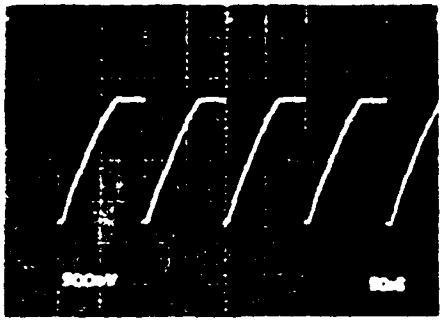
Variable Pulse Duration. Select the duration from 15 to 30 ns which suits your experiment.



Ease of service
Flashlamp Replacement. Pull off the connectors and replace the flashlamps quickly without water loss. No realignment is necessary.
He-Ne Alignment. Sometimes needed for complete cavity realignment. Both ends of the cavity are accessible once protective covers are removed.
Circuit Board Placement. The main control board is located right up front in the laser head for easy access. All timing adjustments are made on this board. Convenient test points are available for quick troubleshooting.

Safety
Electrical Interlocks. All covers are interlocked to protect against accidental exposure to high voltage or laser radiation.
Water Flow and Temperature Interlocks. Both the closed cycle and external water systems are interlocked against flow stoppage and excessive coolant temperature.
Remote Interlock. This connector permits easy integration to a laboratory warning system such as the LS30 Laser Safety and Interlock System.





High Voltage Power Supply. Both the oscillator and amplifier use high-efficiency inverter power supplies which have a switching rate of 12kHz and are barely audible. These supplies are current regulated to charge the storage capacitor at a near constant rate until the desired voltage is reached at which time the supplies switch to voltage regulation.

Both 600J/s and 1200J/s supplies are used. The near constant current charging cycle is shown above.

The 600J/s supply can charge the oscillator to 60J at 10pps. However only about 30J are normally used leaving a residual capacity for higher repetition rates. At 30J the maximum voltage is reduced to 1.5kV so the maximum average power delivered is 450W. Thus the storage capacitor will be fully charged up to about 15pps. Above this rate the stored energy decreases rapidly. The flashlamp joules meter on the service panel indicates the lower stored energy at high repetition rates.

Similarly, the 1200W supply for the amplifier can deliver 120J pulse at 10pps. At the typical 60J level there is enough reserve capacity to operate at full energy to 15pps. The 20pps mode uses double the normal power supply capacity and can operate at full stored energy to about 30pps.

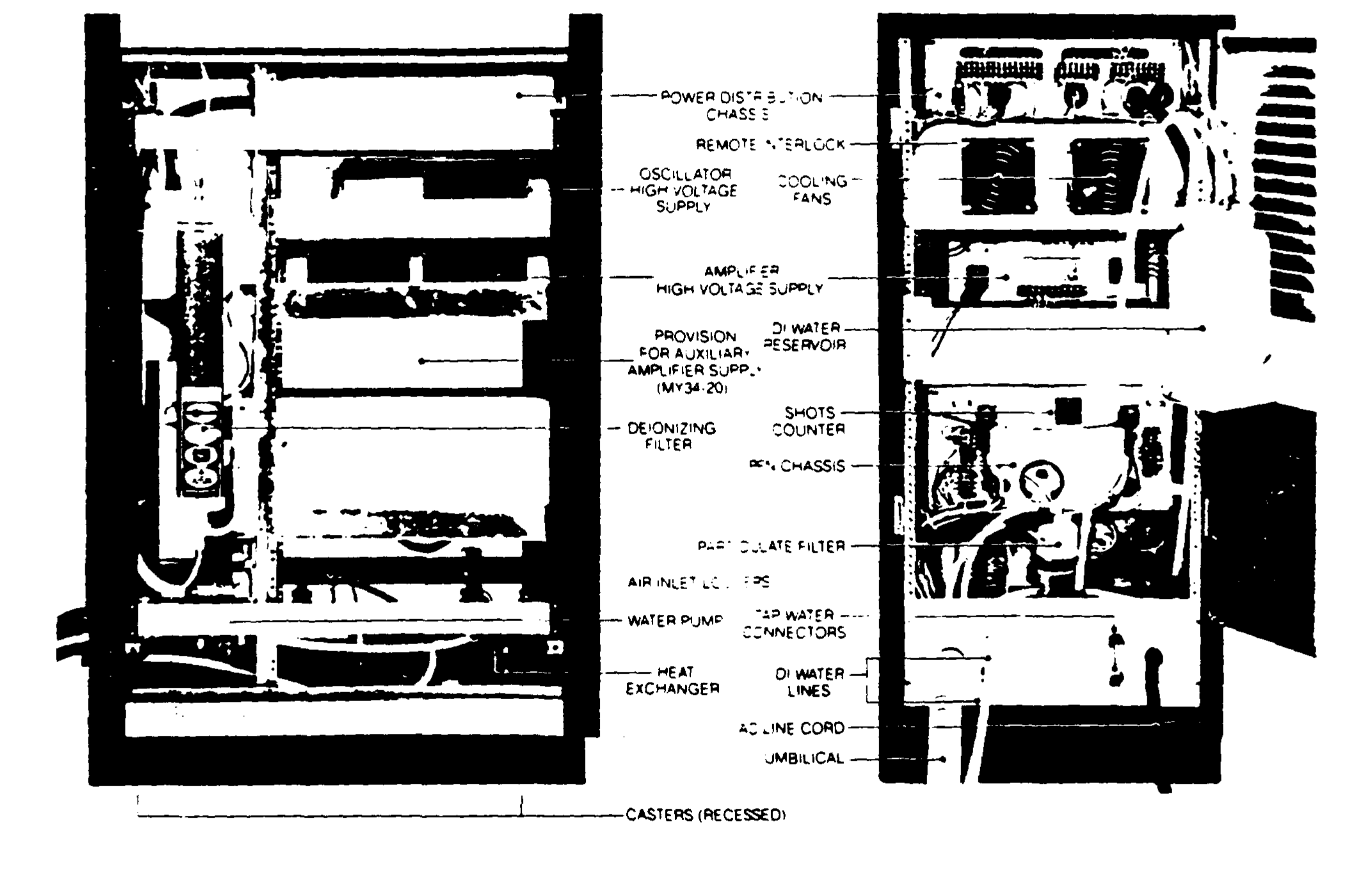
Power Distribution Chassis. All fusing, control relays and low voltage supplies are contained in this chassis.

PFN Chassis. Contains the pulse-forming networks for both oscillator and amplifier plus the associated simmer power supplies. A shots counter at the rear displays a running total of the number of pulses. The six-digit counter can thus display up to 10^6 pulses.

Closed Cycle Cooling System. A deionized water system is used to cool the laser heads and the beam dump. The system consists of a pump, 6 liter reservoir, deionizing cartridge, particulate filter and water-to-water heat exchanger. This system is filled with an alcohol-water mixture for shipment during cold seasons. Tap water is required at the rate of only 2 liters/minute.

Remote Interlock. This safety interlock requires a contact closure to operate the laser. A mating connector with jumper wire is included. The LS30 Laser Safety and Interlock System described on page 14 wires directly into this connector.

Umbilical. Approximately 40 wires are contained within the 4 meter flexible umbilical hose connecting the laser head to the power console. All wires are permanently attached at each end so the two units cannot be separated for shipping.



MY-E Intracavity Etalon. The solid fused silica etalon is mounted in an oven temperature controlled to 0.05 C. The assembly is mounted in the cavity between the polarizer and pump head. Following initial alignment no further adjustment is necessary. Bandwidth at the fundamental wavelength is reduced from 0.5cm⁻¹ to 0.05cm⁻¹. The insertion loss of 10% can usually be overcome by increasing the flashlamp energy. Note that the frequency bandwidths of the second, third and fourth harmonics are roughly 2, 3 and 4 times respectively those of the fundamental.

MY-SAM Single Axial Mode Accessory. With the MY-E Intracavity Etalon in place the bandwidth of 0.05cm⁻¹ corresponds to approximately 10 axial modes of the cavity. The temporal waveform exhibits the beats characteristic of multi-axial mode operation.

The MY-SAM further reduces the bandwidth by controlling the Q-switch voltage so only the highest gain mode crosses threshold. Over 90% of the pulses are single mode but not always the same mode. Any single mode pulse will have the near transform-limited bandwidth of approximately 50MHZ or 0.0017cm⁻¹ while the envelope of all such pulses is larger, approximately 0.01cm⁻¹.

In addition to reducing the laser bandwidth, the MY-SAM produces a smooth output pulse with no "beats." Pulse-to-pulse energy and peak power stability are improved as well. The energy loss to achieve single mode operation is approximately 20% including etalon insertion loss.

Harmonic Generator Systems. The MY-Series Nd:YAG lasers are efficient generators of all the common harmonics. The second (532nm) and third (355nm) harmonics are excellent pump sources for dye lasers and, as with the fundamental beam, are useful for mixing with the dye laser output to generate both ultraviolet and near-infrared wavelengths. The fourth harmonic (266nm) is neither an efficient nor reliable dye laser pump but it does have many applications as a powerful UV source.

MY-HA Harmonic Assembly. The basic housing for all the possible harmonic configurations. This sealed container protects all of the optical components from dust, just as the beam tubes protect the remainder of the system.

Harmonic Crystals. All are KDP or KD*P crystals 14mm square by 25mm long and housed in an oven assembly with AR-coated windows. All crystals are angle tuned via the external thumbwheel controls. Temperature control for long term stability becomes more critical for each succeeding harmonic. SHG is reasonably forgiving, THG is less so, and for FHG temperature control is essential for even short term operation.

MY532-2. Type II KD*P. The most efficient generator of 532nm. Rotation axis is vertical and output polarization horizontal. The residual 1064nm beam is elliptically polarized. Pulse energy specifications at 532nm are with Type II SHG.

MY532-1. Type I KD*P. Approximately 70% as efficient as Type II SHG but the residual 1064nm beam is linearly polarized vertically. Rotation axis is vertical and output polarization horizontal.

MY355. Type II KD*P. Rotation axis horizontal and output polarization vertical. Requires horizontal 532nm and vertical 1064nm input beam polarization. While Type I SHG provides the ideal polarization properties, Type II SHG results in higher output at 355nm. The pulse energy specifications at 355nm are with Type II SHG.

MY266. Type I KDP. The residual 1064nm beam is removed prior to FHG to eliminate heating of the crystal by the fundamental. KDP is then used rather than KD*P as with the other harmonics.

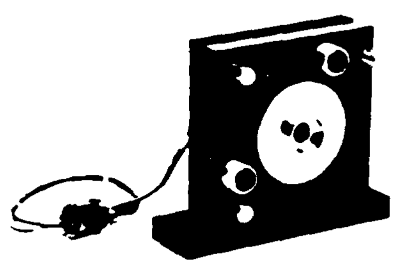
The FHG crystal absorbs some of the generated 266nm beam and self-heats to 90° phase-match where efficiency is a maximum. Any loss in power reduces the self-heating and crystal temperature and efficiency is lost. As a result the 266nm beam is relatively unstable but can remain stable for as long as one hour if carefully walked into 90° phase-match.

Beamsplitter Assemblies. All of the harmonics are separated from longer wavelengths by dichroic beamsplitters which reflect >99% of the desired harmonic and transmit >85% of the longer wavelength beams. Two beamsplitters are used in series to reduce the amount of unwanted radiation to less than 1-2%. Absorbing filters are available to further reduce the background radiation.

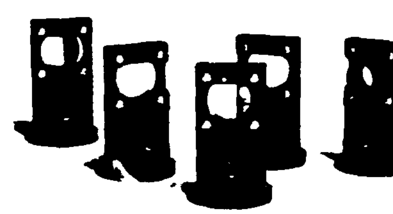
The beamsplitter assemblies include two dichroic mirrors mounted on removable stands plus an AR-coated output window for the harmonics assembly. The removable stands are designed as "chess pieces" with locating pins for rapid change of harmonic configuration.

MY532-VBS Variable Beam Splitter. Many applications require that the 532nm beam be used for two purposes, for example, to pump a dye laser and to provide the second beam in a two-beam experiment such as CARS. The MY532-VBS uses a polarizer and rotating waveplate to produce two parallel output beams whose relative intensities are externally adjustable over a 10:1 range.

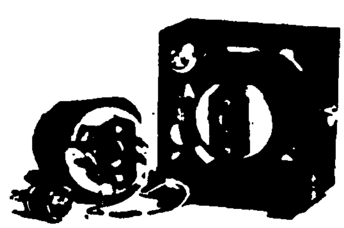
Intracavity Etalon



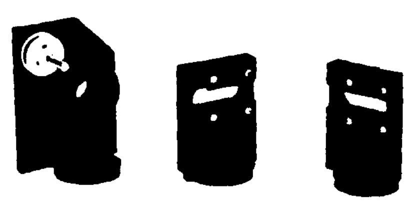
Beamsplitters



Harmonic Generators



Variable Beam Splitter



CONTROLS

Control Panel. Safety key switch controls main power. Pushbutton switches conveniently start and stop the laser. READY light indicates all interlocks are satisfied. ON light serves as emission warning indicator and satisfies the BRH requirement. SHUTTER OPEN light indicates beam is on; shutters are controlled by the remote pendant.

Service Panel. Recessed behind the service door.

Flashlamp Joules Controls. Potentiometers control the high voltage applied to the oscillator and amplifier pulse-forming networks. Panel meter indicates corresponding joules of stored energy.

Repetition Rate Controls. FIXED position is 10 or 20 pps depending on model. VARIABLE position enables the potentiometer above for 5-20 or 10-30 pps. EXT position enables the flashlamp trigger on rear panel. Q-switch can be driven either internally or externally when the flashlamps are controlled externally.

Q-Switch Controls. LONG position disables the Q-switch and gives a 100μs pulse useful for alignment. INT position drives the Q-switch from internal timing circuits. The Q-switch delay is adjusted on the main control card. EXT position enables the Q-switch trigger on the rear panel.

Q-Switch Voltage. Controls the hold-off voltage applied to the Pockels cell.

Rear Panel Connectors. Convenient control and input output lines.

Flashlamp Sync. Output pulse occurs approximately 170μs before the laser pulse. Jitter is less than ±25ns.

Q-Switch Sync. Output pulse occurs approximately 100ns before the laser pulse. Jitter is less than ±1ns.

Flashlamp Trigger. For external control of the laser over the range 5-20pps or 10-30pps depending on model. Lockout circuits prohibit operation outside these ranges.

Q-Switch Trigger. For external control of the Q-switch. A variable delay generator is required which is triggered by the flashlamp sync output or external trigger.

Remote Pendant. Convenient remote control box on a 4 meter cord which can be placed near the experiment.

Shutter Control. Lighted switch controls both shutters in the laser head. The shutters will close automatically if the external interlock on the power console is opened.

Q-Switch Control. NORMAL position enables control from the service panel. SINGLE SHOT position disables the Q-switch trigger in the FIXED rep rate mode. Depressing the pushbutton enables the Q-switch on the next pulse. This single shot mode is useful for aligning optics prior to an experiment.

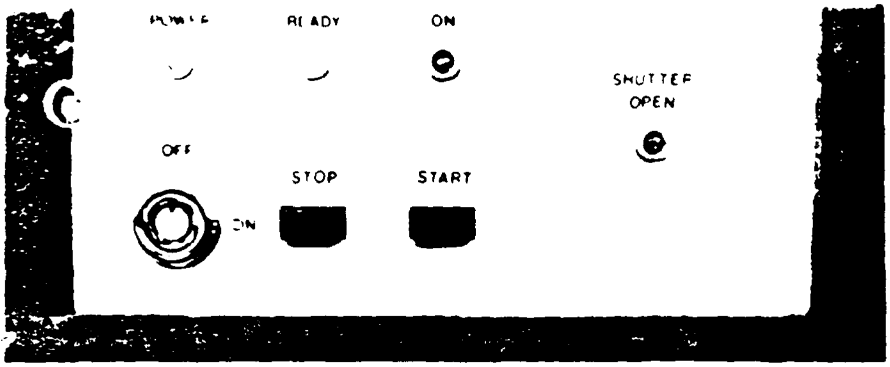
COMPONENTS

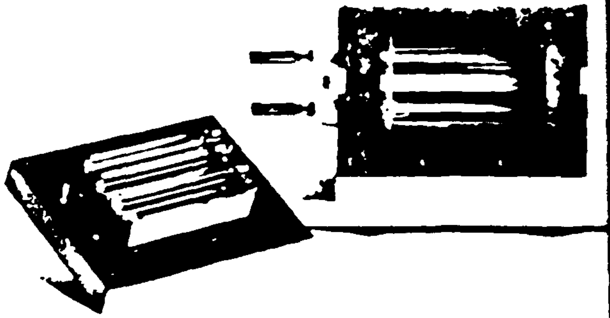
Pump Cavity. The pump cavity contains the Nd YAG rod and flashlamps in a gold-coated double elipse. Water from the closed cycle cooling system floods the cavity to cool the rod and flashlamps. A tube of UV-absorbing glass surrounds the laser rod to filter out short wavelength flashlamp energy which does not pump the laser transition. Flashlamps are removed by simply pulling them out. The top lamp is removed first to break the water seal and allow the water to drain back to the reservoir in the power console.

Q-Switch. The Q-Switch is a KD*P Pockels cell contained in an index matching fluid with AR coated windows for low loss. The avalanche transistor chain surrounds the cell for low inductance and high speed. The entire assembly is contained in a Faraday shield to suppress RFI. The Q-switch is virtually the only source of RFI in the system, but its low energy and shielded design keep RFI to a minimum.

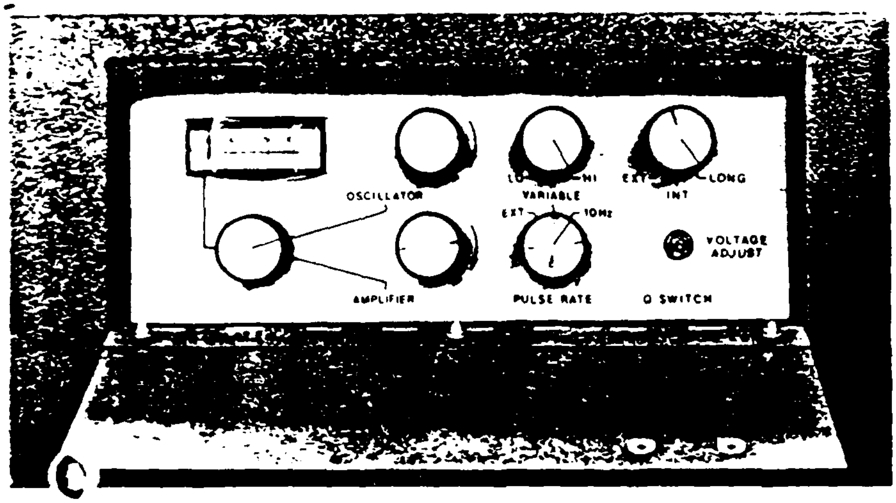
Flashlamp Simmer Supply. A 50-60 mA current is used to maintain an arc in the flashlamps at all times. This "keep-alive" current increases flashlamp life and reduces pulse-to-pulse energy fluctuations in the laser output. Should the main discharge extinguish the simmer, an automatic circuit restarts the current before the next pulse.

Q-switch Power Supply. This programmed supply applies high voltage to the Q-switch crystal only during a flashlamp pulse to reduce "time-at-voltage", the most important determinant of Q-switch lifetime.

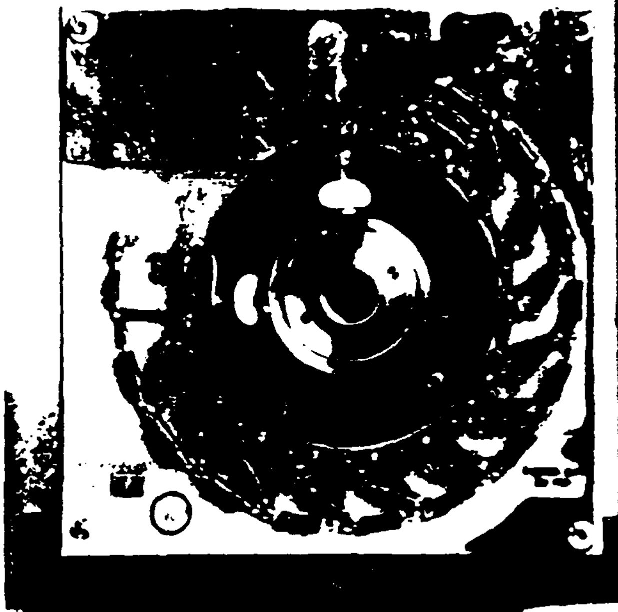




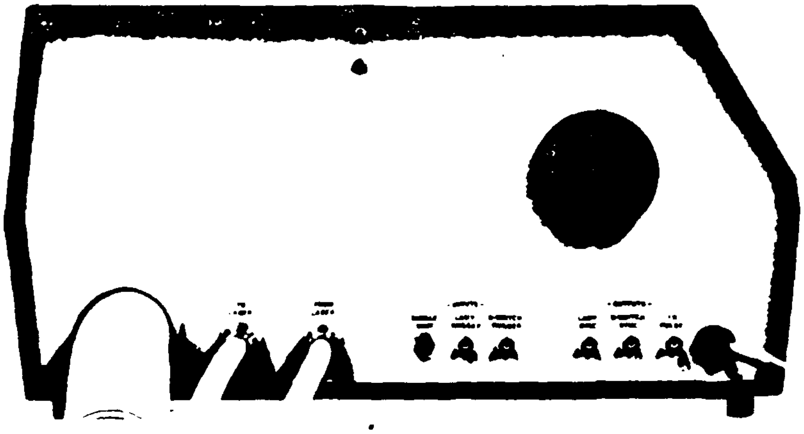
Service Panel



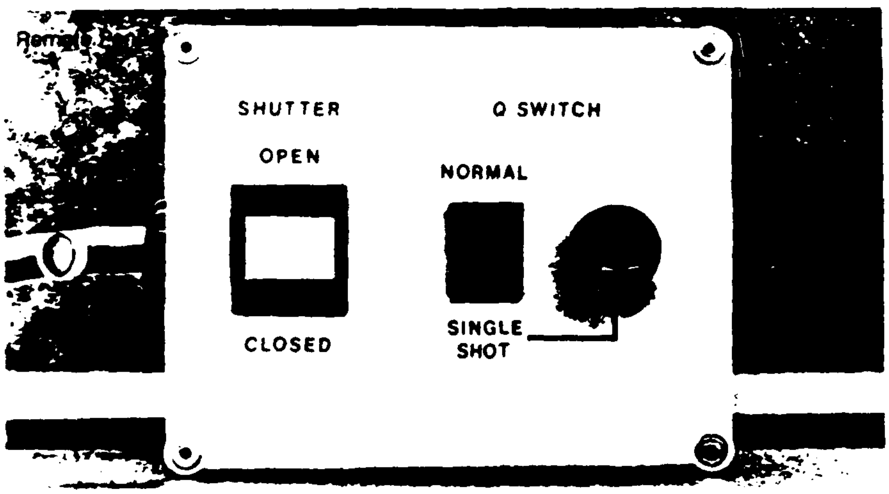
Q Switch



Rear Panel



Remote Pan



Auxiliary Accessories

P38-0101 Power Meter Head. Thermopile average power meter head with 1" diameter volume absorber. Scientech Model 38-0101. Can accept unexpanded MY Series beams up to 300mJ pulse at 532nm and 1064nm and up to 20mJ pulse at 266 and 355nm. For higher energies the PFR Fresnel Reflector is recommended.

P36-0001 Power Meter Head. Thermopile average power meter head with 1" diameter black surface absorber. Scientech Model 36-0001. Can accept unexpanded MY-Series beams up to 20mJ pulse at any wavelength. For higher energies the PFR Fresnel Reflector is recommended.

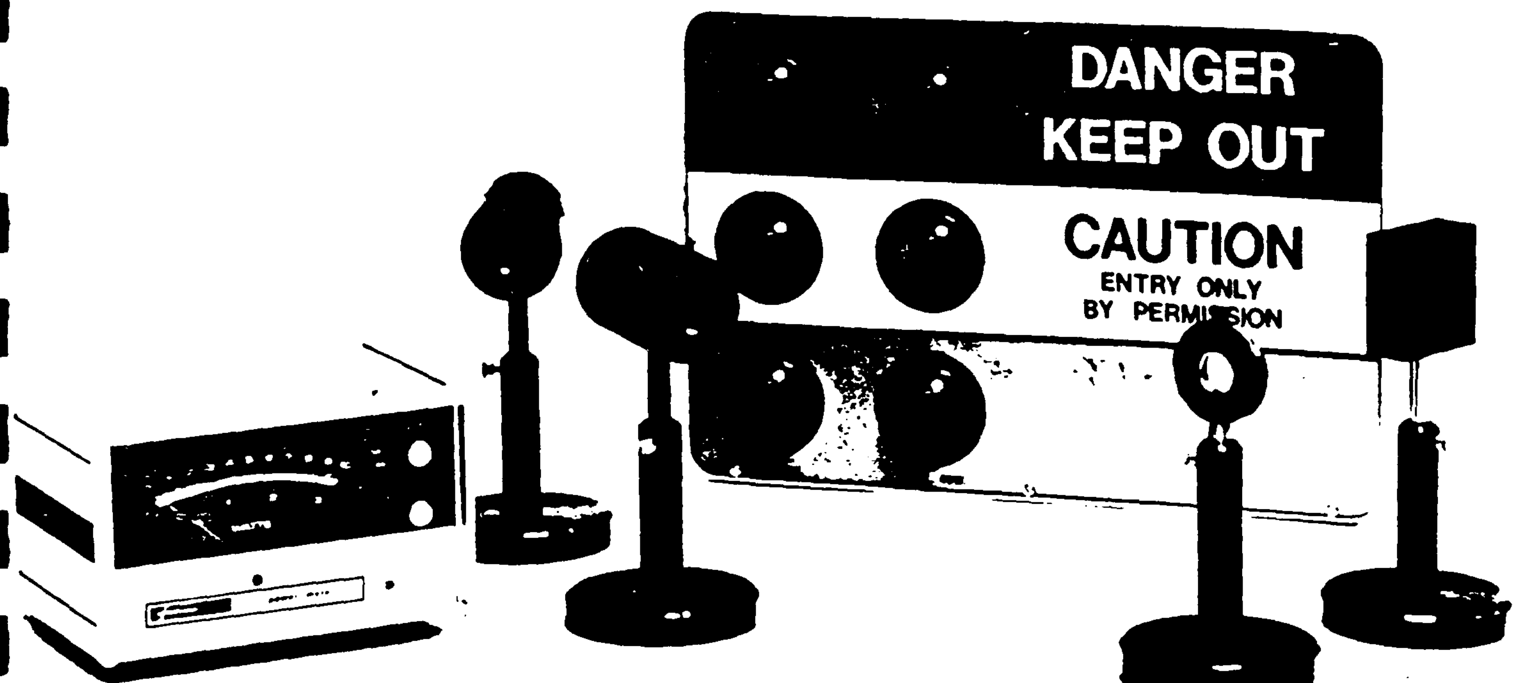
PS Adjustable Stand. For P38-0101 or P36-0001 power meter head.

P36-1002 Power Meter Display Module. Indicator unit for above heads with ranges from .001 to 10W full scale. Scientech Model 36-1002.

PFR Fresnel Reflector. Uncoated fused silica wedge 1" in diameter in adjustable mount. Fresnel reflection of about 4% attenuates high power beams to avoid damage to the power meter heads above. Accurate calibration factors are provided for each wavelength. BD40 Beam Dump is often used to stop transmitted beam.

BD40 Beam Dump. A [illegible] beam dump on adjustable stand [illegible] the beam's external to the laser without dangerous scatter.

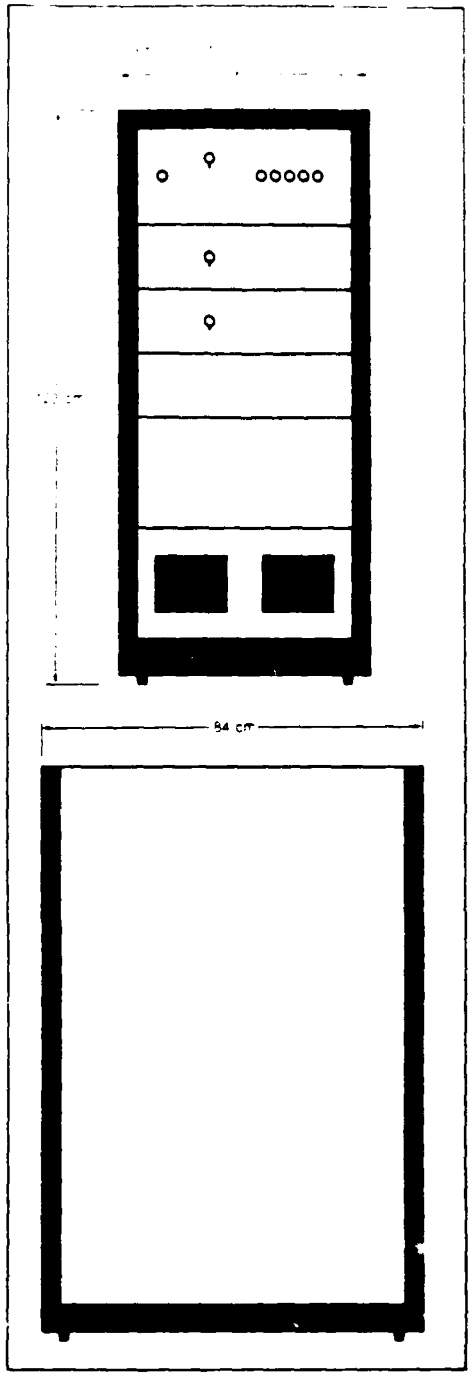
LS30 Laser Safety and Interlock System. A warning and interlock system which mounts on the outside of a laboratory door to indicate status of laser inside. (Green light for OFF, yellow for STANDBY and red for ON). Door interlock will close the beam shutters if the laboratory door is accidentally opened.

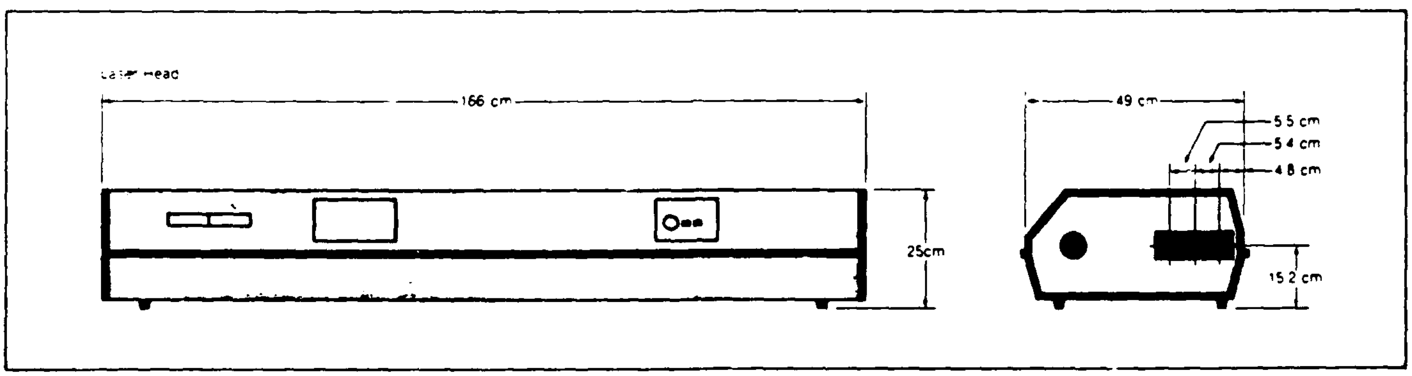


Specifications

		MY32	MY33	MY34	MY35	Units
Pulse Energy*	1064nm	200	400	700	1000	mJ
	532nm	75	150	250	350	mJ
	355nm	30	60	125	175	mJ
	266nm	15	30	50	75	mJ
Repetition Rate	MY3x-10	10pps fixed 5-20 variable single shot				
	MY3x-20	20pps fixed 10-30 variable single shot				
Beam Diameter (nominal)		8				mm
Beam Divergence (half angle)		0.3				mr
Beam Quality		Uniphase near-Gaussian maximum deviation from Gaussian at any point is 20°.				
Pulse Duration (nominal)		15ns standard 15-30ns variable				
Full Energy Bandwidth	without etalon	0.5				cm⁻¹
	with etalon	0.05				cm⁻¹
	with etalon and MY-SAM	0.01				cm⁻¹
Pulse-to-Pulse Energy Stability (90% of pulses)	1064nm	±2				%
	532nm	±4				%
	355nm	±6				%
	266nm	±8				%
Timing Jitter — from Q-switch trigger		±1				ns
from flashlamp trigger		±25				ns
Peak Power Stability — 1064nm (90% of pulses fixed time)		±5				%
Flashlamp Sync Output —	Voltage	6-8				V
	Impedance	50				Ω
	Risetime (max)	100				ns
	Duration	150				μs
Q-Switch Sync Output —	Voltage	6-8				V
	Impedance	50				Ω
	Risetime (max)	3				ns
	Duration	0.2				μs
Flashlamp Ext Trigger —	Voltage	5-12				V
	Impedance	50				Ω
	Risetime (max)	1000				ns
	Duration (min)	100				μs
Q-Switch Ext Trigger —	Voltage	5-12				V
	Impedance	50				Ω
	Risetime (max)	400				ns
	Duration (min)	1				μs
Electrical — Voltage		208 ±10, 3 phase, 4-pole, 5 wire "wye"				Volts
Current	MY3x-10	7	12	12	22	Amps
	MY3x-20	12	17	17	n.a.	Amps
Weight —	laser head	75				kg
	power console	80				kg
	shipping	200				kg

*at design repetition rate of 10 or 20 pps





Characteristics of all pulsed Nd:YAG lasers

There are a number of characteristics inherent to all pulsed and Q switched Nd YAG lasers. These characteristics often represent design constraints to the engineer

1. **Sensitive cavity.** Optical alignment of the cavity mirrors is extremely critical. Beam quality deteriorates with a misalignment of only 25 microradians, although pulse energy does not degrade so rapidly. Thus Invar or quartz stabilization and kinematic mounting techniques are essential for long term alignment stability
2. **Thermal lensing.** The YAG rod acts as a thin lens whose focal length varies inversely with the average power delivered to the rod by the flashlamps. (The effect of this lens is usually corrected by a corresponding negative curvature on a cavity mirror.) If the focal length deviates from the design value, performance deteriorates—first divergence, then pulse energy. As a result, pulse energy is usually specified at the design repetition rate

   There is strong motivation to minimize the effect of thermal lensing by minimizing the average power of the flashlamps. The benefit accrued is a broader range of repetition rates at near-optimum performance. Efficient cavities require less pump energy and are less sensitive to changes in repetition rate
3. **Q-switch lifetime.** Most lasers use a KD*P Pockels cell Q-switch which is kept at high voltage to hold off the laser pulse and switched to zero potential at the time of maximum gain. Such crystals have a limited lifetime at high voltage due to ion migration from one electrode into the crystal, reducing the transmission at 1064 nm.

   Heavily-used lasers are often built with a programmed Q-switch power supply which applies high voltage just prior to the laser pulse and then turns off the voltage after the pulse. While more expensive than standard power supplies, such programmed supplies increase the lifetime of an even more expensive and critical component —the Pockels cell itself
4. **Clean optics.** High energy pulsed lasers place a severe strain on optical components. The smallest amount of dirt on a mirror surface can result in coating damage. Skeptics (sometimes called realists) say that it is not "if" a mirror will be damaged, only "when." Clearly, great care must be taken to insure that optical components are clean when they are installed and kept clean during operation. Most lasers use a sealed beam line to protect the optics from dirt
5. **Waveform.** The temporal waveform in all Q-switched Nd YAG lasers depends critically on how many axial modes are lasing. If only one mode is active the pulse is very smooth and resembles the pulse of a nitrogen laser. However if more than one mode is active, beating between modes produces a modulation on the temporal profile. Several prominent peaks or "beats" appear which are separated by the oscillator round-trip transit time

   Typically 3-4 beats are present regardless of the resonator design. Short cavities produce shorter pulses than larger cavities, but the round-trip transit time is less, so the beats are closer together.

   The temporal stability of the beats depends on the jitter in the system, which is discussed below. With low jitter the temporal waveform can be extremely stable from pulse to pulse
6. **Jitter.** The jitter in a Q-switched Nd:YAG laser is usually referred to the Q-switch trigger. Once the Q-switch is "turned on," a delay of approximatey 100 ns occurs before the pulse appears. This delay is gain-dependant and decreases when the flashlamp energy is increased.

   The jitter in the timing of the output pulse depends on two factors, the switching speed of the Q-switch and the pulse-to-pulse gain reproducibility. At high switching speeds, essentially all axial modes of the laser are activated simultaneously and threshold is reached at almost the same time for each mode. Conversely, a slow Q-switch may permit several modes to cross threshold in sequence which increases the jitter.

   Gain reproducibility is important for low jitter because the delay from the Q-switch trigger to the laser output is gain-dependant. The most important factors affecting gain reproducibility are power supply regulation and flashlamp reproducibility. Supply regulation insures that the stored energy is constant from pulse to pulse while flashlamp reproducibility insures that a constant fraction of the stored energy is delivered to the Nd YAG rod. Small flashlamp bores and simmer currents improve flashlamp reproducibility
7. **Nd:YAG Rods.** There are a number of factors which influence the choice of rod quality and size in a pulsed Nd YAG laser. Of course the factors differ depending on whether the rod is used in an oscillator or amplifier stage

   The rod chosen for the oscillator should be of the finest optical quality available, with wavefront distortion of $\lambda/4$ at 633nm over the entire length. Rods of lesser quality will still give high output energy, but beam quality will be sacrificed. In a properly aligned laser, poor beam uniformity is almost always caused by poor rod quality

   The choice of an amplifier rod is slightly more complicated. Unlike the oscillator, an amplifier rod need not be of the highest quality. Wavefront distortion of $\lambda/2$ at 633nm will do very well. This reduced requirement is indeed fortunate, for larger rods of oscillator quality are difficult to produce and are very expensive.

   In an amplifier the rod size should be chosen to match the output of the oscillator. For a low power TEM_{00} oscillator, a first amplifier is almost always 6.3mm in diameter. However, for high energy oscillators such rods are inadequate—the gain is saturated immediately at a low level. If too large a rod is used, for example a 9.5mm diameter, the gain is never saturated and energy is left wasted in the rod. A reasonable compromise is 8.5mm diameter. The resulting stored energy can be extracted efficiently, and such rods are far less costly and have far better quality than 9.5mm rods

   If a second amplifier were used, a 9.5mm rod would be in order, but experience has shown that the poor optical quality of such rods severely reduces the harmonic efficiencies because the beam is highly distorted. As with the oscillator, pulse energy in the fundamental beam is not sacrificed, but "usable energy" is.

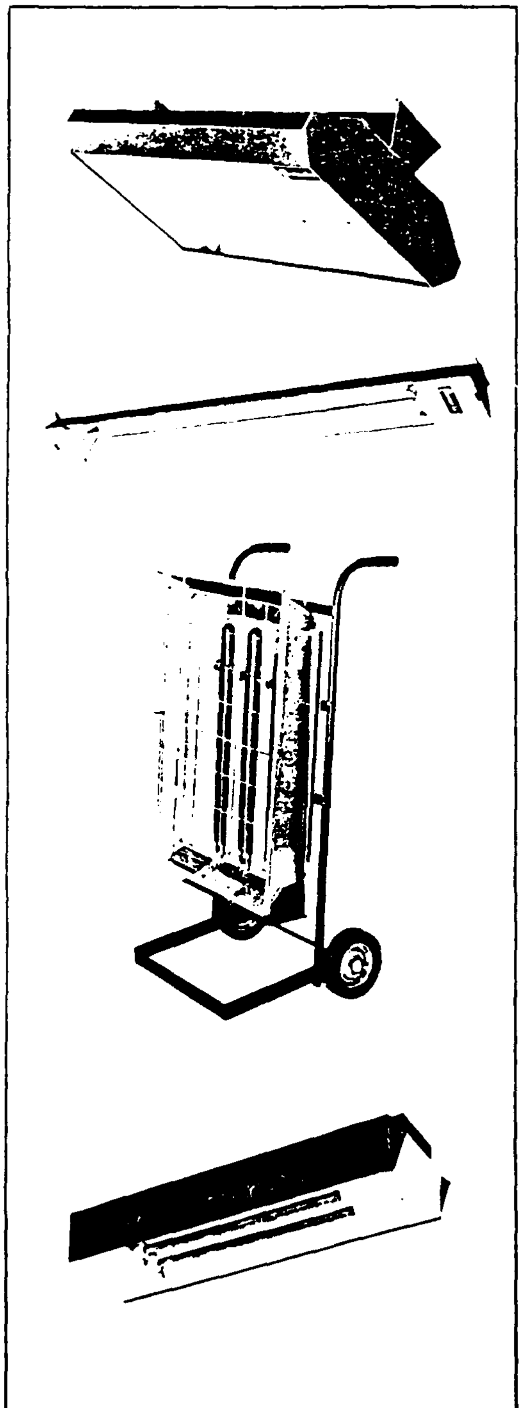
LASER PHOTONICS
12351 Research Parkway
Orlando, Florida 32826

Printed in USA 10M 5 79

Appendix C

PRODUCT INFORMATION
ON
INFRARED HEATERS

fostoria® SUN-MITE®



General Products Division

Electric

Heating Manual

Complete Guide To:

"TOTAL AREA" HEATING
SPOT HEATING
SNOW/ICE CONTROL

Price: $3.50

REFLECTORS AND BEAM PATTERNS

The method of transferring and directing the infrared energy to the work level is an important factor in the heating design and will greatly affect the efficiency of the heating system.

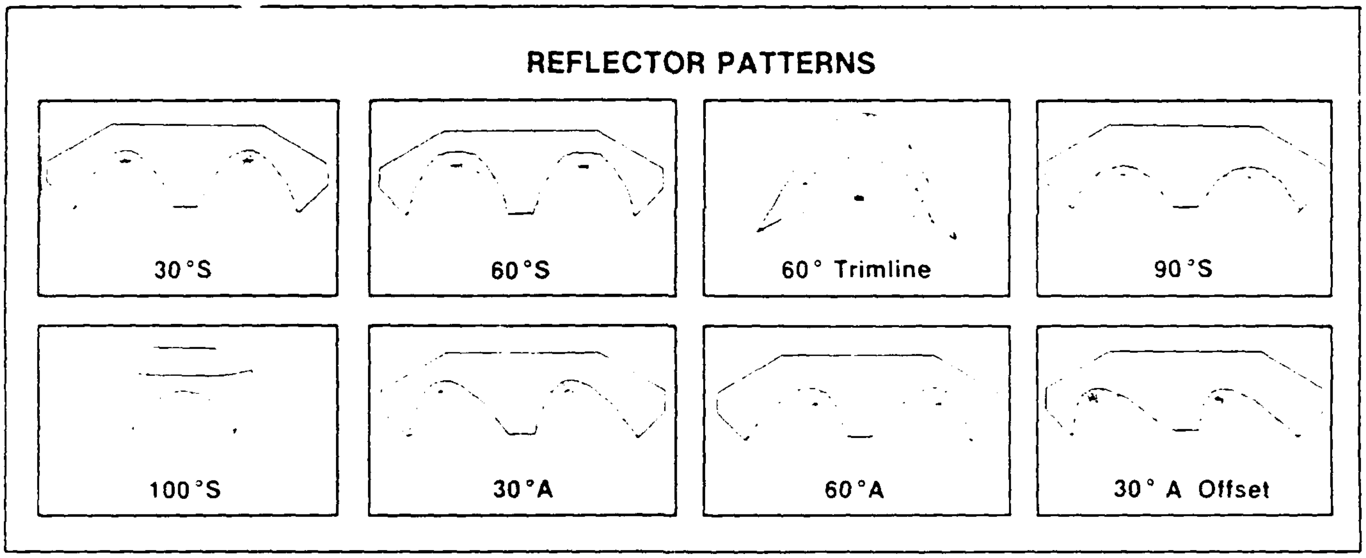
Reflectors are used to direct the radiant energy from the source to the work area. The higher the efficiency of the reflector, the more radiant energy will be transferred to the work level. The reflector efficiency is influenced by the reflector material, its shape and contour.

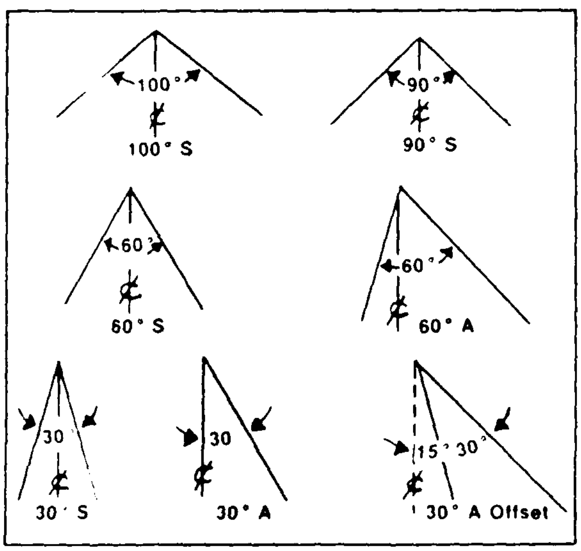
One method of measuring the efficiency of the material is by the emissivity factor. Emissivity is defined as the ratio of the amount of energy given off by radiation from a perfect black body; and is equal to the rate that material will absorb energy. The lower the emissivity number the less the material will absorb; hence the better the reflectivity of the material.

Few materials can be considered for use as reflectors in comfort heating equipment. They must have high reflectivity of infrared energy; resist corrosion, heat, moisture; and be easily cleaned.

Aluminum is a common reflector material and must be anodized to provide suitable reflectivity and withstand the heat levels present in an infrared heater. Gold anodized aluminum is best suited as a reflector material when the combined factors of cost, workability and weight are considered. Dirt will accumulate ON the surface and not IN the chemical composition with the gold. Within the infrared energy portion of the spectrum, clear anodized aluminum reflectors achieve 89 percent reflectivity. **Gold anodized** aluminum reflectors achieve 92 percent reflectivity. The most highly efficient reflector readily available is a specular **gold plated** material, which is rarely used due to the prohibitive cost of gold. Fostoria uses **gold anodized** aluminum for reflectors and end caps in their electric infrared heating equipment to provide the highest economical reflectivity and durability.

The beam pattern created by the reflector must be emphasized in the heating design. First the reflector must create a straight vertical line from the heat source to the work area. This is the pattern centerline. Secondly, the reflector will converge or concentrate the energy into a choice of wide, medium or narrow patterns. In the electric infrared comfort heat industry, reflectors are also designed for asymmetric, symmetric and offset patterns as shown below.





A specific heat pattern can easily be identified by the number of bends in the reflector in addition to the angle of the reflector.

Pattern	No of Bends	Pattern	No of Bends	Pattern	No of Bends
30°A	9	60°A	[illegible]	90°S	5
30°S	9	60°S	8	100°S	5
30°A Offset	8	60°S (Trimline)	Molded Curve		

HEAT ELEMENT AND FIXTURE SELECTION CHART

This Chart is designed to aid in proper selection and usage of heat elements in the corresponding heat fixtures.

KEY:		FIXTURE MOUNTING HGT.	
1	Indoor	A	8′ — 10′
2	Outdoor	B	11′ — 12′
·	Not Recommended	C	13′ — 15′
X	Will not physically fit the fixture	D	16′ — 18′
		E	19′ — 30′

FIXTURE	CLEAR QUARTZ LAMPS	QUARTZ TUBES	STRAIGHT METAL* RODS	U-SHAPE METAL RODS
CH-100	1A	X	1A	X
CH-200	1A or 1B	1A or 1B	1A	X
CH-300	1B	1A or 1B	1A	X
CH-400	1B	1A or 1B	1A	X
222-30-TH	1C, D, E or 2A	·	·	X
342-30-TH	1C, D, E or 2A	·	·	X
462-30-TH	1C, D, E or 2A	·	·	X
222-A30-TH	1C, D, E or 2A	·	·	X
342-A30-TH	1C, D, E or 2A	·	·	X
462-A30-TH	1C, D, E or 2A	·	·	X
222-A31-TH	1C, D, E or 2A	·	·	X
342-A31-TH	1C, D, E or 2A	·	·	X
462-A31-TH	1C, D, E or 2A	·	·	X
222-60-TH	1B, C or D	·	·	X
342-60-TH	1C or 1D	·	·	X

FIXTURE	CLEAR QUARTZ LAMPS	QUARTZ TUBES	STRAIGHT METAL* RODS	U-SHAPE METAL RODS
462-60-TH	1C or 1D	1B	·	X
222-A60-TH	1B, C or D	·	·	X
342-A60-TH	1C or 1D	·	·	X
462-A60-TH	1C or 1D	1B	·	X
222-90-TH	1B or 1C	1A or 1B	1A	X
342-90-TH	1B or 1C	1A or 1B	1A	X
462-90-TH	1C	1A or 1B	1A	X
CH-46/CH-46C	X	**1A or 1B	X	X
CH-57/CH-57C	X	**1A, B	X	X
OVERHEAD HEAVY DUTY				
2 KW (120V-277V)	X	X	X	1A
4.5 KW (208V-480V)	X	X	X	1A or 1B
6 KW (208V-480V)	X	X	X	1A, B or C
13.5 KW (208V-480V)	X	X	X	1B, C or D
27 KW (208V-480V)	X	X	X	1C or 1D

*Straight metal rods recommended **only** for unique cases where an extreme high vibration exists. In ALL other cases, a Quartz Tube is a BETTER CHOICE. **Special Quartz Tubes are designed for the Trimline only.

PORTABLE UNITS***

	NON-PROTECTED		SEMI-PROTECTED	
	Below 35°F	Above 35°F	Below 35°F	Above 35°F
Fixture	Area Size-Sq. Ft.		Area Size-Sq. Ft.	
2.0KW	25	36	40	50
4.5KW	64	75	90	125
6.0 KW	85	100	120	150
13.5 KW	192	225	270	375

***as a general rule, it is better to use two smaller units in place of one larger unit to achieve a more uniform coverage

HEATING ELEMENTS

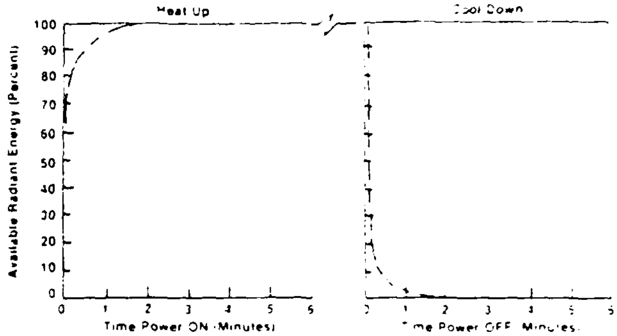
CLEAR QUARTZ LAMPS

- ⅜" diameter clear quartz envelope
- Coiled tungsten filament positioned on tantalum spacers; sealed porcelain end caps; inert gas filled
- Color temperature emitted: approximately 4100°F — high brightness
- 96% radiant efficiency****
- Fastest heat-up and cool-down (Refer to Graph A)
- Moisture resistance: highest
- Mechanical ruggedness: average
- Available wattages: 500-3650; available voltages: 120-480
- Highest cost per watt (average)
- Life expectancy: 5000 hours with a 4-year pro-rated warranty

  APPLICATIONS: All snow/ice control; all outdoor and most indoor applications; high bay applications; indoor area highly exposed to cold air infiltration.

  MOUNTING HEIGHTS: 12' and ABOVE (Indoor), 10' and BELOW (Outdoor)

Graph A



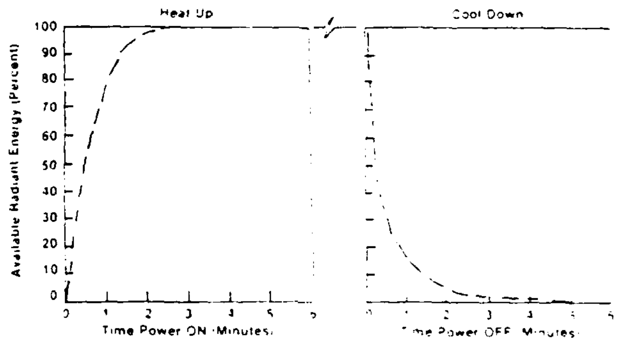
QUARTZ TUBES

- ⅜, ⅝, ⅞" diameter quartz envelope
- Nickel-chrcme alloy coiled element with porcelain end caps and pigtail termination
- Color temperature emitted: approximately 1800°F — bright orange glow
- Approximately 60% radiant efficiency****
- Fast heat-up and cool-down (Refer to Graph B)
- Moisture resistance: high
- Mechanical ruggedness: good
- Available wattages: 450-3200; available voltages: 120-480
- Lowest cost per watt (average)
- Life expectancy: 5000 hours with 4-year pro-rated warranty.

  APPLICATIONS: Indoor spot heating and total area heating; Preferred when controlling application with percentage input timer

  MOUNTING HEIGHTS: 12' and UNDER

Graph B



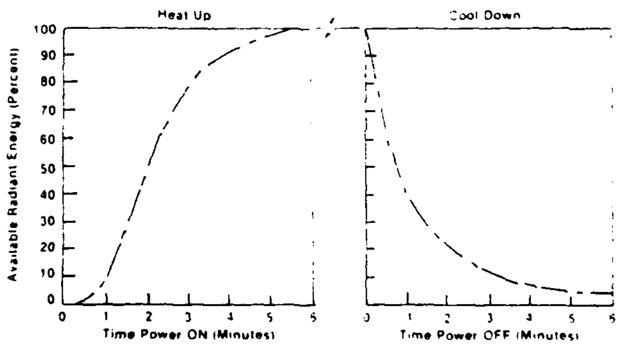
STRAIGHT or U-SHAPED RADIANT METAL RODS

- .430" diameter inconel metal sheath envelope
- Nickel-chrome alloy coiled element imbedded in magnesium-oxide insulating powder
- Color temperature emitted: approximately 1600°F — dull red glow
- Approximately 50% radiant efficiency****
- Slowest heat-up and cool-down (Refer to Graph C)
- Moisture resistance: lowest
- Mechanical ruggedness: highest
- Available wattages: **Straight rod** - 300 - 2200; **U-Shaped rod** - 1800 - 4500
- Available voltages: **Straight rod** - 120 - 240; **U-Shaped rod** - 120 - 480
- High cost per watt (average)
- Life expectancy: 5000 hours with 4-year pro-rated warranty

  APPLICATIONS: **Straight Rod** - Indoor spot heating; total area heating; desirable in unique cases when extreme high vibration condition exists.

  APPLICATIONS: **U-Shaped Rod** - Indoor spot heating; total area heating; (these rods are used in the heavy duty series.)

Graph C



FOR SUGGESTED MOUNTING HEIGHTS, SEE PAGE 11.

****All electric heat is 100% efficient when compared to other fuel energies. RADIANT EFFICIENCY refers to the amount of INFRARED radiation given off, i.e., a quartz lamp carrying a design load of 1600 watts will emit .96 × 1600 = 1536 watts as infrared energy and 64 watts in convection heat

EFFECTS of UNDER and OVER-VOLTAGE on HEAT ELEMENTS

Operating any of the three heating elements **below** their design voltage has the following effects

a) Lowers the delivered wattage/heat output (see Graph D)

b) Lowers the color temperature, therefore lowering the infrared efficiency (See Graph E)

c) Increases the life of the heating elements

Operating any of the heating elements **above** their design voltage will have the opposite or reverse effect of those shown above.

Some heating elements are intentionally used at under voltage design to increase the life of the elements. CAUTION should be used to insure that over-voltages do not exist in excess of 2 percent.

Reducing the voltage by "X" percent does **not** reduce the wattage by the **same** "X" percent. Refer to Graph D to determine proper voltage/wattage relationship. Graph D shows the relationship of wattage vs voltage for **under-voltage** applications.

NOTE: The wattage reduction also varies with the type of heating element.

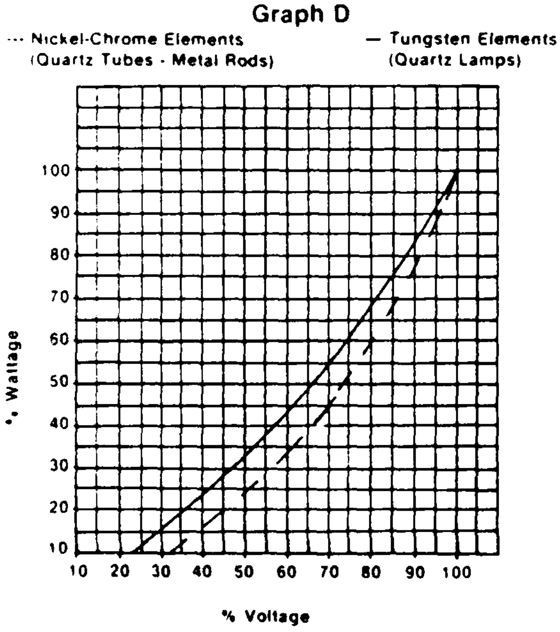
Usage of Graph D

1) Select proper graph (depending on the type of heat element being de-rated)
2) Divide "voltage applied" by "element design voltage" to determine "percentage of applied voltage"
3) Find this percentage on the horizontal axis of the graph. Move vertically from that point until it intersects with plotted line. Move directly left at the point of intersection to corresponding "percent of wattage" as shown on vertical axis.

Example 1 — Graph "D" (Quartz Lamp)
A #GF-1624H quartz lamp is designed to have an output of 1600 watts at 240V. If operated at 208V (86.67% of design voltage) it will have an output of (78% × 1600) = 1248 watts.

If operated at 120 volts (50% of design voltage) it will have an output of (33⅓% × 1600) = 533 watts.

Graph D



Example 2 — Graph "D" (Metal Rod/Quartz Tube)
A #G71-3489 quartz tube is designed to have an output of 1600 watts at 240V. If operated at 208V (86.67% of design voltage) it will have an output of (71% × 1600) = 1136 watts

If operated at 120 volts (50.0% of design voltage) it will have an output of (25% × 1600) = 400 watts

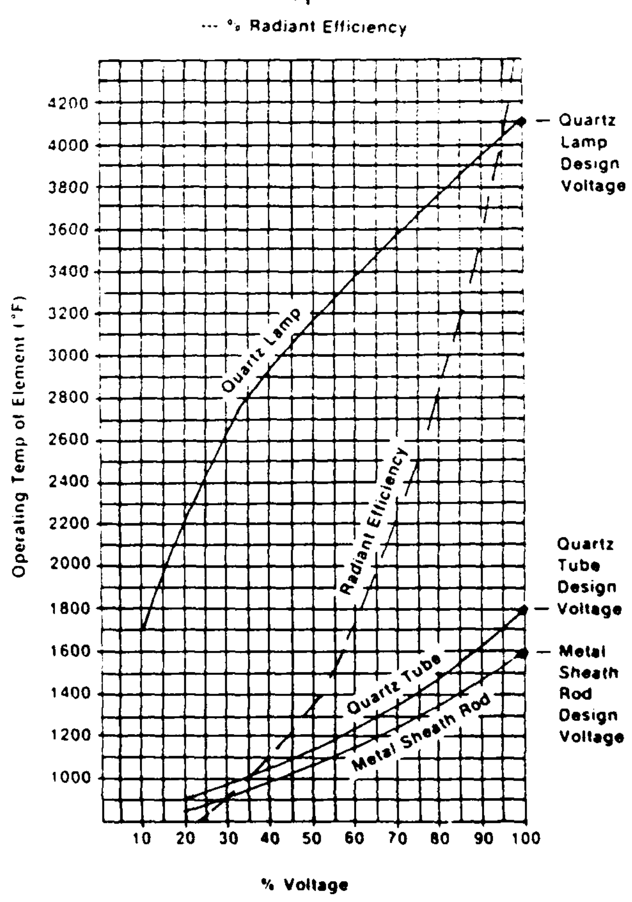
To determine the effects of using less than design voltage on either of the three heat sources, Graph E should be consulted.

For instance, if you wish to determine the effects of using a quartz lamp at half voltage, you can determine the resultant wattage (33⅓%) from Graph D, you can further determine the operating temperature, or color temperature, (3150°F) of the element from Graph E, and the resultant radiant efficiency (85%) from Graph E.

By decreasing the voltage to 50 percent, there is not only a ⅔ reduction in actual wattage, but an additional decrease in RADIANT EFFICIENCY of 11 percent (96%-85%). Therefore the RADIANT output is now only 453 watts (85% of 533 watts) for a 1600 watt lamp operated at ½ voltage. This can direct you as to whether or not the half voltage operation will be a good choice for your specific application.

NOTE: It is seldom, but occasionally, recommended to use heat sources at a lower than design voltage.

Graph E



INFRARED FIXTURE EQUIPMENT

GENERAL DISTRIBUTION — MOUNT HORIZONTAL

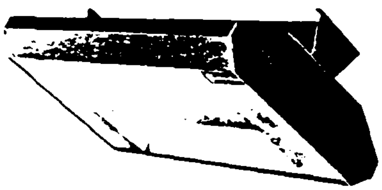
- 100° Symmetrical heat pattern
- Corrosion resistant aluminized steel housing
- .040 **GOLD** anodized aluminum reflector
- Heat Source — Refer to selection chart. Page 7
- Accepts one or two elements (not three)
- Four Models:

Models	Lgth.	Watts	Volts
1) CH-100	1'	300-1000	120
2) CH-200	2'	1000-3200	120. 208. 240. 277
3) CH-300	3'	1200-5000	208. 240. 277. 480
4) CH-400	4'	1200-6000	208. 240. 277. 480

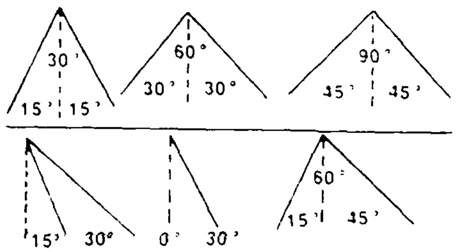
GENERAL USES/LIMITATIONS:
UL Listed for indoor and semi-protected outdoor areas.
USE AT MOUNTING HEIGHTS OF 12' OR LOWER.
Total Area Heat. Spot Heat.

REFER TO SPECIFICATION SHEET 70-605 FOR FURTHER DETAILS

MULTI-MOUNT — MOUNT HORIZONTAL



- 30°, 60°, 90° Symmetrical and 30°, 30° Offset, 60° Asymmetrical heat patterns available.
- Corrosion resistant aluminized steel housing.
- Double reflector for maximum heat pattern control.
- *.040 **GOLD** anodized aluminum reflectors*
- Heat source — Refer to selection chart, Page 7
- Two elements per fixture required
- Three lengths available:



	Lgth.	Watts	Volts
222 Series	2'	2000-3200	120-277
342 Series	3'	2400-5000	208-480
462 Series	4'	2400-7300	208-480

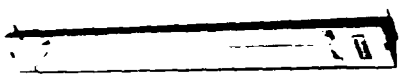
GENERAL USES/LIMITATIONS:
UL Listed for indoor and totally exposed outdoor areas.
Total area heat; Snow/Ice Control; Spot Heat

MOUNTING HEIGHTS

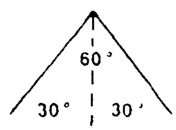
A30°, 30°, A31°	-14'-30'
A60°, 60°	-12'-18'
90°	- 8'-12' (indoor mtg)
A30°	- 8'-12' (outdoor mtg)

REFER TO SPECIFICATION SHEET 70-320 FOR FURTHER DETAILS

TRIMLINE SERIES — MOUNT HORIZONTAL



- 60° Symmetrical heat pattern
- Corrosion resistant aluminized steel housing
- .040 **GOLD** anodized aluminum reflector
- Brown hi-temperature baked on enamel
- Compact design
- Single heat source — Quartz tube with stud termination — refer to selection chart, Page 7
- Single end wiring
- Two lengths available



	Lgth.	Watts	Volts
CH-46	46"	1500 or 2000	120 or 240
CH-57	57"	3000	240 or 480
*CH-46C	46"	1500	120
*CH-57C	57"	3000	240

GENERAL USES/LIMITATIONS:
UL Listed for indoor and Semi-protected outdoor areas.
Spot heat

MOUNTING HEIGHTS

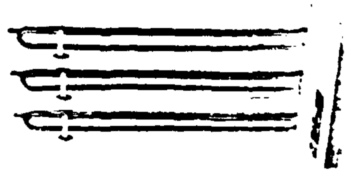
CH-46 and CH-46C	7'-9'
CH-57 and CH-57C	8'-10'

**Heating element included with heater*

REFER TO SPECIFICATION SHEET 70-366 FOR FURTHER DETAILS

INFRARED FIXTURE EQUIPMENT (CONT'D.)

HEAVY DUTY METAL SHEATH OVERHEAD



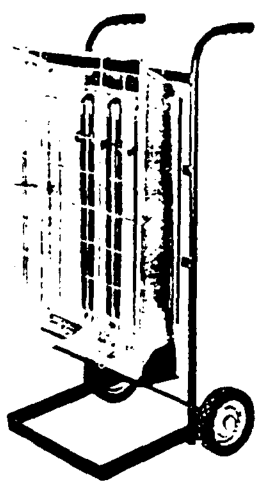
- 60° symmetrical heat pattern
- **GOLD** anodized aluminum housing
- Extruded aluminum reflector
- Rugged U-shaped metal sheath elements (included in fixture)
- Available in 5 sizes

KW	MOUNTING HEIGHT	PHASE	VOLTS
2.0	8'-10'	1	120-550
4.5	8'-12'	1	208-550
6.0	10'-14'	1 or 3	208-550
13.5	12'-16'	1 or 3	208-550
27.0	15'-20'	1 or 3	208-550

GENERAL USES/LIMITATIONS:
UL listed for indoor use
Total area heat
Spot heat.

REFER TO SPECIFICATION SHEETS 70-360, 70-361 FOR FURTHER DETAILS

HEAVY DUTY METAL SHEATH — PORTABLE



- 60° symmetrical heat pattern
- **GOLD** anodized aluminum housing
- Extruded aluminum reflector
- Rugged U-shaped metal sheath elements (included in fixture)
- Safety wireguard — standard
- Stand or hand cart standard with all units.
- Available in 5 sizes

KW	PHASE	VOLTS
1.8	1	120
2.0	1	208-550
4.5	1	208-550

2.0 and 4.5 KW have double wall housing for safer outer housing Wireguard extends over top for additional safety

KW	PHASE	VOLTS
6.0	1 or 3	208-550
13.5	1 or 3	208-550

6.0 and 13.5 KW have double top and back baffles for improved operator safety.

KW	PHASE	VOLTS
27.0	1 or 3	208-550

GENERAL USES/LIMITATIONS:
Spot heating — as a general rule, it is better to use two smaller units in place of one larger unit to achieve a more uniform coverage.

REFER TO SPECIFICATION SHEETS 70-363, 70-364 FOR FURTHER DETAILS

NOTE: *For complete information on exact heat pattern coverage, refer to specification sheets 70-601 and 70-602.*

SNOW AND ICE CONTROL

Principles:

1) **ALWAYS** use clear quartz lamps as proper element selection. **NEVER** use any other element.

2) **ALWAYS** use the Mul-T-Mount series. The Mul-T-Mount units are UL approved for both semi-exposed and completely exposed areas.

3) For BEST results use the 30° symmetric or asymmetric units (30, A30, A31). SATISFACTORY results can be obtained when using 60° symmetric or 60° asymmetric patterns in semi-protected or shielded areas. If 60° heat pattern is required for exposed areas, consult factory for watt density. **NEVER** use 90° pattern for snow and ice control.

4) Table B shows watt densities needed when units are mounted at 8' - 10'. For best results strive for this 8' - 10' level. Consult factory for densities required when mounting above 10'. **NEVER** mount above 14'.

5) Strive for blanket coverage.

Snow Control Factors

To determine the watt density of infrared required for any area, see Table 4 (located at the back of the manual) to obtain outside design temperature (I) and annual snowfall (II). From Table A, obtain the value for each factor, and add Factor I and Factor II together. Refer to Table B to obtain watt density based on the **total** value.

Table A

Factor I		Factor II	
Outside Design Temp. °F	**Value**	**Annual Snowfall**	**Value**
−20° to −60°	4	80" to 115"	4
−10° to −19°	3	50" to 79"	3
0° to −9°	2	20" to 49"	2
+19° to +1°	1	10" to 19"	1
+40° to +18°	0	0" to 9"	0

Table B

	Watt Densities per Square Foot		
Total Value	***Exposed**	***Semi-Protected**	***Protected**
8	200	185	160
7	175	160	145
6	125	110	100
5	110	100	90
4	100	90	85
3	95	80	75
2	90	70	65

*Exposed = Totally open area
*Semi-Protected = One side closed plus roof or overhang
*Protected = Three sides closed plus roof or overhang

Example: Albany, New York has an outside design temperature of −6° or a Factor I value of 2. The yearly mean snowfall is 65.7 inches or a Factor II value of 3. The total value is 5; therefore the watt density needed for an exposed area is 110 watts per square foot.

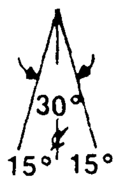
fostoria ® **ELECTRIC INFRARED**

REFLECTOR AND HEAT DISTRIBUTION PATTERNS

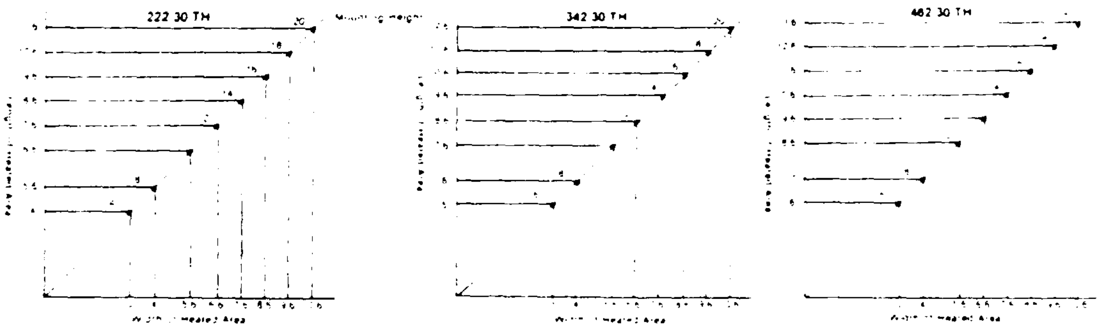
Table 5

The graphs shown can be used in conjunction with other material pertaining to Electric Infrared heating and snow melting to aid in the selection of proper fixtures for the application being considered.

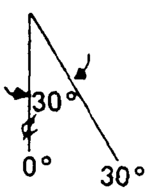
MUL-T-MOUNT — NARROW BEAM (30°S)



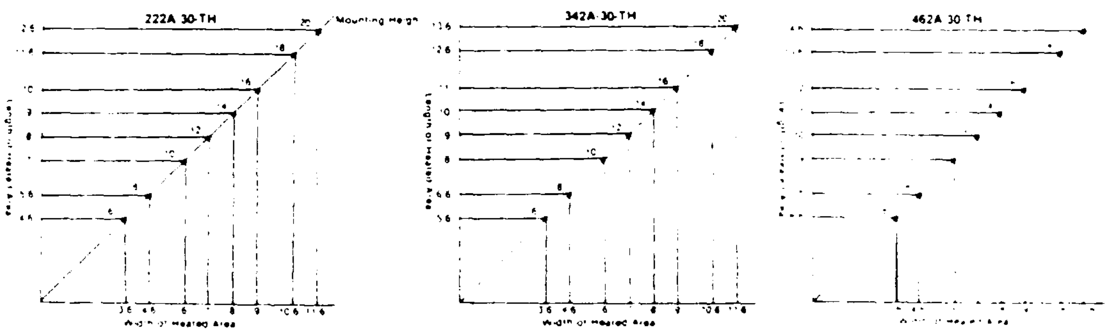
30° SYMMETRIC — Narrowest beam fixture available. Total Area and spot heating ideal for snow melting. Recommended for 14 to 30 mounting heights



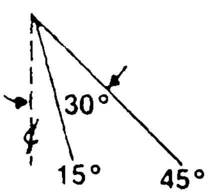
MUL-T-MOUNT — NARROW BEAM (30°A)



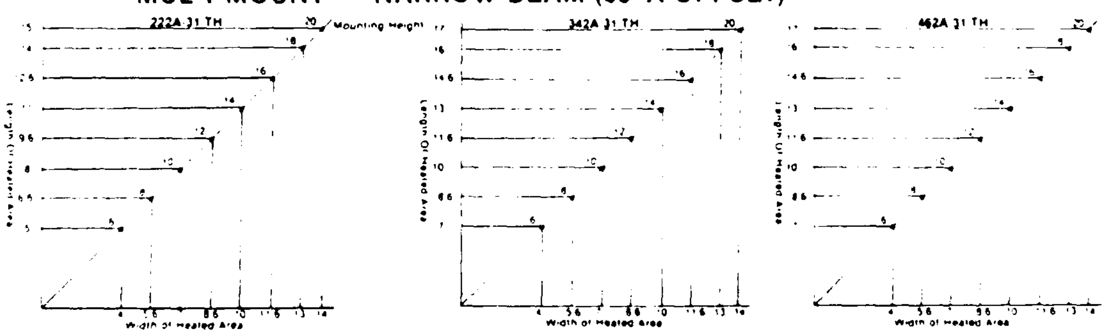
30° ASYMMETRIC — 0° to 30° perimeter heating snow melting close to buildings. Recommended for 14 to 30 mounting heights



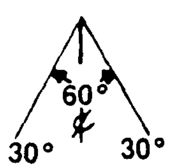
MUL-T-MOUNT — NARROW BEAM (30°A OFFSET)



30° ASYMMETRIC — 15° to 45° perimeter heating ideal for snow melting at a distance from buildings. Recommended for 14 to 30 mounting heights



MUL-T-MOUNT — MEDIUM BEAM (60°S)



60° SYMMETRIC — Total Area and spot heating. Recommended for 12 to 18 mounting heights

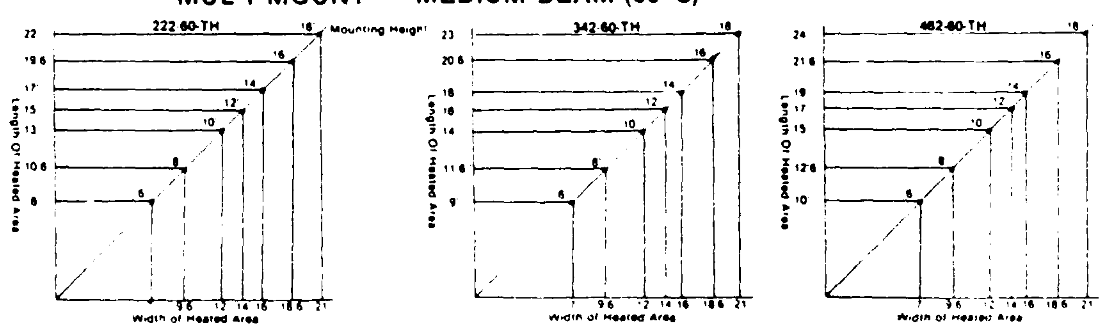
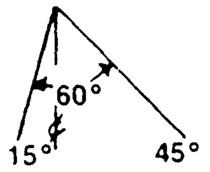
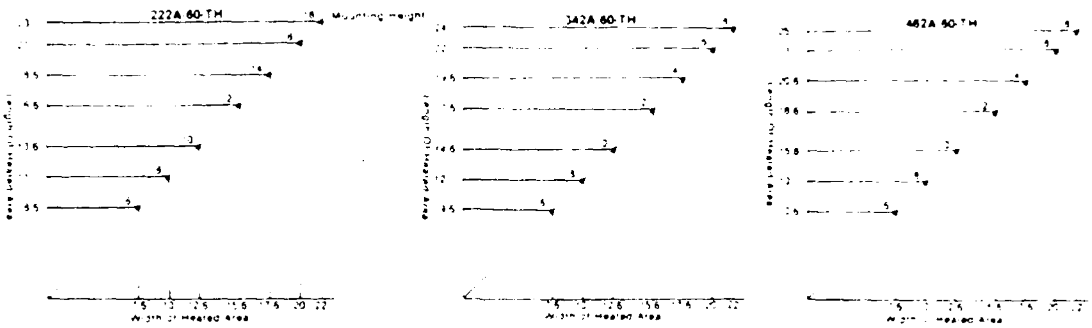


Table 5 (Continued)

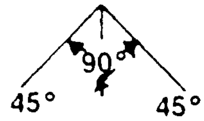
MUL-T-MOUNT — MEDIUM BEAM (60°A)



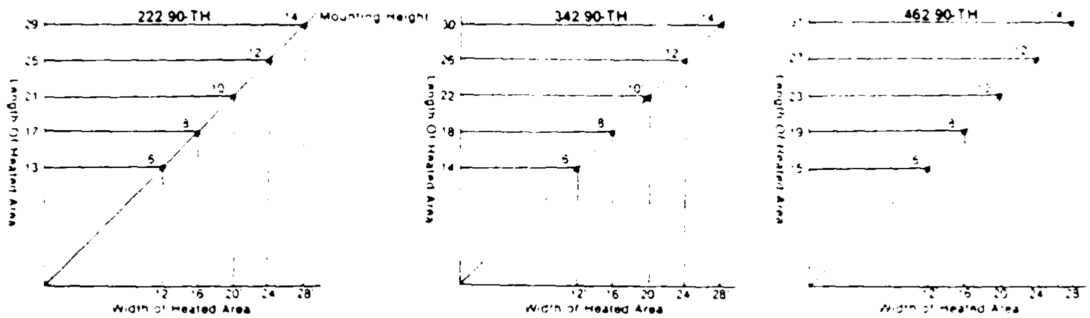
60° ASYMMETRIC — Perimeter heating Recommended for 12' to 18' mounting heights



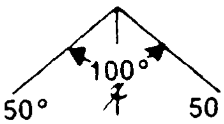
MUL-T-MOUNT — WIDE BEAM (90°)



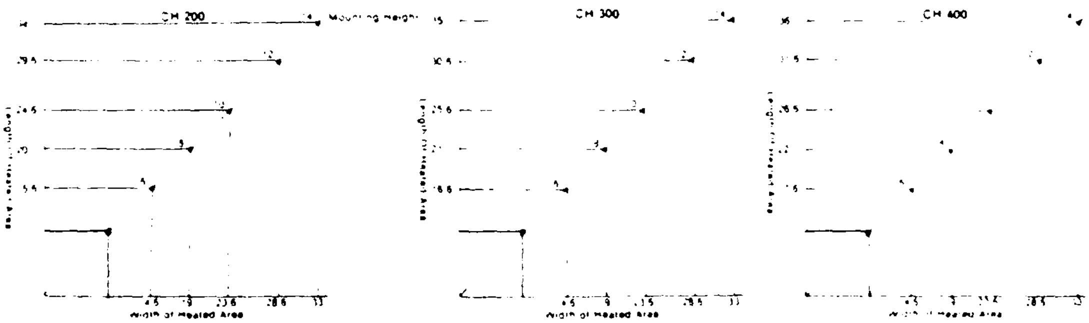
90° SYMMETRIC — Indoor — Total Area and spot heating Recommended for 8' to 12' mounting heights



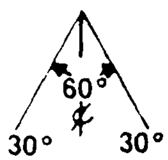
GENERAL DISTRIBUTION FIXTURES — WIDE BEAM (100°)



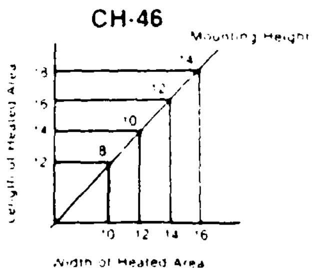
100° SYMMETRIC — Indoor Total Area or spot heating where a wide distribution of radiation is required. Recommended for 8' to 12' mounting heights

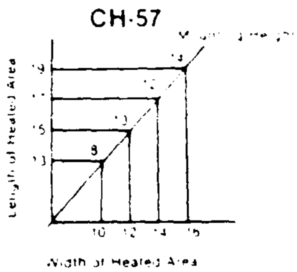


TRIMLINE FIXTURES — MEDIUM BEAM (60°)



60° SYMMETRIC — Indoor spot heating Recommended for 8' to 14' mounting heights





fostoria® SUN-MITE® **Electric Infrared**

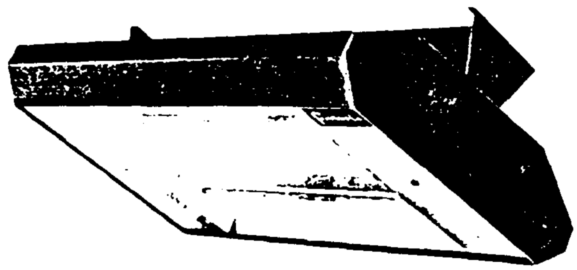
70 - 553 - 35

CATALOG SHEET

NAED EDP 78-3045

MUL-T-MOUNT SERIES

TOTAL AREA HEAT/SPOT HEAT/ SNOW & ICE CONTROL



UL

FEATURES:

- 30°, 60° or 90° symmetrical and 30° offset, 30° or 60° asymmetrical heat patterns available
- Corrosion resistant aluminized steel housing
- Double reflector for maximum heat pattern control
- GOLD anodized aluminum reflectors and end caps
- Two elements per fixture required — refer to catalog page 70-554 for proper selection
- 4 high temperature lead wires for single or two-stage
- Can be wired for single or three-phase systems
- 3 lengths available for a wide selection of wattage/voltage
- Dark brown baked enamel finish
- Has knockouts for ½" conduit on both ends and centered on top of wiring channel

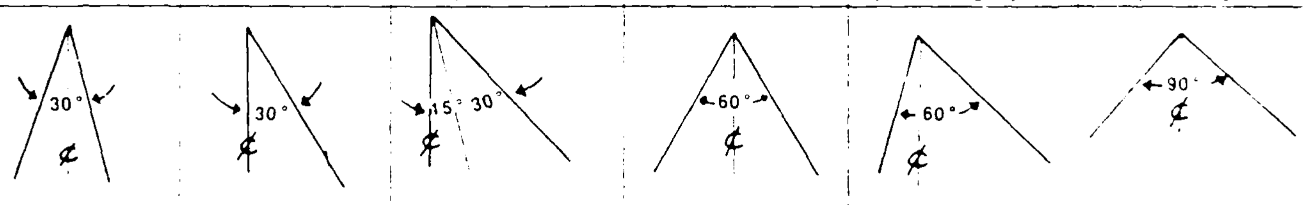
Mount Horizontal

COMFORT HEAT FOR:

- Indoor and totally exposed outdoor areas
- TOTAL AREA HEAT, SNOW/ICE CONTROL, SPOT HEAT
- MOUNTING HEIGHTS
  14' - 30' A30°, 30°, A31°
  12' - 18' A60°, 60°
  8' - 12' 90°

MUL-T-MOUNT AND RECESSED FIXTURES HAVE THESE HEAT REFLECTOR PATTERNS AVAILABLE

30° SYMMETRIC	30° ASYMMETRIC	30° ASYMMETRIC OFFSET	60° SYMMETRIC	60° ASYMMETRIC	90° SYMMETRIC
-30-TH	-A30-TH	-A31-TH	-60-TH	-A60-TH	-90-TH



Refer to specification sheet 70-601-80 for detailed heat distribution patterns

Fixture Model Series	Fixture Dimensions	Maximum Wattages Available Per Fixture	Voltages Available Per Fixture
222	24" Length 15" Width 7⅞" Depth	Up to 3200 W	120 208 240 277
342	32" Length 15" Width 7⅞" Depth	Up to 5000 W	208 240 277 480
462	46" Length 15" Width 7⅞" Depth	Up to 7300 W	208 240 277 480 577
51-222 (Recessed Model)	24" Length 24" Width 4⅞" Depth	Up to 3200 W	120 208 240 277

MODEL NUMBER EXPLANATION:

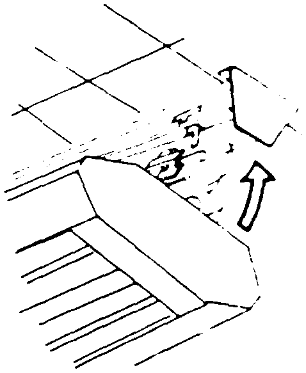
To order, simply add the suffix for the desired pattern to the model series required. For example, to order a 30° offset in the 342 series: 342-A31-TH

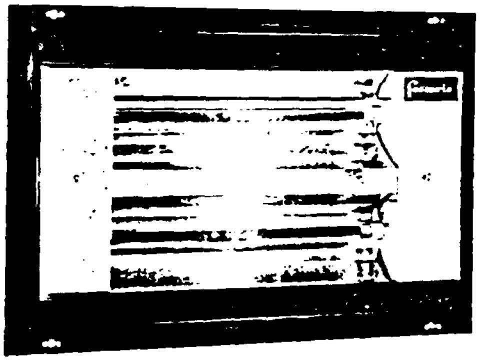
Refer to specification sheet 70-320 for wiring and installation instructions

TOTAL BUILDING HEAT WITH FOSTORIA COMFORT HEAT

MUL-T-MOUNT HIGHLITE

- Fostoria's exclusive hinge feature for easy installation
- Less expensive — why pay two people when one can install
- Full length wireways permits continuous rows





OPTIONAL RECESSING FRAME FOR STANDARD MUL-T-MOUNT

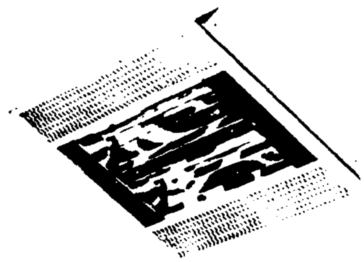
- Used as an option with the Mul-T-Mount series to recess the fixtures in a ceiling canopy type installation
- Corrosion resistant aluminized steel
- Brown baked enamel finish

Model	Ceiling Cutout Dimensions	Flange Dimensions
RMF-222	16¼" x 24½"	18" x 27¼"
RMF-342	16¼" x 33½"	18" x 36¼"
RMF-462	16¼" x 46½"	18" x 49¼"

Recessed Ceiling Mount Infrared Heaters

FEATURES:

- 30°, 60° or 90° symmetrical and 30° offset, 30° or 60° asymmetrical heat patterns available
- Double reflector for maximum heat pattern control
- GOLD anodized aluminum reflector and end caps
- Attractive design for all recessed applications
- Modules 2' × 2' for suspended T-bar ceiling
- 4 high temperature lead wires for single or two-stage
- Can be wired for single or three-phase systems
- White baked enamel finish



RMT-222 Series
One style will work in all type ceilings.

— Mechanical Suspension Systems
— Plaster Ceilings
— Inverted "Tee" Ceilings

APPLICATIONS AND MISCELLANEOUS USES:

- Offices
- Entryways
- Marquees
- Hallways
- Cold spots
- Spot heat
- Total building heat
- Snow melting
- Garages

MINIMUM ORDER
— 12 UNITS —
for RMT Series

Consult factory on less than 12 units.

NOTE: *Recessed fixtures must be in fire-proof construction only with high temperature wire.*

Fostoria INDUSTRIES, INC.
Box E, Fostoria, Ohio 44830 419/435-9201
GENERAL PRODUCTS DIVISION

IN YOUR AREA CALL:

TOTAL BUILDING HEAT WITH FOSTORIA COMFORT HEAT

Fostoria SUN-MITE

Electric Infrared
Installation Instructions For
Mul-T-Mount Heaters
222, 342 & 462 Series

UL

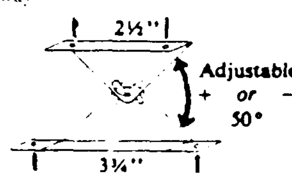
Specification Page
70-320-83

● MOUNTING

Fostoria Mul-T-Mount Sun-Mite Heaters are UL listed for indoor and unprotected outdoor use. For suspended mounting below the ceiling, use rigid rod, hardware chain, optional VMB vertical mounting brackets, or CHB-2AX adjustable mounting brackets. **CAUTION – these heaters should always be mounted so that the quartz tube or lamp is** *horizontal,* **if not, the heating element within the tube may sag and cause premature burnout.** Any surface or object should be at least 24 inches away from direct radiation from the unit. For surface mounting UL requires fixtures to be 3 inches from ceiling, 24 inches from a vertical surface and separated by a minimum of 36 inches.

The optional CHB-2AX adjustable mounting bracket, (see figure "A"), may be used in conjunction with the 3" standard spacer bracket to provide for adjustment of the heater at any angle from straight down (vertical) to 45° either way.

FIGURE "A"

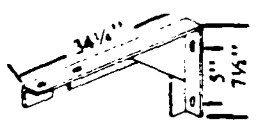


HORIZONTAL MOUNTING ONLY

CHB-2AX

The optional VMB vertical mounting bracket, (see figure "B"), may be used in conjunction with the optional CHB-2AX or the 3" standard spacer or bracket.

FIGURE "B"



VMB-34

For chain suspension, use 14 gauge jack chain in the manner shown in figure "C" (chain supplied by others).

FIGURE "C"

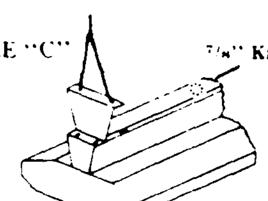
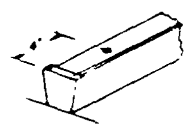


FIGURE "D"



For stem suspension, standard tubing stems used on light fixtures, or solid steel rods (¼" dia. min.) may be used by drilling holes into top wiring channel 4" from each end (see figure "D").

● TOP CHANNEL ASSEMBLY

Fasten 3" spacer brackets to channel with hardware provided.

1. Hook comfort heater body into mounted wiring channel cover. Unit will hang freely by the "T" Tabs, leaving both hands free to wire unit. (see figure "E").

2. Close wiring channel using the two snap fastners provided - (see figure "F").

FIGURE "E"

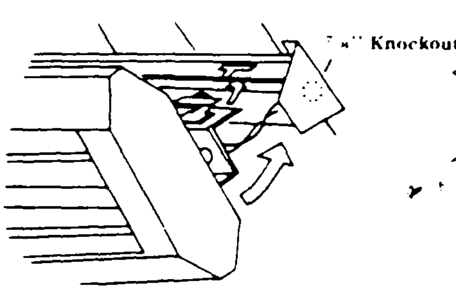
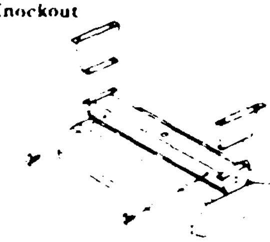


FIGURE "F"



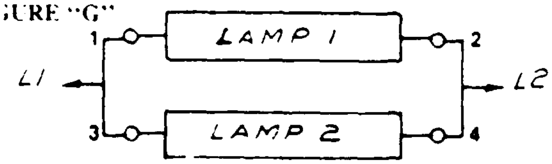
● WIRING

The Mul-T-Mount Fixtures are equipped with 4 hi-temperature [illegible] lead wires to accommodate either single stage or two-stage cont[illegible] heating elements.

Single-Stage Wiring

For single-stage operation connect both wires from one side to L1 and both wires from the other side to L2 (see figure "G").

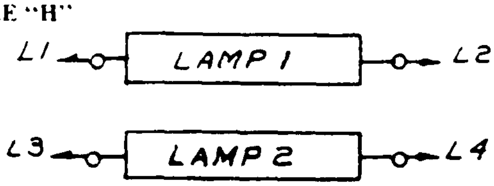
FIGURE "G"



Two-Stage Wiring

For two-stage operation connect only one wire from one side to L1 and the other wire from that same side to L3 with the corresponding wires to L2 & L4, (see figure "H"). Supply wires must be rated for at least 90° C. Wiring connections should always be made through the center knockout on the top of the wiring channel.

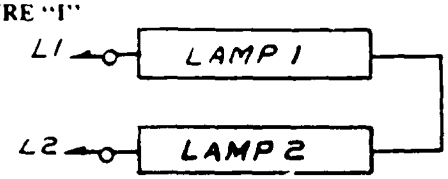
FIGURE "H"



Two-Lamps in Series

To wire Fixture for series operation connect the wires from one side together and connect incoming line to the 2 lead wires from the other side (see figure "I"). Due to the inconsistency in resistance, Fostoria does NOT recommend using metal rods or quartz tubes in series type wiring. (Applies to Quartz Lamps only).

FIGURE "I"



Fostoria INDUSTRIES, INC.
Box E Fostoria, Ohio 44830 419/435-9201
GENERAL PRODUCTS DIVISION

In Your Area Call:

• INSERTION OF HEATING ELEMENTS

To insert quartz lamps or tubes:

1. Remove 2 sheet metal screws (one each end) that hold fixture end caps in place. (see figure "I")
2. Position heating elements in "L" slots at ends of reflector.
3. Carefuly wrap heating element pigtail clockwise around terminal screws. (see figure "J") — NOTE: cut excess pigtail off at terminal to prevent lead from touching metal parts.
4. Tighten Terminal Screws. (see figure "J") — *CAUTION: Do not draw pigtail so tight that pressure is put on heating element.* Maintain a partial loop (or looseness) in the pigtail.
5. Install tinnerman clip in slot on lamp positioner to keep heating element in key slot (see figure "K".)
6. Replace end caps using sheet metal screws removed in Step 1.

Typical Wiring Diagram for Controlling FOSTORIA Mul-T-Mount Fixtures

(2-Stage Wiring Shown)

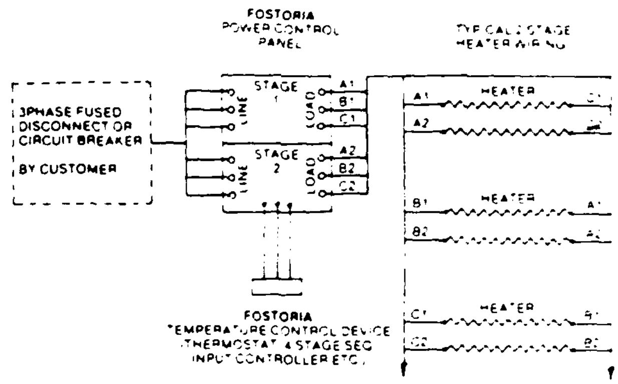


FIGURE "I"

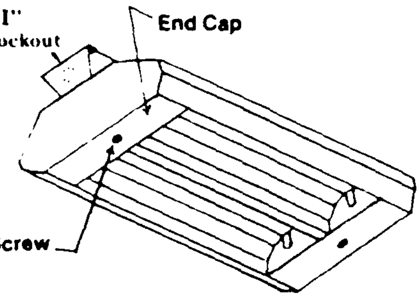


FIGURE "J"

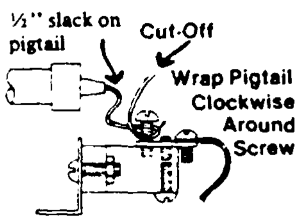
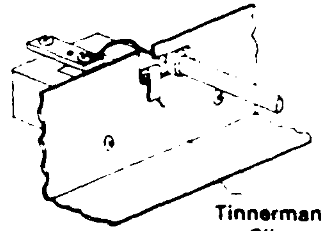
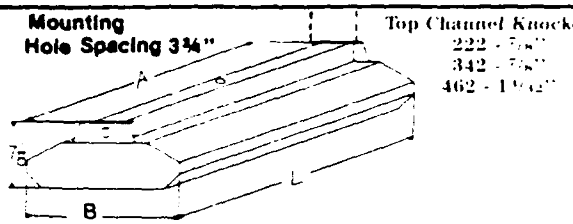


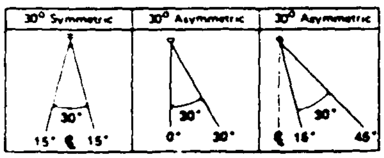
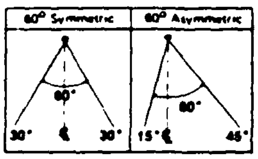
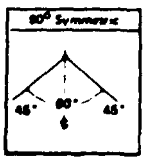
FIGURE "K"





SPECIFICATIONS

Housing is of 24 GA. corrosion resistant steel, dark brown plastic paint finish. Reflectors are .040 gold anodized aluminum. (Gold porcelain enamel reflectors are available for use in corrosive atmosphere.) UL listed for unprotected outdoor applications.

HEAT PATTERNS		MODEL NO.	"L"	"A"	"B"	HEATING ELEMENTS	Max. Watts	Max. Voltage	Wt. Each
 30, A-30, A-31	NARROW BEAM 30°	222-30-TH 222A-30-TH 222A-31-TH	24	23½	15	Quartz Tubes	3200	208 to 277	19
		342-30-TH 342A-30-TH 342A-31-TH	33	32½	15		5000	208 to 480	23
		462-30-TH 462A-30-TH 462A-31-TH	46	45½	15	Metal Sheath	7300	208 to 577	27
 60, A-60	MEDIUM BEAM 60°	222-60-TH 222A-60-TH	24	23½	15		3200	208 to 277	19
		342-60-TH 342A-60-TH	33	32½	15		5000	208-480	23
		462-60-TH 462A-60-TH	46	45½	15	Clear Quartz Lamps	7300	208 to 577	27
 90	WIDE BEAM 90°	222-90-TH	24	23½	15		3200	208 to 277	19
		342-90-TH	33	32½	15		5000	208-480	23
		462-90-TH	46	45½	15		7300	208 to 577	27

"A" in model number designates an asymmetric pattern. The number at the end of the model designation denotes the main energy beam spread. No. 31 designates 30° asymmetric from 15° — 45°.

Fostoria SUN-MITE® — *Electric Infrared*

70 - 554 - 85
CATALOG SHEET
NAED EDP 78-3045

HEATING ELEMENTS

CLEAR QUARTZ LAMPS *(Mount Horizontal)*

- 3/8" diameter **clear** quartz envelope
- Coiled tungsten filament; sealed porcelain end caps; inert gas filled
- Color temperature emitted: approximately 4100°F — high brightness
- Approximately 96% radiant efficiency
- Instant heat-up/cool-down
- Moisture resistance: highest
- Mechanical ruggedness: average
- Available wattages: 500 - 3800; available voltages: 120 - 575
- 6 - 8 lumens per watt light output
- Life expectancy: 5000 hours with 4-year prorated warranty

APPLICATIONS: All snow/ice control; all outdoor and most indoor applications; high bay applications; indoor areas highly exposed to cold air infiltration.

MOUNTING HEIGHTS: 12' and above for indoor. 8' to 10' for outdoor.

Element Number	Watts	Volts	Overall Length	Heated Length	Tube Dia.	Use ONLY with Heating Fixture Model:
GF-0512H	500	120	8 11/16"	5"	3/8"	CH-100
GF-1620H	1600	208	19 11/16"	16"	3/8"	CH-200 Series, 222 Series, or 51-222 Series
GF-1624H	1600	240	19 11/16"	16"	3/8"	
GF-1627H	1600	277	19 11/16"	16"	3/8"	

Element Number	Watts	Volts	Overall Length	Heated Length	Tube Dia.	Use ONLY with Heating Fixture Model:
GF-2548H	2500	480	28 11/16"	25"	3/8"	CH-300 Series or 342 Series
GF-3857H	3000	480	41 11/16"	38"	3/8"	CH-400 Series or 462 Series
GF-3648H	3650	480	41 11/16"	38"	3/8"	462 Series

QUARTZ TUBES *(Mount Horizontal)*

- 3/8", 5/8" and 7/8" diameter quartz envelope
- Nickel-chrome alloy coiled element with porcelain end caps and pigtail termination
- Color temperature emitted: approximately 1800°F — bright orange glow
- Approximately 60% radiant efficiency
- Fast heat-up/cool-down
- Moisture resistance: high
- Mechanical ruggedness: good
- Available wattages: 450 - 3200; available voltages: 120 - 575
- Life expectancy: 5000 hours with 4-year prorated warranty

APPLICATIONS: Indoor spot heating and total building heat; preferred when controlling application with percentage input timer.

MOUNTING HEIGHTS: 12' and under.

Element Number	Watts	Volts	Overall Length	Heated Length	Tube Dia.	Use ONLY with Heating Fixture Model:
G71-3454	450	120	12 5/16"	10"	5/8"	FFH-912A
G71-3492	550	120	19 1/2"	16"	3/8"	FFH-512
G71-3508	1100	120	18 5/16"	14 7/16"	5/8"	CH-200, 222 or 51-222 Series or FCH-213
G71-3459	1200	208	27 5/16"	23 7/16"	5/8"	CH-300 Series or 342 Series
G71-3461	1200	240	27 5/16"	23 7/16"	5/8"	
G71-3462	1200	277	27 5/16"	23 7/16"	5/8"	
G71-3499	1600	240	27 5/16"	23 7/16"	5/8"	
G71-3706	2200	240	27 5/16"	23 7/16"	7/8"	
G71-3460	1200	208	40 5/16"	36 7/16"	5/8"	CH-400 Series or 462 Series
G71-3522	1200	240	40 5/16"	36 7/16"	5/8"	
G71-3463	1200	277	40 5/16"	36 7/16"	5/8"	
G71-3465	1200	480	40 5/16"	36 7/16"	5/8"	
G71-3489	1600	240	40 5/16"	36 7/16"	5/8"	

Element Number	Watts	Volts	Overall Length	Heated Length	Tube Dia.	Use ONLY with Heating Fixture Model:
G71-3524	1600	480	40 5/16"	36 7/16"	5/8"	CH-400 Series or 462 Series
G71-3466	2000	208	40 5/16"	36 7/16"	5/8"	
G71-3488	2000	240	40 5/16"	36 7/16"	5/8"	
G71-3467	2000	277	40 5/16"	36 7/16"	5/8"	
G71-3509	2400	240	40 5/16"	36 7/16"	5/8"	
G71-3575	2400	277	40 5/16"	36 7/16"	5/8"	
G71-3707	3200	240	40 5/16"	36 7/16"	7/8"	
G71-3784	1500	120	38 7/16"	34 3/16"	5/8"	CH-46
G71-3785	2000	240	38 7/16"	34 3/16"	5/8"	
G71-3786	3000	240	49 7/16"	45 3/16"	5/8"	CH-57
G71-5038	3000	480	49 7/16"	45 3/16"	5/8"	

TOTAL BUILDING HEAT WITH FOSTORIA COMFORT HEAT

fostoria® SUN-MITE®

70 - 561 - 85
CATALOG SHEET
NAED EDP 78-3045

PARTS/ACCESSORIES

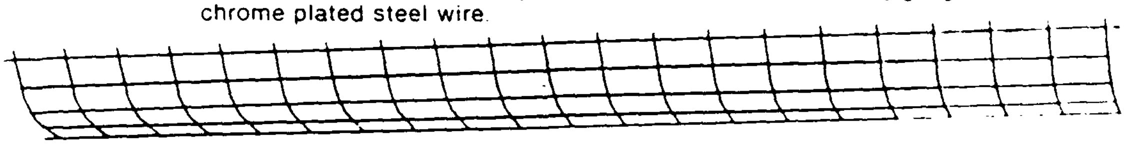
RUBY RED VYCOR SLEEVES

Recommended when visible glare from quartz lamps is objectionable. Ruby red sleeves will eliminate approximately 96% of visible light output while only reducing heat output by approximately 4%.

Model Number	Outside Diameter	Length	Use with QUARTZ LAMP Number:
31-942	5/8"	6"	GF-0512H
31-939	5/8"	16¼"	GF-1620H GF-1624H GF-1627H
31-940	5/8"	23¼"	GF-2548H
31-941	5/8"	38¾"	GF-3648H GF-3857H

WIRE GUARDS

Optional use for protection. Standard on heavy duty portable heat caddies for operational safety. All models constructed of heavy gauge chrome plated steel wire.



GENERAL DISTRIBUTION SERIES

Model Number	Use with Fixture Model Number	Mesh Size	Model Number	Use with Fixture Model Number	Mesh Size
CHWG-100	CH-100	1 1/8" x 1 3/16"	CHWG-46	CH-46	6" x 1½"
CHWG-200	CH-200 Series	1 1/8" x 2¼"	CHWG-57	CH-57	6" x 1½"
CHWG-300	CH-300 Series	1 1/8" x 2"	CHWG-2HD	1.8 KW or 2.0 KW Metal Sheath Fixtures	3" x 3"
CHWG-400	CH-400 Series	1 1/8" x 2¼"	CHWG-4HD	4.5 KW Metal Sheath Fixtures	3" x 3"
CHWG-222	222 Series 51-222 Series	2" x 2"	CHWG-6HD	6.0 Metal Sheath Fixtures	3" x 3"
CHWG-342	342 Series	2" x 2"	CHWG-13HD	13.5 KW Metal Sheath Fixtures	3" x 3"
CHWG-462	462 Series	2" x 2"			

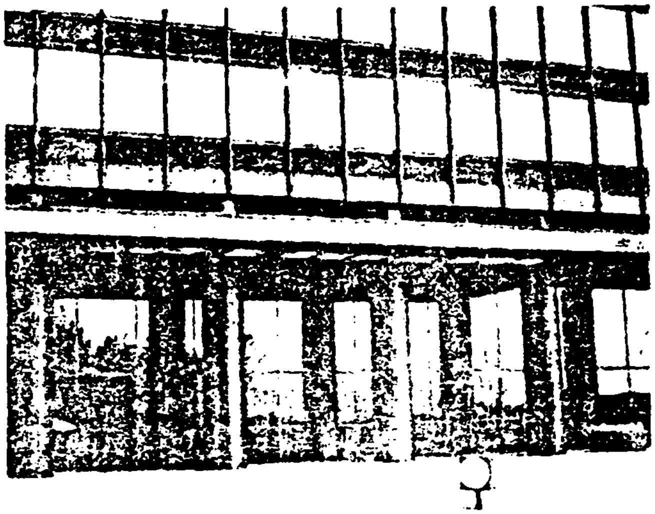
fostoria®

ELECTRIC INFRARED

CASE HISTORY

NO. 72

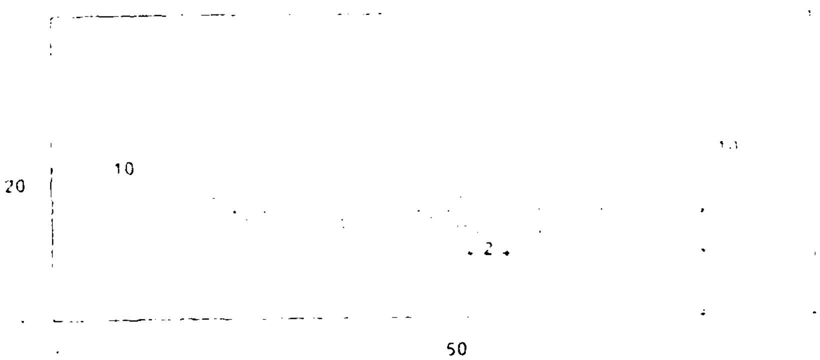
SNOW/ICE CONTROL



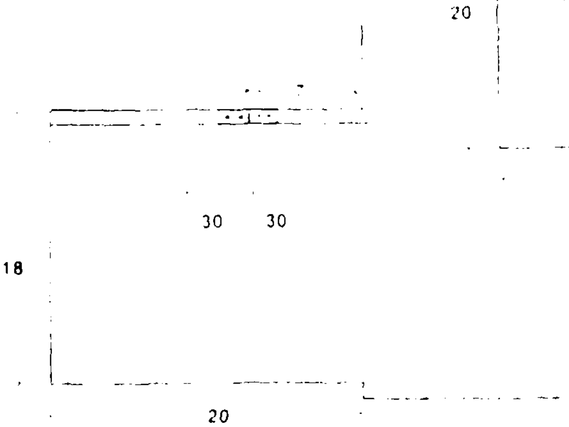
Harbor Point Condominium • 155 Harbor Drive • Chicago, IL

Located just off Lakeshore Drive in the heart of Chicago, this installation [illegible] for snow/ice control and [illegible] comfort. Harbor Point, with its park and lakefront setting, became a beautiful addition to Chicago's [illegible] when construction was completed in 1974.

Mounted under the main entrance [illegible] units of Model 2[illegible] A [illegible] quartz lamps. The heaters are [illegible] ering an area 50' wide by 2[illegible] [illegible] mounted [illegible]

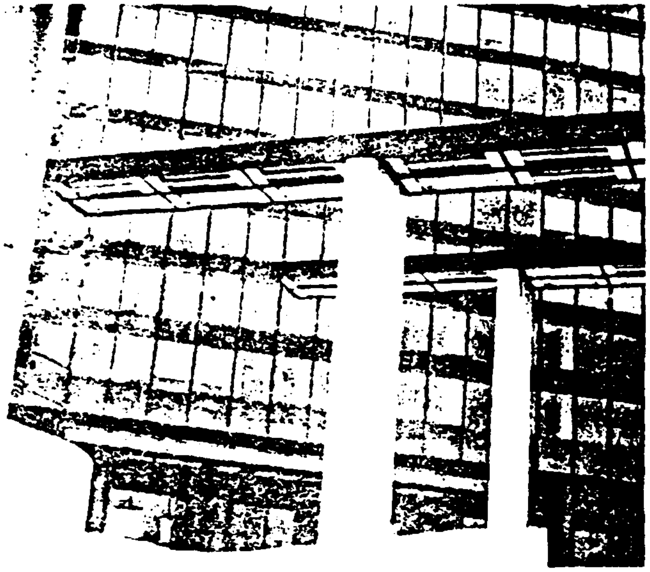


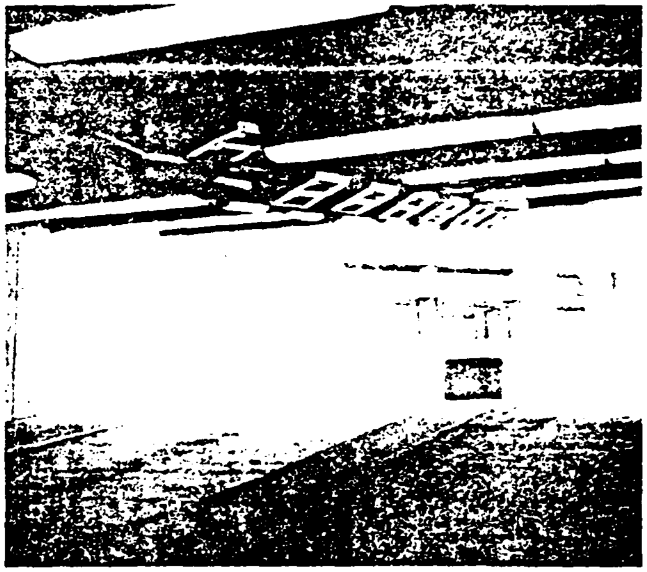
Underview Main Entrance Canopy



End View

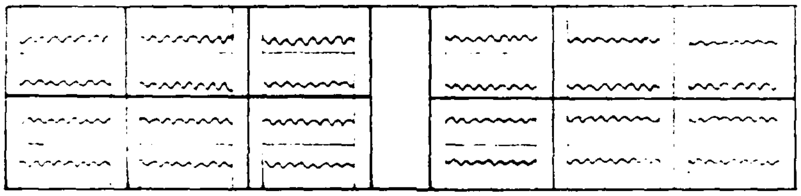
Infrared heat gives warmth and comfort for people entering or exiting the building or waiting under the canopy. The heat pattern also extends beyond the front of the canopy to keep exposed pick-up area free of ice/snow and moisture. This helps avoid an accumulation of slush which would normally be tracked into the building.



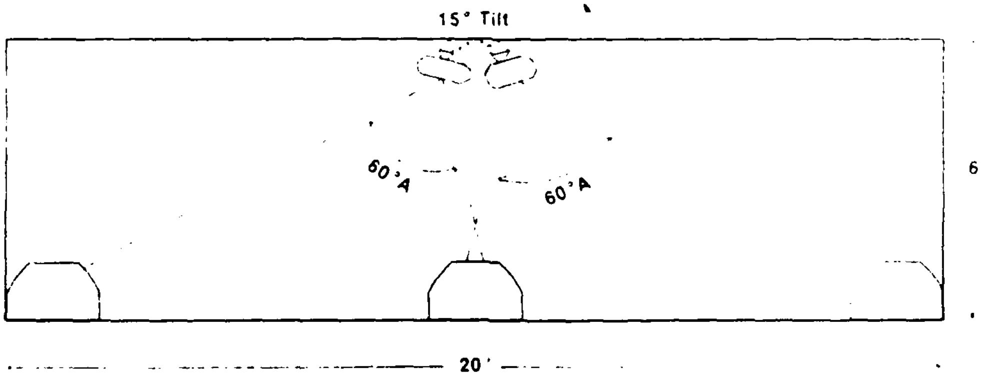


The up-down ramp leading to an underground parking garage for the condominium presented a critical snow/ice control problem due to the degree of incline. Specially designed T-bar frames were built to house 12 each 222-A30-TH Mul-T-Mount heaters equipped with clear quartz lamps. These are mounted at a 12' height from the ramp surface. The asymmetric 30° fixtures were mounted in two rows back to back to provide a combined heat pattern of 60°, yet utilizing the high efficiency 30° reflector.

The last photo displays the continuation of the ramp going underground. This semi-exposed snow/ice control area utilizes 28 of Model 222-A60-TH mounted at the center of the ramp at a [illegible] distance from the surface. Using [illegible] CHB2AX, the units are tilted 15° toward the ramps.



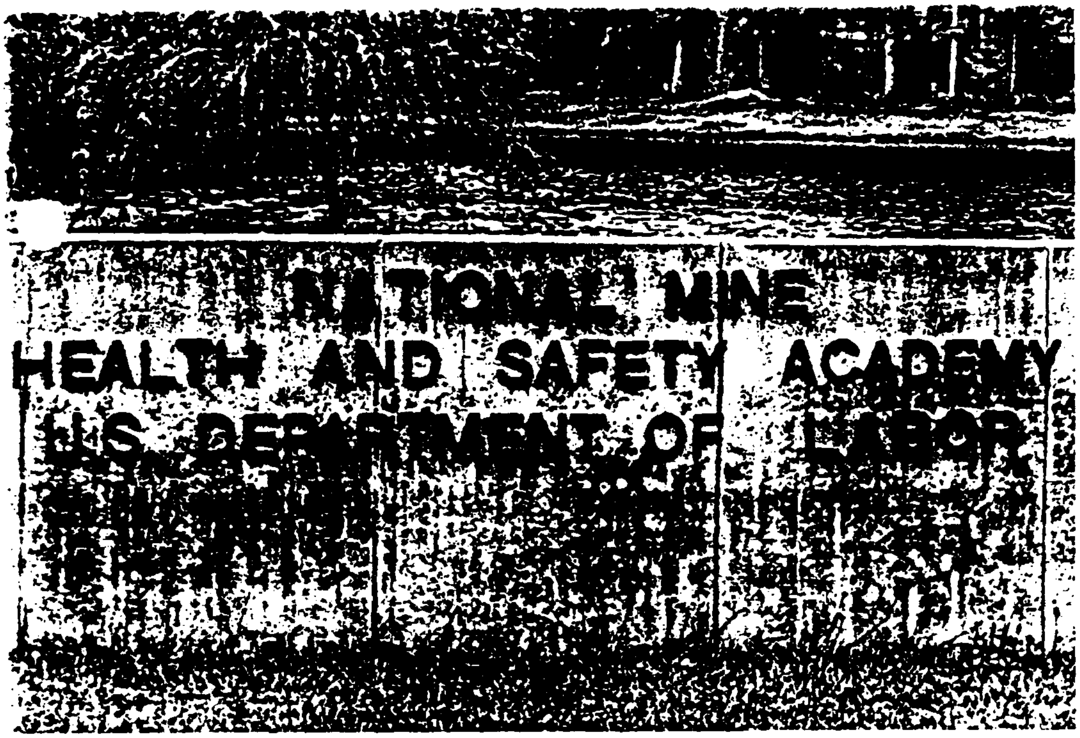
Underside View of T-BAR
1 of 3 T-BAR Frames 18' Apart



End View — Ramp Going Underground

CASE HISTORY
NO. 74

Solving Corrosion Problems while Heating Effectivel[y]



Entrance to the campus of the National Health and Safety Academy where Fostoria Industries, Inc. solved a corrosion and heating problem.

The National Mine, Health, and Safety Academy of the U.S. Department of Labor is located near Beckley, West Virginia. It was established to provide an academic background in mine safety for those who are appointed to inspect mines, render technical assistance, and train the nation's miners.

The spacious indoor swimming facility, built for staff and student use, was experiencing serious corrosion problems.

The ceiling and three walls consist of a combination of glass and milky fiberglass with a very low R factor of approximately two. Therefore, the surrounding surfaces are usually very cold. Coupled with high humidity conditions on the inside, the surrounding surfaces frequently are colder than the dew point. This causes severe condensation from the ceiling and walls. High condensation, coupled with high chlorine content, causes the atmosphere to be corrosive which is damaging to most equipment.

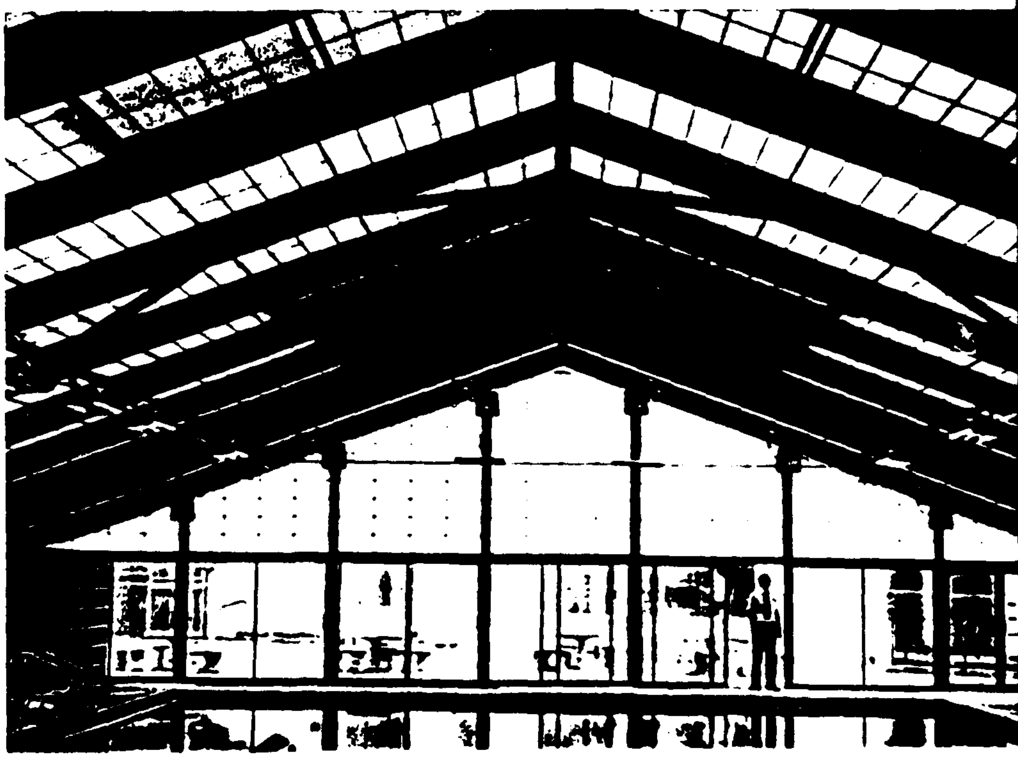
Because the previous heating equipment failed, the mine academy approached Fostoria Industries, Inc. to solve their corrosion problems and at the same time effectively heat their indoor facility.

To solve the heating and corrosion problem, Fosto[ria] fabricated Mul-T-Mount infrared heaters, using number 3[…] grainline stainless steel. The heaters (462-A60-TH, asymme[tri]cal, 4 feet long) were completely made of stainless steel [in]cluding the outer housing, all brackets, and internal hardwa[re].

The infrared reflector surface is made of Fostoria's standa[rd] gold anodized aluminum. Clear quartz lamps with porcela[in] ends were used, giving a 7300 watt output per heater. T[he] quartz lamps use ruby-red sleeves to cut down the lig[ht] output and also add a warm red glow to the environme[nt].

The heaters are mounted 15 feet high and approximate[ly] three feet over the water from the edge of the pool. Th[is] enables the asymmetric pattern to extend to the ou[…]

(continued on reverse si[de])



Swimming pool for staff, and students who are attending the Academy. Note heater locations.

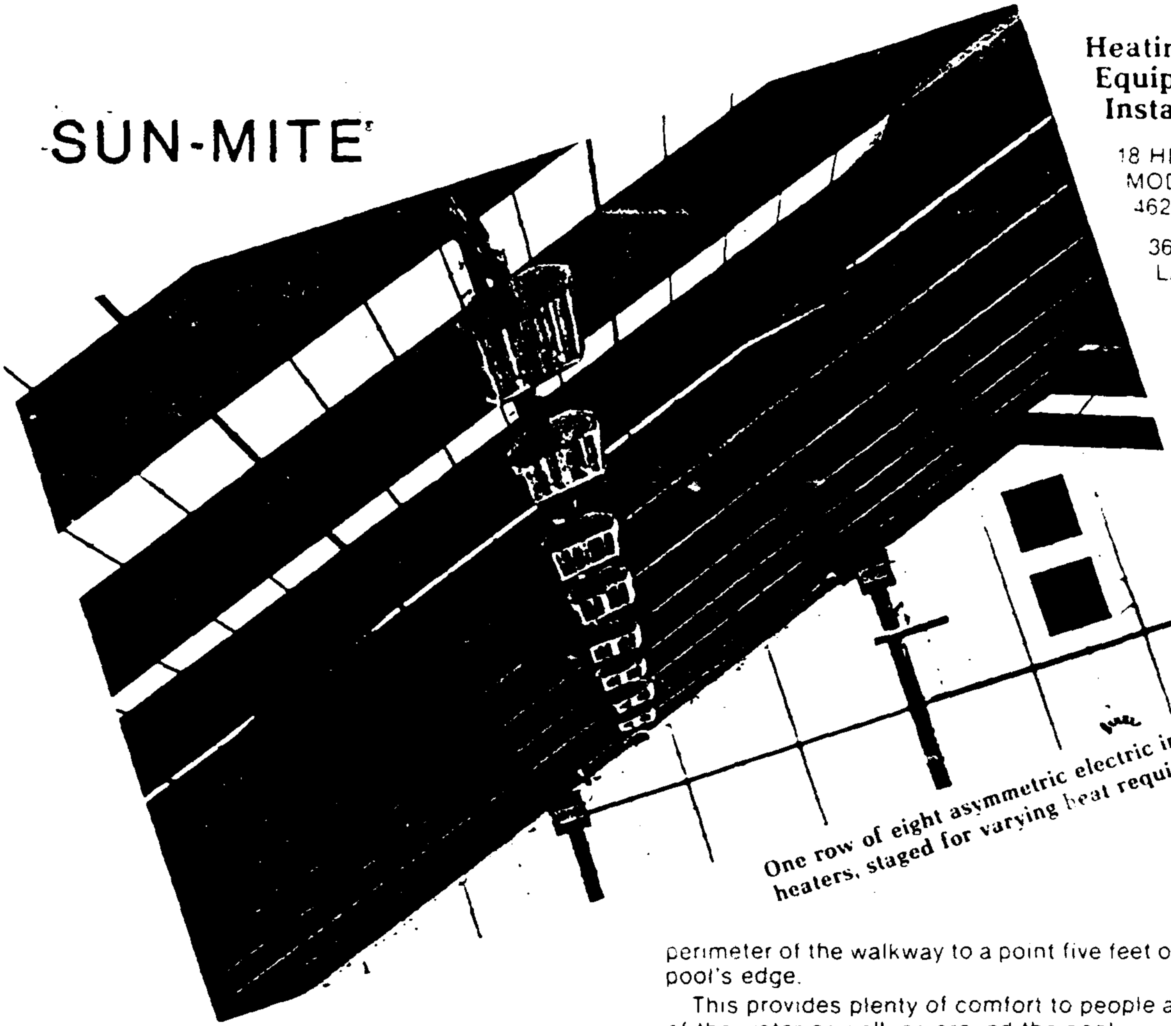
SUN-MITE®

Heating Equipment Installed:

18 HEATERS
MODEL
462-A60-TH

36 QUARTZ
LAMPS, GE 3648H

Total load: 131.4 KW



One row of eight asymmetric electric infrared heaters, staged for varying heat requirements.

perimeter of the walkway to a point five feet over the water from the pool's edge.

This provides plenty of comfort to people as they are getting out of the water or walking around the pool.

Adjustable brackets (CHB-2AX), also made of stainless steel, connect the heaters directly to the horizontal I-beams. One row of eight heaters line up on each side of the pool.

Each row is controlled independently from the other with its own two-stage thermostat. This allows for maximum uniformity of the radiant energy when the system is only required to be at a 50 percent level.

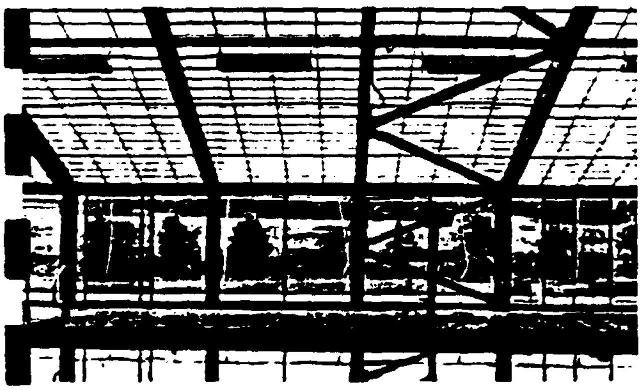
For instance, when the thermostats are set to maintain a temperature level between 67 and 70 degrees, the staging device is programmed like this:

At 70 degrees, both quartz elements turn off. As the temperature drops to about 69 degrees, one element is energized. If the temperature continues to drop until it reaches 67 degrees, then both elements are energized. This brings the temperature back up to 70 degrees.

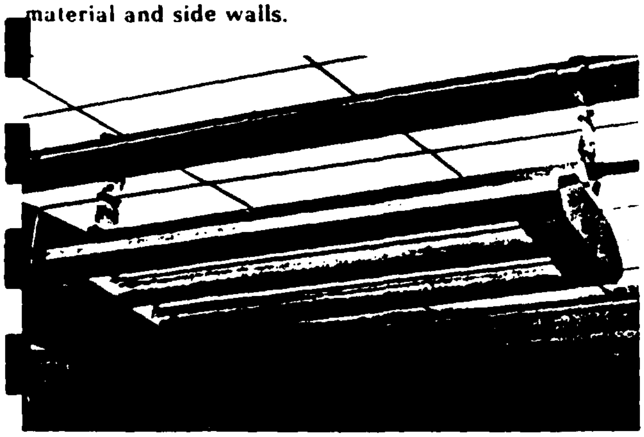
This type of control eliminates the all-ON, all-OFF condition and substantially increases the overall comfort level of the facility. In addition, the individual thermostat for each side adjusts to accommodate the side which is normally colder than the other. This requires those heaters to be energized more often than the opposite side.

To save energy, a single night-time setback allows all heaters to automatically revert to a third thermostat which is set substantially below the daytime thermostats. This system automatically turns back the heat demand during those hours when the pool is not open to the students.

The thermostats are also housed in a stainless steel enclosure and operate from a capillary tube that extends beyond the enclosure.

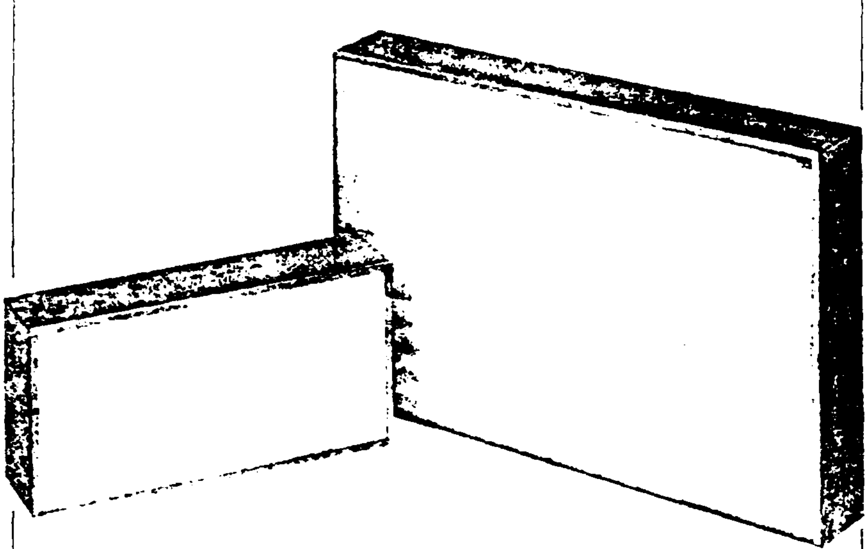


The low R factor is evident from this view of the roof material and side walls.



Energized electric infrared heater is attached with adjustable mounting brackets.

PROTHERM™



- Series CV heaters are manufactured from the highest quality components available to exacting standards
- Rugged and reliable
- Unique Vycor® Quartz face delivers uniform full area heat to product
- PROTHERM™ Series CV heaters are designed to meet the exact requirements of the application
- Long operating life
- Can withstand water shock at full output and absorb minor physical impact.
- High watt density - to 45 w.s.i. (6480 watts per s.f.).
- Maximum face temperature of 1600° F at 45 w.s.i.
- Can be supplied with Type K thermocouple installed.
- Heats to processing temperatures in approx. 4 minutes.
- Available in all standard voltages within design limitations.
- An operating life in excess of 6000 hours is expected when operated at 80% of rated output.
- Complete prewired controls, housings or engineered systems can be supplied by PROTHERM™.

SERIES CV

High watt Density panel heaters manufactured to customer specifications.

PROTHERM™ Series CV heaters are highly efficient long to medium wavelength infrared panel heaters for use in higher temperature industrial process heating applications. The Series CV heaters offer quality emmission of infrared energy through the Vycor® Quartz face. Elements are held in a special high temperature refractory board. PROTHERM™ Series CV heaters are ideally suited to applications requiring product temperatures to 900° F or faster heat up rates for lower temperature products.

PROTHERM™ Series CV Features

Standard Design Features:

- Aluminized steel case construction
- ¼-20 weld nuts or ¼-20x1" studs for mounting
- Maximum width is 18 inches
- Maximum length is 60 inches
- Thickness from 3 to 6 inches
- Elements run in direction of heater length
- Electrical leads 12 inches long through conduit nipple
- 230 V, single phase

Fast Delivery

Optional Features (at extra cost):

- Stainless steel case construction
- Elements across width, and zoning
- Thermocouples
- Electrical junction boxes
- Long electrical leads
- Flexible metallic conduit
- Conduit fittings
- Voltages over 230 V, and three phase design

Warranty: PROTHERM™ Series CV heaters are warranted to be free from defects of workmanship and materials for 1 year or 2000 hours from date received by customer. Evidence of field modification or repair voids warranty. The liability of Process Thermal Dynamics, Inc., is limited to replacement of faulty materials or workmanship at no charge, FOB So. St. Paul, MN.

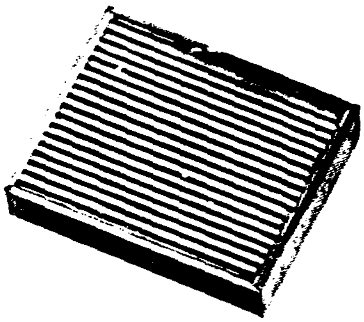
Process Thermal Dynamics Inc.
1200 N. Concord St.
So. St. Paul, MN 55075
(612) 450-4702

BULLETIN NO 202-10/86

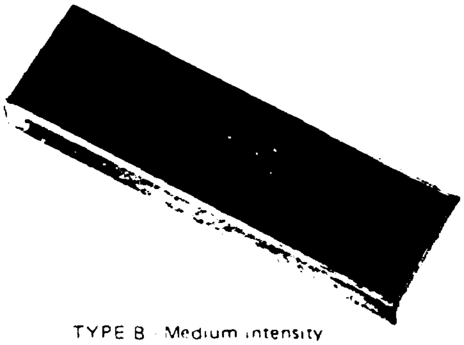
THERMA-TECH™

INFRARED PANEL HEATERS

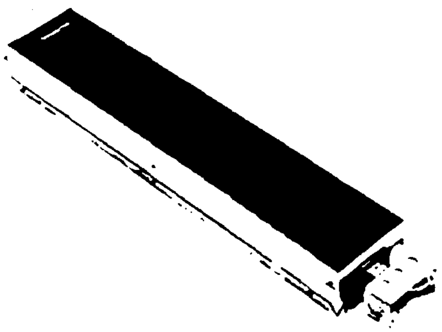
FOR EFFICIENT HEATING OF LARGE AREAS THREE TYPES OF HEATERS ARE AVAILABLE



TYPE V · High intensity
up to 40 watts/in^2
to 1500° F
4 minutes heat up time
2.6 · 6.0 microns wave length



TYPE B · Medium intensity
up to 20 watts/in^2
to 1200° F
4 minutes heat up time
3.5 · 6.0 microns wave length



TYPE PYREX 12 · Low intensity
up to 10 watts/in^2
to 660° F
5 minutes heat up time
4.5 · 6.0 microns wave length

TYPE V · High intensity· with clear Vycor® glass face plate

TYPE B · Medium intensity· with black ceramic glass face plate

TYPE PYREX 12 · Low intensity· with Pyrex glass face plate

- All heaters are in aluminized steel case 3″ deep
- Maximum width 24″ maximum length 96″
- Avialable in all voltages
- Standard or custom sizes

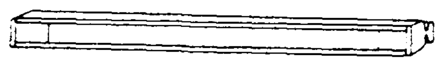
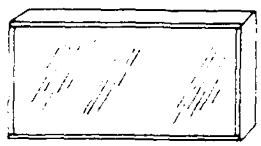
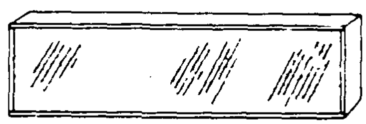
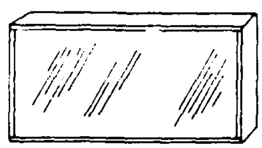
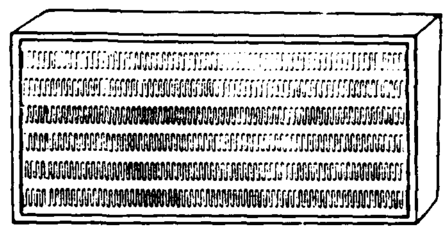
Standard Sizes:

24″ x 24″ 16″ x 24″	10″ x 24″ 6″ x 30″	6″ x 24″ 6″ x 18″	12″ x 12″

Therma-Tech panel heaters are clean and efficient. They offer an economical solution to virtually any processing problem requiring heat.

- Easy to install
- Durable
- Easy to maintain
- Longlife · in excess of 10,000 hours
- No scaling or warping
- Withstand the shock of water splash
- Gentle heating · will heat your product uniformly
- Can be supplied and fitted with thermocouple controls.

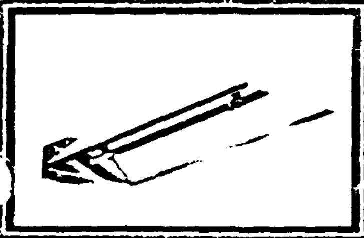
THERMA-TECH BROAD RANGE OF INFRARED HEATERS

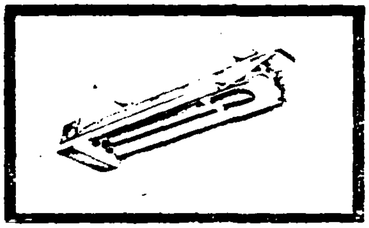
HEATER TYPE	MAX WATTS SQ. IN	MAX TEMP	HEAT UP TIME	WAVE LENGTH MICRONS	
CH 40	40	1400	4 min	2.6 - 6.0	 **CH-40 INFRARED PANEL (CORNING PATENT)** has two rows of stamped serpentine elements radiating through Corning Vycor faceplate. [illegible] to 1400°F. Extruded [illegible] available in ten heated [illegible] 14" to 120" 2¼" wide. High intensity heater - for high [illegible] space allows only small [illegible] heaters-for fast heating.
TYPE V	40	1500	4 min	2.6 - 6.00	 **TYPE V - INFRARED PANEL** with [illegible] radiating through Corning Vycor faceplate. Operates up to 1500° F. Made in sizes from 4" x 6" to 20" x 24" and 12" x 84" with 3" deep aluminized steel case, custom sizes available. Efficient, high intensity heater-for high speed lines, where space allows only small number of heaters-for fast heating.
TYPE B	20	1200	4 min	3.5 - 6.00	 **TYPE B - INFRARED PANEL** with elements radiating through black glass ceramic plate. Operates up to 1200°F. Made in sizes from 4" x 6" to 20" x 24" and 12" x 84" with 3" deep aluminized steel case, custom sizes available. Efficient medium intensity heater - good where line speed is medium to high and only heat penetration of surface is needed. Process may only require a few seconds.
TYPE PYREX 12	10	660	5 min	4.5 - 6.00	 **TYPE PYREX 12 - INFRARED PANEL** Replaces Corning Pyrex infrared heaters. Available in seven sizes up to 24" x 24" with 3" deep aluminized steel case. Long wave length, low intensity heater - best for heating sensitive materials with poor thermal conductivity. Heating time 1 to 2 minutes.
THERMA KING	60	2000	25 sec.	2000°F	 **THERMAKING** operates up to 2000°F. Has stamped serpentine elements pinned to a 2400°F instulating board, in stainless steel case. The hottest electric infrared panel available in the process industry - highly efficient. Very high intensity heater for high speed heating or for heating larger mass at higher rates.

Select the operating characteristics best suited for your process: heaters also designed to your specifications for O.E.M. applications. Specify size, type, wattage and voltage desired.

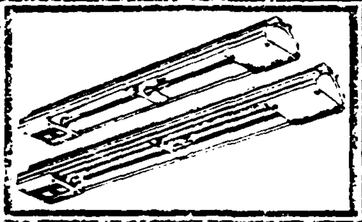
- Thermocouples are recommended in the heater for close control of your process and to maximize life of the heater.
- Cooldown time - generally cooling occurs about half as fast as warm up time.

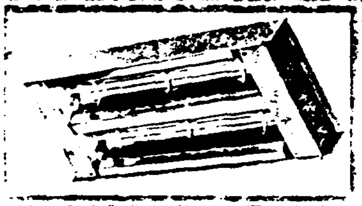
THERMA-TECH CORPORATION • 300 Dakota Street • P.O. Box 218 • S. Paterson, NJ 07503 • 201/345-0076

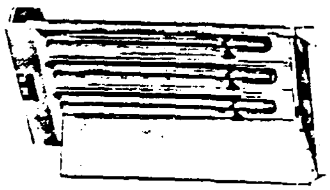


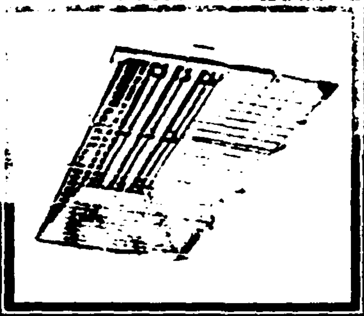


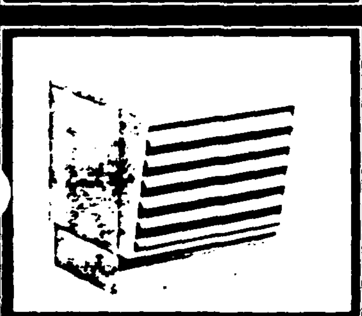
Aitken
Electric Heating Equipment







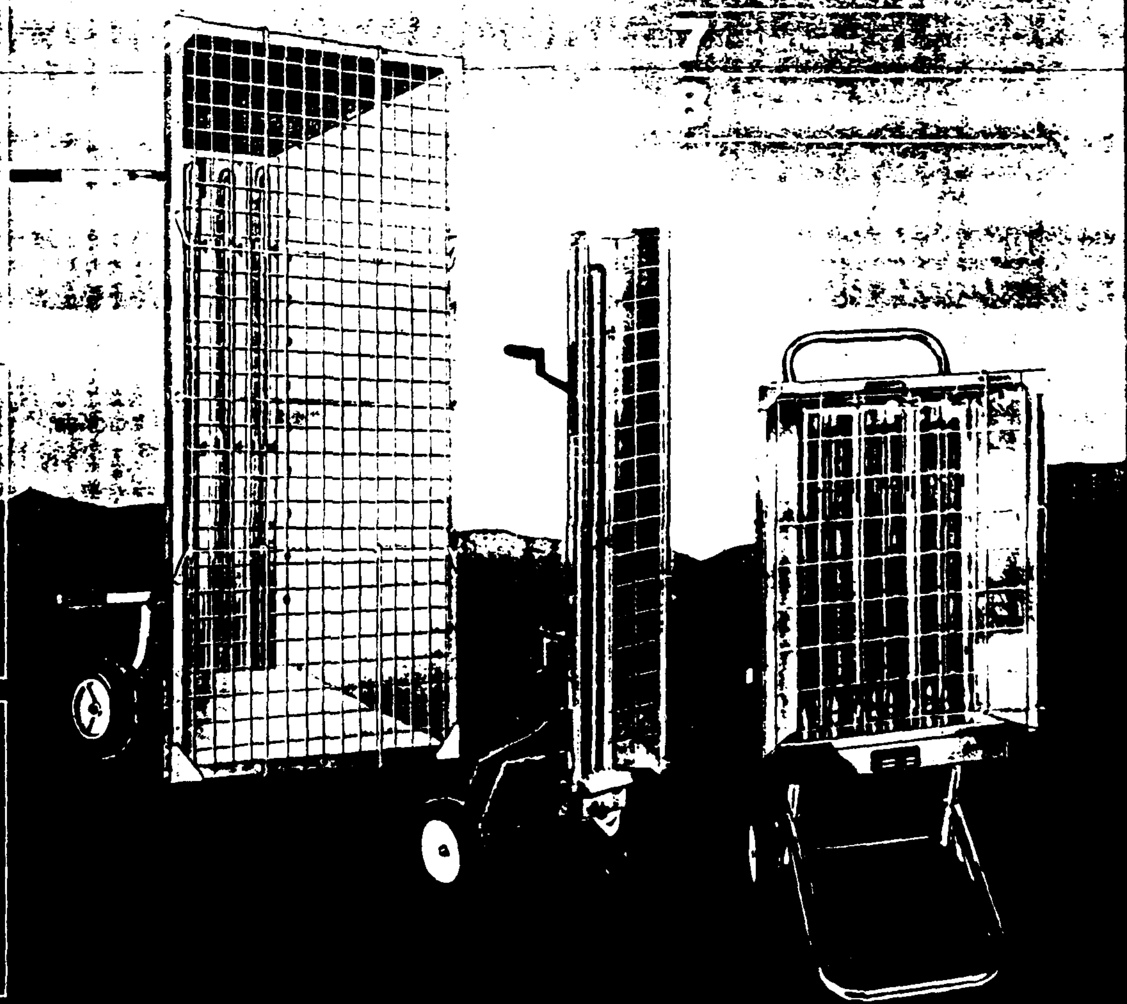




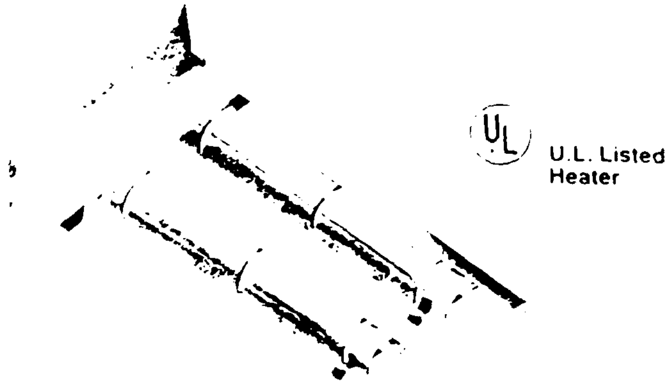
- **Infrared Metal Sheath**

Portable • Overhead • Comfort

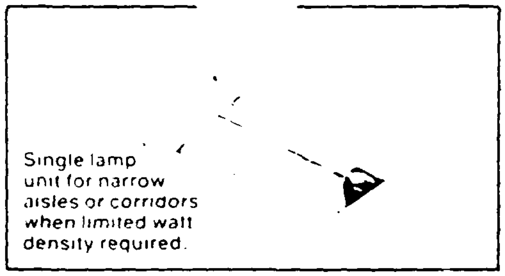
1. Infrared Radiant Portable for Inside & Outside "People Heating"
2. Infrared Radiant Overhead Heaters
3. Infrared Radiant Process Modules for Drying, Baking and Curing
4. Accessories and Application Data for Infrared Radiant Heaters
5. Infrared Quartz Heaters Application Data
6.
7.
8.



AITKEN PRODUCTS, INC. • P.O. Box 151 • 566 N. Eagle Street • Geneva, Ohio 44041 • (216) 466-5711 • Fax: (216) 466-5716



save up to 20% on electric heating bills! Available with butt socket or pig tail lamp connections for indoor or outdoor application.

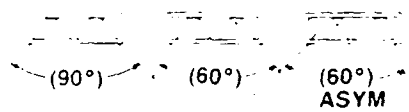


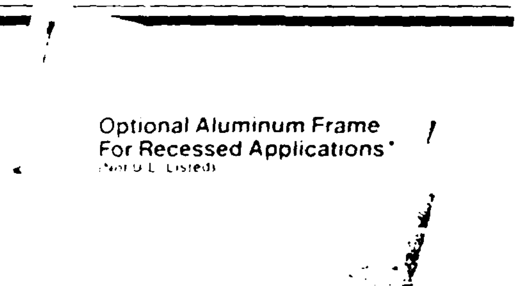
Aitken Quartz Lamp Infrared Heaters are now available in Universal "All Weather" models for indoor or outdoor installations. Two kinds of lamp connectors are also available — "*butt socket*" (push pull spring loaded silver tipped contact for easy snap-in connection) or "*pig tail*" for a more positive connection on process heating and other rugged applications where physical abuse is a problem.

All models can be positioned and mounted as easily as fluorescent lights. *Rugged construction* is "rain-tite" for indoor-outdoor installation.

Protective wire guard available as an option.

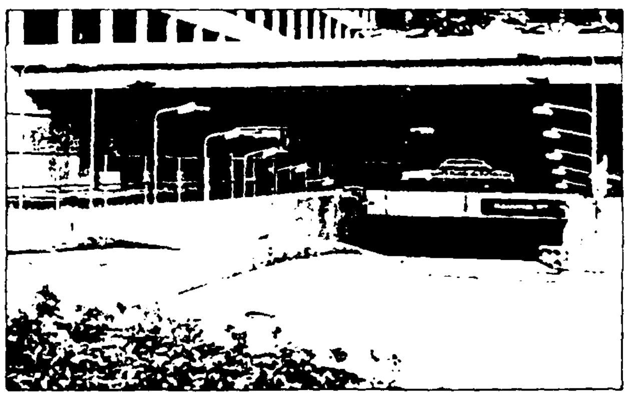
And Aitken Quartz Lamp Infrared Heaters use up to 20% less KW's than conventional electric heat.





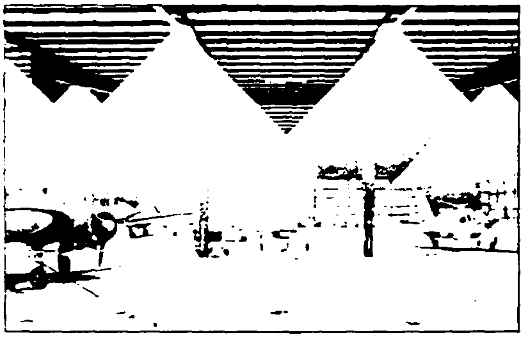
...High bay Factories

...Waiting areas and entrances

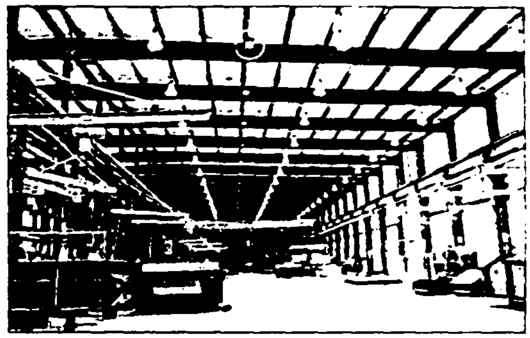


...Parking Ramp Snow Melting

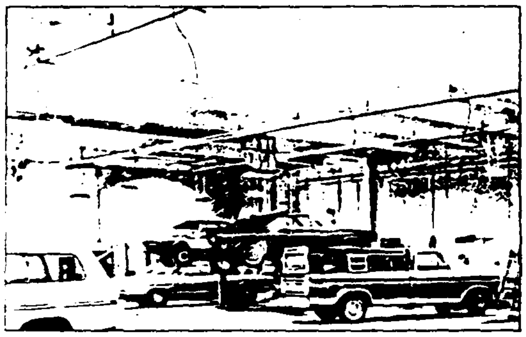
. . . not subject to impact or rough use



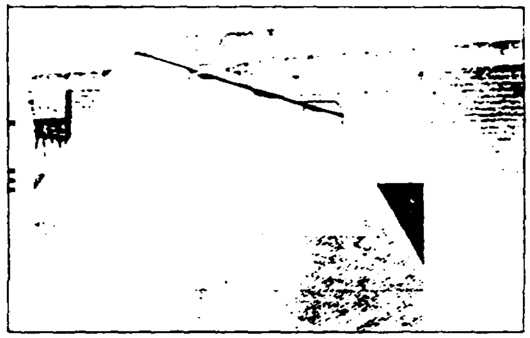
Drafty hangar



High ceiling metal building

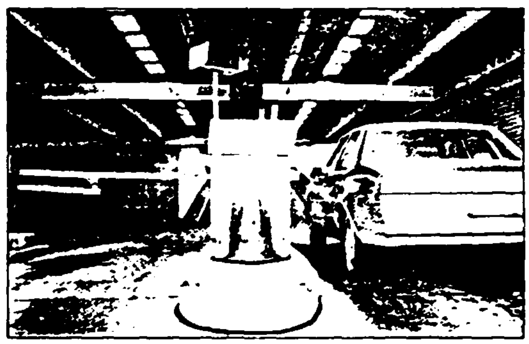


Hard-to-heat car dealer



Convenience and service for car wash

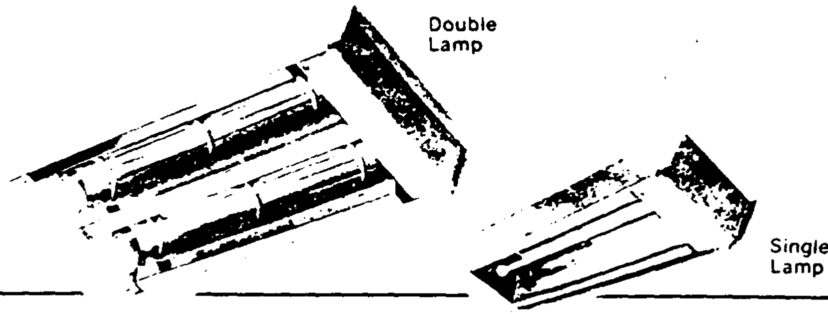
For Outdoor Heating Where Wind Chill Is A Factor



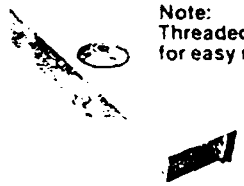
Parking garage entrance

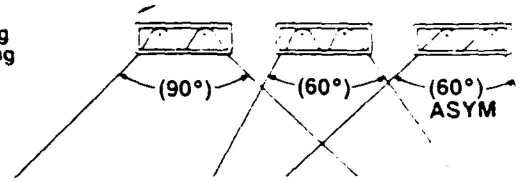
Quartz Lamp Infrared Heaters are now used for . . .

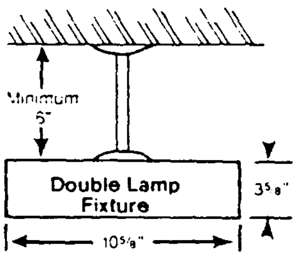
Bank entryways
Basketball courts
Bus shelters
Canopies
Car washes
Drive-ins
Factories
Farms
Foundries
Garages
Grandstands
Gymnasiums
Indoor tennis courts
Kennels
Laundries
Loading docks
Lobbies
Locker rooms
Lumber mills
Machine shops
Milking parlors
Parking lots
Patios
Restaurant fronts
Guard houses
Service stations
Skating rinks
Ski lodges
Snow melting
Stadiums
Stock rooms
Store fronts
Toll booths
Utility rooms
Warehouses
Water compressors



Minimum mounting height — 10 feet. Where ceilings are under 10 feet... or other reasons seem to dictate less than a 10-foot mounting height, consult a qualified infrared authority for advice. Do not install closer than 24 inches to a vertical surface. Can be stem mounted to any supporting surface. For supply connections use wire suitable for at least 75°C (167°F).

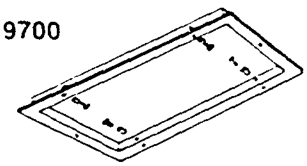




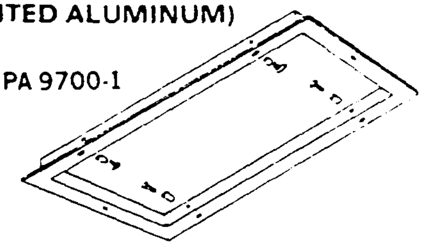


RECESSING FRAMES (PAINTED ALUMINUM)

PA 9700



PA 9700-1



Installation
Cut out dimensions are 12⅞" x 28" for Part PA 9700
12⅞" x 37" for Part PA 9700-1
Mount recessing frame in ceiling. (6) holes (5/16") dia. are provided in frame
Holes must be drilled in heater housing.

NOTE: USE ONLY IN FIREPROOF CON STRUCTION. USE ONLY WHERE LOCAL CODES OR INSPECTION ALLOWS MOUNTING OF HEATER IN THIS MANNER VOIDS U.L. LISTING. MINIMUM CAVITY DEPTH — 12"

Model		Dimensions (Ht. L. W.)	Reflector	No. Lamps	Watts	Volts	Amps	Ship. Wt.
Single Lamp Fixtures								
Butt Socket	**Pigtail**							
QH 169	QHL 169	3⅝ x 25½ x 5¾	90°	1	1600	208V, 240V, 277V	(See Lamps)	6.5 lbs
NA	QHL 259	3⅝ x 34½ x 5¾	90°	1	2500	480	5.21	8 lbs
Double Lamp Fixtures								
Butt Socket	**Pigtail**							
QH 109	QHL 109	3⅝ x 14½ x 10⅝	90°	2	1000	120V	8.3	8 lbs
QH 106	QHL 106	3⅝ x 14½ x 10⅝	60°	2	1000	120V	8.3	8 lbs
QH 106A	QHL 106A	3⅝ x 14½ x 10⅝	60°A.	2	1000	120V	8.3	8 lbs
QH 329**	QHL 329**	3⅝ x 25½ x 10⅝	90°	2	3200	Specify*:	15.4 @ 208V	12 lbs
QH 326**	QHL 326**	3⅝ x 25½ x 10⅝	60°	2	3200	208V, 277V	13.4 @ 240V	12 lbs
QH 326A**	QHL 326A**	3⅝ x 25½ x 10⅝	60°A.	2	3200	or 240V	11.6 @ 277V	12 lbs
NA	QHL 509	3⅝ x 34½ x 10⅝	90°	2	5000	480	10.4	15 lbs
NA	QHL 506	3⅝ x 34½ x 10⅝	60°	2	5000	480	10.4	15 lbs
NA	QHL 506A	3⅝ x 34½ x 10⅝	60°A	2	5000	480	10.4	15 lbs

*The 3200 watt units available in either 208V, 240V or 277V. Specify on order **Can be series wired with 240 V lamps to operate on 480 V

Accessories	
Recessing Frames	**Description**
PA 9700	For 3200 watt units
PA 9700-1	For 5000 watt units
Red Vycor Sleeves Mask out illumination from lamps For butt socket or pigtail lamps.	
P 70069 *	⅝" x 7" Fits 500 watt
P 70070 *	⅝" x 18" Fits 1600 watt
P 70080 *	⅝" x 27" Fits 2500 watt

*For ¾" dia. for pigtail lamps add (-1) after these part numbers

Wire Guards

P 54580	Fits 3200 watt double lamp unit
P 54580-1	Fits 5000 watt double lamp unit
P 54581	Fits 1600 watt single lamp unit
P 54581-1	Fits 2500 single lamp unit
P54580-2	Fits 1,000 watt double lamp unit

Quartz Lamps		Watts	Volts	Amps
Butt Socket	**Pigtail**			
P70010	P80005	500	120	4.17
P70013	P80208	1600	208	7.69
P70014	P80240	1600	240	6.67
P70015	P80277	1600	277	5.78
P70016	P80480	2500	480	5.21

Danger — Hazard of fire. Infrared radiant heaters must not be operated where [illegible]

Custom Designed

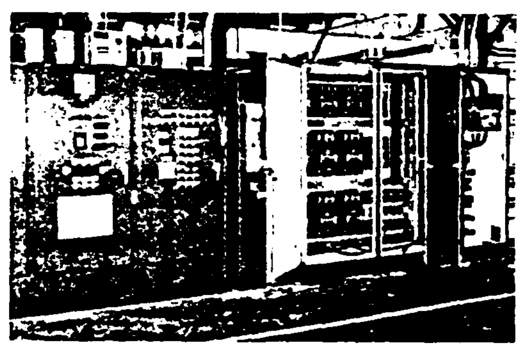
Scientifically Controlled

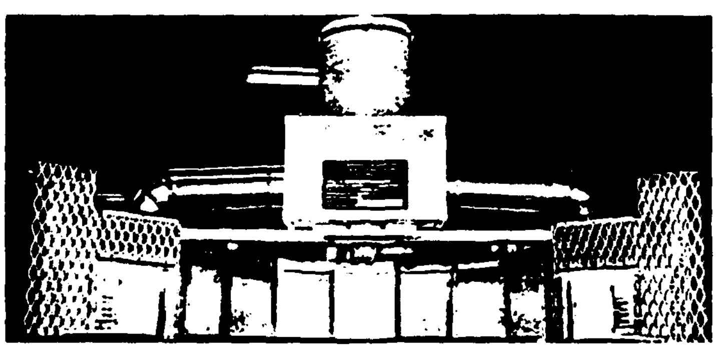
GAS & ELECTRIC INFRARED

INDUSTRIAL PROCESSING OVENS and APPARATUS

THERMAL DEVICES DIVISION, through many years of extensive research and processing experience with heating problems offers today, to industry throughout the U.S. and Canada, a complete service in consultation, research and development, engineering and fabrication.

A trained staff of engineers and technicians including specialists in controls, research, technical coatings, and equipment design provide "custom" service upon your request.





THERMAL DEVICES DIVISION *John J. Fannon Co., Inc.*

16025 23 Mile Rd., Mt Clemens, MI • 48044-9747 • (313) 263-8850 • Telex: 211894 DOSS UR
D-U-N-S 10-687-1536 • GOV.'T CAGE CODE I.D. No.: IHJ00

THERMAL DEVICES DIV.

CUSTOM INFRARED OVEN SYSTEMS

Thermal Devices designs and engineers infrared systems for many varied uses over a large cross section of industry. Most of our applications are highly controlled processes wherein product temperatures are carefully controlled, usually with remote optical systems and P I D controllers with automatic voltage control to guarantee correct product temperature with no overshoot. Many systems are provided with comp control and interfacing with associated operations.

Applications that are most commonly requested of us are:

- Curing, drying, softening, preheating & laminating of coatings and adhesives on paper, textiles, and plastics.
- Curing, drying, preheating coatings, water on metals.
- Systems for catalysed repairs to high quality enamel paint finishes.
- Preheating of dies and electronic parts
- Curing of electronic potting materials.
- High velocity air heaters for drying electronic parts.
- Drying, melting, dehydrating chemicals.
- Web drying, curing, shrinking, and finishing textiles.
- Drying of films.
- Curing & drying finishes on wood parts & furniture.
- Drying inks, varnishes, poster paints, bindings and silk screen application.
- Many other interesting applications for all industries.

THERMAL DEVICES PARTIAL CUSTOMER LIST

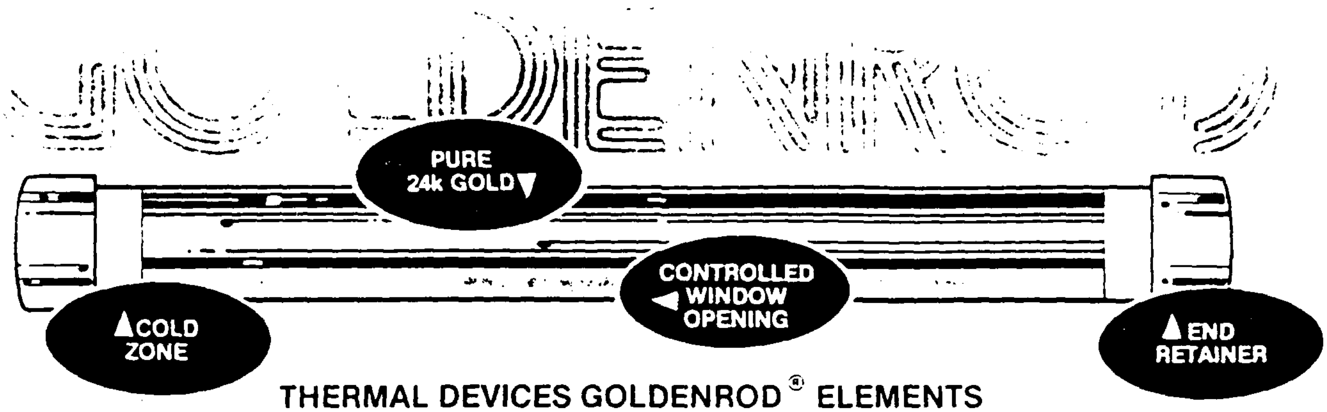
• Chrysler • Ford Motor • DuPont • General Motors • Sherwin Williams • Joanna Western Mills • Motorola • Hewlett Packard • Dow Chemical • Federal Mogul • Northrop • IBM • G.E. • RCA • Warner Swasey • Barber Coleman • Naval Weapons Support Center • Hitachi Corp • Inmont Corp • Kelsey Hayes • U.S. Air Force

INDEX CONTAINS:

- Remote sensing infrared heating control systems
- Heater fixture assembly
- INFRA-ARM™ Infrared spot heater and specifications
- Hi-density infrared quartz heater
- Modulus® infrared radiant
- Goldenrod® infrared directional quartz heating elements and fixtures
- Custom gas and electric ovens

THERMAL DEVICES DIVISION *John J. Fannon Co., Inc.*

16025 23 Mile Rd., Mt Clemens, MI • 48044-9747 • (313) 263-8850 • Telex 211894 DOSS UR Patents applied for 1984
D U N S 10-687-1536 • GOV'T CAGE CODE I D No. IHJ00



THERMAL DEVICES GOLDENROD® ELEMENTS

SAVE 23.5% ENERGY!

Thermal Devices new controlled GOLDENROD® directional infrared heating elements are 23.5% more energy efficient due to the inter-radiation between the resistance wire and the gold exterior. This causes the resistance wire to rise in temperature and allows for the reduction in wattage design

As an example—If you are now using elements rated at 1500 watts and switch to GOLDENROD®, you can reduce the 1500 watts of each element to 1150 watts and get the same radiant value. This would save you 350 watts per hour, per element

If you have an infrared application that is not satisfactory, you can replace your existing infrared elements with GOLDENROD® directional elements and raise your temperature curve without increasing wattage.

Reflectors are cooler with GOLDENROD® *directional elements.* The gold exterior in GOLDENROD® *reflects the radiant energy through the controlled radiant window opening only. Virtually 100% radiant energy produced is directed in a controlled pattern.*

It's time to replace your old costly INFRARED elements with energy efficient GOLDENROD

COOLER REFLECTORS

Reflectors and oven parts are cooler with GOLDENROD® directional elements in that the GOLDENROD® outer reflector directs energy through the controlled radiant window opening to the work

CONTROLLED RADIATION

Where radiant heat must be controlled, such as machines and appliances GOLDENROD® is ideal because it doesn't heat other parts.

FLEXIBILITY

GOLDENROD® allows you to design applications where they can be used more effectively especially where controlled patterns are necessary. GOLDENROD® can be nested together, used in narrow or confined areas and be used horizontally or vertically

SPECIFICATIONS

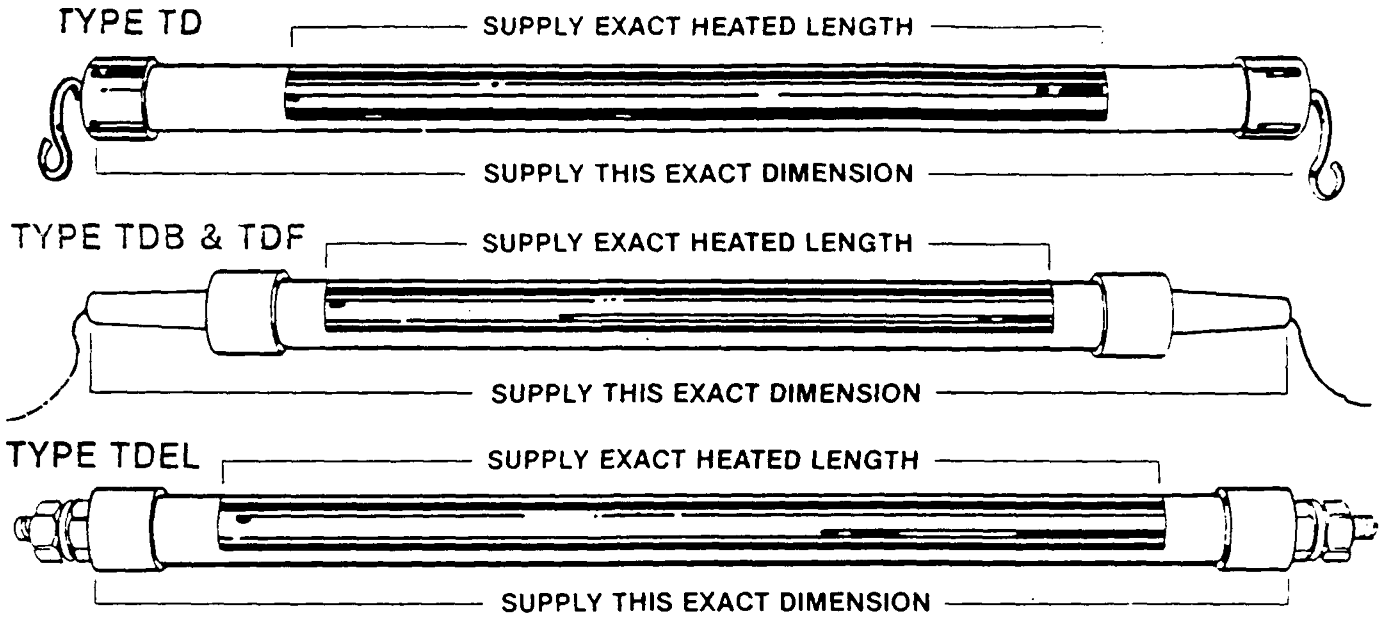
GOLDENROD® directional elements are available in standard element sizes to fit your existing reflectors such as 3/8", 1/2" 5/8" and up to 96" long. We can also design for special applications and O.E.M. work. We give you control up to 50 watts per inch or 7.4 kw per sq. ft maximum, when nested together.

COMPETITIVE PRICE / LONG LIFE

THERMAL DEVICES DIVISION John J Fannon Co., Inc

16025 23 Mile Rd., Mt Clemens, MI • 48044-9747 • (313) 263-8850 • Telex: 211894 DOSS UR
D-U-N-S 10-687-1536 • GOV.'T CAGE CODE I.D. No.: 1HJ00

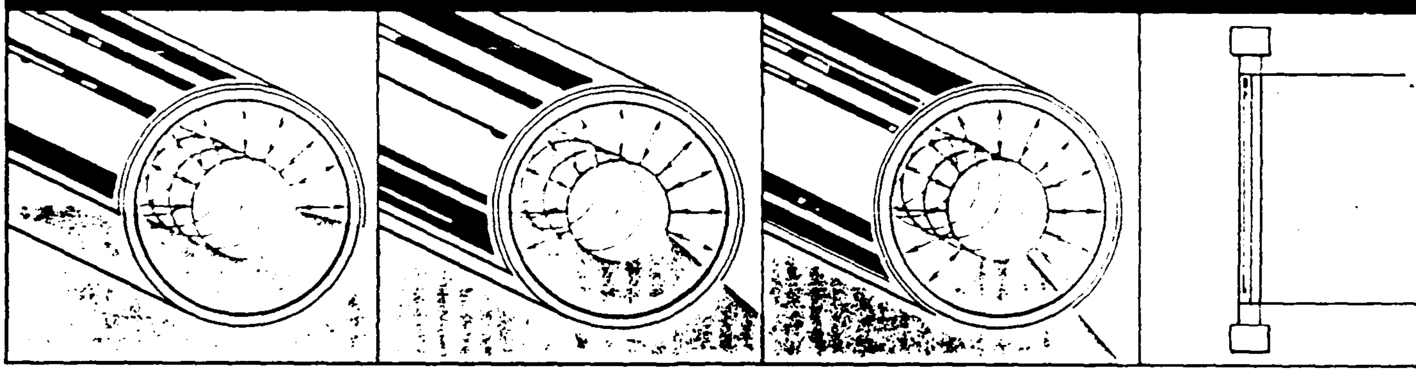
When requesting quote information...



...also wattage, voltage, part number and manufacturer.

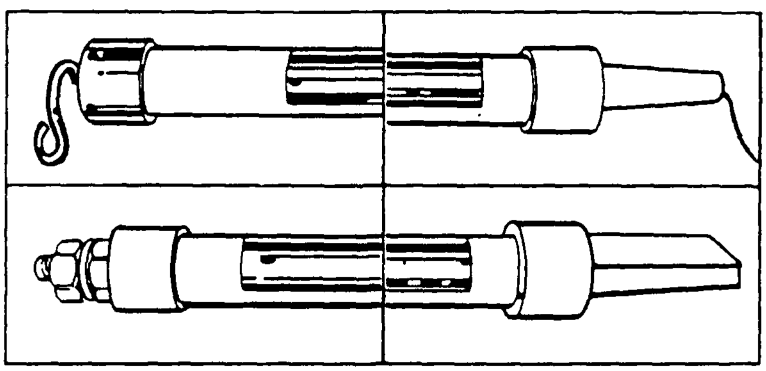
NOW—PATTERN CONTROL TO MEET YOUR NEEDS

WIDE MEDIUM NARROW VERTICAL



TYPE TD
Stainless steel for use with 1/2 and 5/8 in. O.D. quartz.

TYPE TDEL
Ceramic with stainless steel stud connectors. To be used with 1/2 and 5/8 in. O.D. quartz.



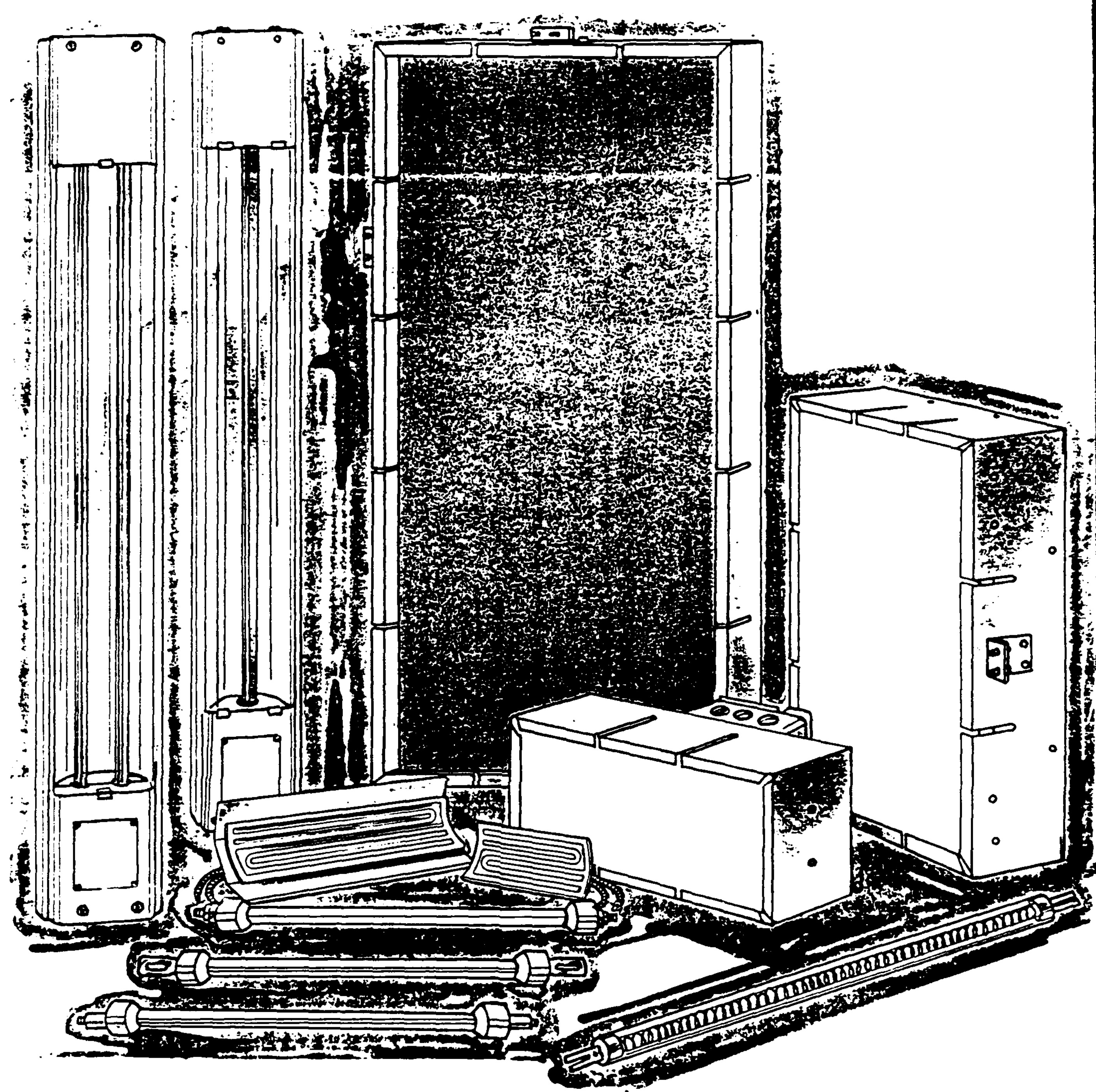
TYPE TDF
Ceramic with wound wire connectors. To be used with 5/8 in. O.D. quartz.

TYPE TDB
Ceramic with wound wire connector. To be used with 3/8 in. O.D. quartz.

GOLDENROD™ elements can be custom designed.
O.E.M.'s invited.

THERMAL DEVICES DIVISION *John J. Fannon Co., Inc.*

16025 23 Mile Rd., Mt Clemens, MI • 48044-9747 • (313) 263-8850 • Telex: 211894 DOSS UR Patents applied for 1983
D-U-N-S 10-687-1536 • GOV.'T CAGE CODE I.D. No. IHJ00



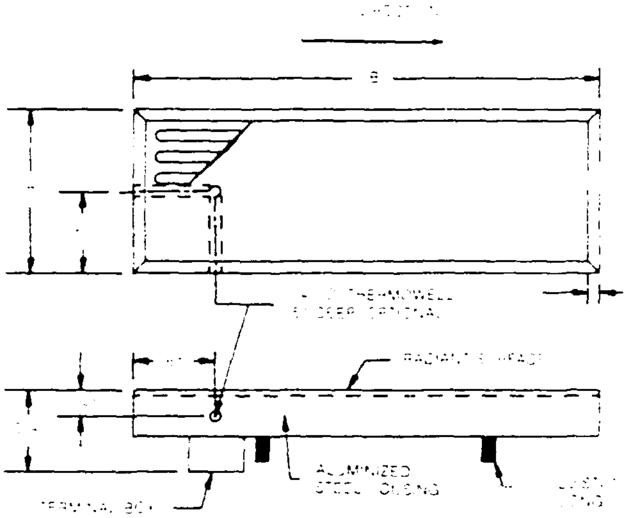
PAGES
199
THRU
216

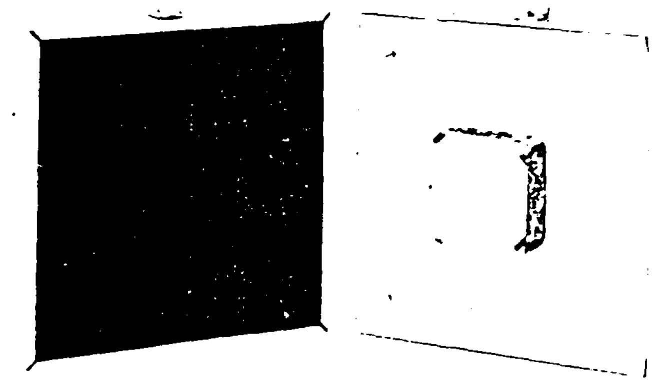
RADIANT PROCESS HEATERS

TYPICAL HEATING APPLICATIONS...

- ✓ AGGREGATE HOPPERS
- ✓ APPLIANCES
- ✓ CHEMICAL PROCESSES
- ✓ COMFORT AND SPACE
- ✓ DRYING AND CURING
- ✓ FILM SHRINKING
- ✓ FOOD EQUIP.
- ✓ HEAT SHRINKING
- ✓ INK DRYING
- ✓ LABORATORY TEST EQUIP
- ✓ LAMINATING
- ✓ MEDICAL EQUIP.
- ✓ MOLD AND DIE PREHEAT
- ✓ OUTDOOR EQUIP.
- ✓ OUTDOOR WORKERS
- ✓ OVENS AND TUNNELS
- ✓ PACKAGING MACH'Y
- ✓ PAINT DRYING AND CURING
- ✓ PIPELINE THAWING
- ✓ PLASTIC MACH'Y
- ✓ PREHEATING
- ✓ RESTAURANT FRONTS
- ✓ SNOW MELTING
- ✓ WELD PREHEATING

Quartz Infrared Radiant Panel Heaters
Style RB





TYPICAL APPLICATIONS

- THERMOFORMING
- PAINT DRYING
- INK DRYING
- CURING OF PLASTIC COATINGS
- HEAT SETTING
- SOLVENT REMOVAL
- SILK SCREEN PAINTING
- FOOD WARMING
- LAMINATING
- PLASTIC FORMING

CONSTRUCTION CHARACTERISTICS

TEMPCO style RB quartz infrared radiant panel heater has a woven quartz cloth surface which is transparent to radiant energy and is coated with black ceramic for high emissivity. Helically wound iron alloy based resistance coils are placed into a grooved refractory board and are cemented in place. The resistance coil and the grooves are carefully designed to provide uniform heat distribution. The refractory board is backed by layers of insulation to minimize heat loss. The housing is made of heavy gauge aluminized steel. The backside of the housing has a terminal box with ceramic terminal bushings and stainless steel terminals.

Style RB heaters are available with an optional quartz tube thermowell and a thermocouple bracket for standard 1/8" diameter thermocouple. When ordering heaters with thermowells, use prefix "T" before the catalog number. For various thermocouples and temperature controllers, see pages 225 throu[illegible] 246.

DESIGN FEATURES

TEMPCO style RB quartz infrared radiant panel heaters can transmit up to 80% of the input energy. They can operate at temperatures up to 1600°F (872°C) and watt densities up to 25 watts per square inch, to emit radiant heat in the usable wave length range of 2.5 - 6.0 microns. The wave length of the emitted radiant heat can be matched to the peak absorption wave length of the material being heated with proper temperature control. The heat-up time for style RB heaters at 25 watts per square inch is 2 - 5 minutes. They can be positioned as close as 2" from the material being heated.

Style RB heaters are available in convenient building block sizes and are equipped with mounting studs for easy installation. These can be mounted in any direction, and due to the bonded construction, they are resistant to shock and vibration. The simple yet rigid construction enables it to be easily adapted to many applications. These heaters do not require any reflectors which must be periodically cleaned or replaced.

STANDARD SIZES AND RATINGS

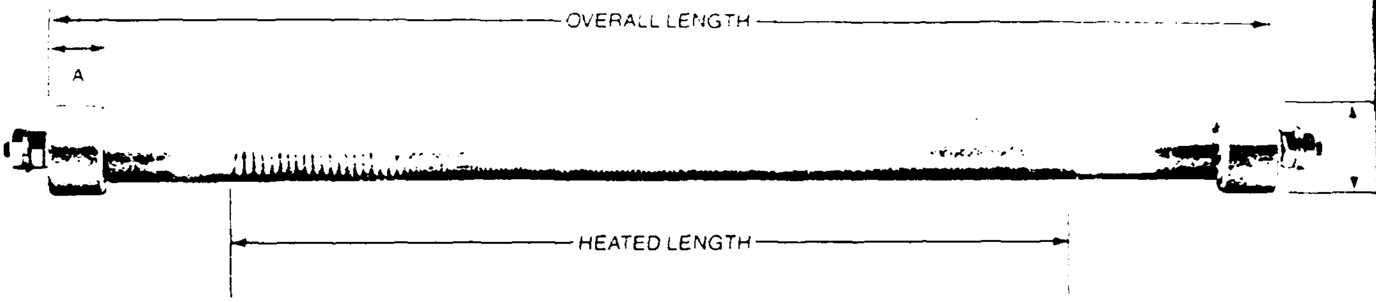
SIZE (IN.)		KILOWATTS		VOLTS			PHASE	CATALOG NO.
A	B	15W/IN²	25W/IN²	240/480	240	480		
12	6	—	1.8	•	—	—	1	RB1206
6	24	2.16	3.60	•	—	—	1	RB0624
12	12	2.16	3.60	•	—	—	1	RB1212
12	24	4.32	—	•	—	—	1	RB1224
12	24	—	7.20	—	•	•	3	RB1224
12	36	6.48	10.80	—	•	•	3	RB1236
12	48	8.64	14.40	—	•	•	3	RB1248
12	60	10.80	18.00	—	•	•	3	RB1260

HOW TO ORDER

Standard sizes and ratings of style RB heaters are listed in the table. When ordering, specify catalog number, kilowatts and volts. If thermowell is required, add prefix "T" to the catalog number.

Various other sizes are available upon request. Wattage ratings up to 25 watts per square inch and voltage ratings up to 600 volts are also available. Consult TEMPCO with your requirements.

Radiant Quartz Heaters



QUARTZ HEATERS ARE DESIGNED TO BE U[illegible]
HORIZONTAL POSITION ONLY

FEATURES

- COMPACT AND VERSATILE
- QUICK HEAT AND COOL RESPONSE
- FUNCTIONAL DESIGN
- CLEAN HEAT ENERGY
- LOWER POWER CONSUMPTION
- HIGH OPERATING TEMPERATURES
- MADE TO CUSTOMER SPECIFICATIONS

TEMPCO RADIANT QUARTZ heaters are specially designed for applications that require infrared radiant heating. **QUARTZ** heater basic design consists of a helically wound resistance coil housed by a pure vitreous silica fused quartz tube. The heating coil is specially designed to provide long life at rated voltage. The quartz tubing is terminated with specially designed ceramic insulating caps that allow the quartz tubing to breathe. The ceramic caps are securely fastened to the quartz tube with high temperature cement, providing excellent support to the power connecting termination.

TEMPCO RADIANT QUARTZ heaters are one of the most efficient sources of radiant energy. **QUARTZ** heaters can deliver near and far infrared wave lengths which are more effective than a single wave length, capable of generating full heat output capacity in 40 to 50 seconds and cool down in less than 15 seconds. They offer excellent life characteristics whether operated continuously or intermittently. For most efficient heating and longer operating life, quartz heating applications should be rated around 35 to 40 watts per square inch. Quartz heating elements do not give off an objectionable glare because of a very low emission in the visible spectrum. Optimum design provides a clear red color on the translucent quartz tube when operating at full voltage, providing an infrared wav length at energy peak of 2.5 to 3.0 microns. The wav length is almost completely absorbed by the process, an considered best for most industrial applications.

RADIANT QUARTZ heaters are primarily manufacture to customer specifications. When your products or process ing equipment require radiant energy, one of **TEMPCO'** standard **QUARTZ** heaters may be the perfect answer t your needs. For a full range of standard physical dimen sions, electrical ratings and a complete arrangement o screw terminals and lead terminations, see page 211.

TEMPCO ENGINEERING STAFF, WITH MANY YEARS OF EXPERIENCE IN HEAT PROCESSING AND TEM PERATURE CONTROL APPLICATIONS, CAN ASSIST YOU IN DESIGNING THE RIGHT **QUARTZ** HEATER FOR YOUR SPECIFIC APPLICATION

QUARTZ HEATER SPECIFICATIONS

DIMENSIONAL	
CERAMIC END CAPS:	QUARTZ TUBE O.D. A — B
	3/8" 5/16" 5/8"
	1/2" 1/2" 7/8"
	5/8" 1/2" 7/8"
DIAMETER:	3/8" — 1/2" — 5/8"
MAXIMUM LENGTH:	72"
MINIMUM LENGTH:	12"
LENGTH TOLERANCE:	Minimum ± 1/8" up to 12" long ± 2% over 12" long
SCREW TERMINAL:	10-32 threads
TERMINATION:	Type T1, L1, C4, ST, FT
ELECTRICAL	
RESISTANCE TOLERANCE:	Nema standard + 10% -5%
WATTAGE TOLERANCE:	Nema standard + 5% -10%
MAXIMUM VOLTS:	480 Volts when applicable
MAXIMUM AMPERAGE:	20 Amps when applicable
MAXIMUM WATT DENSITY:	40 Watts/IN²

HOW TO ORDER

Select a QUARTZ heater from page 211 which includes a wide range of diameters, lengths and electrical ratings. State quantity, part number, diameter, length, wattage and voltage, and termination type. If not otherwise specified, all QUARTZ heaters will be supplied with Type T1 termination.

For sizes, electrical ratings and terminations not listed, TEMPCO will manufacture a QUARTZ heater to your specifications— consult us with your requirements.

Radiant Quartz Heaters
Standard Terminations Sizes and Ratings

TYPE

10 flexible lead wire externally spliced standard. If longer leads required — SPECIFY.

TYPE

This termination provides 10-32 screw terminals insulated with ceramic terminal covers. Screws are prewired with 10 flex lead wire. If longer leads required — SPECIFY.

TYPE

STANDARD

10-32 thread screw terminal standard termination

TYPE

TABS WITH

1/2" wide X 3/4" long, with a 9/32" x 3/8" slot. Alternate mounting method.

TYPE

QUICK DISCONNECT

Fuse type connector provides ease of installation. Bar 3/8" diameter X 1/2" long.

TYPICAL APPLICATIONS

- SHRINK PACKAGING TUNNELS
- LAMINATING
- THERMO FORMING
- PLASTIC FORMING
- FUSING PLASTICS
- VULCANIZING RUBBER
- STERILIZATON
- SEALING
- FOOD WARMING
- THAWING
- ELECTROSTATIC COPYING EQUIPMENT
- FOOD PROCESSING
- DRYING PHOTO FILM EQUIPMENT
- CURING RUBBER
- DRYING TEXTILES
- DRYING LACQUERS, PAINTS
- DRYING SAND CORES
- SPACE HEATERS
- THERMAL DIAZO EQUIPMENT

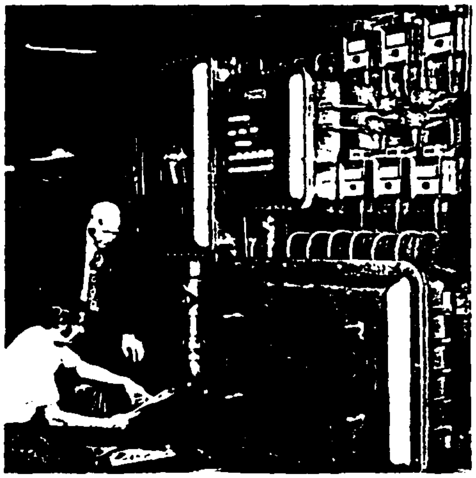
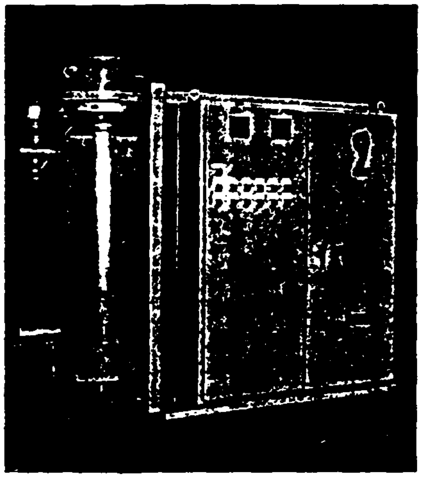
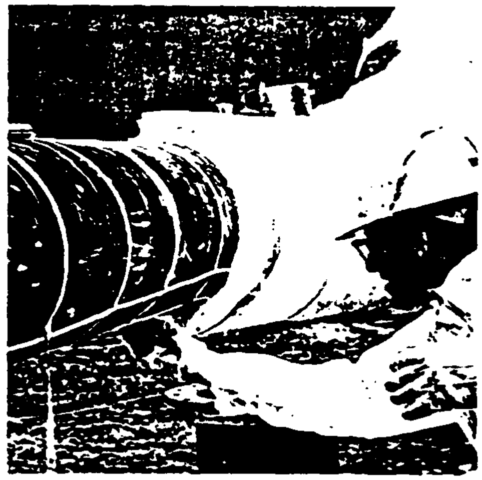
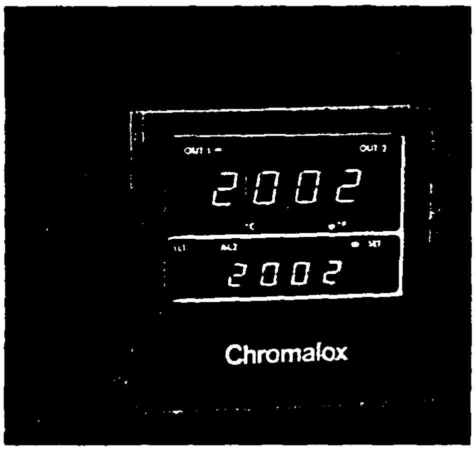
DIMENSIONS IN INCHES

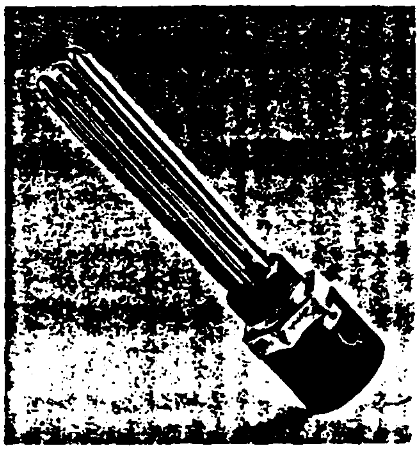
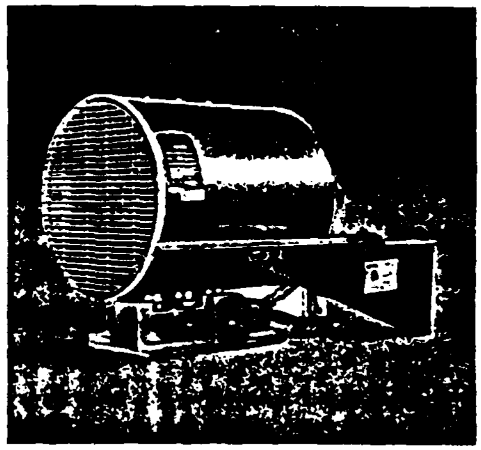
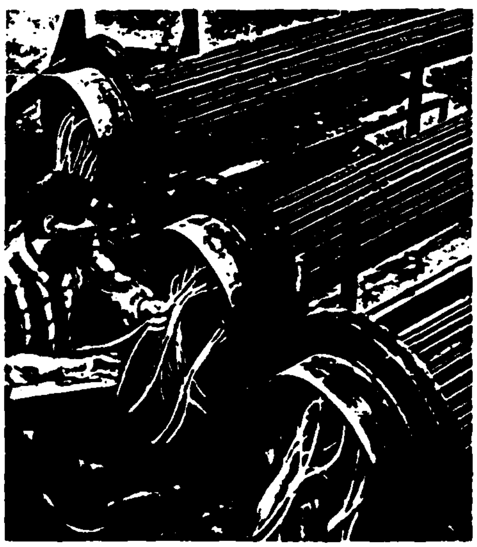
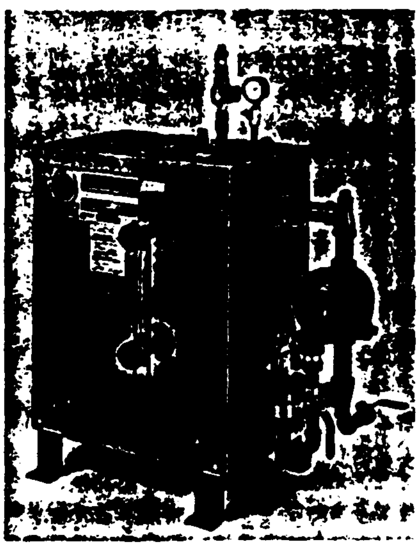
QUARTZ TUBE DIA.	OVERALL LENGTH	HEATED LENGTH	WATTS	VOLTS 120	VOLTS 240	CATALOG NUMBER
3/8"	14	12½	480	•	•	RT06-1400
	20	18½	720	•	•	RT06-2000
	26	24½	960	•	•	RT06-2600
	38	36½	1450	•	•	RT06-3800
	48	46½	1900		•	RT06-4800
1/2"	18	16½	900	•	•	RT08-1800
	20	18½	900	•	•	RT08-2000
	26	24½	1200	•	•	RT08-2600
	36	34½	1800	•	•	RT08-3600
	38	36½	1800	•	•	RT08-3800
	42	40½	1580	•	•	RT08-4200
	48	46½	1820	•	•	RT08-4800
	50	48½	2400		•	RT08-5000
	54	52½	2060		•	RT08-5400
	60	58½	2300		•	RT08-6000
	66	64½	2540		•	RT08-6600
	72	70½	2780		•	RT08-7200
5/8"	24	21	1075	•	•	RT10-2400
	26	23	1800	•	•	RT10-2600
	30	27	1375	•	•	RT10-3000
	38	35	2500		•	RT10-3800
	42	39	1975	•	•	RT10-4200
	48	45	2275		•	RT10-4800
	50	47	3400		•	RT10-5000
	54	51	2575		•	RT10-5400
	60	57	2875		•	RT10-6000
	62	59	4200		•	RT10-6200
	66	63	3175		•	RT10-6600
	72	69	3475		•	RT10-7200

P-120

Chromalox

Electric Heating Products, Controls and Systems


Quartz radiant heaters

0.5 to 3.8 kW

120, 208, 240, 480, 600V

Source temp. to 4000°F

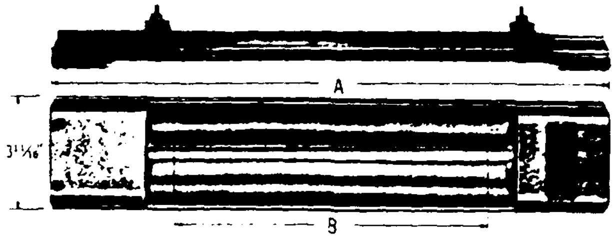
Type QR with quartz lamp element (3.9 kW/ft²)

Applications

- **Textiles and non-woven fabrics** — drying, resin finishing, heat setting and shrinking, booster pre-heating, controlling dye migration, fiber bonding, silk screen drying.
- **Plastics** — thermoforming, laminating, embossing, post-forming, film shrinking around palletized loads. Fusing coatings (plastisols, organisols), preheating and postheating materials for fluidized bed coatings, ink and paint drying.
- **Paper, paperboard** — curing latex and resin for high wet and dry strength selective drying of corrugated board liner, booster preheating, setting protein derivatives and clay coatings, laminating, fiber bonding, drying adhesives, ink drying.
- **Metals** — baking or curing finishes, water dry-off, weld preheating, shrink fitting, stress relieving.

Features

See following page.



Dim.-In. A	B	kW	Type QR — with 3/8" Quartz Lamp Volts	Catalog No.	Status	PCN	Element Used	Cat. No. Optional Grille
13 1/16	5	0.5	120	QR5B130	S	113849	500T3	N/A
13 1/16	5	0.5	120	QR5B131*	S	113857	500T3	N/A
18 1/16	10	1.0	208	QR10B830	NS	118527	1000T3	GR-800
18 1/16	10	1.0	240	QR10B230	S	113865	1000T3	GR-800
18 1/16	10	1.0	208	QR10B831†	NS	118535	1000T3	GR-800
18 1/16	10	1.0	240	QR10B231†	NS	118543	1000T3	GR-800
24 1/16	16	1.6	208	QR16B830	NS	118551	1600T3	GR-2
24 1/16	16	1.6	240	QR16B230	S	113902	1600T3	GR-2
24 1/16	16	1.6	208	QR16B831†	NS	118560	1600T3	GR-2
24 1/16	16	1.6	240	QR16B231†	NS	118578	1600T3	GR-2
33 1/16	25	2.5	480	QR25B430	S	113945	2500T3	GR-3
33 1/16	25	2.5	600	QR25B630	NS	118586	2500T3	GR-3
45 15/16	38	3.8	600	QR38B630‡	NS	118594	3800T3	GR-4

*Includes 6" BX and grounding plug
†Includes 6" BX and polarized plug
‡Produces 3000W on 480V
NA—Not Available

Specify: Quantity, catalog no., PCN, volts, kW, radiant heater

Quartz radiant heaters

0.35 to 4.30 kW

120, 240, 480V

Source temp. to 1600°F

Type QRT with 3/8" quartz tube element (1.33 kW/ft²)

Type QRT with 1/2" quartz tube element (1.75 kW/ft²)

Features

Higher operating temperatures than metal sheath elements permit faster work speeds in some applications.

More responsive heat-up/cool-down makes quartz heaters suitable for applications requiring immediate operating temperature and/or quickly reduced heat in event of work stoppage.

Quartz elements are mounted in a sturdy extruded aluminum housing containing a highly polished aluminum parabolic reflector.

Specially designed terminal blocks adjust for 3/8" or 1/2" dia. quartz elements.

Easy mounting in horizontal position only. Mounting clamps and bolts are furnished for back attachment to straight or specially formed steel straps, etc. Housing may be in any position in horizontal plane.

Modulation of radiant output with input controllers can be achieved by manual switching, variable transformers, or SCR controls. Type QR is not recommended where supply voltage fluctuates widely.

Note: Because terminal temperature can not exceed 650°F, forced cooling is sometimes necessary. Intense brightness of the quartz element may also cause visual discomfort if mounted in line of sight.

Available in other sizes and ratings. Quartz tubes are available in other sizes and ratings. Contact your Chromalox representative for price and availability.

Caution — Hazard of fire. These radiant heaters must not be operated in the presence of flammable vapors, gases or combustible materials without proper ventilation and/or other safety precautions, in compliance with either the National Fire Protection Bulletin 86A entitled "Ovens and Furnaces" or the authority having jurisdiction.

Dim. In.		Type QRT — with 3/8" Quartz Tube						Type QRT — with 1/2" Quartz Tube						Cat. No.
A	B	kW	Volts	Catalog No.	Status	PCN	Element Used	kW	Volts	Catalog No.	Status	PCN	Element Used	Optional Grille
18 1/16	10	0.35	120	QRT-10B130	NS	118607	1-047624	0.47	120	QRT-10B150	NS	118674	1-050048	GR-300
24 1/16	18	0.55	120	QRT-16B130	NS	118615	2-047624	0.73	120	QRT-16B150	NS	118682	2-050048	GR-2
24 1/16	18	0.55	240	QRT-16B230	NS	118623	4-047624	0.73	240	QRT-16B250	NS	118690	4-050048	GR-2
33 1/16	25	0.85	120	QRT-25B130	NS	118631	5-047624	1.10	120	QRT-25B150	NS	118703	5-050048	GR-3
33 1/16	25	0.85	240	QRT-25B230	NS	118640	7-047624	1.10	240	QRT-25B250	NS	118711	7-050048	GR-3
45 15/16	38	1.30	240	QRT-38B230	NS	118658	10-047624	1.70	240	QRT-38B250	NS	118720	10-050048	GR-4
45 15/16	38	1.30	480	QRT-38B430	NS	118666	12-047624	1.70	480	QRT-38B450	NS	118738	12-050048	GR-4
60 15/16	53	—	—	—	—	—	—	2.40	240	QRT-53B250	NS	118746	14-050048	GR-5
60 15/16	53	—	—	—	—	—	—	2.40	480	QRT-53B450	NS	118754	16-050048	GR-5
72 9/16	65	—	—	—	—	—	—	2.90	240	QRT-65B250	NS	118762	18-050048	GR-6
72 9/16	65	—	—	—	—	—	—	2.90	480	QRT-65B450	NS	118770	20-050048	GR-6
85 7/8	78	—	—	—	—	—	—	3.50	240	QRT-78B250	NS	118789	21-050048	(2) GR-4
85 7/8	78	—	—	—	—	—	—	3.50	480	QRT-78B450	NS	118797	23-050048	(2) GR-4
103 7/8	96	—	—	—	—	—	—	4.30	240	QRT-96B250	NS	118800	24-050048	(1) GR-2, (2) GR-4
103 7/8	96	—	—	—	—	—	—	4.30	480	QRT-96B450	NS	118818	26-050048	(1) GR-2, (2) GR-4

Specify: Quantity, catalog no., PCN, volts, kW, radiant heater

Quartz elements

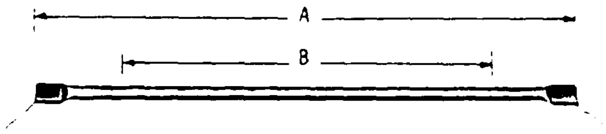
0.5 to 3.8 kW

120, 208, 240, 480, 600V

Source temperature to 4000°F

3/8" dia. quartz lamp

Type T-3 (100 W/linear inch)



Quartz lamp for type QR heater

Applications

- Install in QR quartz radiant heaters, LN or LW oven sections or LC reflectors.
- Produce near infrared radiation with peak wavelength of approximately 1 8 microns for a wide range of commercial and industrial heat applications.

Features

Coiled tungsten resistor is supported by round tantalum spacers which center the resistor in a quartz sheath.

Filament is sealed into each end of the sheath. (Seals are limited to 650°F)

Forced cooling of terminals may be required in some installations.

Sheath is exhausted and filled with inert gas.

Control. Radiant output may be accurately controlled with Type VC input controlle or SCR controller See Controls Section

Caution — Hazard of fire These radiant heaters must not be operated in the presence of flammable vapors, gases or combustible materials without proper ventilation and/or other safety precautions in compliance with either the National Fire Protection Bulletin 86A entitled "Ovens and Furnaces" or the authority having jurisdiction

kW	Volts	Dim.-In. A	Dim.-In. B	Catalog No.	Used in Quartz radiant htrs.	Status	PCN	Wt. lbs
Type T-3 quartz lamp (3/8")								
0.5	120	8 13/16	5	500T3*	QR-5B130, QR-5B131	AS	114614	[illegible]
1.0	208	13 13/16	10	1000T3	QR-10B830, QR-10B831, LN-15AL, LW-15AL	AS	114278	[illegible]
1.0	240	13 13/16	10	1000T3	QR-10B230, QR-10B231, LN-15AL, LW-15AL	AS	114286	[illegible]
1.6	208	19 13/16	16	1600T3	QR-16B830, QR-16B831, LN-21AL, LW-21AL	AS	114294	[illegible]
1.6	240	19 13/16	16	1600T3	QR-16B230, QR-16B231, LN-21AL, LW-21AL	AS	114307	[illegible]
2.5	480	28 13/16	25	2500T3	QR-25B430, LN-30AL, LW-30AL	AS	114315	[illegible]
2.5	600	28 13/16	25	2500T3	QR-25B630, LN-30AL, LW-30AL	AS	114323	[illegible]
3.8	600	41 13/16	38	3800T3	QR-38B630, LN-43AL, LW-43AL, LC-4	AS	114331	[illegible]
3.8	600	41 13/16	38	3800T3VB*	LN-43AL, LW-43AL, LC-4	NS	127317	[illegible]

*May be used in vertical position. All others must be used in horizontal position only

Specify: Quantity, catalog no., PCN, volts, kW, radiant element

Quartz elements

0.35 to 4.3 kW

120, 240, 480V

Source temperature to 1600°F

34 W/linear inch for 3/8" dia.

45 W/linear inch for 1/2" dia.

3/8" and 1/2" quartz tubes

Applications

Install in QRT radiant heaters, LN or LW oven sections or LC reflectors.

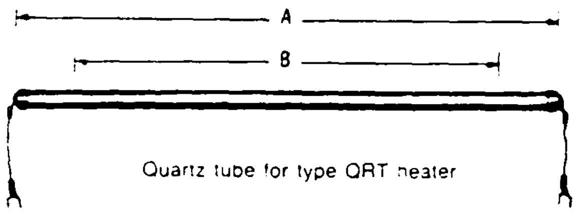
Produce intermediate infrared radiation with peak wavelength of approximately 2.55 microns.

Features

Coiled high temperature alloy resistor is supported by the quartz sheath which encloses it.

Additional sizes and ratings are available. Contact your local Chromalox representative for price and availability.

Caution — Hazard of fire. These radiant heaters must not be operated in the presence of flammable vapors, gases or combustible materials without proper ventilation and/or other safety precautions in compliance with either the National Fire Protection Bulletin 86A entitled "Ovens and Furnaces" or the authority having jurisdiction.



Quartz tube elements (3/8")

kW	Volts	Dim.-In. A	Dim.-In. B	Elem. Part No.	Used in Quartz radiant htrs.	Status	PCN	Wt. lbs.
0.35	120	13½	10	1-047624	QRT-10B130, LN-15AL, LW-15AL	AS	114235	2
0.55	120	19½	16	2-047624	QRT-16B130, LN-21AL, LW-21AL	AS	127925	3
0.55	240	19½	16	4-047624	QRT-16B230, LN-21AL, LW-21AL	AS	114243	3
0.85	120	28½	25	5-047624	QRT-25B130, LN-30AL, LW-30AL	NS	127933	4
0.85	240	28½	25	7-047624	QRT-25B230, LN-30AL, LW-30AL	AS	114251	4
1.3	240	41½	38	10-047624	QRT-38B230, LN-43AL, LW-43AL, LC-4	AS	114260	5
1.3	480	41½	38	12-047624	QRT-38B430, LN-43AL, LW-43AL, LC-4	AS	127941	5

All units are used in horizontal position only

Quartz tube elements (1/2")

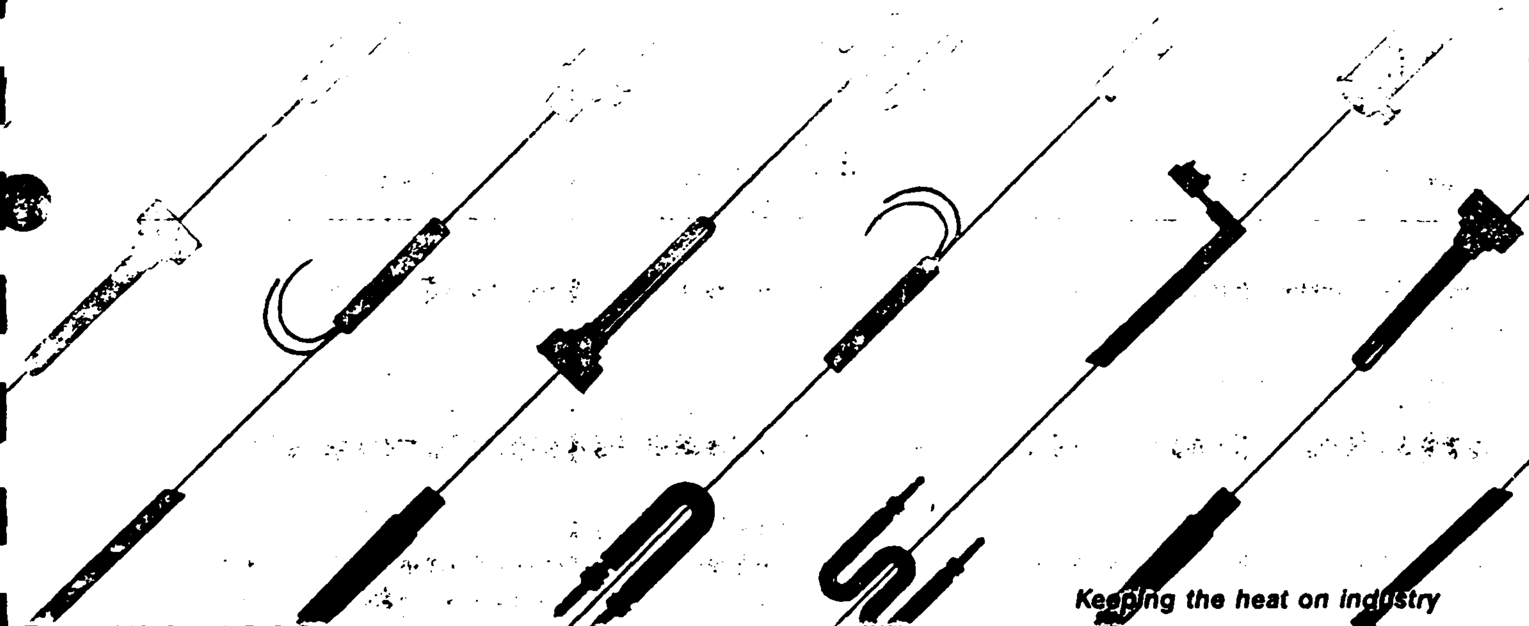
kW	Volts	Dim.-In. A	Dim.-In. B	Elem. Part No.	Used in Quartz radiant htrs.	Status	PCN	Wt. lbs.
0.47	120	13½	10	1-050048	QRT-10B150	AS	148507	1
0.73	120	19½	16	2-050048	QRT-16B150	AS	148515	1
0.73	240	19½	16	4-050048	QRT-16B250	AS	148523	1
1.1	120	28½	25	5-050048	QRT-25B150	NS	148531	1
1.1	240	28½	25	7-050048	QRT-25B250	AS	148540	1
1.7	240	41½	38	10-050048	QRT-38B250	AS	148558	1
1.7	480	41½	38	12-050048	QRT-38B450	NS	148566	1
2.4	240	56½	53	14-050048	QRT-53B250	AS	148574	2
2.4	480	56½	53	16-050048	QRT-53B450	AS	148582	2
2.9	240	68½	65	18-050048	QRT-65B250	AS	148590	2
2.9	480	68½	65	20-050048	QRT-65B450	AS	148603	2
3.5	240	81½	78	21-050048	QRT-78B250	NS	148611	3
3.5	480	81½	78	23-050048	QRT-78B450	AS	148620	3
4.3	240	99½	96	24-050048	QRT-96B250	NS	148638	4
4.3	480	99½	96	26-050048	QRT-96B450	NS	148646	4

All units are used in horizontal position only

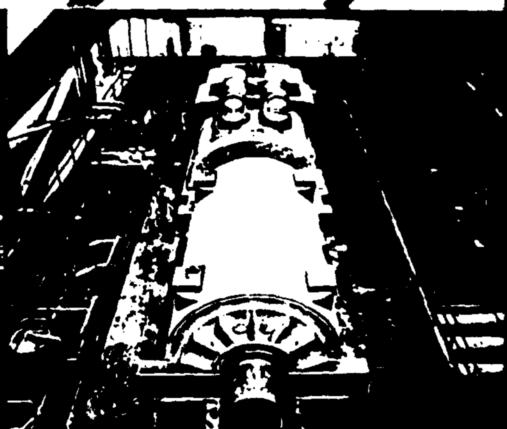
Specify: Quantity, PCN, volts, kW, radiant element.

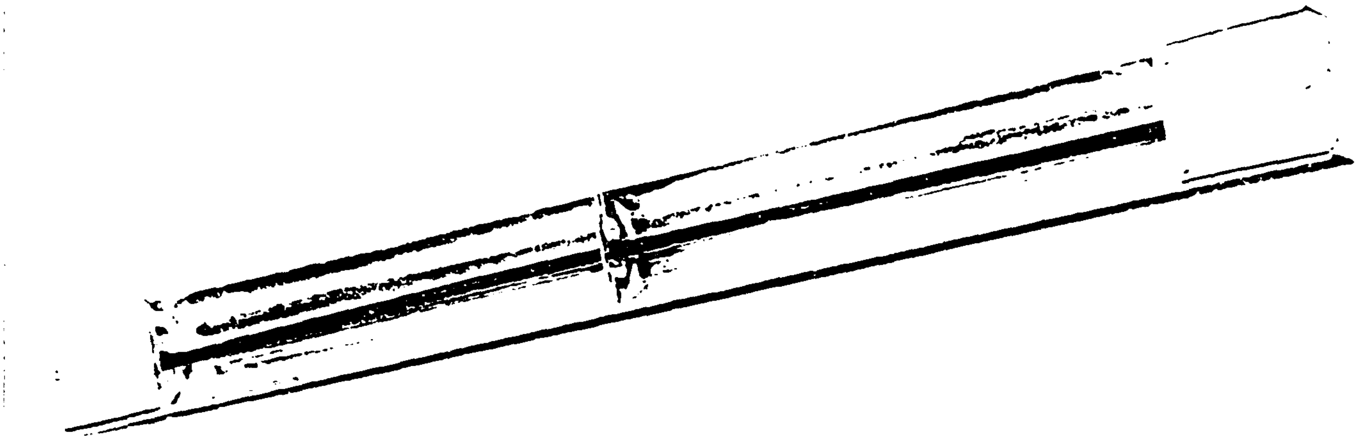
WELLMAN

INDUSTRIAL HEATERS AND CONTROLS



Keeping the heat on industry





Radiant Heaters
300—4,600 Watts using single element

Wellman™ General Purpose Infrared Radiant Heaters are uniquely designed to provide dependable, even radiation wherever safe, reliable performance is necessary. Uniform, efficient heat distribution assures product uniformity and high quality in process heating applications such as baking and curing, drying and fruit drying, softening of plastics and mass heating of steel parts such as molding.

Wellman radiant heaters are also used as comfort heaters as the sole heat source in manufacturing, warehouse or other localized areas that cannot be conveniently or economically comfort heated by other types of heaters—especially in exposed or semi-exposed areas and uninsulated buildings.

Wellman Series RH Radiant Heaters are available in eleven versatile heating lengths. Radiant heater housings and heating elements are ordered separately to ensure the most efficient and economical radiant heater best suited to specific applications. Selection data and examples of radiant heater calculations are found in the Technical Section of this catalog. Further assistance may be obtained from your local Wellman factory representative or from Wellman Thermal Systems Corporation.

Housing Data

Radiant Length (Inches)	Overall Length (Inches)	Radiant Housing Catalog Number Radiant Efficiency 85%
5	14	RH0500
8	17	RH1000
10	19	RH1500
16	25	RH2000
20	29	RH3000
25	34	RH4000
32	41	RH5000
38	47	RH6000
50	59	RH7000
62	71	RH8000
74	83	RH9000

Standard Features

- Available in 11 versatile lengths—from 5 to 74 inches.
- Accurately die-formed aluminized steel housing is sturdy, lightweight and corrosion resistant. Temperature expansion is minimal. All eleven housings have identical width and depth, varying only in length. Precise rectangular shape permits simple multiple assemblies.
- Multiplane reflector is superior to conventional curbed reflectors. Multiple overlapping reflector optics minimize uneven streaks in radiation distribution.
- Insulation behind each reflector—one inch of spun mineral fiber—reduces heat loss through the housing, providing cooler ambient temperatures behind the heater.
- Multiple terminal blocks, suitable for high temperature operation, permit series, parallel or open-delta connection of elements. Built-in wiring enables the power supply to be connected from either or both ends. Conduit knock-outs are conveniently located on the sides, ends or backs of the housing.
- Wide radiation patterns approximately 45 degrees wide with a single element provide broad heat coverage.

Benefits

- Broad selection of heater housings and heating elements to meet application requirements.
- Rugged construction for long operating life.
- Quickly and easily mounted and installed.
- Clean, efficient heat—with broad heat coverage.

Heating Elements

Wellman offers three different types of elements to match specific applications. All elements are shipped unmounted to avoid damage in transit.

The .430 and .496 inch metal sheath elements, the T-3 quartz lamp and the quartz tube are installed one-per-housing. The .315" elements can be installed two-per-housing to provide twice the wattage at rated voltage.

Metal sheath tubular elements are constructed of alloy sheath with nickel chromium coil imbedded in magnesium-oxide insulation. They are symmetrically round for uniform heat radiation. Flexible leads connected to terminal pins minimize terminal block exposure to high temperatures. 0.315 inch diameter, up to 240 volts; 0.430 up to 600 volts—provides safe operation. Secondary insulators are **not** required.

Quartz tubular elements are constructed of high temperature alloy coil inside a ½ inch diameter quartz tube. Translucent fused quartz provides highest infrared transmission capability of any material available. The quartz sheath shields radiating coil from ambient loss due to external drafts. Stainless steel terminal pins, fusion welded to flexible leads, provide dependable service. Standard elements are designed for horizontal installation of low (20 watts per linear inch) and moderate (50 watts per linear inch) intensities. Special elements are available for loading up to 75 watts per linear inch. Consult your Wellman factory representative.

T-3 quartz lamps feature a rugged tungsten filament operating in an inert gas atmosphere. The translucent fused quartz tube is hermetically sealed. Standard lamps are designed for horizontal operation at intensities of 100 watts per linear inch.

Element Data

5-inch Radiant Length for RH0500 Hsg

Element Type	Watts	Volts	Catalog Number
T-3 Lamp	500	120	RH0501

8-inch Radiant Length for RH1000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal	300	120	RH1301
Quartz Tube	400	120 208 240	RH1101 RH1100 RH1102
0.430" Metal	450	120	RH1601
T-3 Lamp	800	120	RH1201

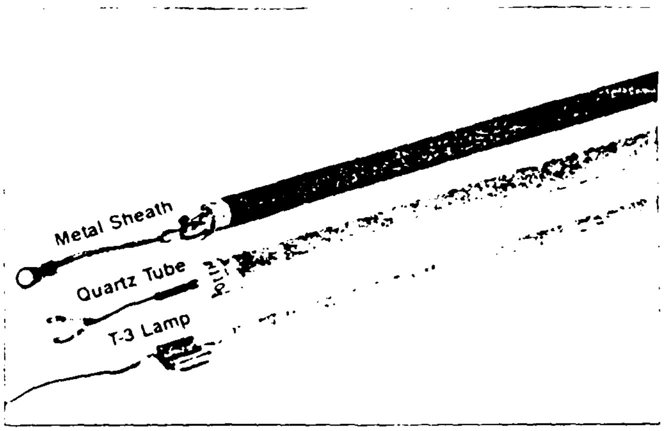
10-inch Radiant Length for RH1500 Hsg

Element Type	Watts	Volts	Catalog Number
T-3 Lamp	1000	208 240	RH1520 RH1522

16-inch Radiant Length for RH2000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal Sheath	600	120 208 240	RH2301 RH2300 RH2302
Quartz Tube	800	120 208 240	RH2101 RH2100 RH2102
0.430" Metal Sheath	900	120 240	RH2601 RH2602
0.496" Metal Sheath	1000	120 240	RH2501 RH2502
T-3 Lamp	1600	208 208 240 240 277 277	RH2200 RH2210 ▲ RH2202 RH2212 ▲ RH2203 RH2213 ▲

Typical radiant heating elements



20-inch Radiant Length for RH3000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal Sheath	800	120 208 240	RH3301 RH3300 RH3302
Quartz Tube	1000	120 208 240	[illegible] [illegible] RH3102
0.430" Metal Sheath	1100	120 208 240 277	RH3601 RH3600 RH3602 RH3603
0.496" Metal Sheath	1250	120 208 240 277	RH3501 RH3500 RH3502 RH3503

25-inch Radiant Length for RH4000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal Sheath	1000	120 208 240	RH4301 RH4300 RH4302
Quartz Tube	1250	120 208 240 277 480	RH4101 RH4100 RH4102 RH4103 RH4104
0.430" Metal Sheath	1400	120 208 240 277	RH4601 RH4600 RH4602 RH4603
0.496" Metal Sheath	1600	120 208 240 277	RH4501 RH4500 RH4502 RH4503
T-3 Lamp	2500	480 600	RH4214 ▲ RH4205

32-inch Radiant Length for RH5000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal Sheath	1250	120 208 240	RH5301 RH5300 RH5302
Quartz Tube	1600	120 208 240 277 480	RH5101 RH5100 RH5102 RH5103 RH5104
0.430" Metal Sheath	1800	120 208 240 277	RH5601 RH5600 RH5602 RH5603
0.496" Metal Sheath	2000	120 208 240 277 480	RH5501 RH5500 RH5502 RH5503 RH5504

[illegible] Radiant Length for RH6000 Hsg

Element Type	Watts	Volts	Catalog Number
0.315" Metal Sheath	1500	120 208 240	RH6301 RH6300 RH6302
Quartz Tube	1900	120 208 240 480	RH6101 RH6100 RH6102 RH6104
0.430" Metal Sheath	2100	120 208 240 277 480	RH6601 RH6600 RH6602 RH6603 RH6604
0.496" Metal Sheath	2400	120 208 277 480	RH6501 RH6500 RH6503 RH6504
T-3 Lamp	4020	600 600	RH6205 RH6225‡

50-inch Radiant Length for RH7000 Hsg

Element Type	Watts	Volts	Catalog Number
Quartz Tube	2500	208 240 277 480	RH7100 RH7102 RH7103 RH7104
0.430" Metal Sheath	2750	120 208 240 277 480	RH7601 RH7600 RH7602 RH7603 RH7604
0.496" Metal Sheath	3100	120 208 240 277 480 600	RH7501 RH7500 RH7502 RH7503 RH7504 RH7505

62-inch Radiant Length for RH8000 Hsg

Element Type	Watts	Volts	Catalog Number
Quartz Tube	3100	208 277 480	RH8100 RH8103 RH8104
0.430" Metal Sheath	3400	120 208 240 277 480	RH8601 RH8600 RH8602 RH8603 RH8604
0.496" Metal Sheath	3800	120 208 240 277 480 600	RH8501 RH8500 RH8502 RH8503 RH8504 RH8505

74-inch Radiant Length for RH9000 Hsg

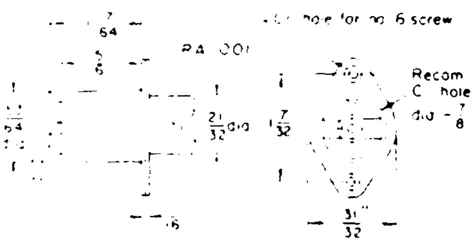
Element Type	Watts	Volts	Catalog Number
Quartz Tube	3700	208 277 480	RH9100 RH9103 RH9104
0.430" Metal Sheath	4100	120 208 240 277 480	RH9601 RH9600 RH9602 RH9603 RH9604
0.496" Metal Sheath	4600	120 208 240 277 480 600	RH9501 RH9500 RH9502 RH9503 RH9504 RH9505

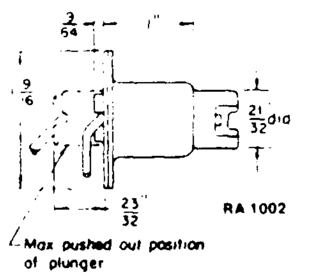
▲ Recessed single contact for spring loaded base

‡ Vertical burning lamp

Standard Options and Accessories

- Spring-loaded Sockets

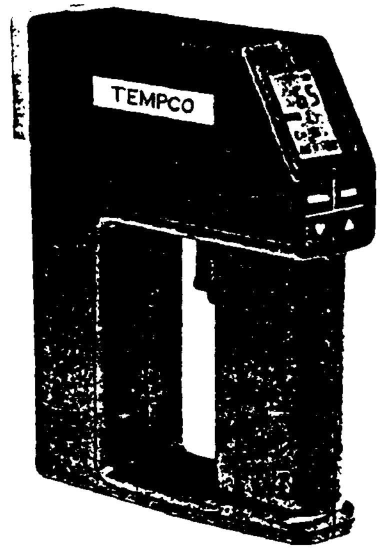




Accessories

- **Spring-Loaded Sockets** may only be used with T-3 heating elements factory-equipped with terminations for spring-loaded sockets. Wire size No. 18 AWG with 18 inch leads (2 required per element with terminal).
- **Mounting Bracket Kit**, Cat. No. RA1003, includes two complete bracket assemblies (four mounting angles plus hardware) for assembly to a radiant housing. Kit provides angular postioning of the housing through 180 degrees of rotation, in 15-degree increments.
- **Percentage Timer** for input control—refer to Controls Section.
- **Magnetic Contactor** for disconnecting heater circuits where circuit current exceeds amp limit of automatic temperature control devices. See Controls Section.

Beam-A-Temp™ Infrared Thermometer Noncontact-Handheld



NEW

DESIGN FEATURES

- RUGGED, PORTABLE, EASY-TO-USE
- MEASURE TEMPERATURE WITHOUT CONTACT
- -50° TO 1600°F
- 30:1 OPTICAL RESOLUTION
- DUAL DIGITAL TEMPERATURE DISPLAY
- ± 1% ACCURACY
- HIGH/LOW AUDIBLE ALARMS
- ANALOG AND RS 232 OUTPUTS
- 9 VOLT BATTERY OPERATION
- HANDY BELT-POUCH AND OPERATOR'S MANUAL

THE BEAM-A-TEMP™ IS AN EVERYDAY TOOL FOR USE THROUGHOUT THE PLANT AND YOUR MANUFACTURING PROCESS. FOR CHECKING TEMPERATURES OF ELECTRICAL AND HEAT EMITTING COMPONENTS, BEARINGS, STEAM TRAPS, ROOFING MATERIALS, INSULATED LINES, CONCRETE, PUMPS AND COMPRESSORS AS WELL AS PRODUCT TEMPERATURES.

PORTABLE NON-CONTACT INFRARED THERMOMETERS

If temperature is a factor in your quality, yield, equipment, safety, or research, then put the technology in the BEAM-A-TEMP™ (BAT) series to work for you.

The BAT series of portable IR thermometers is the most versatile available. Designed with form and function in mind, the microprocessor-based instrument is accurate and easy-to-use. A rugged, trigger-actuated, staple gun form factor gives unprecedented tool-like portability. The liquid crystal digital display provides you with two temperature readings at all times.

Operation is easy. You simply aim, pull the trigger, and read the temperature. There's no need to focus and no need to calibrate. The trigger is electronically lockable. A simple, 9-volt battery provides at least 40 hours of continuous operation.

GENERAL PERFORMANCE

The overall temperature range of the BAT series is -50 to 1600 degrees Fahrenheit. Response time is 250 mSec, far superior to any conventional contact method. For added accuracy, most models include digital adjustments for emissivity and ambient temperature.

The BAT precise infrared lens provides measurement of objects 0.7" or greater in size (0.9" for the BAT-2). Accuracy is NOT affected by measurement distance as long as your target fills the field-of-view.

DISPLAY FEATURES

Actual and MAX temperatures are always displayed. Fahrenheit or Celsius units are switch-selectable in all models. Most models also display the emissivity setting.

For added flexibility, some models calculate and display AVERAGE, MINIMUM, and DIFFERENTIAL values, as well as High and Low Alarms.

A low battery indication is included in the display for all models.

MEMORY AND DATALOGGING FEATURES

All models, except BAT-2 retain all temperature and statistical values in memory after every measurement. They are available for recall to display at any time. Every time the trigger is pulled to begin a new measurement, old values are erased.

All models, except BAT-2, have analog (1 mV per degree) AND digital (RS232) outputs, switch-selectable, for datalogging and recording. A printer accessory is available.

The BAT-5 has a built-in datalogging function which stores up to 64 readings. These could be taken from different sites around your facility, or at different times during a process. The information may be displayed, printed out, or transferred to a Lotus 1-2-3 spreadsheet on any IBM compatible p.c.

TYPICAL END USE APPLICATIONS

PLASTICS
- BLOW MOLDING
- THERMOFORMING
- VACUUM FORMING
- EXTRUSION
- INJECTION MOLDING
- LAMINATING
- RUBBER EXTRUSION
- RUBBER CALANDERING

MAINTENANCE
- FIND HOT SPOTS IN ELECTRICAL EQUIPMENT
- BEARING TEMPERATURES
- EQUIPMENT TEMPERATURES
- HVAC
- BOILER HOT SPOTS
- STEAM TRAPS
- PETROCHEMICAL

CONVERTING
- WEB MONITORING
- COATING
- DRYING AND CURING
- LAMINATING
- PAPER PROCESSING
- TEXTILES
- PRINT DRYING
- PACKAGING AND SEALING

CHEMICALS
- SINTERING
- CALCINING
- MANUFACTURE OF ASPHALT, COKE, CEMENT, ETC.
- PROCESSING PROPELLANTS AND EXPLOSIVES
- DRYING OF POWDERS, GRANULAR MATERIALS AND RESINS
- MIXING TEMPERATURES

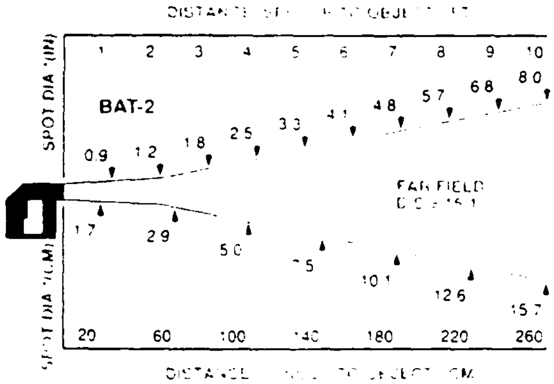
FOOD PROCESSING/ PHARMACEUTICAL
- MIXING
- COOKING
- ROASTING
- CANDY EXTRUSION
- CANDY MOLDING
- FONDANT/ICING
- COOLING DRUMS
- TEMPERATURE OF STORED PRODUCTS
- TABLET DRYING
- PILL COATING
- TOBACCO PROCESSING

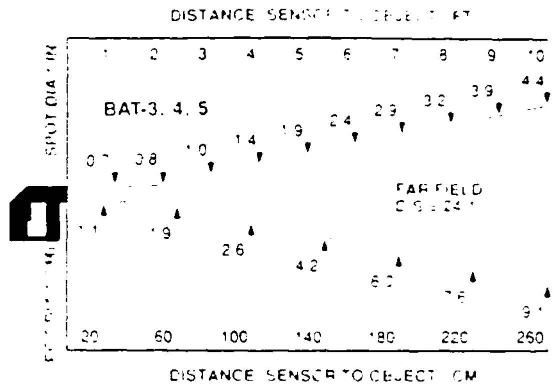
ELECTRONICS
- WAVE SOLDERING
- CIRCUIT-BOARD TESTING

CONSTRUCTION
- ROOFING TEMPERATURES
- ASPHALT

Beam-A-Temp™ Infrared Thermometers

Design Specifications



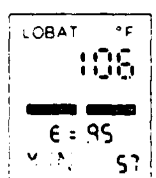


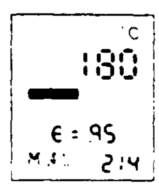
SPECIFICATIONS		BAT-2	BAT-3	BAT-4	BAT-5
Temperature range		0 to 1000°F (−18 to 540°C)		0 to 1600°F (−18 to 870°C)	
Emissivity		Fixed @ 0.95	0.10 to 1.0 Digitally Adjustable		
Temperature measurement	Current, MAX	✓	✓	✓	✓
	MIN, DIF, AVG			✓	✓
	Recall of last reading		✓	✓	✓
	Stores 64 points in memory				✓
Hi/Lo audible alarm				✓	✓
Ambient temperature compensation (T_a)				✓	✓
Locking trigger			✓	✓	✓
DC power input			✓	✓	✓
Data output: RS232C or 1 mV per degree (°C or °F)			✓	✓	✓
Accuracy		± 1% of Reading, ± 1 digit			
Repeatability		± 0.5 of Reading, ± 1 digit			
Spectral response		8 to 14 microns			
Response time		250 mSec			
Temperature display		°F or °C, switch selectable			
Ambient operating range		32-120°F (0-50°C)			
Power		9 VDC Alkaline or Lithium battery			
Dimensions (L × W × H)		5.5" × 1.75" × 7" (15 × 4.5 × 18 cm)			
Weight		1 lb, 4 oz (0.6 Kg)			
Tripod mount		1/4−20 UNC			
Accessories (BAT 3, 4, 5)					
AC Adaptor		9 VDC output at 100 mAmp, tip positive			
Output cable		36" (91 cm) Analog/Digital			
Printer		Thermal-type with internal battery or AC adaptor 1.8 × 5 × 8.5 in, (4.6x13 × 22 cm) 25 oz, 0.7 kg			
Spreadsheet software program		5¼" disk for data transfer to Lotus 1-2-3 (BAT-5 only)			

LCD DISPLAY FUNCTIONS

A UNIQUE LCD DISPLAY SIMULTANEOUSLY PROVIDES CURRENT TEMPERATURE IN °F OR °C AND EMISSIVITY ALONG WITH MAXIMUM, MINIMUM, AVERAGE OR DIFFERENCE.

Hi and *Lo* temperature limits may be set and an audible alarm activated when these limits are exceeded. *Lo Bat* indicates a low battery.





The *Lock* function allows you to lock the trigger in the on position. The BAT will also store *Last Temperature Read* and *Max* temperature for instant recall.