Millimetre Waves, Lasers, Acoustics for Non-Lethal Weapons?
Physics Analyses and Inferences

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Executive Summary

New technologies of non-lethal weapons (NLW) are under military research and development, mainly in the USA. Due to incomplete information, judgement under criteria of the laws of warfare or of human rights is hampered. This study analyses four potential NLW technologies which are based on physics to provide reliable information for such assessment.

The *Active Denial System* (ADS) produces a beam of electromagnetic millimetre waves; such radiation is absorbed in the upper 0.4 mm of skin. The beam stays approximately 2 m wide out to many hundreds of metres. With a power of 100 kilowatts, the beam can heat the skin of target subjects to pain-producing temperature levels within seconds. With a prototype weapon, mounted in a military multi-purpose vehicle, the effects have been tested on hundreds of volunteers. In order to produce pain while preventing burn injury, the power and duration of emission for one trigger event is controlled by a software program. Model calculations show that with the highest power setting, second- and third-degree burns with complete dermal necrosis will occur after less than 2 seconds. Even with a lower setting of power or duration there is the possibility for the operator to re-trigger immediately.

Collateral damage is not much of a problem. Use in armed conflict would bring much less injury than flamethrowers which count as legitimate weapons. However, such use is not very probable because the system is large, needs to be exposed for action and is vulnerable to many kinds of light weapons. More likely is its use for internal security, by occupation forces against uprisings etc. Taking into account that the operator may be up to one km away, in such circumstances overdoses with severe burn injuries could only be prevented if technical devices would reliably limit the skin temperature, i.e., would limit beam power or duration depending on target distance and would prevent re-triggering on the same person before a certain cooling time has passed.

The *Advanced Tactical Laser* (ATL), to be carried by a transport aircraft, is to emit an infrared laser beam of 300 kilowatts power, provided from a chemical reaction. Via a 0.5 m wide transmitting and directing mirror, the beam can be focused – under ideal conditions – to a spot of 0.1-0.2 m size over 10 km and more. With the 100-fold power of a stove plate applied over a similar area, wood or textiles would start burning and metal would melt through after fractions of a second, under usual atmospheric conditions on the order of one second. Strong turbulence will limit the range, fog, dust or heavy rain can reduce it markedly. With fuel for about 40 seconds of radiating on board and dwell times below a second, the beam will often be directed and fired automatically.

The ATL can destroy equipment and kill people, it is not a non-lethal weapon. Its usage in armed conflict against combatants could be compared with flamethrowers which are accepted under international humanitarian law. Compared to other means of applying force at many kilometres distance (artillery, bombs), the ATL would allow much more discriminating destruction.

The ATL has limitations: the fuel is sufficient only for around 100 "shots". A clear line of sight is also needed, preventing action through fog or heavy rain and exposing the carrier aircraft.

Due to its size, long range and drastic effects, the ATL is not suitable for police. In peace-enforcing operations it could allow more precise targeting than possible with artillery or

guided bombs, but collateral damage is nevertheless possible to several metres from an exploding tyre, fuel tank or munition.

The concept of the *Pulsed Energy Projectile* (PEP) is to use short, powerful, infrared laser pulses to produce a mechanical impulse. The laser works with a chemical reaction. If the pulse intensity is high enough, the uppermost target layer is explosively vaporised and the vapour heated to a plasma which absorbs the rest of the pulse and produces a laser-supported detonation wave. This shock wave exerts a mechanical impulse on the target. With a range of 0.5-2 km, the PEP is to be used against humans and equipment in armed conflict and law enforcement.

The ratio between impulse and laser-pulse energy is such that for a relatively high pulse energy of 1 kilojoule requiring a big, heavy laser (1-2 metres, hundreds of kilograms), the mechanical impulse with 0.1 newton-second is one to two orders of magnitude below the one from a rubber baton or an existing blunt-impact munition.

Multiple pulses in fast sequence would add, but then the target would be ablated to corresponding greater depth, measuring by millimetres. If bare skin were hit, bad wounds would ensue. In addition, permanent hearing damage may occur from the shock wave even from one laser pulse. If the eye is hit, serious injury by cornea ablation or mechanical impulse is probable.

In clear, non-turbulent air the spot focus will remain at a few cm size out to a few kilometres, but dense fog or rain will strongly limit propagation.

The PEP is a lethal weapon. It could be used selectively, without significant potential of collateral damage. Comparison with penetrating projectiles or flamethrowers shows that its use in armed conflict would not a priori contradict the rules of warfare. However, it should be investigated if severe wounds produced on bare skin, in particular to the face, and the loss of vision from eye injury may count as unnecessary suffering or superfluous injury.

The PEP has limitations. It needs a clear line of sight to the target so that it will be exposed and cannot work in thick fog or rain, it will be big, heavy, complex and expensive.

Due to its size, range and potential injurious effects, the PEP would neither be appropriate as a weapon for law enforcement nor for peace-enforcing operations. For mechanical blows and pain, blunt-impact projectiles provide much easier, much cheaper options with less risk of injury.

The *Long Range Acoustic Device* (LRAD) was developed in a weapon programme but is now denoted as a hailing and warning device. It is a flat loudspeaker which due to its diameter of 0.8 m has a relatively high directivity (beam opening angle 5-15°). It transmits mainly high frequencies (above 1 kilohertz); voice messages have a range above 500 m, warning tones (1000-fold intensity, level 30 dB higher) to above 1000 m. Since 2003, hundreds of copies have been sold to and used by mainly military forces, in particular of the USA in occupied Iraq, but police, port authorities and border patrol have also ordered the LRAD.

In the high-power warning mode the sound in front of the system is at levels dangerous to unprotected hearing. In order to prevent permanent hearing damage, the exposure has to be limited to a few seconds out to 50 m distance.

The LRAD has been used to expel snipers and repel pirates. For such use as a weapon, an evaluation under the laws of warfare should be done explicitly. The same holds for human-rights or constitutional law for weapon-like use by internal security forces. To

prevent hearing damage, technical devices should be introduced that limit the sound power and/or duration depending on the distance to the target subject(s).

The four technologies differ widely. The first three are clearly weapons, one (ADS) potentially lethal, the other two (ATL and PEP) lethal. The LRAD can be used for hailing and warning or in weapon mode. Final judgement whether introduction and use of these technologies is legally or morally justified, will strongly depend on the scenarios. Because all technologies can be problematic, continuous attention of human-rights organisations, the International Committee of the Red Cross etc. is needed.

Zusammenfassung

Neue Techniken nicht-tödlicher Waffen (ntW) sind in militärischer Forschung und Entwicklung, vor allem in den USA. Durch unvollständige Information wird die Beurteilung unter Kriterien des Humanitären Völkerrechts oder der Menschenrechte behindert. Diese Studie analysiert vier mögliche ntW-Techniken, die auf physikalischer Grundlage beruhen, um verlässliche Information für eine solche Beurteilung zur Verfügung zu stellen.

Das *Active Denial System* (ADS) erzeugt einen Strahl elektromagnetischer Millimeterwellen; solche Strahlung wird in den obersten 0,4 mm der Haut absorbiert. Der Strahl bleibt bis zu vielen hundert Meter etwa 2 m breit. Mit einer Leistung von 100 Kilowatt kann der Strahl die Haut von Zielpersonen innerhalb von Sekunden auf Schmerz erzeugende Temperaturen aufheizen. Mit einer Prototypwaffe, eingebaut in ein militärisches Mehrzweckfahrzeug, sind die Wirkungen an Hunderten von Freiwilligen erprobt worden. Damit Schmerz erzeugt wird, aber Verbrennungen vermieden werden, werden die Leistung und die Strahldauer für eine Waffenauslösung durch Software gesteuert. Modellrechnungen zeigen, dass bei der höchsten Leistungsstufe Verbrennungen zweiten und dritten Grades mit vollständiger Hautnekrose nach weniger als 2 Sekunden auftreten werden. Selbst mit einer niedrigeren Leistungsstufe oder Dauer hat der/die Bediener/in die Möglichkeit, sofort erneut auszulösen.

Kollateralschaden ist kein großes Problem. Anwendung im bewaffneten Konflikt würde erheblich geringere Verletzung hervorrufen als Flammenwerfer, die als legitime Waffen zählen. Solche Nutzung ist jedoch nicht sehr wahrscheinlich, weil das System groß ist, sich zur Wirkung exponieren muss und gegen viele Arten leichter Waffen verletzlich ist. Wahrscheinlicher ist die Anwendung für innere Sicherheit, durch Besatzungsstreitkräfte gegen Aufstände usw. Wenn man in Rechnung stellt, dass der/die Bediener/in bis zu einem km entfernt sein kann, könnten Überdosierungen mit schweren Verbrennungen unter solchen Umständen nur verhindert werden, wenn ein technisches Gerät zuverlässig die Hauttempera-tur begrenzen würde, d.h. die Strahlleistung oder –dauer in Abhängigkeit von der Zielentfernung begrenzen sowie verhindern würde, dass gegen dieselbe Person noch einmal gestrahlt würde, bevor eine gewisse Abkühlzeit vergangen ist.

Der *Advanced Tactical Laser* (ATL) soll in einem Transportflugzeug montiert werden und einen infraroten Laserstrahl von 300 Kilowatt Leistung aussenden, die aus einer chemischen Reaktion stammt. Über einen 0,5 m großen Sende- und Richtspiegel kann der Strahl – unter Idealbedingungen – auf einen Fleck von 0,1-0,2 m Größe über 10 km und mehr fokussiert werden. Mit der 100-fachen Leistung einer Herdplatte, die auf eine ähnliche Fläche einwirkt, würden in Sekundenbruchteilen Holz oder Textilien in Brand gesetzt werden oder Metall durchschmelzen. Starke Turbulenz begrenzt die Reichweite, Nebel, Staub oder starker Regen kann sie erheblich verringern. Mit Treibstoff für etwa 100 Sekunden Strahlung an Bord und Zielzeiten unter 1 Sekunde wird der Strahl in vielen Fällen automatisch gerichtet und abgefeuert werden.

Der ATL kann Gerät zerstören und Menschen töten, er ist keine nicht-tödliche Waffe. Nutzung im bewaffneten Konflikt kann mit Flammenwerfern verglichen werden, die nach dem humanitären Völkerrecht erlaubt sind. Verglichen mit anderen Mitteln, Gewalt über viele Kilometer Entfernung auszuüben (Artillerie, Bomben), würde der ATL viel selektivere Zerstörung erlauben.

Der ATL hat Beschränkungen: Der Treibstoff reicht nur für ungefähr 100 „Schüsse". Eine freie Sichtlinie ist nötig, was die Wirkung durch starken Nebel oder Regen verhindert und das Trägerflugzeug exponiert.

Durch seine Größe, lange Reichweite und drastische Wirkung ist der ATL für die Polizei nicht geeignet. In Friedens-erzwingenden Einsätzen könnte er genaueres Treffen erlauben, als das mit Artillerie oder gelenkten Bomben möglich ist, aber dennoch sind bis zu mehreren Meter von einem explodierenden Reifen, Treibstofftank oder von Munition Kollateralschäden möglich.

Das Konzept des *Pulsed Energy Projectile* (PEP) ist es, mit kurzen, starken, infraroten Laserpulsen einen mechanischen Impuls zu erzeugen. Der Laser arbeitet mit einer chemischen Reaktion. Wenn die Pulsintensität hoch genug ist, wird die oberste Schicht des Ziels explosionsartig verdampft und der Dampf bis zu einem Plasma aufgeheizt, das den Rest des Pulses absorbiert und eine Laser-unterstützte Detonationswelle erzeugt. Diese Stoßwelle übt einen mechanischen Impuls auf das Ziel aus. Mit einer Reichweite von 0,5-2 km soll das PEP gegen Menschen und Gerät benutzt werden, im bewaffneten Konflikt sowie in der Rechtsdurchsetzung.

Das Verhältnis zwischen Impuls und Laserpuls-Energie ist so, dass bei einer relativ hohen Energie von 1 Kilojoule, die einen großen, schweren Laser erfordert (1-2 Meter, hunderte Kilogramm), der mechanische Impuls mit 0,1 Newton-Sekunde eine oder zwei Größenordnungen unter dem von einem Gummiknüppel oder von Wuchtmunition für stumpfen Aufprall liegt.

Viele Pulse in schneller Folge würden sich addieren, aber dann würde das Ziel bis zu entsprechend größerer Tiefe abgetragen, die nach Millimeter misst. Wenn nackte Haut getroffen würde, wären schlimme Wunden die Folge. Zusätzlich kann es dauerhafte Hörschäden schon von der Stoßwelle nur eines Laserpulses geben. Wenn das Auge getroffen wird, sind schwere Verletzungen durch Hornhaut-Abtragung oder mechanischen Impuls wahrscheinlich.

In klarer, nicht turbulenter Luft wird der Brennfleck bis zu wenigen Kilometer bei wenigen Zentimeter Größe bleiben, aber dichter Nebel oder Regen wird die Ausbreitung stark begrenzen.

Das PEP ist eine tödliche Waffe. Es könnte selektiv genutzt werden, ohne großes Potential für Kollateralschäden. Der Vergleich mit durchdringenden Geschossen oder Flammenwerfern zeigt, dass seine Anwendung im bewaffneten Konflikt nicht von vornherein den Kriegsführungsregeln widersprechen würde. Es sollte jedoch untersucht werden, ob auf nackter Haut, inbesondere im Gesicht, erzeugte schwere Wunden oder der Verlust des Sehver-mögens durch Augenverletzungen als unnötiges Leiden oder überflüssige Verletzung zählen können.

Das PEP hat Beschränkungen. Es braucht eine freie Sichtlinie zum Ziel, so dass es exponiert ist, und funktioniert in dichtem Nebel oder Regen nicht, es wird groß, schwer und teuer sein.

Durch seine Größe, Reichweite und mögliche Verletzungswirkungen wäre das PEP als Waffe weder für Rechtsdurchsetzung noch für Friedens-erzwingende Einsätze angemessen. Für mechanischen Stoß und Schmerz bieten stumpfe Wuchtgeschosse eine viel leichtere, viel billigere Möglichkeit mit weniger Verletzungsrisiko.

Das *Long Range Acoustic Device* (LRAD) wurde in einem Waffenprogramm entwickelt, wird aber nun als ein Ruf- und Warngerät bezeichnet. Es ist ein flacher Lautsprecher, der wegen seines Durchmessers von 0,8 m eine relativ hohe Richtwirkung hat

(Strahlöffnungswinkel 5-15°). Es sendet vor allem hohe Frequenzen aus (über 1 Kilohertz); Sprachbotschaften haben eine Reichweite über 500 m, Warntöne (1000-fache Intensität, Pegel 30 dB höher) bis über 1000 m. Seit 2003 wurden hunderte Exemplare verkauft und von Streitkräften, insbesondere der USA im besetzten Irak, benutzt, aber Polizei, Hafenbehörden und Grenztruppen haben das LRAD ebenfalls bestellt.

Im Hochleistungs-Warnmodus hat der Schall vor dem System Pegel, die für das ungeschützte Gehör gefährlich sind. Um dauerhafte Hörschäden zu vermeiden, muss die Einwirkungsdauer in bis zu 50 m Entfernung auf einige Sekunden begrenzt werden.

Das LRAD ist verwendet worden, um Scharfschützen zu vertreiben und Piraten abzuwehren. Für solche Nutzung als Waffe sollte eine ausdrückliche Bewertung unter den Kriegsführungsregeln durchgeführt werden. Dasselbe gilt für die Menschenrechte oder das Verfassungsrecht für den Fall waffenartiger Nutzung durch innere Sicherheitskräfte. Um Gehörschäden zu vermeiden, sollte ein technisches Gerät eingeführt werden, das die Schallleistung und/oder –dauer abhängig von der Entfernung zu der Zielperson begrenzt.

Die vier Techniken unterscheiden sich stark. Die ersten drei sind klar Waffen, eine (ADS) potentiell tödlich, die anderen beiden (ATL und PEP) tödlich. Das LRAD kann für Rufen und Warnung oder in einem Waffenmodus benutzt werden. Die endgültige Beurteilung, ob Einführung und Nutzung dieser Techniken juristisch oder moralisch gerechtfertigt sind, wird stark von den Szenarien abhängen. Weil alle Techniken problematisch sein können, ist ständige Aufmerksamkeit von Menschenrechtsorganisationen, dem Internationalen Komitee des Roten Kreuzes usw. nötig.

1. Introduction

1.1 Rising Interest in Non-Lethal Weapons

Traditionally, so-called non-lethal weapons (NLW) have been used by the police for limited application of force under the principle of proportionality, with the intent of saving citizen's life and health. Typical police NLW are rubber or wood batons, tear gas and water cannons. On the other hand, armed forces have always used lethal weapons, from bayonets via machine guns to nuclear bombs.

Since the early 1990s a trend toward new types of NLW can be observed,[1] at first and mainly in the US,[2] with the Department of Defense the main promoter.[3] NLW are to provide new options for the military as well as for internal security forces (police, jail personnel etc.).[4] In the US, there were at first a few individual proponents,[5] then the Department of Defense set up a committee and in 1996 issued the directive "Policy for Non-Lethal Weapons".[6] In 1997 it founded the Joint Non-Lethal Weapons Program and Directorate (JNLWP, JNLWD).[7] Their task is to provide non-lethal weapons to the armed forces, including research and development (R&D) of new technology. Annual funding for this programme was at several tens of millions of dollars in the early 2000s – which is very small compared to the total military R&D budget of many tens of billions of dollars per year.[8]

The International Committee of the Red Cross and non-governmental organisations are concerned about the new discussion of non-lethal weapons. They fear an erosion of the international humanitarian law or of human rights.[9] Some see NLW developments as a strategic concept of Western states to cope with insecurity from proliferation of military technologies, a widening rich-poor gap and global environmental constraints, in particular to stop mass migration caused by resource depletion and climate change.[10]

The purpose of NLW is to apply force with a low risk of killing or permanently injuring target subjects or destroying target objects.[11] For NLW application one can differentiate between four broad areas: war/armed conflict, peace operation, use against crowds and use against criminals. The actors, rules of operation, possibilities of legal checks etc. are markedly distinct – which is often left vague by NLW proponents.[12] Also within these areas there are

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1   For the history of NLW in the 1960s to 1980s, in the 1990s and since 2000 see Davison, 2006, 2007, 2007a, respectively.

2   Among other countries with NLW activities are Brazil, Czech Republic, Germany, India, Israel, Netherlands, Russia, Sweden, United Kingdom.

3   However, the National Institute of Justice is also involved and has a research program of its own.

4   Dando, 1996; Lewer/Schofield, 1997; Alexander, 1999; Future 2001.

5   One of the most prominent proponents has been former special-forces colonel John B. Alexander, see Alexander 1999, 2003, 2007.

6   US DoD, 1996. NATO followed in 1999 with a similar declaration, NATO, 1999. These directives stress that NLW are to complement, not replace lethal weapons. NLW motives of the US military stem more from concern about public opinion than about the fate of the target subjects, see Altmann/Reppy, 2008.

7   https://www.jnlwp.com.

8   Average annual funding 2000-2003 was at $22 million and around $44 million 2004-2007, Davison, 2007a, pp. 18f. A task force of the Council on Foreign Relations has recommended a marked increase to around $300 million per year, Allison/Kelley/Garwin, 2004.

9   E.g. Loye 2003, 2007; Amnesty International, 2006, 2007.

10   Rogers, 2000; Wright, 2007. I want to thank Steve Wright, Praxis Centre, Leeds Metropolitan University, for helpful remarks on the context of NLW use.

11   Because any application of force can result in death, sometimes the term 'less lethal' weapons is used; others put "non-lethal" in quotation marks.

12   E.g. Alexander's books are titled „Future War" (1999) and "Winning the War" (2003), but discuss mainly non-war conflicts.

strong differences, e.g. between smugglers and hostage-takers. Thus the judgement of NLW under ethical and legal viewpoints will turn out differently, too.

There are a few "NLW" where lethal effects are explicitly included, where the force can be "rheostatically" controlled on a spectrum from annoyance to killing. Examples are the Advanced Tactical Laser and the Pulsed Energy Projectile discussed in Chapters 3 and 4, respectively. Here the designation as "non-lethal" is obviously not justified, as one can also apply non-lethal force with a rifle.[13]

From the beginning of the new debate, there was much speculation about new types of NLW. Effects ascribed to infrasound or explosive-eating microbes bordered on miracles. Scientifically unfounded allegations made by individual proponents were echoed in the military press, in reports of military contractors to defence departments and in studies by peace researchers.[14] Policy recommenddations and decisions should be based on thorough knowledge, not on assumptions and impressions from the media. Thus, if – as usual in military research and development – there is no complete, reliable knowledge about a potential new weapon technology, it is important that independent academic research is done to fill gaps and correct false impressions. This scientific-technical information is needed as a basis for well-founded decisions on deployment, regulation, preventive limitation.

Such analyses need not start from scratch. Often there is at least rudimentary information available, e.g. from press releases by military agencies or contractors, media reports or conference contributions. Beginning here one can firstly apply well-known laws of physics, such as beam widening from diffraction of propagating waves. Secondly, one can use published experiments and theoretical models that fit to the application at hand. Thirdly, there is the technological state of the art, e.g. concerning the efficiency of engines or of certain laser types. In the case of the millimetre-wave weapon Active Denial System (treated in Chapter 2), there are even scientific publications giving results of the research on weapon effects. On heating and ablation by high-power lasers – applicable to the laser weapons discussed in Chapters 3 and 4 – much research has been published in various contexts. Acoustics is a well-known field, and several specifications of the commercial Long Range Acoustic Device analysed in Chapter 5 have been published by the manufacturer.

Among the new NLW technologies that can be taken seriously there are several which are based on principles of physics.[15] Four of them are analysed in this report.[16]

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13 Note that some call the narcotic-gas operation of October 2002 in the Moscow Nordost theatre non-lethal even though about 130 of the 700-800 hostages died – a portion of dead that is similar as in armed conflict (International Committee, 1997). Because of different sensitivies of people and varying conditions, death of a significant portion of the people summarily exposed to narcotics cannot be avoided. This is not to say that such an operation is never justified, but calling it non-lethal is inappropriate. See Klotz/Furmanski/Wheelis, 2003; Klochikhin, 2005.

14 For example, Alexander (1999, p. 121) wrote of consumption of dry explosive by microbes; this ties in with his advertising energy from vacuum, anti-gravity or cold fusion (2003, pp. 229-232). On NLW allegations and the echoes see Altmann, 2001a.

15 Various concepts of chemical or biological NLW should also be taken seriously – first because of their principal feasibility, second because they are used to question the Chemical and the Biological Weapons Conventions. See e.g. Dando, 2002; Sunshine, 2003; Klotz et al., 2003.

16 The manuscript was finished in February 2008.

1.2   Structure of the Report

The NLW concepts analysed here use millimetre waves, laser radiation or sound waves. The first has become known as the *Active Denial System* (ADS). Its 95-Gigahertz radiation is strongly absorbed in water, in human skin in the first 0.4 mm, producing intense heat pain. The *Advanced Tactical Laser* (ATL) uses near-infrared radiation from an aircraft-based oxygen-iodine laser to heat the surface of any material so fast that it melts, vaporises, catches fire or explodes after a second or faster. The *Pulsed Energy Projectile* (PEP) works with a deuterium-fluoride laser, producing intense, very short mid-infrared pulses which heat up only a very thin surface layer so fast that it immediately vaporises and forms a plasma. Further heating of the plasma produces a shock wave that exerts a mechanical impulse on the target. With many pulses, the total impulse can become strong while the target surface is ablated further. The *Long Range Acoustic Device* (LRAD), which derives from weapon R&D, but is explicitly not called a weapon, but a hailing and warning device, acts as a directional loudspeaker to address people over hundreds of metres in distance, or to distract and annoy them by a loud warning signal.

These four technologies are analysed in the following chapters.[17] In each chapter, research, development and current status are presented. Then the technology is analysed, starting at the available information and applying scientific-technical methods to find out important features and fill gaps in published information. Based on both, the properties of the technology or weapon system are given. The evaluation sub-chapter looks at potential problems considering arguments from international humanitarian law and human rights and presents first considerations on preventive limits or on rules of engagement. Then needs for further research are identified. The final chapter gives a few concluding remarks. The Appendix explains basic facts about radiation, its units, and heating.

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17   The Directed Stick Radiator is a different acoustic-weapon concept; because not much R&D have been reported lately, it has not been included in the present analysis. The same holds for vortex rings, a non-acoustic means of applying slight force or transporting gases or aerosols over tens of metres..

2.   Active Denial System (ADS)

2.1   Research and Development, Status

In the past decade a millimetre-wave weapon for use against humans has been developed in the USA. It is to produce heat pain from radiation absorption in the uppermost layers of the skin, with a range greater than that of small arms. The target subjects are to be repelled by the pain, while burn injury is to be prevented.

Research of skin heating by millimetre waves for a non-lethal weapon and and development of what was first called Active Denial Technology, then the Active Denial System (ADS), began 1992.[18] A frequency of 95 GHz (wavelength 3.2 mm) was chosen, probably because here the atmosphere has a transmission maximum and because here the water absorption is so strong that the radiation is stopped in the upper tenths of a millimetre of skin. This work, done under the auspices of the Joint Non-Lethal Weapons Directorate (Quantico, VA) and the Air Force Research Laboratory (Directed Energy Directorate, Kirtland AFB, NM, Human Effectiveness Directorate, Brooks AFB, TX), was secret until 2000. Research of effects was done at the Human Effectiveness Directorate, Directed Energy Bioeffects Division, at Brooks. Prime contractors were: Raytheon AET (Rancho Cucamonga, CA) for systems integration, Communication and Power Industries (CPI, Palo Alto, CA) for the mm-wave source and Veridian Engineering (San Antonio, TX) for biological-effects research.[19] Even during the secret phase, some results on effects were published in scientific journals, the motivation given was that the mm-wave region was being more widely used, so that it was important to know the thresholds for pain and injury.[20] When the researchers wanted to do secret experiments with human subjects, they encountered an administrative problem. After unethical radiation experiments with humans in the 1940s to 1970s had become uncovered, President Clinton had strongly tightened up the procedures for approval of secret human testing.[21] The Secretary of Defense him- or herself had to sign approval. Defense regulations demanded that this occurs within 30 days of approval by the institutional review board, which requirement could not be met twice. The way out was to de-classify the project – this was achieved in December 2000 – and apply for human experiments under the normal rules.[22] Thereafter, press releases and fact sheets were published which provided at least some basic information, and more scientific publications appeared which now explicitly acknowledged the interest in mm-wave non-lethal weapons.[23]

At a frequency of 95 GHz the penetration depth (amplitude decrease to 1/e, intensity decrease to $1/e^2 = 0.14$) in human skin is 0.4 mm,[24] thus heating occurs only at the surface of the body, internal organs are not directly affected.

Millimeter-wave radiation of 100 kW maximum power is produced by a gyrotron tube with a superconducting magnet of 3.7 Tesla, cooled by a cryo-refrigerator.[25] In public, the military

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18   AFRL, 2001; Murphy et al., 2003. The concept emerged in 1989, JNLWD, 2006: p. 8.
19   AFRL, 2001. Several more military institutions are involved.
20   E.g. Ryan et al., 1999 ; Walters et al., 2000.
21   Memorandum, 1997.
22   Beason, 2005: Ch. 9.
23   E.g. Walters et al., 2004.
24   Nelson et al., 2000, 2003.
25   Johnson, 2007; for the power value see Section 0.

have stated that the ADS can act "beyond small arms range" and that the weapon is effective from the "muzzle" to 500 m.[26]

The first prototype, ADS system 0, was built into an immobile 20-ft. container, powered from the electricity grid, between 1997 and 2000 (Figure 1a).[27] This was used in the first human experiments. In 2001/02 the program was designated as an Advanced Concept Technology Demonstration (ACTD) to accelerate transfer to the troops.[28] Under this program, a mobile prototype was mounted on a wheeled vehicle (HMMWV) in 2005 (Figure 1b).[29] Here the system is powered by a large lithium-ion battery which is charged by a 100 kW peak, 85 kW continuous generator driven by the vehicle Diesel engine.[30] With this ADS system 1, Military Utility Assessments (MUA) have started in 2005. In late 2006, the Extended User Evaluation phase has begun which will run throughout 2007. A more modular ADS system 2 is under construction, capable of working in hotter environments; this will be mounted at a fixed site or on a tactically mobile truck (Figure 1c, d).[31]

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26   JNLWP, 2007, 2007a.
27   JNLWD, 2006; p. 8, 2007: p. 2.
28   JNLWP, 2007, gives 2001; JNLWP, 2006a, gives 2002 for the ACTD.
29   AFRL, 2001; JNLWP, 2006, 2007a; Johnson 2007.
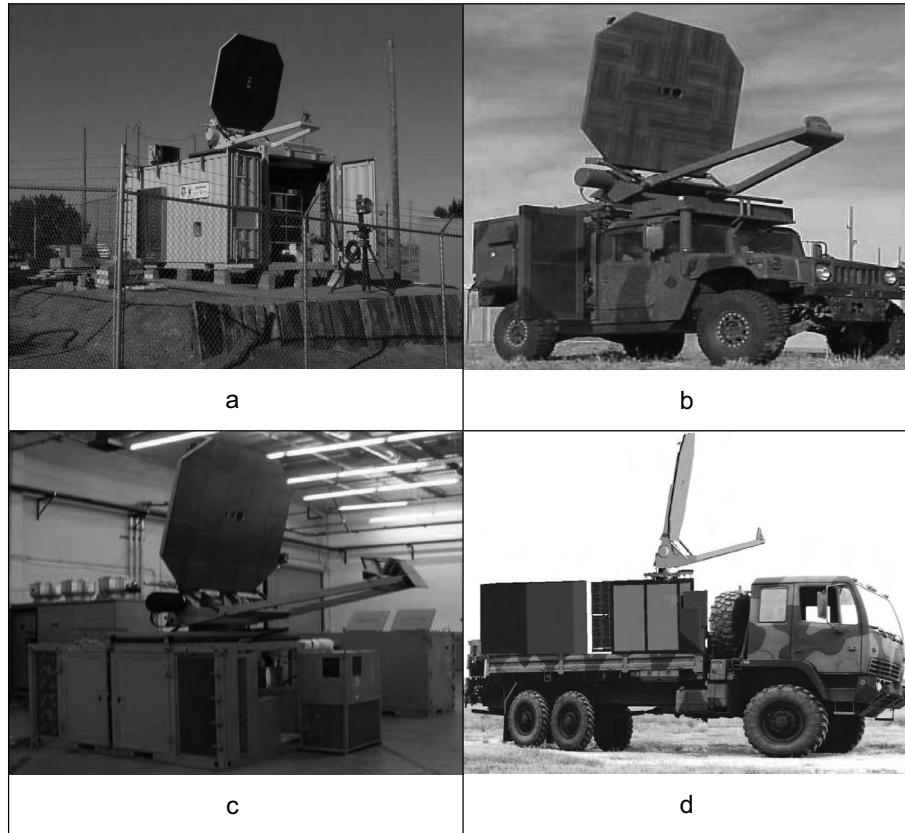30   Johnson, 2007.
31   JNLWP, 2006a.

Figure 1 Stages of the Active Denial System. [32]
a) Technology Hardware Demonstrator (ADS System 0).   b) ADS system 1.
c) ADS system 2,   d) intended mounting on truck. (US DoD images)

Further work is going on in several directions: Raytheon is offering a commercial system, Silent Guardian, which is smaller than ADS (antenna 1.14 m * 1.14 m, beam power 30 kW, range above 250 m), at a cost below $10 million.[33] Sandia National Laboratories is investigating a much smaller system (400 W power) where the emitter and antenna (about 1 m * 1 m) are mounted on a tripod.[34] A system for deployment on aircraft is under development – Communications & Power Industries got a first contract of $7 million in 2004; the goal of gyrotron-tube development is a power of 2.5 MW, 25 times the ADS value.[35] Also the possibility of a hand-held option has been mentioned.[36]

In 2001, a series of tests with human volunteers began, starting with exposing standing people from the back, then from the front, and then in settings that increasingly simulate operational conditions (e.g. repelling violent demonstrators trying to intrude into a US

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32   AFRL, 2001; JNLWP, 2006a; JNLWP, 2007.
33   Raytheon, 2006; AWST, 2006. The system is housed in small container that fits on the bed of a Ford F550 medium-duty truck. Power for the gyrotron comes from an auxiliary 200-kW generator.
34   SNL, 2005; AWST, 2006.
35   Hilltop Times, 2004.
36   JNLWP, 2007.

military base in a middle-eastern country).[37] As of autumn 2006, more than 600 subjects were subjected to ADS radiation in over 10,000 exposures.[38] These experiments and their results have not been published, however the experiment designs have become available due to requests by the US-based Sunshine Project under the US Freedom of Information Act.[39] The Project got about 14 human-testing protocols (classified "official use only"). These protocols describe the planned experiments, discuss benefits and risks to subjects etc., for getting permission to carry them out.

Laboratory research with animals and human subjects that was published scientifically has investigated various basic issues. For short-term exposure (3 s), the pain threshold for a small exposed area (around 1 cm^2) is at 1.25 W/cm^2 intensity, corresponding to 3.8 J/cm^2 fluence,[40] leading to a skin-temperature increase of 9.9°C.[41] The threshold seems to be lower by only 20%, namely at 1.0 W/cm^2, if an area slightly above 30 cm^2 is exposed.[42]

Minor eye injury in monkeys has a threshold of 5 J/cm^2 for intensities between 2 and 8 W/cm^2.[43] Several human-testing protocols argue that the blink reflex limits the corneal exposure to < 0.25 s.[44] If one could rely on this time, the fluence at the highest intensity probably used in human testing, 8 W/cm^2 (see note 72 below) would be limited to 0.25 s * 8 W/cm^2 = 2 J/cm^2, clearly below the threshold for minor damage.[45,46]

In an animal model of cancer promotion, no such effect was observed with exposure to 1 W/cm^2 for 10 s or repeated exposures to lower intensity.[47]

Skin-heating experiments were carried out using intensities of 1-2 W/cm^2, leading to a temperature increase by up to 10°C in a few seconds; the process was successfully modelled, blood-flow cooling and thermoregulation are not relevant with such fast heating.[48] Citing earlier literature, it is reported that the heat-pain threshold is reached at

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37 Protocol FWR-2003-03-31-H.
38 JNLWP, 2006b.
39 http://www.sunshine-project.org. Special thanks go to the Sunshine Project for providing access to the human-testing protocols. The available protocols are from the period 2001 to 2006. Some can be accessed via http://www.wired.com/ news/technology/0,72236-0.html.
40 Intensity I is (incident) beam power P per area A: $I = P/A$ (power is energy per time, $P = E/T$). Fluence F is intensity integrated over irradiation time T, for constant intensity $F = I\,T$, that is, fluence is total impinged energy per area: $F = E/A$. For short times, the increase in temperature depends on fluence; however, if there is more time so that heat energy can flow to deeper layers (or, at even longer times, be removed by blood flow or sweating), intensity becomes the more relevant quantity. See Appendix.
41 Walters et al., 2000. Temperature differences are often given in Kelvin, the unit of the temperature scale which starts at the absolute zero point (0 K = -273.2 °C). Differences are numerically equal between Kelvin and °Celsius.
42 This information is given in one of the human-testing protocols, Protocol FWR-2002-0046-H.
43 Defined as epithelial fluorescein staining plus epithelial edema, Chalfin et al., 2002. When 5 J/cm^2 was applied within 1 s (i.e., with intensity 5 W/cm^2), the maximum corneal temperature reached at the end of irradiation was 61°C.
44 E.g. Protocol FWR-2003-0028-H. Also the Joint NLW Program maintains that the eyes are protected by the natural blink reflex, aversion response and head turn, JNLWP, 2006b.
45 Note, however, that there are some inconsistencies. In Protocol FWR-2003-0028-H it is reported that "D'Andrea et al. (in preparation) have shown that monkeys and humans produce blink reflexes that protect the cornea at energy densities of about 1 J/cm^2, with response latencies less than 250 ms." Protocol FWR-2003-03-31-H makes similar statements, referring to "D'Andrea et al., 2002" and "D'Andrea et al. (in preparation)". In Protocol FWR-2005-0003-H now the full list of authors and the article title are given (D'Andrea JA, Ziriax JM, Cox DD, Henry PJ, Kosub KK, "Eye Aversion To 94 GHz Radiation By Non-Human Primates (Macaca mulatta)" – note that humans are not included, different from the statements in the protocols), the year varies between 2002 and 2004, still "in preparation". The same holds for Protocol FWR-2005-0037-H. Protocols F-BR-2005-0057-H, FWR-2006-0001-H and F-BR-2006-0018-H state "2005" and "in preparation". A data-base search in PubMed in January 2008 showed that the article still has not appeared – it might not even have been submitted. Thus, the assertions about eye protection by the blink reflex (in particular for humans) cannot be taken as scientifically valid for the time being. This puts into some question the thoroughness of the review process for human testing.
46 The mechanism here is the cornea reflex. It is noteworthy that the blink reflex caused by visible light impinging on the retina for lasers of class 2 (visible light, not dangerous for the eye if exposure time ≤ 0.25 s) does not work with 80 % of the people, Reidenbach et al., 2006, see also BAUA, 2006. Whether a similar restriction applies to the cornea reflex which does not use visual pathways, is unclear.
47 Mason et al., 2001.
48 Nelson et al., 2000; Walters et al., 2000; Nelson et al., 2003.

about 10°C increase (skin temperature approximately 45 °C) above which pain increases, to a maximum between 55 and 60°C (about 20°C increase). Further heating does not produce more pain, but increases burn injury. Second- and third-degree burns (complete dermal necrosis) occurs at 45°C after 2 hours, at 48°C after 15 minutes and at 60°C after 5 seconds.[49]

In the human experiments, nobody could stand the pain to more than minor injury. According to the JNLWP, until autumn 2006 there had been only one case where medical attention was needed, namely for a 2-cm-size second-degree burn due to an accidental overexposure during laboratory testing in 1999. "Thereafter, design configurations have been revised, and there have been no injuries that have required medical attention."[50] The human-testing protocols state that in few exposed subjects skin reddening or few minor blisters may occur.[51] Until May 2006, six cases of blistering were observed in more than 10,000 exposures of more than 600 people.[52] However, in April 2007 an airman in an ADS test got an overdose and received second-degree burns on both legs that needed to be treated in a hospital for two days.[53]

From 1995 to 2006 the US Air Force Research Laboratory and the Joint Non-Lethal Weapons Directorate have spent about $51 million on the technology.[54]

In 2005 the military press reported about requests from the armed forces and mentioned fast deployment to Iraq.[55] However, in September 2006 Secretary of the Air Force Wynne was quoted as being reluctant to deploy ADS on the battlefield; to avoid vilification in the world press it should be used on crowds in the US first.[56]

In January 2007 a media day with live demonstrations of ADS system 1 was held at Moody AFB, Georgia.[57] A deployment date of 2010 was mentioned; press reports said that the beam heats the skin to 50°C without lasting harm, not mentioning the fact that this depends on the beam being switched off immediately when such a temperature is reached.[58]

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49   Ryan et al., 2000 ; Protocol FWR-2002-0046-H ; Moritz/Henriques, 1947.
50   JNLWP, 2006b.
51   E.g. Protocol FWR-2004-0029-H.
52   JNLWP, 2006b.
53   Osborn, 2007; Hambling, 2006; WALB, 2007.
54   JNLWP, 2006.
55   Roque, 2005.
56   CNN, 2006.
57   JNLWP, 2007.
58   E.g. BBC News, 2007.

2.2 Analysis

2.2.1 Important Features

Neither the maximum power nor the intensity in the beam of the ADS have been published by the US military, but information on the first is available. According to the manufacturer of the gyrotron (Communication and Power Industries, Palo Alto, CA), the device of 1.1 m height and 170 kg mass produces continuous-wave radiation at 94.9 GHz with a power of 100 kW (maximum 120 kW); the efficiency is 50%.[59,60] This means that 200 kW have to be provided as electrical power of which 100 kW have to be removed by cooling, mainly at the electron collector. Additional electrical power has to be provided for cooling the superconducting magnet, for the control electronics, etc.

The total power consumption may be around 300 kW.[61] Most or all of this power is provided by the lithium-ion batteries. In ADS model 1 they can be charged by the Diesel engine of 85 kW power (which was separated from the drive train, the vehicle was converted to electrical drive). If one assumes 90% efficiency of the generator, the latter provides 76 kW at full engine power. If the engine is running during radiation, the batteries have to provide correspondingly less, that is 220 kW. Assuming the minimum number of around 120 cells of 1.1 kg mass each results in a total radiation time of 3.5 minutes.[62] Since the engine provides one quarter of the power, the engine could make up for the energy taken from the batteries if on average the beam were on one quarter of the time. Assuming a tank of 100 l = 60 kg of Diesel fuel with its energy content of 2.4 GJ, the engine could run at full power for 1.6 h.[63]

The power emitted by a gyrotron can be modulated and switched on or off very fast.[64] From the experiment protocols it seems that the system is set to a power level which is kept throughout the duration of the radiation.[65] This power level can be controlled by software.

The antenna is equipped with boresight cameras for visible and infrared light and a range-finder (see also Figure 1b,c). Radiation starts when the operator presses the trigger, on trigger release it stops. If the trigger is not released, then emission is stopped after a pro-grammable maximum duration. The total energy emitted and the fluence (energy density) on target can be limited by controlling the beam power, and thus intensity, and the duration. However, immediate re-triggering is possible – in experiments the operators were instructed to not re-engage subjects for at least 15 s. The settings of power and duration were such that the fluence did not exceed 12 J/cm^2.[66]

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59 CPI 2007, 2007a; these mention 100 kW, produced by the VGB-8095 gyrotron. Thumm (2007): Table 6 gives 120 kW, based on conference publications from the manufacturer. I want to thank M. Thumm, Karlsruhe Research Centre, for helpful comments and hints at literature.

60 Because the power was not known earlier, I had assumed constant intensity I = 8 W/cm^2 (see below) over a constant beam area of A = 3.7 m^2 = 37,000 cm^2, which results in a total power $P = I\,A$ = 300 kW, 3 times the actual value. Unfortunately, I had made a calculation error arriving at 30 kW in Altmann, 2007.

61 If the same ratio applied as with the silent guardian (200-kW generator for 30 kW of beam power, see note 33) the total power would be 670 kW.

62 The Li-ion batteries in the ADS are based on the SAFT VL30P series and come in modules of 48 V voltage and 30 Ah capacity, SAFT 2006, specifications in SAFT, 2005. With 3.6 V nominal cell voltage one module has about 13 cells connected in series. To provide 220 kW at 48 V requires 220 kW/48 V = 4.6 kA current. With a peak current of 0.5 kA per cell/module (allowable for 10 s) about 9 modules have to be used, in total 9*13 = 117 cells. At 1.1 kg per cell, the total mass of the batteries is then 129 kg. With a total energy content of 9*48 V*30 Ah = 13.0 kWh = 46.7 MJ one charge would suffice for 46.7 MJ/0.22 MW = 212 s of beam time. If the battery would have to work without the engine, the cell number and total mass would increase by a factor 300 kW/220 kW = 1.36.

63 Diesel fuel has an energy density of 40 MJ/kg, thus 60 kg contains 2.4 GJ. With 20% thermo-mechanical efficiency, 480 MJ mechanical energy can be produced. Dividing this by 85 kW gives 5650 s = 1.6 h.

64 Kartikeyan/Borie/Thumm, 2004.

65 Modulation of the power during beaming (such as high at first for fast heating, then low to just keep the temperature) seems not to be used, see the following discussion.

66 Protocol FWR-2006-0001-H.

Whereas an infrared-camera image allows qualitative assessment of how exposed skin becomes hotter, a quantitative determination of temperature and thus of a critical threshold for burn injury is not provided. Probably in order to correct for this deficiency, the US military have contracted a few projects on remote determination of skin temperature.[67] However, if infrared emission (at two wavelengths) is used, this cannot work through clothing whereas the millimetre waves penetrate through textiles.

Figure 1 suggests that the mm-wave beam is led via a coaxial waveguide to the rotating antenna set, then along (one of) the metal holders to an opening – an off-axis horn – facing the big reflector which acts as the emitting antenna.[68] It has the shape of a square of sidelength 2.0 m with corners cut off diagonally; the area is A = 3.7 m^2. The reflector probably has a metal surface with a curvature such that waves leave it with parallel wave fronts.[69] If the horn converts the waveguide mode to an expanding Gaussian beam, a suitably curved reflector could convert it to a Gaussian beam of larger diameter which would start with parallel wave fronts – the so-called beam waist would be at the emitter.[70] The beam would remain at about constant size out to some distance (depending on the radius of the beam waist), then start to grow. Farther out the beam would diverge with the radius increasing linearly with distance, while the intensity correspondingly would drop in proportion to the inverse squared distance. In order to keep a Gaussian beam and not introduce additional diffraction effects from cutting off the beam margins, the size of the emitting aperture has to be 1.7 to 2 times the beam-waist diameter. Taking 2.0-2.3 m as the reflector diameter, the beam-waist radius may be somewhere between 0.50 and 0.68 m.

Absent actual information on the beam properties I have used these values and computed the peak intensity of a Gaussian beam of 100 kW power (Figure 2). At the Rayleigh distances of 248 m and 460 m, respectively, the intensity drops to 1/2 of its initially constant value, with inverse-square decrease beyond.
Figure 3 shows the beam profiles at 50 m and 500 m distance for 0.68 m beam-waist radius.

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67   Navy, 2007a: Optra Inc., Physical Sciences Inc., Voxtel Inc.; Voxtel, 2006; DoDSBIR, 2007: Qortek Inc., Scientific Applications and Research Associates, Voxtel Inc.
68   It is also possible that a beam is led from the back through one of the holes of the reflector towards a concave mirror held 3 m in front of the latter which would form a diverging beam towards the convex main reflector. Typically, for mm waves corrugated waveguides are used.
69   As in a reflecting optical telescope, if the waves leave the horn with spherical wavefronts from a virtual focal point, they become parallel after reflection if the spherical mirror at distance f from that point has a radius 2 f. With f around 3 m from photos, the centre of a circular mirror with the horn on the axis would be recessed 8.4 cm from the plane of the circumference. Slight deviations are possible because the actual mirror is off-axis, in addition it may be paraboloidal instead of spherical. The seemingly flat surface (see Figure 1) may be due to a protective cover transparent to millimetre waves.
70   A Gaussian beam has an irradiance profile following a Gauss function. The radius where the irradiance has dropped to $1/e^2$ =0.14 of the peak value is called the beam radius w. In a distance d it is given by $w(d) = w_0 (1 + d/d_0)^{1/2}$ where $d_0 = \pi w_0^2/\lambda$ is the so-called Rayleigh distance, w_0 is the beam-waist radius, λ is the wavelength. At d_0 the beam radius has grown to $\sqrt{2}$ times w_0, farther out the radius grows in proportion to the distance. If the total power P_0 is emitted, the irradiance on the axis is $I(d) = 2 P_0 / (\pi w^2(d))$. See e.g. Meschede, 2004: pp. 37-43.
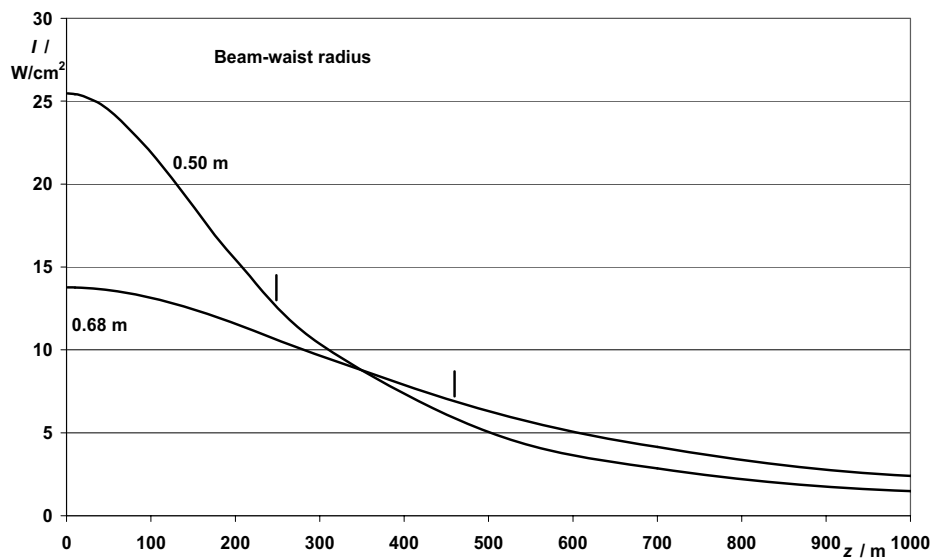
Figure 2 Theoretical irradiance I on the axis of a Gaussian beam of wavelength 3.16 mm and power $P_0 =$ 100 kW versus distance z from the beam waist for two values of beam-waist radius w_0 which could be used with an emitting aperture of 2.0-2.3 m diameter. The vertical lines mark the Rayleigh distances where the intensity has dropped to 1/2 of its initial value.
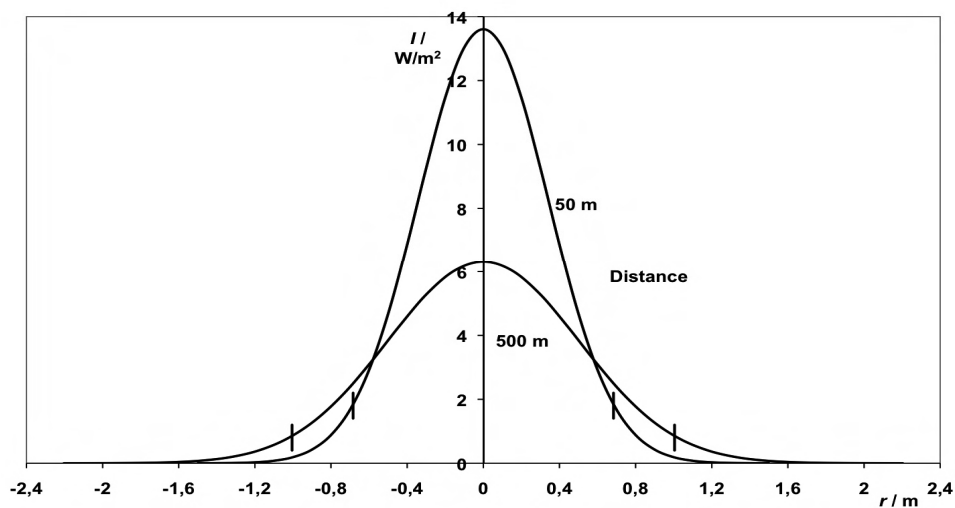
Figure 3 Theoretical beam profiles (irradiance I versus radius r from the beam axis) at 50 m and 500 m distance, for the beam-waist radius 0.68 m. The vertical lines mark the respective beam radius w where the intensity has fallen to $1/e^2 = 0.14$ of the peak value on the axis.

The theoretical values should be compared with the actual ones. The maximum intensity used in human testing can be derived from the conditions given for one experiment: ADS model 1 was to be used for 1, 2, 3, 4, 5, or 6 s, with 25, 50, 75, and 100 % of the maximum intensity, in such a way that the fluence (energy/area = intensity times duration) for one exposure was limited to 12 J/cm^2, and the skin temperature did not rise above 60°C.[71] Assuming that 25 % was used with the longest time, that intensity results in 2 W/cm^2 to reach 12 J/cm^2 in 6 s, producing a temperature of 55.7°C according to the model described below. Thus, 100% correspond to 8 W/cm^2, and the other percentages coupled with appropriate durations result in plausible values of fluence and temperature.[72] This intensity also fits to the statement in the protocols that "exposures may exceed permissible exposure limits specified by the relevant safety standard (AFOSH 48-9, 1997) by as much as 20-fold";[73] the permissible exposure limit for partial-body exposure in a controlled environment at 95 GHz is 40 mW/cm^2;[74] 20 times this value is indeed 8 W/cm^2.

This value is about 40% lower than the constant intensity of nearly 14 W/cm^2 of the theoretical curve for the larger (0.68-m) beam-waist radius in Figure 2, it would only apply at around 330 m distance. Since the protocols seem to indicate that most experiments were done in the near field with about constant intensity, the difference may be due to a non-ideal Gaussian beam and/or a larger beam waist. The narrower beam waist (of radius 0.50 m) can probably be excluded because the close-distance intensity with 25 W/cm^2 is 3 times the actual one which would lead to heating too fast. In addition, a strong distance dependence would start already below 100 m. This conclusion is corroborated by the statement that the ADS is safe and effective from 15 m to 500 m.[75] A Gaussian beam delivering 8 W/cm^2 in the near field would have a beam waist of 0.89 m radius (1.78 m diameter); such a wide beam would be cut off by the reflector of 2.0 to 2.3 m effective diameter at an intensity which has not yet decreased to negligible values. Diffraction at this too small aperture would cause a deviation from the Gaussian profile so that the intensity versus distance is more complicated. For a qualitative picture the 0.68-m curve in Figure 2 can be used.

In the course of research of ADS effects, a model of skin heating by 94-GHz radiation has been published.[76] It uses the solution to the bioheat equation with blood flow; as electromagnetic energy is absorbed and converted to heat, exponentially decreasing with depth, heat energy is conducted to deeper layers and partly removed by blood flow. The results fit very well to experiments at intensity 1.0 W/cm^2 for exposure times from 0 to 3.0 s (end fluence 3.0 J/cm^2), and blood flow turns out to be irrelevant at such high intensity.

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71   Protocol FWR-2006-0001-H.
72   The consistent combinations of duration and relative power with the resulting skin temperature according to the model of
      Figure 4 are given here. Note that 2 s with 0.75 results in markedly above 60°C.

t/s	1	1	2	2	2	3	3	4	5	6
P/P_{max}	1	.75	.75	.5	.25	.5	.25	.25	.25	.25
$I/(W/cm^2)$	8	6	6	4	2	4	2	2	2	2
$F/(J/cm^2)$	8	6	12	8	4	12	6	8	10	12
$\Delta T/K$	26.4	19.8	32.2	21.4	10.7	28.0	14.0	16.9	19.4	21.7
$T/°C$	60.4	53.8	66.2	55.4	44.7	62.0	48.0	50.9	53.4	55.7

73   E.g. Protocol F-WR-2002-0024-H.
74   AFOSH, 1997. The IEEE standard gives the same value, IEEE, 1999: Section 4.4.
75   JNLWP, 2007, 2007a.
76   Nelson et al., 2003. The authors come from a university, the Air Force Research Laboratory and Army and Navy medical research.

Using the same model, I have computed the skin temperature also for longer exposures and higher intensities, from 1 to 8 W/cm^2.[77]

Figure 4 shows the results. The faster heating with higher intensity reflects the fact that in shorter time less energy convects to deeper layers.

Figure 4 shows that skin heating does not stop when critical temperatures for pain or injury are reached, if the radiation continues to deposit energy in the skin. The pain maximum and approximate onset of burn injuries (at 20 K temperature increase) are reached within seconds, at 8 W/cm^2 even after 0.7 s. Also shown is the threshold for second- and third-degree burns (complete dermal necrosis) as measured with exposure at constant temperature. Even though exposure to ADS radiation produces a fast temperature rise in time instead, the time-temperature pairs should give an adequate indication of when to expect such injury.

The fluence limit of 12 J/cm^2 used in human testing is marked in the figure. Comparison with the necrosis threshold curve shows that this limit does not by itself prevent severe injury, this holds only if the intensity is 2 W/cm^2 and lower. As indicated in note 72, probably at the highest intensity, a duration of 1 s with fluence 8 J/cm^2 was used; still this results in a maximum skin temperature of about 60 °C (increase by 26.4 K) for a fraction of a second.

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[77] Input parameters were: absorption length 0.4 mm, energy absorption coefficient 1.0, thermal conductivity 0.3 W/(mK), thermal diffusivity 10^{-7} m^{2}s, no blood flow, following Nelson et al. (2003) and earlier publications.
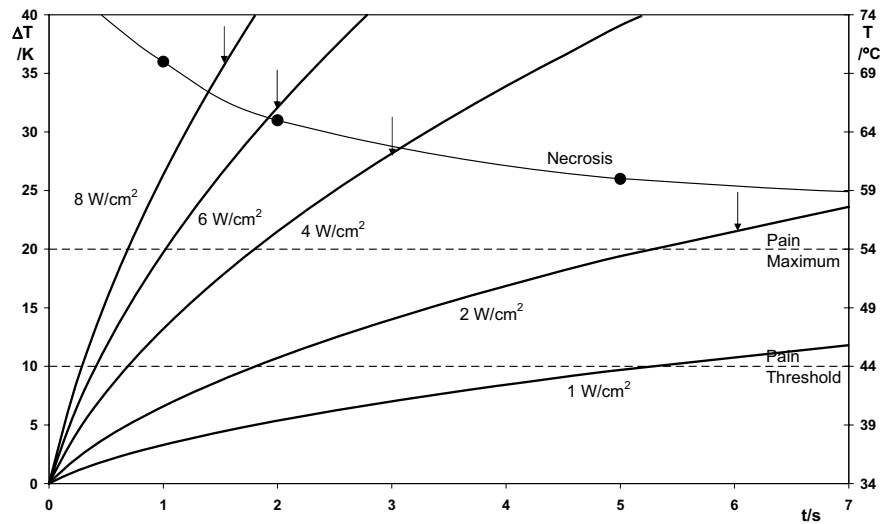
Figure 4 Skin temperature increase ΔT in Kelvin versus irradiation time t in second for constant intensities from 1 to 8 W/cm^2; this increase adds to the normal temperature of around 34 °C (absolute temperature on the right). For 1 W/cm^2 from 0 to 3 s, the model fits very well to experimental data.[78] Values for pain threshold and pain maximum are indicated. The dots (with interpolating curve) indicate conditions for which second- and third-degree burns with complete dermal necrosis were observed with pig and human skin for constant-temperature exposure.[79] Arrows denote the times and temperatures when the fluence reaches 12 J/cm^2, the upper limit used in human testing.

As a consequence, the ADS provides the technical possibility to produce burns of second and third degree. Because the beam of diameter 2 m and above is wider than human size, such burns would occur over considerable parts of the body, up to 50% of its surface. Second- and third-degree burns covering more than 20% of the body surface are potentially life-threatening – due to toxic tissue-decay products and increased sensitivity to infection – and require intensive care in a specialised unit.[80] Without a technical device that reliably prevents re-triggering on the same target subject, the ADS has a potential to produce permanent injury or death.

Propagation

In case of a Gaussian beam, diffraction preserves the Gaussian beam profile with linear beam widening in the far field as described above. If the beam waist is bigger than 1/2 or 1/1.7 of the reflector, the profile does not stay Gaussian, but gets dark and bright rings – or spots for a non-circular shape –, approaching the case of constant intensity in the exit aperture.

Gas absorption in the atmosphere around 100 GHz is dominated by the water (H_2O) molecule, with a small contribution from oxygen (O_2). With a typical water density of 7.5 g/m^3 (corresponding to 50% relative humidity at 20 °C), attenuation over 1 km is only around 10%.[81] At 100% relative humidity at 15 °C, the loss over 1 km increases to about

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78   Nelson et al., 2003.
79   Temparature-time pairs: 70°C/1.0 s, 65°C/2 s, 60°C/5 s, 58°C/10 s, Moritz/Henriques, 1947: Table II, Table III.
80   E.g. International Dictionary, 1986, p. 400f.
81   The attenuation at 95 GHz with 7.5 g/m^3 water density is around 0.5 dB/km (Altshuler 1983: pp. 189, 207f.). Thus the transmission over 1 km is $10^{-0.5/10}=0.89$.

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50%, still not really relevant for the ADS range.[82] On the other hand, high contents of liquid water will limit the beam range. Because 0.4 mm of water absorbs 86% of the power, heavy rain or dense fog will strongly impede propagation: with 20 mm/h precipitation rate (moderately strong rain), only 10% intensity remains in 1 km, 50% is reached in 300 m.[83] However, in such weather visibly targeting a person over longer distances is impossible anyway.

Potential Countermeasures

As the weapon works by the high absorption of 95-GHz radiation in water (in skin 86% of the energy are absorbed within 0.4 mm), one could use a 1 mm thick layer of water for shielding. However this may be somewhat impractical, and after some time the water would start to boil. However, electromagnetic radiation of any frequency below the plasma frequency (around 10^{15} Hz = 10^6 GHz for typical metals) can be shielded by electric conductors. In metals the radiation is absorbed in a very thin layer and mostly reflected. In aluminum for example the penetration depth is 0.27 micrometres (μm).[84] Ordinary household aluminum foil of many μm thickness covering all parts of the body exposed towards the antenna would provide protection; gaps where the radiation could enter would have to be avoided. To allow vision a very fine-grained mesh in front of the face would be needed (holes markedly smaller than the wavelength of 3.2 mm, that is not bigger than, say, 0.1 mm).

Such shielding could fairly easily be developed by armed forces; demonstrators, on the other hand, would have more difficulty in making it.

A rough estimate on the price range for the ADS could be a few million dollars.[85]

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82   With 100% relative humidity at 15 °C (that is, 11 g/m^3 water density), the attenuation is around 3 dB/km (McMillan, 2005: Fig. 1), the transmission over 1 km is $10^{-3/10}$=0.50.

83   At 20 mm/h rain rate, the attenuation is around 10 dB/km (McMillan, 2005: Fig. 1), the transmission over 1 km is $10^{-10\cdot1km/(km\,10)}$=0.10, over 300 m it is $10^{-10\cdot0.3\,km/(km\,10)}$=0.50.

84   With the skin-effect formula $\delta = \sqrt{(\rho/(\pi\mu\nu))}$ the penetration depth for aluminum (with specific resistance $\rho = 2.64\cdot10^{-8}$ Ωm, magnetic permeability $\mu = \mu_0 = 4\,\pi\,10^{-7}$ Vs/(Am)) at ν = 95 GHz is δ = 0.27 μm.

85   This is corroborated by a press article on an ADS demonstration in Nov. 2007 which has reported a price of $10 million for ADS system 1 and an expected production price of $2-$5 million, Sherwell, 2007.

2.2.2 Weapon Properties

Table 1 summarises the specifications of the ADS as they are available publicly or have been derived here.

Table 1 ADS specifications from various sources and present analysis (see text and refs. above)

Frequency	95 GHz
Wavelength	3.2 mm
Beam power	100 kW
Maximum intensity in beam	around 8 W/cm^2
Time to reach pain threshold (at intensity 2-8 W/cm^2)	1.8 to 0.3 s
Time to reach pain maximum and injury threshold (at intensity 2-8 W/cm^2)	5.3 to 0.7 s
Time to reach severe-injury (dermal-necrosis) threshold (at intensity 2-8 W/cm^2)	8 to 1.5 s
Range (of about constant beam width and intensity)	0.5 - 1 km in clear air $\leq$ 100 m in hard rain or dense fog
Antenna size	2 m (side length, square with corners diagonally cut off), area 3.7 m^2
Power source	Lithium-ion batteries (model 1: charged by generator driven by Diesel engine of 85 kW power)
Electrical power consumption during radiation	around 300 kW
Maximum total beam time	around 3.5 min. (with one battery charge, supported by engine) around 1.6 h (beam on 1/4 of the time, with 100 l Diesel fuel)
Dimension	several m
Mass range	1-2 t
Price range	few $ million

2.3   Evaluation

2.3.1 Considerations About Limits

Because the beam is about 2 m wide and the target is in view of the operator by way of video cameras, the potential for collateral damage by the ADS is relatively low. One possibility is another person suddenly moving into the beam, but the duration and heating would be less than for a target subject in most such cases.

Concerning use of the ADS against combatants in armed conflict, there seem to be no technical arguments that would result in its exclusion, given that the weapon would be lethal only after relatively long exposure, and considering that flame-throwers – which can produce severe burn injuries and death much faster – are an accepted means of combat. Thus, specific limitations under international humanitarian law do not seem appropriate. (Of course, the general rules – avoid unnecessary suffering, do not attack combatants hors de combat or surrendering etc. – would apply here as with all other means of warfare.)

However, use of the ADS in armed conflict is not very probable: the system presents a large, relatively immobile target that due to its line-of-sight propagation cannot take cover easily. It seems vulnerable to many kinds of light weapons, above rifle range a machine gun may be needed to attack it. A second reason is that armed forces could prepare for millimetre-wave weapons of an opponent relatively easily by adding electromagnetic shielding material to the battle dress, covering the hands, and providing a transparent, but conductive face shield. The latter will be not so easy to achieve for non-state actors.

The more probable use is against (largely) unarmed civilians, such as by occupation forces, in a police-like context or against intruders in protected areas. Here human rights or even constitutional rights form higher requirements. The developing agencies (JNLWD, Air Force) state that there are safeguards against misuse.[86] These consist of computer control of beam power and duration for each single trigger event, and of cameras and range-finders assisting the operator in selecting targets and observing their behaviour. If the weapon were only used in situations where application of force is justified, and in a measured, proportional way, then it would not raise many objections.

However, the possibility of re-triggering on the same target subject puts avoidance of burns at the discretion of the weapon operator. It is unclear if a 15-second non-re-engagement rule – as was used in human testing – will also apply in real operations, above all, if it would be followed under all circumstances. Overdose and misuse are of course possible with all police weapons, but with the operator at many hundreds of metres distance, just pressing a button, experiencing the reactions of the target person only visually, there seems to be more leeway for applying more force or harm than absolutely required. Technical limiters that would reliably prevent hitting the same person again after too short cooling time would be needed to allay fears of misuse.

Further, indirect consequences are difficult to assess – e.g. will police tend to more freely use force against demonstrators if the ADS as a distance weapon were widely available? Will video-game culture influence how operators use their trigger? Would demonstrators become more aggressive with experience of growing ADS use? Such questions are beyond scientific-technical analysis, but attention by human-rights groups and a critical public will be helpful to prevent/minimise misuse.

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86   JNLWP, 2006b.

Critics have argued that millimetre-wave weapons could be used for torture.[87] Whereas the ADS itself – a big, very expensive system designed for outside use – would be impractical for such purposes, smaller systems for close distances could principally used to produce intolerable pain. Avoiding burn injury that could provide proof e.g. at inspections of prison camps would require stopping the heating after appropriately short exposition. But after waiting for 10-20 seconds, the procedure could be repeated. It is unclear if such torture would be more "effective" than traditional methods (of pressing glowing cigarettes to the skin, using torches, etc.). But the possibility to accurately determine the dose so that burns are avoided while the heat pain is maximised could make heat torture more attractive and more practical for torturers. Attention by the human-rights community in particular for the end use of small millimetre-wave systems is certainly required. Such systems should be placed under strict export controls or even be prohibited from exports altogether, as are leg shackles in the European Union.[88] Scrutiny is also recommended with respect to a potential future airborne system with 25 times the power of the ADS.

Final judgement whether introduction, and then, in each instance, actual use of the ADS is legally or morally justified, will strongly depend on the scenarios. Fending off intrusion into nuclear-weapons storage sites or preventing small boats from coming too close to navy ships in port would probably be assessed differently from repelling demonstrators on a public road. Here the additional problem may arise that the people in the front line may not be able to escape due to others pressing from behind. Generally, it will be unclear for the target subjects where to escape because the beam is invisible and wider than the body.

Whereas a restrictive approach to police weaponry can plausibly argue for non-deployment of the ADS, the present analysis has not found convincing arguments that the ADS would be immoral or illegal in each foreseeable circumstance.

However, the ADS could be called non-lethal beyond any doubt only if technical limiters were built in which guarantee that a target subject would not be heated to more than 55-60 °C skin temperature under any circumstance.

2.3.2 Further Research

Future research should find out more details about the ADS, in particular the irradiance profile at various distances. Then atmospheric conditions such as humidity, precipitation, low visibility should be investigated in detail, as should be modifications by beam reflection in particular on water.

It would be helpful to have access to the results of human testing, including details about the accidents.

Actual developments with ADS should be followed up; this holds in particular for the development, deployment and eventual use of smaller millimetre-wave weapons.

A particular study should investigate whether the cornea blink reflex is a reliable protection against corneal damage. Another topic is the design of limiters which would prevent hitting the same target subject again, before sufficient cooling time has passed.

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87   See e.g. Wright, 2005, 2007: pp. 10 f.
88   Wright, 2005.

3. Advanced Tactical Laser

3.1 Research and Development, Status

Laser weapons have been in research and development for decades.[89] Since the 1980s a major focus was on their use for ballistic-missile defence,[90] but use against aircraft and other targets has also been envisaged. Laser weapons for permanent blinding of humans were banned in 1995 by Additional Protocol IV to the Convention on Certain Conventional Weapons of 1980.[91]

One of the laser projects that was partly done in the context of non-lethal weapons is the so-called Advanced Tactical Laser (ATL). This is a chemical oxygen-iodine laser (COIL) which radiates in the near infrared, at 1.315 μm wavelength. This wavelength is in an atmospheric window where absorption by molecules is low (however, scattering by droplets in rain, clouds or fog can stop propagation). The stimulated emission of light[92] is from iodine atoms which are excited by energy transfer from oxygen molecules in a supersonic gas flow. The oxygen is released in a chemical reaction.[93]

The concept of the ATL was developed by Boeing in the 1990s. Special features used include a sealed exhaust system, trapping the exhaust gases in cryogenically cooled zeolite.[94] The first laser demonstration took place in 1999, the power produced was 20 kW. The development contract for the weapon system was awarded in 2002. The technology demonstration is being managed by the Special Operations Command, additional support comes from organi-sations of the Air Force, of the Army and from the Joint Non-Lethal Weapons Directorate. In January 2006 a C-130 Hercules transport aircraft was delivered to Boeing for installation of the laser and the beam-control subsystems. The chemical laser was first fired on the ground in October 2006. In the same month, a smaller test laser using fuel (hydrogen peroxide and chlorine) recycled from waste products of earlier laser operation was fired for the first time. Ground and flight tests with a lower-power surrogate laser have been done in summer 2007. The same laser was to be used in a test flight to destroy a communication tower and disable a moving truck. Afterwards the full-power laser was to be installed in the aircraft and tested, also in 2007.[95]

The amount of the main contract (2002-2005) was $ 176 million. The funding request for further development of the ATL for Fiscal Year 2006 was $ 62 million, but the Senate Armed Services Committee recommended a reduction by $ 15 million due to remaining technical challenges.[96]

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89   For a recent short overview see Zimet, 2002; see also Beason, 2005.
90   For independent analyses in general see Altmann, 1986; Bloembergen et al., 1987; Barton et al., 2003; on the Airborne Laser, also a chemical oxygen-iodine laser, but in the megawatt class, see Forden, 1997; Mark, 2002. See also Stupl/Neuneck, 2005.
91   Morton, 1998.
92   "Laser" means light amplification by stimulated emission of radiation. Stimulated emission can occur if a photon of the right frequency – stemming from an excited atom or molecule of the same type – hits another excited system whereupon the latter releases its excitation energy, going to a lower energy state, in the form of a second photon that has the same frequency, phase and direction of the first one. If there are more systems in the excited state than in the lower state, a chain reaction can produce many such photons. Usually the photons are reflected back and forth many times between two mirrors which form the laser cavity or resonator.
93   Gaseous chlorine reacts with hydrogen peroxide in aqueous solution, releasing oxygen molecules in the so-called singlet delta state. Its excitation energy is close to one of the iodine atom so energy transfer to the latter occurs fast.
94   Zeolite has microscopic pores and can adsorb up to 20% of its own mass. It can be recycled by heating. DSB, 2001: p. 47.
95   DSB, 2001; Boeing, 2003, 2006, 2006a; Garcia, 2006; Polt, 2007.
96   AFRL, 2006; SASC, 2005.

The first concept comprised a laser of 50-70 kW power with 3,900 kg mass, operated in a sealed manner without exhaust, to be deployed on aircraft. The operating altitude was to be 0-1,500 m, the lethal range to a ground target 5-15 km, with a 10-cm focal spot at many km. Fuel would suffice for 5-10 shots.[97] Platforms under consideration included the C-130 Hercules (transport aircraft, payload 20 t, Lockheed), CH-53 Sea Stallion (transport helicopter, 15 t, Sikorsky), CH-47 Chinook (transport helicopter, 12 t, Boeing), and the V-22 Osprey (vertical-/short-take-off transport aircraft, 9 t, Bell Boeing). (Deployment on ground vehicles was also mentioned as an option.) The system would be modular – coming on four pallets – and could be installed fast (Figure 5).[98]
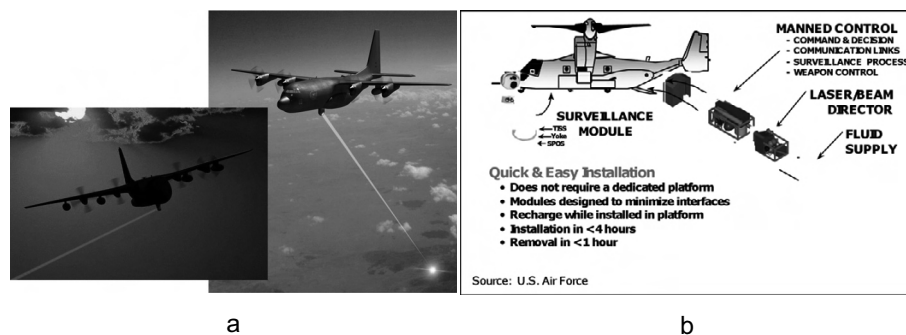

a   b

Figure 5 a) Concept of ATL on C-130 transport aircraft   b) Concept of ATL modules with V-22 Osprey vertical/short-take-off aircraft.[99] (Images: US Air Force)

Other reports speak of 300 kW, markedly higher power, and 100 shots, with total beam time of 40 s.[100] These data seem to reflect developments over time. In 2007, the total mass to be integrated into the C-130 is given as 20 tons, thus the other aircraft mentioned above are excluded now.[101]

The military task of the ATL is to achieve damage on an extremely small area (10-20 cm diameter) and to do so from a standoff distance of many kilometres, so that the weapon carrier could not be attacked by small arms or man-portable air defence systems (MANPADS). Because the beam is invisible, the weapon could remain covert in some conceivable scenarios – mainly if a lower-technology opponent has neither radar nor infrared sensors available.

The military functions of a non-lethal, "ultra-precise" ATL attack would include:[102]

– disabling communication lines,

– disabling radio and TV broadcast antennas,

– disabling satellite or radar dishes,

– breaking electrical power lines and transformers,

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97   Boeing, 2001.
98   DSB, 2001, pp. 43-48.
99   AFRL, 2006; DSB, 2001: p. 44.
100   Fenton, 2000 (the beam time and shot number were given in the back-up viewgraphs, part of the presentation downloaded on 13 Dec. 2000; in 2007 they are no longer contained in the document); see also Freedman, 2001; Global Security, 2002.
101   Polt, 2007.
102   DSB, 2001: p. 46.

- disabling individual vehicles (via attacking tyres, canvas coverings, maybe even engine components),[103]

- creating various forms of distractions by setting small fires.

"These actions would serve to isolate and control hostile individuals and groups without casualties and with minimal, repairable damage."[104]

Alternative targets have been mentioned for lethal employment of the ATL:[105]

munitions, small arms, rockets/mortars, optical and radar surveillance systems, and fuel tanks. Another role would be defence against cruise missiles or naval force protection.[106] However, the treatment here will focus on the alleged non-lethal uses only.

A notional scenario of such uses is the following, which seems to have been developed by Boeing in interaction with the JNLWD.[107] The targets are depicted in an artist's concept:[108] On the left side of a curved, narrow road in a valley there is a military column consisting of about 7 armoured vehicles, 5 trucks and 1 missile-launch vehicle, about 100 m long. On the opposite side, just beyond the road margin, there is a group of 30-40 refugees, accompanied by armed guards; the former are to be saved from oppression. The C-130 transport aircraft with the ATL is shown in an inset.

To assess the situation, the ATL pops up from behind a mountain ridge, takes a picture from 7 km distance and goes below again. Then about 100 aim points are selected and assigned. The aircraft rises again to get an unobstructed line of sight and attacks these targets during two periods of radiating, one 14 seconds long, the other 26 seconds.[109] The mirror is steered rapidly from one target to the next, necessarily under computer control. The breakdown of aimpoints includes 32 tyres, 11 antennas, 4 mortars, 4 interior seats and 22 armed soldiers, the refugee group on the other side of the road between is spared. The closest aimpoint is maybe 8 m from the refugees, beams directed toward targets behind the group pass maybe 1 m above their heads.

3.2   Analysis

3.2.1 Important Features

Whereas first reports had given an aperture size of 0.3 m (and a power of 50-70 kW), the output mirror has increased with the overall parameters of the ATL. Relating the window size in the photo of the turret to the turret diameter leads to a diameter of 0.50 m.[110]

Propagation

Absorption reduces the beam power to a small extent, at 8 km by about 30%.[111] With an optics diameter of 0.5 m, at many kilometres distance far-field diffraction conditions hold.

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103   Cook, 2004: p. 37.
104   DSB, 2001: p. 46.
105   Boeing, 2001.
106   DSB, 2001: p. 46.
107   Fenton, 2000 (see note 100).
108   Contained in Boeing, 2001. The figures in the back-up viewgraphs of Fenton (2000) are similar (see note 100). Unfortunately, my request for reprinting permission did not get a response from the company.
109   This fits to the total beam time of 40 s mentioned above.
110   The photo in Polt (2007) shows a part of the turret from which one can assess its dimension, together with the beam window. The turret diameter is given as 50"=1.25 m in AFRL, 2006.
111   The absorption at 1.3 μm is 30% for a vertical path through the whole atmosphere, corresponding to 8 km length at sea-level pressure.

Assuming emission of nearly plane wavefronts (slightly curved towards a focus in 10 km) and unperturbed propagation, in 10 km distance a bright spot of 6 cm diameter is expected, fitting to the developer's statement of 10 cm spot size.[112] The theoretical minimum value will not be fully attainable. Air turbulence will lead to fluctuations of the intensity and size of the focal spot, not all can be corrected for by adaptive optics.[113] Absorption along the path will heat the air, thinning it in the beam axis, so that it acts as a diffusing lens. This so-called thermal blooming is to some extent compensated for because due to the aircraft motion the beam continuously goes through new air near the source, but this mostly does not hold at the target.

Assuming unimpeded propagation, 300 kW on a spot size of 10 cm diameter (area about 80 cm^2) would mean an intensity on average around 4 kW/cm^2, on the axis around 13 kW/cm^2.[114] Assuming that a target fails if its material is melted, the energy deposited on the target, that is the portion not reflected, at least has to heat it to the melting point and provide the latent heat of melting. With this requirement, 1 mm of steel or aluminum needs a fluence of around 1.3 kJ/cm^2, which is reached after about 0.3 s.[115,116] Setting wood or textiles on fire requires a much lower impinged fluence of about 80 J/cm^2.[117] At 5 kW/cm^2 intensity, this is reached after less than 0.02 s.[118] However, at such short heating time bulk material may just burn off superficially without actually catching fire.

Model calculations including extinction, turbulence and thermal blooming have – for one set of conditions – shown a 30 cm wide illuminated area with a maximum intensity on a ground target around 0.6 kW/cm^2 from 2.5 km altitude, 6 km horizontal range (6.3 km slant range).[119] This is one order of magnitude below the value derived above from diffraction only. In this case, the time for melting 1 mm of metal would increase to about 2 s, for ignition of wood or textiles to about 0.13 s.

Potential Countermeasures

Principally passive protection from a high-power laser beam is possible by reflecting most part of it, by adding heat-absorbing material or by taking cover. Whereas highly reflecting surfaces could be used in space systems and missiles, it seems impractical to apply them on ordinary military hardware which is exposed to the weather, dust etc. Also this would contravene the interest in camouflage. Covering vehicle bodies by heat-absorbing material would be possible in many cases, but it is unclear if the effort is warranted because some

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112 The angle between the beam axis and the direction of the first intensity minimum is given by $\phi = 1.2\, \lambda/D = 3.1\ \mu$rad for an optics diameter of $D = 0.5$ m and a wavelength of $\lambda = 1.3\ \mu$m. In $d = 10$ km distance thus the minimal radius of the bright spot is $r = d \tan \phi = 0.03$ m.

113 While sources mention compensation of beam jitter from aircraft vibrations by mirror control (e.g. Polt, 2007), precision beam control for the turbulent lower atmosphere and the turbulence from the downwash of rotor systems or the boundary layer around the aircraft presents significant hurdles, DSB, 2001: p. 48.

114 For constant irradiance on the transmitting aperture, in the far field the intensity on the axis is given by $I = P \pi D^2 / (4\, r^2\, \lambda^2)$ where P is the beam power, D is the aperture diameter, r is the distance and λ is the wavelength. With $P = 300$ kW, $D = 0.3$ m, $r = 10$ km and $\lambda = 1.3\ \mu$m, $I = 12.6$ kW/cm^2.

115 The corresponding inequality reads $(1-R)\, I\, t_m \geq \rho\, l\, [c\, (T_m - T_0) + Q_m]$ where the absorbed beam energy per area is on the left and heat energy per area taken up is on the right (I: intensity, R: reflection coefficient, t_m: time to melt through layer of thickness l, ρ: density, c: specific heat, T_m: melting and T_0: starting temperature, Q_m: specific heat of melting); the equality holds if molten material is immediately removed and no vapour impedes propagation (Bloembergen et al., 1987: p. S120). With $I = 5$ kW/cm^2, $l = 1$ mm and parameters for steel ($R = 0.5$, $\rho = 7.85$ Mg/m^3, $c = 477$ J/(kg K), $T_m = 1643$ K, $T_0 = 293$ K, $Q_m = 205$ kJ/kg) $t_m \geq 0.26$ s. Putting in the corresponding values for aluminum: (0.8, 2.70 Mg/m^3, 896 J/(kg K), 933 K, 293 K, 397 kJ/kg) gives a similar limit: $t_m \geq 0.26$ s.

116 If vaporisation were required, additional energy would be needed to reach the vaporisation temperature and to convert liquid material to gas, increasing the required fluence and the beam time to failure by about a factor 10.

117 Glasstone/Dolan, 1977: pp. 286-296.

118 $t = F/I = 80$ J/cm^2 / (5.1 kW/cm^2) = 0.016 s. The value of 0.2 s given in Altmann, 2007, was wrong due to a typographical error.

119 West Pacific Median atmosphere, HV 5/7 turbulence, transmitter speed 120 m/s, target speed 0 m/s, crosswind speed 5 m/s; with 300 kW power from a 0.5-m transmitter the total power in a circle of 5 cm diameter (20 cm^2 area) is 12 kW, McGovern et al., 2000. Note that much variation is possible in particular with atmospheric conditions.

weak spots (such as tyres, windows, optics) could not be covered anyway and the number of ATL systems will remain limited for quite some time. Persons could probably not protect themselves using aluminium foil because the reflectivity is not high enough and the material is very thin so that it would melt or burn through fast. Thus, taking cover (under a roof, in a wood) may be the only realistic possibility where such an option exists.

A rough estimate on the price range for the ATL could be a few million dollars.

3.2.2 Weapon Properties

Table 2 summarises the specifications of the ATL as they are available publicly or have been derived here.

Table 2 ATL specifications from various sources and present analysis (see text and refs. above)

Laser type	chemical oxygen-iodine laser
Wavelength	1.3 μm (near infrared)
Beam power	300 kW
Maximum intensity in beam	around 5 kW/cm^2
Time to ignite textiles, wood (at intensity 5 kW/cm^2)	$\geq$ 0.02 s
Time to melt 1 mm of metal (at intensity 5 kW/cm^2)	$\geq$ 0.3 s
Range	10 – 15 km in clear, calm air much less with turbulence, dust, rain or fog
Emitting aperture diameter	0.5 m
Power source	chemical reaction, sealed exhaust
Maximum total beam time	around 40 s
Dimension	many m
Mass	20 t
Price range	few $ million

3.3 Evaluation

3.3.1 Considerations About Limits

Classifying the ATL as non-lethal is obviously incorrect. With 30-100 times the heating power of a stove plate applied at a spot of the same size the weapon can kill people, set combustible objects on fire or explode munitions. It is clearly a lethal weapon, as comparison with an assault rifle shows. Also the latter can be used in a way which reduces or prevents injury and death; for example, in order to stop a vehicle one can shoot at the tyres, not the driver. However, the rifle cannot justifiably be called a non-lethal weapon, of course.

Use of the ATL against combatants in armed conflict would represent a new means of warfare, but not one that would be prohibited by creating unnecessary suffering or superfluous injury. Applying heat and burning humans or materiel – by flamethrowers at close range – is an accepted method under international humanitarian law. Compared to older means of applying force at many kilometres distance (such as artillery, guided missiles with explosive warhead, bombs dropped from aircraft), the ATL would allow much more discriminating destruction and thus would rather be more fitting to the law of warfare which stipulates that collateral damage is to be minimised. At least this holds when focused propagation is possible and if the weapon is used appropriately.

Discussing secondary effects (would introduction of the ATL strengthen the tendency toward asymmetric warfare or would it increase terrorism?) is beyond the scope of the present work. However, one argument is worth considering: ATL could well be the first laser weapon actually deployed for armed forces. As such, it could act as a precedent and door-opener for more potent laser weapons, such as the Airborne Laser or the Space-Based Laser. These systems, directed against strategic ballistic missiles, would have direct strategic significance. If such long-range laser weapons were deployed by potential opponents, they would on the one hand increase first-strike fears and arms-race motives. On the other hand, such weapons could also attack each other at split-second notice which would cause correspondingly high direct destabilisation.[120] In order to prevent such a development, the international community should consider a ban on laser weapons in general, or at least beyond a certain power or range.[121]

In armed conflict as well as other operations, the ATL would provide an option for ultra-precise strikes, however with clear limits: The fuel supply is sufficient for tens of seconds of operation only, that is around 100 "shots". A clear line of sight to the target is needed; this means firstly that the carrier aircraft can be detected (only rarely will hiding behind a mountain ridge be possible) and attacked by air defence missiles (even though shoulder-fired ones (MANPADS) may not suffice). Secondly targets can take cover e.g. in a wood. Propagation over many kilometres to a 10-cm focus may only be possible in favourable atmospheric conditions. Thus, it is unclear whether the effectiveness will be high enough so that the disadvantages and the considerable expense of the ATL will appear justified.

It is relatively obvious that the ATL with its size, long range and drastic effect will not be suitable as a police weapon. In a peace-enforcing operation, precise targeting over kilometres range could reduce collateral damage markedly compared to artillery or guided bombs. However, collateral damage is nevertheless possible, and scenarios such as the

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120   Altmann, 1986, 1986a, 1988.
121   Proposals see Altmann, 1986, 1994.

one discussed above pose several more questions. What can happen if the ATL selectively attacks weak spots of a military convoy while sparing refugees, hostages or other captives who are very close to the targets? When a tyre is exploded, people can be hit by pieces of rubber. When a fuel tank or munition is exploded, they can be hit as well. Or the beam itself can hit them due to inaccurate aiming or fluctuations. Generally, collateral damage will be limited to a few metres.

Operationally the first question is what happens after the attack of less than a minute, when the ATL needs to fly back for re-fuelling? The second is: Will the military unit just give up when some vehicles or antennae are out of order? A significant portion of soldiers will not be injured, and their small arms will continue to function. A third problem is: If the military unit is bent on keeping the refugees under control, it can take cover, use the hostages as human shields, or even kill some of them as a reprisal. In order to effectively fight against the military column, physical presence and combat on the ground may be needed anyway, with all the traditional risks to the hostages. Thus, the ATL may add an additional layer of force application, but without real change of the situation.

Also with the ATL, judgement on the morality of the weapon depends strongly on the scenarios. Because this large, lethal, long-range weapon would only be used by armed forces, such use would have to follow the general rules which apply in armed conflict or in peace operations.

3.3.2 Further Research

Future research should follow up the developments around the ATL, with particular emphasis on experiences of weapon tests. Beam propagation under realistic atmospheric conditions should be investigated in some detail, as should be countermeasures and attack scenarios, including consideration of collateral damage. Because transition to a similarly powerful solid-state laser could make an ATL-like weapon more feasible, the potential for such change should be studied continuously.[122]

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122   The term solid-state laser is used generically in this report, including e.g. fibre lasers.

4. Pulsed Energy Projectile

4.1 Research and Development, Status

The concept of the Pulsed Energy Projectile (PEP) is to use short, powerful laser pulses to provide a mechanical impulse to the target subject or object. The mechanism is the following: when a high-intensity light pulse impinges on matter, the uppermost layer is heated so fast that it vaporises explosively, producing recoil. The vapour is heated further, producing a plasma in the air where nearly all laser energy of the later part of the pulse is absorbed. If the heating is strong enough, a shock wave, the so-called laser-supported detonation wave, forms which exerts a pressure pulse on the target. The force pulse produced in this way is to act similarly to an impact round, but at a much larger distance.[123]

Not much information on the PEP is available. The general idea and the intended effects have been described.[124] The laser is to use chemical fuel, deuterium fluoride (DF), created in an excited state from a chemical reaction with fluorine (F_2). Because it contains the heavy hydrogen isotope deuterium (D), the DF molecule transmits laser radiation in the mid-infrared, between 3.5 and 4.1 μm wavelength where the atmosphere is transparent. (If the much cheaper normal hydrogen (H) were used, emission would come from the HF molecule, at shorter wavelengths, between 2.5 and 3.1 μm, which are strongly absorbed by the atmosphere.)[125] The gas flows through the resonator once, then to be discarded. F_2 and the reaction product DF are very corrosive; this is probably one of the reasons why there was a study of the environmental effects in 2002 which, however, is not publicly available.[126] A solid-state laser requiring only electrical power would be more practical, but research and development have not yet achieved pulse energies and average powers as they are provided by chemical lasers.

Development of the PEP is done by Mission Research Corporation, now acquired by Alliant TechSystems Inc.[127] In 2001, their DF laser produced 270 joule pulse energy, 2.1 megapascal peak pressure and 170 dB acoustic level.[128] In an artist's rendition the PEP is carried inside a wheeled vehicle (HMMWV) with a rotatable emitting turret on top (Figure 6).[129] The mass of the PEP was given as 230 kg in 2002.[130]

In Fiscal Year 2002, \$3.2 million were spent on PEP hardware development and effects testing, for FY 2003 \$2 million were planned.[131] Funding has continued at around \$3 million per year and is to rise to \$4.5 million in FY 2009.[132] (In 2004, the National Institute of Justice let a contract for a much smaller, portable laser-plasma weapon.[133])

For the range of the PEP, 0.5 and 2 km have been given.[134] Lethal or non-lethal use would be for area denial, crowd control, facility protection, operations other than war, military operations on urban terrain or law enforcement.[135]

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123   A similar concept has been discussed for ballistic-missile defence in space, Bloembergen et al., 1987: pp. S128-S136.

124   Fenton, 2001; Kennedy, 2002; Alexander, 2003: pp. 16f.; Hambling, 2002; Naval Studies Board, 2003: p. 30, 83.

125   The price of deuterium (D_2) gas is around 1,500 €/m^3 at atmospheric pressure, compared to about 14 €/m^3 for H_2, telephone information from L'Air Liquide Germany, Jan. 2008.

126   Access via the Internet was secured by password in 2003, NEER, 2003.

127   Fenton, 2001: viewgraph 22.

128   Alexander, 2003: pp. 16 f.

129   ATK, 2008.

130   Col. G. Fenton (JNLWD Director), as quoted in Kennedy, 2002.

131   Hambling, 2002.

132   Navy, 2005, 2007. Recent funding may include work on direct nerve stimulation, see below.

133   Davison, 2007a: p. 6.

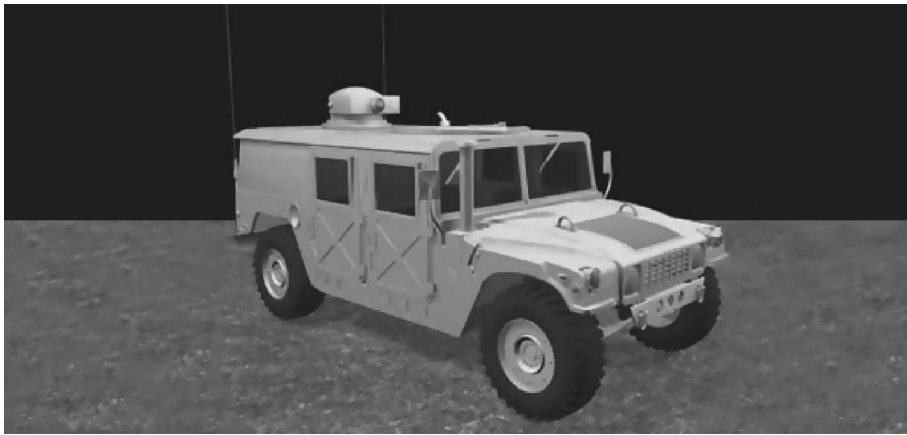134   0.5 km: Alexander, 2003: p. 16; 2 km: Moore, 2000.

Figure 6 Artist's concept of the PEP mounted in a HMMWV.[136] (Image reprinted by courtesy of Alliant Techsystems Inc.)

Some technical detail is available only from a set of viewgraphs about a similar concept, called Pulsed Impulsive Kill Laser.[137] To explore the concept, a DF laser was built at Los Alamos National Laboratory in 1993. With about 17 cm tube diameter and around 1 m length, this laser produced pulses of more than 300 joule energy and 3-5 microsecond (μs) duration. Obviously this did not suffice to produce a laser-supported detonation wave. For tests with higher energy, a CO_2 laser with 100-1200 J and 32-34 μs was used, with a spot size of 2·3 cm^2. At the Armstrong Labs of the Army Tank-automotive and Armaments Command (Picatinny Arsenal NJ), the effects were analysed. Detonative coupling occurred above 400 J. Impulses were measured when hitting chamois (as a skin simulant), kevlar and battle-dress-uniform textile (mechanical impulse is the integral of force over the time of application, its unit is newton-second; 1 Ns results if 1 N force acts during 1 s time). The maximum impulse was 0.1 Ns, the maximum pressure was 2.5 megapascal, 25 times normal air pressure (however for very short time only so that the total impulse is quite low, see below for comparison). Dividing the impulse by the pulse energy gave the impulse coupling coefficient, values of $(0.7-1)\cdot 10^{-4}$ Ns/J were observed.

Figure 7 shows photographs of the pulse-produced plasma and the detonation wave and of one target after ablation. No further explanations are given in the viewgraphs. The target seems to be battle-dress-uniform; from the scale provided the hole is 4 to 6 cm wide. This gives a sense of the ablation depth which seems to be around 1 mm. The number "37" in the photo probably indicates that the photo was taken after the 37th pulse had hit the same spot.

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135   Moore, 2000.
136   ATK, 2008.
137   Moore, 2000.
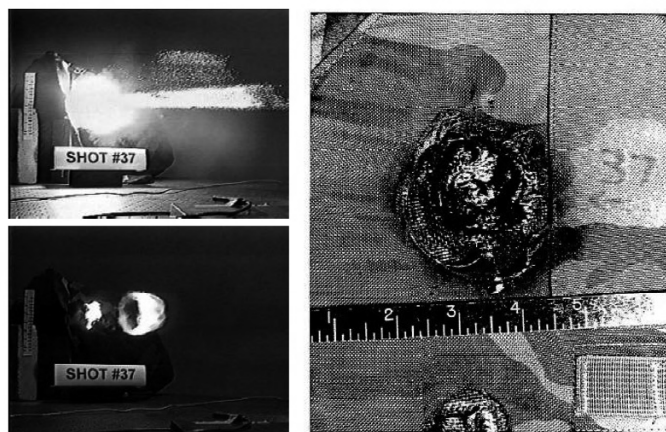
Figure 7 Laser-ablation experiments by the US military. The photos on the left probably show lateral views of the laser-pulse-produced plasma and the ensuing detonation shock wave. The hole in the fabric (of battle dress uniform?) visible in the right photo is 1.5-2.5" = 4-6 cm wide, judging from this the ablation depth is around 1 mm. This probably means that 37 shots have been fired in total. (Viewgraph 17 from Moore, 2000, US government material)

In recent years, a completely different idea of using pulsed lasers has received interest. It is about controlling the plasma in front of the target subject in such a way that its electro-magnetic field acts on nerve cells in the skin or deeper layers. This could either stimulate pain receptors directly, producing an aversion reaction without strong mechanical or thermal effects on the surface, or lead to paralysis by disruption of the neuromuscular connections.[138] Experiments on shrimps and single cells have shown that application of strong electric fields (on the order of 10 kV/cm) over very short times (tens to hundreds of nanoseconds) can produce immobilisation which lasts from seconds to many minutes, apparently with recovery.[139] In these laboratory experiments, the samples were placed between two capacitor plates. In a potential weapon application, the electro-magnetic field produced by the plasma would be controlled by a laser with much shorter pulses than those of the PEP, possibly down to femtoseconds. This concept is still at the stage of basic research. Whether the short, intense electric fields required for nerve interaction can be produced by laser pulses from a distance, whether the effects work with mammals and whether they are reversible, are all open questions at present. If pain receptors could be stimulated by this principle without other injury, it could be used at close range for torture.[140] Analysis of this concept goes beyond this report.

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138   E.g. Hambling, 2005.
139   Schoenbach et al., 2004; Nene et al., 2006; Pakhomov et al., 2006; and respective refs.
140   Hambling, 2005.

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4.2 Analysis

4.2.1 Important Features

Mechanical impulse from explosive laser ablation in air has been studied experimentally and theoretically. A detailed theoretical treatment (including effects from two-dimensional expansion of the shock front beyond the beam diameter)[141] resulted in maximum theoretical values of the impulse-coupling coefficient of about 10^{-3} Ns/J, expected for the case when the pulse duration is equal to the time needed for the shock wave to travel one beam diameter (on the order of 10 μs for several cm with shock speeds of several km/s). For longer durations, the coefficient decreases inversely proportionally to the duration. For various conditions, there was good agreement with experimental values. With the parameters used in the CO_2-laser tests, a value of $(2\text{-}3)\cdot10^{-4}$ Ns/J results.[142] The coupling coefficient actually measured, $0.7\text{-}1\cdot10^{-4}$ Ns/J, was thus only one third of the theoretically predicted value. One reason could be that in the tests a laser-supported detonation wave was achieved only marginally.
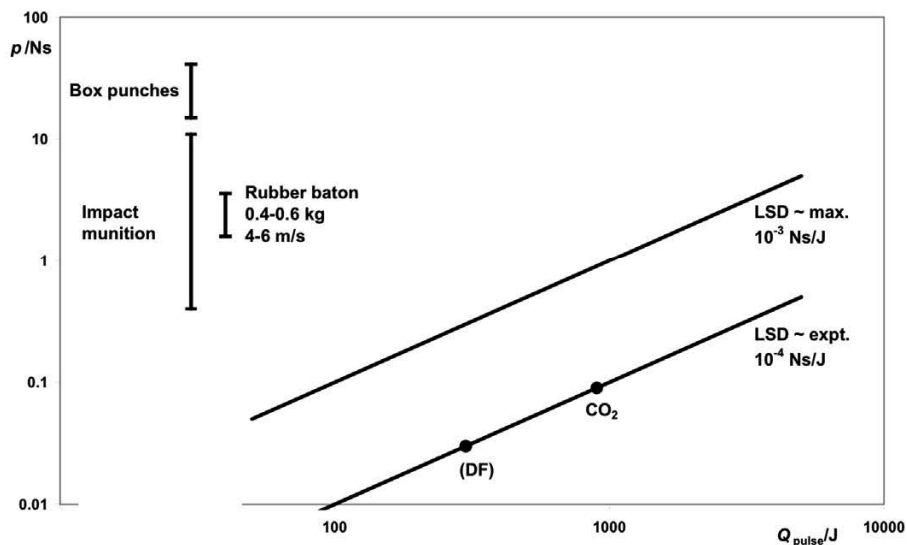

Figure 8 Mechanical impulse p in newton-second from one laser pulse versus pulse energy Q_{pulse} in joule for laser-supported detonation (LSD) waves, maximum theoretical values (upper line) and experimentally observed ones (lower line), in double-logarithmic scale. Test results for a CO_2 laser (pulse energy 1 kJ, duration 33 μs) are shown; the DF laser developed (300 J, 3-5 μs) did not reach detonative coupling.[143] For comparison the impulses measured with strong box punches and blunt-impact munitions are indicated,[144] together with the impulse of a rubber baton of m = 0.4-0.6 kg moving at v = 4-6 m/s ($p = m\,v$ = 1.6-3.6 Ns).

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141   Pirri, 1973.
142   With eqs. (18) and (19) of Pirri (1973), I_0 = 900 J / (6 cm$^2 \cdot$ 33 μs) = $4.5\cdot10^6$ W/cm^2, τ_p = 33 μs, adiabatic exponent γ = 1.2 (average of plasma), unperturbed air density ρ_0 = 1.2 Mg/m^3, pressure p_0 = 101.3 kPa, duration τ_{2D} = 8.7 μs, the coupling coefficient becomes $2.3\cdot10^{-4}$ Ns/J.
143   Moore, 2000.
144   Walilko et al., 2005 ; Kenny et al., 2001.

To assess the mechanical effect, the impulse from one laser pulse as a function of pulse energy is depicted in Figure 8, using the maximum theoretical coupling coefficient (for optimum pulse duration) and the upper limit of the one observed in the CO_2-laser tests. With the latter, the impulse results in 900 J · $1 \cdot 10^{-4}$ Ns/J = 0.09 newton-second. For comparison, impulses from mechanical blows are shown, too: the range of impulses measured with punches to the head by olympic boxers (15-41 Ns),[145] the range measured with various blunt-impact weapons (0.4-11 Ns),[146] and the impulse of a rubber baton of 0.4-0.6 kg mass hitting with 4-6 m/s speed are indicated.[147] It is evident that one pulse of the test laser is one or two orders of magnitude below blunt-impact weapons and thus will not have a significant mechanical effect on a target person. If the maximum theoretical coupling coefficient could be achieved (upper curve), a single laser pulse would need 3 kJ, three times the pulse energy of the CO_2-laser tests and ten times the DF-laser value, to become comparable to impact weapons, and up to 10 or 30 times more, respectively, if the coefficient found in the experiments would hold. Such pulse energy would require a fairly big and cumbersome laser, measuring 1-2 m and having hundreds of kg mass.

A laser-supported detonation wave on somebody's body produces a flash and a bang at close distance to eyes and ears, so some effect on a target person is expected, even though the mechanical impact is not relevant. However, there are flash-bang grenades available which are much smaller and cheaper than a big laser – the only difference would be the range.

In order to achieve stronger impacts, one could use many pulses in sequence the impulses of which would add. Assuming that one detonation wave has passed after a millisecond, pulses could follow each other at a rate of several hundreds per second – requiring correspondingly high consumption of the laser fuel gases. However, in this case successive layers of the target would be ablated, which would create bad wounds if bare skin were hit (see the hole probably produced by 37 pulses in battle-dress uniform shown in Figure 7). Both results fit to the statements that "impulses and pressures developed were two orders of magnitude below those needed to produce serious injuries with single pulses" and that "pulse 'trains' can literally chew through target material".[148]

Experiments to assess the skin damage by single pulses from a DF laser were done in the US Uniformed Services University of the Health Sciences in model skins and on pigs.[149] The pulses of 4 μs duration and around 350 J maximum energy were focused on an area of 4 cm^2. By varying the energy and thus fluence, the ED_{50} (effective dose that elicits a specific response in 50% of the cases) for marked damage (prominent tissue erythema and edema, stratum corneum generally thinned, generalized epithelial vacuolation) in vivo was found to be at a fluence of 51 J/cm^2, with a penetration depth of around 60 μm.[150] (This is more than 2000 times above the maximum permissible exposure which is 0.0224 J/cm^2.[151]) Apparently, ablation and plasma formation did not yet occur with these pulse parameters. The fluence values used by Moore (2000) with the 900-J CO_2 laser hitting an area of 6 cm^2 were 150 J/cm^2, three times as high.

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145   Walilko et al., 2005.
146   Kenny et al., 2001.
147   Impulse p is mass m times speed v: $p = m\,v$ = 1.6-3.6 Ns in this case.
148   Moore, 2000.
149   Williams, 2004. The maximum fluence used was 91 J/cm^2 on a 4 cm^2 spot, i.e. about 360 J total energy for constant fluence. The laser make is not given; the similarity of the laser parameters suggests that the prototype built by the Los Alamos National Laboratory used by Moore (2000) was used here, too.
150   The ED_{50} values for mild and moderate damage were 8 J/cm^2 and 18 J/cm^2, respectively.
151   For laser pulses of 4 μs at 3.8 μm, ANSI Z136. 1-2000, quoted after Williams, 2004.

If such or stronger fluence is used, ablation will occur. Using many pulses can no longer be called non-lethal – in order to produce a mechanical impulse that would be comparable to a rubber or foam bullet or a bean bag one would risk heavily injuring the victim. One would need a device of metre size and hundreds of kilograms mass, with complicated gas supply etc., while the same effect, without the risk of heavy injury, could be gained by a 40-mm calibre hand-held gun of a few kilograms.[152]

In addition, it is possible that the shock waves cause permanent hearing damage. The peak level of 170 dB apparently observed with a 270-J DF-laser pulse[153] is comparable to a rifle shot at very close range and can cause permanent hearing-threshold shifts (the eardrum will rupture at around 185 dB).[154] If the eye is hit, serious injury from cornea ablation or mechanical impulse on the eyeball is probable. The blink reflex (occurring after about 0.25 s) would come too late; it could not prevent the mechanical impulse anyway, and the eyelid would start to be ablated if pulses continue.

Propagation

In clear air, propagation will mainly be affected by diffraction. If the beam would start with 20 cm diameter and plane wave fronts, the beam would stay at about this size out to several km. Thus the intended range of 1-2 km may reflect non-ideal wave fronts and/or a smaller emitting area. Due to the longer wavelength, turbulence is less of a problem than for the ATL, however dense fog or rain will also prevent the mid-infrared radiation from propagating far.

Potential Countermeasures

Normal reflective material (smooth metal) will not protect from PEP pulses because the first one will already damage the surface due to its high power. However, because it takes many pulses to ablate to a significant depth (say, one millimetre), adding ablative material of several mm thickness would be effective. Deformation of the lower layer could absorb much of the fast mechanical-blow effect (although the total impulse would still be delivered). In many cases the existing material (steel casing, thick winter clothing) may already provide significant protection. The head could be covered by a helmet with visor; the latter would lose its transparency after the first pulses.

A rough estimate on the price range for the PEP could be several hundred thousand dollars.

4.2.2 Weapon Properties

Table 3 summarises the specifications of the PEP as they are available publicly or have been derived here.

Table 3 PEP specifications or (probable) design goals from various sources and present analysis (see text and refs. above)

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152   Note, however, that in some circumstances rubber bullets and bean-bag rounds can produce strong injury, too.
153   Alexander, 2003: p. 16.
154   Altmann, 1999: Section 2.5, 2001: pp. 186-191.

Laser type	chemical deuterium-fluoride laser[155]
Wavelength	3.5-4.1 μm (mid-infrared)
Pulse energy	$\geq$ 1 kJ
Pulse duration	several μs to few 10's μs
Emitting aperture	0.1-0.2 m
Power source	chemical reaction
Intensity on target	10^7-10^8 W/cm^2
Mechanical impulse from single pulse	0.1-1 Ns
Range	0.5-2 km in clear air
Dimension	1-2 m
Mass range	few 100 kg
Price range	several $100,000

4.3   Evaluation

4.3.1 Considerations About Limits

Due to its narrow beam and limited ablation per single pulse, the potential for collateral damage by the PEP is low. Only if a tyre or a casing around energetic material were penetrated by many pulses could exploding parts hit bystanders.[156]

The PEP clearly would be a lethal weapon, though with mostly less effect than traditional firearms. To achieve considerable mechanical impulse, many laser pulses would be needed. If bare skin is hit by many pulses (maybe after burning through clothing), it is ablated to considerable depth and one has to expect ugly wounds. The eyes could be in danger even from one or a few pulses.

If the PEP will be used against combatants in future armed conflict, it will represent a new means of warfare. If battle dress is hit, this does not produce a very strong mechanical effect even with multiple pulses. The shock wave would produce a bang acting on the ears. Ablating clothing to the skin is possible by many pulses, but probably only after irradiating the same spot for several seconds, so that a victim would have a chance to evade it. If compared with traditional weapons of war (gun fire, artillery shells etc. which penetrate and create deep wounds, or flamethrowers which burn both, clothing and skin) this would probably not be seen as creating unnecessary suffering or superfluous injury. The judgement could potentially be different if bare skin or the eyes are hit: due to the size of the wound to be expected, in particular in the face, and the possible permanent loss of vision, the question of unnecessary suffering or superfluous injury should be looked at in more detail, in co-operation between international humanitarian lawyers, physicists and physicians.

With 0.5-2 km range, the PEP would create less of a precedent for introduction of long-range beam weapons for ballistic missile defence or anti-satellite attacks than the ATL.

The PEP would have limited capabilities. It needs a clear line of sight to the target, exposing it to the adversary. It would be expensive and complex. It would be a relatively

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155   Work is going on towards similarly powerful solid-state lasers that would be powered by electricity.
156   Note that the total laser energy of, say, 100 PEP pulses would be in the order of 100 kJ, comparable to the ATL beaming with 300 kW power for 0.3 s. However, because the plasma formed absorbs most of the pulses only a small part of the PEP energy would go into ablation whereas it is a significant part (say, 0.5) of the energy in the case of the ATL. But in the PEP case penetration may be helped by mechanical shock to some extent.

big and heavy device of size above 1 m, with a mass of a few 100 kg even without fuel. Thus it would need a larger carrier vehicle, at least the size of a HMMWV as with the ADS. Even if in the future solid-state lasers emitting in the mid-infrared of the necessary pulse energy (above 1 kJ) and repetition rate (above tens of Hertz) will become available with significantly less mass of the laser proper, the average beam power of around 100 kW would necessitate a few times 100 kW of electric power as in the case of the ADS, so that similarly big batteries and a Diesel-driven generator would be required. In case the carrier vehicle would not be armoured, then it would be vulnerable to light weapons.

As with the ATL, because the PEP uses an (infrared) light beam, the propagation through haze or dust is limited, however due to the lower range and longer wavelength less deterioration is expected. With its limited military effectiveness and various disadvantages, it is not clear if further development of the PEP will end in a deployment decision.

Due to its size, range and potential injurious effects, the PEP would neither be appropriate as a weapon for law enforcement nor for peace-enforcing operations. For producing mechanical blows and pain, blunt-impact projectiles provide much easier options with much less injury risk – the smaller range of tens of metres seems more appropriate for such operations anyway.

As with the other weapons discussed here, judgement on the morality of the PEP depends strongly on the scenarios. There seem to be practically no uses in a police context. Use by armed forces would in many cases not contradict international humanitarian law, however, whether this applies to hits on bare skin or the eyes is open. What kind of use would be compatible with the general rules for armed conflict needs to be clarified if development of the PEP will advance towards eventual deployment.

4.3.2 Further Research

Future research should follow up the developments with respect to the PEP (as far as secrecy permits). This should include an analysis of the ablation depth as a function of pulse number.

Specific analyses are needed of the potential of the shock wave to produce permanent hearing damage and of damage to vision if the eye is hit.

A broader study should be devoted to the different concept of direct electromagnetic stimulation of pain receptors or of neuromuscular disruption by the laser-produced plasma in front of a target subject.

5. Long Range Acoustic Device (LRAD)

5.1 Research and Development, Status

In the renewed interest in non-lethal weapons of the 1990s there had also been significant discussion about acoustic weapons, in particular those using infrasound, i.e. frequencies below 20 Hz. The latter were attributed practically ideal properties: making target subjects incapable of acting while the sound was on, with fast recovery when it was turned off and without lingering damage. However, such promises ignored scientific results,[157] and were mostly laid to rest when in 1999, after almost ten years of research, the JNLWP stopped funding infrasound-weapon work for lack of "a reliable, repeatable bio-effect with sufficiently high infrasound amplitude at a minimum specified range".[158] A recent detailed review came to the conclusion that also in the audio range acoustic weapons will remain impractical.[159]

Nevertheless, in the audio range (sound frequencies 20 Hz to 20 kHz), effects on the ears, including ear pain, do occur if the amplitude is strong enough. Work on such acoustic weapons continued, but the first actual system was explicitly denoted as a "hailing and warning device", not a weapon. (One effect of this classification was that no legal review of compatibility with the international law of warfare was needed.)[160] This system was called the Long Range Acoustic Device (LRAD) and is produced by the firm American Technology Corporation (ATC), San Diego, CA.

They have a directed loudspeaker system which by emitting modulated ultrasound that is converted to audible sound by non-linear effects in the air achieves much higher directivity. Proceeding from this technology, ATC have first developed the so-called High Intensity Directional Acoustics (HIDA) – obviously a planar array of speakers that are individually controlled to direct and focus the beam, similarly to a phased-array radar. A hailing range in excess of 450 m was given.[161]

LRAD (Figure 9) seems to an offshoot of HIDA where all sources are moving in phase, controlled by the same signal. The moving membrane, which is driven capacitively, may be a piezoelectric foil. Beginning in 2004, ATC reported a multitude of LRAD sales.[162] As of September 2005, about 350 copies had been deployed.[163] Interested in promoting their product, ATC have provided much information about the system.

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157   Altmann, 1999, 2001, 2001a.
158   JNLWP, 1999: p. 19.
159   Jauchem/Cook, 2007: "it seems unlikely that high-intensity acoustic energy in the audible, infrasound, or low-frequency ranges will provide a device suitable to be used as a non-lethal weapon."
160   But note that e.g. the Norwegian military call it a weapon, Sævik, 2006.
161   ATC, 2003.
162   Among others, to the Navy, Coast Guard, Marine Corps, Army, New York Police Department, including for use in occupied Iraq; various press releases at http://www.atcsd.com (Sept. 2004). Combat use started in 2003, it was deployed at sea since May 2004 and used for maritime security and for public safety since August 2004, ATC, 2007b.
163   Davison/Lewer 2006: Section 2.4. See there for more information on LRAD.

Figure 9 LRAD 1000 on tripod during a test by the Norwegian Defence Research Establishment (FFI) in April 2006.[164] The hexagonal object on the box in front is the smaller LRAD 500. (Photo reprinted by courtesy of FFI)

LRAD can work in two modes: Voice, with the level limited to 121 dB in 1 m, and Tone (for warning) with up to 151 dB in 1 m. In the voice mode, it achieves beyond 500 m hailing range. Table 4 shows the specifications given by the manufacturer.[165]

Table 4 Specifications of the LRAD 1000 [166]
(SPL: sound pressure level, SPL = $10 \log_{10}(I/I_{ref})$ where I is the intensity and $I_{ref} = 10^{-12}$ W/m^2 is the reference value; THD: total harmonic distortion, THD = square root of (sum of spectral powers of harmonics / power of fundamental) or value in bracket, for sinusoidal signal).

Emitter array dimension	84 cm outer diameter * 15.5 cm thick
Mass	21 kg
Maximum SPL	151 dB instantaneous max. @ 1 meter
Maximum SPL regulated power mode	121 dB @ 1 meter
Emitter harmonic distortion	< 2.2% THD @ 2 kHz < 1% THD @ 2.5 kHz @ 126dB @ 1 meter
Power consumption	240 W (normal), 480 W (peak)
Nominal beam width	$\pm$ 15° at 2 kHz
Range	warning tone > 1000 m voice > 500 m

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164   Graven, 2006, Sævik, 2006.
165   There is also an LRAD 500 with 145 dB at 1 m in the warning mode.
166   ATC, 2007, mass and ranges from ATC, 2005: viewgraph 47. Second entry for harmonic distortion from ATC (2004) when the model was called LRAD 3300. The first, higher, value is given without an SPL; probably it applies to the warning mode. See also ATC, 2007c.

For government uses, the manufacturer mentions the following applications:[167]

– border security,
– crowd control for public safety agencies,
– long range communication for public safety agencies,
– search and rescue for harbour/port police,
– coastal surveillance for harbour/port police.

These are the military missions given:[168]

– enforcement of exclusion zones,
– critical infrastructure protection,
– psychological operations,
– traffic control points/access control points,
– interdiction operations,
– checkpoint operations,
– detainee operations.

Apparently LRAD has been used for several of these purposes in occupied Iraq. One problematic application was to draw out enemy snipers who were then destroyed by US snipers.[169]

One incident has gotten wide publicity: In November 2005, pirates in a small boat attacked a cruise liner 160 km off the Somali coast with rocket grenades and rifle fire. They were successfully driven back by an LRAD on board the ship.[170]

The New York Police Department had deployed two LRADs during the protests at the Republican Convention in August 2004, but did not use them because the protesters to be addressed were at close range.[171] The price was $35,000 per copy.[172]

Despite the generally low prospects of acoustic weapons, there are efforts underway to find sounds and amplitude levels which have sufficient non-lethal effect on target subjects. In order to test such effects, there have been calls from the Applied Research Laboratory of Pennsylvania State University (PSU) to soften the thresholds for exposure to high sound levels. The existing exposure limits are aimed at preventing (or keeping at low probability) permanent hearing damage in case of long-term, repeated exposure at the workplace. The argument is that for acoustic-weapons testing one or a few exposures to a level of 130 dB should be allowed.[173] Whether this proposal will be accepted and whether such tests would lead to more practical weapons, is open. Here the treatment will be limited to the LRAD which is not seen as a weapon.[174]

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167   ATC, 2007a
168   ATC, 2007b.
169   Davison/Lewer, 2006: Section 2.4.
170   BBC News, 2007a.
171   Personal communication from an observer.
172   Davison/Lewer, 2004: p. 11, 31.
173   Nicholas et al., 2007, see also Weinberger, 2007.
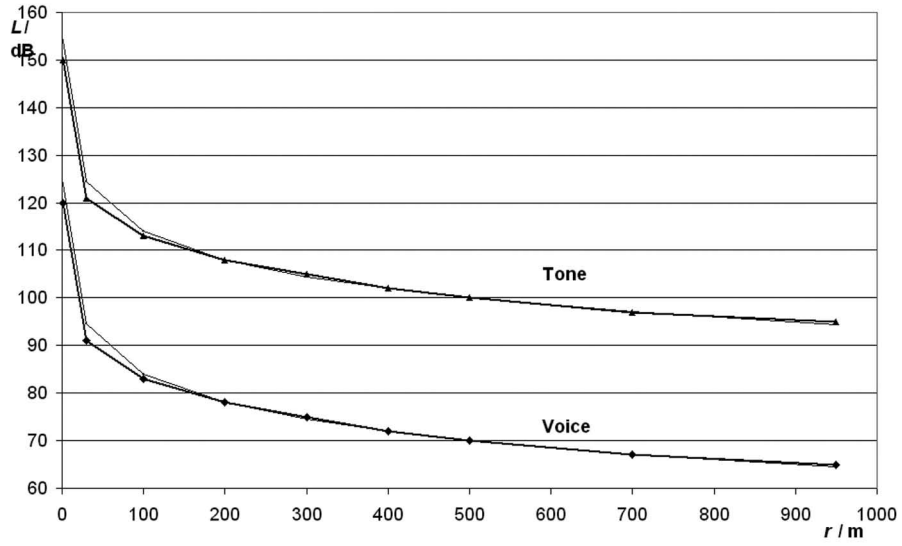174   Partial results have been published in Altmann, 2005.
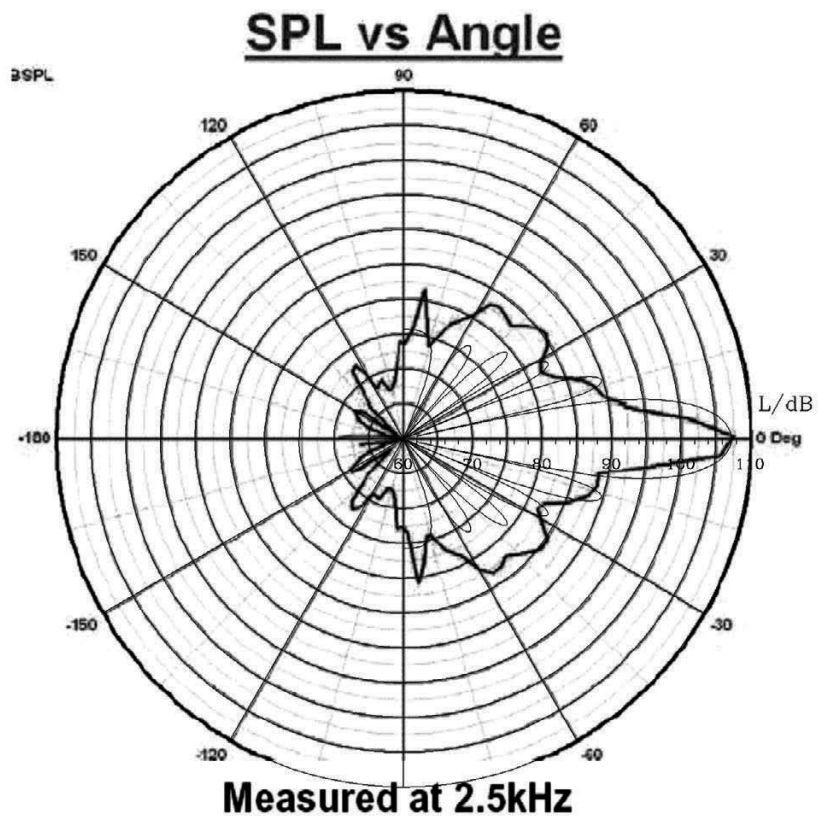
Figure 10a)

Figure 10b)

Figure 10 LRAD properties and overlain theoretical results.

a) Sound pressure level versus distance. Fits of theoretical model (thinner lines) to curves shown on manufacturer data sheet; theoretical acoustic power 88 W (Tone), 0.088 W (Voice), at 2.5 kHz.
b) Angular characteristics of sound pressure level. Theoretical model (baffled piston, 2.5 kHz, thin line, $\pm 90°$ from axis) overlaid on curve shown on manufacturer data sheet. The central lobe becomes narrower for higher frequencies and vice versa

5.2   Analysis

5.2.1 Important Features

In sell sheets the manufacturer has published curves of sound level versus distance (Figure 10 a).[175] Both curves show the usual decrease of sound intensity in proportion to $1/r^2$ (r: distance), level -6 dB per doubling of distance, which holds for linear acoustics due to beam widening with distance, with the warning tone 30 dB above the voice.[176] Using the expression for the acoustic intensity on the axis in front of a piston and fitting it to the curves, the acoustic power emitted is estimated as about 100 W (Tone) and 0.1 W (Voice), respectively.[177] The theoretical curves are shown in Figure 10 a, too.[178]

The frequency response of the LRAD is more or less flat from 2.5 kHz to 10 kHz, but drops strongly at lower frequencies.[179] Compared to the value at 2.5 kHz, it is down by 6 dB (½ amplitude, ¼ intensity) at 1.8 kHz, at 1.0 kHz it has already decreased to -30 dB (1/1000 intensity). This means that there is nearly no emission at low frequencies and that voice messages will appear more high-pitched than even over the telephone where the traditional transmission band is 0.3 to 3 kHz. For emission into a small cone, higher frequency is advantageous, of course.

Propagation

The directivity diagram of the LRAD is shown in sell sheets of various years, with a main lobe in the forward direction.[180] Its width is specified as $\pm 15°$ (for -20 dB decrease) from the axis at 2.5 kHz;[181] from a diagram of the beam margins (at -6 dB) versus distance one gets $\pm 4.6°$ for 2.5 kHz and $\pm 15°$ for 0.8 kHz.[182] The manufacturer's directivity diagram is shown together with the theoretical curve of a circular piston from diffraction theory in

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175   ATC, 2004, here no frequency is given explicitly, but since the adjacent directivity diagram is identical to the one shown in ATC (2003/04) which states "measured at 2.5 kHz" this frequency probably applies to the intensity curves, too. ATC, 2005: viewgraph 13 gives curves which are 2 dB higher, indicating "2.1-3.1 kHz tone"; this difference would correspond to the wavelength ratio 2.5/3.1, see the equation in note 177. ATC (2007) shows similar curves where the scale on the level axis is shifted by 5 dB from the grid on the graph, which would lead to 5 dB lower levels – probably this shift is a mistake. The general agreement of the curves and the identical maximum levels given (151 and 121 dB @ 1 m, respectively) show that the LRAD 3300 of 2004/5 has the same characteristics as the LRAD 1000 of 2007.
176   The levels in this chapter are sound pressure levels without any (e.g. hearing-related A) weighting, unless explicitly noted.
177   In the far field of a circular piston of radius a in a baffle, the intensity on the axis at distance r is $I = P \pi a^2 / (\lambda^2 r^2)$ where P is the acoustic power and $\lambda = c/f$ the wavelength (c: sound speed, f: frequency). Solving for P and introducing various (r,I) pairs gained from the curves (with $I = I_{ref} 10^{L/10}$, $I_{ref} = 10^{-12}$ W/m^2), e.g. at $r = 300$ m $L = 105$ dB, $I = 0.032$ W/m^2 for the warning-tone curve, one gets 88 W if one assumes $f = 2.5$ kHz – this frequency is indicated in the neighbouring directivity diagram. The voice power is 1/1000 thereof.
178   Note that the value for 1 metre is not real, it applies to a fictitious point source with the same far field. For a source of finite radius a emitting at wavelength λ the far field is like that of a point source at a distance above $a^2/(0.6\ \lambda)$, here with $a = 0.4$ m, $\lambda = 0.14$ m above 2 m, see also Figure 11.
179   ATC, 2005: viewgraph 14.
180   ATC, 2003/04, 2004, 2007, 2007a show the same diagram, as does ATC, 2005: viewgraph 15.
181   ATC, 2003/04. ATC (2007) gives "Nominal Beam Width +/- 15° at 2 kHz" without specifying a level.
182   ATC, 2005: viewgraph 17.

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Figure 10 b.[183] Both agree reasonably well. The theoretical curve shows the first zero at 12° from the axis.[184] That the measured curve shows no sharp minima may be due to the fact that the LRAD has several individual segments the membranes of which are fixed at the respective margins, so that the sound pressure is not constant over the emitting area, which is not exactly circular additionally. The general appearance and level decrease with angle up to 90° from the axis agree well, however.

From the directivity diagram one can conclude that the LRAD emits the audio frequencies directly, they are not produced by non-linear interaction from modulated ultrasound. In the latter case, the beam would be much narrower.

Finally, it should be noted that for longer ranges the transmission direction will be deflected in case of strong winds.

Safety of Target Subjects

The Applied Research Laboratory of Pennsylvania State University has written an Interim Safety Report and has concluded "that LRAD can be safely employed as 'hailing and warning device' based on applying the MIL-STD 1474D standards for operators and OSHA standards for target population."[185] The US National Institute for Occupational Safety and Health (NIOSH) has recommended that for workers, the time-weighted average of the A-weighted sound level over 8 h must not exceed 85 dB(A). E.g. the duration at 110 dB(A) must not exceed 1.5 minutes, at 120 dB(A) 9 seconds, at 129 dB(A) 1 second. In the range 130-140 dB(A) the duration has to be shorter than 1 second. Another rule stipulates that levels above 140 dB(A) must not occur at all, and if necessary, by use of hearing protectors.[186] These recommendations assume an 8% excess risk of hearing loss during a 40-year lifetime exposure. (The level difference due to A weighting is 0 dB at 1 kHz and 1.3 dB at 2.5 kHz; the difference between both is not relevant here.)

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183   This is for a circular piston in a baffle, the expression contains a Bessel function, see e.g. Morse/Ingard, 1968: p. 381. In case of forward-peaked emission (wavelength smaller than piston radius) this is similar to an unbaffled piston with back enclosure (or a piston in the end of a pipe) to nearly 90° from the axis, see Beranek, 1986: pp. 102-104. Since the forward level is of interest here, the complicated backward emission was not calculated.

184   The angle θ_1 of the first intensity zero of the Bessel expression (note 183) follows from $\sin \theta_1 = 1.2 \, \lambda/(2 \, a)$, here with f = 2.5 kHz, λ = 0.132 m, a = 0.4 m: $\sin \theta_1 = 0.20$ and $\theta_1 = 11.6°$.

185   ATC, 2004a. The manufacturer states: "LRAD has been evaluated by an independent test lab, field tested, with operational practice set to perform within the guidelines of the National Institute for Occupational Safety and Health (NIOSH) for combined noise exposure source levels and durations." (ATC, 2003/04) The Interim Safety Report was written under contract from JNLWD. Unfortunately, several requests to JNLWD for the report were not answered. See also Davison/Lewer, 2006: Section 2.4.
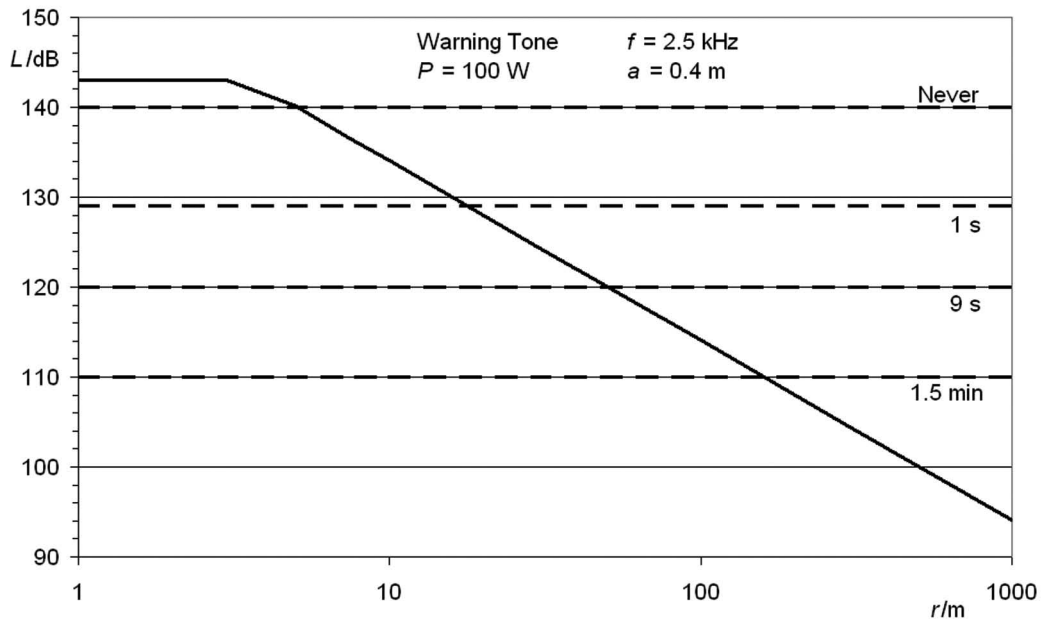
186   NIOSH, 1998.

Figure 11 Approximate sound power level on the axis versus distance for a circular source of 0.4 m radius, emitting 100 W acoustic power at 2.5 kHz frequency. In the far field, the values are about equal to the curves given by the manufacturer for the LRAD warning tone (Figure 10 a). The voice level is 30 dB lower. Above 120 dB, there is a feeling of discomfort; ear pain starts around 140 dB. The horizontal dashed lines mark the level thresholds with their maximum daily exposure times for a worker according to the NIOSH recommended standard, using A-weighting (the weighting difference is 0 dB at 1 kHz and 1.3 dB at 2.5 kHz).

To check the statement about safety for target subjects, the same model source was assumed – a circular piston of 0.4 m radius, emitting a warning tone of 100 W sound power at 2.5 kHz. The sound-power level versus distance is shown in Figure 11, using the simplified assumption that the intensity in the near field is constant (at the quotient of sound power divided by the emitting area, I_0 = 200 W/m^2, L_0 = 143 dB)[187] up to the distance where the far-field intensity drops below this value.The far-field intensity level is close to the curves given by the manufacturer (as in Figure 10 a). Also shown are the maximum NIOSH exposure times for various (A-weighted) levels. Comparison with the LRAD curve shows that the warning tone must not be used closer than 5 m. The exposure duration has to be kept at a few seconds out to 50 m. Time limitations are needed to more than 100 m distance. Conversely, a target subject will likely suffer from permanent hearing damage if the exposure time significantly transcends the respective maximum duration.

The manufacturer states that behind the LRAD the level is less than 40 dB below the one in front.[188] In the warning mode with about 143 dB in front, this means around 100 dB. The recommended daily maximum duration at 100 dB is 15 minutes, at 103 dB 7.5 minutes.[189] Thus, if the warning mode is only used rarely and for less than a few minutes, operators need not wear ear protection.

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187   For the warning tone at the source, I_0 = P / A_{Source} = 100 W / (πa^2) = 100 W / 0.50 m^2 = 200 W/m^2. Thus, L_0 = 10 log (I / (10^{-12} W)) = 143 dB. This is below the level given for 1 m in Table 4 (151 dB) because the latter assumes a small (point) source. Fictitiously extrapolating the far-field level to 1 m one arrives at 155 dB, somewhat higher than specified.
188   ATC, 2007; 40 dB level difference means a sound-pressure ratio of 100:1. ATC (2005) had given 60:1.
189   NIOSH, 1998.

The voice mode with 30 dB lower level, at about 113 dB up to 3 m distance, is unproblematic.

Potential Countermeasures

Protection from high sound levels is possible. In the high-frequency range where the LRAD emits strongly, ear plugs and/or ear muffs can provide 15 to 45 dB of level reduction.[190] If the warning tone is used to produce ear pain or a feeling of discomfort (level above 140 dB or 120 dB, respectively, at distances up to several 10 m), this can be avoided by ear protection. However, annoyance and distraction (at the remaining, say, 100 dB) may still occur.

5.2.2 System Properties

Table 5 summarises the specifications of the ADS as they are available publicly or have been derived here.

Table 5 LRAD 1000 specifications from manufacturer information and present analysis (see text and refs. above)

Emitter	segmented capacitive membrane loudspeaker, direct audio emission
Frequency range	1.8 kHz (-6 dB) to > 10 kHz 1.0 kHz (-30 dB) to > 10 kHz
Acoustic power	$\approx$ 100 W (warning tone), $\approx$ 0.1 W (voice mode)
Total harmonic distortion	1-2 %
Emitting aperture (diameter)	0.8 m
Beam width (at 2.5 kHz)	$\pm$ 5° (-6 dB), $\pm$15° (-20 dB)
Nominal sound power level at 1 m	151 dB (warning mode) 121 dB (voice mode)
Range	> 1000 m (warning mode) > 500 m (voice mode)
Dimension	0.84 m diameter, 0.16 m thick
Mass	21 kg
Approximate price	$35,000

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190   Nixon/Berger, 1991.

5.3 Evaluation

5.3.1 Considerations About Limits

LRAD is called a hailing and warning device, not a weapon. This categorisation seems appropriate as long as the device is not being used to produce ear pain and as long as levels and durations are limited in such a way that permanent hearing damage is avoided. Pre-lethal use to expel combatants or use to repel pirates, however, suggest that in these cases the LRAD actually is used as a weapon. Thus, for use by armed forces an evaluation under the laws of warfare should be done.

For use by security personnel other than hailing and warning, an evaluation in the context of police law and human rights is needed. One can make the case that producing permanent hearing damage while attempting to repel criminals who do not shy away from firing at people, is fully justified. However, this consideration should be made explicitly and systematically before such use, with tests and evaluation, as with other types of police weapons and equipment.

In the warning mode the LRAD produces sound pressure levels which are dangerous to hearing if unprotected target subjects are exposed longer than certain durations: a few seconds to 50 m distance, 1.5 minutes at 100 m. Below about 5 m any exposure can produce permanent hearing damage. For avoiding such injury, the rules for weapon operation are decisive. In order to prevent overdoses e.g. from operator errors, technical precautions – limiting the sound power and/or duration according to the target distance – are recommended, at least as long as the LRAD is to be seen as a hailing device, not a weapon. In case of lethal threats where damage to hearing would be justifiable and could help to avoid using lethal force by the operator, an override switch could permit higher levels, but to prevent misuse every such event should be documented automatically, e.g. by video recording.

5.3.2 Further Research

While some technical details of the LRAD are not known (such as: Is the speaker membrane piezoelectric? What is the maximum membrane movement?), there is sufficient information available to allow judgement in the context of humanitarian international law or national security-force law. Future scientific-technical research should be devoted to on-going research and development of different acoustic weapons, such as the directed stick radiator[191] or potential experiments using very high sound levels.[192]

Interdisciplinary work with the social sciences should mainly look at the on-going uses of the LRAD, in particular by US forces in Iraq, but also by security personnel elsewhere, in order to check if general laws and rules are being complied with or if changes are needed.

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191   Being investigated at the Fraunhofer Institute for Chemical Technologies in Germany, Krebs et al., 2007.
192   As requested by the Applied Research Laboratory of PSU, Nicholas et al., 2007.

6　Concluding Remarks

The four non-lethal-weapon concepts investigated here use very different technologies and produce very different effects.

– The Active Denial System (ADS) emits millimetre waves, producing pain by heating the upper skin layers. It is a big device for mounting on a small truck, with many hundreds of metres range. It has been tested on a large scale and is a few years from potential deployment. It is mostly non-lethal, however heating to life-threatening second- and third-degree burns on large areas of the body is technically possible.

– The Advanced Tactical Laser (ATL) is at the technology demonstration stage. It emits an intense infrared laser beam to a spot of tens of centimetres out to 10 kilometres and more. Material hit is heated within split-seconds to melting or burning. It is so big and heavy that a transport aircraft is needed to accommodate it. It is a lethal weapon which could allow more discriminating destruction at a distance than artillery or bombs, but not in all atmospheric conditions.

– The Pulsed Energy Projectile (PEP), at the development stage, emits intense infrared laser pulses to an area of about 0.1 m size to a range of 0.5-2 km. The uppermost layer of material hit is vaporised immediately and converted to a plasma which emits a shock wave. The mechanical impulse from one pulse is not impressive, whereas multiple pulses lead to significant ablation of the target. If bare skin or the eyes are hit, serious injury up to death can occur. Thus the PEP is a lethal weapon. Due to its size and weight the weapon would have to be vehicle-mounted. With plasma flash and acoustic shock wave, it could act as a long-range distraction device but not in all atmospheric conditions and at much higher cost than flash-bang grenades.

– The Long Range Acoustic Device (LRAD) is a big loudspeaker emitting mainly at high frequencies. The only commercially available system among the four technologies, it has been deployed in the hundreds with US armed forces and law-enforcement agencies. It is called a hailing and warning device, not a weapon, capable of transmitting messages over 500 m and warnings to 1000 m. However, at close range damage to hearing is possible, and it has been used as a weapon.

Some idea of the strength of the effect of the various weapon types can be gained from a comparison of the power emitted and the intensity impinging on a target. These values are given in Table 6, together with the respective dimension, mass and price. It is evident that the ATL, the biggest system, provides by far the highest intensity, and that the LRAD can only be dangerous to very sensitive sensors (the ears).

Table 6 Basic data of the systems, comparison of emitted power and impinging intensity values (intensity: ADS: derived from experiment descriptions, ATL: computed average over assumed spot areas, PEP: computed average over assumed spot area, LRAD: computed on-axis value from diffraction). Dimension, mass, price without carrier vehicle. Whereas for ADS and ATL a large part of the impinging intensity is absorbed, heating the target, in case of the PEP the plasma produced by the very first portion of each pulse absorbs the most part so that less energy hits the target.

Type	Dimen-sion Mass	Price / $	Range / km	Conditions	Emit-ted power / kW [a]	Impinging intensity / (W/cm^2) [a]	Remarks
ADS	several m 1-2 t	few million	0.5-1	maximum power, several 100 m	100	8	not in thick fog, hard rain
ATL	many m 20 t	few million	10-15	spot 0.1 m spot 0.3 m	300	3800 400	not through thick fog, clouds, hard rain; turbu-lence?
PEP	1-2 m several 100 kg	few hundred thousand	0.5-2	spot 0.1 m 1 pulse / s 10 pulses/s 100 pulses/s	1 10 100	3.2 32 320	not in thick fog, heavy rain
LRAD	0.8 m 21 kg	35,000	0.5-1	warning tone at 10 m at 100 m	0.10	0.0027 0.000027	dimension, mass without power supply

a   For PEP, power and intensity are average values for constant pulse frequency.

Whereas in general all means of applying force can be misused, the four technologies studied can be problematic specifically. Under international humanitarian law, if used in armed conflict, this concerns two areas:

–   For the Pulsed Energy Projectile it should be clarified if the injuries from hitting bare skin, the face or the eyes would create superfluous injury or unnecessary suffering.

–   For the Long Range Acoustic Device, use for incapacitation or pre-lethal use qualifies it as a weapon, not a hailing and warning device. Thus, a legal review under international humanitarian law is needed.[193]

In the context of use for law enforcement and other situations not counting as armed conflict, two technologies are inappropriate and should not be used at all

–   The Advanced Tactical Laser is too destructive and has too long range.

–   The Pulsed Energy Projectile also is too destructive and has too long range. The only exception would apply if it were only used as a diversionary (that is, flash-bang) device without risk of serious injury, using only one or very few pulses and hitting only clothing, no bare skin.

For the other two technologies, the normal procedures of assessing new weapons and devising rules for their operation should be followed. Problematic are grey areas, such as use by occupation forces where there are no or fewer constitutional rights for the target subjects. In order to truly protect victims from serious or permanent injuries, the rules for operation should be supported by technical devices:

–   In case of the Active Denial System, the power and duration of irradiating a person should be limited depending on the distance in such a way that heating to second- or third-degree burns cannot occur. In particular, re-engaging the same subject before appropriate cooling time (around 15 s) has passed, has to be prevented.

–   To avoid permanent damage to hearing, the Long Range Acoustic Device should be provided with a component which in the warning mode limits the exposure time depending on distance.

For armed conflict, all four technologies are not a priori excluded. The three real weapons (working with beams of millimetre waves or lasers) would be less destructive than traditional conventional weapons and could allow more discriminating application of force. However, they would not work in all weather conditions, they use high technology, are big, complex and extremely expensive. It may turn out that for routine use they will not be efficient enough so that, if they will be deployed at all, only very few copies will be used for very rare operations.

Concerning misuse for torture, the question hinges mainly on the capability to afflict pain without leaving marks. This could apply to a very small (hand-held, table-top) version of the Active Denial System. Such a system should either not be built at all or at least it should not be exported without strict controls.

Export controls should apply to all three high-power weapons (ADS, ATL, PEP). Preventive arms control seems advisable only in the case of the Advanced Tactical Laser which would fall under a prohibition of laser weapons which is mainly recommended for strategic stability concerning ballistic missile defence and space weapons.

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193   As required for new weapons, means and methods of warfare by Art. 36 of Additional Protocol I to the Geneva Conventions of 1949, see ICRC, 2007.

I want to conclude with a few general remarks:

– Because the assessment of new NLW types depends on the scenarios of use, future research should include interdisciplinary work including social science and law.

– The practical limitations (and the relative funding) show that these weapons do not usher in the "next revolution in military affairs ... [by] directed energy weapons".[194]

– In all cases information about the systems is restricted, be it for commercial property rights or for military reasons. Except for basic 95-GHz effects, there are no scientifically valid publications. Where media events have been held, their messages and the ensuing media reports have conveyed incomplete information. This corroborates the statement made in the introduction: independent academic research of potential new weapons technologies is required to provide a basis of reliable facts for judgement.

– If such weapons will be deployed, it should be for a trial period at first. Independent audits of their parameters should be done, actual uses should be documented and analysed by independent bodies, and decisions on continued deployment should be based on their findings.

– It goes without saying that also for the weapons studied here, there should be a general rule of restraint. The technologies should only be used if they are urgently needed and if they bring improvements in saving lives and health. A sliding transition from an alternative to lethal force to a general compliance device should be prevented. They should not be seen or used in a context of making military interventions easier.

Because the technologies can be problematic, have a potential for overdoses and misuse, and because the rules of operation are still being shaped, continuous attention of human-rights organisations, the International Committee of the Red Cross etc. is needed.

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194   Beason, 2005: p. 5.

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Appendix

Basics of Radiation Quantities and Units, Heating

Electromagnetic radiation represents flow of energy E, with unit joule (1 J = 1 newton·metre = 1 watt·second). It is usually emitted from a source of area A_{Source}, and propagates into the surrounding space, here air. Depending on the curvature of the wave fronts, in the near field the beam expands, stays at about constant width or converges to a small focus area. In the far field, the beam expands always, distributing its energy over an area A_{Beam} the diameter of which increases in proportion to the distance, the area thus in proportion to the distance squared. In the far field the fluence or area density of energy F thus decreases in proportion to the inverse distance squared. In the far field the energy impinging on a target of fixed area A_T thus decreases similarly. If the antenna is large enough and the wavelength small enough, the beam width and thus the fluence can be made about constant out to sizable target distances, as is the case with the ADS. The fluence $H = E / A$ is measured in the unit J/m^2 or here J/cm^2. While the radation propagates through a medium, it can in addition be attenuated by absorption (as with millimetre waves by rain or fog). When it impinges on a target, a part of the radiation is absorbed on entering the target material, another part is reflected. Typical absorbed portions are 0.7 to 1 for millimetre waves on skin, 0.001 to 0.01 for millimetre waves impinging on metal and 0.3 to 0.8 for infrared waves impinging on metal.

The same amount of energy can be emitted or absorbed in a short or a long time. How fast energy is delivered is measured be the power P (or Φ) of the radiation, the quotient of energy by time of delivery: $P = E / t$. The unit of P is 1 watt = 1 joule/second. A similar relation holds for the respective area densities: the irradiance (or intensity) I is the quotient of fluence by time: $I = H / t$, its unit is W/m^2 or here W/cm^2.

As always, when a target is heated by radiation, the conservation of energy holds. Thus, the absorbed energy is converted to heat energy. How the temperature increases depends on many factors, however. At first the absorption layer becomes hotter, then heat convects deeper into the target. Since this takes time, the surface temperature gets higher if the energy is delivered in a shorter time, that is with higher power. Additional effects which can occur if high enough temperatures are reached are melting (consuming the latent heat of melting) and vaporisation (consuming the latent heat of vaporisation). If material becomes fluid in this way, it can flow off or even blow off, exposing fresh surface – thus more material can be heated and removed. On the other hand, as the surface becomes hotter, it increasingly emits thermal radiation itself which subtracts from the energy flown into the material. Another counteracting effect exists if the target is cooled, such as with blood flow (where the blood carries off some thermal energy) or sweating (where the latent heat of evaporation removes some energy) – however, the latter two effects are not important on the time scales of seconds or fractions of seconds relevant for beam weapons. In any case, radiation heating is a complicated phenomenon which is non-linear often.

Acronyms

ADS	Active Denial System
AFB	Air Force Base
ATC	American Technology Corporation
ATL	Advanced Tactical Laser
CA	California
COIL	chemical oxygen-iodine laser
DoD	Department of Defense
DSB	Defense Science Board
FFI	Forsvarets forskningsinstitutt (Norwegian Defence Research Establishment)
FY	Fiscal Year
HMMWV	High Mobility Multipurpose Wheeled Vehicle
JNLWD	Joint Non-Lethal Weapons Directorate
JNLWP	Joint Non-Lethal Weapons Program
LSD	laser-supported detonation (wave)
MANPADS	man-portable air defence system
MUA	Military Utility Assessment
NLW	non-lethal weapon
NM	New Mexico
ntW	nicht-tödliche Waffe
PEP	Pulsed Energy Projectile
PSU	Pennsylvania State University
R&D	research and development
SPL	sound power level
THD	total harmonic distortion
TX	Texas
US(A)	United States (of America)
VA	Virginia

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