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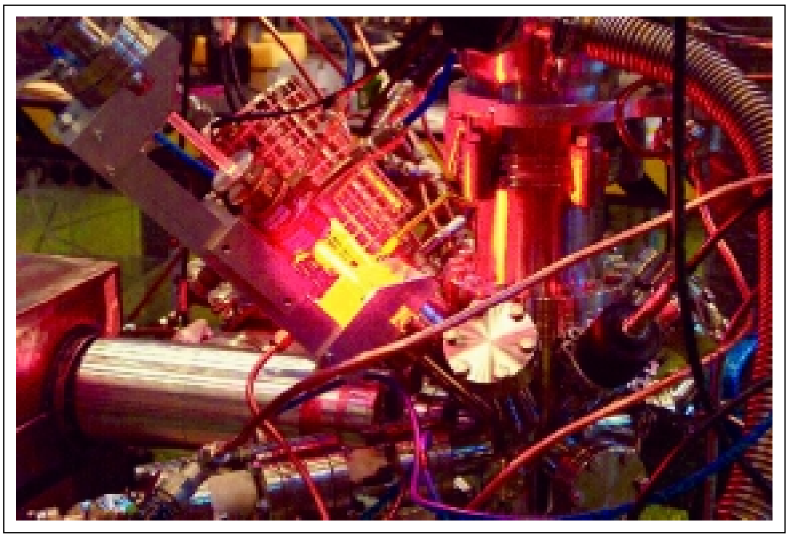
Progress Report

Bo Janzon, Kristina Wahlgren (Editors)

# WEAPONS AND PROTECTION DIVISION
# Annual Report
# 2000



WEAPONS AND PROTECTION DIVISION
SE-147 25 TUMBA, SWEDEN

# Brief history

FOI Weapons and Protection is located at the Grindsjön Research Centre, about 40 km south of Stockholm in the forests of the Södertörn peninsula, comprising an area of about 7.5 square km. The site was founded in 1941, during WW 2, as the Institute of Military Physics. In those days several noted Swedish Physicists, such as Nobel Prize Winner Professor Hannes Alfvén, worked here. In 1945 it merged with other defence research activities, mainly the Defence Chemical Institute, and the National Inventions Board, which among other things worked with radar, to become FOA.

The initial research areas at Grindsjön in 1941 were shaped charges and rockets. After 60 years we still do research on shaped charges and rockets. From time to time, authorities have thought that now was the time to end this research and do other important things, and there have indeed been shorter periods of lower activity of that. So far, these opinions have always been proven wrong. Anti-tank warfare has been a core activity at Grindsjön, and when the protection levels have increased as a result of technical developments and breakthroughs such as Chobham armour and reactive armours, requirements of increased performance of anti-tank munitions have again become a strong driving force for Sweden and FOI. FOI Weapons and Protection is still among the world leaders in high-precision shaped charges, as well as in high-velocity rockets, but now also in other areas such as energetic materials and computational physics.

In the 1950's nuclear weapons research, mainly detonics, became an increasing and important activity at Grindsjön. New land and the bulk of todays facilities were added to enable research, experiments, development, and finally preparations for production of "the bomb". Grindsjön became the "Los Alamos" of Sweden. The site was highly secret until a large forest fire in 1954, which required the assistance of all fire brigades of the Stockholm area, and of many hundred military personnel, made its existence known to the public. Vegetation on the long rock ridge on the western shore of the Grindsjön, which was completely obliterated in the fire, has only started to grow back in the last 20 years.

In 1958 development of the nuclear weapons was curbed by the Parliament of Sweden, and in 1968 came the final decision that Sweden would abandon all further work and procurement of nuclear arms. After this, conventional weapons and protection against weapons effects have been at the focus of Grindsjön.

The new Weapons and Protection Division was established in 1994

Going down from the early 70's maximum of about 140 to a minimum of about 85 in 1994, in December 2000 about 135 persons, including service personnel, work at Grindsjön. This was accomplished by the merging and moving of all research on explosives and underwater effects, originating from the Defence Chemical Institute established in 1935, from FOA's site at Ursvik to Grindsjön. The combined explosives and propellants group, now denoted "Energetic Materials" has created a new and important hub and driving force for most other activities at the Division.

In 2000 the Protection and Materials Department finally moved to Grindsjön from a test station, located at Botele udd, Märsta, close to Arlanda Airport, about 40 km north of Stockholm. One medium-sized blast tunnel will be kept by FOI at Botele Udd, and can be used for campaign testing. Also the activities of a research group on materials, especially their dynamic properties, moved from Ursvik to Grindsjön.

The potential for further developments in conventional weapons effects, earlier judged as very limited, now seems to be quite high, based on the possibility to create new materials with much higher (3-10 times, or more) energetic content than the present most potent explosives, such as HMX. Combinations with sensors and computers in smart and brilliant weapons also serve to greatly increase performance potential. Fortunately enough there seem to be similar possibilities to increase protection, e g using ceramics, gradient composite materials and active armours with sophisticated sensors and warning devices. Relieved security political stresses may, contrary to common beliefs, mean an increased risk of more long-term development efforts and introduction of entirely new weapons principles.

Information technology warfare will be an important new element in future conflicts. Electromagnetic weapons such as HPM, NNEMP and laser warheads may play an important part in this, as the ultimate means of electronic warfare. With much more energetic explosives, traditional effects such as shaped charge or fragmentation may prove incapable of effectively transporting the energy to the target, and direct conversion to electromagnetic energy may become preferable.

On 1 January 2001 there was a merger between the Aeronautical Research Institute (FFA) and the Defence Research Establishment (FOA). The new research organisation is the Swedish Defence Research Agency, FOI, comprising an intact and developing Weapons and Protection Division.

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*Cover illustration:*

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# FOA's Weapons and Protection Division

**Director:**
Dr Bo Janzon, M.Sc. (Eng.Phys.), Ph.D. (Med. Sci.)

**Deputy Director:**
Mrs Carin Lamnevik, M.Sc. (Eng.Phys.)

**FOA Weapons and Protection, Area of Activity:**

- Energetic Materials
- Rapid mechanical and energetic processes
- Dynamic properties of materials

especially applied to

- Weapons, munitions and warheads
- Their effects and protection against effects

including, also for the needs of civilian society:

- Risk and process analysis
- Fire initiation and evolution, including smoke spread
- Sensitivity testing of explosives

**Business Concept**

- Physics, Chemistry, Mechanics, Materials and Strength of materials
- Close interaction between theory and experiments
- High competence in modelling and simulation
- Highly advanced, superfast measurement equipment
- Good contacts with Universities etc. (KTH, UU, CTH, LTH, LiTH, LuTH, and abroad)

# Weapons effect on humans

By Gunnar Wijk

The subject “weapons effects on humans” is very broad. Only a few aspects of this subject are studied within the project. The focus is on physical instead of medical matters, since the latter are dealt with in the other projects in the “weapons trauma” research area. Physical models of weapons effects on biological material are required as an input to large computer programs for assessment of effects and vulnerability for complex targets, in which personnel are vital components. The general intention of the project is to develop new models and improve old models.

A new model for fragment penetration into biological material is developed. Experimental results for steel sphere penetration into gelatin, which is commonly used to simulate live biological material, are found to agree with the model. The steel spheres’ diameters are 4.0, 6.3 and 8.0 mm and the impact velocities are from about 100 to 500 m/s. The deepest penetrations are about 25 cm. Further experiments with much lighter spheres of polypropylene are accurately predicted by the model and the target material parameters obtained with the steel spheres. Steel sphere penetration into board, which is a much harder material than gelatin, is also well described by the model. It remains to establish a method with which real (irregularly shaped) fragments can be simulated by spheres. It is believed that fragment penetration depth is quite important for determination of the kill probability of a human target.

Impulse noise, or air pressure waves, from weapons may cause hearing damage if adequate hearing protection is not used. This problem is discussed in a separate article below.

A computer program for calculation of pressure waves in the air around weapons is being developed. Presently pressure waves from gunpowder gas expansion can be determined. It remains to incorporate the pressure waves from the motion of the projectile.

### Hearing damage from impulse noise

Impulse noise, or air pressure waves, from weapons may cause hearing damage if adequate hearing protection is not used. A workshop with invited foreign specialists was organized in October, with the purpose of giving FOI a basis to should recommend a criterion for permissible impulse noise to be used by the Swedish Armed Forces. The criterion that is chosen for the recommendation is originally proposed by ISL in France. It is based on calculation of the energy in the pressure waves. The manner in which hearing protection should be investigated is a part of the recommendation.

Most criteria for permissible impulse noise exposure are based on measurement of the maximum amplitude of the pressure wave and some duration. The latter is the time during which the pressure differs from the normal air pressure in some specified way. Different criteria yield different results for the permissible noise, depending on the shape of the pressure wave and on the definitions of the duration in the criteria. Furthermore, the manner in which successive exposures should be accounted for is only defined in the simplest case, namely for identical exposures. A practical criterion must account for successive exposures with different maximum amplitudes and durations.

The opposite of impulse noise (excepting silence) is continuous noise. Continuous noise is produced by machines, which may be running constantly, for instance vehicle engines, or intermittently, for instance pavement breakers. Continuous noise consists of a sum of periodic pressure waves with different discrete frequencies, as in Figure 1 below. In each of these the maximum amplitude occurs twice per cycle as long as the noise goes on. The human ear sensitivity to periodic sound depends on the frequency of the pressure wave. The smallest frequency that can be heard is about 20 Hz and the greatest is about 16 kHz. The smallest amplitude that can be heard is when the frequency is about 4 kHz. Normal conversation is between 200 Hz and 4 kHz.

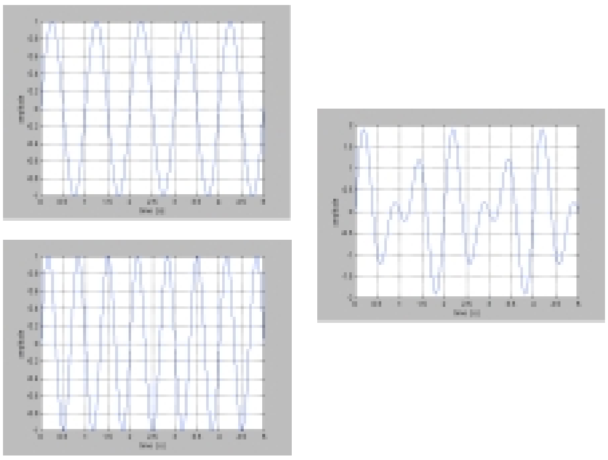


*Figure 1: Two periodic pressure waves (to the left) and the sum of these (to the right).*

ISO 1999 describes the standardized (mathematical) manner in which continuous noise, namely several simultaneous pressure waves of different amplitudes and frequencies, should be evaluated to yield the noise level, namely a standardized average value measured in the non-dimensional unit dB(A): dB is the abbreviation for decibel, and (A) stands for the way in which the sensitivity of the human ear has been accounted for in the calculation. The smallest amplitude that can be heard, at 4 kHz, corresponds to 0 dB(A). Normal conversation is somewhere between 50 and 70 dB(A). If the pressure wave amplitude is doubled, then the noise level increases with 6 dB(A). If the pressure wave duration is doubled, then the noise level increases with 3 dB(A); if it is doubled once more the total increase is 6 dB(A).
ISO 1999 does not specify the maximum permissible noise level, but national standards are practically always chosen to be 85 dB(A) for constant exposure during a full working day of 8 hours. If the exposure only occurs during 2 hours, namely one fourth of a full working day, then the shorter time corresponds to a reduction of 6 dB(A) and hence the permissible noise level during the exposure time is 85+6=91 dB(A).

Impulse noise cannot be described as a sum of periodic waves with finite, constant amplitudes and discrete frequencies. Simple cases of impulse noise correspond to pressure waves like those in Figure 2 below. Mathematically these waves may be described as sums of periodic waves with initially infinitely small amplitudes that become even smaller for every new cycle. Every frequency is present in the sums, so that the number of frequencies is infinitely great. The (mathematical) combination of infinitely small amplitudes and infinitely many frequencies is a pressure wave with finite instantaneous amplitude, which changes with time.

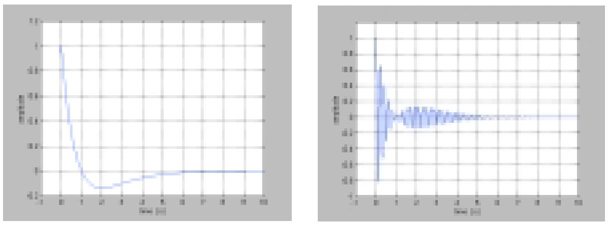


*Figure 2: Two simple examples of pressure wave corresponding to impulse noise.*

The mathematical description of impulse noise in terms of pressure waves of every frequency and infinitely small amplitudes makes it possible to apply the same principal way of calculating a noise level as for continuous noise (the sum over a finite number of discrete frequencies is replaced by an integral over the whole frequency range). Thereby the sensitivity of the ear is accounted for in the same principal manner as for continuous noise. From the physical point of view the noise level is a (non-dimensional) measure of the energy content in the pressure wave that reaches the measurement point, whereby the (infinitely small) energies at every different frequency have been weighted to account for the ear sensitivity. When there are successive exposures, namely several separate impulse noises, then the (weighted) energies of these are simply added to yield the total exposure. To obtain maximum similarity with the criterion for continuous noise the permissible level for impulse noise is also chosen to be 85 dB(A) during a full working day of 8 hours.

The effects of hearing protection may be evaluated in different ways. The simplest way is to determine the frequency dependent factor, with which the amplitude of periodic pressure waves must be increased, in order to just exceed the hearing threshold when hearing protection is used. The method is called REAT, which is the acronym for "Real Ear Attenuation at Threshold". This experimentally determined factor is used together with the ear sensitivity, and in the same principal manner, to calculate the (weighted) level of noise consisting of different frequencies, whether it is continuous or impulsive.

Certain hearing protections are designed so that high amplitudes are transmitted to a smaller degree than small amplitudes (the hearing protection is then "nonlinear"). With such protection it is possible to communicate orally, which often is quite necessary in military applications, and yet obtain sufficient attenuation of high amplitude impulse noise. The REAT method will then yield an over-protective result, so that the criterion yields a noise level that is significantly below the really damaging level. The only ethically acceptable way to determine the real attenuation of such hearing protection, namely when the noise is close to or possibly above the damaging level, is to use an Artificial Test Fixture (ATF) as in Figure 3. An ATF simulates a human head and measures pressure waves that reach the eardrum via a microphone. However, it must be emphasized that there is yet no standardized ATF.

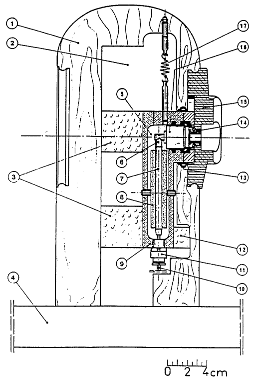


*Figure 3: An example of an Artificial Test Fixture.*

The FOI recommendation to the Swedish Armed Forces is to use REAT until research results make it possible to change to ATF in the criterion for permissible impulse noise exposure.

# Energetic Materials Department

**Head of Department:**
Dr. Henric Östmark, M.Sc. (Eng. Phys.), Ph.D. (Phys. Chem.)

## INTRODUCTION

The Energetic Materials Department conducts basic and applied research within the area of explosives and propellants and their ignition, as well as technical development and specialized small-scale production. We also act as expert advisors to the armed forces concerning explosives, propellants, ignition systems, mines and ammunition safety. The aim for the department is to be one of the world's leading research organizations in the field of energetic materials and energetic processes.

The department staff consists of 30 persons, 24 of whom hold academic degrees (12 Ph D, 11 M Sc). A positive sign is that 40% of the staff are women.

We also have an extensive co-operation with the Royal Institute of Technology and the Stockholm University: 5 graduate students. During the year we have had a visiting scientist from DERA in UK working on the $N_4$ project, and a post doc from Finland working on melt casing ADN and on activated aluminum. The Energetic Materials Department has a number of international co-operation projects, e.g. US (Department of Defense Project Agreement NO. SW-N-96-1505 "Synthesis & Characterization of "Green" Energetic Materials and Formulations for Rocket Motors and Warheads") and US (Department of Defense, Defense Advanced Projects Agency, Washington D.C., Project agreement NO. TRDP-US-SW-D-98-0001, High Energy Density Materials), UK (DERA, "The uses of ADN in formulations containing PolyGlyn or PolyNimmo"), Finland (DFRIT), Netherlands (TNO Prince Maurits Laboratory, IA 13 "FOX-7").

## NEW ENERGETIC MATERIALS

In the short range, research and development is focused on 4th generation energetic materials (e.g. CL-20, ADN, FOX-7, TNAZ) with application in shaped charge warhead, high performance warhead, higher performance rocket and gun propellants and better underwater explosives. During the fiscal year a successful scaling up of the synthesis of FOX-7 to pilot plant scale (2kg batches) was carried out, this process was also transferred to NEXPLO Bofors AB. FOX-7 has also turned out to be a good burn rate modifier for LOVA propellants. These new substances have a potential use both as propellants and as explosives, with a performance 20 to 30 % higher than those in use today. Another important issue is the development of rocket propellants and explosives, based on the new substances, with better safety than that available today with equivalent or better performance. There is a trend towards greater variation in the choice of explosive/propellant depending on the application, and on safety and performance requirements. A new dinitramide salt has been synthesized namely triaminoguanidinedinitramide, TAGDN, which turned out to be very high in performance in a gun propellant application but unfortunately very sensitive. A new type of aluminum, activated aluminum, has been invented and tested. This test showed that this activated aluminum is more reactive than nano-sized aluminum (ALEX) in spite of the fact than it is more than 100 times larger. It is also much cheaper to produce. Another trend in the explosives community is the movement towards more environmentally friendly explosives (both from the point of view of manufacturing and of use).

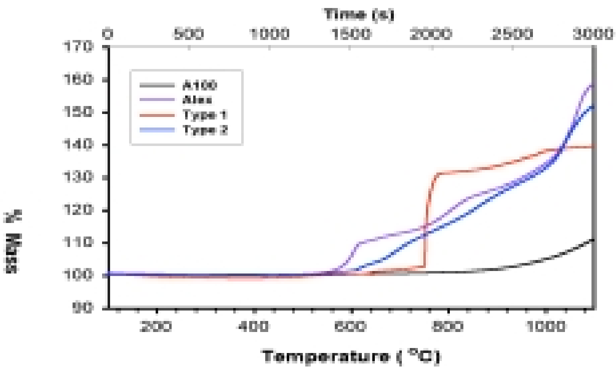



*Figure 1. Reactivity of activated aluminum in comparison with normal aluminum and with ALEX*

The long-range research perspective focuses on substances more or less dependent on new principles for storage of chemical energy. It is known today that this type of substance has a theoretical potential performance at least 100 - 500 % better than today's explosives. In the search for new explosives, nitrogen clusters have surfaced as a potential candidate and the focus of the department is the synthesis of $N_4(T_d)$. During the year the detection principles of $N_4$ have been worked out and the detection limit determined.

A number of synthetic routes towards $N_4$ have also been established and several pieces of synthesis equipment have been constructed. This work has been sponsored by DARPA and an agreement has been made to continue this line of work the third and final year.

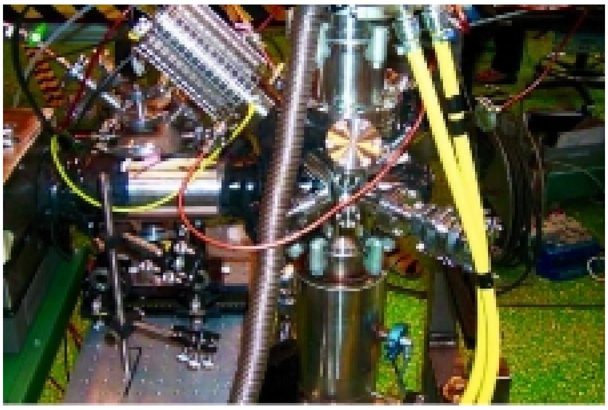


***Figure 2.*** *Synthesis equipment for* $N_4$

## NEW UNDERWATER EXPLOSIVES

New underwater weapons systems have a need for more powerful underwater explosives. We have explored the possibility to utilize ADN as an ingredient in melt cast explosives. During the year, a technique for melt casting ADN and ADN/Al compositions has been developed. A study of the ADN detonation properties has also been carried out. The casting technique was also scaled up to a 5 kg size at which the new ADN/Al underwater explosive was tested in the sea. These tests reveal that this composition is probably the world's best performing underwater explosive.

***Figure 3.*** *Test of the new underwater explosive ADN/Al*

## MINE DETECTION

The department's focus is the detection of mines by chemical methods. The reason for this is that the only thing that definitely distinguishes mines from every thing else is that they all contain explosives. The Energetic Materials Department is also involved in work in the field of mine clearance and for expert advice regarding demolition work and for equipment for combat engineers. A large part of the work is currently devoted to the development of a mine identification database. In the field of mine detection the focus has been towards the migration of explosives from buried mines. This knowledge is essential in the development of the mine dog and for the development of chemical mine detection methods, as well as for the research on bacteriological biosensors. An important result of this line of research is that it is not necessarily TNT that should be looked at for the detection of mines, but rather DNT or different bio-decomposition products of TNT, and what to look for is strongly dependent on the environment.

Another line of research is the study of biodegradable explosives.

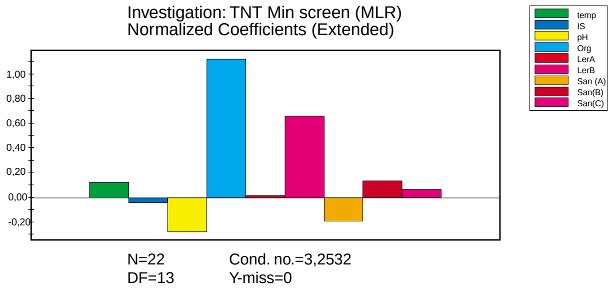



***Figure 4.*** *The environment plays a large role in the transportation of TNT in nature, it hence force influence the ability to detect mines by chemical means. In this figure the influence of soil type on the distribution of TNT between water and soil is shown (Soil/Water* $C_{soil} = K_d{}^*C_{water}$*).*

## DEMILITARIZATION AND RISK ANALYZES

An increasingly important line of research is the environmentally safe dismantling of old ammunition. As ammunition with time becomes obsolete or unstable due to ageing it must eventually be dismantled. This was earlier accomplished by dumping in lakes and mines or by open-air detonation and burning. This is not only environmentally harmful, but also economically unsound as much of the explosives could be reused e.g. in the mining industry and in road building projects.

Today, a large proportion of the disused ammunition is being partly reused or recycled and in the long run open-air detonation and burning will probably be completely discontinued or forbidden. This however creates new problems with waste disposal or recycling, while at the same time there are some types of explosives for which it is difficult to find alternative markets, e.g. pyrotechnics. Because of the risk of explosion, disposal or recycling of explosives will have higher safety requirements than the handling of ordinary refuse. Present methods for waste disposal will not be applicable and will have to be replaced by new or modified processes capable of meeting the requirements of both environment and safety. The risk analysis team has during the year performed risk analysis concerning the handling and transport of dangerous materials for companies and authorities.

## LECTURES AND COURSES

The Department has been responsible for a number of courses and lectures on explosives chemistry and explosives safety, e.g. high explosives course (3 parts of 3 days each with about 35 participants from the defense industry, FOA, Police, and other Government authorities), and two lecture series at the Royal Military College (MHS) on Chemistry; High Explosives and propellants (25 hrs each). Apart from the activities mentioned above, a large number of presentations and laboratory tours for visitors from both Sweden and the rest of the world have taken place.

# Warhead and Propulsion Department

**Head of Department:**
Dr Anders Wätterstam,
Ph.D. (Theor.Phys.)

The department has 27 employees and our main research areas are launch techniques for guns, propulsion, conventional warheads and detonics, underwater warheads, RF-warheads and computational continuum dynamics. During the past year one of our main efforts in an ongoing development of our activities has been the development of experimental techniques, primarily for combustion studies (see below).

### Research on launch techniques

The research in this area is primarily focused on electro thermal-chemical (ETC) launch techniques were mainly chemical but also electrical energy is utilized for accelerating a projectile. The purpose of supplying electrical energy is to enhance and control the combustion of the propellant and thereby improve the gun performance in terms of muzzle velocity and/or -energy, while decreasing variation in muzzle velocity. Thus impact velocity, range and hit probability may be increased and a heavier projectile may carry a greater payload.

### Redesign of the ETC-bomb

To enhance the understanding of how the burning of propellants is effected by supplying electrical energy, an ETC-bomb was constructed. This ETC-bomb is designed for conducting an electrical current through the flame of a burning propellant slab and as a result raising the temperature of the flame further by Ohmic heating. Thermal energy of the flame is transferred to the unburnt propellant and the burning rate is increased. The previous design of the ETC-bomb used a tubular charge, burning on the inner surface only. However, in that configuration a magnetic pinch effect forces the current paths away from the unburnt propellant surface, thus reducing the electrical heating of the flame zone near the propellant. The ETC-bomb has therefore been redesigned (see figure 1) for use with a test charge in the shape of a rectangular slab and with both electrodes entering the chamber from the same end. This means that the current paths now instead are forced towards the surface of the solid unburnt propellant and the burning area is constant throughout the process.

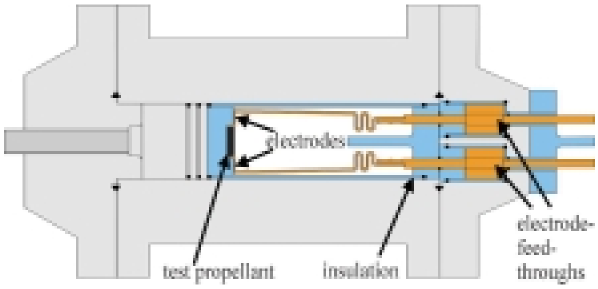



*Figure 1. Design of closed ETC-bomb.*

### Closed vessel ETC-experiments with alkali doped propellants

In a closed vessel firing the volume is constant during the combustion of the propellant, which makes it easier to calculate the burning rate from the pressure/time recordings. The pressure depends on the amount of gas generated from the burnt propellant and heat losses to surrounding material in the bomb. Two different pressure gauges, located at different positions in the chamber, are used for measuring the pressure. Since the combustion of a conventional nitrocellulose propellant gives a flame with a very low electrical conductivity, samples of a double base propellant were prepared with additives of 1% and 5% of either potassium nitrate ($KNO_3$) or potassium dinitramide (KDN). Calculations indicate that by doping propellants with alkali the electrical conductivity of the combustion products is substantially increased. This has also been partially verified in experiments at pressures around 1-5 MPa. In the few initial firings carried out at 100 MPa, the electrical energy has been released with a short delay in a rapid avalanche discharge rather than in an extended continuous discharge. One firing, however, indicates that the combustion rate is somewhat increased. Varying parameters like, for instance delay, amplitude and width of the electrical pulse and propellant composition will prove whether this technique is able to substantially increase the burning rate.

### Additional activities

In addition to the above-mentioned activities, work has also been done on preparing new low vulnerability

high performance propellant formulations based on the energetic polymers GAP and polyNIMMO. Propellants with HMX as the main oxidizer containing 5% $KNO_3$ has been prepared, characterized and sensitivity tested.
In cooperation with the Department of Computational Physics at Lund University of Technology, FOI has been working on the development of a new computational code for simulating the two-phase flow in a flame. The objective is to gain a better understanding of physical processes taking place during the combustion of propellants.
Extensive work has been done on establishing routines for operating the security system of the 300 kJ TZN pulsed power supply.
To upgrade the competence within the launch technique area, five members of the department have participated in a course on interior ballistics.

## Research on Propulsion

The main research project in the field of propulsion is dedicated to air-breathing engines, which compared to rocket engines have significantly higher specific impulses. Hence, these engine types show considerable potential in increased range. Specific efforts were made, to study the Pulse detonation engines (PDE), to make the ducted rocket engine test facility fully operational, and to (in collaboration with the computational physics group) initiate research on high-speed combustion and on our part mainly the required experimental techniques.

## Development of experimental techniques and experimental equipment for combustion studies

In order to achieve more efficient numerical models and to gain a more fundamental understanding of combustion phenomena, there is a growing need to develop and apply experimental techniques for comparison and validation. Most desirable are measurement techniques, which give two- and three-dimensional information without disturbing the process under study. The most suitable techniques for these purposes are optical, non-intrusive methods.
The quantities that are considered to be of primarily interest to study are:

- Concentration fields
- Density variations
- Pressure variations
- Temperature distribution
- Velocity fields

An experimental facility is under construction for developing and testing different optical techniques for experimental combustion studies. The test set-up is made of stainless steel with a quadratic cross section. It is modularly designed, thereby making it possible to easily adjust it to new experimental situations by supplying new modules. Each module has connections, which can e.g. be used for gas feed and connection of pressure and other transducers. One module is prepared for optical measurements, having observation windows on each side. The facility will be ready to use for experimental work during 2001.
The optical methods that initially will be tried out are LIF - Laser Induced Fluorescence, schlieren techniques and interferometrical methods (primarily holography), the latter in cooperation with the division of Experimental Mechanics at Luleå University of Technology.
LIF – Laser induced fluorescence is the spontaneous emission from a molecule that has been excited through absorption of laser light. LIF can e.g., be used for:

- Detection of concentrations of reaction products such as OH, CH and NH.
- Measurement of temperature fields by comparison with the Boltzman-distribution.
- Velocity measurement through Doppler shifts.

In figure 2 examples of LIF images are shown which indicates the OH-concentration distribution in a Bunsen burner flame. An ICCD-camera (Intensified CCD) was used to record the images resulting from excitation by laser light in the UV-range (309.464 nm). The laser beam was expanded into a thin light sheet of 20x1 $mm^2$.

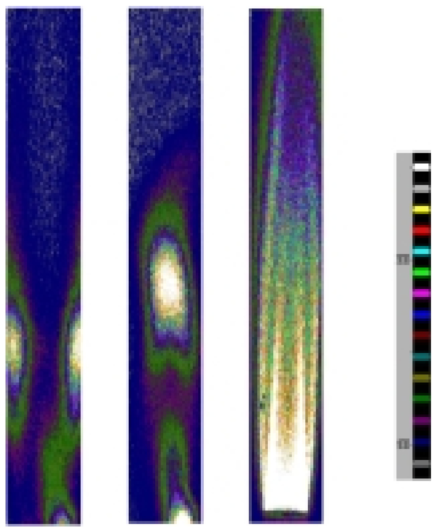
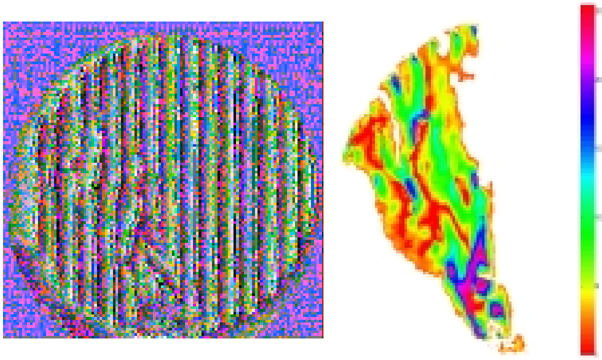


*Figure 2. Laser induced fluorescence images showing the OH-concentration at two different cross sections of a Bunsen burner flame.*

The Schlieren method, originating from the nineteenth century, is a matured technique for detection of gaseous inhomogeneities. The method is sensitive for variations of the index of refraction, which in turn depends on variations in density, pressure and temperature and, in the case of gas mixtures, on the distribution of the different gases. The method can be made very sensitive and is relatively easily handled. However, it has two main drawbacks: The result is achieved as contrast variations, which can be difficult to quantify with satisfactory resolution and reliability. It is an integrating method (which is also true for interferometric methods), i.e. the result is essentially the sum of the variations between the light source and the detector. The second drawback may in theory be overcome using tomography, i.e. combination of the results from many illuminations–recording directions. However, in practice this can be difficult, or even impossible to accomplish, especially if the experiment must be performed in a confined volume. Another approach is to use the numerical simulation of the process under study along with raytracing, to predict the resulting Schlieren image and compare it with the one achieved experimentally. To overcome the first drawback, defocused grid methods can be used where a known pattern, e.g. a parallel grid, is imaged through the media under study. Instead of contrast variations, the result is established as deviations from the original pattern, which can be evaluated using Fourier based image-processing techniques. In figure 3 an example of an evaluated schlieren image of a candlelight flame is shown where a Ronchi ruling has been used to produce parallel lines. The left image shows the deflected phase pattern and the right image shows the evaluated phase change (color coded).

*Figur 3. Example of processed schlieren images of a candlelight flame using the defocused grid method. Left: phasemap of deflected parallel lines. Right: evaluated phase differences*



*(color coded) between original and disturbed field. The color scale is in this case not calibrated, but gives in principle a measure of the deviations due to temperature variations in the flame.*

## The Pulse Detonation Engine

During the year a series of single cycle experiments have been performed. The purpose of these was to investigate different means to produce consistent transitions to detonation with a minimum of extra oxygen added to the mixture. Two different approaches have been employed:

- The predetonator has been augmented with up to four disks of different blockage ratios in order to provoke successively more violent combustion in the chambers between the disks and finally a transition to a detonation in the main chamber.
- A turbulence-generating spiral — a Shchelkin spiral — has been inserted in the main chamber.

Of these two approaches the second one has proven to be slightly more effective, and is also the most commonly used method. It has the potential of being more effective in a practical application since it represents less resistance to the internal flow than the first procedure. It is also worth noting that an engine equipped with a Shchelkin spiral, of almost identical geometry as the one in this investigation and also using hydrogen as fuel but operating under multi-cycle mode, has demonstrated extremely reliable transitions to detonations, without any extra oxygen at all. Results of successful operation for this engine are even reported for equivalence ratios as low as 0.4, which is remarkable since the energy requirement for direct initiation for equivalence ratios that low are about 20 times higher than for stoichiometric mixtures. In contrast it has been necessary to add more than 12% extra oxygen in the single cycle experiments performed at FOI in order to obtain transition to detonation. This rather big difference between single and multi-cycle experiments are currently not thoroughly understood, but two probable reasons for this difference have been identified:

- In the single cycle experiments at FOI the gases are quiescent prior to the ignition whereas in multi-cycle experiments the gas mixture are in motion. Therefore turbulence and vortical structures will be present in the flow field prior to the ignition in the multi-cycle experiment, which have a positive effect on the transition to detonation.
- In multi-cycle experiments the structure will become rather hot after just a few cycles, and consequently the gas mixture will be heated prior to the ignition, which might also explain the ease of initiation in the multi-cycle experiment.

Due to this new information the goal of the research at FOI have shifted from trying to optimize initiation of single cycle experiments to trying to explain — and take advantage of — the differences between single and multi-cycle experiments.

Although the chief goal of the investigation (obtaining reliable transition to detonation without any added oxygen and with a minimum of energy) has not been obtained, transitions have been recorded with as little as 2.5% extra oxygen. Moreover, the importance of shock waves in these transitions has been illustrated, and thereby verified findings in theoretical/numerical work also performed at FOI.

## Research on the ducted rocket test facility

The existing facility for studies concerning ducted rocket engines has been further improved and tested in order to make it fully operational. Fuel-rich propellants have been successfully test fired in the facility and the evaluation codes have been improved. For heat protection of exposed surfaces at small complex places in the combustion chamber, a castable new silicone based insulation material has been developed. Furthermore, a literature study on boron compositions for ramjet engines has been started and a theoretical study on adjusting of mass flow rate and temperature measurements has been initiated.

### Additional activities

In addition to the above mentioned projects FOI, performs ageing-control and testing of rocket engines for the Swedish defense, the Swedish Space Corporation and other customers.

### Research on Warheads

Our main focus in this area is on shaped charges and the very closely related area of detonics. Of particular interest have been the areas of warheads suited for new and future energetic materials with increased energy-content (including the use of "new" liner materials), warheads with adaptable effect for use in intelligent weapons systems and warheads suited for warfare in urban areas.

One of the trends today in increasing the performance of shaped charges is the use of other liner materials than the classic copper. Molybdenum and tungsten are of particular interest. The former because of its high speed of sound leading to long jets, and the later because of its higher density. Both of these materials can be manufactured and/or formed to desired shapes with more or less difficulty. The desired final result in the microstructure is a fine grain size, in the order of five to ten microns, and of course with no traces of contaminants. One method by which this can be achieved is High Energy Rate Forming, a technique that has shown to be promising for forming difficult materials such as these. Our effort to study the process in more detail has continued and the results are promising. The technique is somewhat unique because the apparatus used is hydraulically driven and computer controlled. Thus each successive blow is accurately controlled and monitored. Previously a test series consisting of copper, molybdenum and tungsten was performed in order to investigate the chosen materials ductility as a function of temperature and strain-rate. Small cylindrical samples of the materials were subjected to one to four blows at different temperatures and strain-rates. The results were that copper could be processed at room temperature, molybdenum and tungsten required a temperature of a few hundred degrees centigrade and a high piston velocity. Under such conditions even the brittle tungsten flowed nicely and formed almost perfect circular discs. Conical formed liners for shaped charges have been produced in copper and molybdenum with promising results. The copper and molybdenum samples have undergone metallurgical investigation prior to forming, post-forming and after heat treatment in order to determine the adequate heat-treatment.

The main objective in the field that we call adaptive warheads is to study various concepts which within a weapons system have the ability to vary the weapons effect depending on the target, the level of desired effect, the level of acceptable collateral damage etc. One example is the ability to vary between a shaped-charge jet, an explosively formed projectile or a fragmenting warhead depending on the armor of an encountered vehicle. Our focus in this context has been to study variations in the initiation of the charge, primarily variations in the number of initiation points and their separation. As an application these studies will be continued within the field of underwater-warheads. Regarding warheads for warfare in urban areas some preliminary tests have been performed with a specially designed combination of shaped charge jet and an explosively formed projectile. The warhead is intended for penetration of concrete with re-bars and is designed to result in penetration channels with large diameter.

In the area of weapons systems a preliminary study was undertaken regarding "intelligent warheads". This study engaged personnel from several divisions of FOI and its prime objective was to give recommendations for further study. This work is now ongoing.

### Research on underwater explosives and effects of underwater warheads

The department includes a group that carries out theoretical and experimental research in the areas of underwater explosives and effects of underwater warheads. The research can be divided into both fundamental research as well as applied research and is carried out within several projects. The main customers are armed forces and the defense materiel administration, FMV.

In the area of underwater explosives, the research was focused on:

- Performance test of underwater explosives based on ADN. Casted ADN with Aluminum was found to be a very efficient underwater explosive comparable to or even better than the best currently used.
- Efficiency evaluation tests of a Fuel-Water-Warhead concept. The result indicates bubble energy levels exceeding the bubble energy of any now existing conventional explosives.
- Methods of disposal of buried mines with shaped charges. A disposal charge for purposes on land was modified for underwater use and was found to initiate a charge buried in two meters of sand.

In the area of weapons effects, the largest research effort was on:

- An initial validation of a 3-D FEM-package for analysis of ship vulnerability to shock has been carried out using experimental data from a full-scale ship shock trial.
- Final analysis of measurement data from a full-scale ship shock trial.

The research in general is subjected to supervision of a reference group with participants from the armed forces, FOA and FMV.

## COMPUTATIONAL PHYSICS

The computational physics program has grown and diversified even further during 2000 and now covers the research areas: aerodynamics, hydrodynamics, reacting flows and detonics, solid-fluid interactions, computational methods and software development, and molecular dynamics. The program has become more established both internationally and nationally, as well as within FOA, resulting in new research contracts and collaborations. The core of the program is the computational physics project, which is funded by the division, in which most of the general method development is carried out. The underlying idea is that the development of mathematical models and computational methods that are generic to different applications or projects can be performed better and more economically within the framework of this project since synergies can be better exploited. As illustrative examples we have the development of boundary layer models, which are essential to naval hydrodynamics (e.g. fouling and flow noise), missile aerodynamics (drag etc.), and atmospherical turbulence (roughness caused by e.g. small buildings), and the development of radiative transport models, which are important to fire spread, IR-signatures from missiles and engine flames, and neutron transport. Research on such complex issues requires substantial efforts, and often a general approach is needed in order to be successful. The research in this field is driven by the applications – mainly applications from many different areas within the defense sector. In what follows a few highlights will be described.

Collaboration with the contaminant transport group at the NBC-division was started on January 1. This collaboration aims at developing improved models for contaminant transport, and in particular in urban areas and inside buildings, e.g. underground stations. During FY 2000 the LES flow simulation models have been further developed towards more complex geometries, and LES models are under development for atmospherical boundary layers.

The ongoing research program together with Naval Research Laboratory (NRL) has continued regarding Monotone Integrated Large Eddy Simulation (MILES), and is now expanding on reacting flows, and particularly high-speed reacting flows, placing NRL and FOA at the research front in this area. Within this research, previous connections with the Dept. of Aerospace Engng. at Georgia Institute of Technology (Atlanta, USA) have been substantially strengthened, and a joint publication is to be presented at the 2nd Turbulent Shear Flow Conference in Stockholm 2001. The research concerning two-phase reacting flows, with particular emphasis on interior ballistics and Solid Rocket Motor (SRM) combustion, is evolving very well with a publication at the 39th AIAA Science Meeting, Reno, USA, 2001. A new type of simulation model has been developed for SRM combustion, that have the capability of simulating e.g. combustion instabilities and have been applied to a laboratory SRM, see figure 4. This research is performed as a collaboration involving the Propulsion project, the Launch Technology project and the Division of Fluid Mechanics as Lund Institute of Technology.

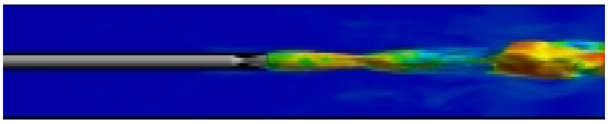


***Figure 4.*** *Snapshot of a SRM plume, showing the plume as an isosurface of the axial velocity colored by the temperature. Inside the rocket engine the model developed incorporates the combustion of a solid propellant and associated physical and chemical processes.*

A research collaboration with Kockums AB concerning submarine hydrodynamics has been initiated, and is involving one PhD student from Kockums AB and the department of Naval Architecture and Ocean Engineering at Chalmers Institute of Technology. So far this collaboration has resulted in a joint paper, presented at the 39th AIAA Science Meeting, Reno, USA, 2001.

We have also taken part in the Gleipner project, aiming at developing improved methods for submarine propulsor design. This project is lead by FMV, and further involves participants from SSPA, Kockums AB, CTH, Rolse Royce (former KaMeWa AB).

Research has also been conducted in the area of hydrodynamic signatures from surface ships and submarines. This work has been conducted in close collaboration with the Future Mine Protection and Clearance project and the Future Torpedoes project. Figure 5 shows a perspective view of the flow past a modern surface combatant, and some particular flow features associated with the underwater part of the hull, such as the bilge vortices and the vortices produced by the sonar dome. It is essential to be able to predict such flow features in order to optimize design of Swedish warships, as well as predict certain features of other ships, e.g. pressure signatures and wake characteristics.

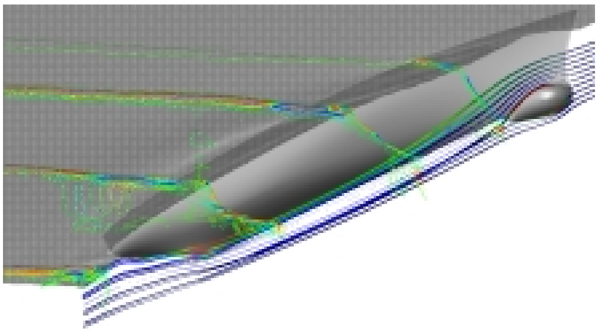


*Figure 5. Perspective view of the flow around a modern surface combatant, showing parts of the wave pattern, the wake and the hull vortices.*

The development of moving boundary and interface methods is probably the most expanding and dynamic area at present. Research and development is carried out along three different lines, aiming at obtaining a state-of-the-art toolbox that will cover the needs of FOA today and tomorrow. The methods presently developed and implemented are: Arbitrary Eulerian Lagrangian (ALE) methods, Overset or Chimera methods, Volume of Fluids and Immersed boundary methods. Together, these three methods have the capability of covering almost any problem within the area of solid-fluid interactions.

## Research on RF-warheads

### Background

The objective of the research in this area is to study technologies, which can applied in order to destroy or disrupt electronic equipment through the generation of high power microwaves (HPM, NNEMP, RF). Our prime interest is pulsed radiation in the frequency range 0.1-50 GHz. having a radiation power in the range 0.1-10 GW. One way of making these devices powerful yet small enough to fit into warheads is to use generators driven by high explosives.

One class of devices generate radiation in a narrow frequency band in the frequency range 1-3 GHz by accelerating electrons in a vacuum tube using a high voltage (typically 500 kV, 1ms) pulse. Typical such radiation sources are the vircator and the MILO. In an application these systems could fit into a missile size warhead if an explosives driven magnetic flux compression generator (EMG) is used to drive the system.

Another class of devices generate broadband radiation in the frequency range 0.1-10 GHz. Using high voltage pulses, electrons are accelerated in a metallic structure which also works as an antenna to direct the radiation. In an application these devices can be made small enough to fit into small warheads (grenades). A candidate is an explosives driven piezoelectric pulse generator .

### Activities and results

Most of our work has been devoted to theoretical and experimental studies of a tabletop size pulsed power system tailored to drive a narrowband radiation source of vircator type. This system called TTHPM is based on an EMG with inductive energy storage, an exploding wire fast opening switch and a spark gap fast closing switch. The system is an example of technology that could be of interest in a missile size HPM warhead. The main goal has been to generate high voltage pulses tailored to drive a vircator and generate HPM. This requires a pulse having >250 kV with a rise time < 100 ns. Another goal has been to increase the current and voltage diagnostics performance to be able to measure more accurately and to improve the theoretical modelling of the performance of the system in a Pspice environment.

To achieve high voltage the critical component in the system is the electrically exploded wire opening switch. For convenience in the experimental studies of the opening switch a 22 kV, 15 kJ capacitor bank has been used as the primary electrical energy source instead of an EMG. For the opening switch 63.5 and 127 mm diameter wires having 300, 400 or 500 mm length embedded in different porous solid materials have been studied.

The best results were obtained using fuse wires with diameters 63.5 mm and 127 mm having a length of 500 mm embedded in bulk 45-85 mm diameter spherical glass spheres. The highest voltage recorded was about 150 kV with a rise time of about 0.3 _s. However the peak voltage in the system has been limited by parasitic electric breakdown in different parts. Considerable efforts have been devoted to redesigning and rebuilding to address this problem. A conclusion is that presently the system cannot generate a pulse that will drive a vircator. To achieve this goal further redesign is required to address the breakdown problem. For future work it is recommended to further examine the effect of fuse wire geometry and quenching materials. Results of this work have been presented in FOA reports. The research has partially been performed in collaboration with Canada and Switzerland.

# Protection and Materials Department

**Head of Department:**
Michael Jacob, M.Sc. (Chem. Eng.), Ph.D. (Chem. Eng.), Assoc. Prof. (Chem.)

The Department of Protection and Materials was formed in late 1999 and has during 2000 been installed at Grindsjön Research Centre, partly through a relocation from the former Märsta and Ursvik sites. In mid 2000 the present head of department was employed, together with two researches in the field of materials, and the number of employees at the end of the year was 21. Of these, 17 are researchers and 4 technical and administrative staff.

The research at the department is based on integrated experimental and theoretical work concerning materials and construction structures, with the main aim towards protection against rapid dynamic deformations and fire. The department consists of four research groups:

- **Fire** - theoretical and experimental research in the fields of fire and smoke propagation and protection.
- **Fortification** - fortification in terms of large scale testing and impact experiments, and estimation of risks.
- **Materials** - synthesis and characterisation of materials, and dynamic material properties.
- **Simulation** - finite element calculations for prediction and understanding of rapid dynamic events.

The activities during the year have been strongly influenced by installation and start-up of the labs and equipment, which was almost fully completed by the end of the year. Parallel to this work, a large number of research projects have been carried out and presented as reports, publications and at several international symposia and conferences around the world. The department has collaborations with several universities and institutes of technology in Sweden, and with research institutes in other countries. Some of the activities are described here below.

## Fire research activities

Main focus of the fire research activities during 2000 has been on large-scale fire testing of building materials and constructions for increased fire safety. For instance, glass facades were tested against a full-scale fire scenario to study how the construction would react when exposed to fire (cf. figure 1). Measurements were done mainly to evaluate temperature and heat radiation at important locations during the tests. Also, full-scale tests were performed to evaluate how long time wooden panelled doors could prevent fire from burning through the material during a realistic fire scenario (cf. figure 1). The purpose was to study different constructions and the effect of protection with, for instance, intumescent coatings. During the course of the experiments, measurements were done to evaluate temperatures on exposed and unexposed sides, as well as heat radiation to the doors etc.

*Figure 1. Full-scale fire testing of glass facades (left) and wooden panelled doors (right).*

Another example of experimental work is the full-scale reconstruction of a fire incident, carried out for an insurance company, with the purpose of studying possible fire spread routes for the particular scenario. Yet another example was the study of "air screens" as a possibility to prevent smoke spread in underground facilities.

A new method for performing non-destructive smoke-spread tests in existing buildings was developed. The purpose of the method is to be able to make more realistic tests focused on evaluating smoke spread paths, testing fire protection installations etc. In short, the method is based on simulating a fire by burning methanol (clean combustion) and adding artificial smoke. A number of tests have been performed of which one was at InfraCity in Upplands Väsby.

## Large scale testing at the shooting-range of Älvdalen

During the later part of the year the department conducted a large scale test concerning ammunition storage in mountains, by direction of the Swedish armed forces headquarter and the Singapore defence. Three tests were performed during 2000, and one of the four planned tests was moved forward to 2001 due to a delay in the construction of the facility.

The facility is a large tunnel system with a total length of 250 m, ending in a 1000 $m^3$ large chamber in which, at most, 10 tons of TNT was detonated in order to study the impact of the shock wave. Besides FOA, researchers from Norway and the USA participated with measuring equipment, and in total 130 channels were recorded in the tests. The experiments were successfully executed, and at the 10-ton test, 23 foreign and 27 Swedish visitors participated as observers to the large-scale blast.

## Impact tests, blast tests and protection

Under contract to Sycon Teknikkonsult AB, tests where a cooling system of a protected structure was exposed to different blast loads were made. Some conclusions from the tests were that most of the tested components in the cooling system received no visible reduction of function for different blast loads, and that area-reduction of a duct system and hatches have a reducing effect on the blast wave.

Tests were also made under contract to the Headquarters of the Swedish Armed Forces where a light fortification was subjected to small arms fire. The light fortification was intended to be a prototype for a protected space for Swedish troops involved in international peacekeeping operations. The results from the tests showed that both planks of high-performance concrete and armour give sufficient protection against the defined threat.

A study of the conditions for stationary and moveable behaviour, with regards to the protection for military units from weapon attacks, was made under contract to the Headquarters of Swedish Armed Forces. One conclusion was that military units could use infrastructure constructions such as bridges, tunnels and other constructions in rock as protection against different weapon attacks.

During the year the department has initiated a co-operation with Norway (FFI and HFK-AMK) regarding further development of the risk analysis model AMRISK. AMRISK calculates individual and collective risk for the general public (third person) in the vicinity of an ammunition storage in the case of a detonation.

## Dynamic Material Properties

The processes that occur when bodies are subjected to impact loads can differ significantly from those that occur under quasi-static situations. The purpose of our research is to increase the knowledge of the dynamic mechanical material behaviour and the coupling between microscopic structure and macroscopic mechanical properties.

Work performed during the year include development of a new type of Hopkinson equipment for high strain rate ($10^3$-$10^4 s^{-1}$) tensile testing. The method gives a better tensile pulse shape than conventional Hopkinson techniques and the wave phenomena that occur in testing equipment and sample is also studied with FEM software. In connection with the mechanical testing equipment an induction heater connected to an IR-temperature sensor has been installed. This allows high strain rate testing at elevated temperatures which is essential for the development of material models.

Other work includes research on the mechanical behaviour of columnar grained tungsten and alloys of tungsten and rhenium. These types of anisotropic heavy metal alloys have a potential as projectile material since it is known that the penetration performance of tungsten single crystals is strongly orientation dependent. Initially quasi-static tensile testing of samples with different grain orientations with respect to the load direction is done.
Further, a study concerning adiabatic shear has been initiated. This phenomena, which can appear when metals are subject to high deformation rates, is for example interesting in the processing of liners for shaped charges.

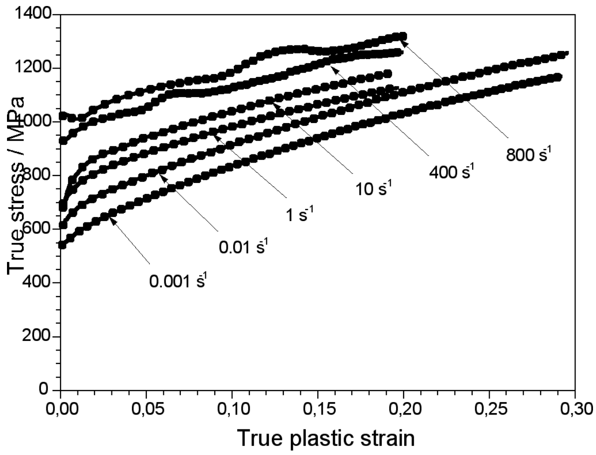



*Figure 2.*

As an example of the effect of different loading rates on the mechanical properties we show the increase in flow stress with strain and strain rate for a nitrogen alloyed steel in figure 2. As may be seen, at low strains the flow stress is almost doubled when the strain rate increases from 0.001$s^{-1}$ to 800$s^{-1}$. A successful material model would explain and predict the behaviour seen in the figure.

## Structural protection for stationary and mobile tactical behaviour

The possibility to use numerical simulation to predict the effect of conventional weapons on protective structures is evaluated in the project "Structural protection for stationary and mobile tactical behaviour". The weapons effects can be divided into blast loads and impact loads, and in several cases these two effects are combined into a weapon effect i.e. general-purpose bombs. The research is based on comparisons between numerical simulations and experiments.

Earlier penetration tests have shown an increase for the protection level of a structure when the normal concrete is replaced with high performance concrete (HPC). However, the structural behaviour for a structure of HPC is more complicated and the risk for a brittle failure might be increased. This type of structural behaviour was studied during the year 2000 with a test series with static and dynamic loaded HPC beams. The dynamic tests were performed with air blast loading in a shock tube. The results show that the shear strength of concrete beams is important to consider. The reason is to avoid a catastrophic shear failure and to obtain the ductile flexural failure.

Earlier performed experiments with air blast loaded concrete panels were numerically simulated during the year 2000 with the code LS-Dyna, and the use of a concrete damage model supplied with the code. This showed that this version of the material model could not describe the material behaviour to an acceptable degree. The company Karagozian and Case has continued to developed this material model since it was released for LS-Dyna, and this later release is now used at FOA as a user defined material model. This work shows promising results for future studies of impact and penetration phenomena in concrete.
Numerical methods in Autodyn for simulation of detonations and shock wave propagation in fluids were evaluated during this year. The simulations show good agreement with earlier performed experiments conducted with 48 kg high explosive charges at FOA, and the numerical methods are considered to be able to predict pressure loads on structures with an acceptable result for a structural analysis. Also structural analyses of wall elements were performed, and comparisons were made with earlier experiments. In figure 3 the calculated pressure in the air and mean stress in the wall element is shown.

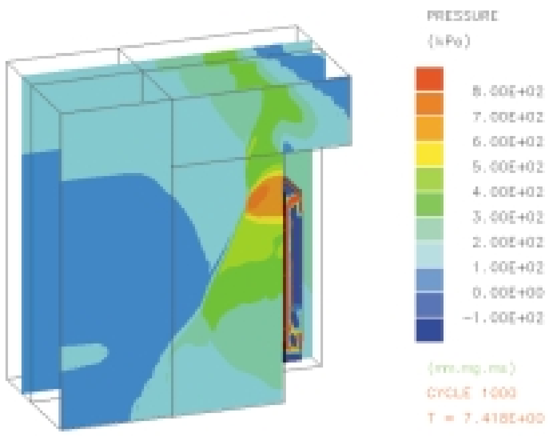



*Figure 3. Calculated pressure for 3D model, 7.4 ms after detonation.*

# Armour and Survivability Department

**Head of Department:**
Ralf T Holmlin, M.Sc. (Dir. of Res)

The Department ”Armour and Survivability” has changed its name from the earlier ”Terminal Ballistics and Vulnerability” in order to give a more precise information about the main areas in our research efforts. The department employs, at the turn of the year, 24 persons.

The “Armour” part of the department consists of fourteen persons, working on the projects “Armour and projectiles”, “Lightweight armour” and “Active armour”. Ten of them are scientists and four are technicians who support the experimental part of the work. Four of the scientists are working actively on their PhD´s under supervision of Bengt Lundberg, who combines his position as Professor of Solid Mechanics at Uppsala University with a part-time position as adjunct head of research in the department.

The “Survivability” part consists of seven persons, and directs the projects “Vulnerability and lethality assessment” and “Human vulnerability criteria”.

Two persons are involved in the Swedish Armed Forces´ studies on requirements to meet future tasks. These are at the same time an essential basis for our research and especially the needs connected to Peace Support Operations, PSO. Directing of the project “Adaptable effects”, previously called “Non-lethal weapons” is a part of the work.

## Armour and projectiles

The focus of the research on armour protection against heavy KE threats has been on passive and active armour components to defeat long rod projectiles at velocities up to the range of 2 km/s. Especially ceramic and reactive armour has been considered.

A review of the work in this field at FOA during the 1990´s was presented at the European Forum on the Ballistics of Projectiles 2000 at ISL (“High velocity KE-projectile interaction with modern armours”).

The work on ceramic armour has been concentrated on continuing the study of the interface defeat phenomenon. The experimental studies to find out the velocity at which transition between interface defeat and penetration takes place in high quality ceramic materials will be continued and new targets have been produced. The work on modelling the behaviour of ceramic targets attacked by long rod penetrators has resulted in a paper accepted for publication in the International Journal of Impact Engineering (“Tungsten long-rod penetration into confined cylinders of boron carbide at and above ordnance velocities”). A theoretical model has been developed of the load exerted by the conical tip of the projectile on a rigid surface and test specimens have been produced for the study of the interaction between the conical tip and ceramic targets.

The basic mechanisms of active armour components have been investigated by studying a long rod projectile hitting a moving oblique plate. This is studied experimentally using the cinematically equivalent case of an oblique plate hitting a yawed penetrator (reverse impact experiments) and a number of experiments have been performed to verify that a new experimental design works. Numerical simulations to study the fracture of the projectile have been started which, together with the experimental results, should enable reliable predictions of the capability of different types of active armours (reactive armour, sensor activated armour).

The study of “capacitor-type” electric armours has been extended to include the influence of scale, projectile material and threads on the projectile.

A survey of the literature on different types of armour piercing medium calibre projectiles has been made.

Two papers have been accepted for presentation at the 18th Ballistics Symposium (“High velocity jacketed long rod projectiles hitting oblique steel plates” and “An experimental investigation of interface defeat at extended interaction time”).

## Lightweight armour

As armour-piercing projectiles from small calibre weapons is a growing threat, we have concentrated our efforts on the possibilities to obtain protection against this kind of threat. There are different types of armour-piercing projectiles and their penetration capability differs a lot. AP-projectiles with tungsten-carbide cores have recently been fielded and are supposed to increase in numbers. The penetration capability of this kind of projectile is so good that it might constitute a very severe threat against most lightly armoured vehicles.

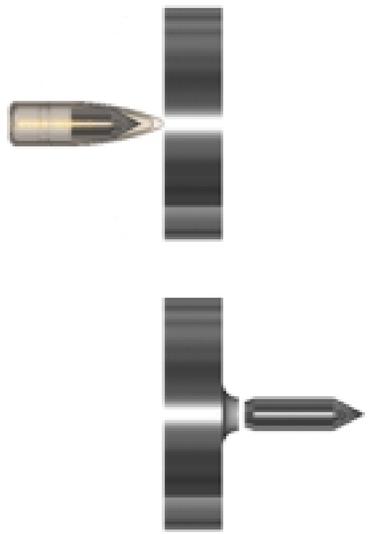
The problem from a protection point of view is mainly that the strength of the projectile core is so high that it penetrates homogeneous armour materials without deforming at all, which is very good for the penetration capability. Additionally the projectile velocity for new kinds of small calibre tungsten-carbide projectiles increases to the same range as that of medium calibre projectiles.

Defeating these armour-piercing projectiles demands materials with extreme strength properties as well as solutions based on geometrical disturbances. To utilize the potential of these new materials in armour constructions, interaction with other materials is often needed. For instance one might use backing and confinement materials or composite materials where the choice of matrix material can be of large importance.

It has been found that the material group with the best potential to overcome the strength of tungsten-carbide penetrators is ceramics. Some high quality ceramic materials combined with suitable backings and/or confinements are, in principle, capable of defeating these projectiles on the surface of the ceramic. If it is possible to make efficient armours for vehicles from this concept is still to be answered. Next step is to understand the influence of the projectile shape and velocity, to produce a material with both ceramic and backing properties in the same tile and construct some examples of armours for lightly armoured vehicles.

Another way to break up the projectile is to transfer geometrical disturbance to the projectile. There are a lot of construction possibilities available to do this. To sort out the parameters of importance in this case studies have been carried out on the influence of material, thickness and obliquity of a thin plate in front of the basic armour. It has been found that this kind of exterior armour can be made very weight effective. It remains to make this kind of armour volume effective.

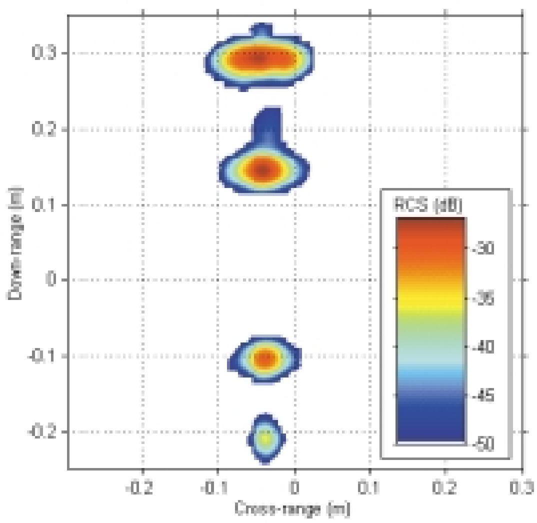
To realize better lightweight armours the methods for dynamic material testing and registration of ballistic events must be improved. The properties for the materials involved have been measured in order to use these results in the constitutive modelling needed for the numerical simulations to be relevant. In the ballistic testing great efforts have also been taken to register the penetration processes so that relevant comparisons with the simulated results can be made.



*The growing small calibre threat*
*The strength of the projectile core is so high that it penetrates homogeneous armour materials without deforming at all.*

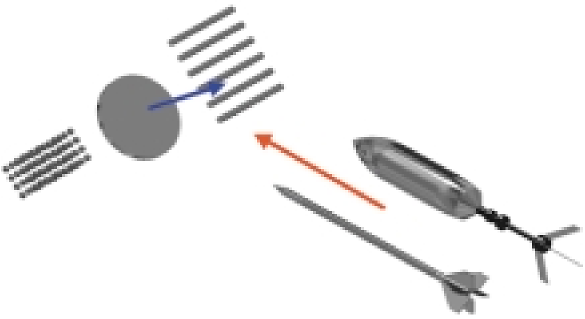
## Active Armour

The Active Armour project is a joint effort between the Weapons and Protection and the Sensor Technology divisions at FOI. The current focus of the project is the detection and defeat of high velocity kinetic energy penetrators. In comparison with chemical energy threats, KE poses a greater challenge for the sensor systems due to the high velocity and relatively small radar signature. The same applies to the defeat system due to the rapid response times required and the substantial momentums involved.




*ISAR-picture of generic KE-penetrator signature*

Theoretical studies, simulations and accompanying signal processing have been performed within the area of radar sensors. Static measurements of generic penetrator radar signature have also been carried out in several suitable frequency bands. A study has also been initiated in the field of IR-sensors. The related topic of aerodynamic heating has been studied numerically with the objective to enable assessment of threat signature.



*Active protection defeat concepts*

A number of defeat concepts have been studied as potential candidates for active protection. Launch and interaction mechanisms have been investigated for fragments, plates and bars in numerical simulations as well as experiments.

One study has also been initiated in the field of IR-sensors. The related topic of aerodynamic heating has been studied numerically with the objective to enable assessment of threat signature.

## Vulnerability and lethality assessment

During later years the emphasis have shifted from lethality studies to vulnerability assessment. This closely follows the shift of focus for the armed forces from outright war to international joint PSO. The development of small arms AP ammunition is a growing threat to armoured vehicles and the personnel inside. Especially projectiles with tungsten-carbide cores have shown large penetration capability. Most light armoured vehicles will need improved ballistic protection.

In the future Swedish naval vessels will take part in international operations. Preliminary investigation shows that this kind of operations puts new demands on protection, which are not fully met today.

A new model for shaped charge penetration of spaced armour plates has been developed. Extensive experimental work has been done during the year and the results and the model harmonize very well. This model has been integrated in our latest vulnerability assessment code.
Parts of the Swedish vulnerability assessment code "LIBRA" has been verified and validated during this year. Especially the module, which handles flooding and ship stability with respect to warhead action, has been thoroughly investigated and tested. The computer code has been corrected and improved and the results agree well with experience and theory.

Extensive smokespread experiments in a scaled ship structure have been conducted in collaboration with Prins Maurits Laboratory / TNO in the Netherlands. The results have been used for preliminary comparison with data computed by the fire- and smoke module in LIBRA and a similar TNO model. The result is quite satisfactory and the work continues with CFD-calculations of smokespread in a simulated ship structure.

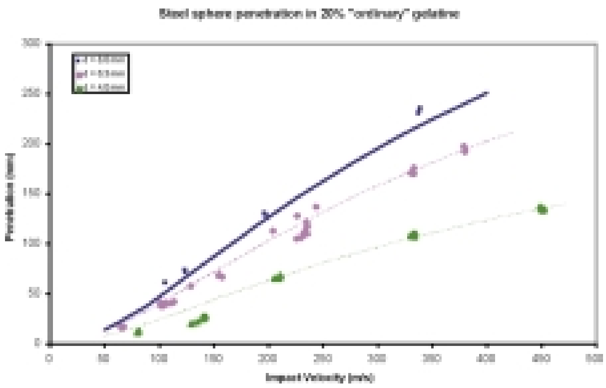
## Human vulnerability criteria

The subject "Human vulnerability criteria " is very broad. Only a few aspects of this subject are studied within the project. The focus is on physical instead of medical matters, since the latter are dealt with in the other projects in the "weapons trauma" research area. Physical models of weapons effects on biological material are required as an input to large computer programs for assessment of effects and vulnerability for complex targets, in which personnel are vital components. The general intention of the project is to develop new models and improve old models.

*Fragment penetration*

A new model for fragment penetration into biological material is developed. Experimental results for steel sphere penetration into gelatin, which is commonly used to simulate live biological material, are found to agree with the model. The steel spheres' diameters are 4.0, 6.3 and 8.0 mm and the impact velocities are from about 100 to 500 m/s. The deepest penetrations are about 25 cm. Further experiments with much lighter spheres of polypropylene are accurately predicted by the model and the target material parameters obtained with the steel spheres. Steel sphere penetration into board, which is a much harder material than gelatin, is also well described by the model. It remains to establish a method with which real (irregularly shaped) fragments can be simulated by spheres. It is believed that fragment penetration depth is quite important for determination of the kill probability of a human target.

A paper has been accepted for presentation at the 18th Ballistics Symposium ("Sphere penetration into gelatine and board").




Impulse noise

Human vulnerability criteria Impulse noise, or air pressure waves, from weapons may cause hearing damage if adequate hearing protection is not used. This problem is discussed in a separate article below.

A computer program for calculation of pressure waves in the air around weapons is being developed. Presently pressure waves from gunpowder gas expansion can be determined. It remains to incorporate the pressure waves from the motion of the projectile.

## Adaptable effects

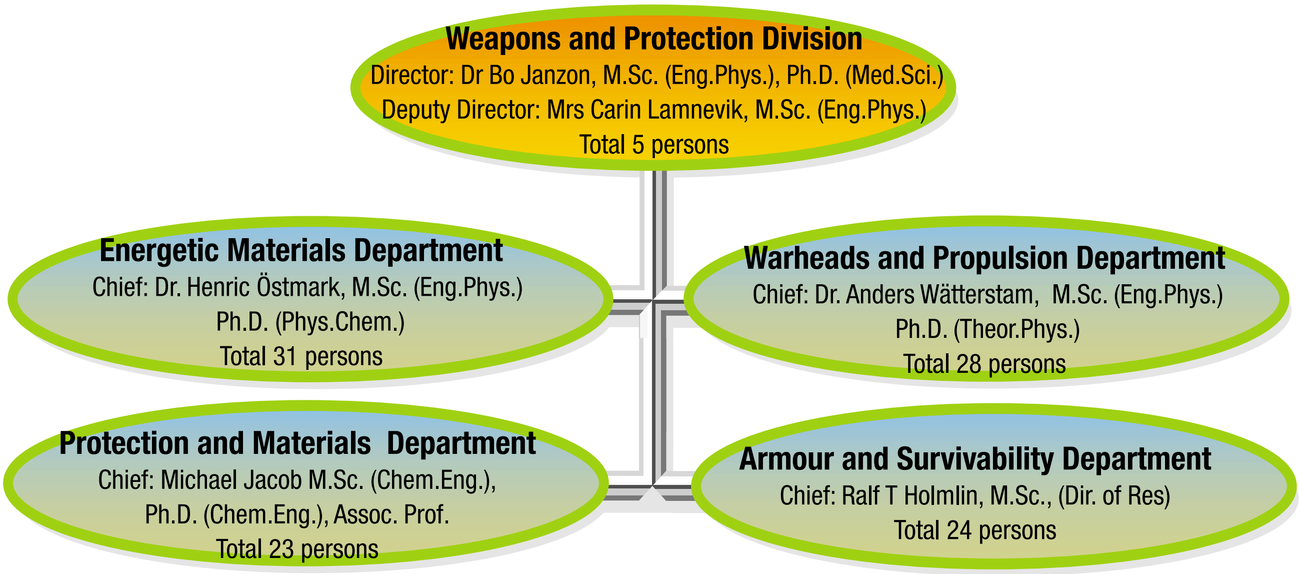
The Project has so far been concentrated to scan usable less-lethal technologies as a background to the Defence Forces studies in problems concerning activities and reliable rules of engagement in Peace Support Operations (PSO) as result of an analysis of estimated scenarios. Policies and decisions about when this type of effects will be permitted are very important for further work and definition of the problems.

Within the frames of the ”FoRMA”-study it is possible that the subject will include a wider area of weapon effects. Effects witch is tailored to the target in terms of armour, weakness points, risk for collateral damage etc.

During FY 2000 FOI has made calculations on transmission of UV-laser in air and the VORTEX - phenomena. A symposium on ”Human Effects of High Power Microwave” was held in September.

FOI participate in the European Working Group on Non-Lethal Weapons (EWG-NLW) together with Austria, Germany, Great Britain, Italy, Norway and the Netherlands. The group prepares seminars and looks on the problem from a holistic point of wiev, including besides legal, medical and psychological as well as technical aspects.

# Organisation, management and personnel




*(The above illustrates the situation in april 2001).*

The division is served by a unit of FOA's Administrative Division, in total about 25 persons. This unit comprises mess and house-keeping, mechanical workshop, service units, field and construction service, transports and heavy machinery.

## Locations and facilities

Division Headquarters and main activities are located at the Grindsjön Firing Range, about 40 km south of Stockholm. An experimental station, comprising part of the Protection and Materials Department, was located at Botele udd, Märsta, close to Arlanda Airport, about 40 km north of Stockholm. During 1998 it was decided to close this latter facility and to relocate activities to Grindsjön during 2000. A SEK 15 Million building program at Grindsjön involving both laboratories and office space was ready in 2000. One medium-size blast tunnel will, however, be kept at Märsta and can be used for campaign experiments also henceforth. About 10 researchers have relocated to Grindsjön in april 2000.
The responsibility for research on mehanical and especially dynamic properties of materials, including the responsibility for a research project on light armours was transferred to the Division from another of FOA's Divisions in 1998. This group of researchers, working at FOA's Ursvik site was relocated to Grindsjön in april 2000. Most of the scientists left the group in the process, and about 3 new, younger and well educated scientists were successfully recruited during 2000 to replace them.

Facilities at the Grindsjön Firing Range is:

- 7,5 km$^2$, 23000 m$^2$ buildings
- ab. 10 test sites (max 600 m risk radius)
- Chemistry Labs
- Terminal Ballistic Building
- Laser Lab
- Detonics Lab
- EM Weapons Lab
- H E and Propellant factories
- Propulsion Lab
- Sensitivity Labs,
- Materials and Chemistry Labs
- Materials Testing Lab
- Concrete factory

## Cooperation

The Division interacted and cooperated with numerous organisations, institutions and companies in Sweden, like:

- Universities and Institutes of Technology
- Military authorities and Schools
- FMV - the Defence Materiel Administration
- FFA - the National Aerodynamic Test Center
- ÖCB - the National Board of Civil Emergency Preparedness
- SRV - the National Rescue Services Board
- SÄI – the National Explosives Safety Board
- Defence Industries

There were well established contacts and cooperations, formal and informal, with universities and research organisations in many countries, such as Australia, Canada, Finland, France, Germany, Netherlands, Norway, Russia , Singapore, Switzerland, UK and USA. In total there were about 40 collaborative projects and data exchanges with foreign organisations.

## Memberships and participation

The Division was a member of:

- The International Ballistics Committee (IBC), represented by dr. Bo Janzon
- The Aeroballistic Range Association (ARA), represented by Lars Gunnar Olsson
- EUROLAB (Organisation for testing in Europe), represented by. Magnus Oskarsson
- European Electromagnetic launch Society (EEMLS), represented by Sten E Nyholm
- OECD-IGUS International Group of Experts on Unstable Substances. National Representative was Stefan Lamnevik
- Swedish Process Safety Promotion Association (IPS). Representative was Stefan Lamnevik, who is also the Manager of IPS.

and other national and international organisations.

## Economy

| Revenues/Customer | Revenue 2000 |
|---|---|
| Defence Forces (1) | 58 % |
| Defence Forces, other | 5 % |
| FMV | 9 % |
| ÖCB/SRV | 2 % |
| Others | 26 % |
| **TOTAL** | **100 %** |

*Note 1) Supreme Commander's general task assignment to FOA.*

The annual turnover of the Division for 2000 was ab. 126 MSEK

## Quality

In June a group was put together to manage and to coordinate the divison's work with total quality management (TQM). Its tasks this year was to build up the division's competence in the area and to compile an overview, according to The SIQ Model for Performance Excellence, of the division. These tasks were carried out and provides a sound basis for future work.

## Environment

The Division participates in FOA´s common Strategic Environmental Program. The Division is organising a recycling system of all scrap, paper and garbage, and we have satisfactory followed our detailed environment plan during year 2000. The plan included energy saving and education of all employees. The energy consuming has not increased in spite of we have been about 20 more employees. About 60% of the employees have got environment education. Half a working day, for all employees at Grindsjön was dedicated to clean up in old store rooms and the forest near the centre. We have engaged about 20 sheep from a nearby farmer, to get open landscape around the centre and the farmer also let three calves be around the new bird pond. We have a new environment plan for year 2001.

## Working environment

The management, safety representatives, and project leaders have participated in a basic three-day work environmental education given by TBV.

An ergonomist from the company health care provider, Previa, has visited all employees with the intent of improving the ergonomic work environment, and therefore also to reduce the amount of strain injuries. (Ergonomic rounds of precaution)

During monthly visits, by a nurse from the company health care provider, Previa, general health check-ups, eye examinations, and vaccinations have been performed.

Aimed health check-ups have been performed on employees working with energetic materials, lasers, heavy metals, and radiological applications.

Rounds of precaution have been performed and work related injury reports and near accident reports have been under scrutiny to aid elimination of danger in the work places and to enhance the work environment.

A campaign of health measures was carried out during the year including seminars and exercise activities with the purpose of minimising the absence due to illness.

A goal is to assure all employees the possibility to participate in an annually occurring heart-lung resuscitation education given by the company health care provider, Previa.

**Acknowledgement**

Many persons have contributed to this report, including Mrs. Carin Lamnevik, all Department Chiefs and many project managers.

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Annual Report 2000

**Abstract (not more than 200 words)**

This is the annual report for FOA Weapons and Protection Division for the Fiscal year 2000. The activities of the Division's research departments are summarised. The report gives an overall description of the Division, its goals, activities, organisation and economy. It also provides information on facilities, scientific and technical competences and equipment. The Division's scientific publications and the customer reports are listed.

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Rapporten ger ägen en allmän beskrivning av avdelningens mål, verksamhet, organisation och ekonomi.

Information ges om våra anläggningar, vetenskapliga och tekniska kompetenser och utrustningar. Avdelingens vetenskapliga publikationer samt rapporter till uppdragsgivare är förtecknade.

Rapporten är skriven på engelska.

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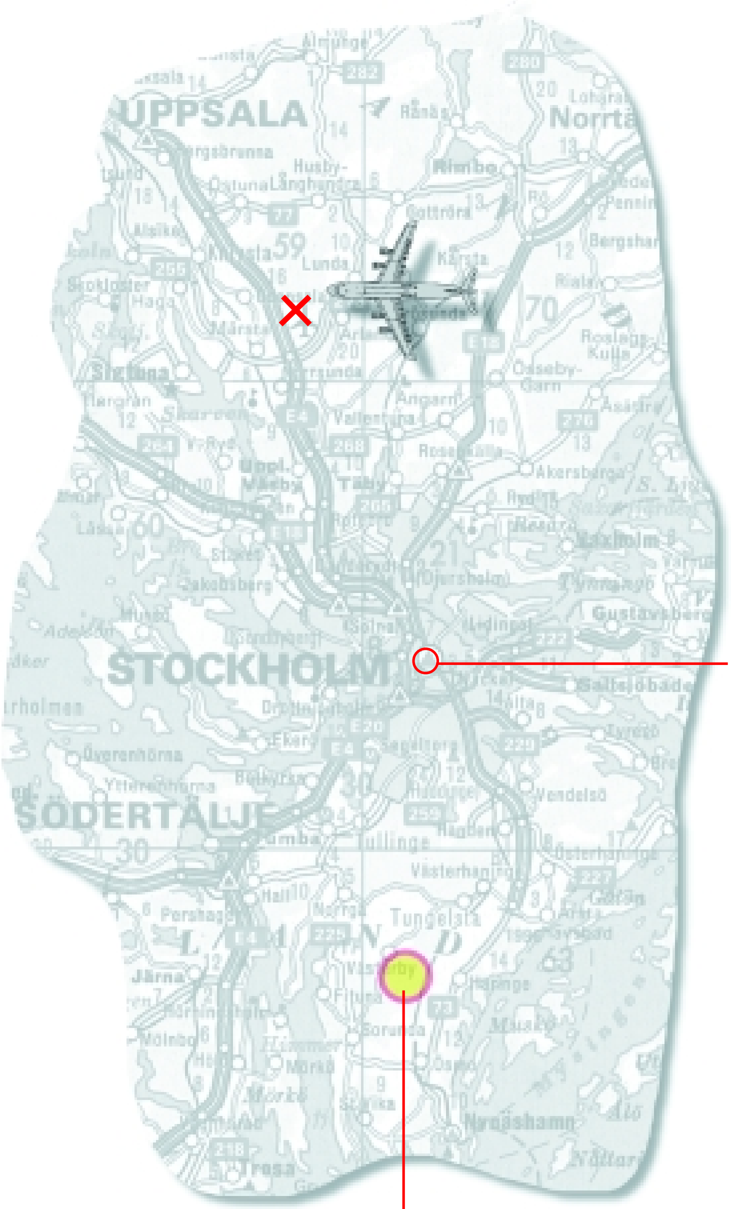


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