CHAPTER 10

NEW TECHNOLOGICAL DEVELOPMENTS AND THE NON-PROLIFERATION REGIME

Re-directing and constraining R&D: the case of laser fusion, laser isotope separation, and the use of highly enriched uranium

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10.1 The need for guiding R&D

The goal of the NPT is to prevent the proliferation of nuclear weapons, and, according to its preamble, to arrive at nuclear disarmament. The basic philosophy is to deter the diversion of fissionable nuclear material for nuclear explosions by non-nuclear weapon states.[1] But it also underscores the free flow of scientific information and nuclear technology for peaceful purposes.

In the 1970s, when several non-nuclear weapon states located in unstable regions of the world, embarked on a course of acquiring enrichment and re-processing plants, doubts arose whether the safeguarding system could effectively deal with this situation. These 'sensitive' facilities as well as the spread of technology would considerably lower the technological threshold for obtaining weapon usable material. Moreover, the warning time between a possible diversion of material from the peaceful fuel cycle and the use in nuclear weapons would then substantially be reduced. These fears resulted in the US Nuclear Non-Proliferation Act (1978) and the Guidelines for nuclear transfers by the Nuclear Suppliers Group (1977), both of which not only asked for stricter safeguards, but also for restraints on the export of sensitive technologies and facilities. Allowing some countries to operate such facilities and denying the technology to other countries, at the same time introduced a new asymmetry in the non-proliferation regime, besides the already existing one regarding the possession of nuclear weapons. The adopted policy appeared to have only a limited effect, slowing down, rather than preventing the spread. (See other chapters in this volume.) The case of the spread of the (URENCO [2]) gascentrifuge technology for uranium enrichment to Pakistan and Iraq shows that even for a very sophisticated technology much of the technological knowledge gradually becomes more 'common' knowledge. Moreover, many of the special materials, like 'maraging' steel, become much wider available, for instance for use in non-nuclear applications.

Effective safeguarding becomes more difficult when the number of sensitive facilities is growing. Up to now, at least 17 countries have access to one or more of these sensitive technologies. (Liebert, 1991) An increasing variety of sensitive technologies poses problems for controlling the spread of these technologies and for detecting clandestine facilities. To enhance the effectiveness of the existing non-proliferation regime, exercising constraints on the application and development of new proliferation-sensitive technologies therefore seems imperative. These constraints, however, should be exercised in a symmetric way, that is they should apply to all countries, in order to be effective in the long term. Experience has shown that the development and application of new technologies by technologically advanced countries serve as an example that in due course is followed by other countries. A symmetric approach regarding constraints on proliferation-sensitive technologies may then reduce the incentives to other countries for acquiring them. These constraints do not necessarily imply the halting of R&D, though this might sometimes be preferable. Often specific R&D tracks are more suited for military than for civilian applications. In such cases, a shifting of the R&D path into directions that still allow for civilian applications, but are less suited for military purposes, would be desirable. Thus while there is a military-civilian ambivalence,[3] the balance is not always even and choices, either implicitly or explicitly made, in the R&D process may shift this balance.

This chapter shows that already at an early stage independent assessments can be made not only of what are conceivable, but more important, of what will be the *likely* applications of the technology resulting from the R&D directions chosen. It is argued that such assessments should be made on a more continuous base in order to support the choices that are to be made during the R&D process. This requires an analysis, first, of the technical feasibility of the conceivable applications by looking at the scientific and technical characteristics, and second, of the social groups involved, and of the organizational context, including the institutional and funding structure of the R&D.

The second type of analysis is important because this context co-determines what will be likely applications. It indicates the type of expertise that is needed for making the necessary technological transformations towards specific, military or civilian, applications. It also enables making assessments of the various motivations and goals of the groups involved, and of the public justifications given. It will then often appear that different actors are interested in the technology for different reasons, for instance for economic competitiveness on the enrichment market, prospects for improving nuclear weapons, potential for electricity generation, (national) prestige, or just because others are working on it. (bandwagon effect: see Fujimura, 1988) This structural analysis may also provide insight into the possibilities and opportunities for (re-)directing the R&D programmes.

Following this scheme, we will examine in this chapter the proliferation risks of two new technologies, namely, inertial confinement fusion (ICF) and laser isotope separation (LIS) as well as the use of highly enriched uranium (HEU), in particular in research reactors and for naval propulsion. The development of LIS and ICF are partly legitimated by their potential civilian application, but they have also important military applications. The prospects for realizing the civilian and military applications are examined, as well as the military-civilian ambivalence of the associated R&D. In particular, attention will be paid to possibilities of pursuing alternative R&D paths, and the implications of such choices for reducing the potential for military applications.

We will pay attention to the risks of both horizontal and vertical proliferation, as a continuing vertical proliferation process is considered to be an important obstacle to an effective regime for preventing the spread of nuclear weapons.

After having analyzed, in the next section, the proliferation risks of ICF, LIS and the use of HEU, as well as their 'social context', we will, in the last section, provide suggestions for steering and controlling such developments into less proliferation-prone directions. These will be based on more general insights of technological developmental processes. Central elements are the introduction of technology assessments, the need for a coupling between assessments and choices made on the direction of R&D programmes and the role of a guiding principle in steering technological developments.

10.2 Inertial Confinement Fusion (ICF) and proliferation risks

Nuclear fusion R&D aims at the release of energy, in a controlled manner by fusion of light hydrogen nuclei. So far, substantial artificial fusion has been realized only in thermonuclear weapons, that is in an uncontrolled fusion process. In nature, fusion processes are only found in the interior of the stars.

ICF is one of the two main roads that are now pursued towards controlled nuclear fusion. In ICF a pellet of a mixture of deuterium and tritium is compressed to extreme high pressures and temperatures, through simultaneous and symmetric irradiation by a number of extremely short and powerful laser or particle beam pulses. These extreme conditions are necessary to transform the deuterium-tritium mixture into a plasma and to cause thermo-nuclear fusion. The highly compressed mixture stays together sufficiently long due to its own inertia before it explodes like a miniature H-bomb, hence the name inertial confinement fusion.

The other road taken, actually initiated already before large ICF programmes were started, is Magnetic Confinement Fusion (MCF). Here the confinement of the plasma is achieved through strong magnetic fields. So far, no fusion has been achieved that has resulted in a fusion energy output that exceeded the energy input, in either of the two programmes. Such a positive energy balance is considered to be essential for any further scientific progress. The most important civilian application, being electricity generation, requires an energy output at least hundred times that of a net positive energy balance. For many military applications of ICF, however, a positive energy balance is not necessary.

Interest in starting a fusion reaction by lasers arose immediately after the invention of the laser in 1960. At first, the idea was that a laser could possibly replace the fission bomb (the 'primary') as a 'trigger' in a thermonuclear bomb. At the time a fission bomb was -and even now it still is- the only practical energy source that could provide the required energy for heating and compressing the fusion fuel. The use of a laser as trigger would avoid the radioactive fall-out of the fission trigger and thus lead to the advertised 'clean bomb'.[4] A classified experimental laser fusion programme was started at Lawrence Livermore National Laboratories, already in 1963. It soon turned out, however, that the laser systems that might provide the required amount of energy, would be very sizeable and therefore unsuitable as a trigger in a thermo-nuclear weapon. Research, nevertheless, continued, while interest shifted to different military applications.

The short term scientific goal of the R&D on ICF is to release as much fusion energy as possible, especially to achieve a *gain* (the ratio of fusion energy yield to input of driver energy) as high as possible. A gain of $G=1$, called *ignition* or *scientific break-even* is regarded as a major milestone in the demonstration of the feasibility of ICF, but has not been reached as yet. But even if it would be achieved it would still not imply a net overall energy yield because of the low laser energy efficiency.

MCF research is non-classified and in a number of cases it is carried out through international cooperation, like the European JET programme. In contrast, ICF research is carried out mainly in national programmes, and in the nuclear weapon states it is to a great extent classified because of its military relevance. Highly classified is the knowledge regarding coupling mechanisms between laser energy and the deuterium-tritium mixture and, therefore, of pellet design, as well as computer codes. ICF research is now carried out also in non-nuclear weapon states, though on a smaller scale, and by now it is common knowledge that the most effective coupling process is considered to be an 'indirect drive', in which laser energy is first converted into X-ray radiation. The X-ray radiation, which isotropically fills a cavity, subsequently compresses and heats the fuel. This is similar to the Ulam-Teller principle of igniting thermo-nuclear weapons, where the X-ray radiation, produced by the 'fission-trigger', compresses and heats the fusion fuel.[5]

Indeed, the ICF thermo-nuclear explosions are miniature H-bombs on a laboratory scale. ICF can therefore be used for research on and support the design of thermonuclear and new -'third generation'- nuclear weapons including a nuclear pumped X-ray laser. As ICF micro-explosions can deliver the same mixture of forms of energy and radiation as thermo-nuclear weapons, they can also be used for testing the effects of nuclear weapon radiation on military equipment, replacing underground tests.[6] The main ICF programmes in the USA are concentrated in the nuclear weapons laboratories, and have primarily such military objectives. ICF is a tool that, to a great extent, can replace underground nuclear tests, and maintain the nuclear weapons expertise in case of a comprehensive nuclear test ban.[7] For these reasons it could undermine the effectiveness of a future comprehensive test ban as a measure of halting 'vertical' proliferation. The demands for these military purposes are less severe than for civilian applications. For one thing, because the former do not even require a positive net energy yield (G=1), but only the occurrence of a sufficient amount of fusion reactions, whereas the latter requires a gain of at least G=100. Secondly, because military, in contrast to civilian applications do not require a high driver frequency.

ICF also entails a horizontal proliferation risk, as it provides valuable information for R&D on thermonuclear weapons by accumulating knowledge on nuclear weapons physics. Knowledge rather than the nuclear fuel (deuterium, lithium and tritium) is the limiting factor for the spread of thermonuclear weapons to nuclear threshold states.[8] This risk was already recognized at the first Review Conference of the NPT, in 1975, where the issue of ICF was raised, but was not pursued any further (Smit and Boskma, 1980).

10.2.1 *Organizational and funding structure*

After several decades of substantial research efforts, nuclear fusion technology is still in the R&D stage, and it is still not clear whether its projected civilian applications will ever materialize. Nevertheless, many of the industrialized countries have embarked on huge and expensive R&D programmes on fusion.[9]

The motives for pursuing ICF research vary according to national political circumstances, and within a country motives of different groups involved vary as well. In the United States the large Department of Energy (DoE) programmes, carried out in the national weapon laboratories, are funded largely because of their potential military applications. The weapon laboratories for their part see it as a means for keeping at the front of nuclear weapon development and as a field of fascinating research. They also consider it as a way to continue weapon research and maintain expertise in case of a test ban. In public, the motive of developing a nuclear fusion power plant is often mentioned, but it is revealing that congressional lobbying focuses on military applications. For a number of countries an ICF R&D programme may be pursued as a prestige object, similar to other large R&D programmes on advanced technology, like space technology. This may particularly be the case for non-nuclear weapon countries like the FRG and Japan, where nuclear weapon research is a taboo.

Table 10.1 *Inertial Confinement Fusion (ICF) research & development efforts in various countries*

country	**laboratory**	**R&D activities**	**scientific goals**
USA	Lawrence Livermore Nat.Lab.	NOVA (Nd-glass-laser, 80-120 kJ)	physics of high density, high temperature matter
	Los Alamos Nat.Lab.	AURORA (KrF-Laser, 5-10 kJ)	R&D on a potential future ICF driver
	LLNL & LANL	'Centurio-Halite'	R&D on optimum target design by using radiation released by underground testing
	LANL	ICF target fabrication facility	new materials and techniques
	Univ. of Rochester	OMEGA (Nd-glass-laser, 4 kJ)	direct drive high density compression, high energy density physics
	Naval Research Lab.	NIKE (KrF-laser, 3-5 kJ)	direct-drive laser fusion
	Sandia Nat.Lab.	PBFA II (light ion source, 2 MJ)	accelerator research for ICF
	Lawrence Berkeley Lab.	MBE-4 (multiple beam ion induction linac)	demonstration of performance
USSR	Kurchatov Inst. of Atomic Energy	MISHEN 1M (Nd-glass, 50 J)	laser-plasma interaction
	Lebedev Phys. Inst. Moscow	Delfin 1 (E=10 kJ)	high density implosion (not mentioned in IAEA 1991 Report)
Japan	Osaka University	GEKKO-XII (Nd-glass, 30 kJ)	super high density implosion
France	Limeil-Valenton	PHEBUS (Nd-glass, 20 kJ)	laser-matter interaction
Israel	Yavne, Soreq Nuclear Research Centre	ALADIN (Nd-glass, 100 J)	hydrodynamics
Germany	Max-Planck-Inst. für Quantenoptik, Garching	ASTERIX (Nd-glass, 2 kJ)	basic physics of laser fusion
	Ges. für Schwerionenforschung, Darmstadt	SIS/ESR (heavy ion synchrotron / heavy ion storage and cooler ring, 500 J)	driver research
GB	Rutherford Appleton Lab.	VULCAN (Nd-glass, 1.6 kJ)	basic physics, laser-matter interaction, x-ray lasers, x-ray sources
	R.A. Lab.	SPRITE (KrF-laser, 200 J)	laser-matter interaction, x-ray lasers, x-ray sources

In the United States, ICF is a separate programme, centrally funded by the DoE, which is responsible for all governmental funding of military and civilian nuclear R&D and nuclear weapon tests. In 1989, the total funding for ICF was $ 163 million, including funds for operations and equipment. (GAO, 1990) It is difficult to give comparable numbers for other countries as ICF R&D is often embedded in a variety of different research programmes. For instance, in the FRG funding of all fusion research (which in the FRG is supplied by the Ministry of Research and Technology, and MCF) amounted to DM 202 millions in 1988. The costs of the SIS/ESR facility of the Gesellschaft für Schwerionen Forschung (GSI) in Darmstadt (which has been designed also for other purposes than ICF) were DM 117 millions.[10] Table 10.1 gives an overview of major activities in a number of countries.[11]

10.2.2 *Choices for different R&D paths*

The largest existing laser system for ICF is the huge NOVA laser system at Lawrence Livermore National Laboratories (LLNL) in the US, consisting of 10 laser beams, each capable to deliver an energy of 10 kJ. After more than ten years experimenting and upscaling of driver energies, the estimates of laser energy required to achieve substantial fusion has steadily increased. It is now taken to be 50 to 100 times the NOVA energy, based on several experimental and theoretical results, for instance, from target tests using radiation generated by underground nuclear explosions. By 1990 plans for the successor of NOVA, the 'Athena' laser, were already worked out in detail. The costs for the Athena facility are estimated by LLNL at $ 750 million.

NOVA and Athena make use of a Neodymium-glass laser. Because of the required cooling time these laser systems are capable of only producing a few shots per day. This is no obstacle for the military experiments discussed above, but it is prohibitive to the civilian application of electricity generation, which requires 5 to 10 shots per second. The argument, used in public debates, that laser fusion will open up an important source for energy supply, therefore merely fulfils a legitimizing role. Within ICF an alternative technological path exists, notably the use of heavy ion beams as a driver. This type of R&D, however, has not been pushed that hard and is still at a very early stage.[12] The heavy ion driver would allow for the high rate of micro-explosions required for a fusion power plant, but it could, in principle, be used for military R&D on thermo-nuclear weapons as well. Whereas success of the heavy ion route is still uncertain, both for military and civilian applications, the Neodymium-glass laser route will almost certainly lead to military applications and not to a fusion power plant.

The technological choices thus are quite clear. If a fusion power plant is the primary goal of fusion research and if one wants to avoid much of the vertical and horizontal proliferation risks connected to ICF, the preferred R&D route is that of magnetic confinement fusion (MCF). But even if the ICF route is pursued, there is a more promising path towards civilian applications, notably the use of heavy ion beams rather than the Neodymium-glass route that leads straight forward to military applications and in which the power plant option is excluded. To assess the possibilities of implementing such a choice, the analysis should also take into account the organizational and institutional setting -the social context- in which the ICF R&D is embedded. This will be further discussed in the final section. But let us first turn to the case of laser isotope separation.

3. Laser Isotope Separation (LIS) and proliferation risks

In the laser isotope separation process use is made of laser light to separate isotopes, like uranium-235 and uranium-238, by selective excitation of one of the isotopes in an atomic vapour or in a stream of molecules. It provides a possible alternative to the existing commercial enrichment technologies, that is the gaseous diffusion and gas centrifuge technology. LIS methods are under development since the early 1970s. There are basically two LIS methods potentially suited for use on an industrial scale: Atomic Vapour Laser Isotope Separation (AVLIS) and Molecular Isotope Separation (MLIS). (Liebert and Neuneck, this volume; Krass et al., 1983) The MLIS, in a number of respects looks to be more tractable than the AVLIS process, for one thing because it uses uranium hexafluoride rather than the extremely corrosive uranium vapour used AVLIS, but also because a facility might require less complex laser systems. (Krass et al., 1983, 170) The MLIS process, however, is also far from being a mature technology and many problems regarding the interaction between laser beams and uranium hexafluoride still have to be solved. For plutonium separation the MLIS process is considered problematic, although some scientists argue that the problems involved can be solved.[13] The USA has chosen the AVLIS route for this application and a sizeable R&D effort is made at Livermore. (LLNL, 1990)

Table 10.2 *Required number of stages for several enrichment processes*

Enrichment technology	Number of stages required to enrich from natural U to LEU (3%)	Number of stages required to enrich from natural U to HEU (90%)
gaseous diffusion	> 1000	> 3000
gascentrifuge	~ 10	~ 30
LIS	1	2 to 3

For both methods, one proliferation risk is that highly enriched uranium, suitable for nuclear weapons, can be obtained in only two or three enrichment steps.[14] This contrasts sharply with current technologies which require 30 (gas centrifuge) to 3,000 (gaseous diffusion) enrichment stages (see table 10.2). A LIS facility designed for LEU production might produce weapons useable HEU by only a twofold passage with LEU (3% U-235) as feed or by a threefold passage with natural uranium (0.7% U-235) as feed. Especially LIS facilities designed to produce reactor grade uranium from the tails of existing enrichment plants (0.2% U-235) would be very suited for the production of HEU from natural or reactor grade uranium, because of their high enrichment factor.

Commercial LIS facilities will also be much smaller than gas centrifuge (about one fifth) and gaseous diffusion (about one tenth) plants. Electricity consumption, moreover, will be comparatively less, so that a clandestine facility would be much more difficult to detect. Both in France and at Livermore, a modular approach for an intended AVLIS plant is followed. It allows small-sized plant modules to be tested within the laboratory. An obvious disadvantage of small-sized modules, from the non-proliferation viewpoint, is the possibility to hide facilities. Laboratory-sized LIS facilities can produce significant amounts of enriched uranium. France in 1989, for instance, announced that it had produced several grams per hour of enriched uranium with a laboratory-scale AVLIS facility.[15] This implies a production capacity of several dozens of kilograms of HEU per year, sufficient for several nuclear bombs.

Concerns about these horizontal proliferation risks via the laser enrichment route were already expressed when the R&D was still at an embryonic stage (Casper, 1977; Krass, 1977). Since then, also a vertical proliferation risk has emerged, because LIS will be the first large scale technology capable to upgrade reactor grade plutonium (containing 55% to 70% plutonium-239) to weapon grade plutonium (> 93% plutonium-239), either by extracting the desired Pu-239 isotope, or by removing the unwanted isotopes Pu-240 and Pu-242 (Krass, 1982; Palmer and Bolef, 1984). This can be achieved in a one-staged LIS process. Within the nuclear arsenals of the nuclear weapon states more than 200 tons of plutonium are used. Almost 75 tons of reactor grade plutonium are produced annually by nuclear power plants. Depots for storage of plutonium, recycled from nuclear waste, exist at least in the USA, France, the UK, Germany and Japan. Upgrading of reactor grade plutonium for weapons use was an attractive option for the United States in the 1980s when it faced a shortage of plutonium production capacity for its nuclear weapon programme [16] (which by now has become less pressing due to the announced reductions of both strategic and tactical nuclear weapons).

Another possible application of AVLIS is the further enrichment of existing weapon plutonium in order to minimize its spontaneous neutron production rate due to the presence of even numbered isotopes. This could be used to optimize the fission trigger in the so-called neutron bomb (Keller, 1988) and is important for the manufacturing of other sophisticated nuclear weapons. At the same time, the diminished content of Pu-240 may pose a problem to current verification methods of the presence of nuclear weapons, that rely on the detection of neutron emissions by Pu-240 in the warheads. (Fetter et al., 1990)

In the long run, LIS R&D may provide knowledge for other isotope separation tasks with military relevance as well, like the extraction of tritium from water. (Magnotta, 1984; Kato, 1987) Though the technology is complex and the road to the construction of production facilities is very long, knowledge of the principles of the LIS process has spread since the early 1970s, and a world-wide use of LIS technologies is to be expected if R&D in this field makes further progress.

10.3.1 *Organizational and funding structure*

Programmes on LIS for uranium enrichment are now underway in several countries, most vigorously in the US. In the 1970s, when there were still firm prospects for an expanding nuclear energy market, the US company Jersey Nuclear AVCO Isotopes (JNAI) spent $70 million on developing an AVLIS process, for the production of low enriched uranium as a reactor fuel. At the same time R&D on AVLIS was also carried out at Lawrence Livermore National Laboratories (LLNL), while Los Alamos National Laboratories worked on the MLIS process. In the early 1980s, the US DoE has chosen to support and further develop only the AVLIS process (at LLNL). The most likely reason is that DoE viewed the AVLIS process as more suited than MLIS for plutonium isotope separation. The Livermore AVLIS process has overrun all other R&D programmes in the US, including the civilian oriented JNAI AVLIS process,[17] the Los Alamos MLIS process and even the development of advanced centrifuge technologies (Norman, 1982 and 1985). From 1973 to 1987 the DoE spent about $500 million on the AVLIS process. In the late 1980s, more than $100 million per year was spent, mainly for the Special Isotope Separation (SIS) project, dedicated to plutonium separation. A demonstration plant, using a 7.5 kW copper vapour laser, is now in use at LLNL (LLNL,1990), and R&D and the construction of a prototype is continuing, but a plan for a large scale production plant in Idaho, has been cancelled in early 1990, probably because of the now existing (over)supply of plutonium from retired nuclear warheads.

More or less substantial LIS programmes are underway in other nuclear weapon states as well. In France an AVLIS plant at laboratory scale, using a process similar to the LLNL uranium AVLIS process, is operated by the Commissariat à l'Energie Atomique (CEA) at its research centre at Saclay (Rigny, 1989; Plurien, 1989). Another AVLIS R&D project is carried out by the French company COGEMA, aiming at a production plant in the late 1990s.[18] The United Kingdom Atomic Energy Authority and British Nuclear Fuels Ltd (BNFL), have a joint programme to develop AVLIS technology for uranium enrichment.[19] Oxford Lasers successfully develops high power copper vapour lasers for application for LIS applications.[20]

The Soviet Union also carries out R&D on LIS. Results of Soviet basic research on LIS can be found in open literature,[21] but little is known about existing or planned Soviet demonstration or production plants. An exception is a recent report on a MLIS facility using a 4 kW CO_2 laser for separating light and medium-mass isotopes. (Baranov, 1991) China is also engaged in LIS research. (Kokowski, 1990) The development of high power copper vapour lasers at Shanghai Institute of Optics and Fine Mechanics might be an indication of progress in AVLIS technology.[22]

Israel reportedly is investigating the AVLIS process (Kokowski, 1990). An indication of early Israeli interest is given by an Israeli scientific source from 1974 (Nebenzahl and Szöke, 1974). Furthermore, a number of non-nuclear weapon states, like Germany, Japan, the Netherlands, Canada and Brazil, have LIS-programmes. This number of countries is increasing in recent years and some of them are threshold nuclear states.

The German company URANIT (Uran Isotopentrennungs Gesellschaft mbH), engaged in the gascentrifuge technology of the British-Dutch-German enrichment consortium URENCO, has chosen also to develop the MLIS process for uranium enrichment. The funding for 1988 was approximately $7 million. Its Dutch sister company has also embarked on an R&D programme on LIS. These companies have a commercial interest in LIS, as current estimates are that enrichment services using LIS might be provided at considerably lower costs than with any of the other enrichment technologies. (Villani, 1984) Further German R&D projects are going on at some university institutes and at an institute of the Max Planck Society.

The Japan Atomic Energy Research Institute (JAERI) has carried out research on the AVLIS process since 1976. (Kokowski, 1990) The Laser Atomic Separation Engineering Research Association (LASER) of Japan was formed in 1987 by nine commercial companies and the annual spending on AVLIS R&D has grown to about $65 million per year. At the Institute of Physical and Chemical Research the MLIS project has achieved a separation factor sufficient for producing low enriched uranium as reactor fuel. Commercial interests exists in the USA, France, Japan and Germany for construction in the late 1990s of large LIS production plants.

10.3.2 *Choices for different R&D paths*

LIS is much more ambiguous with respect to civilian and military use than the ICF programme, which will certainly result in military applications, but very likely not in civilian ones. This makes it more difficult to weigh civilian benefits against proliferation risks. On a global scale there is already an over-supply of enrichment services, and so no need of additional enrichment capacity.[23]

On the other hand, LIS technology might be cheaper, though in relation to the overall costs of running a nuclear fuel plant, the advantage might be marginal. Nevertheless in the competition between enrichment companies for contracts with electricity companies, price differences might be decisive. Thus, it is primarily the *commercial* interests that are to be weighed against proliferation risks. Another application for LIS technologies is the separation of medium-mass isotopes for scientific or medical purposes, but also here the demand can be met by existing technologies.

It has been argued that the LIS technology is too advanced to spread easily to less technologically advanced countries.[24] (ACDA, 1980) This argument, however, has been used for the gascentrifuge technology as well, but the spread of this technology, for instance to Pakistan and to Iraq, has shown, that knowledge, materials and equipment of a technology, once it has been developed and is used, become much wider available. If the proliferation issue is taken seriously, it would therefore be better, to have neither of the LIS technologies further developed. This would require both national self-constraint and international arrangements.

But also within the LIS technology a choice for different technological routes can be made; either AVLIS or MLIS. It seems that the main motive for the AVLIS route is its potential for upgrading plutonium for weapon purposes. Such an upgrading is not necessary in using of plutonium as reactor fuel. AVLIS, therefore, entails a risk for horizontal proliferation along two routes: not only via its potential for the production of HEU, but also (in a modified version) for the production of weapon grade plutonium. In the nuclear weapon states, moreover, AVLIS might be used for the production of highly purified plutonium-239, thus supporting the construction of more advanced nuclear weapons. It therefore adds to the vertical proliferation problem, and complicates verification of limitations on nuclear warheads. From the proliferation perspective, MLIS might therefore be preferred to AVLIS, but in the long run its further development might pose the same proliferation risks as AVLIS. Its application, therefore, should at least be under international control. A policy in which some countries are to develop the technology, and subsequently try to deny it to others, is discriminatory, and will, because of this asymmetry, help rather than prevent the spread of the technology in the long term.

10.4 Highly Enriched Uranium (HEU) reactors and proliferation risks

Reactors utilizing highly enriched uranium (>75% U-235 isotopic content) are mainly used either as research reactors or for naval propulsion. HEU can be used straightforwardly for the fabrication of a nuclear weapon. As no change of composition is needed, a country that possesses HEU may produce a nuclear weapon within a very short period after diversion of HEU from its original application. But it is not only diversion by the government that poses a problem. At least as important is the possibility of theft of

HEU by non-governmental organizations. The risk of theft is illustrated by the diversion during the mid-1960s, supposedly by Israel, of about 100 kilograms of HEU from a privately owned uranium fabrication plant in Pennsylvania, USA. (Spector, 1987: 131)

10.4.1 *Naval propulsion*

The United States uses nuclear propulsion in submarines and surface vessels. By 1980 the US operated naval propulsion reactors in 125 submarines, and had a further 21 nuclear powered submarines under construction. The nuclear powered surface vessels include the 8-reactor aircraft carrier 'Enterprise' and the 2-reactor 'Nimitz'. US naval-propulsion reactors are fuelled with uranium enriched to about 97.3% in uranium-235 (about 3000 kilograms and 2500 kilograms in fiscal years 1991 and 1992 respectively). A Soviet official has stated that Soviet naval propulsion reactors are fuelled with uranium enriched to less than 10% -not directly useable in weapons. Nevertheless, there still remains a proliferation risk, as at 10% enrichment, about 85% of the enrichment work required to produce weapon-grade uranium has been done, making the material attractive as feed to any clandestine enrichment plant.[25] (FAS, 1991a: 17) If it is assumed that the uranium remains about 15 years within the naval fuel cycle, then the total amount of uranium in this cycle would be about 45000 kilograms at any time.

10.4.2 *Research reactors*

Worldwide, 139 of the 278 research reactors are still fuelled with HEU (U-235 content 75% or higher). For the five nuclear weapon states these numbers are 77 and 156 respectively.[26]

In the United States, with 44 HEU research reactors in 1986, the flows involved were about 1000 kilograms per year. There are three main categories of reactors using HEU (Coates and Barré, 1979). First, the low or zero power reactors for teaching or training purposes. They have requirements that can be accommodated by using 20% enriched uranium. Second, a very few sophisticated reactors aiming at fundamental research, with specifications that can only be met through the use of 93% enriched uranium. Third, reactors for technological irradiation and/or isotope production. Because of their technical specifications it may be difficult to convert this type to using lowly enriched uranium.

10.4.3 *Choices for different technological paths*

Uranium enriched to less than 20% is generally considered to be unsuited for nuclear weapon production, without further enrichment.[27] An important step to improve the proliferation resistance of research reactors, and in general the nuclear fuel cycle, would, therefore, be to halt the production of HEU, to design reactors only for the use of LEU, and to convert existing HEU reactors for the use of LEU whenever possible. As mentioned above, for the majority of research reactors, it is already technically possible to convert them for using LEU. In the United States this has been demonstrated in the Reduced Enrichment for Research and Test Reactors (RETR) programme. (FAS, 1991:21) The programme, however, has been terminated, and no serious attempts now seem to be underway for completely eliminating the need for HEU.

In the United States the use of HEU-reactors for naval propulsion originates from the development programme of nuclear submarines in the 1950s. Technically it is possible to use LEU reactors for naval propulsion, as is evident from the Soviet example, although conversion of the US naval reactors might be expensive.

Whereas until the 1980s only the nuclear weapon states used nuclear propulsion in the navy, other countries have become interested as well. Canada, for instance, had plans to purchase ten to twelve nuclear powered attack submarines from either Great Britain or France,[28] and since 1988 the Soviet Union has leased a nuclear powered submarine to India. (Spector, 1988: 322-326) Brazil, moreover, has started a programme to develop a nuclear powered submarine. An international agreement to avoid the use of HEU reactors and ban the production of HEU, therefore, becomes urgent. In view of the symmetry argument this can only be achieved if the US and other nuclear weapon states would switch to LEU reactors, in the short term at least for new naval reactors, to avoid a discriminatory situation.

In connection with the use of HEU for naval propulsion, it is important to note that the NPT contains a loophole: countries are allowed to use HEU for military purposes other than nuclear explosives, without having to place this material under IAEA safeguards.

10.5 Strengthening the non-proliferation regime by redirecting R&D

Each of the technologies described in the preceding sections has problematic aspects from the perspective of nuclear weapon proliferation. Highly enriched uranium (HEU) can be used straightforwardly in nuclear weapons; atomic vapour laser isotope separation (AVLIS) can be used to produce HEU or weapon-grade plutonium, and inertial confinement fusion (ICF) provides an important tool in designing and testing concepts of thermonuclear and 'third generation' nuclear weapons. Because of these risks one might simply call for a ban on the development and use of these technologies. Such a call in itself, however, is very likely to have no effect, mainly because non-proliferation is only one of many factors that play a role in the developmental process of these technologies. Economical competitiveness, national security, considerations of energy supply independence, prestige, and so on, also play a role. A variety of institutes, organizations and individuals (actors) is involved, each with its own reasons for promoting or supporting development into specific directions. Proposals for strengthening the non-proliferation regime, therefore, should take this heterogeneity into account.

Below, we will draw some lessons from the case studies and formulate some basic elements for policy making on the issue of steering R&D to prevent proliferation.

10.5.1 *Lessons from the cases*

One lesson from the case studies is that statements like "technologies can always be used for civil as well as military applications" are much too crude. The proliferation proneness appears to be quite different for inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). Moreover, even within the ICF area, various options for specific R&D paths exist -e.g., neodymium glass laser versus heavy ion beam- with different prospects for military and civilian applications. Similar assessments on the proliferation risks of alternative enrichment technologies can be made. Within the laser isotope separation area (LIS) area, for instance, different R&D directions can be chosen with different types or degrees of proliferation risks.

For the mentioned cases the stage of R&D itself is already problematic. This is clearly seen for the case of ICF, whereas in other cases, like LIS and research reactors using HEU, R&D itself is more problematic in view of the resulting technologies that pose the problems. Thus, it makes sense to make assessments of the proliferation proneness of new technological developments and of possible alternative R&D routes. In addition to such *Proliferation Impact Assessments* (PIAs), the prospects for and importance of civilian applications should be assessed as well. As the cases have shown, these prospects may vary substantially between alternative R&D paths, whereas the civilian need, as illustrated by the case of LIS technology, may sometimes be less great than suggested by the proponents.

The second lesson is that the organizational, institutional and funding structure (the social context) plays an important role in the process that determines which of the *possible* applications will *most likely* be realized. Illustrative are the different contexts of MCF and ICF R&D programmes: MCF R&D is carried out partly in an international cooperative effort, whereas the big ICF programmes are classified and carried out in national weapon laboratories. Because technology development is a heterogeneous process, in which many actors and factors are involved, an analysis of the social structure of the R&D programmes may support also the assessments of military and civilian applications.

One question often raised in this context is whether R&D can be steered at all, or whether it is a kind of autonomous process that goes its own course ("One cannot stop technological progress", is the essence of the statement). The arguments most often heard, saying that it is impossible to steer R&D, have been discussed elsewhere.[29] (Smit W.A., 1990 and 1991) Generally, they neglect the fact that modern research is not only a matter of developing ideas, but often is costly and has to be carried out in large teams and organizations. Whereas surprises do occur, research more often is organized in programmes -sometimes mission oriented- in which one knows what one is looking for. This is clearly illustrated by ICF and LIS research programmes.

The cases also show that it is important to differentiate between technologies, at least according to their 'social context'. ICF, more than LIS, is concentrated in a few, often national, laboratories and funded by governments. Whereas, indeed, there are some large governmental LIS programmes, here also a few significant industrial R&D programmes exist. In that sense LIS R&D is more institutionally 'dispersed' and ICF more concentrated. When we define 'steering' as 'changing the R&D path', steering may be more difficult for such dispersed technologies, because it involves re-directing the activities of a greater number of actors. So, it may be evident that one should not generalize among all technologies when arguing about the possibility of re-directing the course of R&D.

For many civilian, 'dispersed' technologies there is no central actor. In such a situation a government that wants to interfere and re-direct technological developments, has to do a lot of orchestrating of the interactions between all actors involved in the process of technology development. (Smit W.A., 1989 and 1991) In the case of LIS, however, government, has a special position, either as owner of enrichment facilities (as in the United

States) or because enrichment companies are dependent on governments for getting a licence for building a facility. The special position of the government, regarding LIS, of most countries is due to the fact that enrichment like other nuclear activities are regulated by Atomic Energy Acts. Thus, governments have some leverage for either stimulating or discouraging particular R&D paths. In a certain sense JNAI was discouraged to continue its R&D on LIS, when the US government evidently chose the LLNL enrichment route. In case a new technology would entail an unacceptably high proliferation risk, a government might make clear it beforehand that no licence would be supplied.

It would be most effective of course if such a policy would be supported by international arrangements. To arrive at such arrangements would obviously require a lot of organizing activities. But unilateral actions in constraining those technological developments that require large funding, might have a considerable impact on other countries as well, in particular if these constraints are imposed by countries with the most advanced programmes. One reason for this is that other countries tend to follow the technology path of advanced countries, often taking advantage of the research results of the advanced countries. Moreover, knowing that it is feasible, makes it easier to work.

The transformation of research reactors from using HEU to LEU is another example where government may play an important role by starting and carrying out programmes aiming at such conversion. The termination of the US Reduced Enrichment for Research and Test Reactors (RETR) programme is therefore to be deplored.

Based on the analysis presented above, we propose a course of action that consists of the following elements: *Proliferation Impact Assessments,* a *Guiding Principle* for evaluating and directing R&D, *and intervention strategies.*

10.5.2 *Proliferation Impact Assessment (PIA)*

On the basis of the discussion above, we suggest that assessments of the proliferation risks of particular R&D programmes and their resulting technology are made in the course of these programmes. This should consist of an analysis of both the technological characteristics and the 'social' context. The technological analysis provides insight in the characteristics that are of relevance to either military or civilian applications, and points out what are the most problematic aspects from the proliferation perspective. It should also explore the possibility of alternative R&D paths that are less proliferation prone, so as not to preclude civilian applications.

The analysis of the social context should include the actors interested or involved in the development, and look for the aspects that evoke their interest, for instance economical competitiveness, national security, considerations of energy supply independence, prestige, scientific interest, and so on. It should also analyze the relationship between the actors and the nature of their mutual dependence, and answer questions about the organizational and funding structure. For instance, is the technological development concentrated in only a few institutions and is the decision making highly centralized or is the development more dispersed?

The social analysis is important, because it may support the technical analysis in helping not only to see what are *possible* applications, but also which ones are most *likely* to be realized. These PIAs are to be carried out preferably not only on a national basis, but also within an international context (e.g. IAEA or on a regional level) because perspectives may differ between countries.

10.5.3 *Guiding principle of non-proliferation and symmetry*

For the evaluation and weighing of proliferation risks against civilian benefits, a guiding principle should be formulated. This guiding principle for technological developments should include two requirements. First, the R&D path and resulting technology should be designed to be resistant to both horizontal and vertical proliferation. Secondly, any technology being developed should in principle be available to all countries, if not on a national base then at least within some international arrangement. The latter requirement of 'symmetry' or 'non-discrimination' is a necessary element to prevent proliferation in the long term. As was argued in the introduction, developing and operating a technology in a few countries and trying to prevent the spread to other countries, will be effective only temporarily, if at all.

As participants in R&D projects and technology development programmes often follow certain heuristics, it would be most effective if the guiding principle would become part of these heuristics. To that end the guiding principle should become also part of the interaction process between the various actors involved in R&D projects.[30] Such a guiding principle does not provide a recipe that merely has to be applied: it has to be made operational time and again in every situation. But it provides a base to fall back upon for making one's evaluation and as such can bring some consistency in the process. This type of consistency is lacking up till now.

10.5.4 *Intervention strategies*

One might say that the PIA and guiding principle approach are a kind of 'macro-analysis' of technologies, on a global level, as to what is desirable and what not, from a proliferation perspective.

Making assessments is one thing, making and implementing proposals, suited to a specific situation is quite a different matter. We suggest that to go from assessments to proposals, the 'macro-analysis' should be complemented with a 'micro-analysis' that focuses on the institutional and organizational context in which the R&D is 'embedded' and on the interactions between the actor-groups involved. This analysis partly overlaps with the social analysis within a PIA, but now the emphasis should be on looking for leverages to influence the course of R&D. Intervention strategies for strengthening the non-proliferation regime will depend on the situation (the technology and its social context) at hand. They include incentives for different R&D paths, and the introduction of new actors (organizations, institutes) to the R&D network, that press for taking into account the guiding principle in research choices. Their actions could be related to funding or licence provisions. Such changes in the social realm are sometimes necessary to realize cognitive changes -that is, changes regarding the content of research. In addition to actions aimed at re-directing the course of R&D, actions might aim at embedding R&D in different, for instance international, frameworks, or at terminating specific R&D programmes.

10.6 Concluding remarks

For each of the cases -inertial confinement fusion (ICF), laser isotope separation (LIS) and highly enriched uranium (HEU) reactors- a technical assessment was made of its potential for military and civilian applications. This was complemented by a brief analysis of the various organizational, institutional, and funding structures (the 'social context') of these R&D projects or technologies. The three case studies show that there are alternative R&D paths, which have a different impact on the proliferation problem as well as different prospects for civilian applications. The social context -in particular the distinction between dispersed versus highly concentrated R&D efforts- may influence the degree to which R&D can be steered. A more detailed analysis than was possible within the framework of this contribution, is needed to give proposals for the way how to implement the re-direction of R&D paths in the various cases that is required from a non-proliferation perspective. Instead, the main elements of a general framework were sketched for developing a policy on steering R&D to prevent proliferation. These elements include *Proliferation Impact Assessments,* a *Guiding Principle* for evaluating and directing R&D, and *intervention strategies.*

Notes

1. See also the Chapter of Fischer in this volume.
2. URENCO is the tripartite uranium enrichment consortium, in which the UK, Germany and the Netherlands participate. It developed the gascentrifuge technology for uranium enrichment and by now has enrichment facilities in all three countries.
3. A more extensive discussion of this issue can be found in the chapter by Liebert and Neuneck (this volume).
4. The deceptive concept of the 'clean' bomb was put forward by advocates of further nuclear weapons, to counter the increasing public protests in the late 1950s against radioactive contamination resulting from atmospheric nuclear test explosions (Smit and Boskma, 1980).
5. For a description of the Ulam-Teller principle see (Schaper, 1991a).
6. For an extensive assessment of the military and civilian applications of ICF and its implications for arms control, see Schaper (1991b). For an earlier assessment see Smit & Boskma (1980).
7. In US Congressional hearings, maintaining of expertise is explicitly emphasized as a very important 'application'.
8. It should be added that also the long term goal of a fusion reactor entails a (horizontal) proliferation risk because the fusion neutrons can be used for breeding Pu-239 or tritium.
9. For a detailed overview of all current *civilian* projects of some importance, see *Nuclear Fusion,* Anniversary Edition, Vol. 30, No. 9 (1990).
10. Bundesministerium für Forschung und Technologie (BMFT)-Bericht 1988. Bonn, 1989.
11. Source: IAEA: Worlds Survey of Activities in Controlled Fusion Research, *Nuclear Fusion,* special issue 1991; GAO (1990); Basov et al. (1985); J. Meyer-ter-Vehn et al. (1990).

12. Another suggestion is the use of light ion beams, but in contrast to heavy ions, the problem of focusing these beams on a small spot has yet to be solved. CO_2 lasers that at first seemed very promising, turned out to be unsuitable because of their inappropriate wavelength.
13. Cornelius Keller from the Nuclear Research Centre Karlsruhe (KFk) argues that, because of the chemical instability of plutoniumhexafluoride and its partial dissociation by its own alpha radiation, the molecular approach cannot be applied to plutonium (Keller, 1988). By contrast, Cochran refers to the Los Alamos MLIS programme where intensive research on PuF_6 dissociation is still done (Cochran et al., 1984). Werner Fuss, at the Max Planck Institute at Garching, thinks that the main problems for PuF_6 dissociation have been solved at Los Alamos (Fuss in a talk given at the Tübingen Congress 'Weiter Abrüsten -Friedliche Wege in die Zukunft', December 2-4, 1988).
14. In 1979 a panel invited by Exxon Nuclear Company reviewed the proliferation risk of the AVLIS technology under development by JNAI at the time. It argued that starting from a commercial plant designed to produce LEU, it would be very difficult, though probably not impossible to produce HEU. Very substantial and complex plant modifications would be needed (JNAI, 1979). Indeed, high enrichment factor and high .. are competing factors using higher enrichment feed assays. But there is no doubt that one could produce HEU using an AVLIS plant if one is not interested in a commercially effective throughput.
15. 'Anreicherung von Uran mit Laserlicht', *Frankfurter Allgemeine Zeitung,* 8 November 1989.
16. As the director of LLNL, Roger Batzel testified before the US Congress: "The United States really wants to have the flexibility to use that material." See Hearings on H.R. 1873. The Department of Energy National Security Programs Authorization Act for Fiscal Years 1986 and 1987 before the Procurement and Military Nuclear Systems Subcommittee of the Committee on Armed Services, House of Representatives, 20-22 February, 1985.
17. See also 'Jersey Nuclear quits laser enrichment because DoE offers too little support', *Laser Focus,* May 1981, 42.
18. Cf. F. Sorel, 'Cogema a aussi .... des chercheurs', *Cogemagazine,* 5 June 1990.
19. Cf. 'British investigate laser enrichment of uranium', *Laser Focus,* November 1986, 10.
20. Cf. 'Copper-laser power climbs', *Laser Focus,* December 1986, 10.
21. Cf. Lethokov (1981).
22. Cf. 'Copper vapour laser beam diameter to increase', *Laser Focus,* December 1986, 42.
23. The overcapacity compared to present demand is about 70% (Liebert, 1991).
24. It says: "[....] one or more of the AIS [Advanced Isotope Separation] processes may prove to be inherently more proliferation resistant than centrifuges, primarily because of the greater technological sophistication required to construct, operate or modify an AIS facility. This may make AIS technologies available to far fewer countries than centrifuge technology." (ACDA, 1980, 491).
25. Of course, such 10% enriched uranium would only be of use to a country which possessed an enrichement plant.

26. IAEA (1989), 'Research reactors in the world', Vienna.
27. For instance, the critical mass of an unreflected and uncompressed LEU (20% U-235) sphere is over 300 kg, whereas the critical mass of HEU (90% U-235), under the same conditions, is about 50 kg.
28. These plants have been cancelled for budgetary reasons.
29. Some of these arguments are:
    One cannot stop thinking. By their nature science and technological opportunities are unpredictable. No criteria exist as to which research paths should be pursued and which not. If we don't develop it, others certainly will.
30. This is similar to the role of a guiding principle in the development of defence technology as discussed elsewhere (Smit, 1989; Elzen, Enserink and Smit, 1990, Enserink, Smit and Elzen, 1990).