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Nuclear Weapons Research and Modernization Without Nuclear Testing

The CTBT in danger?

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Summary

Ten years after the conclusion of the Comprehensive Test Ban Treaty (CTBT) negotiations, the global test moratorium is at a critical point. Key players in the international arena refuse to ratify the treaty, thereby preventing it from coming into force. At the same time, the leading nuclear powers (especially the U.S., France and the UK) are engaging in substantial restructuring processes of their nuclear complexes, which create serious risks for the future of the comprehensive test ban.

With the launch of the Science Based Stockpile Stewardship (SBSS) programs, the weapon labs of these countries started an ambitious 'Big Science' endeavor, which should make up for the loss of a testing option. These science programs are not uncontested: they are costly, ambivalent and foresee the cooperation between the weapon labs and the academic community in an unprecedented manner.

The long-term goal of the SBSS programs is advancements in weapon science, whereas the more immediate purpose is the preservation of safe and reliable nuclear arsenals. For this latter purpose, extensive research is carried out on warhead ageing and its effect on weapon performance. The preliminary results of an U.S. study on ageing effects are quite encouraging: they indicate that most warheads currently stockpiled in the U.S. arsenal can be safely maintained for approximately a century.

This fact would suggest that nuclear complexes will concentrate on life-extension programs (LEP) of their weaponry, and replace, remanufacture or refurbish ageing components at critical times in a weapon's life-cycle. Yet, while pursuing LEP, leading weapon labs have also been considering new warheads: these so called Reliable Replacement Warheads (RRW) are new designs without any test pedigree, but allegedly incorporate improved safety and security features, and – as the name suggests – should be more reliable i.e. will withstand the effects of material ageing and other defects more effectively.

At the moment, LEP and RRW programs are pursued in parallel by some nuclear weapon states (NWS), but they are basically competing concepts. Both programs claim to be able to maintain the nuclear complex in a sustainable and cost-efficient manner and, at the same time, to stay within the boundaries of the test ban treaty.

However, this is questionable, at least for a complete stockpile transformation with RRWs, as envisioned by parts of the U.S. nuclear establishment. This transformation could replace current (and previously tested) warheads with untested RRWs within the next three decades. Such a campaign of arsenal transformation bears the considerable risk of returning to fully-fledged tests, as it is unlikely the military planners will accept a whole branch of untested strategic weaponry.

But the RRW programs do not only jeopardize the CTBT, but also the Non-Proliferation Treaty (NPT), and as such, the cornerstone of nuclear arms control. Designing, developing and fielding new warheads (RRWs) is hardly compatible with the claims of the NPT, Art. VI, which works towards the total elimination of nuclear weapons. And the renewed cooperation between the U.S. and the UK on warhead design and moderni-

zation (especially on RRW) clearly runs against the NPT, Art. I, which prohibits NWS from assisting other states with their nuclear weapon programs.

Still, the NWS claims to be fully compliant with international norms of nuclear non-proliferation and arms control. This was specifically emphasized by the British government, who declared that its decision to replace their nuclear Trident system was in line with the wording and spirit of the NPT. This claim is hardly contested, though.

Britain, France and the U.S. are in the midst of an ambitious plan to modernize their nuclear complexes, the outcome of these measures is still uncertain. Huge investments in science programs should prevent a 'brain drain' from the weapon labs after the test moratorium. These 'Science Based Stockpile Stewardship' programs comprise experiments that mimic nuclear weapons on a laboratory scale, and ultra-fast computer platforms that simulate weapon performance. The numerical models used in the computer simulations are continuously calibrated by experiments and should allow better predictions of nuclear weapon performance, including the 'virtual testing' of a warhead.

Some experiments are aimed at understanding the physics of fission weapons and focus on the fast compression of fissile material (or a surrogate). The shock waves traveling through the material can be X-rayed in appropriate hydrodynamic facilities and can deliver multiple snapshots of the imploding target. These so called X-ray radiographies allow the control of the symmetry of the implosion process as well as its speed, and allow inferences on the performance of a fission primary.

Parts of a thermonuclear weapon can be simulated to a certain extent in a so-called 'inertial confinement fusion' (ICF) experiment, where high-power lasers produce similar extreme physical conditions to those within a detonating hydrogen bomb. New ICF facilities, with the world's most powerful lasers, are currently being constructed in the U.S., France and the UK. Their exorbitant costs and their unclear focus raised suspicion and doubt within the arms control community as well as in some non nuclear weapon countries.

ICF facilities are not needed to maintain weapons, nor are they suited to design new warheads and were therefore heavily criticized by different sides. The launch of the new ICF facilities in leading NWS therefore represents only a partial victory of the weapon labs over the disarmament norms of the post-Cold War era, and symbolizes their continuing research excellence and privileged funding. Whether the SBSS programs will be able to retain first class scientists in the weapon labs and hone their design and development skills without ever returning to testing is one of the exciting questions of nuclear arms control in the 21st century.

It should be noted, however, that continuity in nuclear weapon research and in nuclear weapon retention is increasingly questioned, even within the establishments of NWS. The most obvious example is the appeal to ban nuclear weapons, signed by leading American elder statesmen at the beginning of this year. They warn that 'business as usual' in nuclear affairs bears tremendous dangers for peace and security in the 21st century.

Contents

1. Introduction

One of the most prominent nuclear arms control treaties is the Comprehensive Test Ban Treaty (CTBT). It was negotiated from 1994 to 1996 at the Conference on Disarmament (CD) in Geneva, with the aim of preventing any further weapon development. After it was signed by all official nuclear weapon states, there were strong expectations that the test sites would be shut down, the weapon labs downsized and – as a result – their research activities frozen.

But the opposite seems to be the case – at least in the leading nuclear weapon states. Test sites are maintained and used for so-called 'subcritical tests', large and costly experimental facilities are being constructed, and the fastest computer platforms ever seen are being commissioned for advanced weapon simulations. Instead of an expected decrease in the funding of nuclear weapon research over the last decade, there has been an increase, and especially in the U.S., the UK and France, new nuclear weapon programs seem to be looming on the horizon. These states declare that their aim is simply to maintain their existing arsenals and to keep their weaponry safe and reliable without returning to full-scale nuclear testing.

But their nuclear weapon complexes seem to aspire to more than just mere preservation of their current stockpiles. They aim at underpinning their theoretical knowledge on nuclear weapons and retaining their ability to design, develop, manufacture and maintain nuclear warheads 'for an uncertain future'. They claim that this is possible without explosive tests, which can be easily substituted by scientific and computer simulations.

But why are the nuclear weapons states embarking on such an ambivalent upgrade of their complexes? At first glance, it seems that this policy is justified to guard against unexpected geopolitical challenges which might arise in the future, but – at the same time – it paves the way for a comprehensive stockpile transformation that has been envisioned by the nuclear complexes for quite a while. This vision should lead to smaller arsenals with fewer weapon types that have a longer life, higher reliability and better cost-efficiency. This transformation process will require a broader knowledge base and will draw on the 'Big-Science' approach mentioned above. The states pursuing such programs claim that their intention is not the development of new nuclear weapons. Instead, they claim they need to maintain their existing arsenals: Warheads get old and therefore must be remanufactured or repaired; it must be ensured that all warheads in the arsenals are safe and reliable; and it must be possible to study the ageing effects of warheads, to replace components, and to guarantee that their properties do not change over time. In addition, scientists from nuclear weapons labs demand an alternative to the nuclear test, their most interesting experimental activity, so that the labs will continue to attract new young colleagues.

Do these huge efforts result in new warheads, even without nuclear tests? Does this mean that the CTBT would not keep its promise, which is nothing less than putting an end to the *qualitative* nuclear arms race? Or, on the contrary, do the efforts stabilize the

CTBT because nuclear tests are not needed anymore? What is the opinion of outsiders (non-nuclear weapon states or nongovernmental observers)?

These are the questions that are dealt with in this report. We will base the discussion around the U.S. Science Based Stockpile Stewardship (SBSS) program because the U.S. is by far the most active and transparent nuclear weapon state (NWS), both with regard to its technical activities and to publications and information about its decision-making and plans. In contrast, information from the other nuclear weapon states is scarce and sporadic, with the UK being fairly transparent, and with China releasing the least information. Nevertheless, as far as any information is available, we will also attempt to give a short overview of the situation in the other NWS. In the first chapter, we will outline the role of nuclear testing and the CTBT in the development of nuclear warheads. In the next chapter, we will present discussions on the future of nuclear weapon complexes in the absence of nuclear testing. This will be followed by a discussion on the technical abilities of the various SBSS components and a discussion on whether they have met their official goals or not. We will then present the controversies and criticisms of the SBSS. In the concluding chapter, we will try to assess the consequences of the SBSS, whether it serves its official goals, and whether it is damaging to nuclear disarmament because of external opinions. We shall see that research programs might undermine the CTBT and the Non-Proliferation-Treaty (NPT) in the long run and that modernization plans may pose a serious risk to the non-proliferation regime, which is currently already under severe strain.

2. The CTBT and nuclear weapon research

For over half a century nuclear weapons have been developed and tested. Over that time, the number of warheads and their possessors has increased. Furthermore, they have been continuously modernized, miniaturized and adapted to new delivery systems. New strategies and new technologies have mutually promoted each other; ever more sophisticated concepts have given rise to ever newer development programs. Examples of advanced concepts are multiple warheads and neutron weapons. In Reagan's SDI-program, even space based nuclear driven X-ray lasers, microwave weapons and particle beam weapons, the so-called nuclear weapons of the third generation, were discussed. Today, the U.S. has engaged in plans for a new program, the so-called ‘Reliable Replacement Warhead (RRW) program’ in order to ‘improve the reliability, longevity, and certifiability of existing weapons and their components’.[1] It is argued that this may lead to new kinds of warhead. Also, other nuclear weapon states plan to modernize their arsenals.

The development of nuclear weapons needs experimental research, and the most important experiment has been the nuclear test. Each new weapon in the arsenal of estab-

1 Jonathan Medalia, Nuclear Weapons: The Reliable, Replacement Warhead Program, in: CRS Report for Congress, Updated February 8, 2007, www.fas.org/sgp/crs/nuke/RL32929.pdf (last access on May 14, 2007).

lished nuclear weapon states has been repeatedly and successively tested. Over 2000 'tests' and two employments in combat have been recorded to date. In addition to established nuclear weapon states, other countries have conducted tests; the latest was North Korea that carried out a nuclear explosion on 9 October 2006.

A nuclear test is not only the culmination point in the design process of a new warhead, it is also a spectacular and internationally visible symbol of the nuclear arms race and of nuclear proliferation. Therefore, a nuclear test ban treaty had already become prominent as an important disarmament and non-proliferation tool as early as the late 1950s. The aspiration to end nuclear testing has never disappeared from the international agenda since Jawaharlal Nehru, the Indian Prime Minister, first proposed it in 1954. The 1970 Treaty on the Non-Proliferation of Nuclear Weapons (NPT) affirmed the relationship between banning nuclear tests and preventing the spread of nuclear weapons. Successive NPT Review Conferences further emphasized the importance of a CTBT to the non-proliferation cause. In the course of the indefinite extension of the NPT in 1995, the CTBT was explicitly named as a means for nuclear disarmament.[2]

In July 1992, the U.S. implemented a testing moratorium. The U.S. also determined that it would not conduct nuclear tests to develop new nuclear weapon designs for force modernization purposes. This was implemented by national legislation in 1993. The U.S. decision was soon followed by Russian and French moratoria. Since then, strong action against nuclear testing has grown, reinforced by the negotiations of the CTBT, which finally started at the beginning of 1994. The reaction to the resumption of French testing in the summer of 1995 showed how strong international pressure had become in the meantime. The protests against the six tests surpassed all previous protests that had taken place during the more than 2000 explosions over the years. Even China, who in contrast to France, had never announced a moratorium, suddenly became the target of worldwide criticism. A strong desire to end the nuclear arms race fuelled opinion against further nuclear tests. Since then, the established nuclear weapon states uphold a moratorium on testing.

The CTBT negotiations were completed in 1996, and soon after that, a large number of states signed it, demonstrating widespread support. It was clear that there would be obstacles against its entry into force,[3] as the treaty was designed to draw in states that are not party to the NPT – namely India, Pakistan and Israel. The willingness of these states to endorse the CTBT was and is still uncertain. In fact, there have been nuclear tests after 1996, namely the tests by India and Pakistan in spring 1998, and by the NPT dropout in North Korea in autumn 2006.

2 Principles And Objectives For Nuclear Non-Proliferation And Disarmament, NPT/CONF.1995/32/DEC.2

3 In order to enter into force the CTBT has to be ratified by 44 key states that possessed either nuclear power or research reactors in 1996. As of today 41 of these "Annex 2" states signed the treaty, but only 34 states ratified it. India, Pakistan and North Korea neither signed nor ratified the CTBT.

India claimed to have exploded a so-called '*thermonuclear* device', also known by the names '*hydrogen bomb*' or '*nuclear weapon of the second generation*'. Such a device gets its energy not only from nuclear fission but also from nuclear fusion – in contrast to an ordinary fission bomb (of the '*first generation*').[4] This Indian claim must be viewed with skepticism. The development of a hydrogen bomb is technically much more complicated than that of an ordinary fission bomb.[5] The reason is that it requires a highly developed and precise design of the fission bomb – the driver of the subsequent fusion – and this can only be achieved by evaluating a large amount of data from previous nuclear tests. Without the experience and data from other nuclear tests, the ignition of the fusion part of the bomb is unlikely. This probably happened in the Indian 1998 test: fission was successful, but fusion failed. One of the goals of the CTBT is precisely to prevent new states from obtaining such experience and data. Because of the (partially failed) 1998 tests, it is likely that Indian physicists will use the data to develop a better thermonuclear design. Should India conduct another test, the probability is higher that this time, a thermonuclear explosion would be successful. The same holds for Pakistan.

North Korea's 2006 test had a yield that was much smaller than that of other states that had exploded a nuclear device for the first time, and even smaller than it had announced.[6] It is likely that the test performance was very poor, which shows that North Korea would need several more tests before obtaining a usable weapon.[7]

These examples show the benefit of a CTBT on non-proliferation. During negotiations, not only the non-nuclear weapon states in the Conference of Disarmament (CD) but also all nuclear weapon states appreciated this advantage and supported the CTBT. It was expected that only a few states would create obstacles against its enforcement. Nobody expected that one of the most proactive supporters – the United States – not only failed to ratify the treaty in 1999 but has also voiced its strong opposition to it. Therefore, there are rising international suspicions that the moratorium could come to an end. In its Nuclear Posture Review of 2002, the U.S. administration noted that it 'may not be possible, for the indefinite future', to maintain the moratorium, although for the present, it still supports it. The fear that the U.S. might test again is further fuelled by huge expenditures on the maintenance of former test sites in Nevada.

And there are more fears: even if no nuclear test takes place, the spirit of the CTBT could be undermined by the huge scientific and engineering activities that are aimed at

4 For a short overview on the functioning of nuclear weapons see the Appendix I.

5 Annette Schaper, Bombenstimmung in Indien und Pakistan, in: Spektrum der Wissenschaft, Vol. 7, July 1998, p. 110.

6 North Korea's tests yielded about 0.5 – 1 kt TNT. The yields of the other first nuclear tests were: 19 kt TNT (USA), 22 kt TNT (Russia), 25 kt TNT (UK), 60 kt TNT (France), 22 kt TNT (China), 12 kt TNT (India), and 9 kt TNT (Pakistan).

7 Annette Schaper, Der nordkoreanische Test – eine militärische Bedrohung? (The North Korean Test – A Military Threat?), HSFK-Stellungnahme, October 19, 2006, www.hsfk.de/downloads/HSFK-Infoangebot_Raketentests-Nordkorea_19-10-06_Schaper.pdf (last access on.May 14, 2007).

replacing former nuclear tests. They take place not only in the U.S. but also in other nuclear weapon states. The maintenance of former tests sites, huge expenditures on new science programs, discussions and plans for new warheads, and 'subcritical tests', create strong suspicions in other states and among outside observers. There is the fear that these activities may help to increase their ability to replace the formerly indispensable experimental 'nuclear test' with the development of new nuclear weapons. The CTBT – even when in force – would then cease to prevent a qualitative arms race.

However, it is questionable whether these technical activities could indeed be used for the development of new nuclear weapons. U.S. nuclear weapon experts and several U.S. studies maintain that this is not the case.[8] Nevertheless, international suspicion remains. In particular, members of the so-called non-aligned group, which includes many developing states, do not believe this claim.

Suspicion already played a role during the CTBT negotiations:[9] India asserted that the CTBT was designed to draw outsiders into the non-proliferation regime, while at the same time all technical options for further developments were left open for the nuclear weapon states. In India's claim, with the CTBT's alleged sole focus on preventing others from acquiring nuclear weapons, the treaty was only a non-proliferation, but not a disarmament treaty. In this way, New Delhi justified why it rejected joining the CTBT. Instead, it demanded a phased elimination of nuclear weapons within a time-bound framework, a demand for which the time was obviously not ripe, and which was widely considered to be hypocritical. Yet, suspicions about the role of the planned technical test replacement efforts were and are still shared by many delegations. Although they considered India's position to be extreme, they acknowledged that it had a case.

During negotiations the proposals on what should be permitted and what should be disallowed covered a large number of variations, and the *scope*, which defines the line

8 Richard L. Garwin/Vadim A. Simonenko, Nuclear Weapon Development without Nuclear Testing?, October 1996, www.fas.org/rlg/dev_no_test.htm (last access on May 14, 2007); National Academy of Sciences, Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty, Washington (National Academy Press), 2002; Richard L. Garwin, The Future of Nuclear Weapons Without Nuclear Testing, in: Arms Control Today, Vol. 27, No. 8, November/December 1997, pp. 3-11; U.S. Department of Energy, Stockpile Stewardship Program: 30-Day Review, November 23, 1999, www.fas.org/nuke/guide/usa/doctrine/doe/Conrad.pdf (last access on May 14, 2007). See also JASON and the MITRE Corporation, Science Based Stockpile Stewardship (JASON Report JSR-94-345), November 1994. Richard L. Garwin, Stockpile Stewardship and the Nuclear Weapon Complexes, Pugwash Meeting No. 206, Moscow, February 19-23, 1995. JASON, Nuclear Testing – Summary and Conclusions (JASON Report JSR-95-320), August 3, 1995, www.fas.org/rlg/jsr-95-320.htm (last access on May 14, 2007).

9 Jaap Ramaker/Jenifer Mackby/Peter D. Marshall CMG OBE/Robert Geil, The Final Test – A History of the Comprehensive Nuclear-Test-Ban Treaty Negotiations, Vienna (Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization), 2003; The developments in the CD have been described in great detail and accuracy by Rebecca Johnson in the *Acronym Reports* and the periodicals *Nuclear Proliferation News* (until end of 1995) and *Disarmament Diplomacy* (starting 1996).

between allowed and prohibited activities, was utterly disputed.[10] Delegations called for the ban not only of all nuclear tests, but also of some additional technical activities, including computer simulations or tests without the release of nuclear energy.

In contrast, the nuclear weapon states – all subject to strong pressure from their nuclear lobbies to preserve as many technical activities as possible – negotiated a testing threshold only among themselves, although this is not compatible with the aim of a *comprehensive* test ban. But when the other delegations became aware of this, calls for a 'true zero yield threshold' intensified, meaning that any nuclear experiment must not release any nuclear energy, even if it is tiny. This strong pressure was intensified by worldwide protests against the resumption of French nuclear testing in 1995. As a result, the nuclear weapon states agreed to the zero option. But this outcome was not specifically taken up in the treaty text. There is merely a reference in Article 1 to the fact that nuclear test explosions shall be prohibited, without defining the term 'test explosion' more specifically.[11] The absence of a more precise definition can be interpreted in various ways: ratification by the nuclear weapon states with their influential nuclear lobby is thereby simplified, and the wording of a definition would have been difficult and would have risked additional complications. But some states also suspect that the nuclear weapon states wish to keep the possibility of small tests open, despite the fact that during the negotiating process the meaning of the term '*nuclear explosion*' was clear.[12]

3. Reactions of the nuclear weapon complexes

Once the scope of the CTBT was defined and the line between what was allowed and forbidden was drawn, the nuclear establishments reacted. Although negotiated in a political context to advance nuclear disarmament and non-proliferation, the weapon labs never endorsed the CTBT as a genuine disarmament treaty. Rather, they perceived the constraints of the treaty as a challenge they had to respond to with an appropriate adjustment strategy.

10 Annette Schaper, The problem of definition: Just what is a nuclear weapon test?, in: Eric Arnett (ed.): Implementing the Comprehensive Test Ban, SIPRI Research Report No. 8, 1994, pp. 26-47.

11 "Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control." See treaty text under www.ctbto.org.

12 As an example, the German understanding that the zero-option means no nuclear yield is reflected in Foreign Minister Kinkel's press declaration of August 12, 1995, commenting on Clinton's declaration of August 11. It includes the wording "ban of all nuclear explosion, including those of very small yield". Auswärtiges Amt, Pressereferat, Presseerklärung 366/95, 12 August 1995. The official U.S. Government view is: "In the negotiations a shared understanding was achieved, including Russia and China, that all nuclear explosions, however small (including hydronuclear tests), are prohibited, and sub-critical experiments are not prohibited", see CTBT: Regional Issues and U.S. Interests – Fact Sheet released by the Bureau of Arms Control, U.S. Department of State, Washington, DC, October 8, 1999, www.fas.org/nuke/control/ctbt/news/fs_991008_adherence.htm (last access on May 14, 2007).

When the Clinton administration implemented legislation that banned nuclear testing and the development of new nuclear weapons in 1993, the focus of the weapon labs – anticipating a CTBT – shifted from the development of new assets to the conservation and maintenance of their incumbent weapon systems. The safety and reliability[13] of the enduring stockpile was now emphasized instead of the design of new warheads and performance enhancements of existing weapon systems. In particular, ageing effects and non-original remanufacturing processes were seen as having the potential to jeopardize the safety and reliability of the nuclear arsenal in the long run.[14]

During the pre-CTBT era, the safety and reliability of arsenal were less of an issue due to the fact that stockpiled weapons were continuously replaced with (fully tested) newer designs, and these new warheads could again be submitted to tests at some later stage to assure full performance and security during their whole life span in the arsenal.

With the testing option no longer available, the question arose within the nuclear weapons complexes how their arsenals could be kept safe and reliable in the future. This question triggered a lively debate within the nuclear establishment and arms control community, which is still going on now. Within this debate, three major maintenance approaches could be identified. These will be addressed briefly in this chapter:

- A minimalist approach ("Curatorship")
- A conservative approach ("Freeze")
- A maximalist approach ("Big Science")

3.1 Curatorship

Jonathan Katz, a physicist at Washington University and consultant of the JASON[15] Defense Advisory Group, advocated a minimalist strategy where 'design and development skills are allowed to atrophy… [and where] …only those skills required to remanufacture weapons according to their original specifications are preserved'.[16]

This would allow downsizing of the nuclear weapons complex to a minimum number of facilities and to a cadre of technical experts whose sole responsibility would be to remanufacture existing weapons true to their original design. This approach – termed 'cura-

13 A safe weapon does not detonate when it shouldn't, whereas a reliable weapon detonates when it should.

14 Strictly speaking the impact of aging on weapon safety is marginal. Safety is rather a function of the design of a warhead than of its age. Therefore the effect of aging on safety is indirect, as non-identical replacements alter the original design. The effect of ageing on the reliability, however, is assumed to be more substantial. See also Ray Kidder, Problems with stockpile stewardship, in: Nature, Vol. 386, April 1997, pp. 645-647.

15 The JASON committee is a prestigious group of academic and industrial scientists that has been advising the U.S. government for decades on matters of science and technology.

16 Jonathan I. Katz, Curatorship vs. Stewardship, in: Bulletin of the Atomic Scientists, Vol. 51, No. 6, November/December 1995, p. 3.

torship' by Jonathan Katz – would allow the U.S. to preserve its nuclear forces at a minimum cost.

Curatorship can do without costly new experimental facilities and builds an implicit barrier against proliferation, because critical knowledge on weapon development could slowly 'decay' once experienced weapon designers start to retire. Katz argues that nothing can be done to retain these skills, and 'Big Science' can never fill the knowledge gap left after the testing moratorium. Thus, a brain drain is unavoidable.

Since nuclear weapon design is a 'living art', where substantial parts of know-how are learned from hands-on experience with real weapons and passed on to the next generation of scientists by their senior colleagues, a prolonged curatorship approach could theoretically dry out critical skills ('tacit knowledge') and lead to the 'uninvention of the bomb'.[17]

The weapon labs would be left with enormous amounts of data and explicit knowledge stored on written documents and computer files documenting more than half a century of nuclear weapon research, but would have irreversibly lost the additional 'practical' skills that are also needed to design and develop nuclear weapons.

Katz maintains that this loss of skill is unproblematic for the U.S. as a deterrent because it affects all nuclear powers equally and would not alter the strategic balance between them. Furthermore, the curatorship approach clearly supports the spirit of the CTBT as it demonstrates the intention of a NWS to forego warhead modernization in the foreseeable future and avoids misperceptions on its maintenance program.

Thus, curatorship would maintain a deterrence capability at minimal cost by minimizing (horizontal and vertical) proliferation risks at the same time; but is this approach really feasible? Three objections have been voiced by the nuclear weapon complexes:

The first objection concerns *reliability*: a modern nuclear weapon consists of approximately 6000 distinct components. When refurbishing or re-manufacturing a warhead, many of the original components are no longer available. The reason is that most currently stockpiled weapons were designed and developed in the 1980s, and within the last two decades, several components suppliers shut down their production lines, modified and modernized their products, or went out of business. Thus, several components have to be replaced with newer units, which have never been tested in combination with the original weapon design. Since the CTBT prohibits fully-fledged tests, these non-original components can only be tested partially, together with the non-explosive ('non-nuclear') part of the warhead.[18] This situation might reduce the confidence of military planners in

17 Donald MacKenzie/Graham Spinardi, Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons, in: The American Journal of Sociology (AJS), Vol. 101, No. 1, July 1995, pp. 44-99.

18 A warhead can be roughly divided into two major building blocks: the physics-package (or nuclear package) and the non-nuclear package. The former contains only the explosive nuclear fission primary and secondary fusion subsystems, whereas the latter contains conventional explosives, the control electronics re-

the performance of their arsenal. Furthermore, if the ageing effects of the single components are not properly addressed (which a minimalist approach does not foresee), uncertainty about proper weapon performance will increase the longer a warhead stays in the arsenal.

The second objection concerns *costs*: in order to maintain confidence in the arsenal at acceptable levels, the curatorship approach requires steady substitution, refurbishment and remanufacturing of the stockpiled weapons. This does not take advantage of insights gained from recent studies, which indicate that plutonium warheads might be reliable for almost a century. Thus, the cost saving argument of curatorship is questionable in the long run: if all funds are dedicated to remanufacturing, and the potentials of life extension are not explored, the arsenal can only be maintained at the cost of the very short life cycles of any single weapon. Traditionally, weapons were replaced by newer designs approximately every decade: by maintaining this replacement rate and not investing into life-extension programs, the remanufacturing capability might be significantly over emphasized by an extent of factor 10 in the long run. [19]

The third objection concerns *flexibility*: the curatorship approach allows scheduled remanufacturing of Cold War nuclear weapon designs. However, it does not allow for modifying and adapting the warheads to the new Post-Cold-War security environment. But the new nuclear doctrines of the U.S. and France emphasize the radical changes taking place in the international environment (rogue states, international terrorism, and WMD proliferation) and the necessity to tackle these new threats with determination and resoluteness.: responses include the use of suitable nuclear weapons. New software requires new hardware, and so the modified nuclear doctrines were accompanied by calls to devise nuclear warheads with new capabilities ('mini-nukes' and 'bunker busters') in order to allow appropriate responses to the 'new threats' of the 21st century. The curatorship approach does not give flexibility to adapt the arsenal to these new challenges, it just replicates Cold-War weapons, which cannot be upgraded anymore due to the loss of design skills.

sponsible for arming, firing and fusing, a neutron generator, batteries, radar and many other components. More detailed information on nuclear weapons composition can be found in the Appendix.

19 In order to maintain an arsenal of, say 3500 warheads (as recommended by the START II Treaty) and to limit the life span of every warhead to only a decade, an average remanufacturing capability of 350 warheads per year would be required. By monitoring ageing effects more thoroughly through a more aggressive surveillance regime, the life span of every warhead could easily be extended to about 35 years today. Hence, only 100 warheads per year would have to be manufactured as an average. By investing time and money in the study of weapon material ageing and combining the results with regular refurbishment tasks, a nuclear weapon could potentially remain in the arsenal for about a century, and the remanufacturing rate would shrink to only 35 warheads per year, i.e. a tenth of the 'traditional' rate.

3.2 "Freeze"

Another approach, which can be observed mainly in Russian discussions, focuses on the preservation of all physical and human resources present in a pre-CTBT nuclear weapon complex: this includes the capability to design, develop, test, manufacture, refurbish, dismantle and dispose of nuclear warheads.

This genuinely conservative philosophy tries to freeze all skills within a nuclear weapon complex and to project them into the future. The preservation of intellectual skills represents the biggest challenge in this approach since the CTBT puts serious constraints on the weapon labs. It could frustrate ambitious young scientists, who might never see their intellectual creativity materializing in a full-scale test and – as a consequence – in a new, certified warhead.

Thus, the focus of a "freeze" program remains on the incumbent stockpile, its safety and reliability. Maintenance, refurbishment, surveillance and life-extension of the existing arsenal are emphasized, and accompanied by a 'light' science program aimed at preserving the intellectual skills needed to design, develop and test new weapons. The latter also includes test site readiness,[20] i.e. the ability to restore tests at a multi-kiloton yield within a suitable time-frame.

The preservation of *all* intellectual skills and the ability to restore the status quo (before CTBT) in almost no time is therefore the major difference between this approach and curatorship. It does not mean that there are current ambitions for the development of new warheads; however the option to develop such plans at a later time is intended to be kept open.

A nuclear weapon state might opt for a "freeze" approach when it does not have the monetary resources for a more ambitious program (see next caption), but wants to prevent the erosion of critical knowledge within its complex. Russia seemed to be in this position after the end of the Cold War: in the turbulent transition period following the collapse of the Soviet Union, funding of the nuclear complex was inadequate and led to a partial erosion of skills and facilities.[21] Still, the total collapse of the Russian weapons lab could be avoided – not least by substantial international assistance – by a prudent restructuring process which will ultimately lead to the downsizing and consolidation of the nuclear complex: this adjustment process is clearly guided by the conservative approach to slow down the erosion – which set off in the 1990s – and to maintain production facilities, know-how and test sites.

20 As long as the CTBT is endorsed this implies a limitation to subcritical tests only.

21 Oleg Bucharin, Disquiet on the Eastern Front, in: The Bulletin of the Atomic Scientists, Vol. 53, No. 3, May/June 1997, pp. 41-46.

3.3 "Big Science"

The renunciation of nuclear testing by the U.S., the UK and France was accompanied by a substantial restructuring process of the nuclear complexes and by the launch of ambitious science programs, which in the U.S. is referred to as the '*Science-Based Stockpile Stewardship*' (SBSS) program,[22] in France is simply called '*Simulation*',[23] and in the UK is named the '*Warhead Science Program*'[24] or simply '*Stockpile Stewardship*'.[25]

These ambitious and costly programs are 'all-options-open' approaches, which go far beyond the conservative philosophy mentioned above: their intellectual focus is not only the retention; it is much more the expansion of critical knowledge on nuclear weapon science. For this purpose, huge investments were made in new experimental facilities and in ultra-fast computer clusters, which – as a consequence – led to increased funding for all three nuclear complexes over the last decade. The SBSS programs of France, Britain and the U.S. are quite similar and are based on the following cornerstones:

- Supercomputing
- Laser-induced fusion experiments
- X-Ray Radiography
- Material Science

These research programs are carried out with the world' s most powerful lasers, the fastest computer platforms, and the most advanced diagnostics tools, therefore representing the science of excellence.

With the launch of these expensive SBSS programs, the ''peace dividend' of the Post Cold War era seems to be exhausted. Nuclear bureaucracies usually explain the alleged benefits of this massive investment as substantial scientific progress in three fields: warhead science, surveillance and life-extension.

As a consequence , the programs should prevent the feared brain-drain from the weapon complexes, since they allow scientists to do research with leading-edge technology and to operate on the forefront of 21st century physics and engineering. This should retain the national scientific elite in the weapon labs and keep their skills in suspended animation for the eventuality of a new arms race.

22 Raymond Jeanloz, Science-Based Stockpile Stewardship, in: Physics Today, Vol. 53, No.12, December 2000, pp. 44-50. See also Haninah Levine, Stockpile Stewardship in the United States: A Primer, June 2006, www.cdi.org/PDFs/Haninah%20Levine%20Stockpile%20Stewardship%20Primer.pdf (last access on May 14, 2007).

23 Alan Delpuech, Perennité de la dissuasion: le programme Simulation, www-dam.cea.fr/statique/missions/img/defnat_perennitedissusasion.pdf (last access on May 14, 2007).

24 Keith O'Nions/Robin Pitman/Clive Marsh, Science of nuclear warheads, in: Nature, Vol. 415, February 2002, pp. 853-857.

25 For the sake of simplicity we will use the abbreviation SBSS for the U.S. as well as for the British and the French science programs.

The Big Science facilities should compensate the labs for the loss of a testing option and provide critical know-how on weapon performance and ageing effects by performing ad-hoc experiments that simulate parts of a thermonuclear weapon: for example, primaries can be studied by multidimensional X-ray radiographies of imploding plutonium shells, and the performance of secondaries can be estimated by observing laser-induced fusion of small deuterium-tritium targets in apposite reaction chambers. These experiments should allow the derivation of the equations-of-state (EoS) for the regime of high-density and high-temperature that are found within an exploding warhead. These EoS-parameters can then be used in simulation programs to refine existing computer models.

Since nuclear weapons are still poorly understood in theory, and models use approximations and interpolations, the SBSS programs – if successful – will expand explicit knowledge on warhead physics and – as a consequence – decrease their dependency on underground tests. The programs therefore might eventually open up the possibility of designing and developing new nuclear hardware for the future: virtual computer testing could replace traditional explosive testing, and new refined computer models could provide the blueprint for new replacement warheads, which could be tailored to the requirements of the new security environment of the 21st century.

This prospect would clearly undermine the spirit of the CTBT, which aims to stop vertical proliferation and thus the qualitative improvement of the nuclear arsenals. As a matter of fact, some non-aligned countries aired their concern over these test-replacement strategies during CTBT negotiations and asked for stricter control, which would eventually include not only classical 'explosive' testing, but also 'virtual testing'.

Whether the new designs will lead effectively to a modernized nuclear arsenal in the U.S., UK and France is still widely debated; critics of the modernization program (within and outside the nuclear establishments) express strong skepticism that military planners would accept untested weaponry in their strategic arsenal. Therefore ,in the long run, the design of replacement warheads might endanger the test moratorium. Supporters of warhead modernization, on the other hand, highlight the current unsustainable remanufacturing approach (costs, reliability) and campaign for an arsenal transformation with more conservative designs and longer warhead life cycles; they claim this process would not jeopardize the test moratoria and can still be achieved within the boundaries of the test ban that is imposed on weapon labs.

France is clearly heading in this direction and is modernizing its nuclear arsenal with super-computers and high-tech experiments exclusively: after its last contested test series in 1996, it shut down its Polynesian test sites and will now rely solely on numerical simulations and their associated experiments for the foreseeable future.

In the next decade, the UK is due to swap its current nuclear deterrent (the submarine based Trident) with a new system, and the U.S. is discussing a complete arsenal transformation with so called Reliable Replacement Warheads (RRW). Both countries rely on their science-based programs to achieve these modernization goals and additionally, continue to operate at their Nevada Test Site, where they carry out subcritical tests.

Whether this modernization process can continue in future decades without reverting to full-scale testing is one of the challenging arms control questions of the new century.

4. Science Based Stockpile Stewardship

The Stockpile Stewardship programs serve a double purpose: the advancement of general warhead science and tackling the problem of warhead ageing. Advancements in basic science should lessen the dependency on nuclear tests and increase confidence in numerical models in the long run. However, the detection, assessment and correction of ageing defects represent a more direct focus in the program.

For this purpose, an aggressive surveillance regime has been designed, which regularly extracts a representative sample from the arsenal, dismantles and inspects it, and analyses it for ageing defects. This monitoring program – together with simulation tools should lead to a timely detection of ageing effects and allow for their 'pre-emptive' compensation, e.g. by replacing or refurbishing sensitive modules at crucial moments in a weapon's lifecycle.

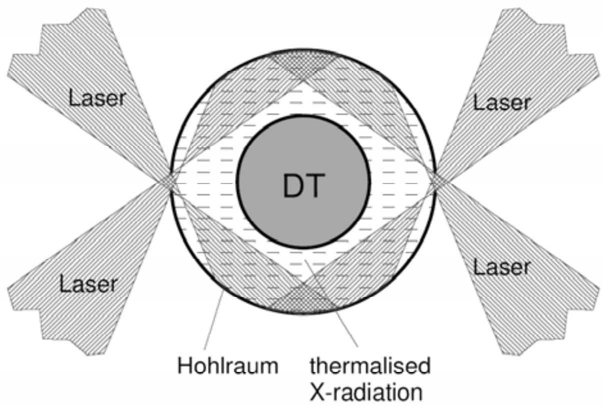
Component ageing and its effect on warhead reliability can be assessed with the full spectrum of diagnostic, experimental and computational tools provided by the SBSS programs: some of these tools will be discussed in the following chapters.

As some critics pointed out, not all of them are essential in addressing ageing problems; some activities could be avoided if maintenance was the only goal of the SBSS. These 'redundant' activities include the ICF research (see next subchapter 4.1.) and the upgraded hydrodynamic facilities (4.2.) with their multiple-axis snap-shots: one axis – as in the default facilities – would suffice.

4.1 Inertial Confinement Fusion

Weapon physicists need to understand the process of a nuclear explosion, and typically, their major experimental tools are nuclear tests. Every test yields a lot of data about the warhead and its materials within the extreme conditions of a nuclear explosion; examples of this are data on temperature, pressure, ionization, propagation of radiation, fission and fusion rates, the interdependence between these values and their time dependence, and more. The possibility of theoretical extrapolation of such data is limited, because the interaction between the physical parameters is complex, and depends on specific properties of the matter involved. The equations of state (EoS) that describe the properties of materials at extreme conditions in a nuclear explosion may differ substantially from those in normal conditions. Therefore, theoretical and computational results always need an adjustment through experimental data. An experiment that can serve this purpose is called '*inertial confinement fusion (ICF)*'. It simulates the extreme physical conditions of a nuclear explosion to a certain extent, but on a smaller scale.

Briefly described, in an ICF experiment, high power laser beams compress and heat up a small container of material – typically a deuterium-tritium (DT) mixture – called the '*pellet*'. This is depicted in the following illustration.[26] The fundamental physical descriptions are the same as in the ignition and explosion of a secondary in a nuclear weapon, but the quantities such as temperature or density do not yet reach the same extreme values.[27] The result is the creation of small, very hot, and dense plasma, in which, provided the laser power is large enough, conditions come near to those in the explosion of a secondary.



Such experiments allow some of the processes that take place in the explosion of a thermonuclear device to be studied. Examples are fusion rates, heating and compression, or radiation flow. But there are differences: Firstly, in ICF, the extreme conditions are only achieved in a tiny volume. Secondly, a secondary can also contain fissile material, but an ICF pellet does not (at least this is not planned at the largest U.S. ICF facility, the '*National Ignition Facility*, NIF').[28] Thirdly, only a few processes isolated from other processes can be studied. In contrast, in a nuclear explosion, additional processes take place and all of them interact with each other. Therefore, in an ICF experiment, the interaction between the processes must be extrapolated using computer data based on decades of nuclear testing data. The ICF data can be used to fine-tune parts of computer codes to a limited extent, and to understand the range of applicability of computer models.

26 Jürgen Meyer-ter-Vehn, Zur Physik des Fusionspellets, in: Physikalische Blätter, Vol. 43, 1987. p. 424.

27 In an ICF experiment, the principal processes taking place in the pellet are the same as in the secondary of a nuclear device (see Appendix I for details). Similarly, the pellet is heated up and compressed by X-radiation filling a casing. The difference is that the energy of the X-radiation does not stem from the explosion of a primary, but from high power laser beams that are directed into the casing through small holes.

28 U.S. Department of Energy, Office of Arms Control and Non-proliferation (NN-40), The National Ignition Facility and the Issue of Non-proliferation: Final Study, December 19, 1995. Principally, it could also be possible to use an ICF facility for compressing and heating fissile material. However, given the tiny quantities, a critical mass would not be reached and the temperature would be much lower than in a nuclear explosion.

This is not enough for the development of new nuclear weapons, which needs the experimental control of many more processes and their interaction. Also, ICF is not applicable for testing the reliability and safety of existing warheads, as it only deals with basic aspects of some of the physics involved. At least some experiments can be used to complement a set of tools that test weapon effects.[29]

It seems that the usefulness of ICF for nuclear test replacements is rather limited. But why do the U.S. and some other NWS still invest colossal sums[30] in huge ICF experiments? In the U.S. at least, a major motivation is more of a sociological than a technical nature. It was argued that a replacement of the most interesting experiment, the nuclear test, was necessary to provide the science labs with a major attraction for new, young and excellent scientists.

The primary role that is assigned to NIF is to maintain the intellectual and technical competency of the U.S. in physics related to nuclear weapons in a more generic sense.[31] There are external critics who exaggerate the military potential of the ICF, some even fear that it may lead to the development of pure fusion weapons.[32] It is unclear whether a pure fusion weapon explosion would be banned by the CTBT because no *fission* would take place. While the explosion during an ICF experiment is indeed a pure fusion explosion, it is extremely unlikely that a pure fusion nuclear *weapon* would be possible. The reason is that the release of any significant fusion energy requires an energy input of the highest density. In the foreseeable future, this is possible only with a fission bomb or with high power lasers.[33] The latter are huge and bulky. A laser with such high energy that could be delivered like a weapon seems impossible today.[34]

29 Ibid. footnote 28.

30 The budgets of the ICF facilities are in the multi-billion dollar/euro range and thus one of the most expensive research facilities nowadays, like the International Thermonuclear Reactor (ITER) in France and the new particle accelerator (LHC, Large Hadron Collider) at CERN in Switzerland.

31 U.S. Department of Energy ..., see above (footnote 28).

32 An example is: Greenpeace International, Weapons Research, Development, Testing, and Production, Presentations by Non-Governmental Organizations (NGOs) at the 2000 NPT Review Conference, 14 April - 19 May 2000, New York, www.basicint.org/nuclear/NPT/2000revcon/NGOpres/peden.htm (last access on May 14, 2007). There are even more futuristic speculations that are widely noticed, but nevertheless belong into the realm of science fiction. A prominent example is: Andre Gsponer/Jean-Pierre Hurni, Fourth Generation Nuclear Weapons, Inesap Technical Report No. 1, 1999.

33 The energy density of any quantity of conventional explosives is principally too small: Annette Schaper, Secondaries ignited by conventional explosives? January 12, 1997, unpublished manuscript.

34 The argument that a pure fusion weapon is a so-called "clean bomb", could be possible with the aid of lasers was used by Edward Teller when the laser was invented. This way, he successfully prevented a CTBT early in the 60ies because the U.S. wanted to conduct more tests in order to develop such a clean bomb. The U.S. has declassified the information that there is the fact (1) that the DoE made a substantial investment in the past to develop a pure fusion weapon, (2) that the U.S. does not have and is not developing a pure fusion weapon; and (3) that no credible design for a pure fusion weapon resulted from the DoE investment: U.S. Department of Energy, Office of Declassification, Restricted Data Declassification Decisions 1946 To The Present (RDD-7), January 1, 2001.

The largest international ICF experimental facilities will be NIF and a comparable French project, the 'Laser Mégajoule' (LMJ).[35] 'NIF's arena-sized building houses 192 laser beams designed to deliver 1.8 megajoules (MJ) of ultraviolet laser energy and 500 terawatts of power to millimeter-sized targets located at the centre of its 10-meter-diameter target chamber.'[36] Its conditions of temperature and density come closer to those of thermonuclear weapons than those of any previous facility and it is likely that '*ignition*' will be achieved. 'Ignition' means that the energy released by fusion will be at least as large as the laser energy input. This is regarded as a milestone, allowing more confidence in experimental results, especially refinement of computer codes.[37] The first ignition experiments on NIF are scheduled to begin in 2010.[38] Laser Mégajoule (LMJ), which is constructed by the French Commissariat à l'Energie Atomique (CEA), is comparable. It is located near Bordeaux and is scheduled to start operations in 2008 and to achieve its full power in 2010. It will use 240 laser beams and will deposit the same energy of 1.8 MJ. It is part of an effort by CEA to simulate nuclear testing. Russia is planning the construction of a facility named 'ISKRA-6', in Snezhinsk, with energy up to 300 kilojoules (kJ) and 128 laser beams.[39] The time schedule is unclear. Britain is constructing a high power laser experiment at AWE in Aldermaston, called 'Orion', to be operating by 2010.[40] This system will combine 10 long pulse beam lines with two short pulse beam lines. China will operate an 8-beam laser with 18 kJ in 2008, a 64-beam laser with 200 kJ in 2010, and is planning a 1.5 MJ laser for operation in 2020.[41]

ICF research is pursued in non-nuclear weapon states (NNWS) as well, both experimentally and theoretically. The motivation is the study of extreme states of matter as prevailing in the centre of stars, with a vague prospect of its contribution to fusion energy research,[42] and general scientific curiosity without a specific view on practical future appli-

35 V – Le Laser Mégajoule, www.senat.fr/rap/r00-154/r00-1547.html (last access on May 14, 2007).

36 www.llnl.gov/nif/project/nif_works.html (last access on May 14, 2007).

37 Office of the Under Secretary of Defence for Acquisition, Technology, and Logistics, Report of the Defence Science Board Task Force on the Employment of the National Ignition Facility, Vol. I, October 2004, www.acq.osd.mil/dsb/reports/2004-10-DSBNIF-Vol_1_final.pdf (last access on May 14, 2007).

38 www.llnl.gov/nif/icf/icf.html (last access on May 14, 2007).

39 M.N. Chizhkov/N.G. Karlykhanov/V.A. Lykov/A.N. Shushlebin/L.V. Sokolov/M.S. Timakova, Computational optimisation of indirect-driven targets for ignition at the Iskra-6 laser facility, in: J. Phys. IV, Vol. 133, 2006, pp. 223-225.

40 AWE Annual Report 2005/2006, www.awe.co.uk/Images/25740%20UNC%20Annual%20Report05_tcm6-4218.pdf (last access on May 14, 2007).

41 W. Y. Zhang and X. T. He, Status of Inertial Fusion Energy Program in China, Presentation, Zhejiang University, Hangzhou, Oct. 2006, http://ifts.zju.edu.cn/upload/200610/status.pdf (last access on May 14, 2007).

42 This purpose is frequently quoted in NNWS in funding requests and presentations for a broad public. In fact, prospects for future energy systems based on ICF are very remote. Scientists mostly do science just as an end in itself. Once on a scientific track, a scientist might be led into various directions without much concern about potential practical applications. In the case of ICF, a motivation is created by similar projects and investments elsewhere.

cations. Also, the mere existence of large experimental facilities in other states motivates related research. In the context of the NPT and the CTBT, NNWS have sought to have unrestricted ICF research.[43] In response to such concerns, in 1975 the U.S. declared, 'Such contained explosions are not "other nuclear explosive devices" in the sense of the NPT, and research in this area is allowed under Article IV.1.'[44] This statement was not opposed by any other delegation.

4.2 X-Ray Radiography

At the French, British and U.S. weapon labs, 'hydro-testing' has been going on for decades. In these experiments, the single steps of a spherical implosion are being X-rayed and photographed; in these implosion tests, solid materials are compressed with high explosives (HE) and – when subjected to these shocks – behave like fluids: hence the term '*hydrodynamics*'.

The experiments focus specifically on how materials behave at high strain rates and how compression and shock waves develop inside hollow plutonium spheres, i.e. inside primaries.

Since shocked plutonium could produce a nuclear chain reaction and explode, most experiments use non-fissile material such as tantalum, lead or depleted uranium to simulate plutonium, but a number of experiments have necessarily used plutonium itself, though well below a critical mass.

Hydrotesting allows both the study of high explosives (HE) and the materials subjected to them. The HE in a nuclear weapon are arranged in such a way that they produce a perfectly symmetrical spherical shock wave that travels inwards with a velocity of more than 10,000 km/h; thus, the X-ray photos control the symmetry of the implosion process and allow inferences on its speed. Since HE are made of organic materials that undergo chemical and physical decomposition as they age, hydrodynamic tests, among others, serve to make sure that aged HE are still imploding symmetrically and at the desired speed.

Furthermore, the plutonium (Pu) which is subjected to these shock waves must be studied at various moments in its life-cycle, as the behavior of Pu in implosion systems is still poorly understood, and the ageing of Pu itself is a complicated matter.

The data provided by hydrotests can then be used to refine numerical models simulating nuclear weapons explosions. In particular, the computer codes describing the physics of the primaries will benefit from these experiments.

43 By signing the CTBT on 24 September 1996, Germany declared: 'It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and development of controlled thermonuclear fusion and its economic use.', in: Trust & Verify, Issue 70, October 1996.

44 NPT/CONF/C.II/SR.5, 1975.

Hydrotest facilities are currently being upgraded in France, the UK and the U.S..Paris launched its new 'Airix' radiographic facility in the year 2000. This facility deploys the most powerful X-ray sources on earth and allows 3-dimensional multi-frame photographs of the implosion process.[45] The ever-stronger X-rays allow deeper penetration into imploding opaque matter and – like in a hospital X-ray screen – reveal what is going on deep inside the imploding shell, not just the outside.

The Atomic Weapons Establishment (AWE) in Aldermaston, UK (the 'British Los Alamos') has a number of facilities where hydrotests are carried out and is planning a new Hydrodynamic Research Facility (HRD) with additional X-ray views (i.e. 'photo shots' from different angles). These are needed 'to adequately capture three-dimensional phenomena for validation of the computer models now being created'.[46]

Finally, Los Alamos and Lawrence Livermore launched their joint 'Dual Axis Radiographic Hydrodynamic Testing' (DARHT) program, where the first axis (the first X-ray source) provides a single-shot picture of the imploding target, whereas the second axis adds four additional shots: the aggregate picture is a three-dimensional multi-staged film of the imploding target.[47]

The costs of these new hydrotest facilities are significant (several hundred millions of dollars), but still substantially lower than the ICF-facilities and the supercomputers, which will cost several billion dollars.

4.3 Subcritical tests

In 1997, the U.S., the UK, and Russia started a series of experiments aimed at exploring the properties of plutonium as it is strongly shocked by forces produced by chemical high explosives. Examples of properties of interest are the flow of plutonium under extreme pressure and shock waves, or equations-of-state (EoS).[48] Many of the diagnostic and recording techniques in these experiments were developed in the context of underground nuclear tests.[49] An example of the latter are the X-ray snapshots mentioned above.

The experiments are called '*subcritical*' because the plutonium does not reach a critical state, and no self-sustaining chain reaction takes place. For this reason, they are not

45 A basic description of Airix can be found on the CEA Website: www.cea.fr/defense/armes_nucleaires_simuler_sans_tester/airix_radiographier_la_matiere_en_un_eclair (last access on May 14, 2007).

46 O'Nions/Pitman/Marsh, see above (footnote 24).

47 A basic description of DARHT can be found in Ann Parker, An Accelerated Collaboration Meets with Beaming Success, in: Science and Technology Review, Lawrence Livermore National Laboratory, April 2006, www.llnl.gov/str/April06/pdfs/04_06.4.pdf (last access on May 14, 2007).

48 Equations of state describe how pressure, temperature, and density are related to each other. They are needed for the simulation of the performance of a nuclear explosion, and they contain parameters that are dependent on the properties of matter.

49 L. R. Veeser et al., Subcritical Plutonium Experiments at the Nevada Test Site, in: Los Alamos Physics Division Progress Report, 1997–1998, pp. 94-101.

banned by the CTBT. They aim at the collection of 'scientific information for understanding physical properties of plutonium (Pu) under conditions relevant to the performance of primaries of nuclear weapons'.[50] Although the experiments frequently are labeled 'tests', they are not weapon tests, but typical material science experiments in which the nuclear properties of plutonium do not play any role.

However, the experiments are being conducted underground, namely at the Nevada test site (NTS), which was formerly used for full-scale nuclear weapons tests, and in Novaya Zemliya, Russia. Outside observers would not be able to tell the difference between allowed subcritical tests, and forbidden, small yield nuclear tests of a few kg TNT, whose energy release is below the detection threshold.[51] If the CTBT was in force, it would be possible to conduct on-site inspections in cases of suspicion. Any nuclear explosion, even a tiny one, would release characteristic radioactivity. Therefore, by examining environmental samples, it would be possible to identify a chain reaction.

The first subcritical tests conducted by the U.S. caused a lot of international irritation because they took place underground at the Nevada test side, and were perceived by many as real nuclear tests, and therefore, as a violation of the CTBT.[52] International concern was also raised in the CD.[53] A major reason for this suspicion was an initial lack of more technical information, which might have confirmed that these experiments had indeed been subcritical.[54] The tests also demonstrated to the world both the existence of a strong nuclear weapons research program and the intention to retain the capability for full-scale underground tests.

Until 30 August 2006, the U.S. had conducted 23 subcritical tests, a large portion of which were in collaboration with the British Atomic Weapons Establishment (AWE). Also, Russia is maintaining a subcritical test program at its former test site at Novaya Zemlya, called '*hydrodynamic experiments*'. The official main objective is the same as in the U.S.: to test the performance of plutonium of various ages. The subcritical tests are aimed at verifying whether there is a possibility of prolonging the service time of nuclear

50 S. Drell (Chair)/F. Dyson/D. Eardley/R. Garwin/R. Jeanloz/R. LeLevier/W. Panofsky/R. Schwitters/S. Treiman, Subcritical Experiments (MITRE/JASON Report JSR-97-300), March 1997, www.fas.org/rlg/jsr97300.htm (last access on May 14, 2007).

51 The detection threshold depends on the seismic environment; it is of the order of 1 kt TNT.

52 Frank von Hippel/Suzanne Jones, Take a hard look at subcritical tests, in: The Bulletin of the Atomic Scientists, Vol. 52, No. 6, November/December 1996, pp. 44-47.

53 Rebecca Johnson, A Comprehensive Test Ban Treaty: Signed but not Sealed – a review of the CTBT Negotiations in the Conference on Disarmament January - September 1996, ACRONYM Report No 10, May 1997.

54 Annette Schaper, Sub-critical tests and the problem of transparency of a nuclear test ban, Paper presented to the 3rd Pugwash Workshop on "The Future of the Nuclear Weapon Complexes of Russia and the USA", Moscow, 24-26 March 1996. A year later, more information on subcritical tests has been provided by the publication of the MITRE/JASON report, see footnote 50. This renowned panel of trustable independent scientists also has certified that the experiments were indeed subcritical. Nevertheless, such a certification is not a replacement of international verification as the panel was composed exclusively of U.S. nationals.

warheads and thereby reducing expenses. When Russian activities were identified, the suspicion of small-scale nuclear tests was voiced immediately. Critics also raised the concern that the experiments serve the improvement and design of new nuclear weapon devices. [55]

In 1997, members of the prestigious JASON group reviewed two subcritical tests. In the unclassified version of their report,[56] they criticized the use of the Nevada Test Site instead of an above ground facility. Their arguments did not touch upon international policy. Instead, they stressed that many of the scientific questions about Pu can be studied in conventional static experiments, above-ground. Also, above-ground facilities offer considerable advantages for planning, design, logistics and costs. They also demanded that, in the future, the designers of the experiments specify the precise gaps of knowledge that the subcritical experiments are supposed to fill, and that are essential for retaining confidence in the safety, reliability, and performance of the enduring stockpile.

4.4 Warhead Ageing

A modern warhead consists of more than 6000 components, most of them located outside the ‘physics package’, i.e. outside the casing containing the fission primary and the fusion secondary.

Many of these non-nuclear components are standard off-the-shelf industry products with specified lifetimes: batteries, valves, electronics, adhesives, plastics and other organic materials. Of course, ageing information from the commercial sector usually does not take into account the special radiation environment within a nuclear weapon. Furthermore, complex interactions with other degrading weapon modules (high explosives, polymers, salts) can affect a component’s lifetime dramatically. Therefore, limited lifetime modules will be replaced or refurbished regularly in order to ensure continuous system performance throughout the weapon’s life cycle.

The three most important potential ageing effects in plutonium are the radioactive decay of the Pu isotopes, the thermodynamic stability of its crystalline structure, and its chemical corrosion.[57] HEU is far less radioactive than Pu, and therefore, similar problems do not occur with HEU warheads.

55 See on the Website of the Bellona Foundation: Thomas Nilsen, Russia performed three subcritical nuclear tests, August/September 2000, www.bellona.no/bellona.org/english_import_area/international/russia/nuke-weapons/nuke-test/17814 (last access on May 14, 2007); see also the publications of the Acronym Institute for a collection of all press releases on sub-critical experiments: www.acronym.org.uk (last access on May 14, 2007).

56 Drell et al., see above (footnote 50).

57 Siegfried S. Hecker/Joseph C. Martz, Plutonium Aging: From Mystery to Enigma, Mallinson (Kluwer Academic/Plenum Publishers), 2001, pp. 23-52.

Plutonium decays spontaneously into a helium (He) and uranium (U) nucleus, with a characteristic half-life for each isotope.[58] Both fission products (He and U) are ejected with high kinetic energy and will cause substantial local damage within the plutonium lattice.[59] Based on theoretical considerations, a single decay displaces approximately 2,400 atoms from their lattice site; 90% of these displaced atoms will return to their normal position after a relaxation time, but 10% will settle between regular positions on the lattice (interstitials), leaving the nominal lattice position empty (vacancy).[60] The accumulated effect of interstitials and vacancies on weapon performance is currently being investigated by the weapon labs.

Furthermore the He nuclei formed after a spontaneous Pu decay might roam through the lattice and eventually coalesce as small helium bubbles. 'This might result in the modest swelling of the material as well as changes in the mechanical properties of the plutonium.'[61]

A second concern is the thermodynamic phase stability of the δ-Pu alloy, which is used in nuclear weapons.[62] At room temperature, plutonium is stable in the so called α-phase; but by doping Pu with small alloying agents like gallium and aluminum, it is possible to stabilize δ-Pu at room temperature, which is otherwise only stable between 310°C and 450°C; δ-Pu has a lower density than α-Pu and a different crystalline structure. Although radiation damage resulting from decaying Pu nuclei might destabilize the δ-Pu and push it back into its α-phase, preliminary experimental results reveal that – on the contrary – the crystallinity of δ-Pu actually increases with age, i.e. the Pu pits – like good wine – improve with age.[63]

Finally, corrosion of Pu is potentially the most catastrophic of all ageing effects, but can be controlled by adapting modern cleaning and sealing methods, which limit the Pu exposition to corrosive agents like air (outside the Pu shell) or hydrogen (inside the Pu shell).[64]

58 For example the spontaneous decay of "weapon-grade" 239Pu into 4He and 235U occurs with a half-life of 24,100 years whereas the decay of the highly radioactive isotope 238Pu into 4He and 234U occurs with a half-life of only 88 years.

59 Pu metal has a crystalline structure, i.e. the atoms of solid Pu are arranged in a well-defined geometric order called the crystal lattice; the grid points of the lattice are thus the nominal positions of the Pu atoms.

60 Joseph C. Martz/Adam J. Schwartz, Plutonium: Aging Mechanisms and Weapon Pit Lifetime Assessment, in: JOM, September 2003, www.tms.org/pubs/journals/JOM/0309/Martz-0309.html, (last access on May 14, 2007).

61 Martz/Schwartz, ibid.

62 Pu can have six distinct solid-state phases: they are called the α-, β-, χ-, δ-, δ'- or ε-phase. Each phase can be observed in a specific temperature range and is characterized by a specific crystalline structure. Changes in temperature can therefore cause a phase transition from one crystal structure to another, resulting in a new spatial arrangement of the Pu atoms in the metal, and eventually an altered density of the material.

63 Jeanloz, see above (footnote 22).

64 Martz/Schwartz, see above (footnote 60).

The science-based surveillance program tries to detect ageing defects in time, to assess the impact of these defects on weapon performance, and formulate recommendations on when to replace a given module. These investigations can return to fully functioning tests of each module, since tests of non-nuclear components are not prohibited by the CTBT. Thus, aged modules can be tested as stand-alone units and together with other (aged) components outside the physics package.

Within the physics package, ageing might affect three subsystems: the high explosives (HE), the fissile core (Pu or HEU pit) and the secondary.

The chemical and physical decomposition of HE have been studied for many years by the material science divisions of the weapon labs with the aim of understanding both the molecular mechanism underlying the ageing process and its consequent changes in (macroscopic) properties. The preliminary results for the U.S. stockpile indicate that the ageing effects in the HE do not affect the performance of the primaries.[65] Even here, aged and young HE can be tested without breaching the CTBT through hydrodynamic tests: these explosive tests compress some non-nuclear surrogate material with similar mechanical properties as Pu. In order to evaluate the HE performance, the X-ray radiographic facilities mentioned above will provide successive images of the implosion of the mock primary. These images help determine the energy and symmetry of the implosion and also help to draw inferences on the quality of (aged) HE.

The fissile core is the most sensitive element within the physics package and its surveillance must be given highest priority. If its yield is inadequate because of undetected ageing defects, the secondary (main stage) will not ignite and the weapon will fail. The failure risk is higher for Pu than for their HEU pits due to the higher radioactivity of plutonium and its more complex material properties.

A statistical analysis of ageing defects carried out on the U.S. arsenal over the previous decades revealed that these defects accumulate by a rate of approximately 1% after a quarter of a century.[66] This preliminary result justifies the current trend to keep the weapons in the arsenal for 2-3 decades and then replace them with newer systems.

But over decades defects within a Pu pit can grow in a non-linear fashion: they can accumulate up to a critical threshold without affecting the performance of a plutonium pit and then instantaneously lead to a complete weapon failure. The task of the weapon scientists is to determine from which point the ageing defects in the Pu pits might lead to performance failures of the system. Most recent results indicate that this incubation time may be up to a century![67]

65 Sidney Drell/Raymond Jeanloz, Signatures of Aging, in: JASON Report JSR-97-320, January 1998, www.fas.org/irp/agency/dod/jason/aging.pdf (last access on May 14, 2007).

66 Jeanloz, see above (footnote 22).

67 Russell J. Hemley/Dan Meiron, Pit Lifetime, JASON Report JSR-06-335, January 2007, www.fas.org/irp/agency/dod/jason/pit.pdf (last access on May 14, 2007).

Reliable statements that address the issue of plutonium ageing require an effective interplay between experimental and theoretical tools. Since existing Pu pits are only a few decades old, accelerated ageing experiments allow faster extrapolations for the future. Still, artificially aged Pu might not be identical to naturally aged Pu.

Fully-fledged tests to assess the performance of aged Pu are not admissible under a CTBT regime anymore, but subcritical tests might still be carried out. Additionally, large-scale molecular dynamics codes will attempt to simulate the effect of shock compression of aged Pu on the supercomputing platforms.

So far, accelerated ageing experiments, subcritical tests and simulations on supercomputers conclude that with respect to Pu, ageing nuclear weapons are safe and reliable for at least 100 years.

No substantial ageing defects were found on secondaries if all its components are as specified: 'provided sufficient radiative energy is delivered from the primary to the secondary, the performance of the fusion secondary can be guaranteed with high confidence.'[68]

4.5 Supercomputing

Experiments create data on partial technical aspects, while nuclear tests offer the possibility of obtaining a picture of the overall nuclear weapon performance, and draw conclusions on how partial technical aspects interfere with each other and influence that performance. An example of such phenomena is the mixing of material from primary and secondary. Many processes within a nuclear weapon explosion are very complex and non-linear, and isolated experiments or analytical theories are not sufficient to cover them. This void must be filled with computer simulations.

In principle, a computer simulation models all phenomena of a nuclear explosion by using 'Monte-Carlo methods'. The bases of these methods are computer generated random values in large numbers, with which individual processes are calculated. For example, in the simulation of a nuclear chain reaction in a plutonium assembly, a starting neutron is assigned a random velocity. The computer calculates the flight time and the path of the neutron until it hits the Pu nucleus. The result of the interaction with the nucleus can be fission, with the release of some new neutrons that have different velocities, ionization, and the release of energy and photons or another nuclear reaction. The computer assigns random results according to the known random distributions of the processes, and calculates the resulting physical values. It then repeats the same kind of calculation with the new neutrons. A weapon is divided into a large number of volumes, and the physical properties are calculated in small steps, e.g. the temperature, density, pressure of each one, as well as the mass and energy flows between them,

68 Drell/Jeanloz, see above (footnote 65).

Two factors influence the value of computer simulations: Firstly, the higher the number of calculations, the more precise and realistic the results. Because of the limitations of computer power, the number of calculated processes is much smaller than the number of processes that take place in reality. Therefore, a prerequisite is computer power that is as large as possible. Secondly, the random distributions that are used for assigning values, and the formulas and parameters that describe the fundamental processes that are used in a simulation must be understood as precisely as possible. An example is the absorption and reemission of photons in hot and dense plutonium plasma. The input of experimental data obtained during experiments with conditions comparable to those in a nuclear explosion is needed, e.g. previous nuclear tests and ICF. Without such input, it will remain unclear how reliable the results are. A state that has never pursued nuclear tests will not be able to achieve the same degree of confidence, even when it has access to enormous computational power.

Until some years ago, simulation was only two-dimensional, but because of the development of computer technology, the U.S. has started with three-dimensional simulations. This is only possible with the newest and highest performing computers. The first three-dimensional simulation of a nuclear explosion ran for nearly 3,000 hours.[69]

Computer simulations are the main tools used when interpreting experimental results and when studying ageing effects. For example, in a simulation, a changed crystalline structure that is typical for ageing effects is assumed. Running the simulation indicates what effects might be expected. The goal is to use them for certification of weapon safety, reliability and performance, and to provide 'virtual prototyping capabilities', 'renewal-process analyses,' and accident analyses.[69] The latter means 'to predict with high certainty the behavior of full weapon systems in complex accident scenarios'.[70]

In U.S. discussions, it is claimed that assessing the safety and performance of the stockpile will require computational power 100,000 times greater than what was needed to design new weapons.[69] There are also claims of urgency because nuclear weapon experts, who are needed to validate new simulations, are coming up for retirement.

The U.S. DoE launched the '*Advanced Simulation and Computing Program* (ASCI)' in 1995. In the U.S., there is 'more supercomputing power than at any other scientific computing facilities in the world.'[69] Since then, a series of ever more powerful machines are being delivered to both LANL and LLNL, each of them breaking world records in performance.[71]

69 Los Alamos National Laboratory, Public Affairs Office, High-Performance Computing for National Security, www.lanl.gov/news/pdf/HighPerf_Computing.pdf (last access on May 14, 2007).

70 JASON/MITRE Corporation, Requirements for ASCI (JASON Report JSR-03-330), October 2003, www.fas.org/irp/agency/dod/jason/asci.pdf (last access on May 14, 2007).

71 Lawrence Livermore National Laboratory, News Release: World's fastest supercomputers dedicated at Livermore Lab, October 27, 2005, www.llnl.gov/PAO/news/news_releases/2005/NR-05-10-06.html (last access on May 14, 2007).

France installed the supercomputer TERA-10 in the centre at Bruyères-le-Châtel in December 2005, There are plans to gradually increase their performance over the next years.[72] By 2010, it is intended that performance will be 10,000 times of that in 1996.[73]

Similarly, in Aldermaston, Britain is installing new supercomputers that are able to run 3-dimensional simulations.[74] In addition, due to the U.S.-UK nuclear weapons collaboration, Britain has access to U.S. simulation results.[75]

At the moment, Russia and China cannot afford supercomputers of comparable performance.

5. Ten years after SBSS launch: striking the balance

The Science Based Stockpile Stewardship (SSBS) programs were launched a decade ago, after the conclusion of the CTBT negotiations. Their scientific aspirations are far-reaching, but their immediate goal was more focused: to maintain the nuclear complex without returning to tests. This preservation program encompasses the ability to design, manufacture, monitor, refurbish and dispose of nuclear weapons. To meet these goals, some of the tools described in the previous chapter are deemed indispensable.

But ten years after its launch, did the SBSS keep its promise and move towards a self-sustained nuclear infrastructure? Are weapons of today as safe and reliable as they used to be, and can they be remanufactured as their predecessors? And do the science programs really support this transformation and allow weapons certification without tests? These questions were answered quite controversially in the scientific and political arena and some aspects of the debate shall be discussed here.

5.1 SBSS: A success story?

'I am pleased to say that the Stockpile Stewardship Program has been an amazing success. It has confirmed the U.S. ability to sustain our enduring nuclear weapons stockpile based

72 Guideinformatique.com, HPC: enjeux stratégiques en France et en Europe, www.guideinformatique.com/fiche-hpc_enjeux_strategiques-754.html (last access on May 14, 2007).

73 Ministère de la Défense, Direction des Applications Militaires, Point de situation sur le programme de simulation, in: Dossier de presse, 26 January 2006, www.defense.gouv.fr/defense/content/download/43036/430272/file/cea_point_de_situation_sur_le_programme_de_simulation_cea.pdf (last access on May 14, 2007).

74 Stephen Shankland, Cray wins British nuclear weapons deal, in: CNET News.com, January 25, 2006, http://news.com.com/Cray+wins+British+nuclear+weapons+deal/2110-1006_3-6031163.html (last access on May 14, 2007).

75 Nigel Chamberlain/Nicola Butler/Dave Andrews, U.S.-UK nuclear weapons collaboration under the Mutual Defence Agreement: Shining a torch on the darker recesses of the 'special relationship', in: BASIC Special Report 2004.3, June 2004, www.basicint.org/nuclear/MDAReport.pdf (last access on May 14, 2007).

on a scientific approach.' This is how Raymond Jeanloz, a leading consultant of the JASON Defense Advisory Group, drew the balance after ten years of SBSS.[76]

The success of the program – according to Jeanloz – comes from three major achievements:

- The capacity to manufacture 'certifiable' plutonium pits after the closure of the Rocky Flats plant.[77]
- The life-extension-program (LEP), which examined and refurbished the W87 (ICBM) and the B61 (gravity bomb), and returned them to the arsenal for another tour of duty.
- The thorough investigation of ageing effects, which – according to a very recent study – allows most Pu pits to be retained in the arsenal for at least a century.

Jeanloz's euphoric account was slightly dampened by former LANL director, Siegfried Hecker, who still maintains that further investigations on plutonium ageing are necessary to confirm that warheads are indeed stable for such a long time.[78]

It is therefore too early – according to Hecker – to draw these conclusions from the actual ageing experiments, which – although very encouraging – might not mirror the exact process of the ageing of future plutonium pits. Hecker presents several arguments:

- The investigated Pu pits stem from the Rocky flats plant in Colorado. Their crystalline structure differs from the new pits, which will start to roll off the line at Los Alamos' Technical Area 55 (TA-55) in the future. TA-55 uses a more sophisticated manufacturing technique than Rocky Flats and yields a product that is more uniform in its microscopic texture and – at the same time – produces less hazardous waste streams. Since these new pits have never been tested, statements about their reliability and longevity should be extrapolated with maximum caution.
- The accelerated ageing experiments – where weapon-grade plutonium (mainly ^{239}Pu) is spiked with the highly radioactive ^{238}Pu – only partially resemble its actual ageing process: these experiments simulate the local radiation damage caused by the radioactive decay of Pu quite accurately, but can only approximate the subsequent diffusion of that damage, and therefore only allow tentative conjectures on pit life-times.

76 Raymond Jeanloz, Prepared Remarks for the 2006 Arms Control Association Annual Meeting, Washington, January 2006, www.armscontrol.org/pdf/20060125_Jeanloz.pdf (last access on May 14, 2007).

77 The Cold War plutonium pits were manufactured in Rocky Flats, Colorado. The plant was shut down in 1989 due to blatant violations against environmental legislation, leaving the U.S. without a proper pit production facility for more than a decade. The ability to manufacture Pu pits was brought back in 2003 in Los Alamos Technical Area 55 (TA-55), though with a different production procedure.

78 An excellent account of the Jeanloz-Hecker controversy on plutonium aging can be found in Haninah Levine's online article: Haninah Levine, Dazed and Confused by RRW, July/August 2006, www.defensetech.org/archives/002629.html (last access on May 14, 2007).

- Plutonium is an element 'at odds with itself',[79] displaying highly complex behavior when critical state parameters change. Theoretical models and experimental simulations will only capture some aspects of this complexity; therefore crude extrapolations derived from these models might lead to imprudent conclusions.

As a result, Hecker's recommendation is to replace current pits every 50 years, and to keep a conservative replacement rate of half a century for the future, until all ageing effects are thoroughly understood. Thus, the proposal emphasizes the importance of basic and applied science within the SBSS program as a means to maintain confidence in the ageing stockpile.

5.2 Life extension, replacement warheads or full-scale testing?

The current SBSS programs are based on three pillars: science, surveillance and life extension. The immediate goal of the science program was to support surveillance and life extension, thus allowing the nuclear complexes to retain their assets from the Cold War well into the 21st century.

Still, France and Britain do not seem to rely on the potential of these life-extension programs (LEP), but instead, are paving the way for substantial warhead modernization. Having signed and ratified the CTBT, we can assume that these new warheads will be certified without nuclear testing and their safety and reliability guaranteed exclusively by the British and French science-programs: thus, 'virtual testing' on the computer and subcritical experiments should provide sufficient confidence in the new assets.

But will the military accept untested new hardware?

At the same time, even the LEP is not uncontested. Although maintenance and refurbishment of ageing warheads relies on original materials and manufacturing processes, this approach is not always viable, as some components may no longer be available; but increased use of non-original replacement units, i.e. the accretion of minor changes, could also erode the confidence in weapons' performance in the long run.

In the U.S., this dilemma leads to a lively discussion on how to maintain or transform the nuclear arsenal in the 21st century in such a way that it remains safe and reliable. Three major strategies could be identified in this debate:

- Replacement with more conservative designs: the RRW proposal
- Life-Extension of existing warheads: the LEP proposal
- Resume Tests and abandon SBSS: still a minority proposal

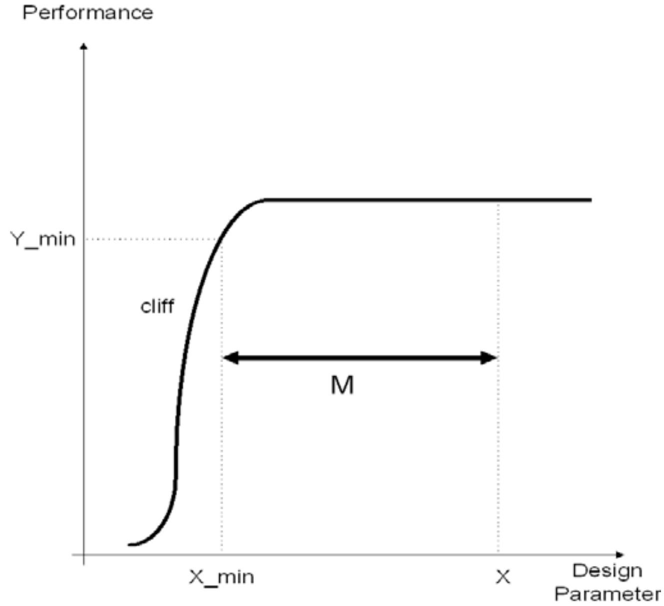
The RRW and LEP proposals are discussed within the framework of SBSS and do not foresee nuclear testing, whereas the last proposal implies the cancellation of both the CTBT and the SBSS, and to do 'business as usual'.

79 Anonymous, Plutonium: An Element at odds with itself, in: Los Alamos Science, No. 26, 2000, pp. 16-23.

5.3 Reliable Replacement Warhead (RRW)

Proponents of the RRW proposal emphasize the alleged unsustainability of the LEP in the long run and campaign for more conservative designs that have improved reliability and safety.[80] These new replacement warheads should be based on existing designs, but feature increased performance margins: this would allow them to be certified without returning to nuclear testing.

The performance margin is illustrated in the figure below. For a given parameter, a minimum value (X_min) is required for a warhead to operate; below this value, the weapon is assumed to fail. The performance margin M is the difference between the design parameter X and that minimum.



Current U.S. warheads have rather tight (small) performance margins: they were designed in the 1980s, where miniaturization of the warhead and maximization of its yield to weight ratio was emphasized; they operated close to the ‘performance cliff’, but extensive test series made sure that the weapon always performed above the critical threshold throughout its life-cycle.

RRWs will be based on increased performance margins and will use design parameters that are further away from the cliff in order to guard against parameter fluctuations, which can be caused by material degradation, or manufacturing defects. Thus, the RRW should be less sensitive to ageing than the incumbent warheads. As a result, this would

80 See for example the Joint Statement of the three U.S. weapon labs: K. Henry O’Brien (LLNL)/Brian L. Fearey (LANL)/Michael J. Sjulin (SNL)/Greg A. Thomas (SNL), Sustaining the Nuclear Enterprise – A New Approach, May 2005. www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/facilities/TriLab-SSP-2005.pdf (last access May 14, 2007).

reduce the number of non-deployed warheads that are kept in hot stand-by for possible unexpected failure of the deployed RRW weaponry.

The RRW concept, nonetheless, does not foresee the design of completely new warheads for new missions such as ‘mini-nukes’ or ‘bunker-busters’, but rather the replacement of the current arsenal with – allegedly – more stable clones. Furthermore, the new warheads should stay within design parameters of past nuclear tests. This would allow easy certification of RRW without recurring to nuclear tests.

RRW supporters stress that by replacing the existing warheads, a number of additional features could be accommodated in the new designs:[81]

- Improved safety and control measures could minimize the risk of unintended or unauthorized detonation of the warhead; these barriers would make nuclear weapons useless for terrorists. As a consequence, external physical security at weapon storage sites could be lessened.
- Increased modularity of the new designs would ease manufacturing and routine maintenance, allowing easier assembly and disassembly of the single components of a weapon.
- Finally, the usage of less hazardous materials would reduce the environmental burden as well as the radiation exposure of the workforce engaged in manufacturing and maintaining the RRWs.

The cumulative effect of all of these features – RRW supporters claim – is a net cost reduction over the long term.

5.4 Life Extension Program (LEP)

LEP supporters and RRW critics, on the other hand, do not buy the claims mentioned above and challenge the RRW vision on every single issue.

The primary performance margins could easily be increased on existing weapons by changing the composition of the tritium boost gas or by replacing it more frequently: this gas boosts the primary, but decays radioactively at a rate of approximately 5% per year. Frequent tritium replenishments would make sure that the primary yield was always well above the minimum threshold needed to drive the secondary. Thus, a standard maintenance routine could increase the performance margin of a weapon and therefore increase its reliability.[82]

81 Jonathan Medalia, Nuclear Warheads: The Reliable Replacement Warhead Program and the Life Extension Program, in: CRS Report for Congress, Februar 2007, www.fas.org/sgp/crs/nuke/RL32929.pdf (last access May 14, 2007).

82 Robert Nelson, Improving Warhead Reliability: Boosting the Boost Gas, in: Arms Control Today, Vol. 36, No. 3, April 2006, p. 20.

Weapons undergoing the LEP have a test pedigree (at least seven per warhead) that makes them more reliable than RRW, which are new designs and therefore have never been tested. Therefore, LEP supporters claim that the introduction of RRWs would inevitably lead to new demands for nuclear testing by the U.S. weapon labs, and, as a result, could seriously undermine the global test moratorium.

Finally, ongoing research on warhead ageing shows very encouraging results, which speak in favor of a conservative LEP[83] rather than a risky and costly RRW program. And the LEP is working: two warheads have already successfully completed the life extension program (the W87 ICBM and the B61 gravity bomb) and were returned to the arsenal for another 30 years. And the LEP of the W76, the most common U.S. warhead, is currently under way.[84]

Furthermore, although the claims of softer environmental impact, increased safety and ease of manufacture for RRW may be valid, it is highly disputable how these features would translate into a net cost reduction in the long run: as a matter of fact, no cost projection exists nowadays that compares the stockpile maintenance under LEP with the stockpile transformation with RRWs. Thus, claims of higher cost-efficiency for the RRW program seem premature at this stage.

As of today, it is not clear which option will prevail in the U.S. and how the enduring stockpile will evolve over future decades.

In 2006, the Californian and the New Mexico weapon labs carried out two competing RRW design studies (replacements of the W76 and W88 SLBM). The former contracting party (i.e. Livermore and the Californian branch of Sandia) was granted a follow-up assignment for another eight to twelve months. During this time, Livermore will work with the Navy on first design specifications of the so-called RRW-1.[85] After this preliminary study, Congress would have to authorize any subsequent activity. The LEP option was clearly boosted by the very recent JASON study on warhead ageing, pending Congress' decision on further RRW R&D.

In the meantime, Britain opted for a replacement program of its Trident SLBM with a new system that is yet to be developed.[86] Critics claim that this decision was taken too hastily and that the life-extension potential of the existing submarines was not sufficiently

83 Hemley/Meiron, see above (footnote 67).

84 Jeanloz, see above (footnote 22).

85 Andrew Koch, Livermore wins warhead design contest, in: Jane's Defence Weekly, Vol. 44, Issue 11, March 14, 2007, p. 9.

86 The new system consists of new submarines, equipped with U.S. made Trident missiles, which will be tipped with British AWE warheads. The latter will stem from the British LEP or the RRW program. The decision to replace Trident was laid out in a government White Paper called "The Future of the United Kingdom's Nuclear Deterrent", December 2006, www.mod.uk/NR/rdonlyres/AC00DD79-76D6-4FE3-91A1-6A56B03C092F/0/DefenceWhitePaper2006_Cm6994.pdf (last access on May 14, 2007).

considered.[87] Although the British Government has not yet decided whether it would prefer to rely on life-extended or replacement warheads, there are clear signs that indicate that the latter might be favored:[88] according to the Sunday Times, work on RRWs is well advanced at Aldermaston's weapon labs and the British designs 'are now ahead of the Americans'.[89]

Also, France announced it would deploy new nuclear warheads soon; still, there does not seem to be an open French debate that would challenge this decision and would plead for an alternative strategy, e.g. life-extension of the current assets. The new warheads should replace the current TN-75 (TN stands for thermonucléaire)[90] and will be based on a similar design philosophy as the RRW. They should exploit the results of the last French test series in 1996 and deliver 'robust charges' with respect to technological variations in the original design, i.e. non-original replacement of components, as well as with respect to ageing effects.[91]

5.5 Resume Testing and Abort the SBSS

A third option would be to cancel both RRW and LEP and resume fully-fledged nuclear testing. Supporters of this approach doubt that the science-based approach of the Stockpile Stewardship programs will be able to maintain the nuclear weapons complex in a sustainable manner.

They also maintain that warhead certification using the SBSS toolkit has been a political assessment rather than a technical one. This is due to the fact that SBSS programs were launched after the test moratoria, and the SBSS tools were never validated with classical underground nuclear tests. Thus, some reservations remain on their actual efficiency.

In that sense, in 1997 Siegfried Hecker stated in a Senate Hearing, 'Of course, if nuclear testing were allowed, we would gain greater confidence in the new tools. We could vali-

87 Richard L. Garwin/Philip E. Coyle/Theodore A. Postol/Frank von Hippel, Comment on The Future of the United Kingdom's Future Deterrent, White Paper presented to Parliament by the Secretary of State for Defence and the Secretary of State for Foreign and Commonwealth Affairs, December 4, 2006, www.publications.parliament.uk/pa/cm200607/cmselect/cmdfence/ucsnd2/snd354.pdf (last access on May 14, 2007).

88 The British warhead strongly resembles the U.S. W76, which is currently both in the US LEP and RRW program. Since the U.S. and the UK cooperate extensively in nuclear weapon research British scientists can have access to critical US RRW data, which they can immediately translate, for their own RRW program.

89 Michael Smith, Revealed: UK develops secret nuclear warhead, in: Times Online, March 12, 2006, www. timesonline.co.uk/tol/news/uk/article740215.ece (last access on May 14, 2007).

90 Joachim Hoelgen, Chirac stärkt sein nukleares Schreckgespenst, in: Spiegel Online, November 26, 2006, www.spiegel.de/wissenschaft/mensch/0,1518,450632,00.html (last access on May 14, 2007).

91 Serge Vincon/Henri Bentegeat/Daniel Verwaerde/Sir Michael Quinlan/Bruno Tertrais, Dissuasion nucléaire francaise, in: Revue Défense Nationale, No. 7, 2006, www.defnat.com/pdf/vin%E7on.pdf (last access on May 14, 2007).

date these tools more readily… One or two tests per year would serve such a function quite well. Yields of 10 kt would be sufficient in most cases. Yields of 1 kt would be of substantial help.'[92]

Some critics go even further and warn against the atrophization of critical skills within the weapon complexes, which could lead to a total collapse of design, engineering and manufacturing resources within a few decades.[93] The only remedy would be to recall the CTBT, resume full-scale testing and do business as usual. For these critics the scientific elements of SBSS are not enough to sustain the nuclear complexes indefinitely.

This radical critique is still a minority position within the U.S. debate though, and has less specific weight than the SBSS based (test-free) proposals, RRW and LEP. Its low popularity is due to the fact that there is widespread consensus that reversing the test moratorium would make the geostrategic position of the U.S. worse, since other NWS would follow suit and could catch up in the nuclear arms race.[94]

5.6 Criticism of the SBSS

Ray Kidder, a leading weapon scientist of LLNL for 35 years, addressed a number of problems with the SBSS right at the start of the program.[95]

First, the prolonged absence of testing might indeed jeopardize reliability (though not safety) of nuclear weapons, but for slightly different reasons than discussed earlier: in Kidder's words, 'first-rate scientists will seek challenging, innovative work that can be developed, tested and published; they certainly prefer this to the work of maintaining a moribund nuclear stockpile whose details must remain secret.' The brain-drain therefore seems inevitable, but may not necessarily lead to a collapse of the nuclear complexes in the next decades. In that respect, Kidder advocated a one-off modification of the warheads at the launch of SBSS to achieve ease of remanufacture for the future, and then to leave the designs unchanged. These modifications could still be performed by experienced 'first-class' weapon designers, which then could hand over a reliable and easily-maintained product to their successors, who would be engineers rather than scientists.[96] RRW supporters are picking up this proposal 10 years later, at a time when most senior researchers are retiring, and the erosion of nuclear weapon skills is well under way.

92 Siegfried Hecker, "Answer to Senator Kyl's questions", in: Safety and Reliability of the U.S. nuclear deterrent, Hearing before the Subcommittee on International Security, Proliferation and Federal services, October 1997, p. 83.

93 James J. Wirtz, Do U.S. Nuclear Weapons Have a Future?, in: Strategic Insights, Vol. V, Issue 3, March 2006, www.ccc.nps.navy.mil/si/2006/Mar/wirtzMar06.asp (last access May 14, 2007).

94 A collapse of the test ban would allow China to resume work on warhead miniaturization and eventually to deploy multiple warheads on a single missile (MIRV); China could then close the gap with the "MIRV-Club" consisting of the U.S., Russia, France and the UK.

95 Ray Kidder, Problems with stockpile stewardship, in: Nature Vol. 386, April 1997, pp. 645-647.

96 Their situation may be compared to that of operators of well tested nuclear reactors.

Second, many facilities of the SBSS are costly and unnecessary for weapon maintenance: they will also fail to attract first-class physicists, as their mission is ambiguous and scientists prefer work that is 'going somewhere' to generic assignments on Big Science projects with an unclear focus.

The main criticism in this respect regards the ICF facilities in the U.S., France and the UK, which are currently under construction: apart from an astronomical cost explosion that accompanies their build-up,[97] their contribution to maintaining the nuclear stockpile is marginal and their scope within the SBSS is blurred. A frequent misconception is that ICF facilities mimic the physics of secondaries and can contribute to the enhancement of the design skills of the next generation weapon scientists. Certainly between the thermonuclear microexplosions within an ICF vessel and a nuclear weapon explosion, 'some of the physics is the same; but the details, "wherein the devil lies", are quite different.'[98]

Furthermore, it is questionable whether the ICF facilities will work as designed and deliver what they promise, i.e. thermonuclear microexplosions followed by a self-sustained fusion burn: there are reservations as to whether the high-power lasers can meet their specifications; and even if the lasers operate perfectly, there is serious disagreement on whether the fusion targets can reach ignition at all, since the physics of laser-target interaction is poorly understood. This induced Stephen Bodner, the former head of the laser fusion program at the U.S. Naval research Lab, to risk the prediction that ignition will fail in the NIF, potentially transforming it into a billion dollar grave.[99]

In order to legitimize the exorbitant costs of their ICF facilities and supercomputers, the weapon labs will enhance their cooperation with the academic world and bring together the weapons and the unclassified community, including scientists from abroad. Thus, scientists from the weapon labs and the academic world will rub elbows, share facilities and engage in scientific debates on technical issues that were traditionally classified. There are critics, from both inside and outside the weapon labs, who claim that as a consequence, sensitive information on weapon physics will diffuse from the classified to the unclassified world and will heighten the risks of proliferation considerably.[100] Asked about the planned experiments at the NIF, Dr. David Crandall from the U.S. Department of Energy (DoE) answered that, 'while perhaps 80 percent of the work will be unclassified, 80 percent is also likely to have some relevance to weapons.'

It must be noted, however, that the contributions of ICF-experiments to would-be proliferators are marginal: they mainly deliver a few state parameters of the hot and dense

97 The estimated costs of the U.S. facility, the NIF, mushroomed from $400 million in 1990 to more than $4 billion within a decade. See Stephen Bodner/Christopher Paine, When Peer Review Fails: Problems with a Giant Laser Project, in: Nature, Vol. 407, September 2000, pp. 129-131.

98 Kidder, see above (footnote 95).

99 Bodner/Paine, see above (footnote 97).

100 Christopher E. Paine/Matthew G. McKinzie, Does the U.S. Science-Based Stockpile Stewardship Program Pose a Proliferation Risk?, in: Science and Global Security, Vol. 7, 1998, pp. 151-193.

plasma, which could be used in computer simulations. These parameters are of no use for beginner states that start in a new nuclear weapon program.

Some of the physics of ICF ignition and the ignition of the secondary of a thermonuclear weapon is indeed similar, at least on a general level. However, it was declassified early in the 90's, because international researchers discovered these similarities independently from the weapon labs and published them.[101] Academic involvement in the new ICF-facilities is therefore less dramatic than it might appear at first glance. On the contrary, civilian projects might have the potential for future conversion.

It is unlikely that researchers from states that are currently interested in advancing their understanding of secondary ignition, e. g. India and Pakistan, will learn much that is beyond their understanding anyway.

Thirdly, these unnecessary and costly facilities might raise doubts in other nations and undermine current arms control efforts. During the CTBT negotiations already, both weaker NWS (like India and Pakistan) and NNWS (like Indonesia), as well as numerous NGOs, voiced their discontent about these ambivalent aspects of the SBSS programs, which would give the leading NWS the opportunity to advance their nuclear programs at the expense of others. Still, they did not succeed in negotiating a stricter scope, which would ban parts of these activities under a comprehensive test ban treaty.

But even the current 'lax' test ban regime (which does not prohibit subcritical testing, microexplosions of fusion targets, and virtual, computer-based weapon tests) might collapse if the nuclear complexes push their stockpile transformation plans too hard. An all-RRW-arsenal, as envisioned by parts of the nuclear weapon complexes,[102] would inevitably come under pressure in the long run. It would have be ensured by some form of testing, and would thereby bury the efforts for a global CTBT.

Finally, the argument of the (allegedly) eroding safety and reliability of the stockpiles, which the weapon labs repeat like a mantra, was itself questioned and with it, the necessity of an 'oversized' program like SBSS. Historical data on defects found in the U.S. nuclear arsenal, for example, does not back the current paranoia on safety and reliability voiced by the nuclear establishments.

Historically, most safety problems were caused by design or production errors and were detected and corrected during the first years of service of a weapon. At the moment, current warheads were manufactured more than a decade ago and have been monitored by an aggressive surveillance program since then. Thus, the sudden emergence of massive safety problems seems unlikely. Furthermore, the very few safety problems, which were

101 Annette Schaper, Arms Control at the Stage of Research and Development? – The Case of Inertial Confinement Fusion, in: Science & Global Security, Vol. 2, 1991, pp. 1-22.

102 See for example Office of the Deputy Assistant to the Secretary of Defence for Nuclear Matters, Stockpile Transformation, 2005, www.acq.osd.mil/ncbdp/nm/stockpiletransformation.html (last access on May 14, 2007).

caused by the ageing of the warhead, never involved the physics package, but only (easily replaceable) non-nuclear components.

Ageing, nevertheless, can affect the reliability of a weapon: but what is the average impact of an ageing defect on reliability? Even here statistics are clear: in more than 90 percent of documented reliability problems in the U.S. stockpile, the performance of a weapon was reduced by less than 10 percent from its nominal value. But since the design yield of a warhead assumedly has a tolerance of 10 percent (i.e. a design yield of 100kt, will most probably deliver something between 90kt and 110kt), we can conclude that a warhead with reliability defects will perform as expected with a probability of more than 90 percent.[103]

Furthermore, military planners are more interested in the overall ('stockpile-to-target') performance of their ballistic arsenal[104] than in the reliability of the corresponding nuclear warheads. Since the reliability of the nuclear warheads is significantly higher than the reliability of their delivery systems,[105] the latter have a stronger specific importance in determining the performance (i.e. the statistical damage expectancy) of nuclear missiles.

Therefore, if the performance of a nuclear tipped ballistic missile is to be increased, it makes sense to improve the weakest link in the stockpile-to-target chain, i.e. the missiles. For example, a rational strategy to improve the performance of a nuclear missile should be to address its accuracy rather than the detonation probability of its nuclear payload.

For this probability is already very high, as the U.S. National Academy of Science (NAS) already pointed out in 2002: warhead reliability can reach 100 percent, if the firing, neutron generator and boost gas subsystem function as specified.[106]

But would 90 percent warhead reliability really jeopardize the nuclear deterrent of a NWS armed with hundreds (UK, France) or thousands (U.S., Russia) of these warheads? If the nuclear doctrines were strictly centered on deterrence, the NWS could still threaten massive retaliation in a credible manner. Only offensive nuclear postures require warheads with highest reliability as every warhead is assigned to a given target, which it would have to eliminate in a pre-emptive first strike.

To summarize, the arguments put forward on safety and reliability are often used in an instrumental and ideological manner in the SBSS debate. While parts of the nuclear complexes emphasize the danger of an (apparently) degrading and unsustainable arsenal in a

103 Stephen I. Schwartz, Defining reliable, in: Bulletin of the Atomic Scientists, Vol. 57, No. 2, March/April 2001, pp. 55-56.

104 Successful performance is defined as detonation at the desired yield and within the desired CEP. The CEP (circular error probability) measures the weapon's precision by specifying a circle (radius) within which 50 percent of all missiles will impact.

105 Robert Nelson, What Does Reliability Mean? Robert Nelson, If it Ain't Broke: The Already Reliable U.S. Nuclear Arsenal, Arms Control Today, Vol. 36, No. 3, April 2006, pp. 18-24.

106 National Academy of Science, Technical Issues Related to the Comprehensive Test Ban Treaty, 2002, p. 25, www.fas.org/sgp/crs/nuke/RL33548.pdf (last access on May 14, 2007).

clear attempt to advance their vested interests and guarantee continuity in funding, independent peer reviews and arms control experts do not accept this alarmism, and stress that the current nuclear arsenals are safe and reliable and will remain so for future decades if standard maintenance routines are performed.

These critics suggest that the SBSS programs could be downsized to curatorship; that the program on replacement warheads could be cancelled; and the idea of a nuclear complex transformation postponed for decades.

6. Conclusion

The Science Programs of weapon labs in the U.S. ('Science Based Stockpile Stewardship'), the UK ('Warhead Science Program') and France ('Simulation') are costly, ambivalent and risky: they accompany the nuclear weapon modernization programs and implicitly undermine the spirit of the NPT (to disarm) and the CTBT (to curb *vertical* proliferation).

Some people claim that at the same time, the alliance programs established between the weapon labs and the academic world in the U.S., the UK and France also pose an unpredictable risk of *horizontal* proliferation as they mix classified and unclassified communities, who might spread critical knowledge to would-be-proliferators.[107] The impact of this effect is, however, unclear.

Undoubtedly, the blurred focus of some of the weapon lab activities will raise suspicion in NNWS, increase misperceptions and give rise to highly speculative conjectures in the long run.

This is particularly alarming in light of the current nuclear crises, which involve the UK and France (together with Germany) as interlocutors with Iran, as well as the U.S. who are trying to discontinue the North Korean nuclear weapon program within the 'Six-Party-Talks'.

In this context, SBSS and RRW weaken the credibility of the Western nuclear powers in their non-proliferation efforts, as these programs are based on a rather controversial interpretation of both the CTBT and the NPT. They push the limits of what should be allowed under a comprehensive test ban to a point that is close to a material breach of the treaty, and they might transform the nuclear stockpiles (irreversibly) in such a way that the resumption of testing becomes unavoidable.

As for the NPT, there are serious concerns about Article I and VI associated with the SBSS/RRW programs. Article I prohibits a NWS from assisting any other country 'directly or indirectly' in its weapon program. This demand is clearly undermined by the renewed

107 Katz, see above (footnote 16), Paine/McKinzie, see above (footnote 100).

British-American Mutual Defence Agreement (MDA),[108] which foresees extensive cooperation between Aldermaston and the U.S. weapon labs on warhead science and development as well as joint (subcritical) experiments at the Nevada test site. As to Article VI, it should be highlighted once again that the wording of the Treaty speaks about *elimination*, not *reduction* of the nuclear arsenals, whereas the nuclear complexes – if at all – envision only some minor cuts in their non-deployed weaponry in exchange of their modernization / transformation to RRW.

Immediate action and creative thinking is needed to avoid further erosion of the non-proliferation treaty, as weapon modernization programs are well under way in the three countries of concern. On 1 March 2007, the U.S. National Nuclear Security Administration (NNSA) announced its plan to continue its RRW plans after selecting the LLNL proposal in the design contest between Lawrence Livermore (LLNL) and Los Alamos National Laboratory (LANL). The decision to replace the Trident based SLBM fleet in the UK was announced in the subsequent week, and the advanced British RRW program already suggests which option the Labour government favors on the future of British warheads. As for France, the modernization program of their nuclear platforms, missiles and warheads is a done deal.

Obviously, restoring the credibility of the global non-proliferation regime is mainly in the hands of the NWS, especially regarding the three Western countries who have been prophesising and enforcing these norms worldwide. Western NNWS, such as Italy and Germany (the home countries of the authors of this report), will play only an indirect role as members of NATO, EU and the Western Group within the Conference on Disarmament (CD). Still, their substantial specific authority within these organizations can contribute to realigning the global non-proliferation norms in the following issues:

- Ratification of the CTBT by the U.S.
- Abandonment of RRW or any other warhead modernization program
- Marginalization of nuclear weapons

American ratification of the CTBT is long overdue, after more than a decade negotiating. It could convince China and the remaining key parties to ratify the treaty as well, and finally allow its effective entry into force. Furthermore, it could recognize the excellent work of the CTBTO, which already certified a substantial part of the global International Monitoring System (IMS) – the world's largest network of seismic, radionuclide, infrasound and hydroacoustic stations. Although the CTBT – as we have seen – might still give some leeway for nuclear force modernization, its formal ratification by the U.S. would

108 The MDA – first signed in 1958 – was renewed in 2004 for another decade. According to Matrix Chambers, a British association of independent lawyers founded by Cherie Booth (Tony Blair's wife), "it is strongly arguable that the renewal of the MDA is in breach of the non-proliferation treaty." See Rebecca Johnson/Nicola Butler/Stephen Pullinger, Worse than Irrelevant? British Nuclear Weapons in the 21st Century, in: Acronym Institute for Disarmament Diplomacy, November 2006, www.acronym.org.uk/uk/Worse_than_Irrelevant.pdf (last access May 14, 2007).

send a strong signal to the international community that multilateral arms control agreements remain central for peace and stability in the 21st century.

In order to avoid misperceptions on weapon lab activities, transparency of the science programs and their exact role in weapon maintenance is essential. As Frank von Hippel pointed out for subcritical tests,[109] generally only those activities that are *essential* for maintaining the stockpile should be pursued. 'We emphasize the word essential, because virtually any experiment can be justified with the argument that "the more we know the better".' This can only be achieved if a panel of independent experts assesses every single module of the science programs and discriminates between what is needed and what can be foregone under a strict conservative maintenance regime. The realigned science programs should then have maximum transparency, a clear focus, and should not give rise to any doubt about their goal, which should only be to preserve the stockpile, but never to modernize it. Of course this implies that the NWS should abort their current RRW programs and any future modernization plans, as the political costs may be too high in the fragile nuclear world order of today. There is substantial technical evidence nowadays that a conservative maintenance approach based on LEP is both feasible and sustainable well into the 21st century.

Finally, Western NNWS can contribute to de-emphasizing nuclear weapons by reviewing the nuclear doctrines of their alliance partners within NATO, and pushing for a less offensive posture and a gradual marginalization of nuclear weapons.

It should be mentioned, that as of today, the modernization programs of the U.S., France and the UK remain unopposed by their Western allies, who incomprehensibly keep a low profile on such vital matters of global security. There was complete silence on the British decision to replace their Trident system, there was no Western objection when the French President trumpeted the modernization plans of his nuclear fleet a decade ago, and there is no critical voice outside the U.S. that opposes their RRW program. Still, we argue, that there should be leeway for criticism within NATO and the EU, especially for the major players within these institutions, and that this potential should be used. The collapse of current regimes of nuclear restraint can only be avoided if both NWS and NNWS do their utmost to repair the cracks within the global nuclear system; and so far, neither has done enough.

This report discussed options of nuclear weapon continuity into the 21st century in the U.S., the UK and France. It discussed warhead science programs aimed at preserving the arsenal (LEP), transforming the stockpile (RRW), and the minority position of ending the test moratoria and returning to the status quo ante of the Cold War.

However, a fourth option seems to be gaining ground on the future of nuclear weapons: their total elimination, as prescribed by Article VI of the NPT. The demand to discontinue nuclear weapon programs found prominent (and unexpected) supporters out-

109 Hippel/Jones, see above (footnote 52).

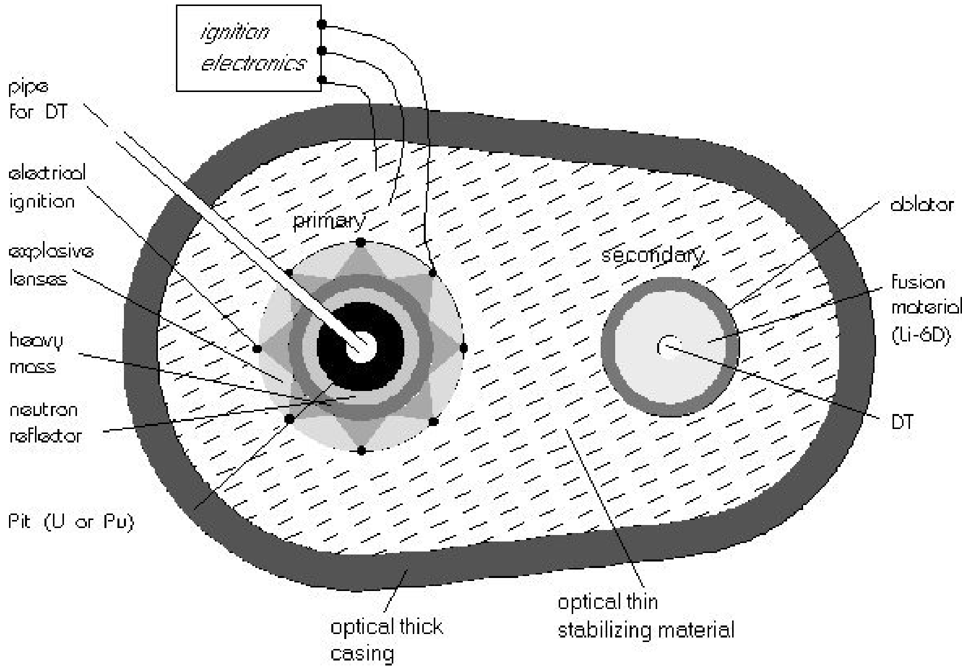
side the classical arms control communities, namely in an op-ed signed by renowned U.S. elder statesmen, calling for a global ban on nuclear weapons.[110] The underlying assumption is that the current nuclear status quo of 'slow proliferation' is no longer sustainable, and that 'fast proliferation cascades' will likely dominate the future spread of nuclear weapons unless the NWS revive the non-proliferation regimes with some truly creative 'out-of-the-box' visions. Business as usual may no longer be able to contain the two dozen states that seem capable of joining the nuclear club within a few decades.

The message had a strong impact on the international press, but did not affect the decision-makers in the U.S., the UK and France, where the warhead science and modernization programs continue at full speed, leading the global nuclear order to a highly uncertain future.

110 George P. Shultz/William J. Perry/Henry A. Kissinger/Sam Nunn, A World Free of Nuclear Weapons, in: Wall Street Journal, January 4, 2007, p. A15.

Appendix I: Functioning of Nuclear Weapons

The following depiction demonstrates the most important elements of a modern warhead.



This depiction only contains information that has been published to date. Technical details cannot be taken from it. Measurements and shapes are arbitrary, and do not correspond to reality.

A nuclear weapon explosion consists of several stages.

The *primary*, which is based on nuclear fission, is a warhead which functions according to the implosion principle: A hollow sphere of HEU or plutonium, the so-called '*pit*', is surrounded by a neutron reflector of, for example, beryllium. The configuration is subcritical. Firstly, the high explosive explodes, and then shock waves compress the pit. The explosive lenses consist of specially shaped and assembled parts made of conventional explosive material that have different detonating speeds and several igniting points. If these are ignited simultaneously (with an imprecision on the scale of a μs), a spherical, inward-directed detonating wave is generated. This wave causes the heavy mass below to accelerate inwards. In order to avoid instability, the process requires precision in terms of space and time. The detonating wave compresses the reflector and the pit so that an overcritical mass is generated. Shortly before maximum overcriticality is reached, starting neutrons for the chain reaction are generated by use of a neutron generator (not included in the depiction). The time for this must be chosen in such a way that there is maximum compression when the energy generated by nuclear fission is just large enough to trigger an additional expansion. This is the principle of the Nagasaki bomb. Most beginner states aim at mastering this technology.

The chain reaction may be additionally reinforced by '*boosting*'. That is, deuterium-tritium gas (DT) is inserted into the hollow space of the pit just before ignition. When the temperature and the pressure exceed specific thresholds, fusion reactions start and release fast neutrons:

$$D + T \rightarrow \alpha + n + 17.6\ \text{MeV}$$

These neutrons accelerate the chain reaction, which means that a greater proportion of the pit is fissioned before the chain reaction stops as a result of the re-expansion. With the aid of boosting, it is possible to vary the yield of a warhead.

The energy that is released by the primary converts to a form of X-radiation and fills a casing that contains both the primary and a '*secondary*'. In other words, the energy rapidly thermalizes with the outer surfaces of the primary and the secondary, and the inner surface of the casing. In order not to hinder this thermalization, all the mechanical holding material is optically thin. The secondary consists mainly of fusion material, namely lithium-6 deuteride (Li-6D), and has an outer skin of heavy and optically thick material that is heated up by radiation. This skin ablates, and as a result, shock waves travel into the fusion material and compress it. The closer the compression comes to an adiabatic curve, the higher the possible density. Therefore, ablator is probably constructed in such a way that several shock waves can be generated one after the other, so that as a whole, the adiabatic compression is approximated.[111] In its centre, the shock waves collide and form a '*hot spark*' with fusion conditions. There, the nuclei start fusing in significant numbers. Their energy is deposited in the adjacent compressed and colder material and heats it up, and as a consequence, fusion takes place there too. This way, a fusion burn wave in the compressed material travels from the centre to the surface of the secondary. This process is quicker than the following mechanical expansion – e.g. explosion – of the plasma.

This mechanism of the ignition of a secondary is called the '*Teller-Ulam-Principle*' after its inventors. It is the same as with inertial confinement fusion (ICF), except that the energy in ICF does not originate from a fission bomb, but from high power lasers. The so-called '*indirect drive*" of ICF pellets became known by non-American publications as early as the start of the 1980s, and were also declassified in the USA in the early 1990s.[112] By this, the conclusion to the Teller-Ulam-Principle was quite obvious.

111 The theory of spherical compression is described in: G. Guderley, Starke kugelige and zylindrische Verdichtungsstöße in der Nähe des Kugelmittelpunktes bzw. der Zylinderachse, in: Luftfahrtforschung 19, p. 302, 1942; for a short summary see K.A. Brueckner/S. Jorna, Laser-driven Fusion, in: Rev. of Mod. Physics, Vol. 46, No. 2, p. 325, April 1974, here: p. 347. See also: J. Meyer-ter-Vehn/C. Schalk, Selfsimilar Spherical Compression Waves in Gas Dynamics, in: Zeitschrift für Naturforschung, 37a, 1982, pp. 955-969.

112 Meyer-ter-Vehn, see above (footnote 26).

Appendix II: Acronyms

AWE	Atomic Weapons Establishment
CEA	Commissariat à l'Energie Atomique
CD	Conference on Disarmament
CEP	circular error probability
CTBT	Comprehensive Test Ban Treaty
CTBTO	CTBT Organization
DoD	Department of Defence
DoE	Department of Energy
DT	deuterium-tritium
EoS	equation of state
ICF	inertial confinement fusion
IMS	International Monitoring System
He	helium
HE	high explosives
HEU	highly enriched uranium
ICBM	intercontinental ballistic missile
kJ	kilojoule
LANL	Los Alamos National Laboratory
LEP	life-extension program
LLNL	Lawrence Livermore National Laboratory
LMJ	Laser Mégajoule
MDA	Mutual Defence Agreement
MIRV	multiple independently targetable re-entry vehicle
MJ	megajoule
NAS	National Academy of Science
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration
NPT	Non-proliferation Treaty
NNWS	non-nuclear weapon state
NTS	Nevada Test Site
NWS	nuclear weapon state
Pu	plutonium
RRW	Reliable Replacement Warhead
SLBM	submarine launched ballistic missile
SNL	Sandia National Laboratory
SBSS	Science Based Stockpile Stewardship
U	uranium