Science & Global Security, 1995, Volume 5, pp.131–203
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International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament

Martin B. Kalinowski[a] and Lars C. Colschen[b]

In this paper, an approach to control tritium systematically on the international level is proposed. The first goal is to prevent the military use of tritium in states other than the five recognized nuclear weapons states. An "International Tritium Control System" (ITCS) would control all civilian facilities producing or handling tritium. The second goal is to restrict the availability of fresh tritium supplies for nuclear weapons programs as a means to avoid vertical proliferation in states that possess nuclear weapons, and as a step towards complete nuclear disarmament. This can be achieved by including tritium in a future weapons-usable materials production cutoff agreement and the approach proposed here is called an "Integrated Cutoff" (ICO). The simultaneous implementation of the ITCS and ICO aims at avoiding any new discrimination against non-nuclear weapon states.

This paper will discuss the possible political and technical modalities to achieve both goals. The rules and decision making procedures are outlined for both control approaches and the implications for the nuclear non-proliferation regime are shown. Various control tasks are derived from a comprehensive analysis covering all diversion paths which can yield more than one gram of tritium within one year.

In the appendix to this paper, the impact of a tritium shortage on the U.S. nuclear arsenal is illuminated. The extreme case of complete elimination of all tritium would result in large yield reductions of the arsenal.

a. Diplom-Physiker, Interdisciplinary Research Group in Science, Technology and Society, (IANUS) Institut für Kernphysik, Darmstadt, Germany
b. Diplom-Politologe, Interdisciplinary Research Group in Science, Technology and Society, (IANUS) Institut für Kernphysik, Darmstadt, Germany

RATIONALE FOR STRENGTHENED INTERNATIONAL CONTROL OF TRITIUM

The control of tritium clearly has important connections to nuclear proliferation, both "horizontal" to states that do not possess nuclear weapons, and "vertical" to declared and de-facto nuclear weapons states. Measures that are designed to control tritium, therefore, must be considered an integral part of the nuclear non-proliferation regime, which consists of a variety of formal and informal instruments on the multilateral, bilateral, as well as national levels.[1] The instruments address different groups of actors and require different sets of obligations.[2]

The underlying principle of the nuclear non-proliferation regime has been recognized almost worldwide. It states that nuclear weapons, because of their unique destructive capability, are a source of instability in the international system, if they are proliferated. The states within this regime have reached a consensus neither to proliferate vertically nor horizontally. These two norms of nuclear non-proliferation have been embedded especially within the cornerstone of the regime, the NPT. The following paragraphs show the role of the dual-use material tritium for nuclear arsenals and how it has been dealt within the nonreactive framework of the nuclear non-proliferation regime.

Tritium has strategic significance in nuclear arsenals because warheads can be smaller and lighter with the same yield, or small weapons with yields of more than 100 kilotons can be built without managing the explosion of thermonuclear weapons (see below in paragraph on military significance). Tritium is known or thought to be used in the nuclear weapons programs of eight declared and de-facto nuclear weapons states.[3]

Although tritium is not essential for a nuclear explosive, there are a number of established as well as novel arguments speaking in favor of international control to prevent its production and use for military purposes. At the time when the NPT was negotiated, the nuclear weapons uses and related dangers of tritium were not fully realized by all the negotiating parties, primarily because the information was still kept classified. Also there was no civilian source of tritium and the gradually growing demand for civilian applications was fed exclusively from military production.[4]

In 1986 and 1987, the German company NTG illegally exported tritium and tritium handling facilities and China also sent tritium to Pakistan. As a consequence of these illegal exports, the German Federal Court of Law stated in its sentence that tritium is, in any case, considered a weapon of war ("Kriegswaffe"). This is irrespective of its quantity and whether in a given case the tritium supplied is actually foreseen to be used directly for a nuclear weapon.[5]

This transfer demonstrates not only the significance of tritium for proliferating states, but also signifies the need for a tighter control of tritium for nonproliferation reasons. This is a daunting challenge. Increasing technological opportunities to produce tritium are being built up worldwide and a considerable increase of civilian uses in the context of fusion research seems likely in the foreseeable future.[6]

This growing surplus of tritium from civilian sources means that more tritium will be around for a potential diversion from civilian to nuclear weapons purposes. At the same time, the military production reactors in some of the recognized nuclear weapon states are either aging or already shut down with no military production alternatives immediately available. Hence, the supply of tritium to these states from other possible civilian sources could become a new matter of concern. These developments further blur the line between military and civilian production and uses of the dual use material tritium, and provide additional arguments in favor of comprehensive and systematic tritium controls. Although the growing civilian production and use of tritium makes its control a challenging undertaking, this does not itself imply that tritium control measures pose insurmountable verification problems. Indeed, while worldwide civilian plutonium quantities exceed total military stocks by a factor of four, this does not prevent them from being put under IAEA safeguards. In the case of tritium, the ratio of civilian to military stocks is the other way around (1 to 4, or perhaps 1 to 7).[7]

Regarding the uncontrolled spread of tritium to states without a recognized nuclear weapons status, it would be a tempting approach to expand the international safeguards, carried out by the IAEA for nuclear materials, to also cover tritium.[8] In addition, the IAEA has a lot of expertise regarding tritium.[9] Such control procedures would make it more difficult for a state with a secret nuclear weapon program to divert tritium and move on to more sophisticated weapons designs.[10]

Although the necessity and desirability of controlling tritium has become evident, only three instruments on the international level within the nuclear non-proliferation regime deal with the control of tritium.[11]

All three aim at preventing the spread of tritium to states other than the five recognized nuclear weapon states. They all embody only a very limited approach and are neither coordinated, nor do they complement each other. On the other hand, no measures have been taken to avoid or reduce the use of tritium within the recognized nuclear weapon states as an approach to halting or reversing vertical proliferation.[12]

This may change in the future. In 1988, it was suggested, primarily within North American scientific circles, to use the tritium decay as a forcing function to reduce nuclear arsenals in the United States and former U.S.S.R. at a rate of at least 5.5 percent per year (the decay rate of tritium).[13] An even more radical suggestion is the elimination of tritium from the entire nuclear arsenal including the supply pipelines in order to significantly reduce the total yield of the remaining arsenals.[14]

Although such proposals sound straightforward, it is unlikely that such technically-induced mechanisms could be politically acceptable. Consequently, the proposals have never reached the agenda of policy makers in the United States or elsewhere. A more realistic approach is centered around the cutoff idea. It would basically consist of an agreement on the verified cutoff of fissionable materials production which would be expanded to include a tritium production cutoff (see section "the integrated cutoff").[15] The developments in recent years have proven that international control of tritium is politically desirable and feasible. The challenge is to develop a set of coherent rules and procedures against the proliferation of tritium which can be viewed by all states involved as beneficial and politically acceptable.

CURRENT TRITIUM CONTROLS

Levels of Control

Facility Level

Tritium inventory control and accounting procedures are well established at the facility level (see figure 1). The left half of the plane represents military tritium facilities and activities. These controls are primarily brought about by radiation protection considerations as opposed to international safeguards. The authorities on the national level typically interact with the responsible authorities on the facility level to implement the safety regulations, because specific technical features of the respective facilities have usually to be taken into account. Specialists (scientists and technicians) working on the facility level are often advisers to the national legislators. Hence, both levels are interwoven.

National Level

Many states have national regulations requiring licences for possession, production, sale and export of tritium exceeding a certain quantity. Most states involved in production, trade, and uses of tritium, adhere to regulations

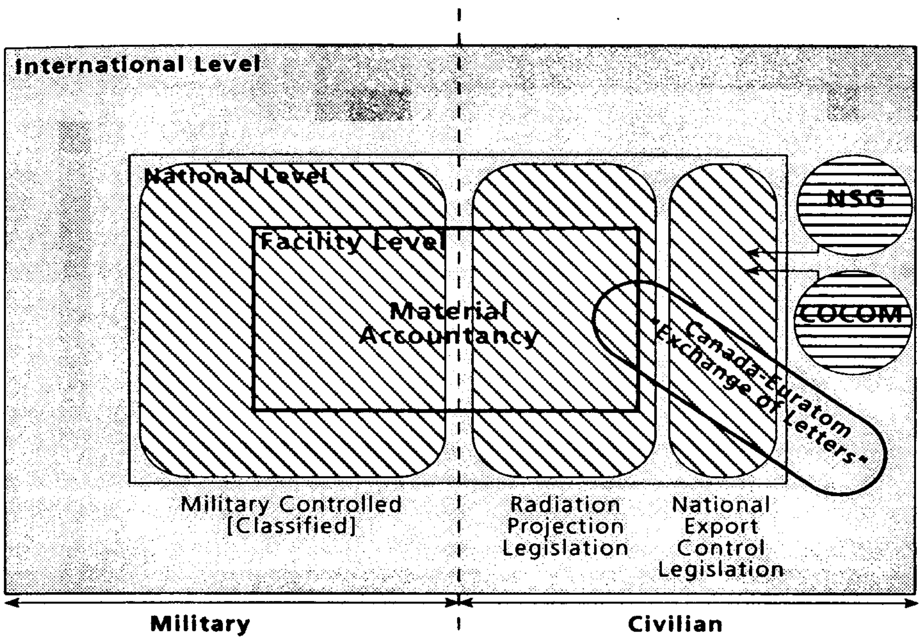

Figure 1: Current situation of tritium control on facility, national, and international levels. The left half of the plane represents military tritium facilities and activities, the right side stands for the civilian realm. Overlapping areas demonstrate qualitatively the fraction of activities and facilities which are affected by the respective control procedures. The proportions of the various areas do not reflect relative importance or quantities.

National level, military: Tritium production and handling are controlled. Information on the control procedures is classified. National level, civilian: (a) Radiation protection measures are required by national law and implemented on the facility level. (b) National export control legislation. International level, military: None.

International level, civilian (a) NSG and CoCom are fora of limited membership. Regulations agreed upon here have to be implemented within the national level and then become part of the export control legislation. (b) The control procedures agreed upon in the Canadian European exchange of letters are carried out by Euratom. The agency is controlling tritium directly on the facility level in their member states

agreed upon on the international level (see below) and are obligated to implement those regulations within their respective national export control legislations. However, there are wide disparities in national regulations of accounting for and control of tritium, and in the requirements for export licences and verification of end-use.[16]

As an example, table 1 illustrates in ascending order the broad range of national limits of licence free export which covers more than 9 orders of magnitude.[17]

Some countries do not even have any regulations regarding tritium, and others have only very weak regulations. These deficits open the door for proliferaters, since they could take advantage of the state with the weakest control laws or procedures in place.

International Level

No instrument to control horizontal non-proliferation applies exclusively or directly to tritium. The first attempt of international coordination of national export control policies regarding tritium can be traced back to 1986 and was made within the Coordinating Committee on Multilateral Export Controls (CoCom).[18]

The limited success, according to a study published in 1991, can be seen from table 1. Seven CoCom member states adhered to the guidelines regarding the limit for licence free export of tritium and were joined by South Africa. Four member states (Australia, Canada, Japan, and the USA) kept different licence limits.[19]

The future of the CoCom export control policy is unclear, since the original body (CoCom) ceased to exist after 45 years following the March 1994 meeting in the Hague. Its successor is not yet in place. However, until this process is concluded, CoCom member states will maintain export controls unilaterally.[20]

Secondly, in September, 1990, the 4th review conference of the parties to the NPT recognized that tritium is relevant to proliferation of nuclear weapons although this was not identified in NPT Article III.2, and, therefore, called for "early consultations among states to ensure that their supply and export controls are appropriately coordinated."[21]

No subsequent activities were initiated directly on this level, but because of the apparent deficiencies regarding tritium control, this material was included in the new dual-use list which has been adopted at the meeting of adherents to the Nuclear Suppliers Guidelines (NSG) in April 1992 at Warsaw.[22] These new guidelines cover not only tritium, tritium compounds, and mixtures, but also tritium facilities or plants and components. The maximum quantity of tritium which is exempted from these guidelines in any chemical or physical from is 1500 GBq, only slightly less than the former CoCom limit. Furthermore, a "notification-of-denial"[23] mechanism has been established within the NSG, as well as periodical consultations among the states about the accomplished exports.

But the NSG as well as the former CoCom measures have to be implemented by the respective national legislations to come into force. Furthermore, the respective practices to enforce legislation on the national level cannot be considered equally effective, as the case of illegal tritium transfers from Germany to Pakistan indicates. Other major shortcomings of NSG and CoCom are that they do not involve verification of end-use and they are dis-

Table 1: Maximum amount of tritium free of licence requirement for export from different countries, Colschen/Kalinowski/Vydra (1991)[24]

Country	Total GBq
Argentina, Austria, Japan, Malaysia, Switzerland	0
Mexico	0.0002
Finland	0.0037
Indonesia	0.0050
Philippines	0.0370
USA	370.0000
Nuclear Supplier's Guidelines, "Dual Use List" (1992)	1,500.0000
Belgium, France, Germany, Italy, Netherlands, Norway, South Africa, UK, CoCom (1986)	3,700.0000
Canada	37,000.0000
Sweden (this is approximately 1 gram)	370,000.0000
CSFR (until 1993), Hungary, Romania	no limit

criminatory because of their selective membership. The CoCom replacement will, although probably somewhat broadened in its membership, contain the same deficits.

New initiatives for International Controls

The United States and Tritium Control

The U.S. Department of Energy (DOE) regards the measures agreed on in the NSG in 1992 as sufficient to deter horizontal proliferation of tritium. But a comprehensive control system that would limit its ability to produce tritium for nuclear weapons is perceived by the DOE as politically unacceptable. On the other hand, the Department of State's (DOS) Offices of Non-Proliferation and Export Control regard the NSG agreement as a good start to put tritium control on the international level, although they do not specify any particular steps which might be aimed at such an internationalization.[25]

The current position of the Clinton Administration on the non-proliferation of tritium appears to continue the above mentioned DOE position. Although the United States is not producing tritium for nuclear weapons at the moment, it intends to maintain the technical and legal capabilities to resume production if such a step should be considered necessary in the future (see section on military production below).[26]

Given this United States policy, the only conceivable measures to contain vertical proliferation seem to be unilateral ones, e.g., a non-binding, and reversible production cutoff. But with the nuclear disarmament process continuing, such a position could be challenged if a coherent concept was presented and debated at an international forum.

The Middle East and Tritium Control

On a related issue, the United States has made diplomatic efforts to encourage the Israeli government to close its nuclear weapons complex at Dimona as a step to the eventual establishment of a regional nuclear-weapons-free zone in the Middle East, but has not succeeded so far.[27] Such a step would basically mean a freeze both on Israel's fissile material production for weapons and its tritium production for nuclear weapons purposes, since Dimona is the only source of tritium.

Moreover, a UN-study on the possibilities of a nuclear-weapons-free zone in the Middle East initiated by UN-resolution 43/65 of December 7, 1988 and presented by the UN Secretary General to the UN General Assembly also calls for safeguarding or closing Dimona.[28]

This document mentions tritium production and stockpiling as examples for activities that could be declared to the IAEA by the states of the region and controlled by an informal system of inspections by invitation as confidence building measures.[29] It is evident that such a proposal would apply to Israel only, since Israel is the only state in the region that is likely involved in any tritium production and stockpiling for nuclear weapons purposes. Israel, like any other state with nuclear weapons, has so far refused to give up any sovereignty regarding the control of its nuclear weapons program to foreign or international authorities.

Canada and Tritium Control

Canada has become the largest civilian producer of tritium worldwide having 21 heavy water reactors with a total capacity of 14,900 GW_e. These reactors produce up to 3.5 kg tritium per year. [30] Canadian tritium extraction capabilities of approximately 2.5 kilograms per year are provided and operated by the company Ontario Hydro at its Tritium Recovery Plant (TRP) at Darlington since 1987. Therefore, the Canadian activities regarding the non-proliferation of tritium are of great importance. Ontario Hydro has a near-monopoly as a supplier of tritium from civilian sources. According to the original estimations from 1988 made by Donald Anderson, Director of Ontario Hydro's New Business Ventures Division (the marketing arm of its technology and isotope sales), the sale of those 2.5 kilograms of tritium could be worth $30 million annually.[31]

This estimation was based primarily on expectations regarding advances in fusion research, since those 2.5 kilograms are about six times as much tritium as the whole world market presently demands. Indeed far fewer than 2.5 kilograms of tritium per year are currently separated by Ontario Hydro so far. From 1988 to June, 1993, only 5.7 kilograms have been extracted at Darlington.[32]

This low extraction figure was mainly due to a long shutdown forced by various operating problems shortly after start-up of the extraction plant. Information on exports of tritium are regarded as commercially confidential and therefore publicly not available. Ontario Hydro and the Canadian Government are very much aware of the political ramifications of tritium sales, especially as far as the dangers of nuclear proliferation are concerned.[33]

The two relevant federal instruments to control exports are the "Export/Import Permits Act" and the "Atomic Energy Control Act." The principle of the Canadian "tritium non-proliferation policy" is to guarantee that Ontario Hydro's tritium is used for peaceful purposes only. To realize this foreign policy objective, Canada, an adherent to the NSG, has established extensive export control legislation. The Atomic Energy Control Board (AECB), which is the responsible authority, regards this legislation to be much stricter than required by the international agreements.[34]

For example, Canadian legislation forbids tritium sales to nuclear weapons programs of the five recognized nuclear weapons states. The NSG, by contrast, has no comparable restrictions. In addition, for the export of tritium, Canadian legislation requires in most cases a specification of the end use of any tritium export.[35]

However, it is also true that Canada has a threshold level for the requirement of export licenses ten times larger than that recommended by CoCom (see table 1). More important, the Government of Canada and Euratom have secured an agreement on the supply of tritium and tritium related equipment, as well as on the control of its use. In May, 1991 the extension of the cooperation agreement between Euratom and Canada was finalized,[36] amending an agreement between Canada and Euratom signed on October 6, 1959 and covering the field of fusion research and development.[37]

Canada does not demand "safeguards" from Euratom and purposely avoids the use of that term. Rather, the agreement makes Euratom the supervising agency authorized to establish control procedures for tritium shipments from Canada to Euratom member states, to verify the inventory at the receiving facility as long as the tritium is supposed to remain there, and to make sure that the tritium is not re-transferred beyond the territories in which the Euratom Treaty is applied without prior written consent of the Government of Canada.[38]

The purchases of tritium by the Kernforschungszentrum Karlsruhe (KfK; 200 grams within the next ten years), Joint European Torus (JET; 90 grams to be delivered from 1994 to 1996), and the European Tritium Handling Experimental Laboratory (ETHEL; 100 grams) are expected to be the precedents for these new control procedures.

Summary of Current Tritium Control Measures

Although tritium control has already tightened, a coherent international strategy has yet to be devised.[39] NSG and CoCom efforts are both based on a policy of technology denial and are discriminatory in nature. Even in combination with the national export controls and the limited control functions carried out by Euratom, the controls do not constitute an effective and systematic control effort to hinder effectively the spread of tritium to clandestine weapon programs, or to regulate the tritium production of the recognized nuclear weapon states.

POTENTIAL USES OF TRITIUM

Civilian Use of Tritium

Tritium is the radioactive, super-heavy isotope of hydrogen and was discovered in 1934. The development of commercial applications of tritium was intensified in the early 1960's, primarily because excess amounts of tritium were made available by the U.S. Atomic Energy Commission (USAEC). One hundred grams were made available in 1959 and subsequently sold by the Oak Ridge National Laboratory (ORNL) for peaceful applications. In comparison 4.1 grams of tritium had been sold in 1958, and only 1.3 grams in the period between 1948 to 1957.[40]

At the end of the 1960's, the worldwide consumption of tritium for civilian purposes was about 20 grams per year increasing to 100 grams per year in the mid 1970's, basically for luminous paints and self-powered lights ("betalights").[41] In 1979, the commercial consumption of tritium peaked at some 800 grams, but in 1980 it dropped markedly back to about 100 grams per year because safety regulations were tightened due to concern about radiation problems. Since then, tritium demands increased again to about 400 grams per year at the beginning of the 1990's. Demands for fusion research constituted about 10 percent of this. International trade in the 1980's averaged little more than 220 grams per year.[42]

Only 4 out of 21 large commercial tritium manufacturing and trading facilities are in non-nuclear weapons states (Canada, Germany, and Switzerland). Nearly all of the civilian demand was satisfied by supplies from the ORNL sales office. Its price fluctuated widely in the 1980's between $13,000 and $26,000 per gram. It is conceivable that China, United Kingdom, France[43] and Russia[44] would be able to export several tens of grams of tritium each year mainly from military production. In the late 1980's, Ontario Hydro appeared as the first competitor of tritium from civilian sources and broke the US-monopoly. The main importing countries are the United Kingdom, Japan, and Switzerland. The stated uses are basically for self-powered lights and luminous paint.

The following industrial applications are given as examples and are arranged in order of decreasing requirements:

- Runway landing lights for remote airfields (50 to 100 milligrams each);
- Radioluminous colors (up to some 100 milligrams per manufacturing charge);
- "EXIT" signs (up to 10 milligrams each);
- Timepieces, instrument display illumination, signs and indicators, various other special applications (μg-quantities each);

There are also some applications in research:

- Fusion energy research (presently worldwide a few hundred grams);[45]
- Nuclear physics, especially for 14 MeV neutron sources (up to 500 milligrams each);
- Biological, medical, chemical, and geological research, especially as tracer (μg-quantities).

Military Use

There are various military applications of tritium having nothing to do with nuclear weapons. These are primarily dual-use applications, mostly using tritium as self-powered light sources for conventional weapons systems or military runway landing lights. However, what is of interest here is the use of tritium for nuclear weapons. Tritium itself is neither sufficient to produce nuclear weapons, nor is it a necessary component to design a simple nuclear warhead. However, tritium is believed to be a component of most nuclear weapons currently in the stockpile of all nuclear weapons states. Its primary purpose is to increase ("boost") the explosive yield of a given amount of fissionable material. The use of tritium in nuclear weapons, therefore, means a vertical proliferation process from first generation fission devices to more sophisticated boosted or thermonuclear weapons.

The following list gives the different uses and estimated quantities of tritium in nuclear warheads:[46]

Boosted fission weapon and boosted primaries in thermonuclear weapons (2–3 g) [47]

In the center of the nuclear explosion, a few grams of tritium fuse with deuterium. The released neutrons induce further fissions thereby increasing the efficiency of the fissionable core and, if present, of the surrounding fertile tamper material. As a result, the yield can be multiplied by a factor of 2 to 10.[48]

As a consequence, boosted fission weapons can achieve explosive yields up to 400 kilotons,[49] but would still have relatively low yield to weight ratios. Thermonuclear weapons with boosted primaries can have high yield-to-weight ratios allowing high-yield (400–500 kilotons) warheads to be light enough (100–400 kilograms) to fit into long-range missiles with multiple warheads, as well as torpedoes and artillery shells. The reduced amount of fissile material is easier to compress and, therefore, results in a more reliable nuclear yield. Boosting is believed to be applied in most of the small fission weapons and in all triggers of thermodynamic weapons in the current U.S. nuclear arsenal (see appendix).

Selectable yield (2–3 g)

This is a special feature used for some boosted warheads. Their yield can be selected by inserting no tritium at all or capsules with all or a fraction of the total content of 2–3 grams.

Neutron bomb (10–30 g)

Tritium is used in enhanced radiation weapons (neutron bombs) in a similar way as in boosted fission weapons but care is taken that a higher fraction of the 14 MeV neutrons from fusion escape before they induce further fissions. Therefore these weapons have a comparatively low yield (about 1 kiloton TNT) and a large flux of high-energy neutrons.

Neutron generator (0.1 milligram)

The nuclear fission chain reaction is started with an electrostatic neutron generator in which deuteron ions are bombarded on a metal (e.g., zirconium) tritide target.

Most information about the military uses of tritium is classified. Therefore, all quantities are educated guesses which have been neither declared nor denied by officials. The strategic significance of tritium on the nuclear arsenal is to guarantee a high total yield or high yield-weight ratio. Without tritium, the total yield of many or most thermonuclear weapons (of current design) would be lower by two orders of magnitude (see appendix).

Relations Between Civilian and Military Productions and Applications

Tritium has various military (nuclear and non-nuclear weapons related), as well as civilian (industrial and scientific) applications.[50] The latter have always lagged behind military applications and were partly enabled or triggered by the availability of tritium from military production. The tritium produced in military facilities is neither technically, nor politically confined to military uses. Neither the quantity of tritium nor its mode of production, chemical state, physical condition or degree of purity determines or indicates its intended military or civilian use. Since it is impossible to differentiate physically between "military tritium" and "civilian tritium," the respective social-technological environment has to be taken into account if a judgment is required.

Since physical barriers can never be completely tight, the most efficient way to prevent the diversion of tritium for military purposes, besides binding and verified political commitments, is to *minimize any production and application.* In fact, for most civilian applications, other pure beta emitters like carbon-14, nickel-63, or thallium-204 could be used alternatively.

MILITARY TRITIUM PRODUCTION FACILITIES AND INVENTORIES

Recognized Nuclear Weapons States

In general, information on military tritium production facilities and capacities are held secret. Some information is available from open literature and is summarized in table 2.[51]

In April, 1988, the K-reactor, which was the last United States source for military tritium and which was exclusively dedicated to tritium production, was shut down and no fresh tritium has since been produced for the U.S. nuclear arsenal. In August, 1988, the United States decided that all remaining production reactors would have to undergo significant upgrading for safety reasons before they could be restarted. The United States spent $2.345 billion between fiscal years 1989 and 1992 trying to restart tritium production in the K-reactor without success. In September, 1992, then DOE Secretary James D. Watson said that the United States could recycle enough tritium from dismantled warheads to supply a reduced U.S. nuclear arsenal until the year 2012. According to an announcement by the present DOE Secretary, Hazel O'Leary, in March of 1993, the K-reactor would not be restarted, but instead would be placed on "cold-standby." This decision is reversible.[52]

The program to design a new production reactor (NPR) has been officially stopped by the Clinton Administration. However, in June 1993, O'Leary declared that a new production source for tritium should begin its operation in 2008. To meet this date, construction of a NPR would have to begin by the end of this century. Alternatively, construction of a proton linear accelerator which could also be used to produce tritium, would have to start by the year 2002. By then, some scientists hope to have developed the technology to produce tritium with an accelerator. As a matter of fact, in contrast to the NPR, research in accelerator breeding of tritium continues, although at a modest pace.[53]

The U.S. military tritium inventory at the end of 1993 can be estimated at (70±25) kilograms.[54] The current operational U.S. stockpile consists of some 9,250 strategic and tactical warheads and bombs and will be reduced according to START II to some 4,450 by the year 2003.[55]

The tritium inventory for the post-START II arsenal will be about 9 to 13 kilograms. In 2005, through radioactive decay, the remaining tritium stockpile would be roughly 25 to 50 kilograms. Depending on which combination of figures describes reality correctly, the year in which the U.S. tritium stocks decay below the demand may be as early as 2016 or as late as 2035.[56] If a stockpile of 1,000 warheads is considered sufficient, existing tritium stocks could last until 2043 or even 2062.

The tritium producing reactors of other countries are likely to face a similar fate to that of U.S. reactors. Most of them have been in operation for 25 to 35 years (see table 2). Russia has already shut down 11 of its 14 plutonium production reactors and has pledged in the Gore-Chernomyrdin-Agreement, concluded in June 1994, to phase out the operation of the remaining three reactors by the year 2000 (see below). One source reports that two additional light water reactors are dedicated to the production of tritium and other isotopes.[57]

In 1989, Soviet officials said that their country would have a continuing requirement for two to three tritium production reactors.[58] Although no official declaration regarding tritium production has been made, this estimate has certainly changed due to the continuation of the nuclear disarmament process in Russia, especially the unilateral declarations by Yeltsin and the signing of START II in 1993. The current annual production of tritium in Russia can be assumed to be between zero and a few kilograms. One educated estimate arrived at a decay-corrected cumulative stock of 66 kilograms at the end of 1991.[59] The decay-corrected worldwide military inventory of tritium can be estimated at about (140±30) kilograms at the end of 1993 (see table).

After the demise of the USSR, Ukraine had inherited some 1800 strategic warheads. Assuming an average tritium content of 2.5 grams per warhead,

Table 2: Military production facilities for plutonium and tritium.

Country	Facilities	Years of Operation or Tritium Production	Production Capacity for Tritium (g/y)[a]
China[b]	Second Ministry of Machine Building Industry	since 1968	?
	Entirely new (larger) production line	since 1979	?
France	Marcoule, G1 (40 MW_{th}), G2 (250 MW_{th}), G3 (250 MW_{th})[c]	since 1956, '59, '60, until 1992	only Pu
	Celestin I/II, 250 MW_{th} heavy water reactors[d]	since 1967, '68	2 x 600[e]
	Accelerator based production	under consideration	?
India[f]	Cirus (BARC), 40 MW_{th} heavy water reactor	since 1960	120
	Dhruva (BARC), 100 MW_{th} heavy water reactor	since 1988	300
Israel	Negev Nuclear Research Center Dimona, IRR-2 (150 MW_{th})[g]	since 1963	500
Russia[h]	Ozersk (former Chelyabinsk-65)	first since 1948,	little[i]
	•5 graphite-moderated water-cooled reactors (total ≈ 6565 MW_{th})	all shut down by end of '90	
	• heavy water reactor, ~50 MW_{th}	~1950 until late 1980's	55[j]
	•2 light water reactors, ~1000 MW_{th} each	still operational	~4000[k]
	Seversk (former Tomsk-7) •5 graphite-moderated water cooled reactors, ~2000 MW_{th} each	since early 1960's, 3 shut down by end of 1992, last 2 to be shut down by 2000	only Pu (?)[l]
	Zheleznogorsk (former Krasnoyarsk-26), •3 underground graphite-moderated reactors, ~2000 MW_{th} each	since 1957, '61, '64, 2 shut down in 1992, last one to be shut down by 2000	only Pu[m]
U.K.[n]	Windscale, two 115 MW_{th} reactors	shut down	only Pu
	Calder Hall, four 220 MW_{th} Magnox reactors	since 1956, '58	only Pu
	Chapelcross, four 220 MW_{th} Magnox reactors	since 1958, '60	4 x 200[o]

Table 2: Military production facilities for plutonium and tritium. (Continued)

Country	Facilities	Years of Operation	Production
USA[p]	Hanford (Washington), nine reactors, including •N-reactor, 4800 MW_{th}, graphite-moderated, light water cooled	1952-1988 short period ~1967	mainly Pu 6250[q]
	Savannah River Plant (South Carolina), five reactors, including •K-reactor, 2400 MW_{th} heavy water cooled and moderated	shut down 1953-1988	mainly Pu[r] 6300-11500
	New reactor or accelerator based production facility	under consideration	?
Total	**> 23 Facilities Operating, 28 Shut Down, and 2 New Under Consideration**		**~7000**

a. Figures are a very crude estimate of the maximum production rate without simultaneous Pu production if running at full capacity and totally dedicated to tritium production, in some cases to simultaneous power production.
b. See JPRS (1988).[60]
c. See Cochran et al. (1987)[61] Tritium breeding from lithium-6 started before 1962. After completion of the two Celestin reactors G1, G2, and G3 were used for plutonium production only. See CEA (1962), p. 129.[62]
d. See Hugony et al. (1973)[63] and Barrilot (1991).[64]
e. Alternatively 45 kilograms Pu could be produced according to Gsponer (1984).[65] The actual tritium production may be far less, probably by one order of magnitude. In fact in 1980 these two reactors were modified to produce plutonium and less tritium Barrilot (1991).[66]
f. See Albright/Zamora (1989).[67] Both reactors are unsafeguarded and it is not clear, whether they are used as production reactors.
g. Upgraded from 24 to 150 MW in 1969, see The Arms Control Reporter 13,5 (1993) 453.E.1.
h. See Cochran/Norris (1993), pp. 45,47[68] and the Arms Control Reporter 12,4 (1993) 611.E-0.4.
i. There was no major tritium production at these facilities. Sometimes tritium was produced in control rods. See NRDC (1989).[69]
j. Value is given in a CIA study which was made in the mid-1950's and is quoted in Cochran et al. (1989)[70]. Reactor is presumably converted to one of the LWR's.
k. These two reactors are used for the production of tritium, Pu-238 and other isotopes. They are only mentioned in Cochran/Norris (1993), p. 51.[71]
l. Tritium production is not known.
m. Tritium has never been produced here. The remaining reactor is simultaneously used for power generation.
n. See Cochran et al. (1987).[72]
o. Dual Purpose Magnox reactors producing electricity and Pu or H-3. Actual tritium production is probably lower by at least one order of magnitude.
p. See Cochran et al. (1987).[73]
q. With simultaneous production of power and 815 kilograms of plutonium. Ragheb (1981).[74]
r. Tritium was produced mainly in C-, later in K-reactor. The restart for the latter was scheduled several times but never successful. In 1993 it was decided to keep the reactor permanently shut down.

the total tritium inventory of these weapons can be estimated at about 4.1 kilograms. Having used those weapons as a bargaining chip, Ukraine has started to transfer them to Russia for dismantlement. In fact, the first three shipments of 60 warheads each have already arrived in Russia. Since all dedicated production reactors for plutonium and tritium are located on the territory of Russia, there are no tritium production facilities in the Ukraine. Therefore, if the political situation in Ukraine should change and nuclear weapons are kept in Ukraine, the supply of tritium could become an issue. Moreover, since the proliferation issue regarding tritium has neither been dealt with in the Lisbon Protocol nor in the trilateral agreement between Russia, the United States, and Ukraine, the whereabouts of the tritium of the warheads to be transferred to Russia remains unclear. Ukrainian authorities or criminal groups with access to the warheads could take the tritium out of the warheads, a technically simple procedure, and sell it to states with nuclear weapons or weapons' ambitions. On the other hand, Russia could reuse the tritium of the warheads if they were transferred completely by Ukraine for its own nuclear arsenal.

States with Undeclared Nuclear Weapon Programs

There are indications that most countries which are suspected of having developed nuclear weapon capabilities have also engaged in acquiring tritium and tritium technology to enhance these capabilities. The following states are suspected of using or having used tritium within their undeclared weapon programs:

Pakistan

Between 1985 and 1987, the West German company Neue Technologien GmbH illegally exported 0.8 grams of tritium as well as some tritium technology to Pakistan, which had requested in total 100 grams. Also in 1986, Pakistan reportedly received tritium from China.[75]

India

India may be using its research reactors Dhruva and Cirus to breed tritium from lithium-6 (see table 2), but it definitely intends to remove tritium from heavy water which was tritiated during normal operation in the CANDU type reactors.[76]

Israel

Alternatively to the production of plutonium, Israel could produce up to 500 grams per year of tritium in its research reactor at Dimona (see table 2). Tritium production for nuclear weapons does not appear to be a problem for Israel, since it reportedly exported secretly some 30 grams of tritium to South Africa during 1977 and 1978 in exchange for 500 to 600 tons of yellowcake. [77]

Iraq and South Africa

Two other states were involved in tritium activities for nuclear weapons purposes, but can no longer be considered a matter of concern in this regard.

Iraq undertook research on lithium-6 enrichment and maintained a facility which was able to process approximately 0.5 to 1 kilogram of natural lithium per year.[78] However, the Iraqi nuclear weapon program was stopped during the second Gulf War, then nearly eliminated by the subsequent UNSCOM inspections and today is still under international supervision.

The Republic of South Africa's armament corporation Armscor built six primitive, tritiumless "gun-type" nuclear devices during the 1980's. There are several strong indications that South Africa also intended to build more sophisticated nuclear weapons. South Africa had pilot projects for the production of tritium and lithium.[79] It undertook theoretical studies to boost the yield of gun-type weapons from less than 18 to roughly 100 kilotons, and it admittedly received some 30 grams of tritium from Israel (see above) as well as more tritium from unspecified "overseas suppliers."[80]

Apparently, the tritium of Israeli origin was never used by Armscor within the weapons program and with about a third of the imported tritium lost to natural decay, the Atomic Energy Commission (AEC) of South Africa decided to convert the remainder to peaceful purposes, i.e., radioluminescent safety signs in the mid-1980's.[81] In anticipation of the loss of political power, the white South African Government officially cancelled its nuclear weapon program in late 1989. However, provided the date and the quantity of the tritium supply are correct and without any use or export of the tritium, there would still be some 10 grams of tritium left in the country today. Therefore, it is necessary for the new South African Government to account for a civilian use or remaining stock.

DIVERSION PATH ANALYSIS

Diversion means the clandestine production of tritium or its illegal removal from existing stocks. In nature, tritium occurs only at concentrations which are far too low to make its extraction practically achievable. One reason for this is its comparatively rapid radioactive decay with a half-life of 12.26 years, i.e., a given quantity of tritium decreases at a rate of about 5.5 percent annually.

Since there are no exploitable natural sources, tritium has to be produced artificially by a nuclear reaction. Significant quantities can only be achieved by a high neutron flux as can be found in nuclear reactors or, potentially, accelerators. Tritium can be produced with different degrees of dedication. It is produced inadvertently as a by-product in the operation of all nuclear reactors, it can be produced deliberately without affecting the normal operation of the used facility, and it can be produced in a reactor or accelerator designed and operated as a dedicated tritium production facility. Only diversion paths by which more than one gram per year can be acquired are considered in this analysis.

A classification of nine facility types which are relevant for tritium controls is given in table 6. In figure 2, possible paths of tritium from production to disposal are broken down into principal steps at facilities of these types.

According to the different raw-materials, four main paths for production of tritium can be distinguished. These are deliberately breeding of tritium from lithium-6 or helium-3, and inadvertent production of tritium as a by-product by ternary fission in nuclear fuel or through neutron capture in heavy water. Possible implementations of these production paths are outlined below.[82]

The production rate is estimated for various scenarios and summarized in table .

Lithium-6 path using the nuclear reaction

$$Li\text{-}6 + n \rightarrow T + He\text{-}4$$

Prior to irradiation of targets containing lithium-6 in a nuclear reactor, the lithium ore has to be mined and milled; lithium is converted to LiCl, and transformed into metal by electrolysis. The enrichment in lithium-6 is most commonly done by a process which uses large amounts of mercury.[83]

Targets are produced as aluminium alloy or ceramic material. After irradiation, the tritium is extracted in a vacuum oven, purified chemically and separated from the other hydrogen isotopes. It requires special handling and storage facilities due to its radioactivity and mobility. Different varieties of this path can be distinguished by the specific mode of operating the reactor and inserting targets into its core.

Case of unreported tritium breeding with lithium targets

- Construct directly or convert an existing reactor to a dedicated production reactor and make use of fuel/lithium assemblies specially designed for tri-

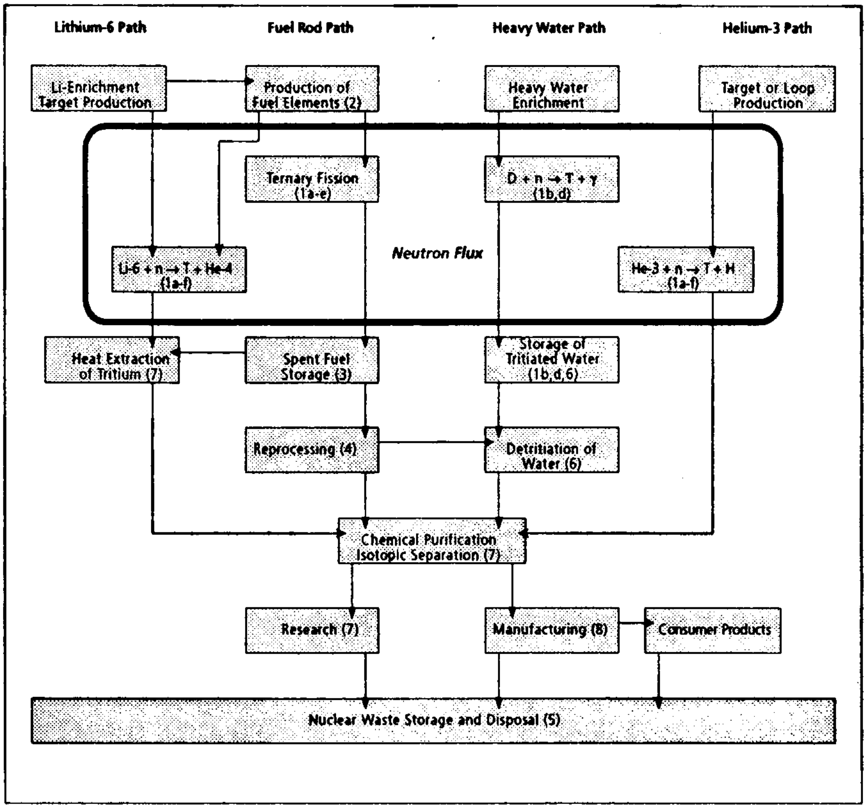

Figure 2: Flow of tritium through facility types from production to disposal. This linear model is only an ideal showing the main pathways. Several other connections are possible especially from various steps directly to waste storages. Numbers in brackets refer to the facility type which are relevant for tritium safeguards as given in table B.1. The upper part shows the four main production paths. In the part below the neutron source, each process step within a box and each transfer between facilities offers opportunities for illegal removal, encounters losses to the environment as well as due to radioactive decay, causes hold-ups, and generates tritiated waste.

tium production. Relative production rates can be derived from estimates of the performance of military production reactors as given in table 2. They range from 1000 to 5000 g/($GW_{th\text{-}y}$).

- Breed tritium in a power reactor without affecting its normal operation. Estimates of tritium production by LWR's are about 100 grams (GW_e-y)$^{-1}$ and 200 g ($GW_{e\text{-}y}$)$^{-1}$ at CANDU type reactors if higher than normal enriched uranium fuel would be used.[84]

Table 3: Relative rates for production of tritium in a fission reactor

Path	Mode	(g/(GW$_{th}$y))
Lithium-6	dedicated production reactor	1000–5000
	LMFBR, lithium coolant instead of sodium	1000[a]
	LWR or CANDU with Li-targets, without affecting normal operation	30–70[b]
	PWR, with 600 to 900 target rods in free control rod guide tubes	30[c]
	PWR, burnable poison rods containing Li-6 instead of B or Gd	2–27[d]
	Any reactor, inadvertent production due to ~0.05 ppm Li-6 in fuel	0.003–0.3
Fuel Rod	inadvertent production by ternary fission	0.5–1.0
Heavy Water	inadvertent production by neutron capture in heavy water moderator and coolant	50–80
Helium-3	experimental reactor loop, NRX reactor at CRNL	4.3[e]
	research reactor, rapid power excursion experiments	<5[f]
	HTGR, inadvertently produced tritium in the helium coolant	0.06–0.23[g]

a. See Ragheb (1987).[85]
b. See CFFTP (1988).[86]
c. Derived from data given in Lu/Zhu/Todosow (1988).[87]
d. See Benedict/Pigford/Levi (1981)[88] for the lower and Ragheb (1981)[89] for the upper value.
e. Derived from data given in Osborne (1979).[90]
f. See Sokolski (1982).[91]
g. See Phillips/Easterly (1980).[92]

- Replace boron-burnable poisons rods (BPR) with lithium BPR's. In the USA such BPR are under development which contain $LiAlO_2$/Zr instead of boron. The production rate in a one GW$_e$ reactor is estimated at 80 grams per year,[93] and 6 grams per year by another reference[94]

- Replace single fuel or control rods with lithium-6 or insert breeding rods in empty grid spaces in a LWR. A maximum of about two grams of tritium can be bred within one year, if only one fuel rod in a PWR fuel assembly is replaced by a rod filled with as much lithium-6 as technically achievable, i.e., 0.1 g cm^{-3} within a volume of some 200 cm^3. Such a high yield per rod couldn't be achieved if several hundred target rods were in the reactor core at the same time. In a 1 GW$_e$ PWR, 600–900 target rods inserted in free control rod guide tubes could be used to produce annually 100 grams tritium.[95] Insertion of lithium targets in unused fuel positions, particular on the periphery of the reactor or in empty regions outside the reactor core (if available) would result in lower production rates.

- Use lithium coolant instead of sodium in a LMFBR, which could give a production rate of 1,000 g/(GWth-y).[96]

Case of breeding in excess of reported quantities

- This set of diversion paths will be relevant if a limited production for military purposes or for the initial inventory of a first fusion power reactor will be permitted and verified. The current worldwide production of tritium in fusion materials research can be estimated to be less than 0.5 grams per year.

Fuel Rod Path Based on Ternary Fission

One tritium atom is produced in roughly 10,000 fission reactions as a third fission product (ternary fission). Depending on the reactor type and fuel, some 1.6 to 3.1 g/(GWe-y) tritium are produced.[97] Most of it remains in the fuel rods. Release estimates from rods with zircaloy claddings range from 0.013 percent to 1.0 percent[98] unless the fuel is reprocessed or specially treated with heat. Within the fuel rod, the tritium is distributed in the cladding (5–15 percent), in the gas plenum (0–10 percent), and the rest in the fuel matrices.[99]

The fraction of tritium that is released in the aqueous or gaseous phase depends on the design and operation of the reprocessing plant as well as on the fuel type. Without decay correction, the tritium content of each ton of spent fuel from a LWR is about 0.062 –0.097 grams of tritium for burnups of 30 –40 GWth d/t.[100]

Allowing for decay after a cooling time of some 150 days and for some tritium remaining in wastes, the fraction of tritium available for release or recovering can be estimated to be 80 percent of the total tritium produced, i.e., 0.05 -0.08 g/t. From this, it follows that in a reprocessing plant for LWR fuel with a yearly capacity of 12.5 t (almost two orders of magnitude smaller than the typical size of a large commercial reprocessing plant), a maximum of one gram tritium is recoverable.

Several diversion modes can be imagined:

- At a reprocessing facility, tritium-bearing off-gases could be collected to extract tritium which would be in contrast to common practice.
- At a reprocessing facility tritium-bearing aqueous effluents could be collected to extract tritium which would also be in contrast to common practice.
- Unreprocessed spent fuel could be heated to extract the tritium. It is technically feasible to extract tritium from spent fuel without reprocessing.[101] The cladding of the fuel rods has to be opened and the fuel to be heated in an oven either in a vacuum or with an inert sweeping gas. A typical fuel

Table 4: Summary of tritium production and inventories, 1993

Facility Type by Numbers as in Table B.1 /Main Production or Flow Path	Annual Production/Throughput Rate (kg/y)			Cumulative Production/Stored Inventory (kg), (Decay Corrected)		
	i: Inadvertent d: Deliberate	c: Collected r: Released t: Throughput	Potential Production	i: Inadvertent d: Deliberate	c: Collected r: Released s: Stored Inventory	Still Extractable
1a,b/Ternary Fission	i 0.45	r < 0.01	---	i 3.2-8.8	r 0.03-0.09	2-7
1a,b/Lithium	d 0	---	10-70	---	---	---
1b,d/Heavy Water	i 3.0-4.4	r < 0.2	---	i ≈ 20	r ≈ 2	≈ 13
1c,d/Ternary Fission	i 0.002-0.004	r < 10^{-4}	---	---	---	---
1c,d/Lithium	d ≤ 0.5	---	10-20	---	---	---
1e USA/Lithium	d 0[a]	---	---	d 70 ± 25[b]	c 68 ± 25[c]	~0.7
1e USA/Heavy Water	d 0	---	---	i 1-2	c 0.05-0.1	~1-2
1e Russia/Lithium	d 0-3.4	c 0-3.4	4[d]	d 66[e]	c 65[f]	~0.5
1e Others[g]/Lithium	d < 0.25	c < 0.25	7[h]	d 2.5-5	c 2.5-5	~0.05
1f 1 GW_e fusion reactor, self-sustaining Tritium Breeding (fiction)/Lithium	---	---	180	---	---	---
3/Storage	---	t 0-1	---	---	s 1-3	---
4/Split to Release and Waste[i]	---	t 0.20-0.33	---	---	r 1-1.4	---
5/Storage	---	t 0.1-0.3	---	---	s 0.5-2	---
6/Extraction	---	t 2.0 ± 0.5	---	---	s 6.2 ± 0.2	---
7/Storage	---	t 0.03-0.05	---	---	s 0.4-0.6	---
8/Manufacturing	---	t 0.3-0.4	---	---	s 0.05-0.1	---

Table 4: Summary of tritium production and inventories, 1993 (Continued)

Facility Type by Numbers as in Table B.1 /Main Production or Flow Path	Annual Production/Throughput Rate (kg/y)			Cumulative Production/Stored Inventory (kg), (Decay Corrected)		
Environment/Nuclear Explosions	---	---	---	i 300-3000	r 30-300	---
Environment/Natural Production	i 0.1-0.4	---	---	i 1.5-6.7	---	---
Total	**2-8.6**			**450-3000**		

a. The last tritium producing reactor at Savannah River Plant was shut down in April 1988.
b. Production rate and stockpile estimates of (Cochran et al. (1987)[102] are extrapolated to end of 1993.
c. Total amount currently in the nuclear stockpiles and production pipeline. At least 1 percent of the produced quantity is lost to the environment, and about 1 percent is expected to be in radioactive wastes.
d. See table 2.
e. Production rate and stockpile estimates of (Cochran/Norris (1993)[103] are extrapolated to end of 1993 assuming annual production of 3.4 kg. There is not much sense in estimating the error of these figures because they are educated guesses.
f. Some 3 to 5 kg of this inventory has been with the nuclear warheads which remained on the territory of the Ukraine at the end of 1993 and some 3 to 4 kg in Kazakhstan. There was some tritium in Belorussia, too.
g. This includes the other nuclear weapon states China, France, and U.K. as well as the de-facto nuclear weapon states India, Israel, and Pakistan.
h. See table 2.
i. See stored inventory in facility type 5 (storage)

assembly of a PWR has e.g. 236 fuel rods each of which contains 2.3 kilograms uranium. From the figures given above, it follows that one significant quantity of tritium can be collected from some 25 spent PWR fuel assemblies.

Heavy Water Path Based on the Nuclear Reaction

$$D + n \rightarrow T + \gamma$$

Tritium is produced inadvertently in the moderator and coolant of a heavy water reactor during normal reactor operation through capture of a neutron by deuterium. Depending on the reactor type, the production rate via the heavy water path is 50 to 80 g/(GWt-y). A moderator of a typical CANDU has 290 tones of heavy water. At equilibrium it would contain about 2.4 TBq/kilograms (total content: 7 x 10^5 TBq, i.e., 2 kilograms). Various scenarios for the illegal removal of this tritium can be imagined. For example:

- Permanent displacement of tritiated heavy water in the heavy water reactor with pure heavy water in order to cheat any measuring device for tritium concentration.
- Unreported detritiation of tritiated heavy water from uncontrolled sources.
- Diversion of tritium from the storage of extracted tritium at the heavy water detritiating facility combined with manipulating the inventory measurement so as to pretend a larger physical inventory which matches with the book inventory.

Helium-3 path using the nuclear reaction

$$He\text{-}3 + n \rightarrow T + H$$

The advantage of helium-3 as raw-material for tritium production is its very high neutron cross-section (5327 barns for thermal neutrons). Since it is a gas, targets cannot be made with high density but on-line extraction of tritium from circulation helium-3 gas in a loop system can be realized.

- Helium-3 can be circulated through an additional system of pipes and pumps within the reactor core or to a gas separation system and back. The gas can either be released after a certain period of time to extract tritium or otherwise the gas could be processed in a continuous manner. A study made for CANDU reactors showed that direct activation of helium-3, contained in a closed loop would have a half-life (time required to convert half of the helium-3 inventory) of about 11 days. Thus, it would be essentially complete within a few weeks without any significant loss.[104] Another study was made on an experimental reactor loop of the NRX reactor at Chalk River Nuclear Laboratory (CRNL) in Canada.[105] The neutron flux reaching fuel elements was controlled by introducing helium-3 into a stainless steel coil in the annular space around the fuel. The expanded volume of the helium-3 system is 15 liters (2 grams). The production rate of tritium was 50 MBq/s when the reactor power and the helium pressure are both maximum (1 MPa). At a capacity factor of 100 percent, this experiment would produce 4.3 grams per year.

- After a rapid-power-excursion experiment with helium-3, the released gas can be collected to extract tritium. A neutron-absorbing gas like helium-3, withdrawn or inserted at a readily controllable rate, can provide the variable shielding needed to produce a well-characterized flux excursion at the location of the fuel pin under investigation. At the end of the experiment, the tritium produced can be collected. From a little under one gram to several grams a year could be produced in the course of routine ramp tests.[106]

- In a high temperature gas cooled reactor, the inadvertently-produced tritium in the helium coolant can be extracted. For a helium-3 content of 0.2 ppm the production rate may range from 0.06 to 0.23 g/(GWth-y) depending on the percentage of helium in the core (4–20 percent).[107] The production rate can be enlarged significantly by enriching the coolant in helium-3.

Illegal Removal of Tritium from Existing Stocks

Once tritium is available in any chemical and physical form there are numerous ways to illegally remove it for weapons purposes. In the following analysis they are summarized in two different categories. One is the removal from storages or handling processes of pure tritium, the other is the recovery of abandoned tritium. For most of these paths, the maximum divertable quantity depends on the total amount of tritium available and the relative accuracy of accountancy and inventory verification (see section on verification below).

Illegal removal from stored or handled tritium (facility types 6 to 8, see table 6), e.g.,

- Non-reported transfer of tritium out of a "material balance area" (MBA);
- Partial discharge of storages during transport;
- Overstate tritium content of waste;
- Claim release to the environment;
- Put only part (e.g., 80 percent) of declared quantity of tritium into self-powered paint or other products;
- Divert accumulated "hidden inventory;"
- Collect and purify all tritium which is produced in a research fusion reactor. 10^{-4} grams per year are produced by Deuterium-Deuterium Fusion in Tokamak experiments at an average level of 10^{16} DD/shot and 10^{4} deuterium shots per year.[108]

Unreported recovering of abandoned tritium (especially facility types 4 to 6), e.g.,

- Clandestine recovery and purification of tritium from waste. The contribution of waste to the unaccounted tritium at a tritium bulk handling facility can be expected to be small because the total waste per year is typically in the order of 1 percent of the inventory. The only exceptions are reprocessing plants which have large portions of tritium in the waste streams (in case of PUREX, some 20 percent).
- Clandestine recovery and purification of tritium from aqueous or gaseous effluents. The contribution of effluents to the unaccounted tritium at a tritium bulk handling facility can be expected to be small, because the total emissions per year are typically achieved to be less than 1 percent of the total inventory. The only exceptions are reprocessing plants which have large portions of tritium in aqueous effluents (in case of PUREX, some 80 percent).
- Clandestine recovery and purification of tritium from consumer products. The main difficulty of this approach is the clandestine collection of enough abandoned products. Remote airfield runway lights contain most tritium per unit (0.05-0.1 gram) but most other products contain much less (up to

0.01 gram). The useful life of a tritium gas-filled light source is from 8 to 10 years. After this time, a substantial fraction of their original charge will have decayed due to the tritium half-life of 12.3 years. The remainder is available for recovery and reuse. At least 20 runway lights or more than 200 large "Exit" signs need be collected to obtain one gram of tritium.

Summary of Diversion Path Analysis

The most efficient and economic way to produce tritium is the lithium path. This path is used in all recognized nuclear weapon states. He-3 targets are considered for future accelerator-based breeding systems. But this option, although technically feasible, is not currently followed on a significant scale. Canada is the largest producer of tritium for civilian purposes. It has the capacity to extract yearly up to 2.5 kilograms of tritium from the heavy water moderator and coolant of 21 CANDU power reactors (see above). From this diversion path analysis, it is obvious that a nuclear reactor can be regarded as the bottle-neck for today's tritium production.

Control measures could, therefore, likewise be confined to nuclear reactors, possibly supplemented by measures at fuel fabrication plants and other facilities with significant inventories or throughputs of tritium. Large commercial reprocessing plants with a throughput of more than 12.5 tones heavy metal per year, as well as detritiation plants, constitute a significant diversion potential because they can have a large annual throughput of tritium (up to 100 grams and 2.5 kilograms, respectively), but their total number worldwide is low (see table 6) and the recovery of diverted tritium from water or solid waste is extremely difficult to achieve clandestinely.

To assess the proliferation risk posed by various stocks of tritium in different facilities, it is of interest to develop a picture of flows and inventories of tritium at various places. Table 4 presents a survey of the world total tritium production rates (inadvertent, deliberate, potential) and inventories in different facility types and in nature. The facility types and numbers worldwide are given in table 6. The distribution of tritium inventories (in countries with more than one gram per year) over the globe are depicted in figure 3.

TWO APPROACHES FOR INTERNATIONAL TRITIUM CONTROL

There are several possibilities to control tritium on the international level.[109] In this section, two selected approaches are outlined. The focus is put on goals, rules, decision-making procedures (especially verification) and the most important dimensions of regime change. From this, the feasibility of the proposed tritium controls is assessed.[110]

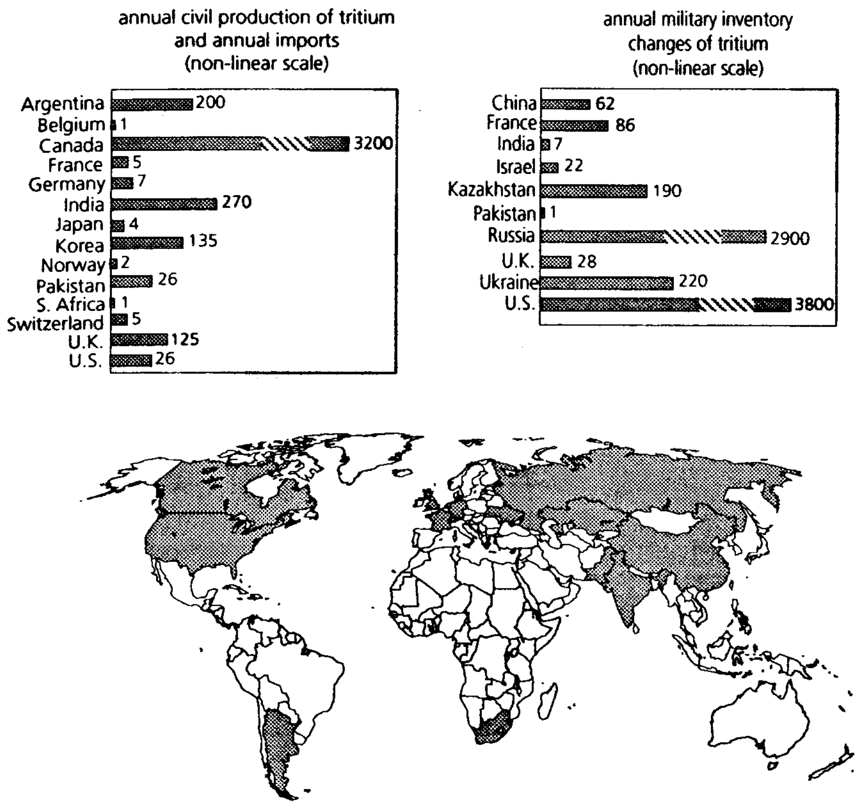

Figure 3: World map of tritium inventory changes. Due to the relatively rapid decay of tritium the dynamic of inventory changes is more important than absolute inventories. In the civilian sector inventory increases are larger than decreases, whereas this is the other way around in the military sector. For the latter, inventory decreases due to radioactive decay are shown since these data are better known than production rates. Numbers indicate grams per year.

The first approach is an expanded version of the much discussed verified cutoff for fissile materials. It includes a cutoff of the production of tritium for military purposes in addition to the production of plutonium and highly enriched uranium (HEU), and is, therefore, called "integrated cutoff" (ICO). The second approach envisages control of all civilian tritium production and handling facilities to make sure that no tritium is diverted for any nuclear weapon programs, and is named the "international tritium control system" (ITCS). The ICO is targeted at all declared and undeclared nuclear weapon states, the ITCS addresses all states.

The nuclear non-proliferation regime and the concept of "diffuse reciprocity:"

The history of the nuclear non-proliferation regime has shown that no existing instrument encompasses concrete rules and procedures for both dimensions (vertical and horizontal) of nuclear non-proliferation despite the fact that the interrelatedness between them is recognized in many instruments on the normative level. This led to the creation of a regime with instruments dealing with vertical and horizontal non-proliferation separately, as far as the level of specific rules and procedures is concerned (see table 5).[111] This concept of "diffuse reciprocity" between vertical and horizontal non-proliferation efforts evolved mainly in the early 1960's and is intended to reflect an "overall balance."[112] Especially the NPT shows this interrelatedness. It addresses horizontal proliferation specifically in terms of concrete rules and procedures. On the other hand, the NPT only defines the norm to reverse vertical proliferation and to work towards complete nuclear disarmament. But neither specific rules or procedures, nor a fixed schedule are laid down in this treaty in this regard. All the recognized nuclear weapon states had to do was to show the required "good faith" (Article VI) in arms control and disarmament negotiations.

A single international tritium control system that encompasses rules and procedures for both dimensions of nuclear proliferation would, therefore, be unprecedented. In order to find politically acceptable solutions regarding the international control of tritium the existing structure of the regime constitutes the basis on which all following considerations are made. Taking this qualified distinction between both dimensions of non-proliferation into account two proposals to control tritium will be presented (see table 5).

The implementation of both control systems would result in adding and changing certain rules and procedures within the regime, but its normative framework would remain the same. Current rules and procedures are not replaced but expanded to be able to include the control of tritium.[113]

Moreover, it is envisaged that both tritium control instruments would be implemented simultaneously. This is a vital requirement because an ICO without a control of civilian facilities, which is done in the ITCS, would leave a potential verification loophole. An ITCS, therefore, is not only a useful measure against the horizontal proliferation of tritium, but also constitutes an important compliment of the ICO. However, in case the ICO is implemented without the ITCS, verification may go beyond what is described in this paper to safeguard civilian stocks and facilities as well.

Tritium in a Fissile Material Production Cutoff

Background

In the 1960's, the USA made several proposals for a cutoff of fissionable weapon material production, namely plutonium and highly enriched uranium (HEU). At that time, such a cutoff was always refused by the USSR. In the 1980's, this was just the other way round. On June 15, 1982, Soviet Foreign Minister A. Gromyko suggested a cessation of production of fissionable materials as a useful initial stage for a comprehensive nuclear disarmament progress.

Encouraged by the recent progress in nuclear weapon reductions (INF, START I and II, and unilateral withdrawal of tactical and other nuclear weapons), proposals for deeper reductions and even for a nuclear-weapon-free world are under discussion. In this context, the cutoff proposal is back on the political agenda. The end of the "cold war" provides a political climate which seems to be more favorable than ever before to agree on such a cutoff.

On September 27, 1993, U.S. President Bill Clinton put forward a comprehensive approach to deal with fissile material, including the proposal for a "multilateral convention prohibiting the production of highly-enriched uranium or plutonium for nuclear explosives purposes or outside of international safeguards." In October 1993, Russia followed suit in proposing negotiations on this issue at the Conference on Disarmament (CD).[114] In November 1993,the First Committee of the CD for the first time in 15 years passed the draft resolution on banning the production of fissile materials for weapons by consensus. The United Nations General Assembly (UNGA) adopted accordingly Resolution 48/75L calling for negotiation on this issue in December 1993. The mandate for the CD to negotiate a cutoff agreement finally became effective in early 1995.

While Clinton's proposal identified HEU and plutonium as the fissile materials to be restricted, both UN resolutions did not specify the substances to be covered leaving open the possibility of restricting tritium production as well. However, tritium was scarcely mentioned in the discussions. The United States and Russia started detailed talks on fissile materials in May 1994. On June 23, 1994, Al Gore and Viktor Chernomyrden signed an agreement on the shutdown of Russia's three remaining production reactors by the year 2000. In return, the United States agreed not to restart its own shutdown production reactors and to help the Russians to find alternatives for generating the heat and electricity still provided by the Russian reactors. The agreement did not mention tritium. In its Annex, a list of plutonium production reactors is given

Table 5: The position of both proposals for international tritium control agreements within the main instruments of the nuclear non-proliferation regime.

Vertical Non-Proliferation	**Horizontal Non-Proliferation**
	CoCom (1949) IAEA (1957) Euratom (1957)
PTBT (1963)	
	Treaty of Tlatelolco (1967) NPT (1970)
SALT I (1972) TTBT (1974) PNET (1976) SALT II (1979)	NSG (1974; Dual Use-List in 1992)
	Treaty of Rarotonga (1985)
INF (1987) START I (1991) START II (1993)	
ICO (suggested in this paper)	ITCS (suggested in this paper)
Plus UN Disarmament Machinery:[a] •UN Special Session on Disarmament (UNSSOD) I-III (1978, 1982, 1988) •Conference on Disarmament (CD) •UN Disarmament Commission (UNDC) •Security Council (SC) •General Assembly (GA; Regular Session, First Committee, Several Ad Hoc Committees)	Plus National Export Controls (partially derived from CoCom and NSG agreements) Plus UN Disarmament Machinery: •Security Council (sanction mechanisms) •General Assembly

a. For details see Department for Disarmament Affairs (1984).[115]

which makes no mention of the shutdown K-reactor at the Savannah River Plant and of the two still operating light water reactors at Ozersk, named Lyudmila and Ruslan, each with a capacity of about 1000 MWth which are used to produce tritium and special isotopes, e.g. Pu-238. This constitutes a severe loophole with respect to verifying compliance with this agreement because they can serve as plutonium production reactors as well. In principal, all tritium production reactors can easily be used for plutonium production as well.

The possibilities to exchange the fertile materials lithium and uranium depend on the configuration of the core and the design of the fuel and target elements. Besides exchanging the target materials, a slight re-configuration of the core might be necessary. Such a procedure could be straightforward where target elements are separated from fuel elements. Where fuel and target material are integrated in the same elements, a substitution of a tritium breeding target to one that breeds plutonium could be costly. But there is no physical reason that impedes such substitution.

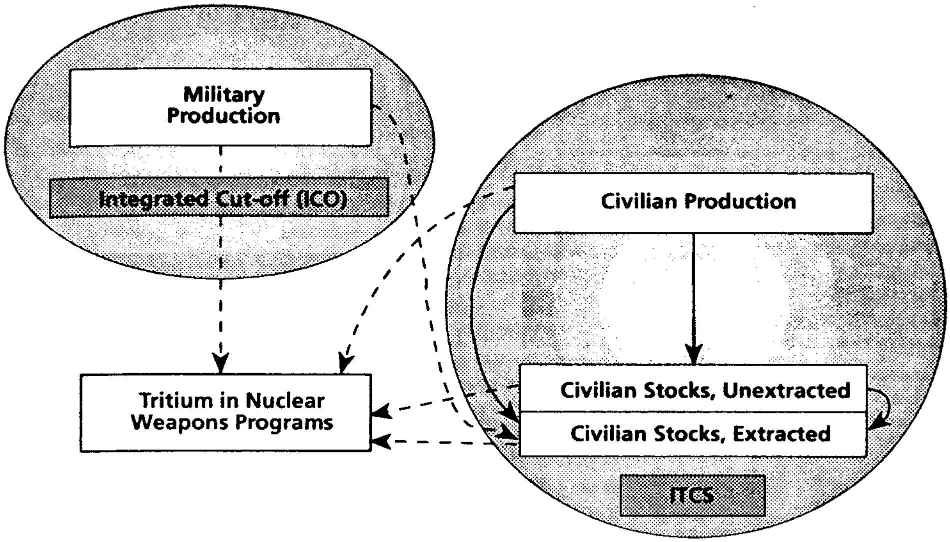

Figure 4: Effects on tritium proliferation paths by the implementation of the proposals "integrated cutoff" and the "international tritium control system." Solid line: Allowed tritium transfer paths. Dashed line: Tritium transfer paths foreclosed by both proposals for an international tritium control, ICO and ITCS.

In fact, the K-reactor, which is nearly identical to the plutonium production reactors L, P, R, and C at Savannah River Plant, has been used since 1983 for several years for the production of supergrade plutonium (3 percent in Pu-240).[116] The mission of this reactor was changed to tritium production after the shutdown in 1986 of the C-reactor which was dedicated to tritium production. Co-production of plutonium and tritium has been current practice. All U.S. production reactors have been shutdown since 1988. Plans to restart the K-reactor have been abandoned and the construction of a new production facility will probably not be started before the year 2000 (see above).

If under a "cutoff" agreement military tritium production reactors continued to operate, and if the production reactor uses HEU as driver fuel, this would cause additional complications for safeguarding military HEU stocks. However, it is very unlikely that a HEU production cutoff would be undermined because neither the United States nor Russia currently has HEU consuming production reactors under operation, and because there is enough HEU in the military stocks from dismantled nuclear weapons as well as from reprocessed submarine fuel to run such a reactor if needed.

The Impact of Military Tritium Production on the Verifiability of a Fissile Material Production Cutoff

To some extent, verification of a fissile material cutoff agreement,[117] could be based on remote sensing.[118] The parties to such an agreement would exchange the relevant data on their tritium production facilities, especially the location of production reactors. The operational status (operating, standby, cold standby, dismantled) of the declared military production facility could be verified by remote sensing using national technical means or by a future international satellite verification agency, possibly under IAEA or UN auspices. If the reactors were shutdown, the non-production of tritium can simply be verified by observing the absence of heat generation which indicates the inactivity of the production reactors. It is well known from various studies that the technological capabilities have progressed sufficiently and that this verification is feasible.[119] Reliance on remote fusing as a method of verification alone would allow states to avoid inspections that could involve unwarranted intrusion and proliferation risks.

However, if tritium production continued under a verified fissile material cutoff agreement, the non-production of plutonium in the tritium production facilities would have to be verified. This is because tritium and plutonium production are in competition with each other in consuming neutrons generated in the production reactor (or accelerator). Such a verification task would be much more intrusive than verification of an integrated cutoff which included tritium and it would provide insight into the tritium production rates.

To begin with, all activities of tritium production would have to be declared. Even without access to the tritium production facility, first indications for illegal plutonium production could be seen from the reactor operating cycles. The reactor would have to be shut down for reloading fuel and targets. In order to get supergrade plutonium, targets are typically irradiated for 30 days, and a period of 60 days is used for weapon-grade plutonium (6 percent in Pu-240). Tritium production typically requires longer production cycles of some 200 days. After such a long cycle, the quality of the isotope composition of plutonium would not be satisfactory for the standards of a nuclear weapon state.

More adequate verification requires access to the production reactor and intrusive control measures have to be performed. Inspections are required at least during the phase of reloading the core. All fresh fuel and target elements have to be non destructively checked against natural or depleted uranium which is the raw material used for plutonium breeding. This can be achieved by determining the uranium content and enrichment using neutron coincidence counters. Any such targets would have to be safeguarded by containment and surveillance so as to verify that they are not reprocessed to extract plutonium. All fuel and target elements will be tagged to be identified again at the next shutdown.

During operating cycles the presence of inspectors would not be required. The charge and discharge machine as well as the access to fuel and target positions in the reactor core would be sealed. Video cameras would be installed to survey the relevant areas inside the reactor building. Seals and video tapes would be examined at regular time intervals to verify that no changes of the reactor core have occurred in the meantime.

In order to verify that neutrons are used for tritium production and not at all for plutonium production, inspectors will have to have sufficient information to assess the rate of tritium production. This information has always been considered highly sensitive to the national security in all nuclear weapon states.

All in all, it is clear that the verification of a cutoff would be much easier and less intrusive if tritium was included in such an agreement. Moreover, a potential diversion path for plutonium would be closed.

Characteristics of an "Integrated Cutoff" (ICO)

The *goal* of the ICO is the non-availability of *fresh tritium supplies* for nuclear weapon programs as a means to inhibit vertical proliferation in states that possess nuclear weapons or weapons capability, and to pave the way towards complete nuclear disarmament, i.e., the denuclearization of those states. Only the recognized and de-facto nuclear weapon states are the potential member states of the ICO. The goal of the ICO is compatible with the principles and norms on which the entire nuclear non-proliferation regime is based. As a matter of fact, the normative framework of the regime would be reinforced by the implementation of an ICO.

The four tritium-related key *rules* of the ICO are the following: [120]

- No tritium will be produced for nuclear weapon purposes.
- All military facilities for the production of tritium are shut down and kept on a status which is comparable for both states. The status proposed here is called "cold standby."[121] This status must be verifiable.
- No new facilities for the production of tritium will be constructed or developed including new tritium production technologies such as, the accelerator-technology.
- No civilian facilities will be converted to military facilities or made use of for military purposes, and no tritium produced in civilian facilities will be transferred to military uses.

The main *advantages* of an ICO in comparison to a "fissile material cutoff" are:

- Compared to the "cutoff" proposal, the ICO would constitute a *stronger commitment* by the nuclear weapons states towards complete nuclear disarmament and is more suited to satisfy those demands by non-nuclear weapon states. Thus, although the proposed ICO would regulate tritium within the dimension of vertical non-proliferation, it contains also some significant repercussions for horizontal non-proliferation. Tritium constitutes an indispensable material for a sophisticated nuclear weapon program which aims at a nuclear arsenal based on second generation nuclear weapons. Since the maintenance of such a arsenal calls for a tritium supply on a continuous basis, whereas plutonium and HEU, once produced, last almost indefinitely, the ICO would add pressure to implement START I and II on schedule and eventually to negotiate cuts beyond START II that would not be evoked by a mere "cutoff."[122] These cuts will be accompanied by changes in related military doctrines and strategies.
- If the START-implementation proceeds as planned, there will be no need to resume tritium production in both nuclear superpowers for more than 20 years.[123] Therefore, any possible asymmetries regarding the impact of tritium shortages on the nuclear arsenal of the United States and Russia will be irrelevant for this period of time.[124]
- *Verification* of this "zero-approach" would be easier and less intrusive (see above). There would also be substantial *cost-savings effects* on two levels accompanying an ICO. Firstly, there are the costs to maintain and possibly even to build new tritium production reactors.[125] Secondly, there would be additional costs involved to verify a "cutoff," that would be absent within the ICO (see above).

The ICO could either last for a specific period of time or be concluded as a permanent treaty. In case of an unlimited treaty, the parties should have the opportunity to exit the ICO. An exit clause should take into account that it takes some time to restart a reactor which is on "cold standby" and further time until fresh tritium is available for nuclear weapon purposes. Therefore, the period after the declaration to exit could be relatively short; maybe three or six months. In the case of a limited approach, it could be agreed to hold a conference after the stipulated time has expired to decide on an extension of the ICO. The treaty would start out at the bilateral level between the United States and Russia and could last at least until the year 2010.[126] This date seems particularly suitable because both nuclear superpowers would have to resume tritium production not before 2016 to maintain their arsenals at the level agreed upon in START II and because six years is sufficient to construct a new production facility or restart a reactor on "cold standby."

The year 2010 would then be the most suitable time to hold the above mentioned extension conference. Any decision to extend the treaty would very much depend on the progress of the nuclear disarmament process, i.e., whether it has gone beyond START II by then. Also, an extension at that time could be combined with the inclusion of other recognized nuclear weapon states into this treaty (see below). If they cannot agree on an extension, the parties to the treaty are allowed to start constructing new facilities for the production of tritium or restart their facilities kept on "cold standby." Here the above-mentioned comparable status of the reactors, i.e., "cold standby," comes into play since the taking up of tritium production could put one side on a disadvantage if it can restart the reactor faster than the other.[127]

Depending on the duration of such a treaty, review conferences could be held periodically, since it could be necessary to make political or technical amendments or clarify interpretations of specific terms. Another reason lies in the three-step-approach taken in this treaty (see section on "Dimensions of Regime Change"). Review conferences could be the forum to decide on taking the second and third step respectively. Also, future parties to the treaty could be granted an observer status before becoming a full member. In case of a limited treaty, a review conference could be held before any decision is taken on an extension of the ICO.

Verification of an Integrated Cutoff

The technical aspects of verification of an ICO are discussed in Appendix B. In general, the parties to the treaty would declare an end to their tritium production for nuclear weapons, and would exchange the relevant data (operating characteristics, time of closure, technical data of the state of the facilities, etc.). The status ("cold standby") of the production facilities could be verified by remote sensing technologies (see above) and on-site inspections. The detection of possible clandestine production facilities is a sensitive issue within such an agreement. Since it is a rule not to build any new production facilities, there is a need to verify such a commitment. To some degree, existing space and airborne remote sensing activities are capable to detect clandestine facilities.[128]

In some cases, pulsed discharges of krypton-85 as indicator for clandestine plutonium separation could be observed from precipitation studies at distances of several hundred kilometers.[129] By following air trajectories, it might be possible to trace plumes back to suspected sources at distances of several hundred kilometers. The same is true for tritium production. Since tritium is a very mobile gas it is not possible to completely contain it. Tritium production and handling involves several processes during which a loss or a leakage of tritium cannot be avoided. Hence, tritium emissions can be used as an indication for clandestine tritium production and handling facilities.

Assuming a containment performance of one part per thousand per year, tritium facilities with inventories larger than 0.01 TBq could be detected from total tritium emissions measured at the stack. This is more than 4 orders of magnitude less than the significant quantity (one gram).* Such a detection could then trigger further on-site inspections to scrutinize the alleged illegal activities.

Safeguards on civilian tritium production facilities would be required, in addition, to ensure that there is no transfer of tritium to military purposes. With no military tritium production, the nuclear weapon states party to the treaty will, after some time due to tritium's decay, be in the same situation as the non-nuclear weapon states with respect to tritium. Therefore, tritium-control, if the ICO was successfully implemented, has to face the problem of diversion of tritium from civilian facilities to military purposes. This is covered in the ITCS approach put forward in this paper. If it is not simultaneously implemented, verification at civilian facilities may be foreseen within the ICO.

Dimensions of Regime Change Discussed for ICO

Regimes may vary over time or across the various regulated issues in several ways. Regarding the changes within the nuclear non-proliferation regime due to the inclusion of tritium control, the variables *strength, organizational form,* and *scope* are especially interesting when the effects of the ITCS and ICO on the regime are considered.[130]

A new agreement covering an additional issue like tritium would only be useful if it strengthens the nuclear non-proliferation regime. *Organizational form* refers primarily to the degree of institutionalization and requirements of an administrative apparatus. *Scope* refers to the range of issues a regime covers. The *strength* of the regime is measured by the degree of compliance. Therefore, a widening of the scope does not per se strengthen an international regime because states may not adhere to the agreed obligations. In fact, an additional regulated issue like tritium control might even weaken a regime if the parties to the treaty do not comply as set down in the respective agreement.

Furthermore, although any detection of rule violation indicates a weaker degree of compliance, its occurrence would not constitute already sufficient

* See Appendix B.

prove that a tritium control system must be considered a weak control instrument. Only if a systemic violation of rules occurs, the strength of the control instrument must be severely questioned.

For the ICO, several alternatives are possible for the *organizational framework* of the agreed rules. Here, a three-step approach is envisaged. The first phase involves the United States and Russia only. The ICO therefore starts out on a bilateral level. The more the nuclear arsenals of both states approach the level of the other recognized nuclear weapon states, the more they would eventually call on France, China, and the United Kingdom to participate in this process (second step), taking it onto the multilateral level. In a third step, the de-facto nuclear weapon states, India, Pakistan, and Israel, as well as any other state as appropriate, might be brought into this treaty.[131]

Even if this third step of the ICO was implemented, no new states would be brought into the nuclear non-proliferation regime. However, some states which are currently only at the periphery of this regime (Israel, India, Pakistan) would be tied closer to it. Since most current "cutoff" proposals only include both nuclear superpowers or all five recognized nuclear weapon states, the proposed ICO with its three-step-approach envisages a larger membership in comparison to the "cutoff." The main reasons for this approach lies in the unequal sizes of nuclear arsenals the respective states possess, as well as the different status of their programs. Although the outlined approach seems the logical solution to gradually increase the ICO membership, the treaty should be open to accession to any nuclear weapon state at any time.

The verification would probably remain on the bilateral level, as long as the parties to the ICO are the United States and Russia only. An international verifying body becomes especially recommendable once the membership is extended beyond the bilateral level and the other three recognized states become parties to the treaty. Since the first stage involves the United States and Russia only, a considerable amount of time will be "bought" for the development of international control procedures.[132]

The issues covered by a regime define the *scope* of a regime in terms of function. A "cutoff" for the production of plutonium and HEU alone, which is currently on the political agenda, would widen the scope of the nuclear non-proliferation regime. The inclusion of tritium, i.e., an ICO, would mean a widening of the scope of the current "cutoff" proposals under discussion, and of the entire nuclear non-proliferation regime.

The *strength* of a regime is measured by the degree of compliance of its parties/adherents. Although the parties to the ICO would formally and legally binding state their political will to comply, governments and national interests might change and "cheating" remains a problem. Another problem would be possible diversion activities by subgovernmental groups. Therefore, technical measures of verification will be necessary.

The International Tritium Control System (ITCS)

Characteristics of ITCS

This approach to tritium control deals with the dimension of horizontal proliferation. All states of the international system are envisaged as members of such an international agreement on a non-discriminatory basis, since it covers all civilian facilities producing or handling tritium worldwide.[133]

The *reason for an ITCS* is that all tritium originally produced or handled in civilian facilities can also be used for nuclear weapon purposes which is due to the ambivalent nature of this material. The *goal* of the ITCS is to detect and deter illegal diversions of tritium from civilian facilities for military purposes.

The four *rules* of this tritium control system are:

- No tritium produced in civilian facilities will be made available to any nuclear explosion purposes anywhere.[134]
- No tritium will be exported to states not party to the treaty.[135]
- States party to the treaty may acquire tritium by import or indigenous production for civilian purposes provided they carry out accountancy measures, report the data (including technical data of the state of the facilities, declaration of production capacities and actual production, important especially for HWR and related extraction facilities, declaration of present tritium stocks, accountancy records) to the supervising international agency, and accept inspections of all their tritium facilities and stocks (for the verification details see below).
- If the accumulated amount or annual throughput of tritium (including imports and indigenous production) in a state party to the treaty exceeds the military significant quantity of one gram, the tritium will be subject to inspection. This includes the verification of the end use of the exported tritium.

The treaty could last for a specific period or be concluded infinitely. As with the ICO, if an unlimited treaty was concluded, the parties should have the opportunity to exit the ITCS. In case the ITCS would be concluded for a limited period, an extension conference could already be envisaged in the treaty.

Depending on the duration of such a treaty, review conferences could be held periodically since it could be necessary to make political or technical amendments or clarify interpretations of specific terms or words. Moreover, if the ITCS was of limited duration, an assessment of its achievements should be made before a decision about the possible extension is taken.

Verification of ITCS

The discussion on the technical aspects of safeguards in Appendix B clearly shows that the ITCS can be verified. The facilities of the parties to the treaty, in which tritium is deliberately or inadvertently produced or otherwise existent (including industrial or scientific facilities with an inventory or annual throughput of more than one gram of tritium), will be inspected. As a precondition, an efficient national system of tritium accountancy has to be in place and all activities have to be declared. Most of the affected facilities are identical to those already inspected by the IAEA. If the IAEA inspected those facilities, they would have to perform only few additional tasks (for the technical aspects of verification see Appendix B).

Since the verification tasks of the ITCS are comparable to those carried out by the IAEA for plutonium and HEU, as indicated above, it seems worth while considering such a "tritium-mandate" for the IAEA. The IAEA is the only international organization within the regime that carries out verification tasks worldwide and without regional restrictions like Euratom or OPANAL. In fact, if the NPT was amended to cover tritium, the IAEA would automatically become the responsible verification agency.

The verification tasks regarding tritium are compatible with the principles and norms of the IAEA Statute. According to Article III,5 of the IAEA Statute, the Agency is authorized: "To establish and administer safeguards designed to ensure that special fissionable and *other materials*, services, equipment, facilities, and information ... are not used in such a way as to further any military purpose" (emphasis added). However, such an inclusion would necessitate an amendment of the model agreement INFCIRC/153 from 1971 or a new model agreement could be drawn up between the states party to the ITCS and the IAEA. The latter could be done by using the structure of INFCIRC/153 and applying it specifically to tritium. Then, all rights for the IAEA as the verifying agency for plutonium and HEU would apply to tritium likewise, including the right for "special inspections" (INFCIRC/153, paragraph 73).

If the IAEA was not the verifying agency, a new instrument would have to be created to perform these tasks. However, the creation of a new international agency with a "tritium control mandate" would be difficult in terms of costs and political acceptability. Since there does not seem to be a high political acceptance for a separate verification agency solely for tritium, [136] the IAEA seems to be the "natural" solution.

Dimensions of Regime Change Discussed for ITCS

There are several alternatives for the *organizational framework* of the agreed rules. The ITCS could be considered as a treaty in its own right. Alternatively, it could be part of an existing regime instrument which, for that matter, would have to be amended. There are a lot of similarities regarding the control of nuclear materials carried out by the IAEA and the control of tritium, as proposed in the ITCS. It can easily be concluded from the scenario outlined above that the NPT could be the treaty to control tritium. Decision procedures for a possible amendment of the NPT are in place (Article VIII). The amendment could be accomplished by changing the text of the treaty or by adding a protocol. The NPT encompasses all the elements which are necessary to control tritium on the international level, but it has a lot of deficiencies.[137]

So, if tritium control is included into the NPT, all its problems and limitations will be inherited as well. However, an opening of the NPT would probably bring up numerous proposals by the parties to change this treaty. In such a difficult bargaining situation without a real prospect of a settlement, the negotiating parties typically fall back on the original agreement without any changes being made. This could eventually bar the NPT from covering any form of tritium control. Therefore, it will be a matter of prudent negotiating by the parties proposing the ITCS within the NPT framework to deal with this problems. Alternatively, an additional protocol to the NPT could be concluded. Signature and ratification of a protocol can be made separately by individual NPT member states which has the advantage of keeping the NPT in force, and not making the existence of the entire treaty, which then would include tritium, dependent on an often lengthy ratification process. However, such a protocol would still be treated by the parties as an opening up of the NPT since a protocol has to be regarded as an integral part of a treaty.

Alternatively, a separate international agreement, modelled after the INFCIRC/153 and especially designed to control tritium, might be an adequate solution. But no matter how the ITCS will be organized, the continuance of the NPT or the replacement by an equivalent agreement is a condition *sine qua non* to achieve the proclaimed goal of a tritium control system since it makes no sense to control tritium but not Plutonium and HEU.

Within this dimension of horizontal proliferation, the *scope* of the regime in terms of function would be widened since a new material would be added to the materials currently controlled. Within the issue of export controls, the scope would also be widened in terms of function since it requires the control of end use, if the recipient state accumulates more than one gram of tritium. Moreover, the ITCS requirement of "fullscope safeguards" goes beyond the wording of the NPT, and could, therefore, complicate an inclusion into the

NPT. However, "fullscope safeguards" have already become common non-proliferation policy in most of the major states exporting nuclear weapon related materials and technology. Therefore, "fullscope safeguard" could be agreed on in an additional protocol to the NPT and then apply to plutonium, HEU and tritium likewise.

It can be expected that a state that has accepted the NPT and its underlying principle of nuclear non-proliferation would also accept additional tritium controls. Therefore, the *strength* of the NPT would not suffer as far as *compliance* of the parties is concerned in case the ITCS would be made a part of the NPT. In fact, since some of the rules of the ITCS are tighter than the NPT rules (see above), the NPT could profit from the ITCS because there could be a spill-over effect if the ITCS rules can prove their effectiveness in terms of compliance. In any case, verification has to be used to detect and deter "cheating," in this case illegal diversion of tritium from existing civilian stocks.

The Relationship Between ICO and ITCS

Although the implementation of just one instrument (ICO or ITCS) would already tighten the nuclear non-proliferation regime, it is recommended in this paper to implement both interrelated instruments simultaneously and on equal terms in order to achieve a tritium control which is more balanced and less discriminatory in its horizontal as well as vertical dimension. Otherwise, verification loopholes would be left. If both were implemented, "fresh tritium" would only be produced in civilian facilities and used for civilian purposes. Existing military stockpiles would not be replenished and decay within a few decades (see above). If the ITCS was implemented alone, the discriminatory nature of the entire regime would be reinforced because once again the nuclear weapon states would be treated less strictly. On the other hand, if the ICO was implemented alone, the necessity to control tritium within the civilian sector would become even more obvious and the demand for an ITCS would become stronger so as to make sure that no nuclear weapon state could clandestinely acquire tritium from civilian sources.

The ITCS, especially if it was made a part of the NPT, could theoretically be merged with the ICO. It could then constitute a comprehensive control system encompassing tritium, plutonium and HEU and dealing with horizontal and vertical proliferation together. Such a control system could be verified entirely by the IAEA, providing this organization obtained the mandate to routinely control military facilities for the non-production of all three nuclear weapon materials. However, such an approach would dissolve the distinction between instruments dealing directly with horizontal and vertical proliferation, i.e., the concept of diffuse reciprocity (see above), on which the entire nuclear non-proliferation regime has been based so far. This can only be done under the premises that the discriminatory nature of this regime would be perceived as politically unacceptable and the international community is prepared to change this situation.

CONCLUSIONS

The political and technical analysis in this paper argues that an international control of tritium is desirable and feasible. This is in contrast to a widespread perception that tritium controls would not be of high importance and would pose a disproportionate burden on the countries and facilities under inspection.

Though it is true that tritium is not a necessary material for first generation nuclear weapons, its importance to de-facto nuclear weapon states aiming at vertical proliferation has been increasingly acknowledged on the international level. Even the potential roles of tritium in the nuclear disarmament process has been under discussion, although without any practical consequences so far. But these perceptions have created a demand for some kind of international tritium control and its inclusion in the nuclear non-proliferation regime.

Consequently, some instruments against horizontal proliferation took tritium control onto the international level (CoCom between 1986 and 1994, NSG since 1992 and exchange of letters between Canada and Euratom since 1991) to complement existing measures on the national level (export control and radiation protection legislation). Thus, the issue of tritium control is proven to be regime capable. However, these control instruments represent only a modest, discriminatory, and insufficient degree of control against the horizontal proliferation of tritium.

Moreover, nothing is in place to avoid or reduce the use of tritium in support of vertical proliferation, although tritium represents a crucial ingredient in sophisticated nuclear arsenals because they allow warheads to be made smaller and lighter while retaining the same yield.

The political assessment presented here concludes that the scope of the nuclear non-proliferation regime would be widened in a meaningful way through tritium control which would provide the regime with two additional control instruments and thereby tighten the nuclear non-proliferation regime as a whole. It appears to be the right time to move towards such a more systematic international tritium control.

The paper argues that the expected burdens and difficulties in verification of tritium control are based on misconceptions. Taking into account the existing tritium stocks and sources as well as the conservative assumptions on verification goals (significant quantity as low as one gram), verification of non-diversion is technically feasible at reasonable costs and *there are no fundamental problems regarding the introduction of verification procedures.*

In this paper, a comprehensive, systematic, and eventually non-discriminatory approach towards tritium control on the international level is outlined and analyzed encompassing measures against horizontal as well as vertical proliferation. It is aimed at the *eventual elimination of any nuclear weapon uses of tritium and the control of actual and potential civilian tritium production facilities and tritium inventories.* Following the structure of the nuclear non-proliferation regime, two different sets of obligations to achieve the proclaimed goals are proposed depending on the nuclear weapon-status of states.

As far as horizontal non-proliferation is concerned, an International Tritium Control System (ITCS), controlling actual and potential civilian tritium production facilities and tritium inventories is proposed. In general, as summarized earlier and discussed in detail in Appendix B, tritium control procedures for non-production in civilian facilities can rely on current IAEA type nuclear safeguards. Tritium accountancy is already applied and technically proven for radiation protection purposes with accountancy capabilities comparable to the requirements for nuclear safeguards. In some cases, additional measures may be introduced some of which in turn enhance the efficiency of nuclear safeguards.

As shown in Appendix B, specific procedures to verify the non-diversion of tritium would have to be introduced at a limited number of facilities (up to some 50 worldwide, depending on the membership) in which no nuclear materials but tritium are handled. However, since the verification goals, tasks and procedures are very similar to those required for IAEA nuclear safeguards, it would be a "natural solution" to assign a "tritium control mandate" to this agency.

To complement an ITCS and to extend tritium controls to existing nuclear weapons arsenals, the paper proposes inclusion of tritium in a general cutoff of fissile materials for weapons (an ICO). Such inclusion would also effectively address problems caused by a continued production of tritium on the verifiability of a fissile materials cutoff. In the ICO, fresh supplies of tritium for nuclear weapon purposes would be stopped in a verified manner as a measure to support a sustained nuclear disarmament process.

From the organizational and financial perspective, there would be no extensive burden if tritium was added to a fissile materials cutoff. Since no tritium will be produced for nuclear weapon purposes, verification would be focused mainly on assuring continued non-production at military production facilities which are either dismantled or placed on "cold standby." Although either ICO or ITCS alone would strengthen the nuclear non-proliferation regime, this paper recommends to implement both interrelated instruments simultaneously and on equal terms. If implemented, *there would only be controlled civilian sources of tritium.* Compared to the existing controls the proposed tritium control system would also be more balanced regarding its horizontal and vertical dimensions and consequently less discriminatory.

ACKNOWLEDGEMENTS

This study was carried out within IANUS and funded by the Center for Interdisciplinary Studies in Technology (ZIT - Zentrum für Interdisziplinäre Technikforschung) of the Technical University of Darmstadt, Germany and by the Volkswagen Foundation. Special thanks to Egbert Kankeleit who provided a fruitful working environment within the Institute for Nuclear Physics at Technical University Darmstadt.

NOTES AND REFERENCES

1. From the regime-theoretical viewpoint an international regime consists of four elements: principles, norms, rules and decision-making procedures. Principles and norms constitute the normative framework of a regime, while rules and decision-making procedures form its substructure. An international regime has been defined by these four elements around which actor expectations converge in a given issue-area. See Krasner, Stephen D., "Structural Causes and Regime Consequences: Regimes as Intervening Variables," in Krasner, Stephen D. (ed.), *International Regimes*, Ithaca, p. 1 (1983).

2. Whereas instruments against horizontal proliferation have been translated into rules and decision-making-procedures and thereby several instruments have been created in the 1950's, '60's, and '70's (e.g., NPT, IAEA, Nuclear Suppliers Group, Treaties of Tlatelolco and Rarotonga), instruments against vertical proliferation had been very much neglected until the late 1980's.

3. In addition, South Africa had also acquired clandestinely some 30 grams of tritium from Israel in the late 1970's.

4. However, the quantities in civilian use are marginal in comparison to the military stocks (less than one percent).

5. Bundesgerichtshof, sentence date January 31, 2StR 250/91 (1992).

6. This is exemplified by the demands of three Western European fusion labs, which exceeds the current total inventory of civilian fusion research labs worldwide. See below.

7. The total of military stocks can be estimated as 110 to 170 kilograms. Civilian stocks are around 23 to 28 kilograms and most of it (2/3 to 3/4) is not separated which

makes control measures easier. Not included are tritium inventories in the atmosphere and hydrosphere. See table 4 in which the world total quantities of tritium produced (inadvertently and deliberately), tritium actually extracted or still extractable, and the potential production capacity are summarized.

8. Colschen, L.C. and M.B. Kalinowski, "Can International Safeguards be Expanded to Cover Tritium?" IAEA-SM-333/27, Proc. IAEA Volume, pp. 493-503, Symposium on International Safeguards, Vienna (March 14-18, 1994).

9. The IAEA has organized and published numerous studies on safe handling and waste management of tritium.

10. The more this argument gains importance, the less the NPT safeguards are considered to be effective. The apparent inefficiency of these safeguards has been plainly demonstrated again by the most recent examples of Iraq and North Korea. However, in the first place, tritium controls would aim at preventing tritium exports to NPT holdouts which have to be considered de-facto nuclear weapon states.

11. The NSG has had tritium as well as tritium technology on its dual-use list since April 1992. But this instrument is informal and legally not binding. The second instrument consists of an agreement between Canada and a regional organization Euratom. In this agreement, Euratom has been handed the mandate to control tritium shipments from Canada to Euratom member states and their end-use in civilian fusion research programs. It is a limited approach as far as the number of involved producer and user states, and also where the purposes of use are concerned. The third instrument was the Coordinate Committee for Multilateral Export Control (CoCom). CoCom, which ceased to exist as of March 31, 1994, included tritium on its list since 1986. See also section "Current Tritium Controls."

12. The term "vertical non-proliferation" as used in this paper, encompasses three different phases to limit, stop and reverse the vertical proliferation process, i.e., nuclear disarmament. In this paper the focal point is on nuclear disarmament.

13. This rate would just match the radioactive decay of tritium. Nuclear Control Institute (NCI), American Academy of Arts and Sciences (AAAS), *The Tritium Factor*, Washington/Cambridge (1988). See also Mark, J.C. *et al.*, "The Tritium Factor as a Forcing Function in Nuclear Arms Reduction Talks," *Science* **241**, p. 1166 (1988); Sutcliffe, W.G., "Limits on Nuclear Materials for Arms Reduction - Complexities and Uncertainties," *Science* **241**, p. 1166 (1988).

14. See Appendix A.

15. Kalinowski, M.B., L.C. Colschen and P. Leventhal, "Why and How Tritium Should be Considered Under a Verified Cutoff of Fissile Materials Production," Proc. of the 42nd Pugwash Conference on Science and World Affairs in Berlin (September 11-17, 1992), Volume I, pp. 473-480, Singapore *et al.* (1994).

16. Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Comparative Documentation. National Regulations of Accounting for and Control of Tritium," IANUS-2/1991, Darmstadt (1991).

17. The limits are quoted in giga-Bequerel (GBq) with 1 GBq = 10^9 Bq. For comparison, roughly 3.6 x 10^{14} Bq = 360,000 GBq are one gram. Some of the values stated in table 1 may well have changed in the meantime, because the regulating authorities of six out of 20 countries stated that their export regulations were under revision at the time of the inquiry and four countries answered that they believed the tritium regulations were inadequate. See also Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Com-

parative Documentation. National Regulations of Accounting for and Control of Tritium," IANUS-2/1991, Darmstadt (1991).

18. According to CoCom regulations, licences were required for exports of equipment especially designed for the production or recovery of tritium and for the export of more than 3,700 GBq tritium and mixtures in which the ratio of tritium to hydrogen by atoms exceeds 1 part in 1000. Exemptions applied for certain commercial products containing tiny amounts of tritium like luminous paint and ion generating tubes.

19. The remaining six CoCom member states were not included in the review. See also Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Comparative Documentation. National Regulations of Accounting for and Control of Tritium," IANUS-2/1991, Darmstadt (1991).

20. A political reform process will result in a new control body with probably partly liberalized export controls. The new controls will be in all likelihood targeted at only a few so-called "rogue states" like Iran, Iraq or North Korea. Also, according to Lynn Davis, Undersecretary of State for International Security of the United States, the new control body will contain no provisions to prevent a particular export by a member state, but its character would be primarily consultative. See Arms Control Reporter, "The End Of CoCom - April 1," p. 250.B.30, idds 5-94, Cambridge (1994).

21. Report of Main Committee II of the 4th NPT Review Conference, Document NPT/CONF.IV/MC.II/I (September 10, 1990).

22. The NSG were dormant since the late 1970's and revived by a U.S. initiative in the aftermath of the second Gulf War. Twenty-seven states adhere to that instrument of multilateral export control. This means that most, but not all, nuclear suppliers are part of this informal forum.

23. States are obliged to inform the other adherents to the NSG when an export has been prohibited.

24. Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Comparative Documentation. National Regulations of Accounting for and Control of Tritium," IANUS-2/1991, Darmstadt (1991).

25. Personal communication with U.S. Department of State on March 31, 1992.

26. Personal communication with U.S. Department of Energy on March 24, 1992.

27. Miller, M. and A. Cohen, "Defusing the Nuclear Mideast," *New York Times*, p. op-ed (May 30, 1991).

28. United Nations, "Establishment of a Nuclear-Weapons-Free Zone in the Region of the Middle East," A/45/435 (October 10, 1990).

29. See United Nations (1990), paragraphs 116 and 117.United Nations, "Establishment of a Nuclear-Weapons-Free Zone in the Region of the Middle East," A/45/435 (October 10, 1990).

30. The tritium is extracted from heavy water to reduce occupational radiation dosage and emissions. Its potential commercial value has only been an issue since the mid-1980's. Unless otherwise stated, figures in this section are valid for December 31, 1992.

31. Sheppard, R., "Tritium Industry May Net $30 Million a Year," *Globe and Mail*, p. B5 (May 11, 1988).

32. Fusion Canada - Bulletin of the National Fusion Program, Issue 21 (August 1993).

33. A study ordered by Ontario as early as 1985 evaluated the proliferation dangers of potential tritium sales by Ontario Hydro. Canadian Environmental Law Association, "The Potential Use, Sale and Export of Tritium By Ontario," Report of The Tritium Issues Working Group, Toronto (February, 1986).

34. Private communication with the AECB of Canada on May 6, 1992.

35. For further details see Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Comparative Documentation. National Regulations of Accounting for and Control of Tritium," pp.32-33, IANUS-2/1991, Darmstadt (1991).

36. Euratom and Canada, "Exchange of letters between the European Atomic Energy Community (Euratom) and the Government of Canada amending the Agreement between the European Atomic Energy Community and the Government of Canada for cooperation in the peaceful uses of atomic energy of 6 October 1959," EL/CEEA/CDN/GER (May, 1991). Reproduced in *Official Journal of the European Communities* No C 215/5, (August 17, 1991).

37. The provisions for tritium supply are modelled after the extension which was made earlier for heavy water. After the conclusion of the new agreement, a Joint Technical Working Group (JTWG) has been established to work out the modalities of tritium controls and accounting methods. In the joint working committee, Canada is represented by the AECB and Europe amongst others by Euratom.

38. Molgat, Daniel, "Letter from the Government of Canada to Euratom," *Official Journal of the European Communities*, No C 215, pp. 7-8, (August 17, 1991).

39. U.S. General Accounting Office, "Controls Over the Commercial Sale and Export of Tritium Can Be Improved," GAO/RCED-91-90 (March, 1991). See also Hibbs, M., "Nonproliferation Bill Introduced to Restrict Export of Dual-Use Items," *NuclearFuel*, p. 16 (July 8, 1991); Zuercher, R.R., "NRC, State May Seek Written Assurance Targeting Retransfer of U.S. Tritium," *Nuclear Fuel*, p. 16 (August 5, 1991).

40. Die Atomwirtschaft, "Mehr Tritium verfügbar," (June 1959), p.268.

41. Tritium was primarily welcomed as a pure beta emitter to replace radium in self-powered light sources whose gamma radiation causes unacceptable radiation doses.

42. Probably the best available survey on international trade of tritium is given in Colschen, L.C., M. B. Kalinowski, and J. Vydra, "Comparative Documentation. National Regulations of Accounting for and Control of Tritium," IANUS-2/1991, Darmstadt (1991). Imported quantities of 14 countries, including the then by far largest importers, Canada, Switzerland, and United Kingdom, for various periods in the 1980's were given in that documentation. The sum of the average yearly import of these countries is 78,000 TBq or about 217 g. The same tritium may be counted more than once, e.g., due to re-exports in the form of luminous paint. In average 58,000 TBq of fresh tritium gas were supplied by the USA each year.

43. Tritium recovery from the heavy water of the high flux reactor at the Laue Langevin Institute in Grenoble was able to separate up to 16 grams per year. This facility was operating since 1972 and is currently put on standby.

44. Alkor Technologies, a private company in St. Petersburg considers bulk exports of tritium. The military facility at Ozersk (former Chelyabinsk-65) together with the state-run Radium Institute in St. Petersburg are planning to manufacture luminescent signs containing tritium.

45. If ever a fusion power reactor would come into operation it would contain a steady inventory of a few kilograms and burn about 180 kilograms per GWe-y.

46. These estimated quantities include not only the amount of tritium actually inserted in the warhead, but also its share of the working inventory in the production and replenishment "pipeline."

47. For a detailed description of the physical principles see Schaper, A., "Kernwaffen der ersten und zweiten Generation: Forschung und Entwicklung," in E. Müller, G. Neuneck, *Rüstungsmodernisierung und Rüstungskontrolle.*, Baden-Baden, pp. 71-90 (1991).

48. Hansen, C., *U.S. Nuclear Weapons. A Secret History*, Arlington, Texas (1988).

49. In 1953 the Soviet Union tested Joe 4, a single-stage boosted fission weapon with a yield in the 400 Kt range. See also Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, Washington (1993).

50. For details see Colschen, L.C. and M.B. Kalinowski, Die Kontrolle der militärischen Nutzung von Tritium, IANUS-1 (1991).

51. This table includes all plutonium production reactors since tritium production is in competition to plutonium production and can be co-produced with plutonium in the same reactor at any percentage from 0 to 100.

52. See in Arms Control Today, U.S. Tritium Reactor to Remain Closed, (May, 1993), p.27.

53. The Defense Program and Energy Research of the U.S. Department of Energy are believed to have joined forces in early 1995 to develop an accelerator-driven pulsed neutron source to satisfy tritium needs for nuclear weapons as well as to achieve neutron-scathering for material and other basic research. It is not clear, however, whether such a source that is built for tritium production would also be suitable for neutron-scathering. The former requires large numbers of neutron in a relatively large area whereas the latter calls for a more focused beam of neutrons.

54. An estimation of total tritium in military stocks of the USA was made in Cochran, T.B. *et al.*, *Nuclear Weapons Data Book. Volume 3: U.S. Nuclear Warhead Facility Profiles*, Cambridge (1987). The figure given here is an extrapolation to their estimate taking into account further production and radioactive decay.

55. Norris, R.S. and W.M. Arkin, "U.S. Nuclear Weapons Stockpile," (July, 1994), *Bulletin of Atomic Scientists*, pp. 61-63 (July/August, 1994).

56. According to the current official U.S. position, the year 2012 would be the appropriate date (see below).

57. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, pp. 45-47, Washington (1993).

58. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, p. 43, Washington (1993).

59. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, p. 154, Washington (1993), assumed an annual production rate of 7.3 kilograms per year until 1984 and 3.4 kilograms per year in 1985 and 1986.

60. Joint Publications Research Service (JPRS), "Selections from China Today: Nuclear Industry," Science and Technology, China, Report JPRS-CST-88-002, Washington (January 15, 1988).

61. Cochran, T.B. *et al., Nuclear Weapons Data Book. Volume 3: U.S. Nuclear Warhead Facility Profiles*, Cambridge (1987).

62. Commissariat a l'Energy Atomique (CEA), "Rapport Annuel" (1962).

63. Hugony, P., H. Sauvage and E. Roth, "La Production de Tritium en France," *Bulletin d'Information Scientifique et Technique*, No. 178, pp. 3-17 (February, 1973), English translation available as, "Tritium Production in France," ERDA-tr-286.

64. Barrilot, B., "Fabrication des Armes Nucleaires en France," Centre de Documentation et de Recherche sur la Paix et les Conflits, Lyon (1991).

65. Gsponer, A., "La Bombe a Neutrons," *La Recherche* **158**, p. 1131 (September, 1984).

66. Barrilot, B., "Fabrication des Armes Nucleaires en France," Centre de Documentation et de Recherche sur la Paix et les Conflits, Lyon (1991).

67. Albright, D. and T. Zamora Colina, "India, Pakistan's Nuclear Weapons: All Pieces in Place," *Bulletin of Atomic Scientists*, **45**(5), pp. 20–26 (1989).

68. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, Washington (1993).

69. National Resources Defence Council (NRDC), "Kysthym Complex and Soviet Nuclear Materials Production," Fact Sheet, Washington (1989).

70. Cochran, T.B. *et al., Nuclear Weapons Databook, Vol. 4: Soviet Union's Nuclear Weapons*, Cambridge (1989).

71. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, Washington (1993).

72. Cochran, T.B. *et al., Nuclear Weapons Data Book. Volume 3: U.S. Nuclear Warhead Facility Profiles*, Cambridge (1987).

73. Cochran, T.B. *et al., Nuclear Weapons Data Book. Volume 3: U.S. Nuclear Warhead Facility Profiles*, Cambridge (1987).

74. Ragheb, M.M.H., "Implementation Considerations of Coupling Dedicated Fissile and Fusile Production Fusion and Fission Reactors," Atomkernenergie/Kerntechnik **38**, pp. 85-90 (1981).

75. Quoted in the Arms Control Reporter 10,6 (1991) 602.B.197.

76. Such a plant is believed to be a small scale pilot plant and under construction in 1989. See also Albright, D. and T. Zamora Colina, "India, Pakistan's Nuclear Weapons: All Pieces in Place," *Bulletin of Atomic Scientists*, **45**(5), pp. 20–26 (1989). But if all Indian reactors ran at a capacity factor of 70 percent, some 150-230 grams of tritium would be produced in their heavy water per year.

77. See PPNN Newsbrief, first quarter 1994, page 12.

78. Report of the 7th UNSCOM inspection in Iraq, 1991. The natural abundance of Lithium 6 is 7.5 percent.

79. See PPNN Newsbrief, first quarter 1994, p. 12.

80. Albright, David, "South Africa's Secret Nuclear Weapons," *Institute for Science and International Security Report* (May, 1994).

81. Albright, David, "South Africa's Secret Nuclear Weapons," *Institute for Science and International Security Report* (May, 1994).

82. For a more comprehensive overview of more than 50 different paths see Kalinowski, M.B., "Monte Carlo Simulation of Neutron Coincidence Collar Response to Burnable Neutron Poisons in PWR Fuel Assemblies," Paper IAEA-SM-333/29, Proc. IAEA Symposium on International Safeguards, Vienna (March 14-18, 1994), Volume **2**, pp. 434-498.

83. Since mercuric impurities turn lithium red, the product was given the code-name "red mercury" in the former Soviet Union. See also Hibbs, M., " 'Red Mercury' is Lithium-6, Russian Weaponsmiths Say," *Nucleonics Week* (July 22, 1993). There are other explanations for red mercury wandering around as well.

84. CFFTP, "Tritium Supply for Near-Term Fusion Devices," CFFTP-G-88024 (May, 1988).

85. Ragheb, M.M.H., "Implementation Considerations of Coupling Dedicated Fissile and Fusile Production Fusion and Fission Reactors," Atomkernenergie/Kerntechnik **38**, pp. 85-90 (1981).

86. CFFTP, "Tritium Supply for Near-Term Fusion Devices," CFFTP-G-88024 (May, 1988).

87. Lu, M.S., R.B. Zhu and M. Todosow, "Unreported Plutonium Production in Light Water Reactors," ISPO-282, TSO-88-1, Brookhaven National Laboratory (February, 1988).

88. Benedict, M., Th.H. Pigford and H.W. Levi, *Nuclear Chemical Engineering*, 2nd edition (1984).

89. Ragheb, M.M.H., "Implementation Considerations of Coupling Dedicated Fissile and Fusile Production Fusion and Fission Reactors," Atomkernenergie/Kerntechnik **38**, pp. 85-90 (1981).

90. Osborne, R.V., "Hazard and Protection from Tritium Produced in an Experimental Reactor Loop," *Health Physics* **36**, pp. 167-174 (1979).

91. Sokolski, H.D., Testimony Provided in Hearing, GPO (1982). Governmental Printing Office (GPO), "U.S. Policy on Export of Helium-3 and Other Nuclear Materials and Technology," before the Subcommittee on Energy, Nuclear Proliferation, and Government Processes of the Committee on Governmental Affairs United States Senate, 97th Congress, May 13, 1982, United States, Washington (1982)

92. Phillips, J.E. and C.E. Easterly, "Sources of Tritium," Oak Ridge National Laboratory, ORNL/TM-6402 (1980).

93. Ragheb, M.M.H., "Implementation Considerations of Coupling Dedicated Fissile and Fusile Production Fusion and Fission Reactors," Atomkernenergie/Kerntechnik **38**, pp. 85-90 (1981).

94. Benedict, M., Th.H. Pigford and H.W. Levi, *Nuclear Chemical Engineering*, 2nd edition (1984).

95. Lu, M.S., R.B. Zhu and M. Todosow, "Unreported Plutonium Production in Light Water Reactors," ISPO-282, TSO-88-1, Brookhaven National Laboratory (February, 1988).

96. Ragheb, M.M.H., "Implementation Considerations of Coupling Dedicated Fissile and Fusile Production Fusion and Fission Reactors," Atomkernenergie/Kerntechnik **38**, pp. 85-90 (1981).

97. IAEA, "Handling of Tritium-Bearing Wastes," Technical Report Series No. 203, Vienna (1981).

98. Phillips, J.E. and C.E. Easterly, "Sources of Tritium," Oak Ridge National Laboratory, ORNL/TM-6402 (1980).

99. Phillips, J.E. and C.E. Easterly, "Sources of Tritium," Oak Ridge National Laboratory, ORNL/TM-6402 (1980).

100. IAEA, "Handling of Tritium-Bearing Wastes," Technical Report Series No. 203, Vienna (1981).

101. E.g., see Bray, L.A. *et al.*, "Thermal Outgasing of Irradiated Fuel," *ANS Transactions* **39**, pp. 219–220 (1981), succeeded in releasing of 100 percent of the tritium at 1500°C within 6 hours. See Campbell, D.O. and W.L. Pattison, "Tritium and Fission Product Behavior During Irradiated Fuel Heat Treatments," *ANS Transactions* **39**, p. 219 (1981), required 24 hours to release 99 percent of the tritium at 1000°C.

102. Cochran, T.B. *et al.*, *Nuclear Weapons Data Book. Volume 3: U.S. Nuclear Warhead Facility Profiles*, Cambridge (1987).

103. Cochran, T.B. and R.S. Norris, "Russian/Soviet Nuclear Warhead Production, Nuclear Weapons Databook," Working Paper NWD 93-1, Washington (1993).

104. Thomas, G.F. and S.J. Bereton, "Enhanced Tritium Production for Fusion Reactors via $^3He_{(n,p)}3H$ in the Heavy Water Moderator of a CANDU Reactor," *J. Fusion Energy* **4**, pp. 27-41 (1985).

105. Osborne, R.V., "Hazard and Protection from Tritium Produced in an Experimental Reactor Loop," *Health Physics* **36**, pp. 167-174 (1979).

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107. Data are given in Phillips, J.E. and C.E. Easterly, "Sources of Tritium," Oak Ridge National Laboratory, ORNL/TM-6402 (1980). An efficiency of 40 percent is assumed.

108. CFFTP, "Tritium Supply for Near-Term Fusion Devices," CFFTP-G-88024 (May, 1988).

109. Colschen, L., "Die Systematische Einführung der Tritium Kontrolle auf Internationaler Ebene als Instrument der Nichtverbreitungsregimes für Kernwaffen unter Berücksichtigung Regimetheoretischer Überlegungen—Voraussetzungen, Möglichkeiten und Perspektiven." Ph.D. thesis to be submitted to Free University Berlin (1995). See also Colschen, L.C. and M.B. Kalinowski, "Can International Safeguards be Expanded to Cover Tritium?" IAEA-SM-333/27, Proc. IAEA Volume, pp. 493-503, Symposium on International Safeguards, Vienna (March 14-18, 1994).

110. The typical problems associated with institutional bargaining processes in general and non-proliferation instruments in particular (e.g., tactical considerations by parties, domestic politics factors, foreign policy linkages) are not discussed in this paper.

111. In the concept of "diffuse reciprocity" the definition of equivalence is kept vague on purpose. The players are rather groups or coalitions than particular actors, and the sequence of events is not narrowly bounded. This is to differentiate from the concept of "specific reciprocity." The latter refers to situations in which specified partners

exchange items of equivalent value in a strictly delimited sequence, as reflected within some instruments of the regime itself, such as START I and II. See also Keohane, Robert O., "Reciprocity in International Relations," *International Organization* **40** (1), p. 1 (Winter, 1986).

112. On December 4, 1961 the UN General Assembly unanimously adopted Resolution 1665 (XVI) on the "Prevention of the Wider Dissemination of Nuclear Weapons." It was sponsored by Ireland and is commonly referred to as the Irish Resolution. One of the most important features of this Resolution was that it did not make horizontal non-proliferation conditional upon measures against vertical proliferation. In fact, in this Resolution horizontal non-proliferation was separated from vertical non-proliferation, since it did not deal with the latter at all. The evolution of the nuclear non-proliferation regime reflected this relation between horizontal and vertical non-proliferation, as expressed by Resolution 1665. United Nations - Department of Political and Security Council Affairs: "The United Nations and Disarmament 1945-1970," New York (1970).

113. In contrast, changes in the normative framework would reflect a change of the regime. In this case, the established structure would be questioned which could finally lead to the disintegration of the entire regime. Only if the participating states could agree on new principles and norms, a new nuclear non-proliferation regime would replace the existing one.

114. The CD is the only multilateral body for negotiations about disarmament and arms control, in which states of all regions of the world are represented.

115. Department for Disarmament Affairs, "Disarmament Machinery," United Nations Fact Sheet No.35, New York (May, 1984).

116. Cochran, T.B. *et al.*, *Nuclear Weapons Data Book, Volume 2:.U.S. Nuclear Warhead Production,* Cambridge (1987).

117. Weinstock, E. and A. Fainberg, "Verifying a Fissile Material Production Freeze in Declared Facilities with Special Emphasis on Remote Monitoring," in Tsipis, C., D. Hafemeister and Janeway (eds.) *Arms Control Verification: The Technologies the Make it Possible*. (1986). See also Thompson, G., "Verification of a Cutoff in the Production of Fissile Material," in Barnaby, F. (ed.), *A Handbook of Verification Procedures*, New York (1990); Berkhout, F., O. Bukharin, H.A. Feiveson, M. Miller, "A Cutoff in the Production of Fissile Material," *International Security*, **19**, 3 (1994/95), pp. 167-202.

118. In 1969, the USA dropped the demand for inspection teams searching the country for clandestine facilities. Instead they announced that IAEA inspections at declared facilities would be considered adequate. The reason for this shift was that the development of surveillance satellites had made such a progress that the USA was confident that they would be able to detect clandestine facilities by national technical means.

119. Richter, R. *et al.*, "Analysis of LANDSAT TM Images of Chernobyl," *Int. J. Remote Sensing* **7**, pp. 1859-67 (1986). See also N. v. Hippel, F. and B.G. Levi, "Controlling Nuclear Weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons," in Tsipis, C. and D. Hafemeister, Janeway (eds.), *Arms Control Verification: The Technologies the Make it Possible.* (1986).

120. The ICO would be composed of a complex structure of rules regarding the cutoff of the production of plutonium, HEU, and tritium. The rules specified here apply to the cutoff of tritium alone. Some of these rules are also valid for plutonium and HEU. Others, not mentioned in this paper, apply solely to HEU and plutonium, but not to tri-

tium. For example, Plutonium and HEU from dismantled warheads would be put in international controlled stockpiles, whereas will be recycled. Since no fresh tritium is added to the weapon programs, the tritium inventories of the states party to the treaty will shrink by the rate of 5.5 percent annually. A different approach that would eliminate all tritium from the nuclear arsenals to achieve the immediate effect of a significant yield reduction is discussed in the appendix to this paper.

121.There is no internationally recognized definition of this status in which a reactor needs preparations of at least a few month to be restarted. Therefore the ICO should contain such a definition. This may include for example: (1) fuel and moderator are removed from the site; (2) only the minimum staff and systems required for maintaining the infrastructure are kept operating; (3) regular safety checks may be continued and a checklist is set up for repairs in case of a restart; (4) some parts of the facility may be placed in a more permanent layup mode; e.g., doors sealed, pipes closed.

122.The possibility of nuclear disarmament by an ICO alone, i.e., using the tritium decay as a "forcing function" for reversing the vertical proliferation process or as a means to achieve a yield limit is different from this proposal. It has been rejected for good reasons and is not proposed by the authors! For the discussion of "tritium as a forcing function." Nuclear Control Institute (NCI), American Academy of Arts and Sciences (AAAS), *The Tritium Factor*, Washington/Cambridge (1988). See also Mark, J.C. *et al.*, "The Tritium Factor as a Forcing Function in Nuclear Arms Reduction Talks," *Science* **241**, p. 1166 (1988).

123.For the United States, the date is explained above. Despite the lack of concrete information, a more favorable situation can be envisaged for Russia, because it has already produced tritium for more than six years after the shutdown of the last U.S. production reactor.

124.The ICO would guarantee that time is bought by definitely postponing new production activities.

125.In case of a limited agreement and the resumption of the military tritium production after the agreement expires and is not extended, the ICO would at least have bought time for further investment decisions. See also paragraph on "Decision making procedures."

126.This is under the assumption that Belarus, Kazakhstan, and Ukraine will be nuclear-weapon-free as envisaged in the Lisbon Protocol.

127.Without major changes of the current state of military reactors, Russia might have a production capability more readily accessible.

128.N. v. Hippel, F. and B.G. Levi, "Controlling Nuclear Weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons," in Tsipis, C. and D. Hafemeister, Janeway (eds.), *Arms Control Verification: The Technologies the Make it Possible* (1986).

129.Weiss, W. *et al.*, "Mesoscale Transport of Kr-85 Originating from European Source," *Nucl. Inst. Meth.* **B17**, pp. 571-574 (1986).

130.For the dimensions of regime change see Haggard, Stephan and Simmons, A. Beth, "Theories of International Regimes," *International Organization* **41** (3) (Summer, 1987).

131.These states are presently dealt with in the regime as if they were non-nuclear weapon states. Therefore, before this can happen, the status of those states might have to be redefined, i.e., adjusted to reality.

132. A possible international monitoring agency would be designed to be multifunctional, i.e., equipped with various types of sensors. It would be enabled to carry out numerous verification tasks in the fields of nuclear, biological, chemical, and conventional disarmament.

133. As long as military production facilities exist, those will be covered by the ICO.

134. This also includes tritium transfers to or between recognized nuclear weapon states. It should be stressed that this rule goes beyond the rules of the NPT regarding the transfer of nuclear materials.

135. This means, in combination with the following rule, that tritium exports require "full-scope safeguards."

136. For example, DOE officials regard these options as "blown out of proportions" and unacceptable from the viewpoint of political, financial, and organizational costs. The Canadian position is very similar in this regard. Since the costs of a new agency would be "unreasonably high," Canadian officials suggest that "one has to build on what is already in place," which would point towards the IAEA. Personal communication during a meeting with officials from the Canadian government and tritium experts of Ontario Hydro in Ottawa/Canada on May, 5, 1992.

137. A good analysis of the NPT and its deficiencies is given in Fry, M.P., P. Keatinge and J. Rotblat, *Nuclear Non-Proliferation and the Non-Proliferation Treaty*, New York, 1990 and also Snyder, J.C. and S.F. Wells, *Limiting Nuclear Proliferation*, Cambridge, 1985.

APPENDIX A: THE IMPACT OF COMPLETE ELIMINATION OF TRITIUM ON A NUCLEAR ARSENAL

By Martin B. Kalinowski

A.1 INTRODUCTION

The consequences of shortages or even complete elimination of tritium from military stocks is discussed in this appendix. The total yield of nuclear arsenals is taken as the measure for this assessment. A more adequate parameter to judge tritium's impact on the military potential of nuclear weapons would be the kill-factor that takes into account the accuracy of delivery systems. Boosting with tritium increases the yield of the warhead while keeping the weight low. A small weight allows a high accuracy in targeting. Therefore, the weight of warheads will be considered in the following assessment as well.

A.2 THE RELATION OF TRITIUM AND WEIGHT TO THE YIELD OF NUCLEAR WEAPONS

The impact of complete elimination of tritium on nuclear weapons becomes apparent if one looks at a graph of the yield of nuclear weapons vs. their weight (see figure A.1). The data used are the best estimates publicly known.[1] When a range of data was given, the lower limit for the weight and the upper value for the yield were used. By doing this, the largest practically achieved yield-to-weight ratios are shown in the graph.[2] Only U.S. nuclear warheads are represented because estimates from other nations' stockpiles are not available in a comparable comprehensive manner.

Different symbols are used to distinguish nuclear weapons which make use of tritium from those which do not. There is slight uncertainty about the use of tritium in some thermonuclear bombs (B53, W78, W56). The three types (fission, boosted[3] fission and thermonuclear) appear in clusters. The line for a constant yield-to-weight ratio of 0.1Kt/kg seems to be roughly a dividing line between fission weapons on the lower side and thermonuclear weapons on the other side. But this does not mark the theoretical limit of the yield-to-weight ratio for fission weapons. Assuming that 100 percent of the nuclear material is burned, the theoretical limit lies at 17.5 Kt/kg for uranium-235 and 20 Kt/kg for plutonium-239. The corresponding value for pure fusion reactions is 80 Kt/kg. These theoretical limits can never be reached in practice because addi-

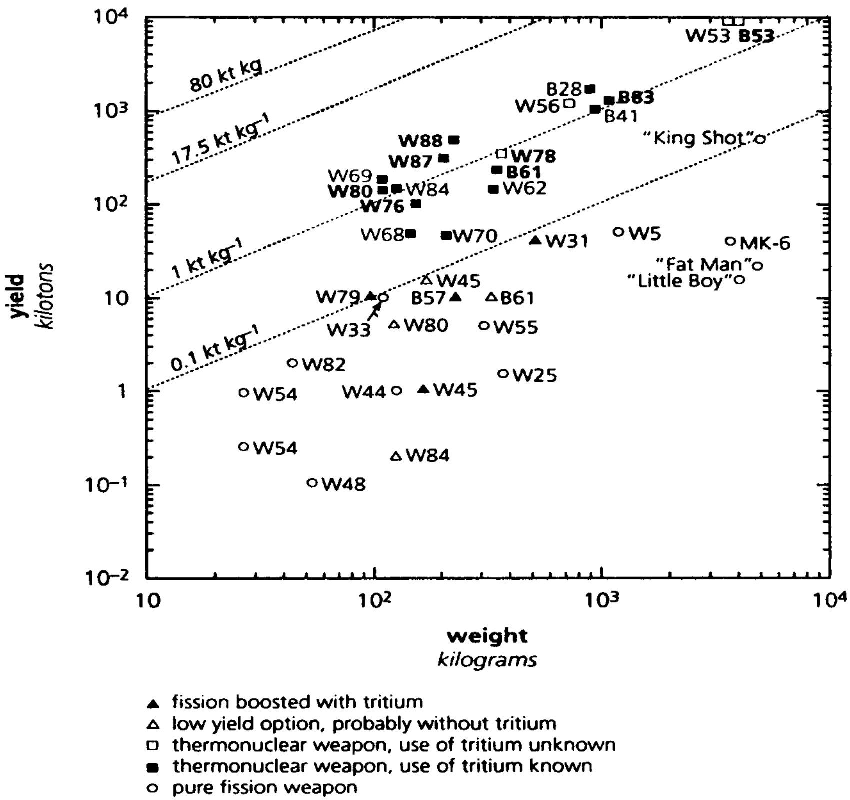

Figure A.1: Yield and weight of U.S. nuclear warheads and some nuclear explosions with tritium use indicated. Warheads in bold-face are in the present U.S. nuclear stockpile. Some retired warheads have not yet been dismantled. Some are kept in "inactive reserve" without plans to be dismantled. Although the details are classified, it can be assumed that some 400 W84 warheads are still in inactive reserve as well as W62, W68, W69, W76 and W78 warheads. The black symbols indicate tritium use, the hollow symbols are used for warheads not using tritium.

tional weight is required for the chemical explosive, the bomb casing, and other parts of the weapon. Also, a 100 percent efficiency in burning the nuclear fuel can never be achieved.

Some nuclear tests with high yields have been conducted without using tritium. The highest yield all-fission test carried out by the USA was the "King Shot" (500 kilotons).[4] Furthermore, the first thermonuclear weapons which were built did not contain tritium. That proves that tritium in principle is not necessary to ignite a fusion reaction. However, in practice, with modern boosted nuclear warheads, tritium may be needed in two-stage weapons.

Constraints on weight and volume by the delivery systems dictate that the nuclear weapons be light-weight. In the early 1950's, this was achieved primarily by improving the effectiveness and reducing the required volume of the chemical explosive. In the mid-1950's, another significant weight reduction of fusion weapons was achieved by replacing their 1.5 meter diameter unboosted primaries with smaller diameter (55 to 75 cm) boosted primaries. It can be assumed that thermonuclear weapons which are in the current U.S. stockpile are triggered by a boosted primary.

There are a number of ways to vary the yield of a particular nuclear weapon design, one of which is boosting. It can increase the yield of pure fission weapons or the fission primary of thermonuclear weapons by a factor of 2 to 10 (the "boosting factor").[5] For some types, more than one yield is shown in the diagram (W54, W45, B61, W80, and W84). The lower ones might be due to a reduction of the amount of tritium and deuterium injected in the core of the nuclear explosion or the total removal of the tritium ampule. However, they may as well be achieved by the timing or intensity of the external neutron source which initiates the chain reaction. In some weapon designs (especially older), it is possible to remove the nuclear core and insert a differently sized core to provide different yield options.

Therefore, there is no simple rule to estimate the reduction in maximum yield of boosted type weapons when tritium is eliminated. Even if the boosting factor is known, the reduction factor is not known because it may depend on more than tritium removal. Operation with and without tritium may be optimum at different configurations as in the geometry of the pit and timing sequences of the explosion.

When estimating the effect of tritium on the yield, it should be noted that the yield of a boosted primary or boosted fission weapon varies with storage time. This is due to the radioactive decay of tritium and the simultaneous increase of its decay product, helium-3, which is a strong neutron absorber. However, this probably does not significantly affect the yield of the secondary stage in thermonuclear weapons as long as the primary is strong enough to ignite the fusion reaction. The initial tritium content is always high enough to allow for a few years' tritium decay.

The crucial question is whether the primary without tritium would still yield enough energy to trigger the fusion stage. If not, all thermonuclear devices would yield no more than an unboosted fission primary — around 1 kiloton or even as low as 0.4 kilotons in the case of miniaturized primaries.[6] This is highly probable and, therefore, it will be no underestimation to assume that the yield of thermonuclear weapons could go down by a factor of 100 if tritium is eliminated and designs are not changed to compensate.

A.3 Consequences of a Yield Reduction by Complete Elimination of Tritium

The assessment of the impact of complete elimination of tritium on the U.S. nuclear arsenal is based on the following assumptions which seem reasonable but cannot be proven by the author:

- There are only two-stage thermonuclear warheads left in the current active arsenal which all have tritium boosted primaries.
- The primary of thermonuclear weapons could not yield sufficient energy to trigger the fusion stage if tritium were missing. Therefore, a yield reduction by two orders of magnitude due to the removal of tritium can be assumed. The yield of unboosted primaries is 10 kilotons at maximum.
- There is no substitute for tritium. Reference [133] states that "isotopes other than tritium, such as helium-3, have been considered for boosting, but use of these is considered not to be within reach of present weapons technology."

To get an idea of the qualitative effect of tritium removal on the U.S. nuclear arsenal, see table A.1. The number of warheads has been multiplied by a yield, and all yields have been added to provide the total yield. This has been done for the upper and lower bounds of given yield ranges as well as for the case of tritium removal. For this latter case a crude estimate has been made by reducing the upper yield bound for thermonuclear warheads by a factor of 100, but down to no more than 10 kilotons. Total yields are presented for four cases:

- present U.S. stockpile;
- future stockpile after retirement of the B53, W62, and W78;
- tentative estimate of a post-START II arsenal;
- nuclear arsenal after further deep cuts down to 500 warheads.

According to these estimates, even after START II, the total yield (upper bound) would be decreased only by a factor of 2, whereas the removal of tritium would reduce the total yield by two orders of magnitude immediately. Even a stockpile of 500 warheads with tritium would still have a total yield which is a factor of ten larger than the current stockpile after planned retirements and without tritium (see table A.1).

For comparison, a weight limit set anywhere between 400 and 1000 kilograms would imply the withdrawal of high-yield strategic bombs and could

Table A.1: Total yield of operational U.S. nuclear weapons stockpile under different assumptions.

Warhead Type	Weapon System	Number in Stockpile[a]	Nominal Yield/Kt Range[b]	Total Yield/ (10^3 Kt) Upper Bound	Total Yield/ (10^3 Kt) Lower Bound	Total Yield/ (10^3 Kt) Without Tritium (rough estimate)
B53-1	Strat. Bomb	(50)	9,000	(450)	(450)	(0.5)
B61	Strat. Bomb	750	10-300	225	8	2.3
B61	Tact. Bomb	600	10-175	105	6	1.1
W62	Minuteman III	(610)	170	(104)	(104)	(1.0)
W76	Trident I C4	3,000	100	300	300	3.0
W78	Minuteman III	(920)	335	(308)	(308)	(3.1)
W80	ALCM, SLCM	1,750	5 and 150	263	9	2.6
B83/B83-1	Strat. Bomb	650	low-1,200	780	7	6.5
W87	MX	525	300	158	158	1.6
W88	Trident II D5	400	475	190	190	1.9
W89	SRAM II	(0)	200	(0)	(0)	(0)
(1) Present		9,255		2,883	1,710	25
(2) After Retiring B53, W62, and W78		7,675		2,021	678	19
(3) After Implementation of START II		≈4,450		≈1,400	≈500	≈13
(4) After Deep Cuts to 500 Warheads		≈500		≈160	≈60	≈1.5

a. Numbers are taken from Norris (1994).[7] Numbers in brackets indicate that the respective warhead is known or likely to be retired or withdrawn within the next few years. Warheads currently in stockpile are designated in bold-face in figure 1.

b. Figures are taken from Norris (1994).[8]

reduce the total upper yield of the U.S. arsenal by a third. The military usefulness of a particular nuclear warhead without tritium is reduced even more than its yield. The military mission assigned to a warhead may not be achievable if the kill-factor, i.e. the product of yield and targeting accuracy, is too low to reach the desired goal, e.g. destroying with a certain probability a hardened missile silo. However, only if no new military mission can be defined for a warhead with reduced yield, its military usefulness would be zero.

Therefore, U.S. governmental officials have said that a halt in tritium production at Savannah River Plant constitutes a national emergency before it became apparent that there is enough tritium released from nuclear disarmament for at least the next two decades.

Assuming that left-over tritium would be redistributed to serve the maximum number of warheads possible, and making further the over-conservative assumption that warheads without tritium would effectively be useless, the deployment of nuclear warheads would decline at the rate of tritium decay, i.e. by 5.5 percent per year.

It remains to be seen how these measures would affect the nuclear stockpiles of the other nuclear weapon states. Ukraine represents an interesting case since it still has on its soil nuclear weapons but does not have means of tritium renewal. If the assumptions made for the United States hold for the strategic nuclear weapons in Ukraine, the total yield would be reduced by two orders of magnitude as well (see table A.2). This is of interest because this country would not have sufficient access to tritium to replenish the amount which has been lost to radioactive decay, if it changed policy and desired to do so.[9]

A.4 Yield Reduction by Tritium Elimination: Possibility for Qualitative Nuclear Disarmament

The reduction of the yield of nuclear weapons by eliminating tritium could be used for a novel approach to nuclear disarmament. The precondition for such a qualitative nuclear disarmament is a decision to abandon high yield nuclear weapons and to reduce the overall yield of the arsenal significantly. Such an approach of nuclear disarmament was presented in 1991 by Trutnev et al.[13] Instead of reducing the number of delivery systems or nuclear warheads, Trutnev et al. suggest limiting the explosive yield of each nuclear weapon to three to five kilotons TNT. Theoretically, the total explosive power of the superpowers' nuclear arsenals — about 6 gigatons total yield — could be reduced by a factor of 100. They argue that such nuclear arsenals would still be adequate to sustain the system of deterrence, but they would no longer pose a threat to civilization. Furthermore, the balance of power would be more stable because the potential first-strike effectiveness of strategic offensive forces would be substantially reduced.

Trutnev et al. believe their proposal would be a decisive step towards a world free of nuclear weapons. The next step would be the numerical limitation of nuclear warheads, while preserving bilateral stability. Eventually the military concepts and political doctrines that rely on nuclear deterrence must

Table A.2: Total yield of nuclear weapons in Ukraine at the end of 1993 with and without tritium. All data are taken from [10].

Delivery System	Number Deployed	Warhead per Delivery System	Nominal Yield/Kt per Warhead	Total Yield/ (10^3 Kt) with Tritium	Total Yield/ (10^3 Kt) without Tritium (rough estimate)
SS-19 ICBM	130	6	550	429	4.3
SS-24 ICBM	46	10	100	46	0.5
Bear Bomber H16	22	16	250	88	0.9
Blackjack Bomber	20	12	250	60	0.6
Total	**218**			**623**	**6.3**

be abolished to clear the way for the elimination of nuclear weapons. The present strategic U.S. nuclear arsenal has a total maximum yield of some 2.9 gigatons (see table A.1).[11] If used in a strategic war, the total yield of the United States and Russia is more than 5 gigatons and could lead to a nuclear winter, although the science of nuclear winter remains highly uncertain. All models of a strategic nuclear war which would lead to a nuclear winter scenario assume total explosive yields in the range of 5 to 10 gigatons, which would kill 750 million to 1.1 billion people in the northern hemisphere immediately and probably another two billion later.[12] Even after START II, the nuclear arsenal remaining in the United States would probably still have an upper bound of total yield on the order of 1.4 gigatons (see table A.1). This reduced yield probably does not preclude the possibility of a nuclear winter.

Some warheads remaining in stockpile have selectable yields. If after START II implementation, yield selections above their lowest options are disabled, the total U.S. yield would be reduced to 0.5 gigatons (see table 1). It is not clear if this could be implemented in an irreversible or verifiable way, and this would bring the world only a modest step away from the horrific scenario of a strategic nuclear war.

Obviously, the feasibility and verifiability of reducing explosive yields are the crucial problems for any approach to disarmament. Trutnev et al.[13] claim that their proposed yield limit could easily be implemented making use of the physical construction peculiarities of the modern nuclear weapons developed in the USSR and the USA. Although the authors do not provide the details saying: "Unfortunately, we cannot present details here," readers can trust their work, because of their access to classified information. In fact, Trutnev is known as the "designer of the Soviet thermonuclear arsenal."

The assertion of this paper is that **tritium elimination might be the key to both feasibility and verification of a yield reduction**. The best way of achieving and verifying a substantial reduction of the explosive yield might be the complete elimination of tritium from all nuclear weapons and from the nuclear weapons production cycle. The yield would immediately go down by a factor of 100 and be 0.025 gigatons with the current stockpile, 0.013 gigatons after implementing START II, and 0.0015 gigatons with 500 warheads.

The idea of using tritium decay as a forcing function was discussed extensively in 1988 in the United States after the last production reactor at Savannah River Plant had been shut down for safety reasons.[14] However, the basic idea of the "forcing function" is different from this proposal in that it was intended to force a reduction in numbers of warheads to keep pace with the radioactive decay of tritium. This proposal is independent of the actual number of warheads that remain in the stockpile. Furthermore, the decay takes years, whereas, elimination is immediate disarmament.

A.5 Implementation and verification of a yield reduction by tritium elimination

Some problems of the tritium approach to reduce the yield are obvious. It is difficult to estimate the potential of the remaining stockpiles, especially because the technical assumptions made in this paper may not hold or cannot be proven because the relevant information is kept classified. Tritium elimination would not be easy to implement as a bilateral verified agreement, because not only may Russian and U.S. warheads be affected in an asymmetric way, but it may be difficult to negotiate a verification procedure that includes on-site inspection of warheads.

If a single country decided to do without high-yield weapons, it could eliminate tritium unilaterally and there would be no need for verification. This could encourage other countries to do the same. If access to nuclear warheads would be permitted to inspectors, tritium elimination could be verified. The removal of the tritium is a simple process because tritium ampules are designed to be replaced. The positions of tritium ampules in the warheads can then be sealed, and the absence of tritium can be verified by a test of seal integrity. Inspections of warheads would not reveal information on their internal design.

Remaining tritium stocks could be handed over to an international inspection agency. Since tritium decays with a half-life of 12.3 years, undeclared stockpiles would be depleted relatively quickly. Complete verification would have to detect any clandestine production or transfer of tritium from civilian stocks for military purposes. Tritium can be integrated in a verified cutoff for the production of fissile materials.[15] Military production reactors could be shut down and verified by national technical means as well as on-site inspections. The main article shows that tritium control procedures could be established which quickly detect any significant diversions of tritium.

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2. The yield-to-weight ratio is defined in this article to be the total explosive yield divided by the total weight of the complete weapon. The mass of the fissile and thermonuclear fuel core is not of interest in this context and in general not known to the public.

3. Boosting means increased efficiency in fission which is achieved by neutrons coming out of the fusion of a few grams of tritium and deuterium gas in the center of the fission weapon. The fusion energy contributes only a small fraction to the overall yield.

4. This test was carried out in 1952. Its core was made out of "oralloy." Hansen, C., *U.S. Nuclear Weapons. A Secret History.*, Arlington, Texas (1988).

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7. Norris, R.S. and W.M. Arkin, "U.S. Nuclear Weapons Stockpile," (July, 1994), *Bulletin of Atomic Scientists*, p. 61-63 (July/August, 1994).

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9. On January 14, 1994 the Ukraine, the United States and Russia signed a trilateral nuclear statement according to which Ukraine agreed to transfer all nuclear warheads on its territory to Russia. As of mid-June 1994, Ukraine was well ahead of schedule in implementing the first stage of the trilateral statement. It had deactivated all 46 of the SS-24 and at least 30 of the 130 SS-19 ICBMs, it had transferred at least 180 of 1240 ICBM warheads to Russia, and it had pledged publicly to withdraw all the remaining warheads within three to four years. See also Larrabee, F.S.: *Ukraine: Europe's Next Crisis*, Arms Control Today, (July/August, 1994), pp.14-19. By continuing the current pace of withdrawal of about 60 warheads per month the whole transfer could be completed within 28 months. For more details about the nuclear weapons policy of Ukraine and its tritium production capabilities see main text.

10. The International Institute for Strategic Studies: *The Military Balance 1993-1994*, London (1993).

11. The total yield of Soviet strategic nuclear weapons that remained on Ukraine territory was higher than 0.6 gigatons (see table A.2).

12. P.R. Ehrlich et al. *Long-term biological consequences of nuclear war*, Science 222 (1983), p.1293-1300.

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APPENDIX B: TECHNICAL ASPECTS OF SAFEGUARDS FOR ICO AND ITCS

One significant quantity of tritium may be set equal to one gram, which is a significant fraction of the typical amount used in one nuclear warhead, 2 to 3 grams. We assume that a diversion of a safeguards system should be able to observe the diversion of one gram in a detection interval d_t of one year. These quantities and the derived details of control activities are depending on the underlying control approaches (i.e., "ITCS" or "ICO"). As a result of the diversion path analysis and the outlined regime scenarios, it becomes apparent that two different control tasks have to be solved: verification of non-production for weapons and verification of non-diversion from civilian facilities.[1]

Verification of non-production of tritium for weapon purposes is required for both ICO and ITCS. For the ICO, verification of the cold standby status of military production facilities is the most important task. For the ITCS, inspections have to be performed at all neutron sources (facility type 1, see table 6) and at fuel fabrication plants (facility type 2). Verification here will rely mainly on non-destructive analysis to detect raw-materials like lithium-6 which could be used for the production.

Verification of non-removal from civilian stocks of tritium is required for the ITCS, and may be foreseen for the ICO in case the ITCS is not being simultaneously implemented. This has to be carried out at all facilities with significant tritium inventories or throughputs (facility types 1b,d, 3 to 8). This task is accomplished by material accountancy complemented by containment and surveillance at tritium handling facilities to deter against or to detect diversion of tritium. Most civilian facilities which are affected by tritium controls are already under international safeguards for nuclear materials, since tritium can - like plutonium - only be produced in nuclear reactors or via other strong neutron sources. This can be seen from table 6 which shows the worldwide number of facilities of the eight types which are of relevance.

The diversion possibilities to extract inadvertently-produced tritium or to remove tritium from existing civilian stocks would make it necessary to put a small number of facilities worldwide under safeguards in addition to those which are already inspected to verify fissile material inventories. The additional number of tritium-handling facilities probably is between 10 to 50 depending on the specific agreement. At nuclear reactors (facility types 1 a-d), most tritium control activities concerned with verification of non-production are already covered by routine nuclear safeguards procedures as carried out by IAEA and Euratom. Current and future nuclear safeguards would be effective in finding anomalies for most scenarios of tritium production and would even suffice for tritium control in 20 percent of all paths.

In other cases, additional measures (e.g., non-destructive analysis to identify lithium-6 or tritium accountancy) may be introduced which in turn may enhance the efficiency of nuclear safeguards. Unreported breeding of tritium of even small amounts would be detectable by those nuclear safeguards activities which are already implemented by the IAEA in order to detect unreported breeding of plutonium from natural uranium. All neutron sources in which more than one SQ (8 kilograms) of plutonium can be produced in one year are under nuclear safeguards. Since tritium production is always in competition to plutonium production, all facilities and possible paths which can breed 110 grams per year (i.e., the tritium equivalence to 8 kilograms plutonium per year) are already under nuclear IAEA safeguards. The introduction of specially designed breeding targets within fresh fuel elements can be observed in fuel fabrication facilities (type 2). If this is accomplished, the fuel elements are sealed.

Further safeguards are carried out by item counting and seal inspection as well as by containment and surveillance measures which is current practice. The detection of tritium breeding targets in fuel elements can probably be achieved with routine measurements of the uranium enrichment and total fissile material content of fresh fuel assemblies after their final assembly. This is done with the Neutron Coincidence Collar (NCC) which would show anomalies on the insertion of undeclared target rods. For example, lithium-6 targets in fresh fuel elements would cause a depression in the count rate as has been shown in Monte Carlo simulations.[2] If these cannot be resolved by explanations given by the plant operators, further, possibly destructive, investigation would be triggered. The most difficult production scenario to detect would be the covering up of lithium-6 target rods by declaring them as burnable poison rods, which are in fact increasingly used to enable higher burnup of fuel. Monte Carlo simulations demonstrate that the NCC response to such scenarios may well result in anomalies.[3]

If this method turns out to be not sufficiently reliable, weighing of fuel assemblies might be used as an additional measure. It is not yet part of IAEA inspection activities. It would, however, be an easy method to provide an indication for substitution of nuclear fuel by lithium-6 because the weight would be substantially reduced. This would at the same time strengthen nuclear safeguards. Although IAEA safeguards to verify the content of fuel rods are applied routinely prior to irradiation, the content of control rods is not checked at all. Insertable control rods require non-destructive examination to identify the neutron absorber material. Nuclear Resonance Absorption (NRA) at the 3.56 MeV level of Li-6 appears to be a promising method for this task.[4]

Further control procedures for non-removal are required at heavy water reactors (types 1b,d) and detritiation facilities (type 6) to detect unreported removal of tritiated water. These can partly rely on IAEA safeguards required for heavy water which, according to their stated goal, would already detect the diversion of moderately tritiated heavy water containing more than 100 grams of tritium within one year. The SQ of heavy water is 20 t. Tritiated heavy water has a concentration of up to about 2 TBq/ kilogram, i.e., 20 t contain some 110 grams. At present, such safeguards are implemented in Argentina only.

Spent fuel at reactors (types 1a-d) or storages (type 3) has to be checked against attempts to extract tritium accumulated in it as a by-product. This can easily be achieved by visual control because any extraction method (e.g., employing heat treatment) would affect the integrity of surface and geometry of fuel rods.

The illegal removal of spent fuel from reactors or storages containing more than 0.2 grams tritium would already be detected. Current nuclear safeguards are designed to detect the diversion of fuel containing more than 8 kilograms plutonium within 3 months. This corresponds roughly to 800 kilograms of spent fuel which contain some 60 to 180 milligrams of tritium depending on fuel type and burnup. Tritium accountancy complemented by containment and surveillance is the appropriate control method at all tritium bulk handling facilities (types 4-8) to verify non-removal of tritium.

Tritium accountancy is current practice at all tritium handling facilities mainly for the purpose of radiation protection carried out by plant operators and verified by national authorities. The precedent for this type is the agreement between Euratom and Canada (see above).

The technical problems in accountancy can be aggregated and compared by defining the expected accountancy capability E as a function of the measurement accuracy in closing a material balance. This relationship can be quantified to a certain extent by

$$E = 3.25 \times \delta_E \times A$$

where E is the *expected accountancy capability* (or relative standard deviation) which is the minimum loss of nuclear material which can be expected to be detected by material accountancy; A is the amount of material in the material balance expressed as the larger of the inventory or throughput, and the factor 3.25 corresponds to a detection probability of 0.95 and a false alarm probability of 0.05; δ_E is the *expected measurement accuracy* for closing a material balance, i.e., the expected accuracy of material unaccounted for (MUF).[5]

Expected measurement accuracies in nuclear safeguards based on international standards of accountancy, i.e., considered achievable in practice at bulk nuclear facilities, range from 0.002 for uranium enrichment plants and 0.01 for plutonium reprocessing plants to 0.25 for separate waste storages.[6] For heavy water in power reactors δ_E is estimated to be 0.005.[7] A study undertaken for two tritium laboratories with a total inventory of around 100 grams arrived at the conclusion that the allowable limit for MUF should be 5 percent of the inventory and at least equal to 3 g.[8]

The main reason for these high numbers is the conservative approach in estimating the amount of tritium bound in the system and the measurement uncertainty in inventory measurements. A more realistic assessment of MUF based on experiences in the USA suggests a more optimistic conclusion. Most measurement accuracies which are actually achieved in various tritium handling facilities (except waste treatment) are between 0.0025 and 0.05. Measurement accuracies at waste treatment facilities are about 0.2.[9]

The conclusion that can be drawn from these data is that a tritium accountancy capability can be achieved which compares well with the capability of nuclear safeguards as performed by the IAEA.[10] Radiation protection regulations pose requirements on both SQ and detection time anyway which are far more strict than necessary for verification of non-proliferation.

Because tritium is a gas, there are specific technical problems which become apparent under certain circumstances. The most obvious one is that tritium could easily be released unaccounted just by opening a valve. Such weak points of accountancy can be managed by adding control measures other than accountancy, e.g., a seal at the valve that prevents undetected releases. However, physical protection of tritium cannot be guaranteed unless access to tritium is successfully prohibited because it is easy to pass a tritium container through a check-out point without being detected. But physical protection is not a goal of nuclear safe-guards while the verification goal can be achieved because any significant theft of tritium can be detected within one year by tritium accountancy.

Taking into account the existing tritium stocks and sources (see table 4), the conclusion can be drawn that *verification of non-diversion of tritium is feasible at reasonable costs.* Not all facilities have to be inspected for tritium controls. Procedures to verify the non-diversion of tritium have to be introduced at a limited number of facilities (up to 50, depending on the specific control instrument and membership) in which no nuclear materials but tritium are handled (see table 6). There are less SQs of tritium to be controlled than SQs of plutonium which are now under nuclear safeguards.[11]

Table B.1: Survey on facilities relevant for tritium control (worldwide)

	Facility Type[a]	Total Number in 1992[b]	Pu/HEU Safeg. Applied in 1992[c]	Minimum Added for ITCS[d]	Maximum for ITCS and Integrated Cutoff[e]
1a)	Nuclear Power Reactors	424	201	0	424
1b)	Heavy Water Power Reactors (included in 1a)	(32)	(28)	(0)	(32)
1c)	Research Reactors and Critical Assemblies	323	169	0	267[f]
1d)	Heavy Water Research Reactors (included in 1c)	(21)	(13)	(0)	(11)[g]
1e)	Military Production Reactors (including those shut-down)	51	0	0	51
1f)	Special Neutron Sources[h]	4	1	0	4
2)	Fuel Fabrication Plants	42	23	0	42
3)	Separate Spent Fuel Storage Facilities	28	19	0	28
4)	Reprocessing Facilities	22	6	0	10[i]
5)	Nuclear Waste Storages and Disposals	23	1	3	7
6)	Extraction Facilities for Tritiated Water	6	0	3	6
7)	Research Facilities with Inventory or Annual Throughput > 1 gram	12	0	4	12
8)	Tritium Manufacturers with Inventory or Annual Throughput > 1 gram	21	0	4	21
	Total	**956**	**420**	**14**	**872**

a. The numbers of facility types are the same as used in figure 2.

b. All figures are given as of December 31, 1992. Some include suspected facilities, some may fall short of the actual numbers because information about the existence of facilities may not be available to the authors. Not included are facilities which are planned, under construction, shut down, or on stand-by except for facility type 1f. Main source: (Varley/Dingle/Gee (1993)).[12]

c. Figures are given as of December 31, 1992. Source: (IAEA (1993a).[13]

d. These numbers show the difference between that required under current IAEA nuclear safeguards activities and that required if tritium is added to the materials controlled under the NPT, i.e., the integration of an International Tritium Control System (ITCS) into the NPT but without controlling the facilities in nuclear weapon states.

e. These numbers assume a combined implementation of an Integrated Cutoff agreement and an ITCS with all relevant states joining the respective treaties. This represents the reference case in which the maximum number of facilities would fall under tritium control including former military production plants which are assumed to be held in stand-by. This number is smaller than the total number of existing facilities because some facilities lie below the critical threshold inventory, throughput, or production capacity.

f. It will be necessary only to control research reactors which can be used to produce more than a certain quantity of tritium within a year. 1 g/y is chosen as an example. In view of the production rates of dedicated facilities as given in table 3 reactors with < 200 kW_{th} can probably be excluded from controls.

g. Only research reactors with > 12 MW_{th} have to be safeguarded to cover the heavy water path with production capacities larger than 1 g/y (cf. table 3).

h. Presently this category covers spallation neutron sources. In the future, fusion research facilities might have high enough neutron fluxes to produce a significant quantity of tritium within one year. They will then fall under this type.

i. Only reprocessing plants with a capacity exceeding 10 tones heavy metal per year are included. Smaller facilities would probably not release more than 1 gram of tritium per year and might therefore not fall under tritium control (see text).

As a result, from the technical perspective, there are no fundamental problems regarding the introduction of tritium control procedures with state-of-the-art technology even if the SQ is set at one gram which is a conservative estimate.

NOTES AND REFERENCES

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