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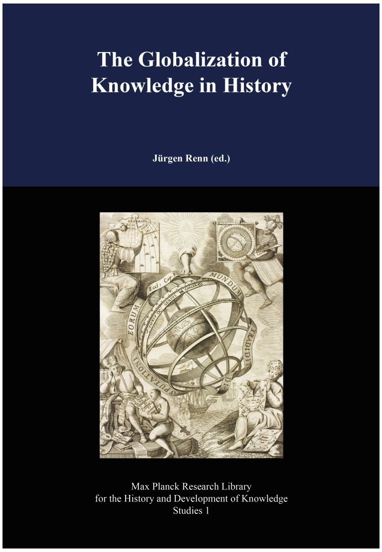
Angelo Baracca:

The Global Diffusion of Nuclear Technology



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Chapter 27
The Global Diffusion of Nuclear Technology
Angelo Baracca

27.1 Introduction

Among the deep changes undergone by science and technology in their organizational forms, social and economic role, structure and contents during the World-War-II and post-war periods, the birth and diffusion of nuclear science and technology are probably among the most far-reaching and significant. Since the beginnings of nuclear technology, its intrinsic *dual-use*—and the associated military implications—have strongly influenced its development and role, with major consequences for international political and economic relations. The strong military implications of this technology unfortunately impede a thorough reconstruction and assessment of its history: several programs with military goals were (and still are) secret, sensitive information and documents are still classified, and much international commerce and interchange remains unregistered, if not illegal.

"Big Science" as a research model, which revolutionized post-war scientific and technical research, had its baptism in the "Manhattan Project," the wartime effort to design and build the first nuclear weapons. However, as nuclear science and technologies took off during the 1930s, local attitudes and conditions intertwined and produced original contributions, leaving different choices open. Since the very beginning of nuclear research, the practical exploitation of the enormous energy contained in the atomic nucleus had been one of the basic goals (Flügge 1939); further perspectives on technical applications played a fundamental role in shaping further choices.

It seems convenient to distinguish between *cultural* and *technical* aspects in the development of nuclear energy, since the early studies on the atomic nucleus tended to show greater effects by local influences, while the later works, beginning mainly from the 1940s, decisively shaped the structure and contents of nuclear science, thus deeply influencing the first aspect as well; in the particular political and economical context that resulted, nuclear technology became globalized.

27.2 “Romantic” Phase: Early Research and Diffusion Mechanisms

27.2.1 Deeply Innovative Features of Nuclear Science and Technology

If the birth of nuclear physics can be traced back to Rutherford’s experiments (Rutherford 1911), which ascertained the concentration of the positive charge and mass at the center of the atom, the study of the internal composition and properties of the nucleus began in the early 1930s. It was not simply a transmission and development of the techniques developed and the results obtained in the Cavendish Laboratory under Rutherford’s direction (the Rutherford-Geiger detector, Cockcroft and Walton’s voltage multiplier, the splitting and transmutation of the nucleus, the discovery of the neutron): besides new techniques, deep structural changes on the economic and social levels boosted and transformed nuclear physics in the 1930s (Stuewer 1979).

The fact that during the war the program for the construction of a nuclear weapon was progressing, not only in the US, but also in Germany and Japan, France, the UK and the USSR—showed that, for both its scientific and technical bases, the time was ripe for such a development. In fact, the war was the launch pad for a spectacular leap in scientific and technical research, built on the recasting of these sectors that had begun over the previous decade (Battimelli et al. 1984). Roosevelt’s “New Deal” was a strategy to recover from the post-1929 depression, an attempt to overcome the recurrent self-destructive overproduction crisis of the capitalist system, through a continuous renewal of industrial sectors and products. Such a strategy was reflected in the promotion of a new dynamics of the development, multiplication and specialization of scientific branches (Genuth 1987) in order to sustain continuous technical and productive innovation.[1]

Nuclear physics was one of the new fields in which this took place (Weiner 1970; Hansen and Stampen 1994), and also coincided with the growing scientific leadership of the US. Two techniques on both sides of the ocean, based respectively on cosmic rays and particle accelerators, contributed to the discovery of the elementary particles necessary for the physical understanding of nuclear structure and processes (1932: neutron, Chadwick, Cambridge; positron, Anderson, Caltech). It was Ernest O. Lawrence in the US who developed a new kind of managerial capability, soliciting huge funds for the innovative projects of his successive cyclotrons (Heilbron and Seidel 1989) during the worst phase of the economic recession, when the budget for research and higher education suffered big cuts (Weiner 1972). Lawrence succeeded in convincing philanthropic societies, as well as electric and medical companies, that the new knowledge in nuclear physics was worth supporting in view of its innovative applications. However, he was interested above all in building more and more powerful machines, foreshadowing the spirit and characters of Big Science (Galison and Hevly 1992; Gemelli 2001).

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[1] For example, (Conkin 1967; Fraser and Gerstle 1989).

In this connection, it is important for our aims to remark that Big Science was not a necessary choice imposed by the very development of the organization and method of scientific research, necessitated by the growing complexity of the problems under study; on the contrary, these early post-war developments showed the simultaneous presence of diverging scientific attitudes, which we could denote as "Big" and "Little" (or "Intermediate") science, and sometimes as their clash (Baracca 1993).[2] On the other hand, the final victory of the Big Science approach also deeply influenced the kind of scientific research results and interpretations, not to mention technical applications concerning the atomic nucleus. In particular, Lawrence's race toward more powerful cyclotrons became a goal in itself, such that he devoted much less attention to the experimental equipment and method, ultimately missing fundamental discoveries like the artificial radioactivity Cockcroft and Walton found using a less powerful and sophisticated accelerator.

27.2.2 Early Local Schools and Approaches

With regard to local factors, a great number of instances can be mentioned (Malley 1979). While particle accelerators became the new frontier of nuclear research, in countries that had no chance for building such machines, fundamental results were obtained with alternative techniques: in fact, this is the way the decisive results for military applications were achieved. One can mention the Joliot-Curie laboratory in France (Pinault 2000), and the studies on slow neutrons obtained with the emulsions technique by the Fermi group in Rome (Segré 1979; De Maria 1999), although their correct interpretation[3] was provided some years later by the group of Hahn and Strassmann, specifically by Lise Meitner.[4] A second instance is given by Japan, where a markedly national approach to physics was adopted, rooted in traditional philosophy, lacking applicative aims but emerging as a forerunner of subsequent approaches and results (Brown et al. 1980). For instance, Yuakawa's meson hypothesis (1936) was not merely the conception of a particle mediating nuclear forces: the meson was rather the central element of a more complex and

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[2] Actually, it was one of the outstanding nuclear physicists of the 1930s, Merle Tuve (Lawrence's contemporary, fellow-townsman and classmate), working at the Carnegie Institution in Washington, who refused to join the Manhattan Project, developing during wartime the proximity fuse instead. But after the war he openly opposed Big Science, ultimately "[leaving] nuclear physics when it turned from a sport into a business." One may add that European physicists visiting Lawrence's Berkeley laboratory during the late 1930s; other scientists (like the biologist Jacque Monod for other laboratories in 1946) felt similarly perplexed about pursuing scientific goals in the face of such dimensions and levels of organization. See, for example, (Heilbron and Seidel 1989, 238–252, 350–352; Gaudillière 2002b).

[3] Although Fermi correctly interpreted most of the results of his group, only the assumption of transuranic elements was not right, but neither was it fully wrong, as was shown later.

[4] See (Meitner and Frisch 1939; Frisch 1979; Lewin Sime 1996; Sánchez Ron 2000, 245 ff.). This circumstance offers occasion to remark on the monopoly of male scientists in the development and transmission of scientific knowledge. It would be interesting to investigate the possible consequences of this factor on the kinds of fields, knowledge and applications that were developed, but that goes beyond the scope of this paper.

coherent philosophical framework (Brown and Hoddeson 1983). What is more, the Japanese case confirms the absence of a strict correlation between the use of particle accelerators and the development of research structures organizing Big Science: cyclotrons were in fact built in Japan during the 1930s, but research proceeded in small groups.

27.3 The War and the Manhattan Project: Diffusion or Secrecy of Knowledge?

27.3.1 Highly Coordinated Scientific Research under Military Rule

I will not discuss the developments of nuclear physics during the war. The Manhattan Project is too complex to be analyzed here; detailed studies have been published since the documents were declassified (Pringle and Spigelman 1982; Rhodes 1986). In contrast, the uranium projects in Germany and Japan still leave many aspects to be clarified.[5] The theatre of war displayed the immense contribution that science-based technologies—such as the atom bomb, proximity fuses, guided missiles and radar—could make to national defense (Kevles 1978). The conflict also spawned entirely new fields such as operations research, which applied statistical methods to improve the efficiency of resource allocation in both military and industrial systems (Fortun and Schweber 1993; Krige 2006a, chap. 8).

An exceptional feature was introduced in wartime in scientific and technical research, which would subsequently characterize the work of a large part of the scientific community, especially in nuclear physics: i.e. *secrecy*, which appears as the opposite of the very spirit of scientific investigation, or at least of its stereotype. For the first time, an entire scientific community was put together to work on a unique project (the Manhattan Project), with extremely fragmented tasks, under strict *military* control. One could pose the problem of how war (in general, military research) may affect the development, orientation and diffusion of knowledge in general.[6]

It must be stressed that the first large-scale application of nuclear technology was military: the “Fermi pile,” the first nuclear reactor for controlled chain reaction, was not conceived to produce power, but served as a central step in the Manhattan Project. Its purpose, in fact, was the experimental proof of the feasibility of the chain reaction, and—after plutonium was discovered by Seaborg and collaborators in 1941—to find a way to produce it in large quantities, while the process for enriching uranium was in progress. In fact, for many years after the war, only military nuclear reactors were built. Since the beginning, therefore, the *dual-use* nature of nuclear technology appeared as a basic, historically

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[5] For the Nazi uranium project, see (Goudsmit 1983; Walker 1992, 1995; Bernstein 1996; Rose 1998). For the Japanese project (Shapley 1978; Grunden 2005; Nagase-Reimer et al. 2005).

[6] In the case of nuclear technology, one can conclude that the bomb would have been built in any case. Without the war, however, it could have required perhaps twenty years, during which research in the field could have led to somewhat different choices, developments and results.

novel feature of the diffusion of science-based technology, and of every subsequent development: in Oppenheimer's famous words, a kind of "original sin."

27.4 After the War: Monopoly or International Control?

The atomic bomb played a determinant role in post-war international politics. This was a crucial period for setting out the nature and mechanisms of transmitting and controlling the new technology in its civilian and military use: several options were actually open, and the choices and changes were determined by political and economic factors. The US trusted in a long-term monopoly on nuclear weapons. Two basic conceptions stood in opposition to each other. Several influential figures advocated international control, shared in particular, but not only, with the Soviets (back in 1944 Bohr had strongly supported this solution, incurring Churchill's denial and harsh criticism). The final failure of the proposal for international control of nuclear technology, and the elimination of nuclear weapons, was the rejection by the Soviets of the "Baruch Plan," presented by the US at the UN in 1946 (Hewlett and Anderson 1962; Smith 1965; Robinson 2004).[7]

Just one month later, the US Congress approved the "McMahon Act" on the control and management of nuclear technology, which established a rigid policy of secrecy on nuclear matters, especially military ones. Such a rigid structure was not appreciated by the advocates of the development of a private industrial sector: indeed, this legislation was changed radically in the 1950s.[8] The United States based its security policy on its sole possession of the scientific, technological and material basis of atomic energy (Herken 1980). In hindsight, such a trust in a long-lasting monopoly on nuclear weapons appears superficial. As a matter of fact, it was broken by the 1949 Soviet nuclear test (Holloway 1994), which inaugurated the process of (military) nuclear proliferation. The Cold War had begun and the nuclear arms race took off.[9]

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[7] A Wall Street businessman charged by Truman with the mission of presenting the proposal to the UN, Baruch modified the plan and presented it with conditions that were not acceptable to the Soviets. The complete text of the plan can be found at: www.atomicarchive.com/Docs/Deterrence/BaruchPlan.shtml. As a subsequent authoritative pledge for "full mutual openness" in the flow of atomic information as a means of reducing "distrust and anxiety" between the superpowers, it is worth recalling Niels Bohr's famous *Open Letter to the United Nations* of June 1950 (Bohr 1950).

[8] It is noteworthy that at the end of the 1940s, the first nuclear engineering technical schools were established and open to foreign students (Oak Ridge, MIT, Berkeley). At the same time a work was published about the Allied World War II effort to develop the atomic bomb, the Manhattan Project (Smyth 1945); also the Field Information Agency, Technical (FIAT) Report was written (Bothe and Flügge 1948).

[9] The subsequent steps of nuclear proliferation have been reconstructed; starting points include (Gowing and Arnold 1974; Frisch 1979; Lewis and Xue 1988; Cohen 1998; Bendjebbar 2000; Perkovich 2001). For an overview, see (Bundy 1988; Reed and Stillman 2009).

27.4.1 Involvement of Scientists in Political Decisions: The New Role of Science in International Relations

Nuclear armaments also played a leading role in the profound post-war transformation of scientists' role in political advice and decisions. Due to the primary role played in wartime, scientists, even those in esoteric fields such as mathematics and theoretical physics, along with engineers, were considered an essential national and strategic asset, and were increasingly integrated into foreign affairs. Vannevar Bush was an enthusiastic proponent of this idea (Bush 1945). Now scientists became essential not only for the development and security of the nation, but also in its dealings with other states, in its efforts to project and consolidate its power in the international domain and build a stable world order.[10] During the war scientists had been appointed, together with politicians, to boards charged with proposing the decisions to be made in the use of nuclear weapons, and after the war those involved in their development (think, for instance, of the role played in the US by Edward Teller, or by other scientists in the USSR), proposed nuclear strategies and international negotiations about their control (Jacobson and Stein 1966; Barth 1998). Especially in nuclear matters and in strategic decisions, scientists assumed a role as experts in presidential decision-making.[11]

The increasing involvement of scientists in political decisions grew in parallel with the increasing role of science and technology as fundamental strategic factors for economic development, national security and international relations. In the first fifteen years after the war, science and technology became an affair of the state, and the governments in the Western industrialized countries implemented formal policies that matched science with national priorities.[12]

27.5 The Turning Point: "Atoms for Peace," the Supermarket of (*Dual-Use*) Nuclear Technology

Not until after the Soviets had exploded their own nuclear weapons in 1949 and 1950 did "Atoms for Peace" become a serious topic of discussion. This revolution in the politics of diffusion of nuclear technology took place in the 1950s, preceded by other basic developments.

27.5.1 Naval Nuclear Propulsion

The federal government had invested huge funds in the development of military nuclear technology, making the new sector ripe for more applications. In particular, besides military nuclear reactors for the production of plutonium, there were proposals for nuclear ships, locomotives, automobiles and aircraft. Only

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[10] See (Kevles 1990a; De Cerreño and Keynan 1998; Manzione 2000).

[11] See (Gilpin 1962; Jacobson and Stein 1966; Jasanoff 1990; Doel 1997; Herken 2000; Schweber 2000).

[12] See (Salomon 1977; Smith 1990; Skolnikoff 1993; Krige and Barth 2006).

marine propulsion was successful: the reactors developed to this end played a fundamental role in subsequent civil applications. The successful development of a nuclear propulsion plant by a group of scientists and engineers at the Naval Reactors Branch of the US Atomic Energy Commission, AEC (1953), led to the construction of the *Nautilus* (1955), the world's first operational nuclear-powered submarine. The subsequent failure of other models led to the selection of the PWR (Pressurized Water Reactor) as the standard US naval reactor type. In the US, a single series of standardized designs was built by both Westinghouse and General Electric; the British company Rolls Royce built similar units for Royal Navy submarines.

Soviet work on nuclear propulsion reactors began in the early 1950s at the Institute of Physics and Power Engineering (Obninsk): the first Soviet propulsion reactor began operational testing in 1956. Aside from a few test designs, the Soviet Navy, too, opted for light-water reactors.

Nuclear propulsion has been practically limited to military ships (submarines and aircraft carriers), with the exception of three freighters and the Soviet icebreakers, and the German nuclear research ship *Otto Hahn* (1968). The introduction of nuclear submarines entailed a deep change in military strategies, in particular with respect to nuclear weapons, especially when the introduction of ballistic missiles (see below) made land-based weapons vulnerable to a pre-emptive attack. At the end of the Cold War there were over 400 nuclear-powered submarines operational or under construction: since many ships use more than one reactor, the total number of military reactors built to date is larger than that of civilian power reactors (439 working at present). From my point of view, it is important to note that the American type of nuclear reactors developed for naval propulsion determined the models that were subsequently adopted for civilian power reactors.

27.5.2 The Development of the Industrial Military Complex

Another aspect was of instrumental importance to the further development and diffusion of nuclear technology and its features: the establishment in the United States of a huge *industrial military complex.* The main companies had collaborated strictly to realize military projects, and established deep ties with political power. However, the military control exerted on research activity during the war could not continue in peaceful times: the majority of scientists who had worked in the Manhattan Project returned to their universities and institutions. The need for the government to keep up cooperation with the scientific community useful for the military programs took other forms. The most direct was the establishment of a huge sector of research devoted entirely to military research, which kept close ties with the main industries. Besides the three main National Laboratories devoted mainly to nuclear armaments,[13] a myriad of smaller centers grew up in

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[13] Los Alamos, Sandia and Lawrence Livermore: note that the last of these was established in 1952 by the above-mentioned inventor of the cyclotron, Ernest O. Lawrence, although the decisive force behind this project was Edward Teller.

the US.[14] The overall costs of the whole system of nuclear armaments (warheads, launchers, alert and control systems, dismantlement, nuclear wastes and so forth) is obviously unknown, but as the main item of national defense is undoubtedly around several trillion dollars, one of the largest items of the US federal government expenses (Schwartz 1998a; Burr 2009). The very fact that a large part of scientific and technical research was developed after the war in *military laboratories* or for military applications, absorbing a very large part of the total budgets for research and design (R&D), is a factor whose relevance and consequences seem far from being fully appreciated, let alone investigated.[15] In this chapter I will discuss at least some of the main consequences for the case of nuclear technology.

In the USSR, too, a huge complex was established for the development of nuclear and other armaments (suffice to recall the "secret cities"[16]): the main difference with respect to the US probably being that, as the whole industrial system belonged to the state, it was a purer *military system*. In my opinion, this had major consequences, not only for nuclear technology, but probably for the entire Soviet economy. In fact, the development of this technology in the USSR did not propel the growth of the economy, but acted rather as a dead weight, whose negative role grew more and more until the final collapse.

27.5.3 Promotion and Diffusion of "Civilian" Nuclear Technology

With huge federal investments, the development of nuclear reactors and all the parts of the nuclear fuel cycle had prepared the ground for the commercial launch of the technology. We have seen that the main American companies were engaged in the development of power reactors for naval propulsion. The same firms could therefore rely on these same models for the design of commercial thermal light-water reactors: pressurized water reactors (PWR) by Westinghouse; boiling water reactors (BWR) by General Electric. The adoption of these military prototypes for civilian use was not without consequences. Many military reactors work with highly enriched uranium, and require peculiar properties for their special conditions of operation and the specific needs of the militaries: they appear to be far from safe, as is evinced in the higher frequency of accidents in nuclear submarines.[17] This poses the question as to whether the development of these same models for civilian use has proved to offer the best safety standards.

Actually, the first power reactor was developed in the USSR in 1954 in Obninsk. But it was in the US that the opportunity for an international diffusion of nuclear technology for peaceful uses was seized, for both commercial and po-

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[14] See (Leslie 1993; Dahan and Pestre 2004); see also an updated list of military labs in (Schwartz 1998b).

[15] See, for example, (Gomatan and Ellison 1986).

[16] See, for instance: www.pbs.org/wgbh/pages/frontline/shows/russia/arsenal/structure.html.

[17] See, for instance, (Olgaard 1996). For a list of sunken nuclear submarines, see: en.wikipedia.org/wiki/List_of_sunken_nuclear_submarines; for the US: www.lutins.org/nukes.html#subs; for the USSR/Russia: spb.org.ru/bellona/ehome/russia/nfl/nfl8.htm.

litical aims. As such, around the mid-1950s—reversing the politics of absolute secrecy chosen after the war—the diffusion of nuclear technology turned into a programmed political and economic operation. This campaign was promoted by President Eisenhower's "Atoms for Peace" speech before the General Assembly of the United Nations (8 December 1953), and launched with the 1955 Geneva Conference with the same name (with 25,000 participants).

In fact, formal international cooperation in atomic science had to wait for the creation of the International Atomic Energy Agency (IAEA) in 1957, along with its system of safeguards to prevent the military use of atomic energy. Atomic scientists were among the last fields of expertise to obtain a UN Specialized Agency dedicated to their field.

One must recall that around 1950—after the Berlin Blockade (1948–49) and the birth of the Atlantic Alliance (1949)—a new phase of the Cold War had begun, with military encounters between the two blocks, in which the danger of the use of nuclear arms appeared quite concrete:[18] suffice to recall the 1962 Cuba "missile crisis" (May and Zelikow 2002). Moreover, thermonuclear weapons were developed (the H-bomb), in a surprising sequence: the test by the US in November 1952 of a substantially stationary device (Mike Test), was followed in an astonishingly short time (August 1953) by the Soviet explosion of a more or less real bomb (Holloway 1994), while the US did not follow with a real bomb until March 1954.

The rhetoric in Eisenhower's speech can be contextualized and marks a peculiar factor in the global diffusion of nuclear technology. Recognizing that "a danger exists in the world [...] shared by all," and "the expenditure of vast sums for weapons and systems of defense can[not] guarantee absolute safety for the cities and citizens of any nation," he proposed "to help us move out of the dark chamber of horrors into the light, to find a way by which the minds of men, the hopes of men, the souls of men everywhere, can move forward toward peace and happiness and well being." Nuclear technology must therefore "be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace": in this sense, "a special purpose would be to provide abundant electrical energy in the power-starved areas of the world," beginning at the same time "to diminish the potential destructive power of the world's atomic stockpiles."[19] In 1954 the secrecy dictated by the McMahon Act was overturned by the Atomic Energy Act, which explicitly allowed the transmission to friendly countries of nuclear knowledge and materials for peaceful uses.

27.5.4 Atoms for Peace, Dual-Use, Proliferation: An Assessment

An analysis of the features of the "Atoms for Peace" campaign is probably the main source for understanding the mechanisms of global diffusion of nuclear technology,

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[18] As General McArthur explicitly requested during the Korean War, 1950– 53; nevertheless, massive use of napalm caused more than one million victims and the destruction of practically all North Korean cities.

[19] See http://www.atomicarchive.com/Docs/Deterrence/Atomsforpeace.shtml.

the role of military and civilian applications, the relationships between center and peripheries, knowledge restrictions deriving from secrecy, industrial protection, and so on. I am necessarily compelled to restrict this analysis to certain aspects.

The basic economic and commercial interests were supported by ideological arguments. An emblematic expression of the latter are the words uttered in 1954 by Lewis Strauss, Lilienthal's successor as Director of the AEC:

> It is not too much to expect that our children will enjoy electrical energy too cheap to meter, will know of great periodic regional famines only as a matter of history, will travel effortlessly over the seas and through the air with a minimum of danger and at great speeds, and will experience a life-span far longer than ours, as disease yields and man comes to understand what causes him to age. This is the forecast for an age of peace. (Hilgartner et al. 1982, 44)

The international campaign that was promoted was impressive, but one may legitimately question its alleged *peaceful* purpose, for more than one reason. It was a truly massive political and economic offensive, aimed to attract neutral or irresolute countries in the Western sphere with huge investments for the purpose of reinforcing a belt of Western-oriented countries around the Soviet Union, and demonstrating the superiority of capitalist technology.[20]

For such goals, the campaign relied, presumably in deliberately ambiguous terms, on the intrinsic *dual-use* feature of nuclear technology, implicitly or explicitly feeding the illusion that any country that adopted civilian nuclear programs could ultimately acquire nuclear arms, and consequently an overwhelming superiority in its regional context. Having a nuclear capability of some kind was at once a guarantee of international recognition, a symbol of modernity for leaders and their allies among national elites, a bargaining chip with which to affirm national autonomy and to protect national sovereignty and national political agendas, and potentially an invaluable addition to military strength.[21]

As a matter of fact, many countries have, at least presumably, developed secret nuclear military programs (Brazil, Argentina, Sweden, Switzerland,[22] South Africa, India, Pakistan, Iraq, Iran, Libya, Egypt, Syria, and so on). In some cases these programs were successful[23] (India, 1974, 1998; South Africa, 1975–1979; Pakistan, 1998; North Korea, 2006), in others they led to the acquisition of the

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[20] For general references, see (Kollert 1994; Medhurst 1997; Lorentz 2001; Lavoy 2003; Krige 2006b).

[21] For general references see, for example, (Ogilvie-White 1996; Sagan 1996).

[22] In the words of Rob Edwards (1996): "Switzerland maintained the option to develop its own nuclear weapons until 1988, according to a detailed account released by the Swiss government. The country's atomic bomb program, which ran for forty-three years, included a secret stockpile of uranium, an attempt to buy weapons-grade plutonium and plans for 400 nuclear warheads."

[23] Some basic references are the following. For India: (Abraham 1998; Perkovich 2001). For South Africa: (Albright 1994; Liberman 2001; Purkitt and Burgess 2005, chap. 3). For Pakistan: (Ahmed 1999). Some peculiar mechanisms underlying the processes of nuclear proliferation can be understood by keeping in mind that for purely political reasons—a stable white South

complete nuclear cycle, probably not too far from the realization of a weapon: Brazil, for instance, has carried out the large-scale process of uranium enrichment without suffering the strong objections raised against Iran.[24] In fact, the possession of nuclear reactors is a necessary step to arrive at nuclear weapons. From the outset Eisenhower was well aware of this danger, and in his speech he proposed the establishment of the International Atomic Energy Agency, devoted to the control of the peaceful use of nuclear technology (as mentioned, the IAEA took up its work in 1957).

Moreover, the "Atoms for Peace" campaign did not limit nuclear weapons at all: under the Eisenhower presidency the American stockpile grew from 10,000 to 20,000 warheads (the Soviet total was one tenth of this number). In addition, in 1953 the US adopted a new nuclear strategy that placed nuclear armaments on the same footing as other weapons: it was substantially the first-use doctrine, which Washington has never abandoned.[25]

27.5.5 Diffusion of Nuclear Technology

The diffusion mechanisms of civilian nuclear programs, although based on almost standard designs, are difficult to synthesize in general terms, since they often followed specific local patterns in each country[26] (political, economic, technical conditions, specific ambitions, and so on).

In general terms, the diffusion of nuclear technology was marked by a peculiar relationship between the center and the peripheries: locally available knowledge and resources were promoted, yet strong limitations were also imposed since the American companies maintained their control over the basic technology. The United States led the process of international diffusion, dictated the conditions, and controlled its dynamics and basic processes, in particular uranium enrichment: scant space was left to other Western countries. A limited market was conquered by the Canadian natural-uranium reactor (Candu), designed precisely for getting round the enrichment process, although it offers advantages for proliferation programs due to higher plutonium production (India, for instance, has bought such reactors). The nuclear industries of some countries have done business with nuclear technology, also collaborating in military programs (like Israel, Germany

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Africa as a barrier against spreading Marxism in Africa, and Pakistani help against the Soviet war in Afghanistan, respectively—the Department of State was willing to blur intelligence on the military programs in the two countries, and the support they were receiving from several countries. See, for example, (Gallucci 2005); cited in (Krige 2006b, 12 and fn. 32).

[24] On Brazil, see (Palmer and Milhollin 2004). An updated and comprehensive overview is offered in (Feldman 2010).

[25] A major "black hole" is the development of nuclear technology and armaments in Israel, which without doubt was strongly supported by foreign collaboration, but still presents deep unclarified aspects (Cohen 1998; Gerlini 2010).

[26] Two international workshops on these aspects were held recently in Barcelona, Spain, at the University Pompeu Fabra: A Comparative Study of European Energy Programs, 5–6 December 2008; and A Comparative Study of European Nuclear Energy Programs from the 1940s until the 1970s, 3–5 December 2009.

and Argentina with South Africa;[27] France and Italy, among others, with Iraq). Only France subsequently achieved technical and economic autonomy in the field when it chose to base its electric power production on nuclear plants, relying on a standardized design: notwithstanding the unique role of the state, one must point out that the alleged efficiency and economy of the French energy system is largely questionable, basically because of the rigidity of nuclear technology.[28]

For the Soviet Union the situation was completely different, since the diffusion of nuclear technology was not supported by profit mechanisms. Since the beginning Russia had a real need for electric power, and nuclear energy truly was seen as a possible solution: furthermore, some scientists saw an opportunity to work not primarily for military but for civilian uses, and the government, too, saw an opportunity to demonstrate to the world its peaceful ambitions. Moreover, the Soviet strategies for the diffusion of nuclear technology seem to have been quite different from the American ones. The Soviet Union, in fact, never allowed the countries in its sphere of influence to acquire, or even control, nuclear weapons (the cooperation with China was very cautious and was broken off at the first sign of disagreement).

27.6 The Landscape Becomes more Complicated: Other Incentives, New Fields

This is obviously not the place to go through all the mechanisms of diffusion of military nuclear technology. A very important aspect that cannot be tackled here was, and still is, the development of the whole system of nuclear armaments of increasing complexity and much higher cost than the warheads alone: from launchers, to warning systems and satellites, control systems, and so on.

27.6.1 One More Leap: The Shock of Sputnik

Precisely the early development of ballistic missiles was the cause for a strong acceleration in nuclear research and development. The launch in 1957 of the first Soviet artificial satellite, the *Sputnik*, came as a bolt from the blue (McDougall 1985): it was a tremendous shock for American public opinion and the political establishment, representing the threat that the Soviet system really could overcome

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[27] For a perspective from those involved in building the South African bomb, see (Steyn et al. 2003).

[28] See (Schneider 2009; Schneider et al. 2009). The power of nuclear plants cannot be easily regulated: in order to cope with the peak demand for electric power, France produces a surplus of electricity, which in standard conditions it sells at very low prices, at the cost of inefficiencies and waste; under exceptional weather conditions it purchases the extra power it needs at high prices. One should further add a point that is anything but marginal for an evaluation of nuclear technology: since nuclear plants produce only electric power, which is generally less than 20% of total final energy consumption, France is no less dependent on oil than other less "nuclearized" countries.

the capitalist one.[29] The reaction to this shock produced a huge effort in the American research, technical, and education systems to face the perceived danger. Between 1957 and 1967 federal research and development expenditures nearly quadrupled, reaching almost $15 billion (Kevles 1990b, xviii).[30] Without a doubt, this acceleration had deep consequences on the development and diffusion of new knowledge and technologies.

27.6.2 Foreign Science Politics and New Fields Induced by Nuclear Technology

One more aspect has played a large role in inducing the development of other scientific and technical changes, derived from or connected with nuclear technology. As remarked above, the kind of direct control exerted by the military on research activity in the US during the war could not continue in peaceful times. However the political and military establishment could not renounce the irreplaceable contribution of the scientific community. The solution was twofold. I have already discussed the creation of large laboratories devoted exclusively to military research, and scientists' appointment as political advisors or as members of Commissions: the role played for instance by the "Jason Division"[31] can hardly be underestimated (Shapley 1973).

But a more subtle endeavor took place as well, which seems more meaningful for the mechanisms being studied. The premise was that "the scientists of this nation be kept currently aware of the latest advances of modern technology, in whatever nation these may occur" (Berkner 1950)[32]; i.e. that the United States should never fail to appreciate an intellectual potential, in any country, that can produce fundamental results important for national welfare and security: such results must be integrated into the American system in a quick and continuous way. This concept grew along with the strategy of using science and technology in the projection of American power abroad, as happened in the clearest, although very subtle, way in the construction of a scientific American hegemony in the

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[29] The 1955 Geneva "Atoms for Peace" conference had already shown to the most attentive people the high level already reached by the Soviet nuclear scientists. In 1954 the Soviet Union produced about twice as many Ph.D.s in the sciences as did the United States, probably of comparable quality.

[30] See also (Killian 1977; Dennis 1994; Krige 2000).

[31] This elitist group of scientists (named after the mythical Greek hero), including several Nobel laureates, was created in 1959. It meets every summer and freely elaborates on problems related to national security, defense and arms control, posed by the Pentagon, the Department of Energy and other federal agencies. Their reports, most of them classified, often directly influence national policy. The role of the Jason Division was particularly remarkable under Defense Secretary Robert McNamara, when its suggestions determined military decisions during the Vietnam war, but it is still influencing basic decisions about nuclear armaments.

[32] See (Anonymous 1950). For more details on the Berkner Report, see (Needell 2000; Miller 2001).

post-war reconstruction of science in Europe.[33] International scientific exchange (in particular in physics) was an instrument in the intellectual and cultural Cold War abroad.

In this context, a stealthier project gradually emerged, of encouraging the development of new branches whose perspectives of military application were quite distant, so that truly free theoretical research could be performed: no doubt the results in such fields would help in designing new and better armaments, but this would take a long time, allowing the militaries to gradually transfer the sensitive results into the zone of secrecy:

> Even if major scientific discoveries of economic and military importance were made [in Europe], America would be far more capable of taking advantage of them. (Krige 2006a, 12)

Under such conceptions, nuclear research itself underwent a process of institutionalization and open research in less sensitive sectors, which in any case provided more or less indirect support to the military activity in the special laboratories. Moreover, the physicists were particularly attracted by the new fields opening up that appeared even more stimulating. It was in fact acknowledged that, fortunately, there were fields of activity relevant to the AEC in which secrecy could, and must, be given up, since the possibility of immediate military application was too small in comparison with the need for further, open investigation. High-energy physics was an example of such a field, and was actually liberally financed.

Moreover, this choice also allowed the exploitation of scientific and intellectual potentials in foreign countries. The United States actually contributed to promoting advanced research in these fields in foreign countries, with the investment of local funds and resources.[34] The best-known case is probably the international laboratory CERN in Geneva (Hermann et al. 1987). The US played a decisive role in the proposal and establishment of CERN. As a matter of fact, a pathbreaking intervention was made in June 1950 by the American physicist Isidor Isaac Rabi, as a member of the US delegation to the UNESCO meeting in Florence (Jungk 1986; Krige 2004, 2005). He had an enabling resolution passed—after authorization by the US State Department and consultation with some European physicists—calling for the establishment of regional research centers grouping together several countries, like France, West Germany and Italy.[35] It was stressed that these centers

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[33] See (Doel 1997, 220; Krige 2006a). Needless to say, at least the most sensitive personalities acutely felt the threat to European culture and values, even the invasion of the deepest layers of the psyche (somebody spoke of the "Coca-Colonization"), the film director Wim Wenders called it "the colonization of the European subconscious" (Wagnleitner 1994, xii).

[34] A comprehensive analysis is undertaken in (Krige 2006a).

[35] Of course, helping rebuild European physics was not without risks: there were fears of a resurgence of German militarism and nationalism, and there were worries of security leaks to the Soviet Union. For an overview of the German problem see, for instance (Krige 2006a, chap. 2). The final solution came with the NATO treaty, and on the scientific plane with the establishment of CERN.

would produce "creative work on behalf of peace," thereby "saving Western civilization."[36] By pooling their human and financial resources, member nations could acquire the expensive instruments of modern research that they could not afford alone. As for the fields that ought to be explored at such centers, Rabi specifically mentioned physics, biology and computing, with accelerator physics as the initial priority. Europeans were encouraged to develop advanced research in *unclassified* high-energy physics. It must be stressed that several European physicists originally interpreted Rabi's resolution as suggesting that the laboratory build both an accelerator and a reactor for low-energy nuclear physics,[37] but Rabi clarified in the discussion the opportunity of foregoing a nuclear reactor at CERN. In 1954 the first Director of CERN was Felix Bloch, who came from the University of Stanford.

These premises help in understanding the leading role of, and financial support for, high-energy physics in the development of physical research in Europe and other countries in the following years.[38] However, high-energy physics is only one of many cases. A second important case is given by the research on controlled nuclear fusion (Bromberg 1982).[39] Widely hailed as a potential shortcut to cheap electric power, after half a century this technique is still far from accomplishing this requirement, but has been institutionalized as an unclassified field, absorbing huge funds and resources, and developed in several countries.[40]

A specific remark is in order, once again, regarding the mechanisms of diffusion in the Soviet Union, where these same choices were repeated, but did not act as an impetus for development and economy in state industry or the satellite Socialist states, becoming in many cases more of a dead weight than an advantage. The mechanisms for diffusing nuclear technology are therefore strongly dependent on the economic and social environment and on local conditions.

27.7 The Establishment and Implementation (or Violation) of the Non-Proliferation Regime

The problems posed by the dual-use nature of nuclear technology increased as ever more countries went nuclear (Great Britain in 1952; France and Israel in 1960; China in 1964), and the technology spread commercially, posing a growing need for an international control regime on its use and transfer. This led the superpowers to negotiate the Nuclear Non-Proliferation Treaty (NPT), which came into force

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[36] Reservations have been raised about the purely peaceful implications of the research performed and the results obtained at CERN. See, for example, (Grinevald et al. 1984).

[37] See, for example, (Krige 2006a, 60 ff.).

[38] As a personal recollection, in Italy fields with more applicative potentialities, such as solid-state physics, were strongly discriminated against in post-war decades in favour of high-energy physics. A critical sociological and methodological analysis of research organization and practice in this field up to the 1970s was performed in (Baracca and Bergia 1975).

[39] For examples of other sectors see, for example, (Forman 1987) on quantum electronics, and (Fortun and Schweber 1993) on operations research.

[40] As concerns its possible military implications see, for example, (Gillette 1975).

in 1970, and in the following years achieved the compliance of the large majority of states, with a few exceptions, in particular Israel, India and Pakistan, which subsequently went nuclear outside the proliferation regime. Some non-nuclear states that had developed secret military projects presumably abandoned them just before signing the NPT (which in any case allows withdrawal at three-months' notice, as was the case for North Korea in 2003).[41]

The growing worries about spreading military nuclear proliferation led US President Jimmy Carter (a former nuclear engineer) to radical decisions in the 1970s—even at variance with sectors of his own administration—in order to try to put an end to plutonium production: he therefore stopped both the reprocessing of exhausted nuclear fuel, by adopting a once-through nuclear fuel option, and the development of fast nuclear reactors.[42] In the meantime France was making radical political decisions, withdrawing from NATO and developing its own *force de frappe*: in this context it remained the only country to develop an ambitious program of fast plutonium reactors[43] (with initial participation by Germany and Italy), which recently came to an end with the final shut-down of *Superphoenix* (1997).

Between the late 1970s and the early 1980s the problem of *tactical*[44] warheads deployed in Europe erupted:[45] the so-called "Euromissiles crisis" once more brought the threat of a nuclear war closer (Podvig 2008) and unleashed a strong peace movement explicitly demanding nuclear disarmament (Evangelista 1999). The final solution to the crisis was provided by the first historical agreement on a reduction of nuclear armaments, the INF (Intermediate Nuclear Forces) Treaty, signed in 1987 by Presidents Gorbachev and Reagan, which imposed the removal of all tactical nuclear weapons deployed on intermediate-range missiles.[46]

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[41] Actually, the NPT is quite an asymmetrical treaty, preventing non-nuclear states from going nuclear through an international system of inspections and safeguards performed by the IAEA, but not providing stringent measures to impose nuclear disarmament on nuclear states. Such an asymmetry between "haves" and "have-nots," and the subsequent enduring polemics, have prevented the quinquennial Revision Conferences of the NPT from achieving substantial results on the path toward the total elimination of nuclear armaments.

[42] Only recently were the documents related to the Carter Administration declassified, so full analyses will appear in the coming years. In the meantime, see a detailed preliminary analysis in (Tiseo 2009); moreover, Joseph Nye, the president's advisor on nuclear matters (Nye 1981). See also (Donnelly 1979; Rana 1980; Potter 1982; Barrow 1998).

[43] At present Russia, India and Japan hold fast reactors programs for the future, see (Cochran et al. 2010); India's program, in particular, raises concerns of military proliferation, see (Ramana 2010).

[44] The distinction between strategic and tactical nuclear weapons is neither official nor accepted by all states (the USSR/Russia prefers to refer instead to sub-strategic weapons). The latter usually have lower explosive power and shorter ranges, but principally tactical military targets.

[45] See (Nuti 2007; Savranskaya and Blanton 2007; Wittner 2009).

[46] Two circumstances deserve mention in this context. On a general footing, the treaty imposed only the removal of intermediate-range weapons, without any obligation for dismantling or keeping track of them: as a consequence, counting how many tactical warheads still exist is one of the main problems presented by today's nuclear arsenals (see below). A relevant historical aspect is that recently declassified Soviet documents show that in the December 1988 New York meet-

In the meantime, around the mid-1980s, world nuclear stockpiles reached their maximum level, with a total of around 70,000 warheads, most of them tactical (the Soviet arsenal peaking at around 45,000, while the American one had been decreasing gradually since the mid-1960s—but its strategic arsenal peaking around the mid-1980s, too), see Figure 27.1 below.[47]

Figure 27.1: Quantitative consistency of strategic and non-strategic American and Soviet/Russian arsenals of nuclear warheads, 1945–2010. (Sourced at www.fas.org/ blog/ ssp/ 2009/04/ usrusnukes.php). This figure comprises active warheads, including spare warheads, but excludes those which are inactive, but still intact, and awaiting dismantling (in 1996 2,542 for US, 12,278 for Russia). The counting of non-strategic warheads is subject to major uncertainties, as is explained in the text.

27.8 What Changed after the Collapse of the Soviet Union and the End of the Cold War?

Deep changes occurred in the development and diffusion of nuclear technology after the end of the Cold War, although smaller than initially expected.

27.8.1 Early Hopes for Nuclear Disarmament ...

In fact, the collapse of the Soviet Union apparently made the deterrence role of nuclear armaments obsolete and opened up great hopes for their gradual elimi-

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ing between Presidents Gorbachev and Reagan, the former was ready to proceed in the short term with the total elimination of nuclear armaments (Savranskaya and Blanton 2008); but the American president-elect participating in the meeting, George H.W. Bush, asked for more time to examine the problem, so this opportunity was lost.

[47] A table with the annual quantitative development of the American, Soviet/Russian, French, British and Chinese arsenals is given by: nrdc.org/nuclear/nudb/datab19.asp.

nation. This perspective seemed to be confirmed by several events, in spite of conflicting factors, until the second half of the 1990s. “Reduction” treaties of strategic stockpiles were established (Strategic Arms Reduction Treaty (START): START-I, 1991; START-II, 1993) instead of the “limitation” treaties (SALT) of the Cold War decades. A Comprehensive Test Ban Treaty (CTBT) was at last established in 1996 (although the main nuclear powers implemented powerful methods for the simulation of nuclear tests, see below).

In 1996 the International Court of Justice established that any threat or use of nuclear weapons would be generally illegal, allowing for the possible but uncertain exception under current international law of a circumstance in which the very existence of a state is at stake. But even then, for such use to be legal it would have to meet the standards of international humanitarian law; in other words, it would have to discriminate between soldiers and civilians, be proportionate, and not cause unnecessary suffering.

The 1995 Revision Conference of the NPT decided on the unlimited extension of the treaty, although the decision was taken at the end of inconclusive discussions, with the impossibility of assuming further binding conditions. The following 2000 Revision Conference resolved, for the first time, thirteen concrete, binding steps toward nuclear disarmament (Simpson 2001). A progressive reduction of the American and Russian strategic stockpiles began (see Figure 25.1).

27.8.2 ...and Subsequent Disappointments

But this positive trend was subverted toward the end of the century. The Indian and Pakistani nuclear tests (1998) were a bitter (although widely foreseeable) surprise. In 1999 the US Congress rejected the ratification of the CTBT, which as a consequence never entered into force. The US withdrew from the ABM treaty,[48] and subsequently from START-II. The SORT (Strategic Offensive Reductions Treaty), or Moscow treaty, established by presidents Bush and Putin in 2002, cannot be considered a substantial improvement: even though it does impose the reduction of deployed strategic warheads to 1700–2200 each for 2012, it imposes no prescription for how to count them, nor for dismantling them (as did START-II), so that many more intact warheads will survive for a long time to come (see below).

Obviously, 9/11 caused a sharp increase in international tensions. The thirteen practical points agreed on at the 2000 Revision Conference were systematically ignored by the nuclear powers. The pace of removal (let alone elimination) of nuclear warheads and armaments was slowing down. Besides improving the

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[48] This was a fundamental treaty (Anti-Ballistic Missile) for the balance of nuclear forces, limiting to two the number of missile defense systems that each block could deploy in order to prevent strategic superiority.

simulation methods for nuclear tests, all the nuclear powers undertook systematic programs of sub-critical tests.[49]

27.8.3 New Doctrines and Roles for Nuclear Armaments (under the George W. Bush Administration)

The main novelty—developed chiefly under the Bush Jr. Administration, and after 9/11—was probably the radical change in the military conception of the role, and possible *use*, of nuclear weapons, which in a few years turned them from obsolete relics into key components of the military systems. Actually, the growth of the Cold War stockpiles had been "justified" by their role of *deterrence*, since their mere existence and consistency would seem to prevent their use. But during the last ten years this strategy has been radically revised: the 2002 *Nuclear Posture Review*, especially, deprived nuclear armaments of a distinctive character, and placed them on the same footing as the other components of the military system. At present, nuclear armaments are therefore increasingly conceived to be materially usable in warfare, even on the battlefield, and in a pre-emptive attack. As such, they seem to have acquired an irreplaceable role, while the (real or supposed) problems of nuclear proliferation have achieved unprecedented relevance.

27.8.4 New Threats and Proliferation Dangers: Diffusion of Nuclear Technologies and Materials

These changes have brought about deep consequences for the transfer and diffusion of nuclear technology, in all their aspects. The environment has changed radically from the days of "Atoms for Peace." Apart from political or strategic considerations, the dangers of nuclear proliferation seem to be selectively and unscrupulously used either as a bait or a harsh complaint (in the latter case coupled with threats or hostile actions), whichever seems more expedient. I already cited the case of Brazil for the process of uranium enrichment. As far as proliferation is concerned, the case of North Korea is emblematic:[50] the 9 October 2006 nuclear test, explicitly justified by the "hostile politics of the US," suddenly sprang five years of unproductive *Six Party Talks*, and led to an agreement (although the negotiations have been subsequently complicated for other aspects). The message is clear: if you feel threatened, go nuclear! A "bivalent potential" adds to the dual-use property of nuclear technology: on the one hand, an instrument of threat or coercion by the main powers; on the other, for those who are—or feel—threatened, the ultimate deterrence.

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[49] A complex class of tests in which no stable chain reaction is triggered. Complete nuclear tests no longer seem so indispensable, neither for verifying the operational status of the stockpiles, nor for designing or improving bombs (Garwin 1995), as compared with partial tests in which specific parts of the weapon are tested (von Hippel 1996; Drell et al. 1997; Younger 2000).

[50] In 2003 North Korea withdrew from the TNP, with the due three months' notice, reprocessed exhausted nuclear fuel, extracted plutonium, and three years later exploded its first nuclear bomb. See, for example, (Wit et al. 2004; Hecker and Liou 2007).

India's 1974 nuclear test demonstrated that the transfer of nuclear technology for non-peaceful goals is a reality. The sensitive aspects of nuclear technology and materials exchanges then led in 1978 to the publication of *Guidelines*, and the establishment of the *Nuclear Suppliers Group*: every exporting country must verify that the receiving country subjects the imported technologies to the system of safeguards. The system has been the target of criticism, from non-state actors as well.[51] On 28 April 2004, the Security Council of the UN adopted *Resolution 1540*, asking states to adopt more stringent internal laws and control measures, in order to prevent non-state actors from acquiring nuclear, chemical and biological technologies, establishing a *1540 Committee* to this end.

Nevertheless, the recent controversial *Civil Nuclear Cooperation Agreement* between the United States and India is a new cornerstone in nuclear technology transfer, legitimating—after three decades of ban on the sale of nuclear technology and material to India—the transfer of nuclear technology outside the framework of the NPT, toward a country which has signed neither this treaty nor the CTBT, and has ongoing programs to enlarge its stockpile. Although the agreement specifies that these transfers are limited to peaceful technology—through which India succeeded in developing its nuclear weapons nonetheless—it poses a new challenge to the *Nuclear Suppliers Group*.[52] The only possible conclusion is that from now on, the United States will set itself up as the utmost judge of which states mean to proliferate, and which not, thus imposing a supreme condition on the diffusion of nuclear technology. Currently it seems increasingly difficult to distinguish clearly between potentially proliferating and solely peaceful technologies, or to exert any real control over them. All the more so, if one takes into account the new or related techniques outlined above.

27.9 Present Problems, Perspectives, Dangers … and Hopes

The framework that is outlined briefly above holds serious challenges for the future. The new strategic context is pushing even more toward the further development of

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[51] Up to 2002 the IAEA had listed 181 confirmed accidents concerning illegal trafficking in nuclear materials, including materials usable for bombs, eighteen of which concerned High Enriched Uranium (HEU) or plutonium (more than half during 1993–1995 and the remainder during 1999–2002) (IAEA 2002); see also, *Information on Nuclear Smuggling Incidents*: atomicarchive.com/Almanac/Smuggling.shtml; and the impressive sequence documented by the US Congress, 1996 Congressional Hearings Intelligence and Security, *Chronology of Nuclear Smuggling Incidents*: www.fas.org/irp/congress/1996_hr/s960320c.htm.

[52] The agreement met with strong resistance, even in India. Resistance was also manifested by several countries inside the *Nuclear Suppliers Group* (Ireland, Norway, New Zealand, the Netherlands, Austria, Switzerland), and was not overcome until September 2008 in the face of strong pressure from Washington and Paris. Authoritative experts claim that the agreement does not forbid the sale of potentially military technologies and materials, let alone the supply of uranium, implicitly permitting the use of India's limited stocks (it should suffice to consider that the IAEA will be allowed to inspect only civilian plants in India, not the military ones). See (Ahlström 2006, app.13B); the agreement is discussed in detail in (Kyle 2008).

connected or collateral fields, which threaten to shape a new arms race of unprecedented dimension and complexity. I will summarize the main aspects below.[53]

27.9.1 Nuclear Stockpiles, Reduction Treaty, Strategies: What Are the Perspectives for Eliminating Nuclear Armaments?

In April 2009 President Barack Obama promised substantial reductions of nuclear stockpiles, reviving the future perspective of their elimination, but the year of negotiations needed for the agreement with Russia on the new START treaty, and the formulation of the new *Nuclear Posture Review*,[54] bear witness to the deep difficulties and hurdles along this path. In fact, on a practical level, these achievements—although they have reopened direct talks between Washington and Moscow—amount to little, if any, progress. While the danger of ultimate recourse to nuclear weapons, although reduced, is not absolutely excluded (thanks to countries' non-compliance with NPT obligations: according to the unique opinion of the US, Iran is indictable but not Israel or India), stockpile reductions will be small: a ceiling of 1,550 warheads each in 2017, *vs.* the limit of 1,700–2,200 imposed by SORT (see above) by the year 2012. Actually, the total number of nuclear warheads still existing worldwide—in addition to those actively deployed (almost 5,000 strategic and nearly 2,500 tactical by the US and Russia, and almost 1,000 more by the other nuclear powers)—must include spares (a hedge that could be reloaded at short notice), and retired warheads awaiting dismantling, for a total exceeding 20,000[55] (to which thousands of plutonium pits and Canned Assemblies (secondaries) in storage should be added).

One more complex aspect concerns the relevance assumed by (or attributed to) non-state actors, and the (exaggerated or not) problem of terrorism, against which a role by nuclear weapons can scarcely be conceived.[56] Even so, the concrete danger of triggering a nuclear war by mistake has existed ever since the nuclear era began—and was avoided only by chance in several instances.[57] The danger of an all-out nuclear war is always with us, but even a local war could have terrible consequences on humankind, as for instance between India and Pakistan (Robock et al. 2008; Robock and Toon 2010).

But the problem is not limited to the reduction of warheads. The most serious danger is the unprecedented leap in the military system represented by the development of missile defence systems and arms deployed in space: even smaller nuclear arsenals could be suitable to increase the efficiency of such systems. The

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[53] A comprehensive analysis of the problems concerning nuclear armaments is presented in (Baracca 2008, 2011).

[54] See (Department of Defense 2010a,b).

[55] Updated information can be found on-line in the "Nuclear Notebook" in the *Bulletin of the Atomic Scientists*, and in the SIPRI Yearbook (SIPRI Yearbook 2010); additional reports are published on the FAS Strategic Security Blog. For a general assessment, obviously limited to the Bush era, see (Cirincione et al. 2005).

[56] See (Ferguson et al. 2005; Allison 2004; UCS 2008; Walker 2010).

[57] See (Goldwater and Hart 1980; Arkin 1984; Sagan 1993; Phillips 2008; Hoffman 2009, 6–11).

ultimate condition for nuclear disarmament is reaching political consensus that it can be phased, transparent, verifiable, irreversible, and subject to strict and effective international control. As the Weapons of Mass Destruction Commission concluded authoritatively in 2006:

> So long as any state has such weapons—especially nuclear arms—others will want them. So long as any such weapons remain in any state's arsenal, there is a high risk that they will one day be used, by design or accident. Any such use would be catastrophic.
> (Weapons of Mass Destruction Commission 2006)

Concrete partial steps of utmost importance could consist in the enlargement of the Nuclear Weapon Free Zones,[58] above all freeing the Near East (even better, the entire Mediterranean basin, with neighboring zones) from nuclear armaments (Baracca 2006).

27.9.2 Programs for Improving Nuclear Armaments

Probably the most striking contradiction is the constant progress, by all nuclear powers, of extremely expensive programs for the improvement of nuclear warheads, above all, the continued development of all the other systems and complements of nuclear armaments (launchers, submarines, bombers, and so on).[59] It is no surprise that the whole military-industrial complex would appear to be the main obstacle on the path to eliminating nuclear armaments.

Research in new and related fields is taking on increasing relevance for novel developments and military applications. The most powerful computers are being built to improve the simulation of nuclear tests.[60] Another case is presented by developments in laser technology, which have given rise to at least two major sensitive military developments. On the one hand, the outstanding advances in super-lasers have made more concrete the possibility of simulating nuclear explosions in huge inertial confinement facilities as a means of designing new warheads, potentially accessible to even intermediate-level countries. In March 2009 the world's largest

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[58] The Nuclear Free Zones already established cover Latin America and the Caribbean, South Pacific, Southeast Asia and Africa. See, for example, "Nuclear-Weapon-Free Zones (NWFZ) At a Glance," http://www.armscontrol.org/factsheets/nwfz.

[59] One concrete example should suffice concerning probably the most futile of the nuclear stockpiles (if any can be considered useful). Recently announced plans to replace the UK's Trident nuclear weapons system have been estimated to cost about £15–20 billion at 2006/2007 prices, not including running costs (Ministry of Defence 2006). The new coalition British Government is critically revising this choice. The Obama administration is seeking more than $5 billion in additional funding over five years to sustain the US nuclear complex and deterrent. The overall cost of the Stewardship Program for nuclear weapons in the US greatly exceeds the average budget for nuclear weapons during the Cold War.

[60] The most powerful to date is *Road Runner*, with 1-petaflop capacity (10^{15} operations per second), developed at Los Alamos National Laboratory. But France is building a 60-teraflop computer.

and highest-energy laser, the *National Ignition Facility*, was certified for operation in the US,[61] equipped with 192 laser beams for the nuclear fusion of a deuterium-tritium micro *pellet* (a true miniature pure-fusion explosion). France is competing with its ongoing *Mégajoule* project, with 240 lasers; other projects are under development in several other countries. The negative aspect is that progress in using such laser techniques for isotope separation seems to promise a method of uranium enrichment[62] that may be cheaper and more difficult to detect by means of inspections (Boureston and Ferguson 2005).

Some concern is also raised by the American *Stockpile 'Stewardship' Program* devised by the "Jason Division," officially for the maintenance of existing stockpiles (Drell et al. 1999), but denounced as overdimensioned and costly, and bearing the potential for designing new warheads (Kidder 1997; Lichterman and Cabasso 2000).

27.9.3 Problems with Fissile Materials and a Fissile Material Cutoff Treaty

Fissile materials, and the dangers of their military use, present at least three kinds of problems, however deeply interwoven: suspension of their production, regulation of their commerce, and controls on theft and illegal exchange. Diffusion models had to take into account both the need for openness essential to scientific innovation and commercial exploitation, on the one hand, and the need for secrecy imposed by the military implications of this technology, on the other. Clandestine markets, and the sensitive aspect of commerce in a dual-use technology have instead yielded "undesired" consequences like the Iraqi nuclear program, in which several Western countries possessing nuclear technology were involved.

Huge deposits of plutonium and highly enriched uranium (HEU) have been accumulated in the world, almost 1,800 tons each[63] (approximately 10% of plutonium has a military origin, as compared with 90% of HEU), as well as other fissile isotopes of military interest.[64] This poses unprecedented and increasing problems for the control of these deposits, increasing the dangers of illicit traffic and of nuclear arms proliferation. Nowadays it is generally believed that the construction of a nuclear weapon is relatively easy for a country with standard technical means: the main problem is probably procuring the nuclear material (plutonium or HEU). North Korea, as is recalled, is probably the most significant example: having nuclear reactors, it has obtained plutonium by reprocessing spent

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[61] See the official site: https://lasers.llnl.gov/. For Mégajoule see, for example, (Allemand 2003).

[62] For general information on uranium enrichment see, for example, "Uranium Enrichment": nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html; "Uranium Enrichment Techniques" globalsecurity.org/wmd/intro/u-enrichment.htm.

[63] In order to manufacture an "implosion" warhead designed sufficiently well, 4 kg of plutonium are potentially enough (the dimension of a beer can), or a triple quantity of HEU; a simpler warhead with the "gun" mechanism can be made with only HEU, not plutonium, and needs around 50 kg (Bunn et al. 2002).

[64] See (Albright et al. 1997; Albright and Kramer 2004, 2005; Albright 2005).

fuel. Most plutonium and HEU in military stores is inside warheads, in dismantled warheads or in stocks and naval nuclear reactors (which use highly enriched uranium), but military stores also contain huge quantities of surplus fissile material: almost 700 tons of HEU, and 100 tons of plutonium (not all from warheads) have been declared, which would be enough for 30,000 warheads. Moreover, for many countries like Israel, India and Pakistan, the estimates of these materials are extremely speculative, since they have not been submitted to IAEA inspections. In addition, there is a greatly underestimated problem of *latent*, or *stand-by* proliferation by some countries like Japan, which hold open the nuclear option as virtual nuclear weapons states, having both the technology and nuclear materials (huge plutonium stocks from reprocessed fuel) to develop nuclear arsenals in a very short time (Nuclear Control Institute 2002; Barnaby and Burnie 2005). Moreover, the IAEA estimates that more than thirty countries have sufficient fissile material, and technical skill, to produce nuclear weapons (Kothari and Mian 2001; Drell and Goodby 2003).

One of the most sensitive problems at present is the negotiation of a *Fissile Material Cutoff Treaty* (FMCT), putting an end to the production of fissile material, but even after decades no agreement has been reached, although the main powers have in fact stopped such production.[65] Several countries rightly maintain that for a FMCT to be credible it must impose on nuclear states, at least for the civilian nuclear sectors, the same verification procedures that the IAEA applies to non-nuclear states.

Concerns are raised by the at least one hundred research reactors around the world supplied with uranium enriched to levels of more than 20%, which is considered of potential military interest (Kuperman 2006; NTI 2007a,b): the case of the Tehran Research Reactor and enriched uranium has taken on great topicality in recent months.

The final step in fissile material control should consist in making such materials unusable for warheads, but the problem is far from solved. HEU can be diluted, but only to a limited extent, and some must be stored in waste depositories. As for civilian plutonium,[66] the main share is still contained inside spent nuclear fuel; another part comes from reprocessing, or is declared surplus military material. The partial use of plutonium in mixed fuel (MOX) in light-water power reactors can be hardly be expected to solve the problem, and may raise other inconveniences (Lyman 2001), unless the prospects of fourth-generation nuclear reactors should come true (see below).

27.9.4 Resumption of Civilian Nuclear Programs?

One more contradiction worth underlining is the increasing pressure all over the world for the resumption of large-scale civilian nuclear programs. As for nuclear

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[65] A complete assessment is given in (IPFM 2008a). See also the synthesis (IPFM 2008b).

[66] See, for example, (Barnaby 2005).

armaments, these new programs rely on justifications quite different from those of the "Atoms for Peace" epoch. At present the main ones are the oil shortage and need to limit emissions of CO_2 into the atmosphere. Apart from the increasing proliferation of dangers and waste problems, critics object that—if one takes into account the whole nuclear cycle, from uranium mining to the management of radioactive waste, and plant and mine decommissioning—several phases emit CO_2: considering that the richest mines will be exhausted within a few decades, both the CO_2 and the energy balances are expected to become strongly negative (Storm Van Leeuwen 2008). Responding to these concerns is clearly crucial in order to evaluate the perspectives and sustainability of nuclear technology. Moreover, the possible development of nuclear production of electric power has no implication on oil dependence.

My personal opinion, which I cannot elaborate here, is that none of the (old and new) justifications for nuclear technology is unbiased, nor conclusive (Gronlund et al. 2007; Schneider et al. 2009). The nuclear production of electricity, after its boost during the 1980s, in fact gradually peaked around 2006 and is now declining: such a decline is expected to increase in the future since, prior to the few dozen new reactors under construction coming on line, many more will be closed over the next decades due to age limits. I maintain that civilian nuclear technology would not be sustainable by itself, and (directly or indirectly) bears heavily on military technology. The tight interdependency between the two sectors remains one of the most important aspects to be analyzed for a general appraisal of nuclear technology and its diffusion. Once again, the belief that a firewall can be drawn between nuclear energy and nuclear weapons is a general challenge to a new nuclear policy. No such firewall is possible, and nuclear reactors, for power or research, have fuelled the nuclear programs of Israel, India, Pakistan, North Korea, as well as presenting future proliferation risks. The designation of peaceful nuclear power as an "inalienable right" in the NPT is a contradiction that must be addressed if nuclear proliferation is to be controlled.

A few words must be dedicated to the so-called "fourth-generation" power reactors. Their putative characteristics are supposed to solve (or highly simplify) the bottlenecks of nuclear power, i.e. the problems of shortages of nuclear fuel, safety, and the amount and dangers of nuclear waste, making nuclear power "sustainable." Some reservations are in order. In the first place, these technologies are still being developed, and are not expected to become commercially viable before 2030–2040.[67] I would add that it seems at least surprising that a technology which promises such advantages requires so long to be completed: since several of the prototypes under development are fast-neutron, metal-moderated reactors, one should probably call to mind the possible surprises such a complex technology might hold in store, as did the French fast-reactor program after three decades of development (although it certainly was successful for the French military program) (Cochran et al. 2010).

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[67] A general assessment in their favour is (European Commission 2007).

Nuclear energy suffers from some basic drawbacks due to intrinsic physical limitations. The (first law) efficiency[68] of a nuclear plant is quite rigidly restricted to around 30% for the intrinsic limitations of uranium fuel and the uranium fuel cycle (although the combined gas-vapor cycle has been improved substantially and now approaches 60%), while the second law thermodynamic efficiency is even smaller, due to the extraordinarily high thermodynamic quality of nuclear energy (which corresponds to millions of degrees) compared with the demanded temperatures of hundreds of degrees. Thermal, low-temperature, use of the energy released from nuclei (corresponding to millions of degrees) can be considered a true "thermodynamic slaughter"!

27.9.5 Radioactive Pollution and the Health Dangers of Ionizing Radiation

Last but not least, the general problems of the radioactive pollution of the atmosphere during the nuclear era, along with the assessment of the health dangers of ionizing radiation, are in my opinion largely underestimated. This problem is extremely complex, and scientifically controversial. Although sixty-five years have passed since Hiroshima and Nagasaki, the main source of information remains the periodic revision of the data from those events. The assessment of the dangers of radiation, and of the "allowed" doses, is officially determined by the ICRP (International Commission on Radiation Protection), but its prescriptions and the very bases of its analyses are deeply criticized by independent scientists.[69] The problem of low radiation doses is particularly controversial. Moreover, a serious problem of radioactive pollution in the planet's atmosphere has been reported, originating from nuclear tests in the atmosphere, subsequently from the widespread applications of nuclear energy and technology, and more recently from the military use of depleted uranium.[70] There is also increasing evidence of the health effects of

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[68] "First law efficiency" is the ratio of the useful (electric) energy output to the total energy developed, as heat, by the chain reaction in the core. "Second law efficiency" is a completely different parameter, which takes into account the respective *thermodynamic qualities* of the input and output energies, related to their temperatures. See, for example, (Gilliland 1978; Wikipedia 2010). Considered as a thermodynamic engine, as it actually is, a nuclear reactor is an *external* combustion engine and could never become an *internal* combustion engine.

[69] It is interesting to recall, however, that the scientific awareness of the damage to health and the environment from ionizing radiations and nuclear tests goes back to wartime research, but was hidden from public opinion. In 1943 the scientists Conant, Compton and Urey sent the director of the Manhattan Project, General Groves, a memorandum, held secret at that time, on the "Use of radioactive materials as military devices": mindfully.org/Nucs/Groves-Memo-Manhattan30oct43a.htm. This document recommended their use in the battlefield, specifying that the thin radioactive particles would penetrate every gasmask. For nuclear tests, too, it is remarkable that the Soviet scientist Sakharov estimated back in 1958 that, for each megaton of nuclear explosive power in the atmosphere, even at low doses, almost 10,000 persons would suffer from cancers, genetic mutations and other illnesses (Sakharov 1958).

[70] See, for example, (Sternglass 1981, 2009; Bertell 1999; Busby et al. 2003; Mangano et al. 2003; Moret 2003; Baverstock 2005; Naruke et al. 2009), suggesting the presence of a late effect of

living in proximity to nuclear plants and of accidents at such facilities.[71] In particular, this group of scientists shares the opinion that the consequences of the 1986 Chernobyl disaster have been covered up.[72] As one of the main inconveniences for seriously tackling this kind of problem, the balance between the WHO and the IAEA, is strongly criticized for depriving the former of autonomy regarding issues related to radioactivity (Tickell 2009).

27.10 Conclusions

The entire set of problems I examined synthetically poses very serious challenges for civil society, for international relations and for the scientific community, in spite of the controversial or debated aspects.

From a general point of view, I would remark that, among all technological advances of humankind, nuclear technology is probably the most artificial, "unnatural," one, since it has activated physical processes that do not occur, not even in small fractions, in the environment in which we live and act (while they are basic processes in the interior of stars, at millions of degrees), therefore yielding artificial products which cannot be recognized and handled by the natural processes which act at the extremely lower temperatures prevailing on our planet. This is a fundamental difference with respect to all chemical processes, which depend only on the external electrons on atoms, but by no means on their nuclei. This is the fundamental root of the peculiarities of nuclear armaments, their terrible power, consequences and unmanageability. This is also the reason why nuclear waste cannot be eliminated. It is deeply striking to me that nobody wonders about the fact that nuclear waste has to be protected and guarded for periods of 300,000 years, a recommendation which goes beyond any reasonable scientific criterion and historical record: can anybody foresee or guarantee the conditions on the planet thousands of years from now? I think that it is scarcely possible to manage any problems that are *created* by nuclear processes by trying to *limit their dramatic consequences*, or stop them once and for all, let alone to actually *solve* them.

As far as the scientific approaches are concerned, it seems worth remarking on the existence of problems that can seriously bias or distort scientific and technical research. The British Association of Scientists for Social Responsibility has produced a series of studies on the dangers that military influence is wreaking on universities.[73] Although devoted mainly to British universities, the conclusions of the reports have more general validity. The military involvement in the R&D of universities supports a narrow weapons-based security agenda, marginalizing both a broader approach to security—which would give much greater priority to

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A-bomb radiation, which may indicate a predisposition to cancer. For the problem of depleted uranium, see (Bertell 2006).

[71] See (Mangano 2000, 2004, 2009; Fairlie 2008).

[72] See (Busby and Yablokov 2006). The most recent and worst prognosis can be found in (Yablokov et al. 2009).

[73] See (Langley et al. 2005, 2007, 2008).

supporting conflict prevention by helping to address the roots of conflict—and underfunding in comparison to other R&D fields that aim to tackle poverty, climate change and ill health, and thus help to provide basic security for human populations. As an example, in 2004, governments in industrialized countries spent a total of $85 billion on military R&D, but only $50 billion on R&D for health and environmental protection, and less than $1 billion on R&D for renewable energy. The reports add that, despite the introduction of the Freedom of Information Act (FoIA), the ability to obtain detailed information on military involvement in R&D, especially within universities, remains so highly problematic that further reform is needed. I could add to these conclusions that such research does not address the other side of the coin, namely the large share of the scientific community which works directly in military laboratories, and the certainly much higher budget on which they rely.

Addressing these problems, and bringing their knowledge and consciousness to civil society, is in my opinion a crucial aspect in the perspective of eliminating the ominous dangers and the problems raised by the nuclear era. An encouraging aspect is the existence of a vibrant movement for peace and nuclear disarmament.

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