50. A. Razin and A. D. Riggs, *Science* **210**, 604 (1980).
51. M. F. Lyon, *Biol. Rev.* **47**, 1 (1972).
52. B. R. Migeon and K. Jelalian, *Nature (London)* **269**, 242 (1977); M. Monk and A. McLaren, *J. Embryol. Exp. Morphol.* **63**, 75 (1981).
53. P. A. Jones and S. M. Taylor, *Cell* **20**, 85 (1980).
54. D. W. Clough, L. M. Kunkel, R. L. Davidson, *Science* **216**, 70 (1982).
55. M. Busslinger *et al.*, *Cell* **34**, 197 (1983).
56. A. Bird, M. Taggart, D. Macleod, *ibid.* **26**, 381 (1981).
57. R. A. Gjerset and D. W. Martin, Jr., *J. Biol. Chem.* **257**, 8581 (1982).
58. D. Mathis, P. Oudet, P. Chambon, *Prog. Nucleic Acids Res. Mol. Biol.* **24**, 1 (1980).
59. M. Groudine and H. Weintraub, *Cell* **30**, 131 (1982).
60. D. Poccia, J. Salik, G. Krystal, *Dev. Biol.* **82**, 287 (1981).
61. J. Ruderman and P. R. Gross, *ibid.* **36**, 286 (1974); L. H. Cohen, K. M. Newrock, A. Zweidler *Science* **190**, 994 (1975).
62. R. Appels, L. Bolund, N. R. Ringertz, *J. Mol. Biol.* **87**, 339 (1974).
63. D. F. Bogenhagen, S. Sakonju, D. D. Brown, *Cell* **19**, 27 (1980); D. R. Engelke, S-Y. Ng, B. S. Shastry, R. G. Roeder, *ibid.*, p. 717.
64. H. Holtzer, H. Weintraub, R. Mayne, B. Mochan, *Curr. Top. Dev. Biol.* **7**, 229 (1972); S-A. Carlsson, O. Luger, N. R. Ringertz, R. E. Savage, *Exp. Cell Res.* **84**, 47 (1974).
65. B. McClintock, *Cold Spring Harbor Symp. Quant. Biol.* **21**, 197 (1956); see also *ibid.* **45**, (1981), parts I and II.
66. C. Brack, M. Hirama, R. Lenhard-Schuller, S. Tonegawa, *Cell* **15**, 1 (1978).
67. P. Borst *et al.*, *Cold Spring Harbor Symp. Quant. Biol.* **45**, 935 (1981).
68. W. Shumway, *Anat. Rec.* **78**, 138 (1940).
69. P. D. Nieuwkoop and J. Faber, *Normal Table of* Xenopus laevis *(Daudin)* (North-Holland, Amsterdam, 1956).
70. Supported by grants from the National Science Foundation and the National Institutes of Health (NIH GM 23635 to M.DiB. and N.H. and NSF PCM-8023077 and NIH GM 31479 to L.F.). This article is dedicated to Robert Briggs (deceased) and Thomas J. King who first accomplished nuclear transplantation in metazoans.

Uranium Power and Horizontal Proliferation of Nuclear Weapons

Chauncey Starr

The spread of nuclear weapons among nations has been of long-time concern to the industrial countries supplying nuclear equipment for civilian purposes. An increase in the number of states with nuclear weapons (horizontal proliferation) presents different issues than the growth of existing weapons stockpiles (vertical proliferation). In the early years of civilian applications, it generally was assumed that the arcane and costly nature of weapons technology and weapons material production would limit nuclear weapons to the major industrial powers. However, extensive efforts of these powers to introduce the world's technologists to the nuclear science and engineering useful for civilian applications also provided them the basic knowledge for a future entry into the military domain.

Early recognition by the major powers that the technical barriers to horizontal proliferation would decrease with time led to international political arrangements, such as the International Atomic Energy Agency (IAEA) in 1957 and the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1968, that were designed to inhibit the spread of military programs. A key assumption of these arrangements was that, in return for active support of civilian applications by supplier states, the states without nuclear weapons would abjure military programs. However, the growth of nuclear electric power and its technological infrastructure in some of the nonnuclear weapons states during the past decade has heightened concern about the adequacy of the barriers to nuclear weapons programs. In the United States, discussion of the risks of horizontal proliferation has tended to focus on technical issues—the adequacy of controls of weapons-usable material, the possible use of uranium power plants to produce such material, and export measures by supplier states to inhibit proliferation capability. It is time, in light of the experience of the past several decades, to examine the effectiveness of this primary technical focus and the role of nontechnical factors.

Because much of the relevant literature addresses only parts of this broad issue, the American Nuclear Society (ANS) appointed a special committee (*1*) to attempt an overview. The committee members had experience in both technical and international aspects of the subject. The committee did not attempt to propose solutions; rather, its objective was to assess present trends in the worldwide expansion of light-water reactors (LWR's) and their supporting facilities, the implication of these trends on the potential connection between civilian and military programs in the nonnuclear weapons states, and the influence of the policies of the major industrial suppliers, particularly the United States. This article is based on the report of the ANS special committee.

The principal question addressed is whether a nonnuclear weapons state that obtains commercial LWR's for electricity would be more likely to embark on a nuclear weapons program than if it had used only coal, gas, or oil. The states of particular concern have limited resources and military organizations, and could not produce or militarily benefit from a large arsenal of nuclear weapons in the foreseeable future. So the issue is their potential acquisition of a few nuclear weapons in the next 20 to 30 years through their use of commercial, uranium-fueled LWR power systems.

Nuclear weapons states have already developed indigenous means of producing weapons material. Except for India, which produced plutonium for its nuclear explosive device with a heavy-water research reactor, the major nuclear weapons states now use plutonium production systems dedicated to weapons material. Some of the earliest natural uranium reactors (moderated by graphite or heavy water) were designed to be dual-purpose, primarily producing plutonium for weapons, with electricity as a by-product. Subsequent improvements in reactor technology, the advent of relatively low cost slightly enriched uranium, and the large extension of fuel element operating lifetimes made single-purpose reactors for electricity production a commercial goal. As a result of these technological changes, the low-cost electricity fuel cycle differs from that best suited for production of weapons-grade plutonium. Although commercial nuclear power programs are now generally independent of military programs, the early history demonstrated that dual-purpose operation is technically possible, although with substantial increases in electricity costs.

Chauncey Starr is vice chairman of the Electric Power Research Institute, Palo Alto, California 94303

Framework of the ANS Study

The ANS study was based on many salient points professionally addressed in the past (*2–5*). The premises that provided the study's framework are summarized below.

1) The growth of uranium power will continue in some fuel-poor developing countries because of the cost of importing fossil fuels and the security provided by supply diversity. There are now about 300 power reactors producing about 200 gigawatts electric (GWe) (10 percent of the world's electric power) in 25 countries, of which seven are developing countries. By 1986 there will be 400 power reactors producing 300 GWe in 30 countries, of which ten are developing countries. Of the nonnuclear weapons states, 14 now have operating uranium power reactors. If their announced plans are fulfilled, 25 nonnuclear weapons states will have reactors by the year 2000 (*2*).

2) There are two processes associated with civilian electricity generation that could, in principle, be modified to extract material suitable for nuclear weapons production: the front-end process, in which fresh, uranium-based fuel is enriched for power plant use, and the back-end process, in which spent fuel is handled after being withdrawn from the plant. The power station, its fresh fuel inventory, and its spent fuel in short-term storage are not practical sources for usable weapons material. Rather, it is the potential manipulation of the separate physical facilities used for the front and back ends of the fuel cycle that creates possible sources of weapons material.

3) As the number of uranium plants increases, there will be an increased need for front- and back-end fuel cycle facilities. These facilities can be physically separated from the power plants since each facility usually can support many power plants. Thus they may be operated either nationally or internationally to meet economic or political criteria.

4) A system of safeguards (such as IAEA inspection and verification) can provide warning of a diversion of fissionable material and thus deter the misuse of civilian activities, but international safeguards alone cannot prevent a nation from acquiring a weapons potential.

5) Every commercial uranium power reactor creates plutonium, which can be separated from the spent fuel. Because of the long fuel lifetime, the isotopic quality of the product from present commercial power reactors will differ from that desired for optimum weapons manufacture, performance, and use. In principle, with sophisticated design, nuclear explosions can be produced even from these poorer grades of material, although such devices would have uncertain effectiveness, low assurance of initial performance, and substantial increase in size. They would also require advanced technology and fabrication skills to overcome the difficulties created by high radiation levels and to avoid low-yield "fizzles." There is no evidence that such materials are used in any existing military program.

6) The complications and uncertainties that would be added to any nation's initial weapons program by the use of spent LWR fuel as a source would almost always justify the investment of resources, effort, and time to produce weapons-grade plutonium from small-scale systems dedicated to that purpose. This is a crucial point and will be discussed more fully later.

7) The technical experience appropriate for the design and operation of the front and back ends of the uranium power fuel cycle is also applicable to military activities. Even without the benefit of experienced people, a new group may eventually perform adequately, as the technical literature is vast and readily available.

8) Research reactors can be used to provide spent fuel containing weapons-grade plutonium at a very low rate, depending on their power rating. In combination with laboratory-scale chemical separation facilities and hot cells, weapons-grade material can be produced. There are now 350 research reactors in about 50 countries, of which 25 are developing countries (*2*). Many of these reactors are too small to produce significant amounts of plutonium. However, most of them have been supplied with highly enriched uranium fuel, which, in principle, might be accumulated to make a single nuclear device. This possibility is now being precluded by conversion to lower enrichment (< 20 percent) designs.

9) In the more advanced developing countries, which have the technical resources to produce a nuclear explosive device, the foreign denial of technology, fissionable material, or equipment may make a weapons program more difficult to achieve but cannot stop it, and may challenge a nation's pride to initiate a symbolic weapons program.

Summary. Only a few nonnuclear weapons states with uranium-fueled power plants have kept the weapons option open, and none has evidenced activities intended for diverting fissionable material from its civilian system. Analysis of alternative strategies shows that acquisition of nuclear weapons material would probably depend on military production facilities rather than diversion. Horizontal proliferation is primarily a political issue and is related only marginally to uranium power development. Restrictions of the Nuclear Non-Proliferation Act on the supply of equipment and fuel by the United States appear to have induced, in some nonnuclear weapons states, the building of small-scale facilities that can be modified for production of weapons material. More attention should be given to the international political, economic, and military factors that persuade such states to abjure nuclear weapons.

10) The technical capability to make a nuclear weapon probably exists in 20 to 30 countries. However, in only six countries have those skills been used to make nuclear explosive devices, and none since India's test (*3*).

11) Small-scale military facilities are more appropriate for the production of a limited number of weapons than commercial power facilities and do not need to be economically operated or designed to meet civilian requirements of performance, reliability, public safety, seismic resistance, or maintenance. For example, a military production reactor could be fueled by natural uranium, moderated by graphite or heavy water, operated at low temperature and pressure, and even air-cooled, thus simplifying design, construction, and equipment requirements.

12) A national decision to acquire nuclear weapons is likely to be planned as a deliberate multi-year program, and national options need to be considered on that basis.

The Weapons Allure

It is apparent that many nations could take advantage of technical knowledge derived from their civilian nuclear power activities to move into the military weapons field. However, they are not visibly doing so. Why not? Perhaps the historical motivations of the major nuclear powers to continually strengthen their stockpiles are not representative of the viewpoints, needs, or goals of developing countries. It may, therefore, be useful to consider the attractiveness of nuclear weapons to such countries.

Possession of a few nuclear weapons might be attractive to some nations as a symbol of power and prestige. It might be viewed as enhancing the image of national achievement and self-determination, and it might create pride in the nation's ability to use high technology. Nuclear weapons may be seen as a long-term military investment because they are viewed as unsurpassable by any foreseeable technology—a perception that may be made obsolete by the continuing improvements in conventional weapons. Some may also view nuclear weapons as an ultimate threat to potential aggressors and an intimidating lever in international negotiations. This last may be the principal motivation for countries that have not signed the NPT and have kept open the option to make weapons.

Most nations have not demonstrated an interest in acquiring nuclear weapons, as evidenced by the 113 nonnuclear weapons states that have signed the NPT. They presumably recognize the doubtful military value of nuclear weapons, perceive no potential threat to their borders, or are under the military umbrella of one of the superpowers. Some have sought weapons-free regions, as in the Tlatelolco Treaty for Latin America, and most have urged a reduction in the world's nuclear armaments.

A few countries, however, have kept the nuclear weapons option open, perhaps because they doubt that the above conditions adequately protect them. There are concerns about the near-term intentions of nations that have not ratified the NPT, have not accepted "full-scope" safeguards (all nuclear facilities), have only limited IAEA safeguarding, or are politically volatile, such as the countries of the Middle East, including Israel; the countries of Southeast Asia, including India and Pakistan; and Brazil, Argentina, Chile, and South Africa. All these countries have publicly renounced weapons activities, although India has already exploded a "peaceful" nuclear device.

National Security Options

Countries that have chosen to expand uranium power plant capacity for electricity but not to add nuclear weapons to their arsenal are probably motivated by economic aspects of national security and not by lack of technical capability to produce weapons material. The major reason for acquiring uranium power plants is that they benefit the peacetime economy by providing electricity at a lower cost than alternatives and by reducing dependence on imported fossil fuels. In 1981 in France uranium provided electricity at about two-thirds the cost of coal-based electricity and one-third the cost of oil-based electricity. Even an oil-rich country may find economic benefit in exporting oil and using uranium domestically.

An equally important reason for using uranium power is security of supply. Fossil fuel plants have inventories that usually are measured in weeks. Uranium power plants operate for a long time between fueling shutdowns (1 to 1½ years for replacement of one-third of the fuel rods), so they are relatively insensitive to sudden international disturbances. Some countries value energy independence so highly that they plan to build small-scale domestic enrichment plants and spent fuel recycling facilities even if they are commercially uneconomic.

Unlike electricity generation, nuclear weapons do not enhance a nation's economy or the security of its energy supply. They may be viewed by some countries as contributing to their ultimate national military security, but this is debatable. Most limited regional wars do not provide an appropriate framework for the use of nuclear weapons because of the limited military objectives involved and the high risk of overwhelming sanctions from allied nations. Furthermore, unless nuclear weapons are developed without external knowledge, preemptive actions—both military and nonmilitary—might be taken by threatened neighboring countries. However, as discussed earlier, there are reasons other than military ones for seeking nuclear weapons capability, such as national pride, status, and the ability to intimidate or to deter perceived threats.

It appears, nevertheless, that many countries consider nuclear weapons undesirable for reasons other than the technical difficulty of acquiring them. The reasons may be economic, military, domestic, or international. Furthermore, the military value of nuclear weapons, even to the superpowers, may be decreasing slowly because of advances in conventional missiles. According to Robert S. Cooper, director of the Defense Advanced Research Projects Agency, "the next generation of advanced surveillance systems and precision-guided standoff weapons may provide a conventional military power so formidable as to rival in the tactical arena the deterrent effect nuclear weapons have had on strategic war" (*6*).

In any event, there is no evidence for a strong technological or military imperative that preordains the proliferation of nuclear weapons states. If, however, some nation does choose to produce a nuclear weapon, what influence will a civilian uranium-fueled power program have had on that decision?

Weapons Material Options

A nation desiring nuclear weapons has a choice of strategies. For most nations, the production of sufficient material, either uranium-235 or plutonium-239, is a matter of time and commitment. The basic technologies are well known and there are a number of possible production routes (*7*), of which diversion from the civilian power cycle is but one. Theoretically, LWR's can be operated in a short-cycle production mode. However, commercial LWR systems involve investment of several billion dollars, depending on the extent of indigenous fuel cycle facilities included. Their electricity output is usually a substantial portion of the total generating capacity of a small country. Any operating interference caused by deviations from the optimum generation cycle in order to produce military quantities of low-burnup, weapons-grade plutonium could result in monthly shutdowns and weeks of plant outages. The economic penalties are large—about $10 million or more in fixed charges alone for each unloading, plus the differential cost of replacement power. Such deviations would be easy to detect. In contrast, small-scale military facilities can be built for about one-tenth the cost of the civilian systems, can be operated without disturbing civilian use, have few economic constraints, and permit much greater concealment. Thus the military program has been, and is most likely to be, the preferred course for a nation seeking nuclear weapons material. For these reasons, concern over horizontal proliferation surfaced in the United Nations in 1946, about a decade before the advent of civilian power plants. The issue of horizontal proliferation would exist even if all civilian programs disappeared.

Any nonnuclear weapons nation embarking on a costly weapons production and delivery system would wish as the centerpiece of its efforts a weapon of assured reliability and performance. As mentioned earlier, nuclear weapons made from reactor-grade, isotopically mixed plutonium will involve increased fabrication and handling hazards, and its performance will be uncertain (*8–11*). A further serious handicap arises if a weapons testing program is economically and politically impractical. However, if a nonnuclear weapons state is primarily seeking international attention, without regard to weapon effectiveness, then reactor-grade material might be adequate.

As an initial step to a national weapons program, alternative strategies must be weighed with regard to (i) availability of knowledge, skills, technical infrastructure, and industrial resources; (ii) time required for producing the first weapon; (iii) effective management of a clandestine project; (iv) probability of success; (v) overall cost; and (vi) probability of premature international disclosure of the technical operations through procurements and otherwise. If reliable weapons performance and ease of fabrication are sought, then one of the following strategies may apply:

1) Enrichment of natural uranium to produce highly enriched uranium-235 by using any of the available technologies in new or existing facilities.

2) Production of weapons-grade plutonium in new military facilities consisting of a low-temperature natural uranium reactor (graphite or heavy water) and a small Purex-type chemical separation plant.

3) Unloading selected low-burnup fuel from existing civilian power or research reactors by modification of their operation, and subsequent processing in a new Purex-type plant. Such operating modifications would probably alert safeguard inspectors and would generally be difficult to conceal from the facility's operating staff.

If expectations for initial performance are lower and more sophisticated fabrication is feasible, then one of the following applies:

1) Diversion of spent fuel from a civilian reactor and separation of reactor-grade plutonium in a new military Purex-type plant. Safeguard inspectors, if present, would be sensitive to such diversion from the spent fuel inventory.

2) Diversion of reactor-grade plutonium from a commercial Purex-type plant under international inspection, if such a plant exists in the country (unlikely in a small nation), with the obvious risk of alerting the inspectors.

The actual choice of a strategy would depend on the specific national resources of skills, experience, industrial infrastructure, existing facilities, available time, and money and on the balancing of these factors with the political risks of failure and international response.

Finally, any national group responsible for the success of a military goal would prefer high-quality weapons material and urge a proof-testing program for the first weapon design. If such a test program were not politically acceptable, there would be increased pressure for high-quality weapons material to improve the chances of having a usable first weapon.

Today the options end here. However, if use were made of suggested schemes for adulterating plutonium to downgrade its weapons usefulness or for strengthened security by design (hardening) of civilian chemical separation plants and other fuel cycle facilities, then diversion of commercial fuel would probably be the most arduous route to follow. Adulteration and hardening would not only substantially increase the number or difficulty of the steps required to extract usable weapons material, but would also increase the likelihood of detecting diversion activity. Neither adulteration nor hardening is supported by the major uranium fuel producers, as they add to the cost and inconvenience of recycling fuel.

Facing these facts, a nonnuclear weapons state must consider that its national allocation of technical and management skills, capital, military support systems, and political prestige domestically and internationally are all at stake. The organization of such a program, involving technical industry and military and civilian bureaucracies, is a formidable task for any country, especially if it must be clandestine. Furthermore, inadvertent exposure of the activity is much more likely if the civilian power cycle is interfered with to divert fuel. Thus the anticipated political repercussions from such a disclosure might discourage a planned diversion from the civilian cycle.

There can be circumstances in which civilian facilities may make a military program easier. Because commercial-scale reprocessing of spent fuel is appropriate only for large uranium power systems, these will be justifiable in only a few advanced industrial nations. However, several developing nonnuclear weapons nations are building, or plan to build, small fuel reprocessing plants, presumably to obtain experience or because their costs of fuel handling and shipping, waste disposal, administration, and small facilities combine to make indigenous reprocessing (and plutonium recycling) attractive compared to fresh fuel purchases. Small reprocessing plants are convertible to production of nuclear weapons material, and safeguarding these operations may be more important than safeguarding large commercial plants. An associated need is the safeguarding of spent reactor fuel in long-term storage, which could be a plutonium resource for a diversion plan (*12*). Thus the availability in a nonnuclear weapons state of unsafeguarded small-scale civilian power facilities might reduce the additional facilities needed for a weapons capability.

Perspective on U.S. Policies

Concern during the 1970's over the technical possibility of plutonium diversion from the reprocessing facilities of uranium power systems deeply influenced U.S. foreign policy. Many decision-makers favored uranium power but also were concerned that civilian activities might provide an important route for weapons material production. Others wanted to shift the emphasis in foreign policy to promoting nonnuclear resources, particularly solar energy.

In 1978 Congress passed the Nuclear Non-Proliferation Act (NNPA), which established strict export policies with respect to civilian uranium technology and fuel (*13*). The impact of the NNPA is that the United States effectively maintains a privilege to unilaterally deny each export, although in practice most exports are licensed without difficulty. The complexity of the licensing process and the opportunities it provides for political intervention have reduced international confidence in the predictability of the outcomes. The forced renegotiation of existing contracts required by the NNPA deteriorated commercial relations that were based on mutual confidence.

So the virtuous attempt to resist horizontal proliferation through the NNPA has created an image of the United States as an unreliable and unpredictable fuel supplier. The NNPA apparently has stimulated other countries to plan or create their own national fuel cycles, including uranium enrichment and fuel reprocessing facilities, for their national security. The recent announcement of Argentina on the start of its enrichment plant (*14*) and the activities of Pakistan (*15*) are evidence of such a response.

The NNPA also symbolized the culmination of U.S. policy in the 1970's to discourage spent fuel reprocessing internationally as well as domestically. This policy was thoroughly investigated in a 2-year international study (*16*) and was rejected by the 52 national groups involved. The NNPA has created uncertainties over and obstacles to any reprocessing outside the United States of spent fuel from U.S.-supplied reactors, and effectively precludes the United States from accepting the return of spent fuel. Forced storage in foreign countries of U.S.-supplied spent fuel may eventually increase the availability of weapons material worldwide, since spent fuel assemblies have a large plutonium content that becomes more accessible with increasing storage time (*12*). This accessibility will encourage indigenous small-scale plutonium reprocessing facilities to recover the fuel.

In the United States commercial reprocessing is not now planned since several facilities, including one very large one, have recently been built but were not licensed to operate. Even without restrictions, however, reprocessing is now economically unattractive in the United States. A 30-year supply of low-cost, enriched uranium fuel is assured domestically for all the reactors that are likely to be built in this century. The constrained domestic programs have reduced U.S. capability to influence international weapons proliferation through fuel cycle management. For example, the absence of commercial fuel reprocessing facilities in the United States prevents acceptance from other countries of spent fuel from U.S.-supplied reactors for reprocessing. If this were possible the separate plutonium might be recycled, used in fast reactors, or placed in an international plutonium storage center. In this manner, both the "aged" spent fuel from other countries and the separate plutonium would be under safeguarded control. The United States has also lost control of enriched uranium fuel supply. The U.S. export market share of the world supply of enriched uranium (excluding the Soviet Union) was virtually 100 percent through the early 1970's. This share started to decline in 1974, and is now less than 35 percent.

In contrast to the primary U.S. policy of technical denial, a review of the international developments of the past shows that success in nonproliferation objectives depends strongly on political measures. The technical focus of the NNPA tends to divert attention from this fundamental lesson. This does not mean that attention to technical safeguards measures is unwarranted. Such measures provide a valuable deterrent, but technical denial by the United States as a means of penalizing recalcitrant nations is unlikely to be productive in the long term with an expanding group of foreign suppliers offering equipment and technology for sale. The states that supply fuel and reactors should recognize the potential for using the positive values of this growing international trade to support political incentives to achieve the goal of nonproliferation.

Conclusion

This discussion has been limited to the role of the LWR fueled by slightly enriched uranium in horizontal proliferation. Different considerations apply to reactors fueled by natural uranium (graphite- or heavy water–moderated) or to reactors that use highly enriched uranium. The article has not addressed vertical proliferation, future nuclear power systems (breeder and fusion), or many aspects not central to actions that might inhibit horizontal proliferation.

An intensified effort by the international community to further strengthen the economic and political factors that reduce the perceived national security value of weapons acquisition is desirable. The widespread commitment to the NPT indicates the potential for removing motivation for weapons acquisition, in spite of the dissatisfaction with U.S. policy expressed by many of the NPT signatories.

If any nation plans to acquire nuclear weapons for national security reasons, it is more likely to build a military facility than divert fissionable material from civilian power systems. The worldwide expansion of uranium power reactors has not been, and is not likely to be, a determining factor in whether additional nations choose to become nuclear weapons states. Even in the absence of uranium power, the nuclear potential would remain undiminished.

With so many developing countries increasing their use of uranium power plants, the attention of the supplier nations should be focused on the plans of the nonnuclear weapons states for the front and back ends of the fuel cycle. Safeguarding by IAEA does substantially inhibit strategies based on diversion of spent fuel from civilian power cycles (*17*), and the IAEA task is made much easier if a nonnuclear weapons state does not have front- and back-end facilities, as is usually the case now. Therefore, to maintain separation of civilian power from weapons programs worldwide, an apolitical and economically attractive international fuel system should be established to provide nonnuclear weapons states with the option of an assured fresh fuel supply and to accept from these states their spent fuel (as the Soviets now do through their fuel leasing arrangements). The sensitive elements of the fuel cycle could thus be maintained in controlled domains, and the need for each nation to close the fuel cycle domestically would be removed.

The NNPA expressed a balance of objectives, but only a few have been implemented (*18*). The combination of activities called for in the NNPA could significantly reduce the risks of horizontal proliferation. The unbalanced emphasis on controls and restrictions is perceived by much of the Third World as U.S abandonment of the spirit of the NPT and "atoms for peace" (*15*). A provision of the NNPA calls for "an assessment of whether any of the policies have on balance been counterproductive from the standpoint of preventing proliferation" (*19*). It seems to be time for such an assessment.

Supply restrictions on the peaceful uses of uranium power encourage uncontrolled and unsafeguarded national programs. Therefore the reactor-supplying states should (i) assist the developing countries in the efficient expansion and management of their uranium power plant capacity; (ii) provide an internationally controlled system for an assured supply of fuel for these plants and for the handling of spent fuel, as is the objective of the IAEA committee on the assurance of supply (*3*); and (iii) strengthen the international safeguarding system to inhibit diversion of material from civilian to military use. Because the horizontal proliferation of nuclear weapons is primarily a political issue, these policies would substantially reduce its marginal relation to uranium power development.

References and Notes

1. This committee, the Special Committee on Nuclear Weapons and Peaceful Uses of Nuclear Energy, has as its members C. Starr (chairman), Electric Power Research Institute; V. Boyer, Philadelphia Electric Co.; M. Feldman, Oak Ridge National Laboratory; E. Hennelly, E. I. du Pont de Nemours and Company; M. Kratzer, International Energy Associates, Ltd.; A. Rossin, Electric Power Research Institute; G. Tape, Associated Universities; and J. Taylor, Electric Power Research Institute.
2. S. Eklund, paper presented at Princeton University, Princeton, N.J., 29 April 1983.
3. H. Grumm, *Safeguards of the IAEA* (IAEA, Vienna, 1982).
4. ——, paper presented at the IAEA International Conference on Nuclear Power Experience, Vienna, 13 to 17 September 1982.
5. J. P. Holdren, *Bull. At. Sci.* **39**, 40 (January 1983); B. Spinrad, *ibid.*, p. 42 (February 1983); A. Fainberg, *ibid.*, p. 60 (May 1983).
6. R. S. Cooper, *Astronaut. Aeronaut.* **20** (No. 10), 73 (1982).
7. For a detailed view of alternative paths, see C. Starr and E. L. Zebroski, *Proc. Am. Power Conf.* **29**, 26 (1977).
8. W. Meyer, S. K. Loyalka, W. E. Nelson, R. W. Williams, *Nucl. Saf.* **18**, 427 (1977).
9. S. Sahin and J. Ligou, *Nucl. Technol.* **50** (No. 1), 88 (August 1980).
10. C. D. Heising-Goodman, *ibid.* (No. 3), p. 242.
11. A. DeVolpi, *Proliferation, Plutonium, and Policy* (Pergamon, New York, 1979).

12. W. Marshall, *Atom (U.K.) No. 282* (April 1980), p. 88.
13. U.S. Public Law 95-242 (10 March 1978).
14. At the completion of Argentina's gaseous diffusion uranium enrichment facility at Pilcaniyeu in Río Negro province 660 miles south of Buenos Aires on 18 November 1983, Carlos Castro Madero, president of the National Atomic Energy Commission, made the following public statement: "The significant decision of launching this project was made in 1978 in the light of the unexpected decision of our supplier of enriched uranium to interrupt the supply of this material which is required for the operation of our research and isotope-production reactors, at the time when we were starting a policy of exporting reactors to Latin America and when we could foresee very promising possibilities with the use of slightly enriched fuel elements in our power reactors. . . . . Once again, as Argentina has stated in several international fora, it has been proven that such policy of denials, enforced by the great powers to the extent of suspending supply of safeguarded materials needed to produce radioisotopes, fails to give the expected results. Such policy will always fail because of its discriminatory nature, particularly when a country is prepared to face with its own technical resources the development of technologies to assure its autonomy and independence."
15. According to Munir Ahmad Khan [*Nucl. News* **26**, 95 (December 1983)], "the policy of denial of nuclear technology and of using technical fixes to promote acceptance of non-proliferation has not worked, and in fact, has been counterproductive. . . . . The existing insecurity of supplies has actually encouraged the proliferation of the nuclear fuel cycle and has compelled countries to seek a greater degree of self-reliance in the nuclear field."
16. International Nuclear Fuel Cycle Evaluation (INFCE), *Summary and Overview* (IAEA, Vienna, 1980).
17. H. Blix, "International nuclear fuel cycle: Some problem areas" in proceedings of the joint (U.S.) Atomic Industrial Forum and FORATOM (European Nuclear Forums) Conference, 31 May to 3 June 1983.
18. Nuclear Non-Proliferation Act goals include improved assurance of fuel supply; establishment of an international nuclear fuel authority; establishing repositories for spent fuel; defined sanctions for violations or abrogation of agreements; determination of national interest in repurchase, transportation, or storage of spent fuel; aid to developing countries in meeting energy needs "consistent with economic factors"; and "procedures to facilitate the timely processing of requests . . . to enhance the reliability of the United States in meeting its commitments to supply nuclear reactors and fuel to nations which adhere to effective non-proliferation policies."
19. Report to Congress, "The NNPA of 1978 should be selectively modified" (OCG 81-2, General Accounting Office, Washington, D.C., 1981).

RESEARCH ARTICLE

Variations in the Rotation of the Earth

W. E. Carter, D. S. Robertson, J. E. Pettey, B. D. Tapley
B. E. Schutz, R. J. Eanes, Miao Lufeng

Abstract. *Variations in the earth's rotation (UT1) and length of day have been tracked at the submillisecond level by astronomical radio interferometry and laser ranging to the LAGEOS satellite. Three years of regular measurements reveal complex patterns of variations including UT1 fluctuations as large as 5 milliseconds in a few weeks. Comparison of the observed changes in length of day with variations in the global atmospheric angular momentum indicates that the dominant cause of changes in the earth's spin rate, on time scales from a week to several years, is the exchange of angular momentum between the atmosphere and the mantle. The unusually intense El Niño of 1982–1983 was marked by a strong peak in the length of day.*

As recently as a few decades ago, the diurnal rotation of the earth served to define the basic unit of time. Clocks were adjusted to agree as closely as possible with the length of day (LOD) determined from observations of successive transits of stars across the meridians of optical astronomical observatories. In 1912 the Bureau International de l'Heure (BIH) was founded at the Paris Observatory to establish a "unified" time system by publishing the offsets between the radio time signals broadcast by various observatories. As technology progressed and clocks became ever more precise, questions arose concerning the uniformity of the LOD. By 1936 the performance of pendulum clocks had so advanced that the director of the BIH, N. Stoyko, suggested that the LOD in January actually exceeded the LOD in July by approximately 2 msec (*1*). A change in the LOD of 1 msec represents a change in the earth's rate of rotation of approximately 1 part in 10^8. Detecting a change in the rotation rate of a few parts in 10^8 over periods of months with mechanical clocks was a remarkable achievement. As quartz crystal clocks became operational and were refined to achieve stabilities of the order of parts in 10^{11} to 10^{12}, it became obvious that the LOD varied in a complex manner, with periodic components at annual, semiannual, lunar-monthly, and fortnightly periods and amplitudes of a few to several tenths of a millisecond. There were also suggestions of irregular variations in the LOD including sudden jumps on the scale of a millisecond per day. Because only optical (stellar) astrometric observations were available, it was impossible at that time to decide whether these apparent high-frequency variations were real or the result of observational errors.

With the development by 1955 of atomic frequency standards having stabilities of a few parts in 10^{13} and sufficient portability to allow accurate comparison of clocks at widely separated observatories, man-made clocks finally displaced the diurnal rotation of the earth as the basic unit of time. At that time the primary purpose of LOD observations changed from defining the fundamental time scale to monitoring the variations in the rotation of the earth for applications in geodetic surveying, navigation, and astrometry, and for basic research in the dynamics of the earth. For most applications it is generally the change in the rotational orientation of the earth over some time interval, that is, the accumulated effect of variations in the LOD, that is required. The rotational orientation of the earth is referred to as UT1.

Early attempts to identify the causes of the observed variations in the LOD were severely hampered by a lack of basic data such as global meteorological measurements. Nonetheless, it was generally accepted as early as 1960 that the seasonal variations were caused primarily by changes in wind patterns (*1*). A study by Lambeck and Cazenave published in 1973 showed the dominant effect to be the periodic exchange of angu-

W. E. Carter, D. S. Robertson, and J. E. Pettey are with the National Geodetic Survey Charting and Geodetic Services, National Ocean Service, National Oceanic and Atmospheric Administration, Rockville, Maryland 20852. B. D. Tapley, B. E. Schutz, and R. J. Eanes are with the Center for Space Research, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin 78712. Miao Lufeng is with the National Bureau of Surveying and Mapping, Beijing, People's Republic of China.