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The key role of the back-end in the nuclear fuel cycle

This two-volume special issue of *Dædalus* highlights the challenges associated with the global expansion of nuclear power. The topics covered include environmental impacts, nuclear safety, and the economics of nuclear power production, but the major emphasis is on nonproliferation and security aspects. To develop an understanding of possible problems and their potential solutions in all of these areas, it is necessary to understand the nuclear fuel cycle. Controlling the flow of nuclear materials "from cradle to grave" creates and sustains a safe and secure global nuclear power regime that can help satisfy the world's energy needs and can reduce CO_2 emissions and their associated impacts on climate.

The nuclear fuel cycle consists of multiple technical activities that take place in locations around the world. These activities form a chain, with each having direct impacts on the characteristics of those farther down the line. Accordingly, one objective of this article is to emphasize the holistic and global nature of the fuel cycle. A key challenge to consider is whether there can be opportunities now or in the future to improve the safety, security, economics, environmental impacts, or public acceptance of nuclear power by vertical integration of the chain or by geographical consolidation of the activities.

Each stage of the fuel cycle should be assessed to judge where improvements could increase technical and societal acceptance of a substantial expansion of nuclear power. However, since other articles in this double issue of *Dædalus* on the global nuclear future deal with front-end issues (enrichment, in particular), we concentrate on the back-end stages – namely, storage, reprocessing, and disposal.

To examine the back-end stages of the fuel cycle, it is useful to begin with a brief summary of their current status.

Used fuel storage. All water-cooled reactors store spent nuclear fuel, once it has been unloaded from the reactor, at the reactor site in an underwater pool. Originally it was planned that spent fuel would be shipped off site after some years of cooling; the fuel would then go for reprocessing or direct disposal. In practice, reprocessing is currently carried out in only a few programs, and disposal of spent fuel has not yet taken place. The need for storage has thus increased.

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The cooling time before the heat generation of spent fuel has declined to a level suitable for disposal in a geological repository is between 30 and 50 years. There are also other arguments for delaying disposal. For small nuclear programs, many years of operation would be required to accumulate an inventory of spent fuel that justified embarking on an expensive deep repository project. Furthermore, by extending surface storage times for decades, the large expenditures required for implementing such a solution can be postponed.

Today, as pools at reactor sites fill up, spent fuel is increasingly placed in dry storage facilities, which have lower operational costs and which can be implemented in a modular fashion. The casks can be purchased as needed; they do not require a strengthened or strongly shielded building; and they can even be placed on pads in the open air. Most storage facilities are built above ground, although there are exceptions, such as the Swedish CLAB spent fuel pool, situated in a rock cavern some tens of meters below the surface.

Reprocessing. In current reprocessing facilities, used fuel is separated into its three components: uranium and plutonium, which both can be recycled into fresh fuel, and waste containing fission products. The waste is then treated to produce vitrified blocks incorporating most of the highly radioactive materials and other low- and intermediate-level radioactive technological wastes. After conversion and enrichment, the uranium from reprocessing can be reused as fuel, if necessary. The plutonium can either be stored or made directly into mixed oxide (MOX) fuel, in which uranium and plutonium oxides are combined. The vitrified waste is a high-quality standardized product well suited for geological disposal. The technological waste is of much lower activity, and much of it can go to near-surface disposal sites. However, there are problems associated with each output stream.

Plutonium and MOX are unstable in storage because of the buildup of Am241. MOX fuel is more expensive than fresh UO_2 fuel; its specific decay heat is around twice that of UO_2 fuel; and the neutron dose from MOX is about 80 times that from UO_2 fuel. Reprocessed uranium is a "free" by-product, but with modern high burn-up levels, there is less residual U235 and more U236. Moreover, reenrichment increases U232 levels and presents a greater radiation hazard. The vitrified waste has a smaller volume than packaged spent fuel, but it still requires disposal in a deep geological repository, whose costs do not increase in proportion to the volume of the inventory. The parts of technological waste that contain long-lived radionuclides and must therefore go to geological disposal can present problems since the waste forms (cement, bitumen, compacted pieces) are less durable than vitrified waste or spent fuel.

The strongest argument in favor of reprocessing is that it saves resources, although the real benefits will be realized only when fast reactors are in use. A further positive aspect is that the highly active vitrified waste, in contrast to spent fuel, does not fall under International Atomic Energy Agency (IAEA) safeguards and presents no proliferation risk. However, the fact that current reprocessing technology involves separation of weapons-usable plutonium has led to concerns about the spread of the technology to many countries.

Disposal. Today, it is widely accepted in the technical community that the only presently feasible method to ensure very long term (many millennia) safety for high-level waste or spent nuclear fuel is isolation in a stable, deep geological repository. Nevertheless, at present there are no disposal facilities (as opposed to storage facilities) in operation in which used fuel or the waste from reprocessing can be placed.

For at least 25 years after the original 1950s publication on the concept of geological disposal, the validity of this approach was not questioned. It was formally adopted as a final goal, through policy or legal decisions, in many countries, including the United States, Canada, Sweden, Finland, Belgium, Switzerland, France, Spain, South Korea, the United Kingdom, and Japan. However, virtually every geological waste disposal program in the world encountered difficulties in keeping to originally proposed schedules.

Despite the slow progress of geological repositories in many countries, advances have been made in some parts of the world. In the United States, the Waste Isolation Pilot Plant (WIPP) deep repository for transuranic wastes has been operating successfully for 10 years. In Finland, Sweden, and France, deep repository programs are very advanced, proving that sites can be selected with the consent of local populations; that all necessary technologies are mature enough for implementation; and that definitive dates for repository operation can be set. In most other countries of the world, the combined technical and societal approaches employed in Sweden and Finland are looked upon as role models. In 2008, when the U.S. Department of Energy submitted a license application for a geological repository at Yucca Mountain, the U.S. program was also perceived as being one of the most advanced. However, with the mid-2009 declaration by the new administration that Yucca Mountain is "not an option," the timescales to implementation may have been set back by decades.

The various stages in the fuel cycle have often been developed by focusing on how to optimize a specific process and not by taking into account influences on later stages. In the following sections, we present some back-end examples that illustrate this point and that highlight how more holistic thinking might drive future developments.

Storage. There are no major technical issues affecting the safety and security of spent fuel storage. Both wet and dry storage systems have been proven over decades. However, a specific disadvantage of pool storage is that a large facility must be constructed at the outset to allow for future accumulation of spent fuel. Another disadvantage is that maintenance can become expensive if final disposal lies far into the future. Pool storage has also been criticized as being particularly susceptible to terrorist attacks, although such vulnerability has also been refuted by technical bodies.

The security and terrorist concerns mentioned above have heightened interest in the potential advantages of building storage facilities underground. This approach has recently been considered in the work of the Committee on Radioactive Waste Management (CoRWM) in the United Kingdom, where such stores are referred to as "hardened" facilities. An alternative would be to have spent fuel storage facilities at repository depths (hundreds of meters) with the possibility of later converting these stores into final disposal facilities. Others have suggested, however, that this appears more like an effort to place waste in a geological facility without first having to demonstrate the suitability of the site for long-term isolation.

Globally, the spent fuel in storage will continue to grow over the coming decades. Even the first repositories in Sweden, Finland, or France will not begin operation for more than a decade, for technical and engineering reasons. Repositories in other countries will be established much later because of institutional delays, because sufficient inventories must first accumulate, or because funding is not yet available. Revived interest in reprocessing (but not at the present time or with the current technology) will lead some countries to extend surface storage in order to keep the option open. Therefore, global efforts are needed to ensure that safety and security are guaranteed at all storage facilities for spent fuel.

Reprocessing. Reprocessing was first developed on a large scale in military facilities in order to separate fissile materials for nuclear weapons. The environmental impacts, the security aspects, and the treatment of waste residues had lower priorities. The technologies commercially applied today are basically the same as they were when the technology was first developed, although much improvement has been made in reducing emissions and developing conditioning methods for non-high-level waste. Today, there is increased interest in recycling, but based on new developments that provide enhanced security by avoiding separated fissile materials.

The advantage of the current PUREX process is that it has been demonstrated to work in a highly reliable fashion. Key disadvantages are that it produces separated plutonium, which is a security risk, and that the plants required are large and expensive. Alternatives are being worked on. The UREX process, developed in the United States, is modified to separate only the uranium, which can be recycled, leaving the plutonium with the fission products and other actinides in "proliferation resistant" form. The COEX (co-extraction of actinides) process, developed in France, leaves a small amount of recovered uranium with the plutonium so that the plutonium is never separated. Approaches using pyrometallurgical and electrolytic processes to separate the fission products from the actinides have been developed and even operated at the pilot plant stage, but not under the current regulatory regimes, which may present significant challenges to their widespread use.

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Geological Disposal. Geological disposal of high-level radioactive wastes and spent fuel is the key part of the nuclear fuel cycle that has not been demonstrated in practice. Technologies have been developed and extensively tested in a number of countries. These technologies are based on different conceptual designs for deep repositories; there are multiple feasible options for the choice of engineered barrier to enclose the used nuclear fuel and also for the geological medium in which the repository will be sited. In all of the programs, the safety of the deep geological system – as assessed by the range of scientific methodologies developed for this purpose – is invariably shown to be high. In the scientific community there is general acceptance of the feasibility of safe disposal, if the site and engineered system are well chosen. Unfortunately, political and societal acceptance remains a challenge in most countries.

The technical concepts developed to date in many countries are, however, generally recognized to be advanced enough for implementation. This does not imply that further technical optimization is unnecessary. In fact, even the most advanced programs are still amending engineering details in order to make the operations in a deep repository safer and more efficient.

The largely technical information about the nuclear fuel cycle discussed so far makes clear that the necessary technologies for open or closed cycles have been developed to a level that allows their industrial application. Furthermore, it is clear that the nuclear fuel cycle is a global enterprise. This is in part because of the widespread and heterogeneous distribution of uranium ore bodies and partly because of the technological development history. The global distribution of fuel cycle technologies today is determined by various factors, including:

- The military origins and continued attractions of nuclear technology; this led to the present situation of seven countries with fuel cycle capabilities that include reprocessing;
- The distribution of natural resources; this has led to countries like Australia, with no nuclear power ambitions of its own as of yet, being directly involved in the fuel cycle as a producer of uranium ore;
- The desire for some degree of self-sufficiency in energy supply; this is a key driver in countries like Japan and a claimed driver in others like Brazil and Iran;
- The real or perceived opportunity to provide commercial services to other countries; this is a driver for enrichment and reprocessing facilities in Europe, the United States, and Russia;
- The recent hunger for clean base-load electrical energy; this is today leading to declarations of interest in expanding or introducing nuclear power in a long list of countries.

This global situation is in a state of flux. The economics and politics of energy supply are changing, and this will have repercussions on many aspects of supply and demand in nuclear fuel cycle services. More importantly, however, the issues of global safety and security are becoming of increasing concern. Intensive debate on these issues has taken place over the past years. Most emphasis has been placed on restricting the spread of enrichment and reprocessing technologies since these can directly produce weapons-usable materials. A more comprehensive approach, however, seeks to control the distribution of all nuclear materials that can be misused by states or by terrorist groups. In this section, we look at actual or potential geopolitical developments in the global fuel cycle that could lead to increased security risks and at measures that could mitigate these risks.

Nuclear programs expand and seek more independence. The spread of nuclear power reactors alone can obviously increase security risks at the back-end as well as the front-end of the fuel cycle. Since new nuclear programs have insufficient spent fuel inventories to justify repository projects and since there are currently few fuel providers that accept the return of spent fuel, expansion of reactor operations will also expand storage operations. If the stores are to operate for a very long period, then they will have to be maintained and safeguarded. These tasks become more necessary as the radiation from the spent fuel decays to levels that allow easier handling. Expansion of nuclear power plants thus implies that increased efforts to ensure safe and secure storage of spent fuel are needed. International initiatives have been suggested to meet this need.

Greater security concerns will arise if increased use of nuclear power by some

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states leads them to conclude that they should implement indigenous facilities for sensitive fuel cycle activities: reprocessing or enrichment. Both of these activities are economically justified only if a sufficiently large nuclear fleet is operated (or if services are provided to foreign countries). Still, some countries may be tempted to push for national fuel cycle facilities even if they do not have this level of nuclear power production. Assurance of supply and national independence are obvious drivers. Since mastering either of the two sensitive technologies brings a nation close to the point where nuclear weapons can be produced, there is great international concern about the spread of these technologies.

Uranium producers move into other stages of the fuel cycle. At present, the high-tech stages of the nuclear fuel cycle are carried out by countries with nuclear weapons programs and/or with advanced civilian nuclear power programs. Some of the biggest uranium producers – Australia, Kazakhstan, and Namibia – fall into neither of these categories. It is not unreasonable for such countries to evaluate periodically the potential economic benefits of moving farther up the supply chain rather than simply exporting ores. Enrichment and fuel fabrication are obvious next steps. However, uranium producers could also conceivably offer back-end fuel cycle services. Reprocessing is unlikely to be introduced where it has not yet been done since very large scale technology is involved, and the economics are not favorable.

An undeniably attractive offer would, however, be a disposal service. In fact, in both Australia and Canada, the two largest uranium producers, the possibility of taking back as spent fuel the uranium that each country has supplied has been debated at different times. It has even been argued that such countries may have a "moral obligation" to accept spent fuel. However, the real driver for a uranium-producing country to accept returned spent fuel for disposal would be economic. Huge benefits could result for the host state, but despite this advantage, the political and public support for such an initiative has nowhere been evident.

Disposal becomes multinational. For some countries, national repositories may be difficult or infeasible because of the lack of favorable geological formations, shortage of technical resources, or prohibitively high costs. Multinational or regional repositories are a potential solution for these countries, and in recent years there has been a rapid increase in interest in this possibility, especially in small countries. The prime drivers were originally the economic and political problems that might be lessened by being shared between countries facing the same challenges. The potential safety and safeguards benefits were also recognized at this early stage. Increasingly – in particular after the terrorist attacks in the United States in 2001 and in connection with nuclear proliferation concerns – attention has focused on the security advantages that could result. The IAEA has been careful to point out that risks must also be minimized at the "back-end of the back-end" of the nuclear fuel cycle – that is, not only in enrichment and reprocessing, but also in storage and disposal (of spent fuel in particular). In its publications in this area, the IAEA has described two potential routes to achieving international disposal: the "add-on approach" and the "partnering scenario."

Both of these potential approaches to multinational disposal have seen significant progress. The add-on option calls for a single country, or a network of countries with appropriate facilities working together, to provide extended fuel-cycle services to countries adhering to the Nuclear Non-Proliferation Treaty (NPT) and wishing to use nuclear power. This option could limit the spread of those sensitive technologies allowed under the Treaty – namely, enrichment, reprocessing, and accumulation of stocks of spent fuel. Crucial prerequisites would be securing supply of services to all cooperating users and close international monitoring by the IAEA.

Within this international fuel cycle scheme, the fuel leasing component is perhaps the most promising. The U.S. government has indicated its support for such a scheme in Russia through the Global Nuclear Power Infrastructure (GNPI) proposal or in the United States through the Global Nuclear Energy Partnership (GNEP) initiative. The proposals are primarily aimed at making the nuclear fuel cycle more secure, but they ultimately require the fuel suppliers to take back the spent fuel or for a third-party, trustworthy country to offer storage and disposal services. Unfortunately, neither initiative appears to be making much progress.

In both Russian and U.S. proposals, the service providers concentrate on offering enrichment, fuel supply, and reprocessing to client countries. Although both proposals mention the take back of spent fuel, this is a sensitive political issue in both countries. Even if in the future it becomes acceptable to return to U.S. or Russian manufacturers fuel that they had provided to client nations, this take back will solve only part of the problem. Spent fuel from other suppliers in the market must also be accepted; there are existing inventories of hazardous radioactive wastes that must also go to a deep disposal facility. A more comprehensive offer of disposal services is necessary. In fact, an offer of this type may be the only sufficiently attractive inducement for small countries to accept the restrictions on their nuclear activities that are currently being proposed by the large powers and the IAEA. The emphasis on ensuring security of supply of other services, such as reactor construction, fresh fuel, enrichment, and reprocessing, is misplaced. All of these services are supplied commercially at present, and a customer country currently has a choice of suppliers that may well be wider than would result from implementation of initiatives that create a two-tier system of nuclear supplier and user countries. The key inducement for small countries to give up some of the "inalienable" rights afforded them in Article IV of the NPT may well be the offer of a safe, secure, and affordable route for disposal based on a multinational repository in another country.

The second option for implementing multinational repositories – partnering by smaller countries – has been particularly supported by the European Union through its promotion of the potential benefits of shared facilities in a regional solution. For the partnering scenario, in which a group of smaller countries cooperates in moving toward shared disposal facilities, exploratory studies have been performed most recently by the Arius Association, which also co-managed the European Commission's SAPIERR (Strategic Action Plan for Implementation of European Regional Repositories) project on regional repositories. The project, funded by the European Commission, has carried out a range of studies that lays the groundwork for serious multinational negotiations on the establishment of one or more shared repositories in Europe. The studies have looked at legal and liability issues, organizational forms, economic aspects, safety and security issues, and public involvement challenges. The proposal that resulted from SAPIERR was a staged, adaptive implementation strategy for a European Repository Development Organisation (ERDO).

At the pilot meeting of potential participants in an ERDO working group, 32 representatives from 14 European countries were present, all of whom had been nominated through their national governments, as well as observers from the IAEA, the European Commission, and American foundations. ERDO, if sufficient numbers of partner nations agree to the final proposals, will operate as a sister organization to those waste agencies from European countries such as France, Sweden, Finland, and Germany that have opted for a purely national repository program.

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If nuclear power is to expand in a safe, secure, and environmentally friendly manner, improvements in the back-end of the nuclear fuel cycle must occur in the coming years. This section outlines some recommendations, both technical and institutional, for improvement.

Centralized storage – maybe even underground. Concentrating national inventories of spent fuel at a few centralized locations rather than having distributed stores (some at decommissioned reactor sites) can obviously help reduce security risks, from malevolent acts in particular. Some countries already have underground storage facilities and others are considering this option. Given the increasing recognition that spent fuel is a valuable resource – but that reprocessing is currently very expensive – the probability that used fuel will be stored for many decades is rising. If this happens, then the arguments in favor of underground stores with enhanced safety and security will grow stronger.

Research on advanced reprocessing. The recent support for nuclear expansion in some countries has also led to proposals for expansion of reprocessing using the current technological approaches originally developed for extraction of plutonium for weapons. The GNEP initiative proposed implementing reprocessing facilities that were copies of current commercial plants. The scientific community, however, led by the National Academies in the United States, was quick to point out that this is unnecessary and uneconomic at the present time, and that it could lead to increased rather than decreased proliferation risks. Nevertheless, the ultimate need to recycle fissile materials was accepted, and the conclusion was drawn that research into advanced reprocessing technologies is the most appropriate strategy today. Future technologies may improve the economics, environmental impacts, and security aspects.

Optimization of engineering aspects of repositories. A variety of repository designs and operational concepts have been developed over the last 30 years. Most of these, however, have tended to be highly conservative, with the explicit aim of demonstrating that deep geological facilities can provide the necessary isolation of long-lived radioactive wastes over unprecedented timescales up to one million years. Relatively soon, the first facilities will be licensed and constructed, and therefore practical engineering issues will rise in importance. Mining and nuclear working methods must be coordinated in a manner that ensures operational safety and efficient operation. Quality assurance is a key challenge. In addition, the potential for cost savings must be addressed. The work in the advanced Swedish and Finnish spent fuel disposal programs illustrates this well. In both of these cases, the original massive copper container has been redesigned to use less copper and more steel. Other disposal programs with differing safety concepts will likely face similar challenges.

Technical and financial assistance to new nuclear states. Leading nuclear nations must commit to work closely with young or new nuclear power nations to help them meet their energy needs and aspirations in a manner that preserves and improves security, nonproliferation objectives, transparency, and stability. The leading nuclear nations will have much better chances for success in assuring continued nuclear safety, security, nonproliferation, and environmental preservation if they work proactively with emerging nations to understand and help them improve their nuclear capabilities.

Providing technical and, in some cases, financial assistance to help emerging nations realize a secure and healthy energy future will be an excellent investment if it results in relationships that promote a high-quality nuclear safety and security culture. In the context of this essay, it is important to note that the assistance offered should extend to the back-end of the fuel cycle. An improved approach would be for providers of front-end services and of nuclear power plants to bundle support for repository design and construction activities with back-end services.

Multinational reprocessing facilities. Reprocessing plants that separate uranium, plutonium, and wastes from spent nuclear fuel can divert the plutonium to weapons use as well. As a result, there have been several attempts to pursue multinational solutions, though with little success to date.

With the spread of nuclear power, the advent of new technologies, and a greater focus on assuring decades-long supply of fresh fuel for nuclear plants, more countries may begin to consider the value of developing indigenous reprocessing facilities. It has also been argued that implementing this technology can ease the problems of waste disposal. However, the waste disposal advantages associated with reprocessing are not enough to justify the technology on their own. Thus, there are ample incentives to pursue the creation of multinational enrichment and reprocessing capabilities. Providing a framework that makes emerging nuclear nations meaningful participants in such initiatives holds great promise for better meeting both the energy and security needs of all involved.

Multinational interim storage facilities and repositories. As already emphasized, new nuclear nations will need assistance, particularly at the "back-end of the back-end" of the fuel cycle. Leading nuclear nations have the opportunity to craft "win/win" relationships by recognizing that many small nuclear programs, or countries starting out in nuclear energy, do not have the technical or financial resources to implement a national repository in a timely fashion. They will have to keep their spent fuel in interim storage facilities; this could result in numerous sites worldwide where hazardous materials could be stored for anywhere from decades to hundreds of years. Multinational cooperation in storage and disposal offers a better alternative.

One safer and more secure option would be for nuclear fuel suppliers to take back the spent fuel under fuel "leasing" arrangements, as described earlier. However, although there is fierce competition among nuclear suppliers to provide reactors, fuels, and reprocessing services, as yet few are willing to pursue this leasing approach. Moreover, some would-be supplier nations, such as France, even have national laws prohibiting spent fuel take back unless the high-level wastes are returned to the user after reprocessing. The user country would therefore still require a geological disposal facility for these wastes. Cost savings, if any, in implementing a high-level waste repository rather than a spent fuel repository would be far outweighed by the prices charged for the reprocessing service.

The most promising option that remains open for small and new nuclear power programs is to collaborate with similarly positioned countries in efforts to implement shared, multinational repositories. The possibility that some country may decide to offer international repository services on a commercial basis cannot be excluded and could be a game changer.

The big challenge, of course, is achieving public and political acceptance in the repository host countries. Is it conceivable that a country and a local community within that country would willingly accept being a host for imported wastes? Recent national siting experience gives hope. Siting initiatives in several countries for either high- or low-level wastes have shown that success can be achieved through a modern strategy based on open communication, transparent documentation of potential benefits to host communities, steady accumulation of trust by the organization developing the repository, and recognition of the necessity of local acceptance. In a few countries (for example, Finland, Sweden, and South Korea), this has even led to competition between communities wishing to host a repository. At the multinational level, it is possible that the same strategy may also succeed, but as in the successful national programs, this may take several years.

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The ERDO initiative mentioned above could act as a role model for regional groupings elsewhere. A number of Arab states have recently made clear that they intend to introduce nuclear power, and have expressed a willingness to do so collaboratively. For example, in the Gulf Region, the United Arab Emirates is developing a complete roadmap, planning all of the activities involved in introducing nuclear power. Close linkages being formed today between nuclear programs in Brazil and Argentina might usefully expand into a Central and South American grouping. In Asia, countries like Taiwan and South Korea have already experienced problems trying to implement disposal programs, and various other Asian states, such as Malaysia, Indonesia, and Vietnam, have nuclear ambitions. An African regional grouping could also emerge, as various nations there have expressed interest in nuclear energy.

Joining forces in developing regional repositories could still have substantial advantages for small nuclear countries, even if the major nuclear powers at some stage reverse their policies and, for strategic or commercial reasons, finally do offer to accept foreign spent fuel or radioactive wastes. With a united front, and with the open alternative of a multinational regional repository, the partner countries would be much better placed in negotiations with potential large service providers over the economic and other conditions attached to any offer to take their spent fuel.

If the spread of nuclear energy production is to occur without increasing global risks of terrorism and nuclear proliferation, there must be close international scrutiny of all nuclear activities. This oversight will be easier if sensitive materials in the nuclear fuel cycle are handled, stored, and disposed of at fewer locations. Shared disposal facilities for the spent fuel and highly radioactive wastes at the back-end of the fuel cycle should be one key component in a secure global system. It would benefit all nuclear programs if initiatives for regional cooperation were started in relevant parts of the world by small or new nuclear countries, and if these initiatives received technical and moral support from the advanced national disposal programs.

Today, developed and emerging countries are striving to maintain or improve their standards of living by assuring a sufficient supply of energy; at the same time, they are striving to deal responsibly with global warming. Accordingly, prospects for a substantial growth and spread of nuclear power and associated facilities are increasing. For this growth to be successful, however, there are a number of concerns that need to be addressed, some technical and some economic. The potential for a systems approach to technical and economic optimization should certainly be examined, explicitly taking into consideration the holistic nature of the fuel cycle. The technical and economic challenges associated with expansion of nuclear power are, however, outweighed by the institutional concerns that need to be addressed.

Because the nuclear fuel cycle is global and because the consequences of misuse of nuclear materials are also global, all nations can be affected by the expansion of nuclear power. Multinational cooperation is essential for ensuring safety, security, and protection of the environment during this expansion. This cooperation must extend to the back-end of the nuclear fuel cycle.

Recent policy initiatives have focused on incentives to nations in the form of fresh fuel assurances in return for promises by recipient nations not to pursue indigenous enrichment or reprocessing. These offers have met with less than popular acceptance. To many in the emerging nuclear world, fresh fuel assurances by the developed nuclear nations look like the start of a nuclear fuel cartel. The assurances appear to perpetuate a division between nuclear haves and have nots, and ask emerging nuclear states to put themselves in a political situation that they believe might threaten their access to fuel in coming decades. Many would prefer a continuation of what they feel they already have: access to a healthy nuclear fuel marketplace.

Nonetheless, revisiting the nuclear bargain established by the NPT and related agreements is being pushed – for different reasons – by both the nuclear-weapons states and the emerging nuclear nations. These efforts present both a concern to many that the NPT may be fraying at the edges, but also a possible opportunity to build a new set of understandings and behavior that will better meet the energy, proliferation, and environmental needs of all concerned.

We should start with a set of clear goals. These goals must be responsive to the needs of the entire international community, not just those of the advanced nuclear provider states. The goals must also include measures at the back-end. The complete list of goals could include:

- Providing access to nuclear power at market prices for any country that desires it;
- Assuring nuclear fuel supplies through a fuel bank and healthy marketplace;
- Eliminating the rationale for enrichment and reprocessing for all but a select few, and ensuring that when

these activities do take place they are under international control/oversight;

- Securing all excess weapons-usable material by putting it in unattractive form or burning it where sensible, and bringing it under international control in appropriate countries; the ultimate goal is to draw down separated weapons-usable materials to as close to zero in as few places as practical;
- Disposing of spent nuclear fuel domestically or shipping it to appropriate countries for management and disposal under international oversight;
- Recognizing countries that agree to host multinational disposal facilities as providers of a necessary nuclear fuel cycle service;
- Entitling all countries that provide fuel cycle services at the front-end or back-end to reasonable commercial profits;
- Entitling countries that use foreign fuel cycle services at the front-end or back-end to security of supply; the unique nature and particular risks associated with nuclear power technologies imply that the above two points must be internationally guaranteed if the free market system fails to work effectively; and
- Ensuring that any move toward weapons development or weapons-usable material acquisition is surely, quickly, and clearly apparent.

Effectively integrating a successful approach to spent fuel and high-level radioactive waste management is a crucial component of pursuing such an agenda. The lack of a credible, sustained program to provide an ultimate solution to the disposal of these materials is a serious hindrance to a healthy nuclear power program. The growth and spread of nuclear power may well lead to more countries accumulating spent fuel. The subsequent buildup of this material in an increasing number of nations will provide a reservoir of plutonium that could later be accessed through reasonably quick and simple, and possibly covert, reprocessing techniques. Along with the spread of expertise and necessary technical knowledge, this buildup can bring countries closer to weapons creation and potentially set off regional instabilities as neighbors begin to hedge their nuclear bets as well.

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Creating an international initiative to explore the prospects for multinational spent fuel storage, with eventual multinational disposal of spent fuel or the high-level waste resulting from reprocessing, can begin a win/win process for solving the waste issue in a manner that addresses proliferation, energy, and waste management issues simultaneously. Companion efforts could pursue multinational enrichment facilities and, as needed, reprocessing facilities with opportunities for financial participation by emerging nuclear nations.

Established nuclear nations, particularly the nuclear-weapons states, should lead by example. As leaders, they can transform waste management and disposal from issues of "nuclear garbage" to integral elements of an internationally accepted system. This system not only would provide for the resurgence of nuclear power, but in doing so would simultaneously reduce proliferation, regional instability, and waste management concerns.