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by

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Since the dawn of the nuclear age in the early 1940s, there has been a slow accretion of radioactive garbage resulting from the production of nuclear weapons and, more recently, from the fabrication and burning of nuclear fuel in electric power generators. Until the early 1970s, it was assumed that the problems of putting these radioactive wastes out of harm's way were strictly technical ones of limited policy significance. Increasingly in the past several years, environmentalists and scientists, concerned respectively about the long-term damage to the biosphere and the threat of further proliferation of nuclear weapons, have called this assumption into question. Considerable public debate has ensued and waste management is now one of the most troubling aspects of widespread deployment of nuclear power reactors. The policy debate about waste management, however, has emphasized the long-term physical isolation of nuclear wastes, ignoring the problems associated with a fully deployed U.S. waste management system operating as part of a mature nuclear economy. This emphasis has resulted in neglecting shorter-term social and institutional challenges of waste disposal systems and focusing primarily on small-scale demonstration of disposal techniques.

The problem of radioactive waste management challenges us, as a society, to take as much care for present and succeeding generations as for those in the distant future. That challenge derives as much from the extraordinary institutional (and perhaps technical) design problems of dealing with large quantities of radioactive materials *before* their ultimate burial as from the scientific and technical puzzles of sequestering these materials deep under the ground for well over 100,000 years. The properties of radioactive materials and wastes, the way society is coming to view them, and the size and complexity of industrial operations reduce the utility of trial-and-error learning as a basis for improving policy and waste-management systems, as well as create the extraordinary tasks of developing nearly error-free operational systems for handling radioactive materials and wastes and nearly escape-proof burial grounds for them. These are remarkable demands upon a society and an intellectual community which have deeply embedded within their institutions and workways a short-time perspective, confidence in incremental, pragmatic procesess of policy and substantive improvement, and an aversion to comprehensive, synoptic plans productive of constraining, inflexible programs. Thus, the social properties of a large-scale nuclear waste management system present unprecedented theoretical and methodological challenges not only for the policy community, but especially for the social science community.

While these dilemmas take an extreme form in the area of radioactive waste management, they are not unique to it. An increasing number of problems—such as pesticides, food additives, air and water pollution, air traffic control, the operation of the international monetary system, and global warfare—are coming to take on many of the same properties. Futhermore, similar problems attach not only to waste disposal, but to the handling of radioactive materials throughout the nuclear fuel cycle.

Analytical Challenges

Much of the policy debate about the disposal of radioactive wastes has been dominated by concerns for the distant future—for the safety of generations thousands of years hence who might be harmed by releases of radioactive materials from deep geological repositories. This is not surprising, for some of these materials remain potentially hazardous for well over 100,000 years. Add to this the fact that a well-developed nuclear economy based on today's Light Water Reactors (LWR) and reprocessing could be expected to last over 200 years, during which all of the nation's, indeed, the world's, nuclear wastes that *could* be produced *would* be produced.

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(If the breeder reactor, LMFBR, were introduced, nuclear power could be produced for about 2,000 years.) Thus, after the close of the nuclear age, sometime around the year 2200 A.D. (or 4200 A.D.), the storage of radioactive wastes would have to be effective for something like 100,000 years—until around 102,000 A.D. In effect, the benefits of energy for the world's economy would have been derived in about 1/500 (or 1/50) the time-span during which nuclear wastes are hazardous to health and possibly to genetic development.

The technical elements of the debate on nuclear wastes have emphasized development of techniques to immobilize the wastes in such a way that they will stay where they are put for a very long time. The heart of this challenge is to design waste forms, containers, and other manmade barriers and to select geological environments for repositories such that the chemical transformations of the wastes and the migration of radionuclides through the ground will take so long that, if there is a release into the biosphere, the effects will be negligible. The emphasis is upon keeping wastes in place once they are buried. This

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is primarily a scientific and technical challenge, albeit an unprecedented one, because it demands assured knowledge of the physical properties of waste forms and their interactions with various geological media.

The social/political elements of the debate, consistently subordinated to its technical elements, have turned on different preferences for the process that should be employed and the factors that should be considered to legitimate the decisions about the safety of the repositories and their location. Often termed " the problem of public acceptance" by the technical community, these elements have emerged at both state and federal levels and are a continued source of frustration to the energy community.

In neither technical nor institutional considerations has there been more than perfunctory attention paid to the problems of preparing and getting nuclear wastes to and into repositories during the next 200-2000 years in a way that will avoid untoward health and/or social consequences. From the nearly exclusive emphasis on the scientific and technical problems of assuring perpetual isolation of radioactive wastes from the biosphere, it could be inferred that these issues do not require special concern. Implicitly, the safety of humanity over the next several hundreds of years seems to be viewed by planners as relatively assured. But is this preoccupation with the potential hazards to distant generations justified? Such a long-term view is unique in bureaucratic perspectives. Is this a rare case of bureaucratic *fore*sightedness, commendable in its focusing on a problem in the distant future and avoiding the usual myopia of large organizations? Or is this perhaps the first instance of bureaucratic *far*sightedness, hyperopically seeing the forest but missing the trees?

Two questions point to conditions that, if not avoided, would suggest we have mistaken farsightedness for foresightedness: (1) How do radioactive materials compare with other toxic substances in their unhealthy effects, especially cancer, and their mutagenic effects that could be passed on to succeeding generations? (2) Could we be in jeopardy of accidentally releasing in the near future as much or more radioactive hazard than would likely be released "by design" from geological repositories in the distant future?

The first consideration is fundamental to our fear of nuclear wastes and of the whole nuclear fuel cycle. It is the sense that radioactive hazards may be potentially greater than those from other toxic materials. There is no question about the general carcinogenic properties of radioactivity. Allowing much radioactive material into the biosphere could add a great burden of sickness and death to an increasingly cancer-ridden planet. Reluctance to export such a burden into the distant future is one reason great care is taken in the design and establishment of nuclear wastes repositories. But if increased likelihood of cancer or other somatic effects were the only hazard associated with nuclear wastes, the public's response to the problem would probably be less agitated.

Radioactive materials—it could be argued—would not be viewed much differently from other carcinogenic substances were it not for the possibility that exposure to radiation might also increase the risk of transmissible genetic damage and/or changes. If cumulative genetic effects were definitely not possible, we would probably continue to treat radioactive materials like other toxic substances. That is, some classes of people would be encouraged to handle them—as needed for industrial and national defense purposes, in reasonable though not absolute safety—and thereby risk a somewhat earlier death. We have for at least a century allowed the uneducated and untrained, and/or the economically disadvantaged, to expose themselves more than the members of society-at-large to a variety of risks, usually in exchange for modest sums of money.

Whether radiation could, in fact, produce a genetically cumulative effect is a matter of some debate. It seems clear that radiation can injure genetic materials, sometimes inducing genetic changes. However, it is not obvious that transmissible change would occur in human beings, nor is it clear what level of radiation a population or person would have to sustain to begin such transmissible effects. It seems that such an untoward consequence is a low-probability risk. Nonetheless, at present there appears to be at least a theoretical basis for not rejecting the plausibility that cumulative genetic damage may be done. From a public-policy perspective, this property of radioactive materials puts them in a toxic class nearly by themselves. While radiation may or may not result in transmissible genetic damage, *if it does*, and as a result of nuclear waste management practices the chances are appreciably increased, the consequences are very troubling indeed. If we are unwilling to export such consequences into the future, we must act as if there were a definite correlation between radiation and mutation.

Settling these matters of radiation safety will consume many years, so many that we are not likely to wait for answers before making plans to deal with present wastes and those to be generated in the near future. There is already a large store of wastes to be put away, and the nuclear industry insists that a long delay—one sufficient to assure a credible resolution of the radioactivity/genetic relationship—would destroy our capacity to build and deploy nuclear power reactors. Thus a great deal of effort is being devoted to developing waste handling, as well as storage, regimes so that further deployment of nuclear energy may proceed.

The need to develop methods for handling nuclear wastes leads into the second central question, which contrasts the hazard likely to be exported to the distant future, due to leakages of dissolved wastes from repositories, with the accidental releases of radioactivity, of a fresher, more dangerous sort, during the operational phases of waste handling, reprocessing, solidification, transport, and emplacement. Such a contrast suggests that at least as much care should be taken with the present and succeeding generations as with those far in the future. This implies an operational goal for the performance of waste management systems (and the rest of the fuel cycle): that no more radiological hazard should be released into the biosphere during active preparation and handling of radioactive materials and wastes over the lifetime of a nuclear economy, say 200 years, than would be released from wastes stored in well-designed repositories throughout their effective lifetimes. To get a clearer sense of how stringent this requirement is, answers to the following questions should be sought from the relevant agencies and industries. (1) What is the estimate of the total amount of the world's wastes that will be stored in repositories at the end of the nuclear fuel economy? (While estimates vary greatly, doubling the estimated 4.2 million tons of U.S. uranium reserves gives some idea of magnitude.) (2) What are the likely release rates of radiological materials per ton of these wastes as they rest in repositories through the long holding times? (If there were the unlikely high cumulative release rate of one percent, some 84,000 tons of materials would escape.)

Such analyses would establish an upper boundary for the magnitude of the management problem (i.e., get it *all* in the ground and keep nearly all of it there). That is the challenge—*if* all goes perfectly in the next several hundred years as we prepare and emplace a growing volume of nuclear wastes. But if we are not so clever as we need to be and all does not go perfectly, then we have a rough guide for the level of performance that should be expected in the management of waste-processing systems throughout their lifetimes. That is, we would have estimated the total likely release from the systems intended to keep wastes isolated from the biosphere. As an operational goal, then, this repository release (hazard) figure should not be exceeded by releases (hazards) experienced during the process of preparing and getting wastes into the repositories.

For this performance standard to be useful, an additional calculation is required: given the character of waste forms likely to be produced in the near future from LWRs and LMFBRs, what volume of materials and amounts of radioactivity, if released accidentally during preparation and handling operations, would equal or exceed the level of radiological hazard resulting from the long-term release of the world's well-stored wastes? A great deal of time and effort is being devoted to the design of waste forms, cannisters, emplacement beds, etc., to assure the integrity of nuclear wastes once they are put to rest. It is plausible that, if given sufficient time and money, nuclear wastes can be so engineered that they will be quite isolated from the environment for many thousands of years. Therefore, when all the calculations are completed, it is likely that, even with an accumulation of all the radioactive wastes from a completed world nuclear energy economy stowed away in repositories, the amount of radiological hazard exported into the distant future as releases from those repositories will be rather small. Thus in the development of U.S. radioactive waste management policy, the distant future is being provided remarkable protection, *and* a very stringent level of performance is being established as a goal for operating nuclear fuel production and waste-handling systems.

If nearly escape-proof burial systems are developed in pursuit of safety for the distant future, it would be ironic if, through insufficient attention to the design of the operational systems needed, we were inadvertently to allow more radiological hazard to foul our present society than is bequeathed to generations many thousands of years from now. If our society holds to the notion that we should be as fair with ourselves as with the future, then we face the challenge of assuring nearly error-free operational management, as well as nearly escape-proof burial, of radioactive wastes.

Management Challenges

These challenges are due in part to the character of error. Radioactive materials have very long lifetimes; most of the releases of wastes produced during the nuclear age will contribute cumulatively to the burden borne by the distant future. Therefore, an error must be defined as any release (escape) of radioactive materials from the operational system such that recapture is either impossible or too costly to effect. There are two major types of situations in which such errors would occur: (1)

the up-take of radioactive substances, especially plutonium by human beings involved in the handling of nuclear materials; and (2) spills and emissions of such materials outside the barriers designed to contain and recapture accidental and/or intentional escapes from the processing, transport, and emplacement systems. There have been some instances of both types of escape.

In late 1967, there was an unfortunate instance at the Nuclear Fuel Service Corporation (NFS), West Valley, New York, in which a young man inhaled a large dose of plutonium as he emerged from a decontaminating room in which he was working. No one knew how much he inhaled initially, but several days after the incident he registered 7800 counts per minute, 40 to 50 times the maximum permissible lung burden. Another instructive situation was the practice of using "transient workers" in these and other facilities to do particularly radiation-prone jobs. Radiation standards are cumulative as a function of time: if a worker's exposure nears them in a period shorter than the standards allow, he is prohibited from entering a radiation-prone area until the required time period has elapsed. Rather than subjecting trained personnel at the facility to quick bursts of radiation that approach permissible monthly or annual doses, thereby necessitating that they stay away from the facility, NFS and other nuclear materials handling facilities would hire transient, unemployed workers, paying them a day's wages for often less than ten minutes work—ten minutes in which they would receive the allowable monthly radiation dose. The obvious problem with this practice is that necessary safety training for such workers may not be sustained, and sufficient information about the hazard may not be given them.

> Much of the debate about the disposal of radioactive wastes has been dominated by concerns for the distant future.

An example of the second type of error comes from the now familiar Rocky Flats facility near Denver, Colorado, where radioactive materials have been discovered in the soil surrounding the main buildings. Even though this contaminated soil has been dug up and is now treated as radioactive waste, there is evidence that sufficient contamination remains to make the facility a public nuisance, if not a serious hazard.

Obviously, we have learned some things that will help prevent such errors in the future. But the nuclear waste management system likely to be necessary to accommodate a mature, large-scale nuclear economy may be such that lessons learned from our early experience will have only limited utility when applied to the fully deployed operational system. Some of the properties that would greatly increase the challenge of nearly error-free management are the degree to which: (1) trial-and-error learning as a mode of system improvement is drastically limited or unacceptable; (2) the system is very large in scale, and (3) internally complex; and (4) its task structure is routinized.

The first, most important, factor is that the public appears to be sufficiently fearful of the consequences of *any* significant error that we seem likely to forego the possibility of learning systematically from trial-and-error. By an essentially tacit agreement, the policy community, perhaps in response to strong pressures from environmental intervenors, seems to be saying that *any* error resulting in significant releases of radioactivity might occasion such untoward, potentially ruinous consequences that committing an error is unacceptable in the first instance. This is an extraordinary situation, i.e., it demands decision making without feedback. When coupled with the requirement for highly reliable, nearly error-free operations in systems which are large, highly complex and routinized, it presents one of the most rigorous challenges faced by social science today.

Decisions without Feedback

For the past three decades, a slowly maturing science of decision making has evolved, based increasingly on a combination of the information sciences, a refined understanding of the social psychology of decision makers, and the limitations of organizational behavior. When faced with increasingly complex situations, the most effective, least error-prone strategy in decision making is employment of an incremental, essentially trial-and-error, method of policy development. Its primary feature is to continue developing in the manner of recent past policies, awaiting confirming or dissenting signals from those most affected, while remaining ready to alter existing policies to rectify errors due to miscalculation or ignorance. This is at root a pragmatic approach trusting to the efficacy of error correction through feedback from customers and from a pluralistic, representative political system; an approach contrasted to the alternative of comprehensively analyzed plans which are impossible to attain.

The incremental approach is tailored best to situations that change slowly, in which errors can be quickly identified by those affected and those responsible, and in which the consequences of errors can be either remedied or repaired at reasonable cost or accepted as a cost against obviously greater benefits. As these conditions become difficult to meet, the utility of the incremental approach diminishes. When relatively rapid change is believed to be necessary, when actual errors take a long time to be recognized, and when the consequences of error are believed to be so ruinous and irreversible that they are too costly to countenance, our established processes of policy development falter as a means of arriving at decisions that can win the support of those groups in society necessary to legitimate and implement them.

The problem of disposing of radioactive wastes challenges us on each count. Demands for rapid resolution of the problem are pressed on the government by those who believe that continued deployment of nuclear energy reactors is necessary now to avoid an unacceptable energy shortage in the near future. In view of substantial uncertainties about the physical properties of wastes stored in the ground, some view these demands as radical and dangerously hasty. Due to uncertainties about the cumulative effects of radioactivity and the long duration of the waste's toxicity and necessary storage period, errors of several kinds, if they occur, could not be detected for many years (and then might not be understood by those threatened). Finally, the consequences of significant error to future generations are seen as so irreversible and so dreadful that we cannot imagine how trial-and-error learning about the overall performance of the system can be used to improve it. When mistakes are made, they will be discovered so far in the future that those responsible for them will be gone and the properties of the wastes will make remedy of the error nearly impossible. In essence, when an error is observed on the basis of the first trial, it is already too late.

Such a construction of the radioactive waste problem poses extraordinary political and analytical problems. Processes of public involvement, agency coordination, and regulatory procedures are designed to evoke opinion and may well aggregate interests and identify people who believe themselves to be jeopardized as well as benefited.

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But in the face of uncertain consequences, magnitudes of harm, and fear of any significant errors, what is missing is the information necessary to reassure those who fear injury or to moderate the enthusiasms of those concerned only with short-term benefits. The process we now use becomes mainly a vehicle for mobilizing opposing factions. Confidence in our procedures of policy review is rooted in the assumption that the participation of many promoting and affected groups will reveal missing information about effects and inspire solutions to unexpected problems before they occur. It also assumes that if significant errors do occur in implementing policies so derived, their consequences will not be so egregious as to seem grievous to those affected. Our now familiar hearing processes bring people together for the airing of complaints and support. They make visible to all the range of potential problems and maldistribution of benefits possibily associated with particular policies. If the questions so raised appear to be quite serious and to require sophisticated informaton for resolution, and that information is unknown, this visibility has the effect of intensifying opposition and may result in paralysis. Such an outcome does little to enhance the legitimacy of agency decision making.

When a society has chosen to forego learning by trial-and-error in a particular area, the usual processes of policy implementation are wanting. Other methods of reducing uncertainty are required. This means paying much greater attention to improving the basic understanding of the phenomenon in question before action is taken; that is, approximating more nearly a comprehensively analyzed plan. The scope of such planning would require coverage of economic, social, and political phenomena, as well as the usually recognized technical elements. But this strategy is increasingly maligned and recognized as difficult, if not impossible, to effect with high degrees of completeness. Nonetheless, this is the approach now being followed increasingly to provide the detailed analysis necessary to assure the escape-proof burial of nuclear wastes. Thus far, it has not been applied to the processes of preparing and getting wastes to the repositories.

When we turn to the matter of processing and emplacing wastes so effectively that few, if any, errors occur, we are required to take the measure of actual operational demands as against the requisites for highly reliable, nearly error-free performance of large-scale organizations. Before we turn to these requisites, let us explore briefly something of the scale of the U.S. waste management challenge.

Whether or not there is further deployment of nuclear reactors in this country, a significant radioactive waste management problem already exists. At a minimum, it will be necessary to process and dispose of the high-level, transuranic, and low-level wastes that exist already in the form of spent fuel, as well as the wastes to be produced by the LWRs likely to be put into operation within the next few years. If the Interagency Review Group on Nuclear Waste Management (IRG) convened by President Carter can be considered authoritative, by about 1990 some 150 plants will be in operation, each one estimated to produce 1000 megawatts or 1 gigawatt of electrical energy. To these wastes must be added those likely to be "imported" from foreign producers into the United States, estimated to be something like ten percent of the wastes generated by foreign, free-world countries. Based on the IRG report figures, this would represent about twenty percent of the total annual burden upon U.S. capabilities by 1990. This assumes that the United States will seek to reduce the risk of nuclear proliferation through agreements to "buy-back" wastes from nations whose nuclear development we have encouraged and who are dependent upon U.S. suppliers for fresh nuclear fuel.

Whether radiation could, in fact, produce a genetically cumulative effect is a matter of some debate.

The following estimated extent of the minimum challenge assumes that no wastes will be reprocessed and that nuclear energy development will be limited to the 150 plants now projected. By late 1980, 17 million cubic feet of transuranic and nearly 9.5 million cubic feet of high-level wastes awaited some sort of disposition. In all, some 66.5 million cubic feet of low-level wastes have already been buried. By the end of the century, an additional 120 million cubic feet of low-level wastes will require burial, and over 6.7 million cubic feet of transuranic wastes and 1.2 million cubic feet of spent fuel will have accumulated for disposal. Perpetual storage of this material will require something like 2,650 acres, or 4 square miles. By the time the approximately 150 reactors generating power have completed their useful lifetimes—30 to 40 years—some 355 to 430 million cubic feet of wastes would require handling, of which some 110,000 to 150,000 metric tons (MT) would be very radioactive spent fuel. Add to these figures the 75 million cubic feet of wastes associated with decommissioning these 150 reactors. This represents an expansion by the year 2000 of annual waste handling capacity to some 3.2 million cubic feet per year, which includes something like 3800 MT per year of heavy metal embedded in spent fuel. The safe transportation of this material alone will pose a substantial operational challege. Thus, the nuclear waste management problem "on hand" is already considerable. It represents an irrevocable commitment to deal with radioactive waste until about 2040; i.e., after the 40-year active life of the "last" nuclear reactor has ended and some 10 to 15 additional years of handling time necessary to dispose of the "last" bits of wastes from spent fuel and the decommissioned reactors themselves have elapsed. In operational and institutional terms, this is already a stiff challenge to put before producing and regulating organizations.

As a rough upper boundary of estimated demand, if upper-level estimates consistent with the national plan announced by former President Carter in April 1977 were followed past the year 2000 and extended to about 2040, we would have expanded the number of nuclear plants to about 1000, adding 850 plants to those 150 likely to be on-line in 1990; i.e., at the rate of about 17 new plants a year over a 50-year period. If all these plants were LWRs (this is not likely—perhaps a third would be breeders) estimated annual waste flows would involve 25,000 MT of heavy metals and 20 million cubic feet of low-level wastes, not including the wastes from decommissioning. If the effective lifetimes of each plant facility were extended to about 40 years, an additional 12.5 cubic feet of low-level wastes would issue from complete decommissioning operations, though such extensive removal each year might not be necessary.

In the process of scaling-up from the 1990s level of 150 power plants to a 1000 plant system in 2040, over 29,000 reactor years of operation would have been added to the approximately 1100 projected until 1990. This represents an 8400 percent increase in power plant operations over the approxixmately 365 plant years (for reactors of 400 megawatt capacity or more) we have experienced thus far. This plan would obviously require considerable investment in reprocessing facilities and involve relatively large annual volumes of high-level wastes from the extraction of uranium and plutonium to be recycled for further use. This system would enable us, if we could accept the social and political requirements, to provide electric energy for some 2000 years and would afford generous opportunity for management error.

Because of the potential magnitude of the annual "throughput" of hazardous materials, we can expect strong pressures to achieve nearly error-free operations. To attempt this, it will be necessary to achieve the following conditions for the design and operation of a highly reliable, large-scale organizational system:

- Unambiguous, nearly complete causal knowledge about the necessary functioning of the system to assure expected outcomes.
- Nearly error-free performance from both personnel and machines that do not deviate from these activities/functions necessary to assure the consistent operation of the system.
- Error-detecting regimes designed to identify very small deviations from the operational norm for each component of the system and for behavior necessary to assure reliable functioning.
- Redundant "channels" of operation and error-absorbing/rectifying regimes that would (1) carry on activities in the face of inoperative components or miscalculations of human performance and (2) repair or eliminate the sources of errors in the system.

Three additional conditions are necessary in the event that the technology has not developed into a large-scale system but exists only at a small-scale demonstration phase, and that the consequences of error are such as sharply to limit the utility of trial-and-error learning.

- Systems to contain the consequences of error of sufficient effectiveness that, if potentially serious errors do occur, their consequences do not affect those outside the system.
- A well-developed, tested, and credible science of analogical learning and simulation of large-scale systems.
- Considerable caution in inferring that what has been learned in the small-scale, experimental phases will be nearly adequate for the design of highly reliable large-scale systems, especially if they are likely to be internally complex and composed of many routinized tasks.

These requisites are very rigorous for any type of technical or organizational system. They are especially stringent when applied to the management of radioactive wastes. Knowledge of the behavior of various waste forms in different types of geological media, both in the short- and long-term, is uncertain. Information about the requirements for the processing necessary to transform spent fuel into various waste forms is equally uncertain. And there is a near absence of knowledge about the scale and dynamics of a complete radioactive waste transforming and disposal system that would take into account the means for handling and transporting wastes necessary to produce highly consistent, nearly error-free performances from the people and machines associated with the process. Furthermore, the design of error-detecting, absorbing, and containing systems, or the requirements for redundancies within such systems, have not been applied rigorously to waste management in toto. This is especially true when considering the large volumes of wastes likely to be produced in a mature nuclear economy. Finally, one cannot put much confidence in our present understanding of analogous learning and simulation technology as a substitute for trial-and-error learning. Experience with waste management systems of any respectable scale must await future development; therefore, knowledge about such systems and their organizational operations can only be derived from analogous systems, i.e., those that are similar but not identical to waste systems yet to be developed. Armed with this inexact information, simulation techniques could be used, though they have not reached more than a modest level of complexity and have rarely been tested against very large-scale, complex organizations.

The fact that our past experience with radioactive waste handling is exclusively at the experimental, early demonstration level simply exacerbates the problem. We cannot confidently suppose that simply scaling-up from existing systems will suffice. It seems clear that a radioactive waste management system, as it moves from a demonstration phase to a fully deployed, mature system, will take on quite different properties.

> Because settling matters of radiation safety will consume many years, we are not likely to wait for answers before making plans to deal with present waste.

Such a system is likely to be very large and quite complex internally, with a variety of technical and management activities that will encourage attempts to routinize many of them. To the degree this is so, it confounds our abilities to devise and operate coordinative processes over which executives have a sure sense of control and which minimize errors and their consequences. Thus, the properties of scale, complexity, and routinization reduce the utility of experience based on experimental, smaller-scale demonstrations and immeasurably complicate the analytical and operations problems involved. It is the combination of these three properties that confounds the development of policies and operations. In situations where only one increases—with the others held constant—problems are interesting and tractable. But in programs employing relatively sophisticated technologies, the properties of scale, complexity, and routinization are likely to increase together.

For systems based significantly on sophisticated knowledge and involving a relatively complicated series of technical processes, an increase in the scale of operations means an increase in internal technical and managerial complexity as well. It is obvious that nuclear waste processing systems meet the first condition. The requirement to process different forms of wastes issuing from military operations and both light water and fast breeder reactors results in the second condition. Increased volume of activities, as the waste processing systems expand in overall capacity, require that more people be employed. If sophisticated technical operations are involved, increased differentiation of specialists and technical groups is likely to occur. This is followed, with some lag, by the spread of both formal and informal means of coordinating these specialists and groups, resulting in the growth of internal interdependencies. As the scale of operations grows to meet the demands of a large number of nuclear reactors, multiple waste facilities and transport links between them are required, further increasing the complexities of operation.

> At least as much care should be taken with the present and succeeding generations as with those far in the future.

If the consequences of error are believed to be very serious, as is the case here, we could expect an emphasis on means for anticipating and/or reducing errors; an emphasis which would further increase both formal and informal interdependencies. It is also likely that internal operations, as well as the links between facilities, will be influenced strongly by externally imposed standards of safety, enforced by agencies monitoring the adequacy of both technological and human performances. The increases of internal and network complexity confront managers with a situation that becomes increasingly problematic and difficult to comprehend fully.

The sense of integrated organizational coordination is apt to decline, and measures would then be taken to reduce managerial uncertainty in an attempt, in part, to prevent surprises and untoward errors. At least two measures are likely to be intensified, each intended to increase the predictability of operations: the use of management information control systems (often utilizing computerized monitoring procedures) and the routine standardization of specialized tasks. The elaboration of control systems would increase reliability insofar as they are based on complete, accurate information concerning the operation of the system to be controlled. Routinizing tasks reduces costs and usually increases the predictability of performance. Both these measures may be satisfactory if the consequences of errors are limited. If they are not, additional efforts are required.

If significant error must be avoided and effective reliability achieved, workers must be attentive to the demands of the task, however uninteresting they become. More importantly, workers must remain watchful for surprises and accommodate to circumstances not usually "programmed" into their routines. As the size and complexity of operations increase, the adequacy of the knowledge base declines and job "programming" necessarily is less complete. The need for both reliable and adaptive behavior from the people involved in waste handling, therefore, remains high, even as they are confronted with routinized, automated systems. This challenges management to provide incentive and training to compensate for the inherently error-inducing conditions of routine, familiarity, and continual success. Boredom and familiarity often result in inattentiveness to early signs of error and, combined with continual success (especially during the first several work generations), erode the experiential basis necessary to motivate subsequent generations to be watchful and to retain the ability to adapt to the unexpected (for it so rarely occurs). The burden on training and incentives is heavy: to so motivate reasonably able people that they will remember (through 7 to 8 work generations or more, covering some 250 years—and possibly a good deal longer) why they should be watchful over a system that seems not to fail, is so routinized and automated as to evoke ennui, yet demands the ability to recognize instantly the first signs of error onset, accommodate to such warnings and, if necessary, endanger one's life to mitigate the consequences of error.

Finally, we do not have (nor can we have) a relatively large-scale waste processing system from which to learn the particular technical and operational difficulties of scaling-up to handle and dispose of nuclear wastes at the volumes likely to be produced annually in the future.

Present and Future Threats

In the development of widely deployed nuclear waste handling systems, we risk increasing the possibilities for incurring error both in the design and in the operation of the system: errors that we do not want to make and from which remedial learning is of dubious value. Moreover, scaling-up and increasing the complexity of, say, a U.S. Nuclear Waste Management Service will increase the likelihood of errors and, implicitly, the economic and social costs of the system. The solution to the design and operation, and very likely the regulation, of radioactive waste disposal systems may not be as straightforward as for other large-scale engineering and regulating systems. The properties of the phenomenon confound established approaches and pose strong challenges for both technical and social science perspectives.

In the past, the Department of Energy (and its predecessors), the Nuclear Regulatory Commission, and the nuclear industry—those party to the deployment and regulation of nuclear power and its wastes—have not seen the need to treat radioactive waste disposal much differently from other technical systems. Rather they have behaved as if (1) the costs of waste management systems are likely to be so small a portion of the benefits of nuclear energy as to be unworthy of clear specification, and (2) the problems of scale-up and increasing complexity can be met without extraordinary efforts, perhaps with near perfect performance (or alternately, the consequences of potential errors are essentially insignificant and/or bearable in view of the benefits). Consequently, a precise specification of the actual scale, internal complexity, and routinized character of the projected system has not been made; and the character and costs of training programs required are uncertain. As a result, the data upon which to base estimates of the consequences of error, the costs of remedy, and the likelihood of error are not available.

> Whether or not there is further deployment of nuclear reactors in this country, a significant radioactive waste management problem already exists.

The behavior of the agencies reflects a large measure of faith that the technical community will be able to devise relatively inexpensive, nearly error-free technosocial systems able to handle and sequester a large volume of very dangerous materials. Technical experts have acted as if there were highly reliable, large-scale, and only moderately expensive systems in other areas from which to derive analytical insight and/or there were available from simulations the high-quality design information needed for the development of such organizations. But there is neither actual experience nor credible causal knowledge to draw upon. It is warranted, therefore, that policy makers and citizens insist upon careful analytical treatment of the design and the socioeconomic questions involved. For the technical and regulatory communities to ignore these matters is now tantamount to intensifying the political conflict about nuclear energy. But when these matters are taken up seriously and attempts are made to improve the precision of social analysis, severe limitations in current social science conceptions are revealed.

These limitations stem in part from the onset of conditions only recently associated with organizational capacities; hence they have not confronted policy makers or social analysts before. The limitations include:

- the perception of potentially ruinous consequences should the preferred policy option turn out to be only partially successful:
- the realization that remedying the consequences of error, should it occur, would be extraordinarily costly, if not impossible altogether;
- the fact that indications of a significant error would occur so far in the future as to limit drastically the possibility of improvement;
- the sense that onset of error, however ruinous, may be quite unlikely;
- the probability that, in our concern to protect the distant future, error and significant shorter-term harm will be increased by the development of large-scale, internally complex, and routinized operational (and regulatory) organizations.

As these factors vary in intensity, so do the challenges of organizational design and the character of organizational regulatory politics. A careful review of social science theorizing and analysis reveals scant systematic development in our understanding of: the analysis of decision/policy situations in which incremental, trial-and-error learning has diminished utility, especially in providing schemes of error analysis, detection, and remedy regarding the internal operations of organizations as well as the outcomes of overall performance; the social design of highly reliable, large-scale organizations, with particular attention to various socialization processes and their fiscal and human costs; the effects upon the reliability and costs of the system of increasing scale of operations and tightening patterns of interdependence within and among organizational units; and finally, the dynamics of dissent and conditions of increased consensus within political systems of varied socioeconomic and ideological characteristics as they confront a growing range of low-probability, high-risk policies. Thus, the emerging and increasingly troubling challenge of radioactive wastes management, indeed of the whole nuclear fuel cycle, poses very substantial general theoretical and analytical problems for the social sciences, as well as enormous practical problems for the society.□

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