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ABSTRACT

The incentives for actinide burning (AB), also known as partitioning and transmutation, were extensively evaluated over a decade ago by U.S. and foreign investigators. The conclusion was that the cost and short-term risk increases resulting from AB substantially outweighed the long-term reduction in repository risk. However, during the intervening years, many factors relevant to this evaluation have changed, such as (a) expectations concerning the ease with which a repository could be sited and licensed, (b) issuance by regulators of a repository licensing standard and supporting criteria, (c) the scenario to which AB is compared, and (d) new technologies for fuel and waste processing. This paper reexamines the incentives for undertaking actinide burning in the context of these new factors.

I. INTRODUCTION

A. Background

Actinide burning (AB) is a concept that greatly reduces the amounts of long-lived transuranic (TRU) nuclides in wastes going to the repository. The concept is implemented by intensified processing (partitioning) to reduce actinide losses to wastes and subsequent recycling of the actinides to a transmutation device [typically a liquid metal reactor (LMR)] to fission them. As a result, AB may simultaneously (a) simplify waste management by converting the TRU nuclides to shorter-lived nuclides, (b) generate electricity, and (c) greatly extend uranium resources.

Previous evaluations[1,2] compared the long-term repository risk reduction from AB with increases in cost and contemporary risk. They concluded that incentives for AB did not exist. Similar conclusions were reached by European investigators.[3]

B. What Has Changed?

During the decade since AB was last evaluated, new developments have occurred in four areas that are important to a proper evaluation of AB. The *first development* is that the challenges inherent in characterizing, licensing, and funding a repository in a highly charged sociopolitical environment have become clearer and are greater than originally anticipated. The need to provide reasonable assurance of performance over tens to hundreds of thousands of years will necessarily require major efforts in all three of these areas, and, even then, with no guarantees of success because of the vagaries of geology and time.

An additional repository-related factor that has evolved is the congressional designation of the Yucca Mtn. site as the sole location of the first civilian repository characterization efforts. Previous studies typically used a hypothetical generic repository to evaluate benefits, such as the bedded salt design used in Ref. 2. The designation of a specific geology and the ability to evaluate the site-specific advantages and limitation of AB constitute significant steps forward.

The *second development* is the establishment of a Standard[4] and Criteria[5] that provide the basis for repository acceptability in the licensing process. This provides a specific measure of repository acceptability, and thus, of the benefits of AB. Previous studies necessarily had to rely on assumed surrogate measures, ranging from the simple toxicity index (based on dilution to maximum permissible concentrations or equivalent) to relatively sophisticated, but still generic, risk analyses that embodied numerous specific assumptions to which the results were sensitive (and which were often debatable).

The *third development* concerns the evolution of national perspectives on the acceptable structure of a future nuclear economy. Before 1977, the U. S. policy was that light-water reactor (LWR) spent fuel would be reprocessed to recover uranium and plutonium, with the latter being refabricated and recycled back to the LWR. This would then be followed by the development and deployment of LMRs, which would use LWR plutonium for the initial core and then be net producers of fissile material thereafter. However, almost coincident with the initiation of the major U.S. evaluation of AB, former President Carter established the policy that reprocessing and plutonium recycle were undesirable. One result of this policy was that the major U. S. evaluation of AB considered an LWR with plutonium recycle as the base case and an LWR recycling all TRU elements as the alternative AB case. LMRs, which are superior transmutation devices, were only given cursory treatment.

A second result of former President Carter's policy was the subsequent focus of civilian nuclear power on the once-through fuel cycle, which represents the current situation. Reexamination of the incentives for AB would use the once-through fuel cycle as the base case, and this is expected to substantially change the cost-risk-benefit comparison.

The *fourth development* during the last decade is the continuing work on actinide partitioning technology. The aqueous technology for the previous evaluation was largely unproven, based on a narrow base of laboratory studies. During the last decade, the technologies initiated during the previous evaluation have been greatly advanced. In addition, nonaqueous technologies have also been significantly advanced. Finally, the potential use of LMRs as transmutation devices also promises to aid AB by reducing the amount of partitioning that is required.

In summary, many changes have occurred that could significantly affect the outcome of an AB incentives evaluation. Some of the changes affect the magnitude of the costs, risks, and benefits of AB. Others affect the criteria by which the incentives are evaluated. The remainder of the paper constitutes a cursory identification and analysis of these changes and attempts to assess whether there may be incentives for AB and whether another detailed evaluation is in order.

II. FAVORABLE FACTORS

A. Repository Acceptability, Schedule, and Cost

1. *Enhance repository acceptability.* During the last decade, it has become very clear that the perceptions of the public and their elected representatives play a major role in influencing the ease with which any facility can be sited. Waste management facilities are among the least desirable, and a repository for waste requiring isolation for a "million years" appears to exacerbate this view. The focal point for much of this dread is the long-lived alpha emitters -- the actinides -- and it is just this issue that AB addresses. Specifically, it may be possible for AB to reduce the total amounts of TRU actinides going to the repository by a factor of up to 1000. This fact is easily explainable and should help to assuage public concerns.

2. *Reduce repository costs.* As the difficulty of repository site characterization, performance assessment, and licensing becomes increasingly apparent, escalation of projected costs (Fig. 1) has resulted. Repository development and evaluation costs are now estimated to be about $14B. To the extent that AB can reduce the need for detailed characterization and performance assessment or facilitate licensing, significant cost savings could be achieved. Even a 10% reduction would save $1.4B, a substantial amount of money in absolute terms.

Additional cost savings could result from AB by reducing the thermal load in the repository. After 10-year decay, the actinides contribute about 25% to the total decay heat from spent LWR fuel, as compared to 60% for Cs+Sr. AB would effectively eliminate the actinides component, reducing repository thermal load by the amount of their contribution. This allows the waste packages to be more closely spaced, which reduces repository operating costs. It also allows more efficient use of available underground space, which extends the potential capacity of the repository.

It should be noted that fully achieving these benefits may not be possible for the first repository because of the time required to assess and develop AB. A second repository would benefit more from AB as well as possible deferral because of the potential to increase the capacity of the first repository.

B. Repository Licensing

1. *EPA Standard.* Reduction of the amount of actinides reporting to the repository should provide a basis for increased confidence that the repository will meet the applicable EPA Standard, which contains the fundamental regulations upon which the repository will be licensed. An analysis was performed to determine the potential impacts that AB might have in meeting the Standard (i.e., the extent to which the Standard might be met by reducing the inventory of actinides initially emplaced in the repository).

The relationship of the repository inventory to the release limits in the Standard is obtained by dividing the amount of a nuclide in the waste (Ci) by its cumulative release limits (Ci) as given in the Standard. *A priori* acceptability would require the sum of these fractions for all nuclides to be less than 1.0. For sums greater than 1.0, probabilistic arguments based on performance assessment are required to ensure acceptability. The ORIGEN2 code[6] was programmed to automate this calculation. The results of a reference case are shown in Fig. 2. This analysis, based on the Standard, is superior to similar curves because the latter were (unrealistically) based on toxicity resulting from direct ingestion, whereas the

Standard includes consideration of transport and uptake and uncertainties in the analysis.

The dotted area represents the range of acceptability according to the Standard. The higher the limit, the lower the probability of exceeding it must be.

The uppermost curve shows the contents of spent PWR fuel relative to the Standard. It exceeds *a priori* acceptability by a wide margin at all times through 100,000 years. The major contributors to this are the long-lived actinides.

The lower curve depicts the contents of repository wastes after AB. In this case, the waste contents become less than the parent uranium ore after about 300 years and approach the range of acceptability at 1000 years. These are based on the actinide losses to all wastes given in the upper right portion of the figure. The lower dashed line denotes the waste contents assuming no actinide losses whatsoever.

Figure 3 shows the principal nuclides contributing to the AB curve in Fig. 2. The actinide losses are such that the fission products and activation products constitute the majority of the total at decay times beyond 1000 years. Further reductions would require measures beyond AB, such as preventing production of selected activation products or fission product partitioning and transmutation.

In summary, implementation of AB would result in the repository waste inventory having a 0% probability of exceeding 44X the release limits in the Standard over 10,000 years. This is to be compared to the Standard's requirement that there be reasonable expectation that the probability of releases exceeding 1X the limits be less than 10%, and the probability of releases exceeding 10X the limits be 0.1%. In essence, the maximum consequences of potential releases from the repository have been capped at a much lower level than that represented by the spent fuel by reducing the inventory available for release. Thus, AB could contribute substantially to providing reasonable expectation that the provisions of the Standard could be met. However meeting the provisions of the Standard *a priori* (i.e., based on inventory considerations alone) does not appear possible without extreme measures.

C. New Base-Case Comparison Alternative

1. *Impact of LMRs on AB incentives.* Previous major evaluations of the technical incentives for AB were largely based on a comparison of the risk reduction from removing actinides from repository wastes with risk increases stemming from intensified contemporary spent fuel processing and actinide recycle, and with cost increases from the facilities necessary to do so. Reductions in repository risk were small and cost increases were significant, as were contemporary processing risk increases, making the determination of "no incentives for AB" trivial. The contemporary risk increases stemmed from the additional processing necessary to partition the actinides from the spent fuel and wastes in the AB fuel cycle. The front-ends of the base and AB fuel cycles (e.g., uranium mining, milling, and enrichment) were essentially identical.

However, with the history of the last decade as evidence, it is clear that a base case involving spent fuel processing and Pu recycle is no longer appropriate. The appropriate base case must be considered to be the once-through LWR fuel cycle based on enriched-uranium feed. The AB case to be compared to this would involve partitioning actinides and using these as fresh fuel for LMRs, sharply reducing the amount of uranium mining, milling, and enrichment. This part of the fuel cycle, especially mining, is a relatively high-risk operation compared to other fuel cycle steps, and a net reduction of contemporary risk might well result. This would significantly alter the earlier cost-risk-benefit comparison and quite possibly make the balance favorable for AB.

An additional consideration is that the previous AB incentives evaluation employed an LWR as the transmutation device. LMRs are clearly superior in this application, yielding larger incentives from somewhat reduced fuel cycle impacts and costs.

2. *Sustainable nuclear future.* The implementation of AB implies the widespread deployment of LMRs. The LMRs will fission the actinides that would otherwise have been sent to the repository, but in doing so will generate substantial amounts of electric power, presumably displacing LWRs or portions of other power sources (e.g., oil, natural gas). This deployment is sustainable in that the LMRs can produce enough fissile material to be self-sufficient. Such deployment also greatly extends uranium resources.

D. AB Technology Base

1. *Partitioning technology.* The partitioning technology base employed in previous major evaluations of AB incentives was largely based on extremely limited research on advanced separation concepts and extrapolation to large scale. During the past decade, development of some key aqueous partitioning technologies applicable to actinide-bearing

waste streams has continued. The TRUEX[7] solvent extraction process for partitioning Np, Am, Cm, and residual Pu and U from aqueous streams has undergone considerable additional development at Argonne National Laboratory (ANL) and at Hanford. Laboratory experiments have shown reductions of actinide levels to less than 10 nCi/g, although achieving this on a production level remains to be demonstrated.

One of the most troublesome aspects of partitioning is not the liquid HLW stream in which the actinides are already solubilized but the solid and refractory wastes containing actinides. Examples of these are dissolver solids and insoluble cladding residues. Pacific Northwest Laboratory's CEPOD process[8] employs silver to solubilize intractable actinide oxides and then regenerates it electrochemically. It has been shown to be effective for some of these wastes at a laboratory scale and holds promise for others.

In addition to the further development of aqueous processes, technology for pyroprocessing spent fuels has been the focus of considerable work[9] at ANL. This technology involves the use of molten salts, molten metals, and electrorefiners to process the spent fuel. The primary focus of the current efforts is metal fuels for LMRs. Pyroprocessing technology may have advantages over conventional aqueous technology because the chemistry of the actinides is very similar in a pyroprocessing system, and this may simplify the flow sheets. However, considerably more developmental work will be required before this concept can be fully evaluated or deployed.

Finally, it should be noted that the processes conceived and developed as a part of implementing AB may have additional uses. Even if AB is not implemented, they may greatly improve waste management in processing facilities. The TRUEX and CEPOD processes appear to have cost-saving and waste-minimizing applications to defense wastes, and this has provided the justification for the development work subsequent to the previous evaluation.

2. *Transmutation device implications.* The previous evaluation was based on an LWR as a transmutation device. Because of the thermal spectrum, these devices are not tolerant of the thermal-neutron-absorbing lanthanide and rare earth elements. As a consequence, the partitioning processes conceived in the previous evaluation included complex and costly ion-exchange systems to separate these elements.

While the fast neutrons inherent in LMRs are clearly superior for actinide transmutation, there are other important consequences of the utilization of LMRs. Specifically, these devices are much more tolerant of thermal neutron poisons, such as the rare earth elements. It is expected that only partial separation of these elements will be required, thus significantly reducing the scope and cost of the processing plant.

III. UNFAVORABLE FACTORS

A. Repository Acceptability, Schedule, and Cost

1. *Excuse for delay.* AB might enhance the acceptability of the repository to many, increase the chances of staying on schedule by facilitating characterization and licensing, and reduce costs. However, it also has to be viewed as a potential inhibiting factor. Specifically, the potential benefits of AB could be used by repository opponents as an excuse to delay progress on the Yucca Mtn. site or to rescind its designation as the first repository site, subject to characterization and licensing outcomes. This could counteract many of the favorable factors in this regard.

It should be noted that AB does not appear to have the potential to eliminate the need for a repository in the foreseeable future. The presence of >100 nCi/g TRU and numerous long-lived fission and activation products will require the degree of isolation that only a geologic repository (or equivalent) can offer. Many of these nuclides do not appear to be amenable to methods similar to AB, thus requiring a repository.

2. *Additional facilities and activities.* Implementation of AB will necessarily imply the need to site, license, and construct LWR fuel processing facilities, LMRs, and LMR fuel processing and fabrication facilities. Further, the recycle of actinides, albeit mixed with highly radioactive fission products, has proven to be a controversial subject to the general public or their representatives. As a consequence, the benefits to the repository would be achieved at the cost of having to face multiple contentious policy, siting, and licensing issues elsewhere.

These additional facilities also clearly imply additional costs that must be borne by some portion of the nuclear fuel cycle. Since the facilities are supplying material to fuel the LMRs, it is reasonable to assume that these costs will become part of the cost of LMR-generated electricity and be largely defrayed by the value of the fissile material provided. However, viewed from a system perspective, there would be additional costs, although they would probably be much less than the cost of the LMRs.

B. Repository Licensing

1. *Repository risk.* While the implementation of AB would result in a repository inventory substantially closer to the release limits in the Standard than spent fuel, its effects on absolute risk may well be less dramatic. The technical documentation underlying the Standard clearly considers the migration of the actinides through the geosphere and their subsequent uptake. However, the final release limits appear to emphasize the importance of the actinide more than would be expected given the fact that they tend to be highly retarded during migration.

As a consequence, one would expect that a repository performance assessment would show only small long-term risk reductions resulting from actinide removal. This would be consistent with the result of the previous evaluation. The caveats to this are (a) a specific site might yield different results, and (b) to the extent that mechanisms such as intrusion and expulsive events are important, reducing the actinide inventory could still yield potential benefits.

2. *NRC licensing criteria.* While AB would result in a repository inventory significantly closer to the release limits in the Standard, its benefits relative to NRC licensing criteria are not commensurate. AB would have little effect on the NRC criteria requiring substantially complete containment for up to 1000 years; assurance in this regard will have to result from engineered barriers (e.g., the waste package).

Further, because of the structure of the longer-term criteria, AB also has little effect. Simply stated, the NRC criterion calls for nuclide release rates to be less than 0.001%/year of the inventory present after 1000 years decay. Reducing the actinide inventory via AB has the effect of also reducing the permitted release rate for the nuclide by the same ratio. Thus, AB does not appear to provide benefits with respect to the NRC criteria as promulgated.

It should be noted that the NRC regulation does include general provisions under which alternative criteria might be approved. Significantly altering the character of the wastes is among these, and AB would seem to qualify in this regard.

3. *EPA Standard.* While AB does appear to provide benefits relative to the Standard, the detail provided in Fig. 3 clearly shows that meeting the Standard *a priori* (i.e., a value less than 1.0 based on inventory considerations alone) would be exceedingly difficult unless the Standard were changed to give credit for the reduced actinide inventory. Meeting the Standard *a priori* would have substantial advantages in terms of acceptability and licensability.

The difficulty results primarily from the fact that the principal contributors to the total between 1000 years and 10,000 years are species such as ^{14}C, ^{59}Ni, and ^{93}Zr, which are very difficult to recover or impossible to transmute. Thus, these nuclides effectively provide a "floor" below which further reductions in actinide concentrations are fruitless

It should be noted that this situation may be amenable to prevention over the longer term. Specifically, if (a) new fuels were to be designed to minimize or eliminate the use of nickel as an alloying element and manufactured to greatly reduce nitrogen (precursor to ^{14}C) concentrations and (b) plutonium recoveries were increased by about another factor of 5, then the total relative to the release limits could be reduced by nearly another factor of 10. This, coupled with a modest modification of the Standard, might well achieve the desired result and beneficially affect subsequent repositories.

C. New Base-Case Comparison Alternative

The utilization of an LMR/AB fuel cycle as the comparison alternative to the once-through fuel cycle will require many more assumptions than previous analyses. The comparison will also be much more complex and, therefore, much more difficult to explain and defend.

Commitment to AB will necessarily involve having to undertake actions to ensure that the necessary capabilities are deployed in a timely manner. This will require (a) a commitment to fully reassess AB, (b) partitioning technology development and demonstration, (c) continuation of the LMR development and demonstration program, (d) a plan for making a decision concerning whether to implement AB, and (e) eventual implementation.

Further, because of the implications of LMR/AB, it is likely that a generic environmental impact statement (EIS), somewhat broader in scope than GESMO,[10] will be required. This activity alone will take years and must be completed early enough to ensure the confidence necessary to invest major sums in facilities.

D. AB Technology Base

While the technology base related to AB has made significant advances during the last decade, much remains to be done, and success is not guaranteed. Promising technologies such as TRUEX, CEPOD, and pyroprocessing still have not been proven at engineering scales under operating conditions. Unforeseen problems could occur that would limit the performance of these technologies or make operations unreasonably expensive.

Beyond this, there are technological needs for which processes have not yet been developed, or for which the need is not yet known. One area that requires much work is the development and qualification of fuels containing significant amounts of minor actinides (Np, Am, Cm). Also, the typical presence of actinide-bearing secondary waste streams will require the development of new processes to eliminate them, recycle them within the plant, or partition the actinides.

The ability to operate a full-size partitioning facility while losing only 0.1% of the Pu and Am to *all* waste streams represents a formidable challenge and remains to be demonstrated. Major obstacles may include variability in feed materials and off-specification products resulting from upset conditions.

Finally, the implementation of AB implies the development and deployment of LMRs. The climate for undertaking such a program does not presently appear to be propitious because of the perceived lack of need for nuclear power and the generally adverse economic situation. However, the driving force for this may result from anticipated electrical power shortages during the next few years.

IV. ANALYSIS

Consideration of the favorable and unfavorable factors for AB as presented above leads to the conclusion that there are so many competing factors, many of which are presently not quantified or detailed, that determination of whether there are incentives for AB is reduced to purely subjective judgment. The reduction in long-term repository risk resulting from AB, its primary historical purpose, will be minimal unless intrusive or expulsive events assume a larger-than-expected level of importance. On the other hand, enough other real and perceived benefits appear to result from AB so that incentives appear likely. However, a commitment to proceed along a path toward deploying an AB fuel cycle could be very controversial and might interfere with the progress of the repository. Such a commitment would have to involve interrelated fuel cycle (e.g., developing partitioning technologies), reactor (e.g., LMRs), repository (e.g., planning for partitioned HLW while preserving options for spent fuel), and regulatory (e.g., modifying regulations to reflect AB effects, generic EIS) activities that would have to be closely coordinated.

V. CONCLUSIONS

The following constitute the authors' conclusions based on the above factors and analysis:

- Real incentives for AB not related to calculated long-term repository risk appear to exist, although there are significant detracting factors.

- A commitment to undertake or deploy AB is premature until a better basis for a decision is in hand.

- Timely deployment of AB requires action on both technical and regulatory items.

- AB should be regarded as a technological option that *may* have benefits for waste management and the energy security of the United States.

- A program plan is needed to guide development of AB. This plan would have the goal of identifying the near-term activities (presumably relatively inexpensive) that would be required to sufficiently develop AB so a deployment decision can be made.

- In parallel with the program plan, a re-evaluation of the incentives for AB based on existing information is needed. This should be maintained current as development progresses.

- Based on the outcome of the evaluation, a decision on whether to pursue full implementation of AB should be made about the end of this century.

These conclusions should enable an important option to be evaluated without unreasonable expenditures or commitment to implementation.

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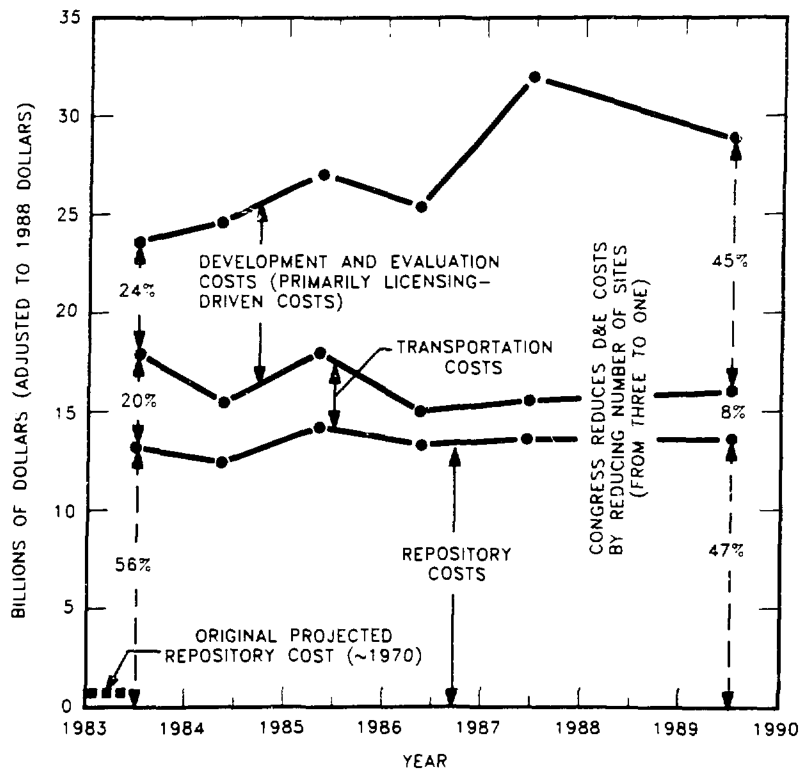

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2. Comparable Case: Two repositories, no new orders case, excludes benefits and MRS costs, low cost estimate for each category.

FIGURE 1. Total HLW/spent fuel disposal system costs vs date of cost estimate

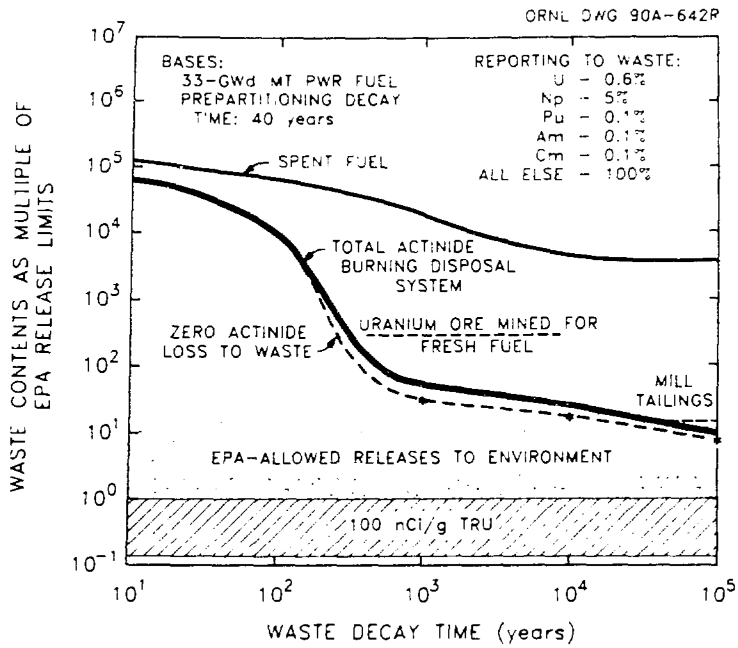

FIGURE 2. Radionuclide inventory of repository relative to EPA disposal standard

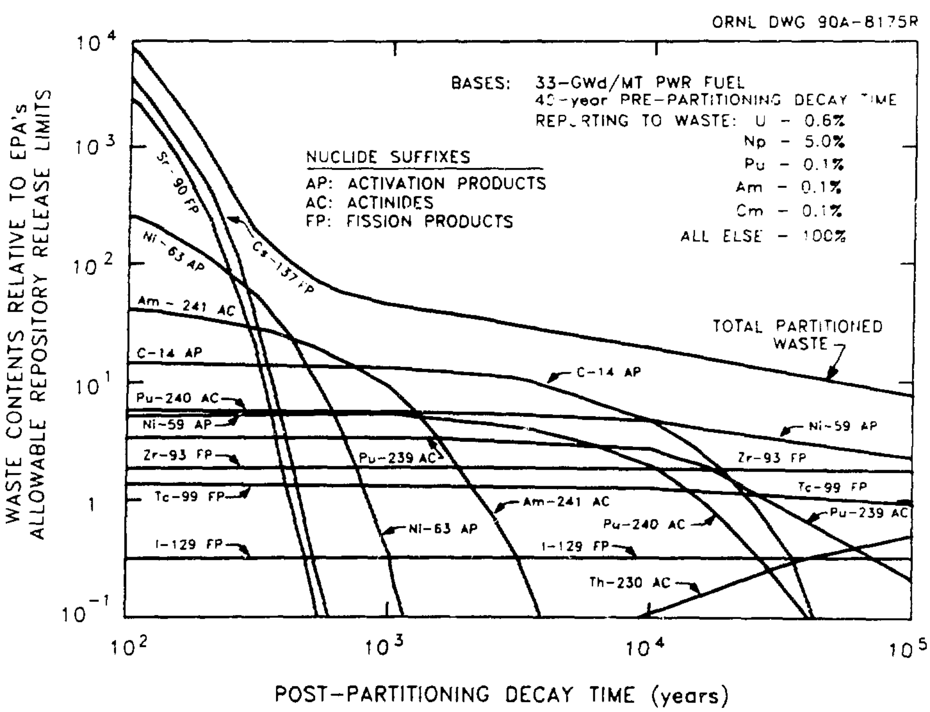

FIGURE 3. Principal radionuclide contributors to repository inventory relative to EPA disposal standard