LOGIC AND MOTIVATION IN RISK RESEARCH:

A NUCLEAR WASTE TEST CASE[1]

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Abstract

After two decades of wasteful investigation, federal approval of a nuclear waste site is drawing to a close. Large-scale research to assure that major hazards such as this are socially acceptable is often highly inefficient. A regulatory remedy is to require, not only that risk assessment based on current knowledge be acceptable, but also that new information would not show it to be unacceptable. Most important, research to test regulatory compliance has to be managed cost-effectively. This calls for an explicit and enforceable discipline on research activities that can resist powerful conflicting interests. A procedure is proposed that

- Sets targets for the first and second-order assessment of contributing risks,
- Allocates research resources to close any gap between current and target assessments cost-effectively, and
- Re-allocates resources, as evidence evolves.

The perspectives of license applicant and society are distinguished. The argument is based on consulting to nuclear waste and other senior risk managers.

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1 INTRODUCTION

1.1 Social control of risky activities

Government routinely decides, on society's behalf, whether to permit operation of a potentially hazardous facility, such as a dam, reactor, pipeline or chemical plant. The risk is commonly evaluated by regulations that specify what risk is acceptable and how to test for it.

Sometimes great expense is spent on that testing without commensurate public protection. Hundreds of millions of dollars are spent on probabilistic risk assessments of US reactors, but a senior NRC regulator admitted to me that he hardly uses them in deciding to close down an unsafe reactor. Nuclear waste disposal appears to have been a prime example of wasted risk research (see below). Other major projects that are vulnerable to comparable waste are in prospect. For example, Congress has considered building a satellite solar power system that could cost up to $1 trillion (sic) over 20 years and risk catastrophic accidents (Chinnis et al. 1986).

The public may be concerned enough in such cases to justify major risk assessment before a permitting decision is made. But it expects the research effort to be in keeping with the social stakes involved and to be efficiently spent.

I worked for more than 15 years as a decision methodology consultant to senior nuclear risk managers, including the heads of regulator (NRC) and regulatee (DOE) agency offices, and also as a technical reviewer of research by their contractors[2]. In particular, I was heavily involved in the early years of the nuclear waste repository program (1980-91), including helping to write regulations and to design a research strategy to test compliance.

In the course of that work, I uncovered what appeared to be major flaws in existing practice, and developed definite ideas on what could have been done to correct them and how comparable risk research planning problems might be solved in future (Brown 1988). This paper is largely an elaboration of those ideas.

1.2 Objectives

Target methodology. I hope to contribute to the applied art of regulatory risk management, with groundwork on methodology for managing research on the acceptability of a major risky activity. It is to guide a license applicant in designing a research program, on progressively allocating and re-allocating resources among research

[2] From 1980 to 1992, author served variously as: at, as consultant on nuclear waste rulemaking for the NRC Office of Nuclear Material Safety and Safeguards, as risk management advisor to the head of in the NRC Office of Nuclear Reactor Regulation (Tom Murley) and as a member of the Oversight Committee for site characterization. AT DOE, he was methodology advisor to successive heads of the Office of Radioactive Civilian Waste Management (Ben Rusche and John Bartlett). The latter relationship was terminated after author's testimony (elaborated here) to the independent Nuclear Waste Technical Review Board (Brown 1990).

efforts, and deciding when to stop research. It should also be defensible to, and reviewable by, outside parties.

For the methodology to be useful, it will need to satisfy a number of conditions: logical, practical, institutional, cognitive and situational. The approach reported here attempts to cover all critical bases, however inconclusively—unlike scientific research that seeks closure on single issues. It should, however, provide immediately usable guidance to, say, applicant's technical staff in devising a specific methodology and research plan in any given case.

Tasks to be aided. The primary intended user client is a license applicant responsible for managing the risk research. However, there are others in the chain of command whose motivations need taking into account. Above him are a regulator, whose requirements he must comply with, and society (represented, say, by "watchdog" organizations). Below him are for-profit contractors whose research he directs.

Situations to be addressed will usually feature:

- Acceptable risk as a major test of compliance
- One major risk variable to be controlled, possibly with other less critical requirements.
- High stakes at risk calling for great risk assessment effort
- Risk assessment provided by the applicant himself, to be confirmed by a regulator
- Research activities subcontracted by applicant to commercial firms

General principles will be illustrated and exercised in the context of a representative problem, along the lines of the "case method" used in law and business schools. My intention is prescriptive: to develop the foundations of an analytic approach to research management that is both used and useful.

1.3 Nuclear waste disposal example

Nowhere is the research management issue more important to resolve than in the disposal of high-level nuclear waste. It has been, and still is, as I write, highly controversial and liable to searching political, regulatory, and ultimately judicial, review. From the start of nuclear power generation in mid 20th century, high-level nuclear waste had been accumulating in surface storage. It represents a major and highly publicized long-term health hazard, which public opinion demands a solution to.

The primary problem addressed here is how DOE should manage the risk research on nuclear waste disposal (to be abbreviated to "waste disposal"), as it presented itself during the late 80s when key planning decisions were made [3]. As of late 2002, the research is essentially complete, a site has been chosen at Yucca Mountain, and it remains for the NRC to grant (or not) a license.

Over a 20-year period, DOE had spent more than $5 billion identifying and evaluating a promising nuclear waste site. Critics have charged that much of that effort has been

[3] I have taken minor liberties with historical accuracy mainly for clarity of exposition

misdirected (National Research Council 1990; NAS 2001) and much of the cost wasted (Keeney and von Winterfeldt 1994). Risk assessment accounted for much of the total cast. The focus of this paper is the *management* of that research. (The actual research management process bore little relation to the approach presented here.)

Regulatory setting. In 1982, Congress directed DOE to identify a geologic nuclear waste site that would meet safety requirements, and to do the research necessary to assure that the requirements were met (Congress 1982). In 1987, DOE was directed to specifically evaluate YM (Congress 1987).

Regulations at that time specified a number of long-term isolation and other "safety performance" requirements for nuclear waste disposal. EPA's general standard for radioactive waste disposal (40CFR191) stated, in part, "(There shall be) reasonable expectation based on performance assessment that the cumulative releases to the accessible environment for 10.000 years …shall have a likelihood of less than one chance in ten of exceeding (specified quantities). … These estimates shall be incorporated into an overall probability of cumulative release to the extent practicable."

Based on this, NRC made specific implementing requirements (10CFR60). They included risk variables other than this long-term release, for example dealing with "pre-closure" risks and certain determinants of the long-term risk (such as groundwater travel time). Specific research activities (such as on-site investigations) were also prescribed, to provide "reasonable assurance". This case study only addresses the site requirements of a repository (not engineered features, covered by different requirements). NRC's licensing a proposed DOE would need to demonstrate to NRC that a repository at Yucca Mountain (YM) complies with regulatory site requirements.

Risk research program. DOE was responsible for conducting research onYM "site performance", with periodic input from NRC and advice from a presidentially appointed Nuclear Waste Technical Review Board (TRB).

In the 80s, DOE agency OCRWM (Office of Civilian Radioactive Waste Management) developed a plan to gather risk data over some ten years. It was to provide the basis of a license application to NRC to construct a repository at YM if findings demonstrated compliance with regulation. In the event, research stretched over nearly two decades, at a cost of some $400 million a year (charged to the power industry). Late 2002, that process was drawing to a close, and DOE was ready to apply to NRC for a license.

Initial research plan. An early DOE "site characterization plan" (DOE 1985) identified a set of research issues, corresponding to a hierarchy of risk determinants, along the lines of figure 1. Research on these issues was subcontracted to specialized commercial engineering firms plus a research organization (USGS). In principle, budget allocation among them was to be informed by analytic exercises, such as system performance assessment, probabilistic goal allocation and acceptance testing.

[FIGURE 1: RADIOACTIVE RELEASE VARIABLES]

Post- case developments. Since the late 80s, when the research management activities this paper most directly refers to were taking place, there have been several developments. The timeline for completing the site approval process[4] doubled from 10 to 20 years and the funding estimates more than doubled, from $2B to $5B. The original EPA and NRC regulations were put "in remand" while changes (such as replacing release by dosage as the primary hazard measure to be controlled) were being considered[5]. The research guidance exercises referred to above (and efforts like my own) were discontinued.

1.4 Structure of paper

Section 2 of this paper characterizes and diagnoses flaws in risk research practice typified by this nuclear waste case. Section 3 proposes changes in setting requirements in environmental regulation. Section 4 proposes research procedures for meeting these requirements, from the applicant's perspective. Section 5 addresses the distinctive interests of society. Section 6 discusses general issues and conclusions.

2 SOURCES OF FLAWED RISK RESEARCH MANAGEMENT

Wastage is often due to three related impediments:

- Conflicts of interest
- Imprecise regulatory requirements
- Inadequate control procedures

2.1 "Conflicts of interest"

Resources may be wasted if serving the public interest does not reward those who control them, and there is nothing to oblige them to do so. It is common practice for risk research responsibility to be given to the regulated party itself (e.g. power companies assess risk at their own nuclear plants), presumably to save public resources. There is substantial scope for conflicts of interest that harm both the cost and effectiveness of the research.

Society. Society as a whole wants a decision on risky activities, as with any public choice, to balance environmental protection and any other impacts of the options, in a way that in some sense reflects social value trade-offs.

Regulator. The regulator (NRC in this case) is charged with controlling just one type of impact, environmental protection, though it typically has authority to make the whole choice on behalf of society. Its staff will also have bureaucratic objectives such as preserving its role and avoiding political embarrassment.

[4] Reported at www.ymp.gov.

[5] See 40CFR197, 10CFR63. The changes are not directly relevant to the historical case analysis. The first, however, would have simplified application of the propose methodology—changing EPA's hazard control parameter from 90 percentile to expectation (see below).

License applicant. If the applicant (DOE) wishes to get his project (the waste site here) approved, neither he nor his research contractors have an interest in aggressively seeking out evidence of unacceptable risk, unless obliged to do so. Misdirection may also arise from researchers having priorities beyond the public interest. Research effort has often been guided more by how it resolved technical or scientific issues than by decision needs[6].

Overspending is encouraged if the cost does not come out of the applicant's budget. YM research was funded by a fixed charge on power used by consumers. This does not motivate DOE to economize, nor to finish early. Indeed, DOE's budget was invariably fully used ("use it or lose it"), and the ten years originally planned more than doubled. Conversely, in the more common case where applicants pay for evaluation research themselves, the pressure is to economize *too much*, without regard for quality[7].

Research contractor. Commercial research contractors have a financial interest in making their pieces of the effort as large as possible (as well as in keeping the client happy). They may resist reallocation of resources to another contractor, in response to evolving evidence on which issues are most critical (e.g., at YM, radioactive retardation giving way to gaseous release). Indeed, the rare reallocations seemed to depend in this case more on bureaucratic politics than on public interest.

2.2 Imprecise regulatory requirements

Conflicts of interest can most readily be indulged if demonstrating compliance with regulatory requirements allows participants great discretion, i.e., if requirements are loosely specified.

Problems with simple acceptable risk. Regulations commonly specify an acceptable probability of mishap. Though this is a major advance over previous deterministic requirements[8], it does not specify when *enough* research has been done. If a site is already in compliance, based on preliminary evidence (which by common agreement among scientists was the case here), there is no assurance that the site will *still* pass after prescribed additional research.

It does not specify how "firm" the assessed probability should be. Sometimes regulation addresses firmness by prescribing a minimal research activity to be done. In the waste disposal case this included on-site exploration and testing for potentially adverse and disqualifying conditions (PACDs) (10CFR960).

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[6] A confidential USGS source acknowledged that DOE had agreed to research projects that claimed no relevance to the repository but were of scientific interest to the USGS.

[7] After I made an unsuccessful bid for an FAA risk assessment contract, the government client told me: "Executive order 12291 requires us to do a risk assessment before we can go ahead on this project. The cost comes out of my budget and yours was not the cheapest proposal."

[8] Notably the much vilified Delaney Amendment, which demanded zero carcinogenic effect from foodstuffs.

"Reasonable expectation/assurance". Waste disposal regulation does have wording that could be interpreted as requiring that the simple risk assessment be "firm". As noted, EPA, for example, requires " a *reasonable expectation* that … cumulative releases … have a likelihood that…" (10CFR191). NRC uses the term "reasonable assurance" comparably (10CFR60). However, these general terms are neither specific nor unambiguous enough to constrain research planners much.

Within the discretion allowed by these directives, there can be a serious motivational problem. The existing test gives no motivation to the interested parties to "look for bad news" (i.e. to vigorously search out PACDs). Moreover, the research that is prescribed in regulation is based on possibly outdated knowledge available when the regulation was set, and so cannot be too specific or limiting.

2.3 Inadequate management control procedures

Discipline. Lack of a responsible, enforceable, and reviewable rationale makes it easier for special interests to dominate the research management process. In the YM case, few procedural controls were in place to guide and discipline the allocation of research resources.

Analytic support. All relevant management science was not incorporated into methodology used in this case. Any failure in how the research was managed may be partly due to DOE attempting to implement a performance allocation technique (at a cost of many millions of dollars) whose conceptual groundwork had not been properly laid. According to a presidential review board (NWTRB 1998), comprehensive risk assessment (on which the technique depends) appears to have played little role in guiding the DOE effort.

2.4 Scope for improvement

Three promising avenues to mitigate these problems are:

- for the regulators to specify acceptable risk differently
- for the applicant to adopt a research management procedure that helps him comply with this regulation
- for some provision to assure the public interest is served.

The next three sections will address these avenues in turn.

3 RECASTING REGULATORY REQUIREMENTS

3.1 Acceptable risk as a regulatory requirement?

Unlike some, I have no objection to using "acceptable risk" as a basis for regulation. It is true that, since there are choice criteria other than safety (like economics), the appropriate degree of risk varies with context (Fischhoff, 1994)[9]. Nevertheless, a fixed acceptable

[9] A significant risk, say from drilling for oil on ANWR, may only be acceptable in oil crises, but not otherwise. Russians accept higher risks from oil than we do because an oil shortage there could threaten economic breakdown.

risk can be an appropriate guide for a class of risky choices that is homogeneous in respects *other than risk*, provided its context dependence is recognized. Nuclear waste siting may be such a case. Moreover, acceptable risk can be made situation-specific.

Society is not a unitary actor. Multiple players, including Congress and business, are involved in setting and enforcing compliance with regulations. Acceptable risk has bureaucratic appeal, in that it is compact, easily understood and lends itself administratively to division of labor among participants. In any case, acceptable risk is a resilient feature of regulatory practice that has to be accommodated.

3.2 Incorporating Assessment uncertainty into acceptable risk

Simple 1st order risk assessments may shift as research uncovers new evidence, giving rise to "assessment uncertainty". I interpret this to mean uncertainty about what the assessment would become with unlimited but realistic research, which I call "ideal" research (Brown 1991, 1993). I suggest the acceptable risk requirement be enriched with an explicit assessment uncertainty requirement. A natural interpretation of the EPA requirement of a "reasonable expectation" of meeting the 1st order test would be that, in addition to first-order compliance, an acceptable risk assessment should exhibit low 2nd order assessment uncertainty, i.e., that no further research could "plausibly" overturn 1st order acceptability.

Complex 2nd order test of acceptable risk. I propose something like the following form of words in safety regulations or regulatory guidelines, which calls for acceptable *complex* (i.e. 1st and 2nd order) risk.

For a facility to be in compliance with safety requirements, it must pass two tests:
a) First order test: the probability of (specified mishap) must not exceed x%.
b) Second order test: the probability that the first order test would be failed given unlimited realistic evidence must itself not exceed y%.

Implications of 2nd order test. The "specified mishap" in the first test above could be any undesirable event, typically a discrete occurrence (like a core melt). In the waste disposal case, the event relates to a variable, viz. "More radioactive emission than (specified limit) reaches the accessible environment over the next 10,000 years." Where to set the acceptable 2nd order probability y% is a question of regulatory policy. For expository purposes, I will use 10% (same as in the 1st order test, but it does not have to be).

A practical problem with a complex second-order test is that it is conceptually difficult to work with, especially if the associated simple 1st order test relates to a percentile rather than an expectation[10]. (The percentile version fitted the regulations of the 80s, and so is used here). Even trained statisticians, familiar with comparable distributions of sample statistics, have had some trouble following the logic illustrated in figure 2. However,

[10] Formally, the only difference an expectation makes is that figure 2a would display a mean rather than a percentile. However, an expectation avoids the cognitive difficulty of talking about a percentile of a percentile.

some kind of quantitative interpretation of complex compliance appears needed to provide clear guidance in planning research to achieve compliance.

Waste disposal example of unacceptable 2nd order risk. Non-compliance with 2nd order acceptable risk is illustrated for the YM case in Figure 2. At the top, Figure 2a shows a plausible 1st order assessment, i.e. a probability distribution on total release, based on information available at the outset of the research program. The dashed vertical line indicates the EPA limit (L), requiring at least a 90% probability that it will be met. The solid vertical line is the 90th percentile of the current assessment. Since it is well below L, the site complies with 1st order acceptable risk on this issue.

[FIGURE 2: ACCEPTABLE 1st ORDER ASSESSMENT, UNACCEPTABLE 2ND ORDER ASSESSKMENT]

Two possible shifts in the simple 1st order assessment of release in Figure 2a after ideal research are shown in Figure 2b. One meets the 90% goal, as a result of favorable findings and the other does not. Figure 2c represents a complete 2nd order assessment, covering all such 1st order assessments. A solid horizontal 80% credible interval bar summarizes it[11]. It shows a 15% chance of failing to meet 2nd order acceptable risk, thereby failing to comply with the assumed regulation.

Prescribed research as safeguard. Even with a 2nd order test, it makes perfectly good sense for regulation to prescribe *some* research, as a kind of "defense in depth" (as it in fact did in the waste disposal case).

3.3 Tests of compliance

Personal probability interpretation. For regulatory purposes, I take a "personalist" position on what assessed risk (1st or 2nd order) is based on: that probability is attributed to some individual, e.g., a regulator, and is based on all evidence (hard, soft, and judgmental) available at the time of assessment.[12]

Assessment method. Determining current 1st order risk is a familiar (if controversial) exercise in probabilistic safety assessment and requires no new methodology. It can be derived by propagating any lower level of risk assessments, taking account of functional relationships[13].

The derivation of 2nd order assessments is more problematic, but it could be propagated from lower level 2nd order assessments (see below), say, by adapting the theory of the distribution of sampling statistics (Kendall and Stuart, 1961). The default assessment would be directly or indirectly elicited professional judgment—by no means a trivial

[11] For an expectation requirement, vertical lines and the horizontal bar would simply move to the left in figure 3.
[12] This is not common "PRA" practice (Brown 2001), including DOE's past interpretations, reflected in "Total System Performance Assessments" for YM by in TRW (2000).
[13] From well-known theory of distribution of functions of random variables.

task. However, this subjectivity somewhat weakens the defensibility of assessments for compliance purposes. ("Garbage in, garbage out." [14])

4 RESEARCH MANAGEMENT: APPLICANT'S PERSPECTIVE

This section presents a research management tool for use by an applicant who is managing research with the objective of complying with complex acceptable risk.

4.1 Task formulation

The task is to help the applicant (in this case, DOE) allocate and re-allocate research resources among a hierarchy of research issues (as in Figure 1), and to determine when to stop.

As noted, the applicant has objectives distinct from the regulator's. The applicant wants to demonstrate that this facility (site) *does* comply with regulation. The regulator, on the other hand, as public protector, is particularly concerned to learn if the facility *does not* comply. "Society" has both concerns and its distinctive perspective will be addressed in section 5.

Output of analysis. Although our ultimate objective is to make planning *decisions*, the formal part of he decision process results in a display of projected option impacts, not an optimal choice. Its function is largely to predict, in a convenient form, the consequences of alternative research plans, in particular the risk assessments they will lead to and how they compare with acceptable complex risk. Integrating these projections with other considerations relevant to research planning decisions is probably best done informally.

Formal optimization imposes the usually impractical burden of making sure that all critical decision considerations are properly modeled. For example, only a single risk measure is addressed (e.g. long term radioactive risk). If it appears that other measures (such as short term risk) could significantly change the research plan, it probably makes sense to factor them in informally.

4.2 Illustrative planning choice: modes of nuclear release

To make the proposed approach more concrete, I will take a particular research planning task at YM as an example: how to allocate resources among what then appeared to be the main modes of radioactive release (gas, water and human intrusion).

The initial YM budget was devoted largely to water-borne release (which had traditionally dominated comparable siting studies and had the most influential research backers). Early findings suggested that gaseous release was also a serious concern and much less was known about it. However, due to institutional pressures, the research managers did not promptly and significantly reallocate research funding from water to gas (which had a smaller and less influential research team). Human intrusion (which

[14] However, Jurist Stephen Breyer (personal communication, 1980) says that the judicial system will generally accept an assessment as not "arbitrary and capricious" if it is *indirect* (i.e., modeled), even if based on subjective judgment.

had fewest advocates of all) was the least well understood, but was assigned the least research effort[15].

4.3 Informal reasoning on mode planning.

The essence of the proposed approach is contained in the following hypothetical informal reasoning (not necessarily authoritative), attributed to a research manager considering different aspects of research on mode of release. (A formal model will quantify the same reasoning.)

Appraising current compliance. "I will periodically appraise the gap between the current and acceptable risk assessments and orient my research activities to bridging the gap. It looks as though the probability of release exceeding the limit is less than the required 10%; i.e., it is 1st order acceptable. However, additional research could easily indicate a probability above 10%; i.e., unacceptable. NRC will probably not consider this 'reasonable assurance'. So we will do more research, which I hope will reduce 2nd order uncertainty enough to comply."

Allocating resources. "Waterborne release has been extensively studied, and much research effort would need to be expended to much reduce 2nd order uncertainty. Gaseous release, on the other hand, has been much less studied and modest research effort is likely to reduce it substantially. So, research on gaseous release would be more productive, up to a point[16]."

"Current uncertainty about human intrusion is immense, but no feasible research is going to affect this uncertainty substantially, so research on human intrusion is least cost-effective. Moreover, there is a quite separate reason to downplay human intrusion. A major use of the risk research may be to compare alternative geologic sites. Since these sites are unlikely to differ much on human intrusion, it becomes less important to research (compared to water and gas release). There are other modes of release than these three (e.g., earthquake), which may also discriminate among options, so they should be researched."

"However, we should check whether non-geologic waste disposal is likely to be considered. In that case, human intrusion risk might well discriminate among options on the grounds, say, of relative accessibility and would deserve research effort".

Halting research. "If it becomes clear that no further research could produce either an acceptable or an unacceptable risk assessment, we will stop work. If neither happens within a reasonable time, say, because human intrusion uncertainties prove irreducible, we will explore with NRC an alternative stopping criterion (e.g. one that considers only risks other than human intrusion)."

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[15] With some justification, as we shall see.

[16] This finding was weakened later in the research program, as the test of acceptable risk shifted from release to dosage, which is less serious for gas. As perspective and knowledge evolve, the preferred research strategy can change.

A research manager might usefully adopt the above informal reasoning as it stands. In any case, it is an essential precursor to formal modeling.

4.4 Formal models of complex risk[17]

Top-level risk assessment. A quantitative model of this informal reasoning may be needed to convince others. In principle, a formal counterpart is always possible, but it may not be worth the trouble. In this case, it makes sense to capture only part of the reasoning, and address the other parts informally.

[FIGURE 3: CURRENT VS. TARGET ASSESSMENTS]

Figure 3 illustrates the form modeling might take, for the "mode of release" research planning decision[18]. The graphic conventions are as in Figure 2. Figure 3a addresses the acceptability of both 1st and 2nd order total release risk. The upper bell-curve is the same current 1st order assessment as in Figure 2a. As noted there, since the 90th percentile (vertical line) is below the regulatory release limit L (vertical dashed line), the site's 1st order risk is acceptable.

The two bars below the curve summarize 2nd order assessments—as 80% credible intervals, with the upper end of the bar marking the 90 percentile[19]. Since that solid bar extends to the right of L, the current 2nd order assessment is *unacceptable*--if the policy should have10% as the 2nd order threshold). Since the dashed target bar (here and elsewhere) touches the limit line, it confirms that the corresponding 2nd order target assessment is just *acceptable*.

Lower level contributors to total risk assessment. All assessments shown in Figure 3a are partitioned by mode of release in the lower Figure 3b. In addition to the risk variables in Figure 1, there is an *error vari*able that accounts for any divergence between the higher order variable and estimating model of the other variables at the lower level. Thus, total release may not be exactly the sum of gas, water and human intrusion, if (for some unclear reason), they may not simply add, or if there may be other modes of release.

As drawn, Figure 3b is consistent with the informal reasoning above. By eye, it can be seen that human intrusion has the widest 1st order curve and is therefore the most uncertain mode; followed by gas, then water, then error.

Uncertainty vs. firmness of uncertainty. However, modes are ranked differently on 2nd order risk (solid bars), i.e., on how firm the risk assessments are. Gas is the least firm (i.e. 1st order risk is most shiftable), then water, then error, and lastly human intrusion. This reflects a judgment that there is much can be learned about gaseous release, but a

[17] The argument in sections 4.4 and 4.5 is somewhat complex and may be skimmed at first reading.
[18] The scales and assessments in Figure 3 are no more realistic than needed to make a point For example, log scales would be more realistic, but would not show equal areas for equal probabilities.
[19] Note that the 2nd order thick line *curve* in figure 2c is not shown in figure 3a, to avoid complicating an already complicated figure, but the summary solid *bar* at the bottom of fig. 2c *is* repeated below Figure 3a.

good deal less about water-borne release. Error uncertainty may be already small, but almost all of it could be resolved with enough research[20]. Intrusion may be extremely uncertain now, but there is very little that research can do to resolve it.

The radioactive release modes thus rank quite differently on how uncertain they are (1st order) and on how stable that uncertainty is (2nd order). This has a major effect on research planning. However, allocating resources among research activities involves more than comparing second order uncertainties. It also involves the cost effectiveness of research to reduce those 2nd order uncertainties.

Extension to lower tiers. Figure 3 as a whole corresponds to the first two tiers of the risk variable hierarchy in Figure 1. The same process can be extended progressively to all lower tiers. Modeling the risk variables at lower levels in the hierarchy performs two functions:

- To help make higher level assessments; and
- To help allocate resources at the lower level.

Assessments at any level (both 1st and 2nd order) are implied by corresponding assessments at the level below, provided:

- The functional relationship among variables is specified, and
- An error term turns the function into an identity (e.g. allowing for unspecified variables).

In planning research on modes, the propagation of release modes into total release (both orders of assessment) is relatively straightforward, since the linking function is (presumably) a simple sum.

4.5 Target assessments as a planning guide

A research plan is an allocation of resources to variables at any level of the hierarchy of risk variables in Figure 1. Ultimately, it must translate into an allocation among specific research activities that directly influence the lowest level variables and through them higher levels, up to release modes themselves.

Possible target sets. The allocation procedure is based on target assessments, illustrated in Figure 3. It is a 2nd order adaptation of a well-known procedure, probabilistic goal allocation, which has usually been directed only at 1st order assessments[21].

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[20] On the other hand, predicting ground water travel time from a given set of geologic variables and any given mathematical flow model may be quite doubtful, as witnessed by disagreements between geologists on the relative merits of certain fracture-flow and equivalent-porous-media flow models. Thus, the top-level assessment cannot be routinely inferred from lower level assessments (e.g., by simulation), no matter how ambitious the intervening physical process modeling has been. In particular, the top uncertainty will be seriously understated if no allowance is made for modeling and residual error. Nevertheless, even without error terms, the assessments are bounded by those below them, permitting a consistency check on the hierarchy of assessments.

[21] See Apostolakis (1985); Sung and Cho, (1989); Hunt and Modarres (1984); OECD (1989). Under the name "performance allocation," this approach was, in fact, attempted for this very problem at DOE in the late1980s (DOE 1988). However, it was not, I believe, successfully completed or followed through, at least to the point of significantly effecting research resource allocation (Brown 1988).

For each risk variable at a given level (release mode in this case), a 2^{nd} order "target assessment" is specified, shown as a dashed bar in Figure 3. A complete set of target assessments is chosen so as to produce an acceptable top-level target assessment, as shown by the dashed bar in Figure 3a. (If a 2^{nd} order target is met, the corresponding 1^{st} order target will automatically be met.)

The 90th percentile of the 2^{nd} order top level release assessment (in Figure 3a) just reaches the limit L, which qualifies it as a target assessment—and similarly for each lower contributing target assessment. Thus, if the target gas release (indicated by an arrow-head in Figure 3b) is x, then a 10% probability (2^{nd} order) is assessed that the 1st order assessment will exceed x[22]. Upward propagation of target assessments uses the same familiar algorithm as for current assessments.

Desirable target sets. There are many sets of possible target assessments, and therefore many research plans, consistent with a single acceptable top-level 2^{nd} order risk. Among them, a set is chosen to be technically feasible at reasonable cost and delay. The choice takes into account how far each target assessment falls short of its target, and what research effort it will take to achieve it. This requires considering:

- The gap between 2^{nd} order current and target assessments (the difference between the solid and dashed bars), and
- The cost-effectiveness of research activities needed to close the gap.

This permits deducing (formally or informally) a research program projected to produce an acceptable top-level risk assessment cost-effectively.

In the "mode" planning decision, the cost of achieving any given reduction in 2^{nd} order uncertainty can be derived by informal argument, along the following hypothetical lines. "The effort studying gaseous release appears to be very cost-effective, since a large reduction in 2^{nd} order risk (shortening the solid bar to produce the dashed bar) can be achieved at modest cost. On the other hand, reducing the 2nd order risk of water-borne release by enough to reduce the total 2^{nd} order risk equally (the same shortening of the solid bar at the top of figure 3) would be more costly. Human intrusion permits even less cost-effective reduction in 2^{nd} order uncertainty (a negligible shortening of the solid bar). Modeling error is already tiny and already thoroughly studied, so not worth much effort to reduce."

Lower level targeting. The same logic could be used to address lower risk levels, down to the very bottom of the hierarchy in Figure 1[23]. This would be an indirect way of both making higher-level current assessments and generating lower level target assessments[24]. If competing research activities address the same sub-tree in the hierarchy of variables,

[22] The sum of the individual mode targets will be greater than L, by established statistical theory.
[23] Engineered features would not be included for the present exercise.
[24] For example, it may demonstrate that spreading effort evenly over several geologic strata representing serial barriers is a more cost-effective way to produce the water target assessment in Fig. 3b than devoting all resources to one primary barrier (taking due account of differing accessibility of strata, and therefore cost-effectiveness of effort).

one need only consider their impact on the lowest of the higher order variables they share[25].

Incorporating other considerations in research planning. If the single release variable were all that mattered to the research manager, this would be enough to determine research priorities. However, the cost-effectiveness of a research plan in producing acceptable risk for this one variable (cumulative post-closure release) is not the only consideration in choosing the "best" plan—though it may be the main one. Other considerations include:

- Risk requirements other than the one(s) modeled by the above approach (e.g., pre-closure release).
- Years of delay in disposing of nuclear waste

Optimization? These considerations *could* all be modeled explicitly in a way that permits explicit optimization, and therefore calculation of the preferred plan. However, this would be unmanageably burdensome to do realistically, and, I suggest, better handled by informal adjustments.

Trial and error. I recommend iteratively evaluating plausible target allocations in terms of what they do to cost and to these other consequences, as well as to the modeled top-level risk assessment. The effectiveness of informal adjustments will be greatest if the above target assessment exercise accounts for most of a comprehensive "bottom line" plan evaluation. How close to an appropriate criterion is maximizing the probability of achieving acceptable risk for just a single variable (release) at minimal cost?

This approach has drawbacks, even for the purpose of advancing only the *applicant's* interest. The output will not explicitly prescribe what research managers and their sub-contractors should do, since it involves no optimizing algorithm—only a clearer representation of the research consequences of options, from which persuasive informal argument can be built. A numerically more explicit refinement and implementation of the approach would carry more weight, and enable a research manager to take more active control of research planning.

Although full numerical application, even without formal optimization, involves ambitious analytic effort and new technical development, it can be used as an informal knowledge-structuring tool. In particular, in cases with lower stakes than YM, it may assure that relevant considerations are taken into account. However, explicit quantification may be needed to be fully effective in *enforcing* sound risk research planning on potentially recalcitrant researchers.

4.6 Evolution of research plan

Much of any value that an explicit resource management procedure may have is in ensuring that desirable research management changes take place, in the face of powerful

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[25] One research task may, however, address several different variables. For example, sinking an exploratory shaft might cast light on more variables throughout the hierarchy, and so deserve high priority.

institutional resistance. It can make it more difficult for well-entrenched research contractors to fight disturbance of the financial status quo, which they may have come to rely on for a major source of income. The same is true for those applicant organizations whose research funds come from outside sources (as in the waste disposal case).

Periodic re-allocation. Nothing more than systematically programmed iteration of the above initial allocation procedure is called for to justify resource re-allocation, as assessments change in response to evolving evidence.

4.7 Halting research

A research program is complete, and can be halted, when it establishes that the facility (e.g., site) either does or does not comply with regulation, however specified. A reasonable criterion for a good research strategy is to minimize the expected cost of such completion (not necessarily derived explicitly).

Successful compliance. An applicant would reasonably halt research if 2^{nd} order acceptability is achieved, i.e. when the dashed bar is entirely to the left of limit L, as shown in Figure 3a. This would be achieved, for example, if all target 2^{nd} order assessments, represented by dashed bars lower in the tree were met.

Failed compliance. Presumably an applicant would also stop when all hope of success had gone; i.e. if the dashed horizontal bar in figure 3a settled entirely to the right of L.

4.8 Hindsught implications of the approach for waste disposal case

If the DOE planning team in the early stages of the waste disposal case in the 1980s had adopted the ideas put forward above, DOE might plausibly have taken the following steps:

- Operationalize NRC regulations by issuing its interpretation of the “reasonable assurance” of first order acceptable risk (probability of cumulative release), by including an additional formal provision in second order probability terms, subject to NRC approval.
- Analyze all evidence on cumulative release available at the outset of the program, and assess how close to first and second order compliance the site is. The conclusions would be expressed along the lines of figure 2.
- Evaluate the degree of existing compliance with regulatory requirements *other than cumulative release,* as best it could (not necessarily numerically). Those that prescribe research activity (such as sinking an exploratory shaft) obviously could not yet be in compliance.
- Attribute primary compliance evaluation to a hierarchy of complex risk assessments, along the lines of Figure 3, with the hierarchy expanded along the lines of Figure 1.
- Construct a corresponding hierarchy of trial target assessments that, if met, would achieve complex compliance. This would derive from judgmental appreciation of the cost-effectiveness of effort on each research activity, in terms of the response of complex assessments to level of effort.

- Note activity costs and delays required to meet these targets, and the implied total cost and delay. This constitutes a trial resource allocation.
- Iterate for other plausible allocations to identify a plan with better cost/delay (With no explicit optimization).
- Augment or adjust this plan to take account of other regulatory requirements.
- Respond to input from NRC to take account of society's priorities diverging from the applicant's (e.g., more attention to bad news).
- Entertain alternative allocations (e.g., proposed by interested research contractors) but subject them to the above evaluations
- Make allocation decision accordingly, and implement.
- Repeat above steps periodically (e.g. every 6-12 months) and reallocate if necessary, as assessments change. (E.g., if early evidence suggests that gas-borne release is a more serious concern than initially thought, then its share of the budget, relative to water-borne release, could dramatically increase. Other possible re-allocations might include shifting effort from one geologic stratum to another, or from ground-water travel to radioactive retardation).
- Stop work and apply for a license whenever DOE convincingly assesses the site to be in both first and second order compliance (and any other regulatory requirements are met).

I cannot tell how this sequence would actually have played out, but I surmise that the research budget allocation among contractors would have been quite different and more radically revised as results came in. Almost certainly the total cost and delay would have dropped substantially.

I did, in fact, urge my DOE consulting client to use an early version of this approach (which implied significant redirection of research resources among research teams in its research planning). It may not have had much practical impact, but it stirred the resistance (ultimately successful) of research contractors who got wind of it and whose budgets it threatened[26].

5 RESEARCH MANAGEMENT: SOCIETY'S PERSPECTIVE

5.1 Distinctive interests of applicant and society

The applicant's interests differ from those of "society". The applicant's primary objective is presumably to have the application succeed, and so the applicant has an interest in maximizing the *unconditional* probability of a "positive" finding, regardless of whether it is in fact true. Society's interest is to properly balance safety, economics, and other considerations. This may, for example, affect the priority given to seeking out

[26] The potential of this work to save DOE money, and the power of contractors to thwart it, are illustrated by the following incident. My consulting contract was administered through one of the major research contractors. When it became clear by 1991 that my interim reports to the DOE Office head and to the Technical Review Board could lead to selective cuts in the research budget that could cost that company many millions of dollars, I was warned by a vice-president "We expect you to be more docile (*sic)*. We are not going to pay for the bullets that will kill us, and can get your contract cancelled". It was.

negative evidence. Section 4 has sought an appropriate research strategy from the applicant's point of view.

Enlightened self-interest in an adversarial process. However, public interest may still be adequately served. In our society, contentious issues are often resolved by participants pursuing their own interests, sometimes subject to an arbiter and procedural constraints (as in a court of law)[27]. The principle of "enlightened self-interest" argues that the better the parties advance their own interests, the better the public interest is served. Thus, in risk regulation, helping the applicant may help society, but we cannot take that for granted.

Furthermore, the applicant's (DOE's) discretion may be limited by direct intervention of others representing society's interests more closely. In particular, NRC and the TRB (nuclear waste Technical Review Board) make suggestions (typically to do additional research) that are often interpreted as directives by DOE. Without some systematic research planning rationale, even these bodies may be diverted from best serving the public interest[28].

A tool to serve society directly. Alternatively, a research-planning tool can be developed to serve the public interest explicitly. There are two promising approaches, one based on the acceptance-testing paradigm, the other on adapting the target assessment approach.

5.2 Decision theoretic acceptance testing

There are well-established decision theoretic approaches to designing information-gathering options. The basic decision theoretic logic from the perspective of the ultimate client, society in this case, is the "preposterior analysis" paradigm of statistical decision theory (Pratt et al. 1993).[29]

Mattson et al. (1991) have applied this approach to YM. They prioritized tests for "potential concerns" about radioactive release, and concluded that "The tests of highest priority are those for gas flow (carbon-14) above the repository, and possibly (other tests)." This is consistent with the above results of target assessment applied to the release mode issue (hypothetically, but with some attempt at realism) [30]. Both approaches

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[27] In the courts, counselors contend, and the jury decides. Economic processes foster enlightened self-interest among competing businesses. The regulator in this case could be treated, not as an arbiter, but as an *opponent* of license approval, rather like a counsel for the prosecution. (The TRB, reporting to the President, would be the judge/jury.) Regulators may justify their existence by "ratcheting"; i.e., progressively piling on requirements. Experts on advisory bodies may urge research on topics they are interested in.

[28] A research-planning tool might be developed for the regulator that paralleled the approach put forward in section 4, but where the target assessment shows a relatively *high* probability of exceeding the limit.

[29] Non-decision theoretic approaches to the "acceptance testing" version of the problem are familiar in engineering (Oliver and Smith 1940, Diamond 1989).

[30]Then, radioactive *release* was treated as the primary risk variable to be controlled. However, when regulatory attention later (and I believe appropriately) switched to *dosage*, the case for gaseous study significantly weakened. A given gaseous release produces less dosage, due partly to dispersion into the

were predicated on the knowledge and regulatory requirements in 1990.

Society has an interest in reducing two types of error: finding a facility acceptable when it is not; and finding a facility unacceptable when it is in fact acceptable. The appropriate research plan depends on the probabilities and relative cost of the errors (false positive and false negative, respectively). However, the complexity of this analytic task (especially the inclusion of value judgments) makes it difficult to do without making simplifying assumptions that sacrifice realism of the model to. Accommodating multiple constituencies adds complexity.

The model that Mattson et al. used may have departed from being an "equivalent substitute" for the real problem by unrealistically treating as discrete both the options (either to test or not on each issue) and the potential test outcomes (false-positive, etc.). The optimizing feature of acceptance testing produces unambiguous direction for research managers to follow, thereby restricting their and others' ability to serve private agendas. However, the very absence of optimizing in the target assessment approach permits informal accommodation of considerations inevitably omitted from a formal model or unrealistically simplified.

5.3 Target assessment as an element of acceptance testing

The target assessment approach can be adapted as a kind of partial acceptance testing. Unlike in section 4, we would not set *unconditional* target assessments aimed at demonstrating compliance (for the applicant) or non-compliance (for the regulator or environmental intervener). Instead, we would specify two sets of *conditional* target assessments. The condition is whether the facility is or is not acceptably safe (2^{nd} order). These correspond to true-positive and true-negative in the acceptance testing model.

Both target sets are compared with current assessments, along the lines of Figure 3. In the true-negative case, the counterpart of Figure 2 would then show a top-level dashed target bar entirely to the *right* of the release limit (rather than to the left). Professional judgment would be introduced (as before) to make the actual resource allocation decision. The resolution would depend *implicitly* on the relative costs of a false-positive and a false-negative, but without formal optimization. (How exactly this idea would be implemented, and how practical it is, needs study).

5.4 Combining both approaches.

These two research-planning approaches might be pooled[31]. They have the complementary strengths of realism for target assessment and optimization for acceptance testing.

Optimization produces a publicly reviewable decision procedure, and reduces irresponsible discretion. That discretion can also be beneficial in giving a responsible

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atmosphere. Reapplication of either approach, with appropriately changed inputs, would probably have confirmed this shift, and possibly made it more convincing.

[31] E.g., with plural evaluation techniques (Brown and Lindley, 1986).

risk manager wiggle room to combat defects in regulation. Calculating an optimum allocation under simplifying assumptions may be insightful, provided that it is not treated as an equivalent substitute for realistic, comprehensive reasoning.

6 DISCUSSION

6.1 Making methodology operational

Requirements of an effective prescriptive methodology. The exposition in this paper has been atypically wide-ranging for a research paper, and may frustrate the reader by leaving the treatment of many issues seriously incomplete. This reflects my conviction that an effective decision aid must meet a large number of diverse requirements, behavioral and technical. This has required *minimal treatment of many issues*, rather than technical closure on any one, and to be broad enough to cover whatever it takes to produce a usable methodology. Attention here has been technically diffuse, but sharply focused on a practical research-planning problem (Brown 1992).
The methodology presented here is certainly still primitive and largely conceptual.

Problem specific implementation. I am firmly convinced that the successful application of an approach like this requires most of the effort to be specifically adapted to the problem at hand, albeit guided by general principles of the type I have presented.

Although making these concepts operational may prove to be a formidable intellectual challenge, if the stakes are high enough it should be worth the cost and effort. In the YM case, redirecting the millions of dollars spent on a version of performance allocation should have been adequate. In any case, the underlying logic can inform a less ambitious research-planning tool than that presented here.

6.2 Work needed.

Nevertheless, there is certainly much valuable work to be done at a non-problem-specific level.

Checking out this argument. This includes most importantly exercising, developing and testing the evolving general methodology in the context of live research management cases. In particular, I recommend checking out the reasoning in this paper. Is the informal argument sound, and do the graphic representations correspond? Only when both these thresholds have been cleared, does it make sense to turn the argument into mathematics, which may be a straightforward technical task.

Applicant's research-planning tool. General-purpose algorithms need to be developed for propagating first and especially second order assessments of risk variables into total risk.

Techniques for making the first order assessments have been extensively researched and are in any case not specific to this problem. However, the methodology of second-order probability assessments, for this and other problems, is a major research opportunity (Brown [AU]).

Acceptance testing. To turn a logical rationale into an operational methodology, and extend it to include the false-negative/positive issue will require work; e.g. to develop the specific procedures and software to implement the rationale in a practical context. What input can be cognitively supplied, what output can be institutionally used, and what logical algorithms are appropriate to link the two?

Expanding scope of method. The scope of the approach presented could be enlarged to address *balancing* an applicant's research effort between *evaluating* a given risk (as here for a repository site with given engineered features) and *reducing* the risk (e.g., through more effective containment and other engineering). This would permit reviewable validation of recent shifts in research planning at Yucca Mountain that favor engineering enhancement, as confidence in the ability of the site on its own to isolate release recedes.

6.3 Conclusion

This paper reports on work that attempts to be prescriptive—in the sense that it produces a usable and useful methodology. In particular, it has proposed a regulatory initiative to motivate responsible research direction by an applicant, and a resource management procedure to help the applicant to control research sub-contractors. If successfully implemented, it may provide an enforceable rationale for research programs that are more cost-effective in the public interest.

It also provides a convenient framework within which to present competing arguments about what should be (or should have been) done in risk research. The approach can be used to validate whatever research management strategy is proposed (even if a less formal approach were used in the first place to design that strategy). It should help the risk manager, DOE in this case, to withstand, not only regulatory and legal challenge, but also the resistance of researchers to having their projects terminated for programmatic (rather than scientific) reasons.

The large scale of the nuclear siting problem is exceptional (but not unique). However, the issues are typical of many risk management problems, especially where public controversy is involved (like genetic engineering, industrial safety, the health risks of consumer product safety or medical mistakes).

I have looked here at how public servants should go about evaluating a large and risky venture. A travel metaphor may give the gist of my message. "If you want to get from here to there, fix sharply where here and there are, and how far there is to go. Take pains to plan an efficient route. Track progress regularly and make mid-course corrections as needed. But keep an eye on the cab driver. Give him clear directions and check that he follows them, especially if plans change. Make sure he does not take detours that suit him (or his boss) better. Otherwise, you stand to waste a lot of time and money."

I have illustrated my argument in the context of a case with which I am very familiar, where I was invited at the most senior management level to advise on methodology (largely disregarded), and where I could observe at first hand the decision process and its consequences. With luck, any insights I have gained will help to avoid massive waste of national resources on future projects of comparable scale.

REFERENCES

Apostolakis, G. Some issues related to goal allocation and performance criteria," Paper M2 4/3, 8th International Conference on Structural Mechanics in Reactor Technology, Brussels, Belgium, August 19-23, 1985

Brown, R.V. Characterizing a Nuclear Waste Site: A Logical Framework for Allocating Resources, Proceedings 1988 Las Vegas Annual Meeting. Decision Sciences Institute. 1988.

Brown RV. Environmental Regulation: New Paradigms for Determining Requirements and Compliance. In UNESCO *Encyclopedia of Life Support Systems.* Ed. A. Gorbaasi. Wiley. In press.

Brown, RV, and Vari, A. Towards an agenda for prescriptive decision research: The normative tempered by the descriptive. *Acta Psychologica*, 80, 33-47 1992

Brown, R.V., and Ulvila, J.W. Does a reactor need a safety backfit? Case study on communicating decision and risk analysis information to managers. *Risk Analysis*, 1988, 8(2), 271-282.

Brown RV. Some Reflections on DOE Nuclear Waste Program. Consulting report to Dr. John Bartlett, Head of DOE Office of Civilian Radioactive Waste Management. Decision Science Consortium, Inc. February 7, 1990a.

Brown, R.V. Assessment uncertainty technology for making and defending risky decisions. *Journal of Behavioral Decision Making*, 3, 213-228, 1990b.

Brown, R.V. Impersonal Probability as an Ideal Assessment based on Accessible Evidence: A Viable Construct? *Journal of Risk and Uncertainty*, 7:215-235, 1993.

Calabria R, Pulcini G, Rapone M. Optimal reliability and maintainability allocation in manufacturing systems. Qul reliab eng int 11 (3) 183-188. May June 1995

Chinnis JO. *Evaluation of a proposed Satellite Power System.* Technical report to DOE. Decision Science Consortium, Inc. 1986

Cho NZ. Multiobjective programming approach to reliability allocation for nuclear power plants. Nuclear Science engineering. 95 (3) 165-188 Mr. 1987

Congress of the US. The 1987 Nuclear Waste Policy Act, 1982

Congress of the US. The 1987 Nuclear Waste Policy Amendment Act, 1987.

Diamond, William J. Practical Experimental Designs for Engineers and Scientists, 2nd Edition, N.Y. Van Nostrand Reinhold, 1989.

DOE, US. Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area. DOE/RW-0199. Washington DC: OCRWM Dec. 1988.

10CFR63. Federal Register 64 FR 8640. 1999a. Disposal of High Level Radioactive Waste in a Proposed Geologic Repository at Yucca Mountain. Proposed Rule.

10CFR963Federal Register 64 FR. 1999b. OCRWM/NWR: Yucca Mountain Site suitability Guidelines. Proposed rule making.

40CFR197Federal Register 64 FR 46976. Environmental Radiation Protection Standards for Yucca Mountain, Nevada. .

Fischhoff B. Acceptable Risk: a conceptual proposal. Risk: Health, safety and the Environment. Winter 1994.

Hunt, R.N.M. and Modarres, M. Integrated economic risk management in a nuclear power plant. In Proceedings of the Annual Meeting of the Society for Risk Analysis, October 1984, Knoxville, TN, Plenum Press, New York.

Keeney RL. An analysis of the Portfolio of Sites to Characterize a Nuclear Repository. Risk Analysis 7. 195-218. 1987.

Keeney, R.L. and Merkhofer, M. A multiattribute utility analysis of alternative sites for the disposal of nuclear waste. Risk Analysis, 2(7), 1987.

Keeney RL and von Winterfeldt D. Managing Nuclear Waste from Power Plants, Risk Analysis, 14, 107-130. 1994.

Kendall, M.G. and Stuart, A. The advanced theory of Statistics. London: Hafner, 1961.

Mattson SR, Judd BR, Sinnock SR, Hoxie DT. Testing Priorities at Yucca Mountain: Recommended Early Tests to Detect Potentially Unsuitable Conditions for a Nuclear Waste Repository. USDOE/OCRWM. March 1991.

? NAS 2001[Report on disposal of HLW]

National Energy Association. Proceedings of an NEA Workshop on Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems, Seattle, February 24-26, 1989, OECD, Paris.

National Research Council (Board on Radioactive Waste Management). Rethinking high-level radioactive waste disposal. Washington, D.C.: National Academy Press, 1990.

NWTRB. Nuclear Waste Technical Review Board. "Report to US Congress and the Secretary of Energy". Jan-Dec 1998.

Sung, S.K. and Cho, N.Z. Determination of performance criteria at hierarchical levels in a nuclear power plant, Reliability Engineering and System Safety, 24:231-256, 1989.

TRW Total system performance of a nuclear waster repository at Yucca Mountain. YMP. Dept. of Energy. 2000

Whipple C, Budnitz B Ewing R, Moeller D, Payer J Witherspoon P. 1999. Final Report. TSPA Peer Review Panel. Las Vegas, Nevada.

Yang XP, Kastenberg WE, Okrent D. Optimal safety goal allocation for nuclear power plants. Reliab eng syst safe 25: (3) 257-278 1989.

Yucca Mountain Project. Timeline/Milestones. www.ymp.gov/timeline. Oct. 2000

10CFR60. Code of Federal Regulations. Nuclear Regulatory Commission Title 10; Disposal of High-Level Radioactive Wastes in Geologic Repositories. Part 60. Washington D.C. Government Printing Office, 1992.

10CFR63. CFR. Disposal of High-Level Radioactive Waste: Amendment. USGO. 1997.

10CFR960. Code of Federal Regulations. General guidelines for the recommendation of sites for nuclear waste repositories. USGPO. 1987.

33CFR404. Code of Federal Regulations. Navigation and navigable waters: Title 33. Part 404 [?] Washington D.C. Government Printing Office, 1986.

40CFR191. Code of Federal Regulations. Environmental Protection Agency: Title 40; Environmental standards for management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes: Part 191. Washington D.C. Government Printing Office, 1985.

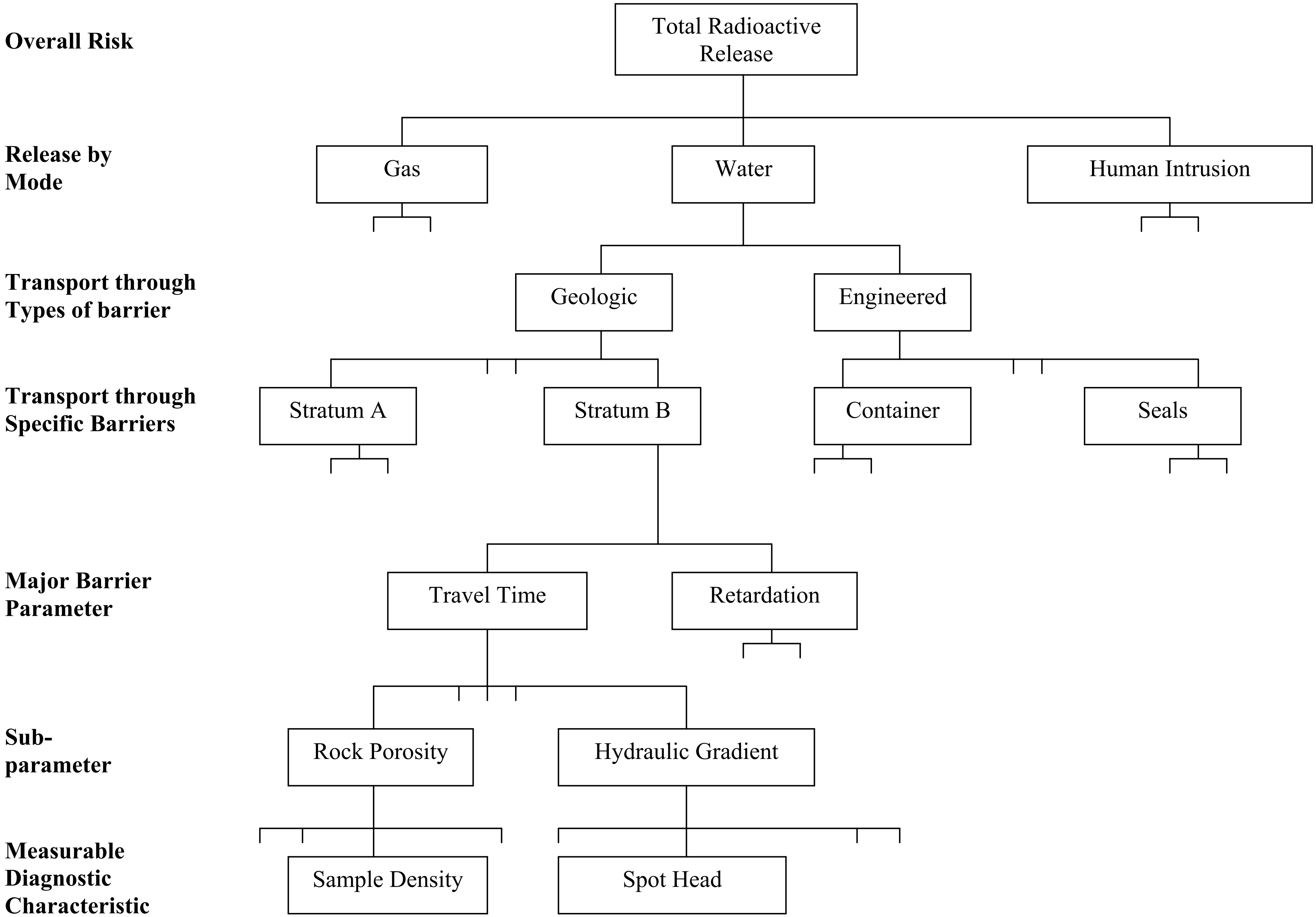

FIG. 1

RADIOACTIVE RELEASE RISK VARIABLES
Partial hierarchy

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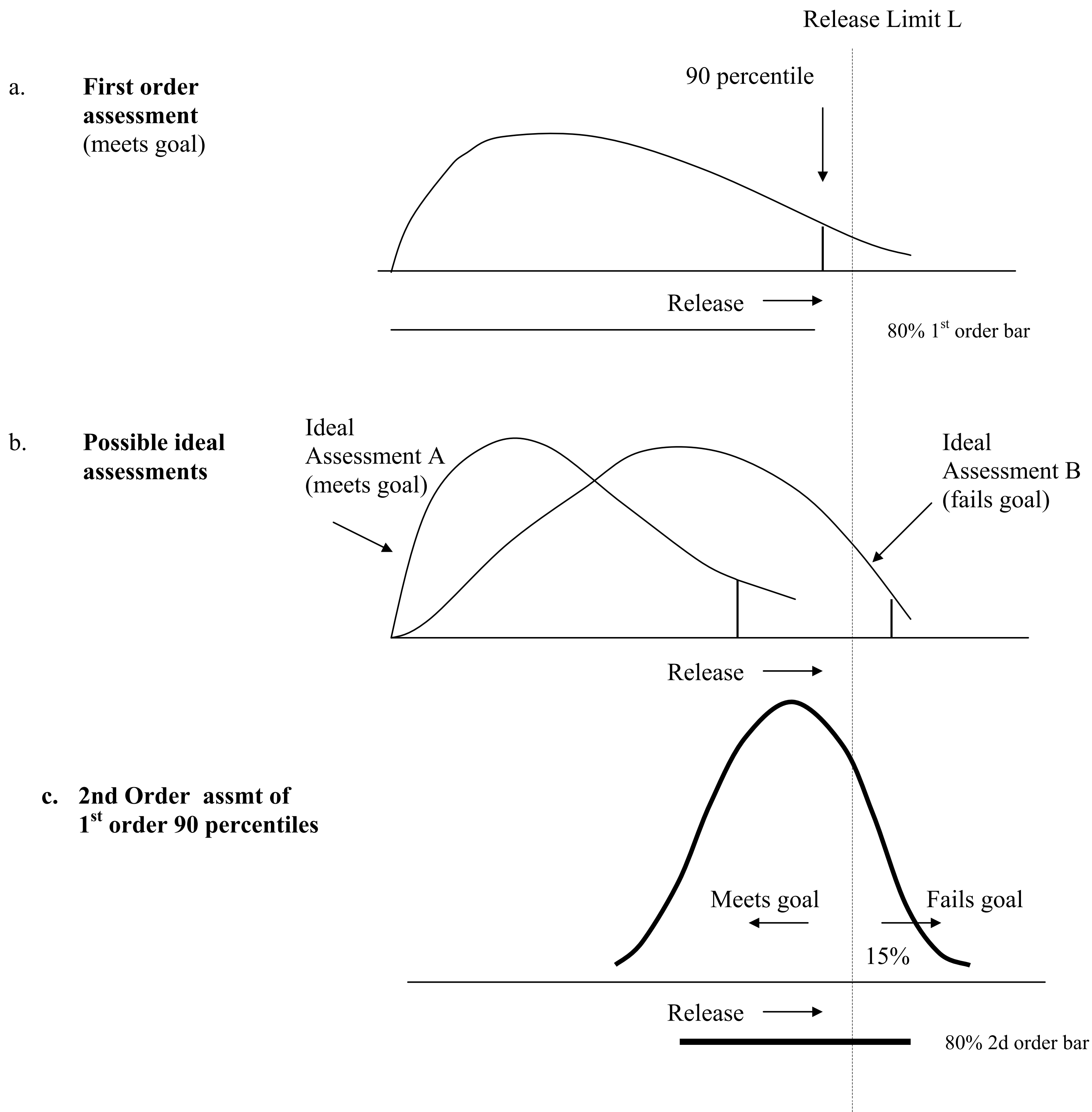

FIGURE 2

ACCEPTABLE 1ST ORDER ASSESSMENT
UNACCEPTABLE 2ND ORDER ASSESSMENT

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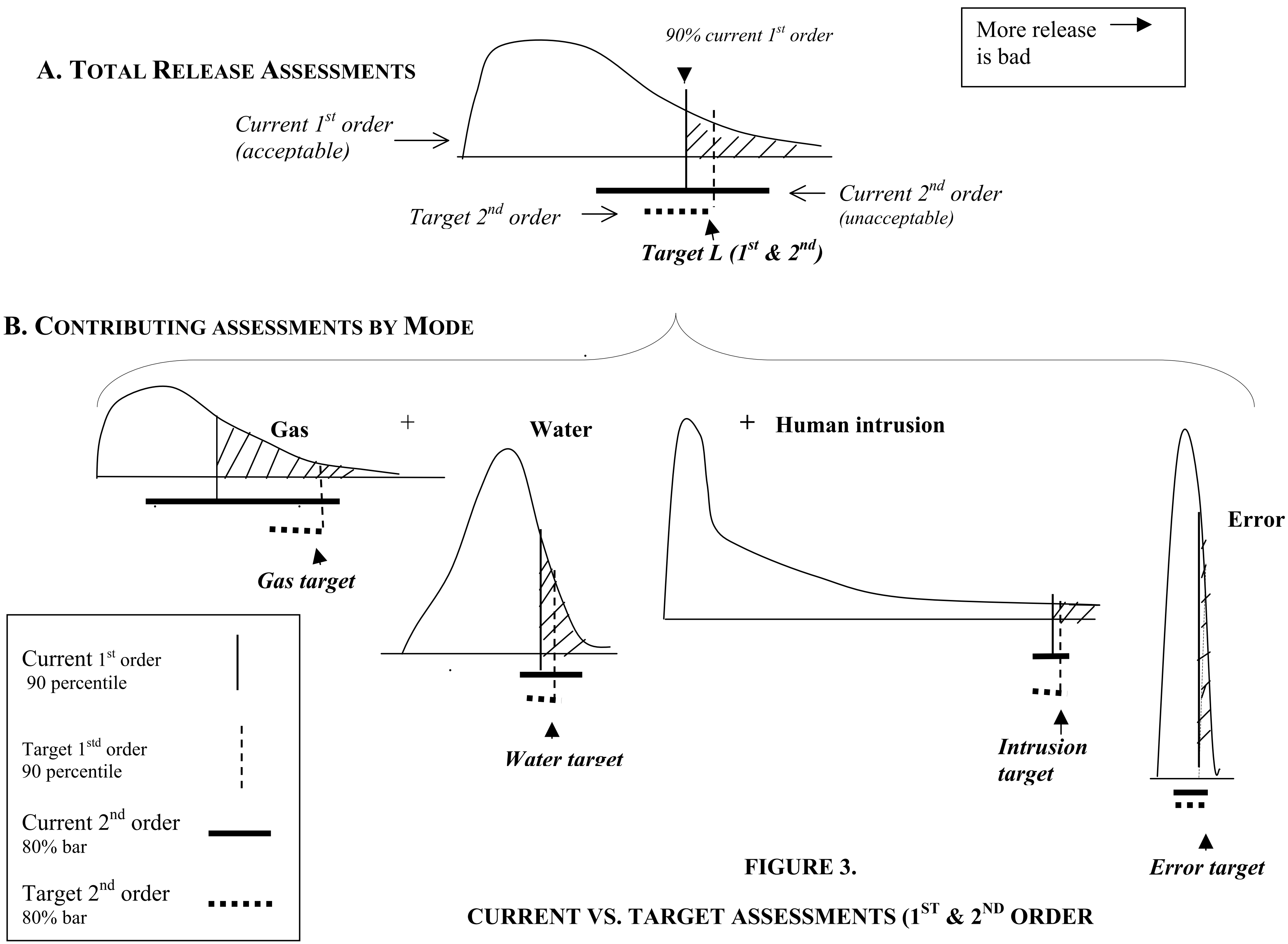

FIGURE 3.

CURRENT VS. TARGET ASSESSMENTS (1ST & 2ND ORDER