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SAND99–8240
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Printed April 1999

DOE Nuclear Weapon Reliability Definition: History, Description, and Implementation

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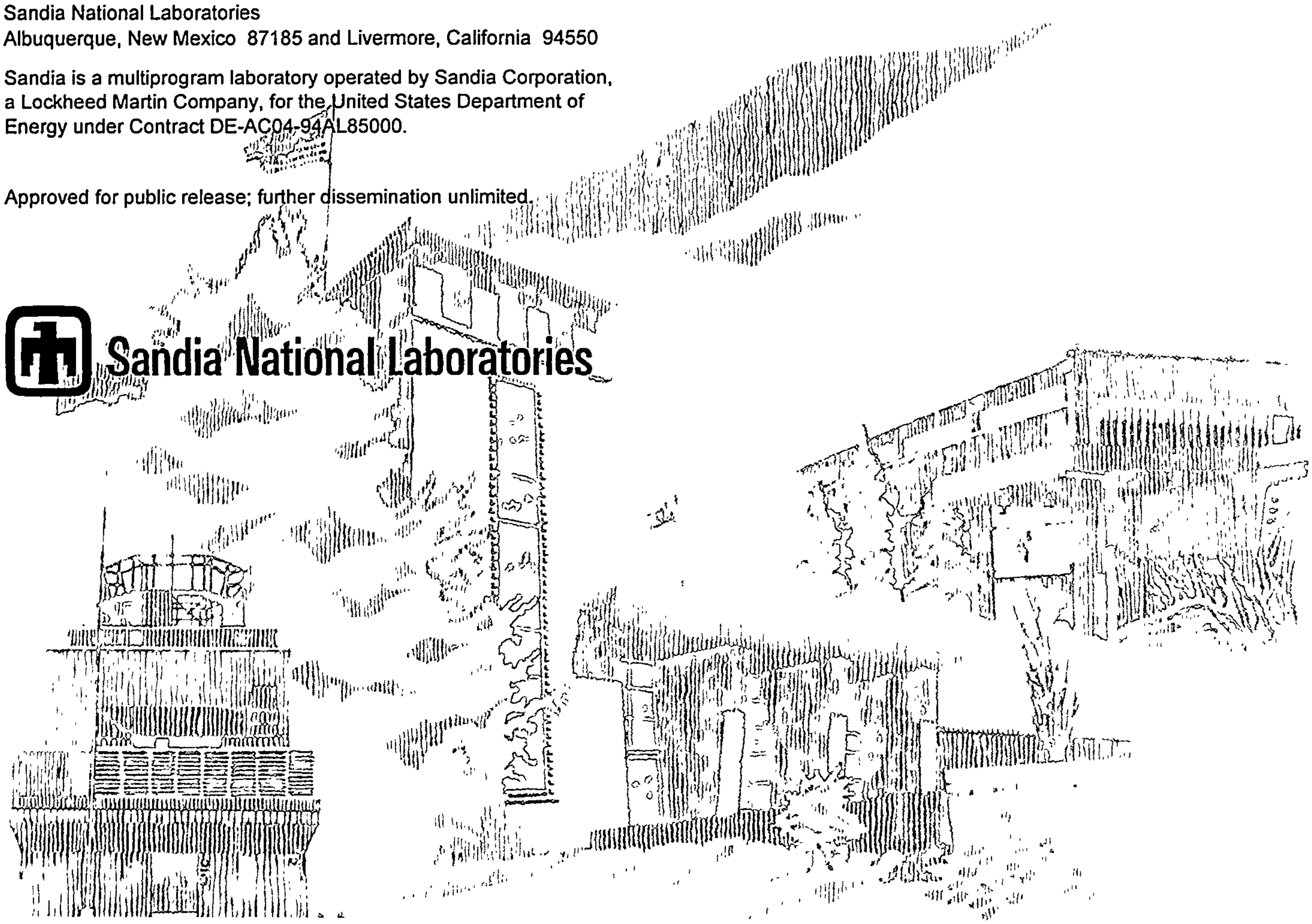

SF2900Q(8-81)

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DOE Nuclear Weapon Reliability Definition: History, Description, and Implementation

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Abstract: The overarching goal of the Department of Energy (DOE) nuclear weapon reliability assessment process is to provide a quantitative metric that reflects the ability of the weapons to perform their intended function successfully. This white paper is intended to provide insight into the current and long-standing DOE definition of nuclear weapon reliability, which can be summarized as:

> *The probability of achieving the specified yield, at the target, across the Stockpile-To-Target Sequence of environments, throughout the weapon's lifetime, assuming proper inputs.*

This paper discusses the historical and academic bases for this definition and the larger Department of Defense (DoD) use planning context for the DOE's reliability metric. Details and examples of each of the elements of the definition of reliability are provided. Finally, the historical evolution of uncertainty statements for DOE weapon reliability assessments is described. Current and future challenges for the nuclear weapon reliability community, including extended weapon lifetimes and reductions in the stockpile surveillance test program, are identified and discussed.

Acknowledgments

Personnel from both Los Alamos National Laboratory (Tom Bement and Dan Varley) and Lawrence Livermore National Laboratory (including Carl Anderson, Terry Bevers, Tom Edmunds, Ron Glaser, Jeff Hagerty, Andy Lundberg, and Al Parziale) provided helpful suggestions and advice during the development of this white paper. Thanks also go to Rena Zurn, Jim Handrock, John Duncan, and George Merren (retired) at Sandia National Laboratories for reviewing and commenting upon interim drafts.

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DOE Nuclear Weapon Reliability Definition: History, Description, and Implementation

Introduction

This white paper is intended to provide insight into the current and long-standing DOE definition of nuclear weapon reliability, the historical and academic bases for this definition, the larger DoD use planning context for the DOE's reliability metric, details of the elements of the definition, and historical evolution of uncertainty statements for DOE weapon reliability assessments.

Current and future challenges in stockpile management provide the motivation for this paper. These include the following:

(1) Our DoD customers need assurance that all DOE anomalies are being addressed clearly and completely. This drives a need for joint understanding of the reliability metric and what it encompasses.

(2) It is imperative that a consistent approach be taken to assess the reliability/performance impact of all DOE anomalies to support decisions in a resource-constrained environment. This drives a need for clear and thorough documentation of the DOE weapon reliability definition.

(3) Because of these resource constraints, the community may choose to tolerate anomalies in the stockpile rather than fix them. When resources were more plentiful, reliability assessments based on limited information were considered acceptable in the decision process in some cases since the fixes could be done immediately. As resources are further constrained the reliability assessment is likely to become a more significant factor in deciding whether or not to fix the problem. Thus it will be increasingly important to have an accurate initial assessment of an anomaly, as well as a process for on-going data collection and reliability updates.

(4) There is increased use of the word "reliability", with various meanings, in today's world. Programs such as Enhanced Surveillance are intended to complement the core surveillance program, but they often define reliability quite differently in order to reflect the objectives and scope of the specific program. For example, Enhanced Surveillance is often addressing "materials reliability". Generally materials reliability is defined as the probability that a material or part meets a certain specification; this metric typically cannot be directly related to success or failure of a weapon subsystem or system. A clear understanding of what information is needed to perform weapon-level reliability analyses is essential for proper interpretation and integration of data and models obtained through Enhanced Surveillance and other reliability-related activities.

(5) Because of the Comprehensive Test Ban Treaty, there is increased concern and scrutiny by DoD regarding the credibility of nuclear package performance assessments (reliability and yield). A consistent assessment and reporting process is needed that will instill and maintain confidence in DOE assessments. Any perception that known anomalies have not been

assessed, or that reliability impacts are assessed without substantive engineering analysis, erodes credibility in current assessments and historical studies.

The above issues highlight a need to clarify the long-standing definition for today's weapon community, both inside and outside of Sandia. Because reliability assessment is a joint process between the nuclear labs, DoD, and DOE, continued communication and education is vital to ensure that weapons are assessed consistently and accurately.

Note that the DOE weapon reliability assessment methodology is discussed in this paper only to the extent that it clarifies the definition. The "Nuclear Weapon Reliability Evaluation Methodology Guide"[1] provides a complete description of the details of the methodology used by the DOE nuclear laboratories to assess the reliability of nuclear weapons. Note also that in this paper, the word "component" will be used to denote Major Components (MCs) rather than discrete piece-parts.

Scope

Nuclear weapons are designed with multiple objectives, including safety, security, and reliability. Reliability focuses on the ability of the weapon to perform its intended function at the intended time under environments considered to be normal. If the weapon is exposed to abnormal environments, there is no longer an expectation or requirement that it perform its intended function at the intended time. Safety analyses address the ability of the weapon to prevent unintended function in either normal or abnormal environments. Security analyses gauge the ability of the weapon to prevent unauthorized use in normal (and some types of abnormal) environments. These objectives are different, and they are analyzed separately. This white paper focuses exclusively on reliability and how it is defined for DOE nuclear weapons. Note though that the objectives of achieving both high reliability (function when intended) and safety/security (won't function if not intended) tend to be conflicting and require careful balancing in actual design and implementation.

DOE Weapon Reliability Definition History and Background

The overarching goal of the DOE weapon reliability assessment process is to provide a quantitative metric that reflects the ability of the weapons to perform their intended function successfully. The general approach to stockpile assessment that has been agreed to by the joint reliability working groups on the various weapon systems is presented in the vugraphs shown in Appendix A. These concepts have been presented in the past few years to DOE Headquarters, the CINCSTRAT Strategic Advisory Group (SAG), the Nuclear Weapon Council Standing and Safety Committee (NWCSSC) Requirements Working Group, and USSTRATCOM. The documents on which these vugraphs are based are not new; for example, "Reliability Technology, a Manual for Nuclear Ordnance Engineers" is dated 1960. In fact, all of the historical documents on which we rely have similar definitions. The words may be slightly different, but the underlying factors to be considered are the same. The most concise way of summarizing the definition that has been used historically is as follows:

[1] "Nuclear Weapon Reliability Evaluation Methodology Guide", D.L. Wright, editor, July 1993.

The probability of achieving the specified yield, at the target, across the Stockpile-To-Target Sequence of environments, throughout the weapon's lifetime, assuming proper inputs.

This definition is the foundation for the balance of this paper. It is also the foundation for the reliability definition contained in the DOE Weapons Reliability Report, which has been expanded to further explain nuclear weapon unique circumstances. The full definition extracted from the May 1998 DOE report is contained in Appendix B.

The DOE weapon reliability definition and assessment methodology were carefully constructed to integrate appropriately into the larger weapon system assessment and planning process. The integration of DOE weapon reliability occurs in the calculation of Damage Expectancy (DE) performed by USSTRATCOM, which addresses the end-to-end mission and includes the complete complement of DOE and DoD hardware and DoD operational procedures used to execute the mission. The first vugraph in Appendix C illustrates the four major terms in the DE calculation: Prelaunch Survivability, Weapon System Reliability (WSR), Probability to Penetrate, and Probability of Damage (PD). These terms are all conditional probabilities — e.g., Weapon System Reliability is calculated assuming a successful prelaunch. Probability of Damage is a function of discrete variables including yield, accuracy (both Height of Burst and Circular Error Probable), and target hardness, and it assumes the yield and accuracy values have been achieved. DOE weapon reliability is part of the WSR term; all DOE material performance information for DE is thus captured in the WSR and PD terms. The second vugraph in Appendix C shows what functions are included in the DOE weapon reliability assessment by weapon system type. The relationship between DOE weapon reliability and Probability of Damage will be discussed in more detail later, particularly with respect to yield and accuracy.

The Elements of the DOE Weapon Reliability Definition

Appendix D lists nine literature sources addressing the general definition of reliability. All are consistent with the DOE weapon reliability definition. For example, the definition from Reference 1 states:

"The reliability of an item is the probability that it will adequately perform its specified purpose for a specified period of time under specified environmental conditions."

Review of these literature sources shows five important elements of all reliability definitions:

1. the probability measure
2. the item of interest
3. the meaning of success (or failure)
4. the environment to which the item is going to be exposed
5. the appropriate time frame

It is helpful here to note how these five academic elements are realized in the DOE definition of reliability:

1. Probability measure = realistic lower bound on the probability of success
2. Item of interest = DOE-designed hardware
3. Success = achieving the specified yield at the target
4. Environment = across the Stockpile to Target Sequence (STS) environments, assuming proper inputs
5. Timeframe = throughout the weapon's lifetime

Controversies have arisen periodically in the DOE and DoD communities over the inclusion of one or more of the concepts contained in the DOE weapon reliability definition. Review of these controversies in the context of the fundamental elements above shows that the real problem is not in the basic definition of reliability but in its interpretation during evaluation of specific anomalies. Poor understanding of, for example:

- who is responsible for the item of interest
- how success and failure are defined
- what the applicable enviroinments are
- what the time frame associated with the assessment is

has led to controversy and confusion in specific nuclear weapon anomaly evaluations in the past. Therefore, several relevant historical and hypothetical examples are discussed below to clarify how the elements of the DOE definition are applied to appropriately assess various types of weapon anomalies.

Probability Measure = Realistic Lower Bound on the Probability of Success

One objective during the design and development process for nuclear weapons is to design to worst-case conditions and to make the weapons' performance (and hence reliability) independent of the environments to which they will be exposed over their required lifetime. It is desired, for example, that weapons operated at hot or cold temperatures (within the STS) will be just as reliable as those operated under nominal conditions. Furthermore, it is desired that the weapons' reliability be invariant with age during the required lifetime, either in terms of years or in terms of environmental or operational cycles. In reality, the weapons may actually have a range of reliabilities depending upon operating conditions, storage conditions, age, mode of usage, etc. Some conditions are not typically controllable by the user at any given point in time, such as operating temperatures and weapon age. Therefore, in general a nuclear weapon reliability assessment is a realistic lower bound best estimate of the probability of success over the entire range of environmental and lifetime conditions specified in the STS. Other conditions are within the immediate control of the user, and a separate reliability can be estimated for each. Typical examples of this can include reporting separate reliability assessments for each fuzing option of the weapon, or reporting a separate reliability assessment for weapon use against hard irregular targets. The issue of determining a realistic lower bound for reliability will be discussed in more detail in the sections on environments and lifetime.

Item of Interest = DOE-Designed Hardware

In general, the DOE is responsible for assessing the performance attributes for all DOE-designed hardware. Note that in certain cases the DOE assessment boundaries are extended to include non-DOE hardware, software, or procedures by joint agreement with the DoD. For most anomalies involving DOE hardware, the approach is straightforward and can be handled using the standard DOE weapon reliability assessment metric and methodology. However, in some instances there are synergistic effects or unusual or ambiguous consequences of the anomaly within the overall system. In these cases, the DOE may need to negotiate with the DoD to address the anomaly in the most useful manner in the DE calculation. The DOE has the responsibility to ensure that the questions below are answered. Communication is essential to arrive at an optimal approach and to ensure that all users of the information are aware of how the anomalies are addressed.

The issues are:

A. What agency should lead the assessment of the anomaly? What other agencies, if any, should be involved in the assessment?

B. What metric is the most useful to the DoD for targeting and using the weapons (DOE weapon reliability, Probability of Damage, etc.)?

C. Is the anomaly accounted for "once and only once" in the overall joint DOE/DoD Damage Expectancy model[2]?

D. Where will the impact be reported? How will it be reported?

E. How will the impact assessment be updated over time? Who is responsible for updating it?

These questions should be answered as early as possible in the course of the investigation of the anomaly to ensure that all relevant technical resources are identified and that there is a clear, credible, and timely reporting process within and outside of the DOE. Documentation of the data and the applied judgment and analysis is always critical, as is a thorough peer review process.

Success = Achieving the Specified Yield at the Target

The discussion of success will begin with general commentary followed by specific issues surrounding yield and target.

<u>Success: General Comments</u>

The purpose of a nuclear weapon is to effectively damage the intended target. It will be

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[2] Note that some anomalies may manifest themselves in multiple locations in the weapon (e.g., solder joint failures). Their cumulative reliability impact should be determined and included in the model. The concern expressed here is that a given anomaly may be included in both the DOE and DoD portions of the model, essentially double-counting the impact. Alternatively, it may not be included in either. Both of these are to be avoided.

successful if the specified yield is achieved at the target. Success can only occur in a small subset of the multi-dimensional time/location/condition space. This is shown in Figure 1 for the example of a bomb. Similar modes of behavior are defined for warheads.

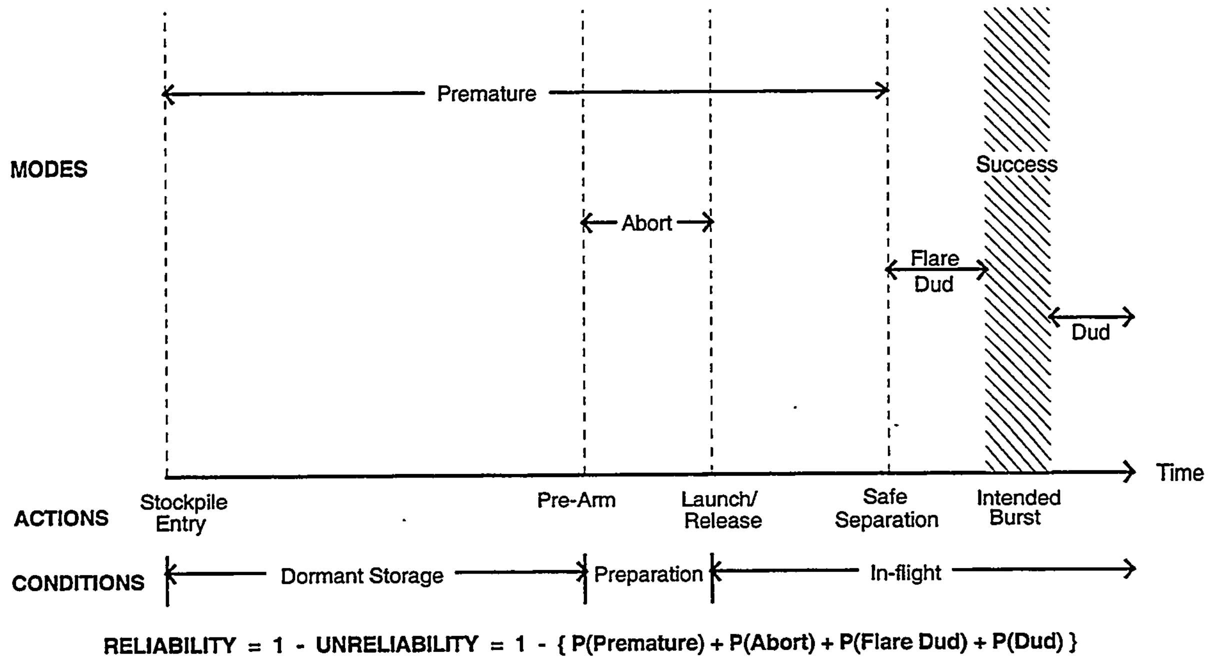

Figure 1: Modes of Weapon Behavior

Figure 1 illustrates the possible modes of weapon performance which are considered in reliability studies in determining the probability of weapon success:

> Premature: An unintended nuclear detonation that occurs in the normal environment prior to safe separation from the carrier.
>
> Abort: Cancellation of use of the weapon, after it is committed to the mission, due to evidence that it would result in a failure.
>
> Flare dud: An early nuclear detonation after safe separation that results in reduced (ineffective) target damage.
>
> Success: Proper detonation with specified yield inside the desired envelope of space (at the target).
>
> Dud: Weapon failure to provide the prescribed function at the proper time, given proper inputs at the time of release/launch or during flight. This can include no/improper or low yield detonation at the target, detonation occurring after the weapon has passed through the desired envelope of space, or detonation occurring to one side of the desired space, due to weapon failure.

As shown in Figure 1, reliability is typically calculated by subtracting the probabilities of non-successful performance (failure) from unity:

$$\text{Reliability} = 1 - \{P(\text{Premature}) + P(\text{Abort}) + P(\text{Flare Dud}) + P(\text{Dud})\}.$$

These general modes of behavior are a collection of all of the weapon contributors to the DE. The weapon may have other functional requirements that contribute to neither the basic weapon intended use nor to the DE. For example, Command Disable (CD) features are required on some weapon systems, and they have separate reliability requirements. Reliability of the CD is the probability of successfully disabling the weapon given the proper command, and premature of the CD is inadvertent disablement in the absence of the command. Premature disablement can result in either a weapon abort or weapon dud and these failure modes are included in the weapon unreliability assessment. However, failure modes that impact the CD reliability rarely affect the weapon's ability to achieve intended yield at the target and thus typically are not contributors to the DOE weapon unreliability assessment.

Included in the description of weapon behaviors is the concept that the weapon must be adequately accurate and provide the specified yield in order to be considered "effective" in damaging the target. Accuracy and yield requirements for weapons are generated by considering the entire set of intended targets and the damage desired, and are defined as discrete quantities with associated error bounds. DOE weapon reliability is an estimate of the probability of proper detonation within these general accuracy and yield requirements. The Probability of Damage term is in essence a conditional probability that estimates, given that the general yield and accuracy requirements are met, what probability of damage is expected for a given target. The Probability of Damage calculation is made with the actual best estimates of expected accuracy (Height of Burst, Circular Error Probable) and yield.

The determination of DOE weapon reliability is made difficult by the fact that fully realistic tests cannot be performed; there are no opportunities to measure both yield and accuracy against a real target. Ideally, target-specific requirements for weapon accuracy and yield could be defined such that fully realistic system test results could be classified unambiguously as either effective or ineffective for the given target (which corresponds to success or failure in the DOE weapon reliability calculation). In reality, formal DOE weapon reliability requirements are specified more generally, as a success probability desired for the overall weapon population without specification of target. Success or failure must be inferred from the test results since there often is not a direct observation of accuracy (e.g., for component-level tests) and currently no direct observations of yield. This inference process starts with the reliability requirements for nuclear weapon hardware designed and produced by the DOE that are contained in the Military Characteristics document, which may also provide a top-level description of success/failure. In order to assess reliability, the Military Characteristics must be further interpreted to be consistently and accurately applied, by both reliability engineers and designers. Usable criteria for success/failure are derived from the design definition drawing package, control drawings, product specifications, and the interface control drawings between the DOE and the DoD. The component level product specification even includes definition of the tests to be conducted and the criteria for acceptance or rejection (i.e., success or failure) of the component. This allows for a reliability assessment of the stockpile based on data taken from a wide variety of tests.

The fact that the Military Characteristics reliability requirements are defined without specification of a target combined with the ambiguity introduced because of the need to infer success/failure means that there is no longer a clear-cut connection between the yield and accuracy requirements and weapon effectiveness against a given target. This results in three regimes, as shown in Figure 2. Effectiveness is shown notionally as a function of different yield and accuracy combinations.

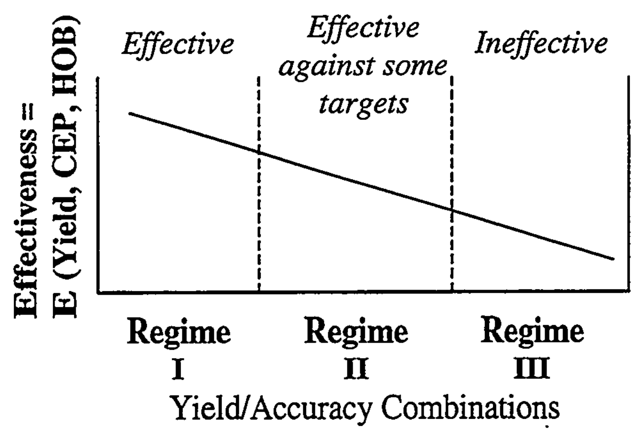

Figure 2: Effectiveness Regimes

For some combinations of yield and accuracy (Regime I), the weapon is considered effective for all targets for which it was designed (success). For other (anomalous) combinations (Regime III), the weapon is considered ineffective for all targets for which it was designed (failure). These regimes lend themselves easily to analysis in the DOE weapon reliability context. Between these two regimes, however, lies a third: a regime where the weapon may still be considered effective under specific conditions (e.g., against certain of its targets). Reliability may not be the best way of reflecting the anomalous behavior in these cases. The nature of an anomaly (e.g., which regime it falls in) and the magnitude of its assessed impact determine the best way to include the effect in the DE (i.e., DOE weapon reliability vs. Probability of Damage). This will be discussed in further detail below for both yield and accuracy. Ensuring complete and consistent evaluation of anomalies can require extensive communication between DOE and DoD. This historically has been the responsibility of the joint reliability working groups, whose members collectively have responsibility for providing all the weapon information required for USSTRATCOM to be able to calculate Damage Expectancy.

Success: "...at the target...."

There are two aspects to "at the target" for DOE weapon reliability. The first takes a broad view of weapon failure; i.e. does the weapon fail to function in the effective vicinity of the target? This addresses situations where the weapon fails to function or functions correctly but at a distance so far from the target that it is ineffective. This is a Regime III situation, and the cause of the weapon failure should be accounted for in the DOE weapon reliability term.

The second aspect of "at the target" is a narrower view focused on the ability of the weapon to detonate at exactly the right place. When thinking about "at the target" in this narrower sense, we generally use the term accuracy. Accuracy is defined in the context of a window of space, encompassing both distance from the target, Circular Error Probable (CEP) and Height of Burst (HOB). The weapon must detonate within this window of space to achieve the desired damage. When a weapon functions close to the target (but not "at the target"), the means of including the anomaly in the DE term can vary depending on the circumstances since the weapon may still be effective against some targets (Regime II).

The DoD approach to the CEP calculation is to exclude any subset of weapon systems that miss the target by unusually large distances and assess their behavior separately as weapon system reliability failures. The cause of these failures is generally different from the factors that cause the normal miss distances. Including these data in the CEP calculation could significantly distort the estimates of Probability of Damage. The DOE assessment approach is consistent with the DoD's — that is, weapon component anomalies that result in large miss distances are included in the DOE weapon reliability assessment. A historical case of radar premature failure provides an example. An unanticipated radar defect (caused by particles in a transistor) caused the system to prematurely fire, resulting in a HOB much higher than considered acceptable for the system. This defect was assessed in the reliability model as a system flare dud and required a new radar premature failure event to be defined. This allowed the DoD to continue to calculate a very accurate HOB and still appropriately address a defect that can cause significant burst height inaccuracies in a small fraction of the stockpile. This example, and other accuracy related examples, have been the subjects of discussion at the appropriate weapon reliability working group meetings, to ensure the reliability community understands and agrees to how the defect is being assessed.

It is impossible to predict what other anomalies related to accuracy we will need to address in the future. The reliability working groups — Quality Assurance and Reliability Subcommittee (QARSC) for the Navy and Safety and Reliability (S&R) subgroups for the Air Force — are formal, joint, well-established forums that have and can continue to address such surprises on a case-by-case basis. Two distinct cases are discussed below, to illustrate some general criteria to be considered for such anomalies.

Case 1: Accuracy Degradation (vs. Catastrophic Miss) Due to DOE Hardware Anomalies

In Regimes I and III, test outcomes can be classified as either success or failure. A difficulty is encountered when a system demonstrates degraded accuracy but not out-and-out failure (Regime II). The degradation may be such that the weapon is still considered effective and usable against certain targets but doesn't meet the fuze accuracy requirements. In this case accuracy impacts may best be captured via the DoD Probability of Damage metric (through changes in either HOB or CEP) rather than the DOE weapon reliability term, even though the source of the problem may be due to DOE hardware. An example of this might be a single-event upset anomaly that causes a programmer memory bit to change state, resulting in a modest degradation to HOB. Because weapons with this anomaly might still be considered usable, it would be more appropriate to change the HOB (and hence Probability of Damage) rather than reducing the overall system reliability. In effect, the requirement against which the reliability function is judged is changed and must be thoroughly documented. In general, catastrophic accuracy problems due to DOE hardware anomalies are best reported through DOE weapon reliability, while degradations that still allow for effective functioning are best reported through Probability of Damage.

Case 2: Accuracy Anomaly Due to Combined DOE and DoD Hardware

There can arise circumstances where quantification of the anomaly impact may require consideration of both DOE and DoD hardware, even though the root cause is DOE hardware. While the probability of a particular DOE phenomenon may be easily calculated, the conditional probability (probability of system failure given occurrence of the phenomenon) may be a very complicated problem requiring analysis of the synergistic effects of DOE and DoD hardware. An example of this might be electrical noise generated by SNL-designed firing set charging circuitry that affects the DoD contractor-designed guidance control for a cruise missile. These situations must be worked jointly between the DoD and DOE on a case-by-case basis to identify the appropriate DE term to capture the impact of the anomaly, any key conditional probabilities, and the agencies best positioned to quantify them.

These cases do not cover the range of ambiguous situations that may arise due to accuracy anomalies. However, in every instance it is important to keep in mind the overall goal of providing a quantitative metric that reflects the ability of the weapons to perform their intended function irrespective of where the problem occurs. Anomalies must be accounted for once and only once in the overall DOE/DoD model.

Due to ambiguous documentation, there has been confusion as to whether accuracy-related anomalies have always been considered in DOE weapon reliability assessments. Beginning in March of 1971 a definition of reliability was included in the DOE Weapons Reliability Report. This definition did not explicitly include "at the target" even though the actual reliability models included certain accuracy-related failure events. The definition did include the phrase "in use" which could be interpreted to imply "at the target". A more explicit definition was included in the report published in November of 1996, which did specify "at the target". However, this clarification was interpreted by some to be a change in policy and led some members of the weapons community to believe that reliability impacts due to accuracy had not been included previously. However, all historical material (including the DOE-approved "Nuclear Weapon Reliability Evaluation Methodology Guide") indicates that the reliability definition, as well as the actual models, includes certain accuracy-related events. A list of these failure events for weapons currently in the stockpile is shown in Appendix E.

<u>Success: "...achieving the specified yield..."</u>

"Achieving the specified yield" has historically been understood to mean nominal yield with an allowable variability of ten percent, although other ranges may be specified. In some instances, a separate requirement for the probability of exceeding the specified yield may be defined. As discussed earlier, yield, like accuracy, is an inherent part of DOE weapon reliability: if the weapon detonates at the target with such reduced yield that it is ineffective against the target, then it is a weapon failure. Determining whether a yield anomaly is better accounted for in the DOE weapon reliability term or the Probability of Damage term depends on the specific circumstances. A hypothetical example might be gaps in the nuclear package that cause a 20% reduction of the yield for the affected units. This could be accounted for in the Probability of Damage if a set of required targets is still held at risk with the decreased expected yield. As with the accuracy example above, the requirement for success against which the reliability function is judged is in essence changed for these units and must be thoroughly documented. An example for which reliability might be a better metric is catastrophic failure of a gas transfer system (GTS) to function, resulting in an ineffective yield. The probability of failure of the GTS would be a part of the DOE weapon reliability metric, which in turn is included in the Weapon System Reliability. The same rule of thumb is applicable for yield as for accuracy: catastrophic degradations in yield are best handled via DOE weapon reliability, while degradations, if still effective, should be considered as part of the Probability of Damage calculation. Again, anomalies must be accounted for once and only once in the overall DOE/DoD model.

Note that the more understanding there is of the anomaly and its consequences, the more likely it is that a clear determination can be made of the weapon's effectiveness under various scenarios, which in turn gives USSTRATCOM more latitude in defining valid SIOP alternatives. Lack of knowledge might drive the community to consider an ill-understood degradation as a catastrophic failure, even though in some circumstances and for some targets the weapons might still be effective.

Environment = Across the STS Environments, Assuming Proper Inputs

The discussion about environment will focus first on the STS environments followed by a discussion about proper inputs.

Environment: "... across the STS environments..."

One of the important elements of the definition of reliability is the set of environments to be considered. Nuclear weapons have specified environments they must survive and still be capable of successful operation. These are the normal environments of the Stockpile to Target Sequence (STS), and it is assumed that they are not exceeded. It is impossible to quantify the probabilities of weapons being exposed to various combinations of environments or the amount of time they may be exposed to these environments over the entire lifetime of the weapons. Even if this environmental characterization were possible, there is not enough data available to quantify the probability of weapon success as a function of these environmental conditions. Finally, it is generally not possible to select or control the environmental conditions present in the event of actual operational use. Thus we make a bounding assumption that weapons may be exposed to any of the set of conditions up to and including the extremes of the STS sometime during storage or operational use. The probability of success may be different depending on the environments to which the weapons have been exposed. The DOE reliability reflects a realistic lower bound of the probability of success no matter what the environmental conditions are, as long as they are within the envelope of the normal STS environments. Note that the worst case environments may not necessarily be at the extremes of the STS. The lower bound of the probability of success is used even if some of those environmental conditions are considered less likely than others or are mutually exclusive. For example, test data may indicate the lower bound of reliability for a weapon's firing set occurs at high temperature while the lower bound for its programmer occurs at low temperature. Each of these lower bounds is used in the reliability estimate for the weapon. This helps ensure that the assessment is a conservative point estimate across all possible sets of environments as specified by the STS. This approach is necessary since the conditions often cannot be controlled by the user. One practical consequence of this assumption is that, in order to make statements applicable over the range of STS environments, it is necessary to conduct tests that sufficiently envelope those same environments.

Environment: "... assuming proper inputs..."

For DOE hardware to operate successfully, certain pre-arming signals and information may be provided by the DoD to the DOE weapon. The reliability evaluation of the DOE weapon assumes these supplied inputs are present and correct. Additionally, certain required position and inertial conditions are dependent upon the delivery vehicle performance (missile or aircraft); these are also assumed to be proper. Failure to receive these inputs indicates a failure in DoD operations or hardware, which is assessed in other DE terms. Being able to determine the cause of a system test anomaly is critical to the fidelity of the overall nuclear weapon DE calculation. Accounting for an anomaly in an inappropriate term in DE (or even within Weapon Reliability) or mistakenly assuming that a problem affects the entire stockpile when it only affects a subpopulation can significantly impact the DE estimate. All test configurations have limitations in their capability to identify the root cause of failure, to widely varying degrees. For example, the uninstrumented flight test program, which intentionally precludes inclusion of monitors to provide the most realistic test possible, can result in an inability to determine where in the overall DOE/DoD system an anomaly occurred. Careful tradeoffs must be made between the relative value of a test configuration and its ability to provide useful reliability and diagnostic information when determining the allocation of test assets.

Timeframe = Throughout the Weapon's Lifetime

Including lifetime as a factor in the reliability definition has both historical and practical bases. As mentioned earlier, academic definitions always include consideration of a specified time period (typically operational life). For nuclear weapons, the operational times are short but the dormant storage times can be very long and this is often the timeframe of concern. One can also think of lifetime not in terms of years but in terms of environmental or operational cycles or exposures. Decisions about how to address identified component aging phenomenon are implicitly affected by what is considered to be the weapon lifetime. Using reliability as a planning tool for addressing aging phenomena is meaningless without an a priori definition of lifetime. In this section, "weapon lifetime" is defined as the original lifetime objective as specified at the time of design. The current enduring stockpile weapons either have, or will eventually, exceed their weapon lifetimes based on current Production and Planning Directive projections. What implications does this have for the reliability definition, and in fact what has the weapon lifetime statement traditionally meant?

Inherent in the statement of "throughout the weapon's lifetime" is that we are projecting reliability through the end of life. That is, based on our knowledge today, we believe that the reliability assessment that we give now will be valid in one year, two years, five years, etc. until the end of the weapon lifetime. In cases where there are known component aging problems with a well-characterized failure rate, we provide for a Limited Life Component Exchange such that weapon performance (and hence reliability) is not affected by that particular component up through end of the weapon lifetime.

In the past our ability to project reliability assessments into the future has been primarily based on design and qualification activities. During the weapon design process, certain specialized parts and materials are selected on the basis of expected stability throughout the weapon lifetime (e.g., o-rings, lubricants), although generally speaking designers do not design electronics to meet a given lifetime. Components are validated for a certain weapon lifetime through a qualification test program. This includes accelerated aging as well as product acceptance Environmental and Destructive (E- and D-) tests featuring operation at one or more environmental extremes (temperature cycling, vibration, etc.). The number of temperature cycles and the type of mechanical tests are to some degree determined by considerations of weapon lifetime. Conversely, weapon lifetime can be thought of in terms of the number of cycles for which a component has been qualified. The qualification process is our avenue for attempting to identify time-dependent phenomena that might cause the reliability to change as a function of time or environmental cycles. Component failures detected during the course of environmental cycling are included in the assessment in order to estimate the component reliability at the end of the weapon lifetime. This reliability assessment is considered to be a realistic lower bound throughout the weapon lifetime.

Because we recognize that we may not be able to predict all time-dependent failure mechanisms, we have an on-going stockpile surveillance test program to continue to look for unknown aging problems. We cannot eliminate the risk of aging, but we can mitigate it by continuing to search for defects over the weapon lifetime. When unanticipated aging anomalies are detected, the ideal approach is to characterize how component performance (and reliability) changes with time. As long as this aging phenomenon affects the stockpile, the current reliability of the component is tracked through periodic updates. When it is impossible to explicitly quantify reliability as a function of time or number of exposures, an estimate is made of the reliability of the component at the end of its life for use as a bound. In such cases we do not calculate or report weapon reliability as a function of time, but may include snapshot assessments for specific components.

While in recent years design and qualification have been the foundations of making weapon lifetime statements, it is acknowledged that some older weapon systems lacked formal lifetime goals. Even for those with lifetime goals, designers were constrained by the knowledge and components of their era and were not necessarily able to assure that weapon lifetime goals would be met. Weapon systems have rarely been in the field for their entire specified life, restricting the amount of relevant data we have been able to obtain on component lifetime-limiting aging mechanisms. In general, it is recognized that projective reliability (assessments that are projected into the future) are not founded on complete knowledge, necessitating an on-going test program. This has sometimes led to the misconception that the DOE weapon reliability assessments are "only good until the next test (or the next periodic assessment) — why else do we need to continue testing?" In actuality, the design and qualification processes lay the foundation for predicting that the current assessment will be applicable until the end of the weapon life. The on-going testing looks for deviations from the qualified design predictions and helps provide improved estimates of known aging mechanisms.

This approach to reliability is different from much of industry but vital to how we have historically implemented stockpile stewardship. It is made possible by the engineering processes that we use to design, produce, test, and maintain nuclear weapons throughout their lives. Key elements of this process are formal qualification, extensive product acceptance testing, planned limited life component exchanges, and an on-going surveillance program. As weapon lifetimes are exceeded, the test data collected early in the life of the weapon may have less relevance. New Material and Stockpile lab tests serve primarily a status monitoring role and may not be the best indicators of aging. Increased uncertainty in the reliability assessment is expected as the weapon lifetime is extended because of dormant storage aging as well as the potential for additional environmental cycles or exposures (or numbers of operations in some cases) beyond those originally anticipated. Because of the increasing potential for unexpected aging problems, the Sandia reliability assessment community cannot support assessments that are projected into the future indefinitely beyond the weapon lifetime. This is the second common misconception related to applicable timeframe of nuclear weapon reliability assessments: that since the definition states "throughout the lifetime", current reliability assessments can be assumed to continue to apply as the DoD extends the planned stockpile life ever further beyond the original weapon lifetime.

As weapon lifetimes are exceeded, we face a new paradigm in reliability assessment and the underlying engineering processes that support it. A new approach must be formulated to provide a reasonable and substantiated timeframe over which reliability assessments can be projected for planning and stockpile management purposes. Several elements are already in place, such as the Core and Enhanced Surveillance programs, although some of them may need expansion or change in focus. Others, such as modeling and simulation and trends analysis, will also need to be integrated into the overall approach to create a robust set of engineering processes to support future reliability assessments for the enduring stockpile.

Estimating Uncertainty

While not directly related to the definition of reliability, uncertainty has long been a focal point of discussion and debate in the nuclear weapon reliability community. Two aspects of uncertainty are discussed below. The first is the uncertainty in reliability assessments due to limitations in the amount of data obtained through the suite of tests that are performed over the lifetime of the weapon. Although statistical methods could be used to quantify this type of uncertainty, it generally has not been done for DOE nuclear weapon assessments. This will be discussed in more detail below.

The second aspect is that of the uncertainty due to the failure to gather sufficient amounts of relevant recent test data on a potentially changing product (e.g., via aging). This is referred to as defect detection uncertainty. Note that this uncertainty underscores the relationship between the reliability assessment process and the engineering processes that support it. An on-going test program is the foundation for finding new or changing problems in the stockpile that affect the assessed reliability. Inadequate recent testing (in terms of either quantity of tests or the defect detection capability of the tests) results in an inability to detect these defects. The goal of reporting uncertainty is to provide a decision-making and communication tool to the DOE and DoD to aid in using the reliability information given the nature and degree of the test shortfalls.

Both of these aspects of uncertainty should be differentiated from the long-standing use of confidence limits with respect to surveillance sample sizing policy. The current DOE nuclear weapon surveillance program sizing policy is commonly described as "90/90/2". The policy is to select enough samples to detect a 10% problem with 90% confidence in a two-year period and equates to eleven samples per year for sufficiently large populations. Such a statistical statement carries with it numerous underlying assumptions about the sampling process (random with replacement), the population being sampled (homogeneous and unchanging with time), and the means of detecting problems (all tests are equally capable of detecting the anomalies present in the population). Experience has shown that these assumptions are not entirely valid for the DOE nuclear weapon surveillance program. The "90/90/2" statement defines the surveillance sample size and has been shown to be an effective policy. It is, however, inappropriate to consider the 90/90/2 nuclear weapon surveillance sizing statement as providing a confidence limit on the reliability assessment; the "90/90/2" statement only describes a theoretical defect detection capability in the absence of the constraints and realities of the nuclear weapon program.

Reliability and Confidence Limits

In the early days of the stockpile evaluation program, both a reliability number (based primarily on lab test results through the end of production) and a statistical confidence limit (based strictly on quantities of a single type of stockpile laboratory test) were reported[3]. The mid-sixties brought recognition of the importance of a diversified testing program in detecting defects and the role of engineering judgment in determining what data are relevant. Test program diversification greatly enhanced our ability to detect stockpile defects but also increased the challenge of assessment because of the need to combine data obtained from widely varying sources and taken under a variety of conditions. We also ended the practice of calculating and reporting confidence limits at this time. To quote from the 1980 Stanley Love report, "Although experience had shown that test data from various sources can be combined meaningfully, it was decided that system reliability would be reported without confidence intervals. No sound statistical approach exists for measuring uncertainties associated with the subjective combining of data; confidence limits could only be a measure of sampling variability, and it was considered desirable to avoid implying that uncertainties in judgments had also been measured." Love also notes, "... misunderstandings were being created by providing DoD with two sets of numbers to describe stockpile quality, that is, figures describing individual systems reliability that were included in the final weapon development reports but were changed only if test results warranted, and statistical confidence limits attached to periodic functionability statements issued by QASL [Quality Assurance, Sandia Laboratory]."

Requests to provide confidence limits on nuclear weapon reliability assessments resurface periodically; however, the preceding counter-arguments remain valid. While confidence limits can help gauge the amount of data supporting an assessment value, they may not include other potentially large sources of uncertainty; hence they can be very misleading. The issue of confidence limits was most recently examined in 1996, when the Nuclear Weapon Requirements Working Group (NWRWG) recommended that USSTRATCOM review their need for error bars or confidence limits for DOE weapon reliability numbers. In a series of interchanges between the NWRWG, USSTRATCOM, DOE, and Sandia, the DoD community reached accord yet again on the current policy of not requiring or desiring confidence limits[4].

Reliability and Defect Detection Uncertainty

While an overarching statement of statistical confidence for reliability assessments is not

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[3] Love, Stanley L., "A History of Stockpile Quality Assurance at Sandia Laboratories", SAND79-0696, February 1980.

[4] "Draft NWRWG Memorandum for the Record (MFR)", June 4, 1997 Meeting of the Nuclear Weapons Requirements Working Group (NWRWG), dated July 14, 1997.

merited, there are factors that dictate other forms of uncertainty statements. As discussed earlier in the time frame section, adequate recent test data are needed to substantiate the continued validity of reliability assessments based mostly on tests performed early in the life of the weapon. Inadequate on-going testing, in terms of both test diversification and total numbers in a recent time span, increase the risk of undetected, potentially worsening defects in the stockpile. This is an additional source of uncertainty in the DOE weapon reliability assessment.

As far back as 1967, reliability has been withheld for weapon systems in the DOE Weapons Reliability Report (WRR) due to gaps in stockpile surveillance system or component testing. In 1974, testing limitations began to be specifically addressed in the WRR on a weapon-by-weapon basis. In 1984, a policy appears to have been formalized such that two-year gaps in system testing (both lab and flight) would result in reliability being withheld. For weapons with reduced testing, increased uncertainty in the reliability assessment was noted. In 1989, the first instance of withholding reliability due to component test gaps occurred (note however that this was triggered by a specific anomaly about which inadequate information existed to make an assessment). In 1991, an explicit policy of withholding reliability for weapons without flight tests in the past three years was adopted by DOE/AL and documented in the DOE Weapons Reliability Report. This was modified to a two-year gap in 1992. Also in 1992, increased uncertainty due to a component test gap was first reported. Since that time component test gaps of three years or more have resulted in the reporting of increased uncertainty[5].

While the policy of withholding reliability made the customer aware of the test gap, it did not effectively convey the degree of concern, nor did it provide the needed reliability information for USSTRATCOM's on-going targeting responsibility. Withholding the reliability assessment clearly expresses our concern that reliability changes could be going undetected during the lapse of testing. However, this approach does nothing to convey the level of uncertainty and does not convey our known best estimate of the reliability.

The most recent advance in this area has been to define a new defect detection uncertainty metric to be reported in addition to the reliability estimate. The intent of this uncertainty metric is to measure the potential for new defects to go undetected in a specified time frame (both aging defects and those newly introduced). The metric quantifies the decrease in defect detection capability and can be calculated separately for reductions in the system or component test programs. It is not intended to be a substitute for the reliability assessment value; rather, it provides a proactive tool for timely coordination and decision-making internally and with the DoD. Test resources have become increasingly constrained over the past ten years for both DOE and DoD, and both face shortfalls in test assets and surveillance program funding. Coordination between DOE, USSTRATCOM, and the Air Force and Navy Nuclear Weapon Commands to develop a consistent approach for characterizing and reporting uncertainty would aid balanced prioritization and decision-making at the weapon system level.

The goal of the uncertainty statement or metric is to provide as much information as possible to the DOE and DoD users while conveying to them the potential for undetected defects due to lack

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[5] For a detailed account of the history of defect detection uncertainty, see "Historic Responses to Test Shortfalls and Gaps by the Sandia Reliability Assessment Community", R.L. Bierbaum to Distribution, December 1, 1998.

of testing. The focus of uncertainty characterization in this context is to understand the potential for new defects to go undetected in a specified time frame. The emphasis is on shortages in individual test programs rather than in the test database as a whole. This recognizes the criticality of each element of the diversified test program (lab, flight, and component) in ensuring realistic reliability assessments and timely defect detection.

Summary

DOE weapon reliability is defined as:

> *The probability of achieving the specified yield, at the target, across the Stockpile To Target Sequence of environments, throughout the weapon's lifetime, assuming proper inputs.*

This definition contains the five elements found from a review of reliability literature sources to be necessary and sufficient for any general reliability definition:

1. the probability measure
2. the item of interest
3. the meaning of success
4. the environment to which the item may be exposed
5. the appropriate timeframe

Inclusion of each of these elements in the DOE weapon reliability definition is required to ensure that complete, useful, and realistic performance assessment information is used in USSTRATCOM targeting and DoD/DOE stockpile management actions.

Proper interpretation and application of this definition requires development of detailed success/failure definitions at subassembly and component levels. Some of the key principles to appropriate implementation of nuclear weapons reliability assessment include ensuring:

- adequate understanding of each stockpile defect and its system consequences
- robust, ongoing programs in diversified surveillance and engineering analysis for potential failure mechanisms, including aging and introduced changes
- a process that accounts for each defect type once and only once in the USSTRATCOM Damage Expectancy calculations

This paper provides insight into these principles by discussing real and hypothetical issues that can arise. Resolution of these issues requires a consistent methodological framework, expert engineering judgment, and ongoing, proactive communication and peer review with all DOE and DoD design and analysis counterparts. Documentation of the data and the applied judgment and analysis is an important part of the assessment process, helping lay the foundation for good communication, consistency, and proper incorporation of new information in the future.

Additional reliability-related challenges exist in the areas of reliability assessment timeframe and uncertainty. As multiple weapon types age beyond their original lifetimes, the appropriate assessment timeframe will require careful definition and additional focused engineering analysis. The recent occurrence and high future likelihood of significant test program shortfalls compels the development of a second reliability metric, a defect detection uncertainty metric, to track the relative level of this uncertainty associated with the weapon reliability assessment.

ACRONYM LIST

CD	Command Disable
CEP	Circular Error Probable
CINCSTRAT	Commander-in-Chief, United States Strategic Command
DE	Damage Expectancy
DoD	Department of Defense
DOE	Department of Energy
D-test	Destructive test
E-test	Environmental test
GTS	Gas transfer system
HOB	Height of Burst
MC	Major Component
MFR	Memorandum for the Record
NWCSSC	Nuclear Weapon Council Standing and Safety Committee
NWRWG	Nuclear Weapon Requirements Working Group
PD	Probability of Damage
QARSC	Quality Assurance and Reliability Subcommittee
QASL	Quality Assurance, Sandia Laboratory
SAG	Strategic Advisory Group
SIOP	Single Integrated Operational Plan
SNL	Sandia National Laboratories
S&R	Safety and Reliability
STS	Stockpile to Target Sequence
USSTRATCOM	United States Strategic Command
WRR	Weapons Reliability Report
WSR	Weapon System Reliability

Appendix A: Reliability Definition Charts

Concern for consequences of nuclear weapon "failures" has historically driven the approach to classifying performance.

- **Premature detonation**
  An unintended nuclear detonation that occurs in the normal environment prior to safe separation from the carrier
- **Abort**
  Cancellation of use of the weapon, after it is committed to the mission, due to evidence that it would result in failure
- **Flare dud**
  An early nuclear detonation after safe separation that results in reduced (ineffective) target damage
- **Dud**
  Weapon failure to provide the prescribed function at the proper time, given proper inputs at the time of release/launch or during flight

(This example uses bomb modes of behavior. Similar modes are defined for warheads.)

Proper classification requires defining the weapon's tactical objectives.

Objectives vary from target to target.

- **Parameters considered include fuzing accuracy, delivery accuracy, and safety of friendly forces which may be in the vicinity.**
- **Fuzing and delivery accuracy requirements are a function of weapon yield, nature of the target, damage desired, and nature of the weapon effect to be employed.**
  - Required accuracies must be defined so that the burst locations can be classified as either proper or ineffective (i.e., reliability success or failure).
  - Deviations in actual accuracy and yield still considered "effective" are accounted for through revised Probability of Damage calculations.

DOE Warhead/Bomb Reliability (1 of 2)

- **Definition:**

"The probability of achieving:

at least the desired yield,
at the target,
across the Stockpile To Target Sequence environments,
throughout the weapon's lifetime".

- **Conditions:**
  - the specified inputs and conditions at the interfaces are present.
  - the normal environments specified by the STS have not been exceeded.
  - the specified lifetime has not been exceeded.

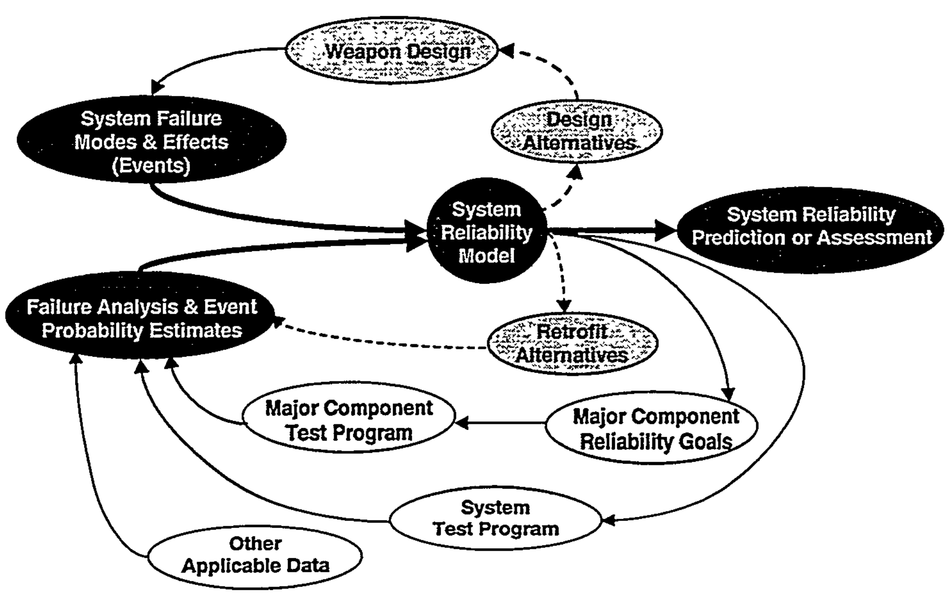
DOE Warhead/Bomb Reliability (2 of 2)

- **Unreliability = 1 - Reliability**
  - Unreliability includes Premature + Abort + Flare Dud + Dud
- **Basis for Assessments:**
  - Valid data from well-designed tests.
- **Intent:**
  - Realistic lower bound

Reliability Assessment Methodology Overview

- **Identify the potential sources of failure in the DOE hardware (failure events -- defined at the component or subsystem level).**
- **Define math model to relate failure events to overall system performance (yield at the target).**
- **Use relevant data to estimate (lifetime) failure probabilities:**
  - Hardware representative of stockpile.
  - Conditions encompassing STS environments and realistic interfaces
  - Includes combinations of System, Subsystem, and Component level tests.
  - Requires ongoing data-source consistency reviews at component and system levels.
- **Update model and assessment periodically and as new defects are discovered.**
- **Assure completeness, accuracy, and consistency through peer reviews.**
  - Continuous internal technical reviews.
  - Periodic reviews with Sandia, LANL/LLNL, DOE, and DoD customers.

The Reliability Analysis Process is Integrated into the Weapon Life Cycle



Appendix B: Nuclear Weapon Reliability Definition[6]

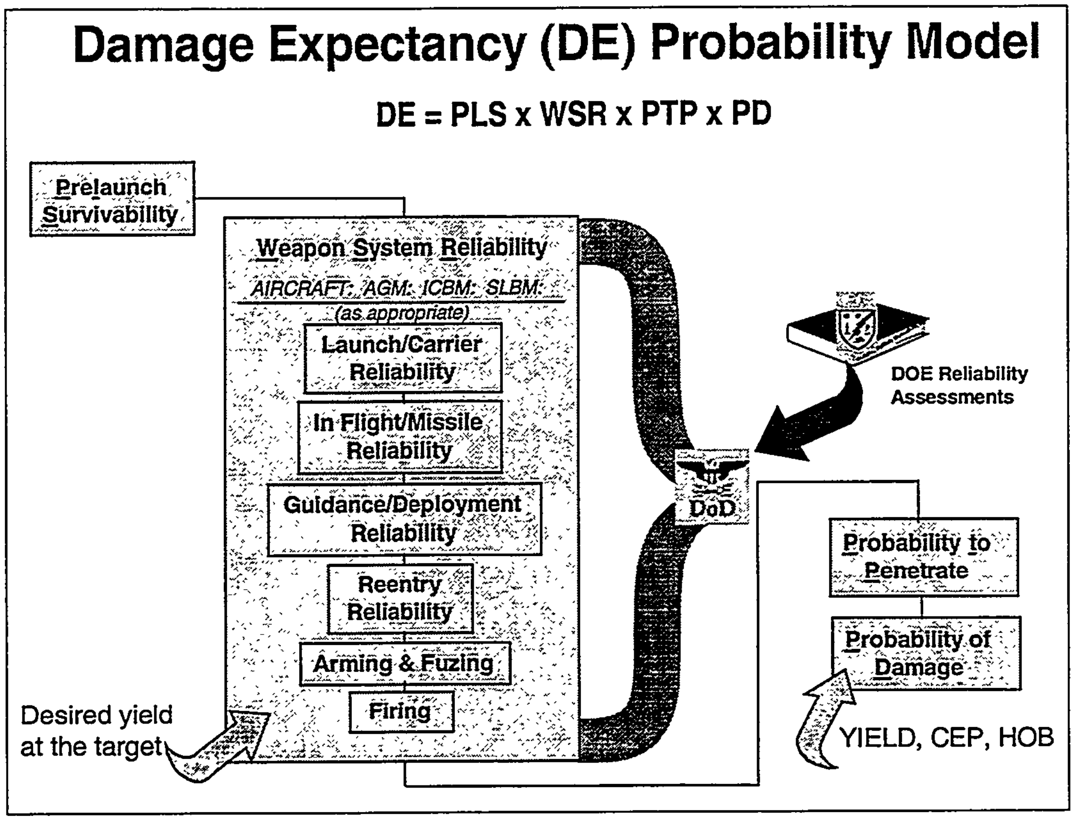
"Weapon reliability is generally defined as the probability that, in use, detonation at the specified yield will occur at the target through either the primary or any backup modes of operation. This general reliability definition is tailored to address weapon-specific performance and functional requirements and is documented in the periodic assessment reports for each weapon type.

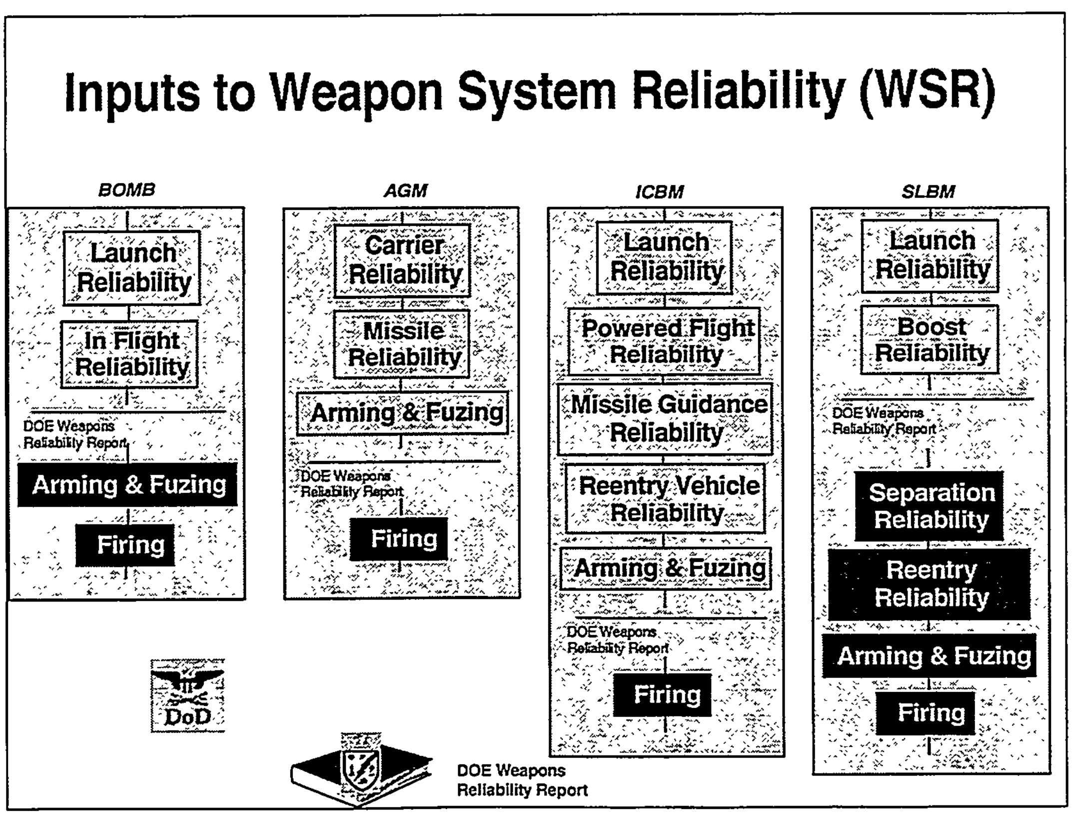
In some cases, DOE hardware performance which impacts the overall system effectiveness may more appropriately be included in the system damage expectancy calculation through other terms (e.g., delivery system assessment or probability of damage terms), rather than directly in the DOE reliability assessment term. Details may be reported through other channels.

Reliability assessments assume that specified inputs and conditions at the DOE/DoD interfaces are proper. These include all aircraft, adaption kit, or fuze input signals in all channels and specified environmental conditions. Premature detonation is considered a dud. Because of the wide spectrum of weapon deployments and potential use conditions, the reliability assessments are not restricted to nominal conditions and age. Therefore, unless otherwise stated, the reliability assessments in this report represent realistic lower bound estimates that apply over the normal environments of the Stockpile-to-Target Sequence as referenced in the latest applicable Major Assembly Release, including exceptions and limitations stated therein. These assessments are assumed applicable throughout the remaining intended stockpile life, unless otherwise specified. The intended stockpile life for each nuclear weapon type is that established in the latest issue of the Long-Range Planning Assessment/Nuclear Weapon Stockpile Memorandum. If significant age-related degradation is identified, discussion of the expected reliability degradation is included."

[6] May 1998 DOE Weapons Reliability Report (U), AL176.

Appendix C: Damage Expectancy





Appendix D: Reliability Definition References

1. Leemis, Lawrence M., "Annual Reliability and Maintainability Symposium 1997 Tutorial Notes", page 1.
   "The reliability of an item is the probability that it will adequately perform its specified purpose for a specified period of time under specified environmental conditions."

2. Healy, John D., "Annual Reliability and Maintainability Symposium 1997 Tutorial Notes", page 1.
   "Reliability is the probability that a device will operate successfully for a specified period of time and under specified conditions when used in the manner and for the purpose intended."

3. Kapur, K.C. and Lamberson, L.R., "Reliability in Engineering Design", page 1.
   "The reliability of a system is the probability that, when operating under stated environmental conditions, the system will perform its intended function adequately for a specified interval of time."

4. Bazovsky, T., "Reliability Theory and Practice", page 11.
   "Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered."

5. Klinger, D., Nakada, Y., and Menendez, M., "AT&T Reliability Manual", page 2.
   "Reliability is the ability of an item to perform a required function under stated conditions for a stated period of time."

6. Breipohl, Arthur M., "Probabilistic Systems Analysis", page 47.
   "Reliability is the probability of success in the use environment."

7. O'Connor, Patrick D. T., "Practical Reliability Engineering", page xviii.
   "Reliability: The ability of an item to perform a required function under stated conditions for a stated period of time. (British Standard 4778)"

8. Lloyd, David K. and Lipow, Myron, "Reliability: Management, Methods, and Mathematics", page 20.
   "Reliability is defined as the probability of successful operation of the device in the manner and under the conditions of intended customer use."

9. Gryna, Frank M., editor, "Reliability Training Text", Institute of Radio Engineers, page 2.
   "Reliability is the probability of performing without failure a specified function under given conditions for a specified period of time. It is worthwhile to emphasize the basic elements required for an adequate definition of reliability: a. Numerical value of probability. b. Statement defining successful product performance. c. Statement defining the environment in which the equipment must operate. d. Statement of the required operating time."

Appendix E: Events in Existing DOE Weapon Reliability Models Addressing "At the Target"

	Flare Dud			Height of Burst				Delivery	
Weapon	**Sprytron**	**Prearm/Fire Short Circuits**	**Programmer/ Sequencer**	**Radar**	**Timer/ Selector**	**FBIA**	**Programmer/ Sequencer**	**Para-chute**	**Spin Motor**
B61	J6		J6	J6,J8,K17	K4,K5		K3,K4,K13,K18	J3	J3
W62		Pi							
W76	E028Q1		E898X5	E823F	BHOHL				
W78		P7C							
W80	g, e	f							
B83	JPi17A		Various	JPi17B			Various	J12	J11
W87	J5.2								
W88	C28		C9	F4R1E	F1	C36			

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