REMANUFACTURE

Study Leader
S. Drell
R. Jeanloz

Contributors Include:
J. Cornwall
P. Dimatokis
F. Dyson
R. Garwin
J. Katz
S. Koonin
R. LeLevier
W. Panofsky
B. Peurifoy
R. Schwitters
S. Treiman
E. Williams

JSR-99-300

October 1999

The MITRE Corporation
JASON Program Office
1820 Dolley Madison Blvd
McLean, Virginia 22102
(703) 883-6997

Contents

1 SUMMARY

A review of the current progress and plans associated with the remanufacturing of nuclear-weapon components within the DOE's Stockpile Stewardship Program (SSP) leads to the following conclusions and recommendations.

1. We commend LANL and Y-12 for their successes in initiating the remanufacture of, respectively, primaries and secondaries. The progress to date gives confidence that both of these key components of the nuclear package can be remanufactured, and that the low production level currently being planned for remanufacturing can be sustained over the coming years.

2. There is little evidence of an overall plan having been worked out for the *long-term* production needs and capabilities under the SSP, including i) the consideration of various scenarios for the steady-state size of the stockpile; ii) determinations of steady-state remanufacturing capabilities required on a component-by-component basis; iii) the implications for key facilities and personnel of long-term component needs (where are the bottlenecks, both under steady-state and if any surge capability is ever required?); and iv) the detailed mechanism by which data from the Enhanced Surveillance Program (ESP) will feed back into the prioritization of remanufacturing processes. A highly simplified example of the kinds of analyses that must be extensively pursued is given in Section 4.4.2.

3. The ESP database is not being analyzed thoroughly enough and kept up to date in a timely enough manner to influence the planning of remanufacturing to the degree that is needed. More detailed and complete analyses of the type presented in Section 4.4.1 must be pursued vigorously. These demonstrate the importance on putting special emphasis in preferentially sampling the oldest weapons of each type. Possible problems due to HE ag-

ing require particular emphasis because they may arise more rapidly than, for example, problems due to pit aging.

4. Multi-component and system-level testing on the ground should have high priority in order to catch problems due either to aging or to newly produced parts. The rapid re-establishment of AAU testing at Pantex, which is currently on hold, is considered a high priority.

5. Increased uncertainty that may arise from unanticipated and unknown processes caused either by aging or by remanufacture can be partially, and perhaps entirely, mitigated by enhancing performance margins on key weapon types.

6. It is essential that a science-based process of planning, development and implementation be used throughout the new program of remanufacturing. This scientific foundation is important, both to ensure the highest likelihood of success and to engage (and therefore retain) the best personnel. Close interaction between the labs and the production plants should be increased, for example. We commend the development of enhanced electronic communication between relevant parties in the weapon labs and plants; this effort should be maintained if not enhanced. The training of new staff can be used to test the success with which knowledge of production processes is being documented and archived.

2 NEEDS AND OPPORTUNITIES IN REMANUFACTURE

The reconstitution of DOE remanufacturing takes place within the commitment to Science-Based Stockpile Stewardship (SBSS), and in an environment of the CTBT. The purpose of remanufacture is to maintain a safe and reliable stockpile of nuclear devices, together with their non-nuclear components that constitute a nuclear warhead.

In reducing the number of plants and labs involved in remanufacture, DOE is taking the opportunity to modernize the manufacturing operation, to bring further discipline to the activity, and to preserve the knowledge involved, so the product can be remanufactured for decades without unintentional change. Except for the nuclear weapon primary and the canned secondary assembly (CSA), all of the parts of the weapon can be tested in a CTBT environment just as well as they could have been previously. They are not constrained against change by a CTBT, but if they are changed in process or product they must be certified as to correct function. TA-55 is well on its way to producing its first pit, given this new responsibility for Los Alamos; and Y-12 at Oak Ridge has recently manufactured its first CSAs under the new regime. Non-nuclear components are manufactured at the Kansas City plant, and neutron generators and the Arming, Fuzing, and Firing (AFF) sets are the responsibility of Sandia.

The nuclear weapons complex must give urgency to developing quantitative plans for remanufacturing weapon components for the war reserve stockpile. The size of the active and inactive forces required by U.S. defence policy decisions will be among the critical factors affecting the plans. These requirements cannot be anticipated with confidence, and the resulting plans must incorporate a built-in flexibility, including the possibility of a stockpile greatly reduced in numbers relative to current plans under START-I and

START-II and changes in requirements for reserve warheads. The second factor of major importance will be the findings of the Enhanced Surveillance Program (ESP) and Stockpile Life Extension Program (SLEP) efforts. Obtaining results in these programs must be given among our highest priority efforts since the size requirement to build a given number of nuclear devices, neutron generators or tritium bottles, for example, will depend on the findings of the ESP and will have a major impact on the overall complex of the future.

There are some specific problems with remanufacture, beyond those associated with the lack of knowledge about aging mechanisms or uncertainties in the numbers of nuclear weapons in the future stockpile. While it has always been true that certain elements of a nuclear weapon are "limited life components" (LLC, such as neutron generators, boost-gas reservoirs and batteries), in the new environment every component of a nuclear weapon is properly regarded as of limited life and is a candidate, therefore, for remanufacture. But the big question regards the actual expected life of each of these components. We have seen on many bar charts the "design life" of a nuclear weapon stated as 20 years, or perhaps 25 years, and one still sees a peak in planned remanufacture at precisely 20 years or 25 years after a weapon was manufactured. However, there is no such thing as a "design life". The designers were not asked or permitted to design a nuclear weapon that would go bad after 20 years. They did their best on a combination of performance and endurance, and after experience with the weapon in storage there is certainly no reason to expect all of the nuclear weapons of a given type to become unusable after 20 or 25 years. In fact, one of the main goals of SBSS is to predict the life of the components so that remanufacture may be scheduled, and results to date indicate a margin of surety extending for decades.

In the last couple of years there has been good news on several fronts of SBSS. The primary is in principle far more problematical than the secondary, composed as it is of plutonium of extremely complex metallurgical properties, which transforms over a period of 24,000 years by the emission of an alpha particle. The accumulation of the resulting helium is expected to be the life-limiting component of the plutonium pit, since it will ultimately deform the material, modify its crystal structure, or the like. Observation of old plutonium and accelerated aging observations of plutonium show this not to be a problem for the oldest plutonium observed thus far, and information is being obtained more rapidly than the pits are aging. Pit lifetimes are now discussed as 60 or 90 years. Minimum data to improve lifetime predictions are being obtained in a timely fashion.

Similarly, measurements of high explosives have not yet shown deterioration in performance with time, despite observable changes in such aspects as molecular weight of some of its components. This is a helpful result from the SBSS program.

Finally, the accelerated scientific computing initiative (ASCI) is being used in conjunction with remanufacture, to provide additional capability to design rapidly, and thus to shorten the cycle time for new components and manufacturing processes. One example, for instance, has been in the brazing of a non-nuclear part of the weapon, where 3-D modeling of the furnace revealed the cause of some bad joints, and its simple remedy. Moreover, we support the development of virtual (electronically networked) communities, even more than is being done now, in addition to the quarterly or semiannual meetings of people with like concerns in technologies or products. The relevant participants from laboratories and production plants ought to share the same database and communicate across the nuclear weapons complex in a secure and flexible fashion. In particular, there needs to be more involvement of weapon designers at the laboratories in the reconfiguration of the electronic-communication network and in the analysis of the production processes as they are ongoing, which means that the designers themselves must be involved in the virtual community.

3 RELATIONSHIP BETWEEN EXTENDED SURVEILLANCE PROGRAM AND REMANUFACTURE

One can construct a remanufacturing strategy in one of two ways. Either 1) declare an arbitrary service life and remanufacture each unit as it reaches the end of its declared life, or 2) implement an aggressive, broad-based and science-driven surveillance program focused on detecting trends (early warnings) that indicate the eventual need to remanufacture product. The selection of an arbitrary service life can ease planning and be less demanding of stockpile surveillance activities, but it does not push for a close monitoring and better undestanding of the *actual* stockpile, as it ages, and is likely to cost more than option 2.

The successful accomplishment of either strategy is, of course, dependent on close cooperation among the 3 weapon labs, and between the labs and the downsized production complex under the policy direction of the DOE. Based on government regulations and budget cycles, as well as construction times for special facilities, a minimum time for early warning and recovery should probably be not less than 10 years (though shorter time periods can no doubt be achieved in an emergency). The evidence we are beginning to see from the ESP currently supports the view that a 10 year lead on unacceptable degradation is achievable. The confidence that a 10 year lead is appropriate will be enhanced if continuously operating pilot production lines (e.g. a few a year) are maintained to replace hardware destroyed during surveillance activities.

We heard briefings describing the details of remanufacturing processes at LANL and Y-12, aimed at establishing reliable production lines for pits and secondaries. In both places, good progress has been made in building teams of people and equipment capable of producing these critical weapon-components to satisfy WR specifications. We commend these efforts and urge that they be continued until the remanufacturing processes are fully operational.

Thus, our confidence that ESP-driven remanufacturing can succeed is based on information supplied by LANL regarding pit fabrication and Y-12 on CSA fabrication. Much additonal data must be examined to fully validate this assertion, however. Although we have seen data related to HE aging we need more information before we can take a firm position about its implications. With regard to neutron generators and boost system hardware (production assignments now at Sandia and Los Alamos,) progress appears to be satisfactory. Other hardware and components, while essential to the assembly of a complete warhead or bomb, appear to be of lesser concern if only because they are more akin to items available from high-quality commercial sources.

The main thing that we found lacking in the LANL and Y-12 briefings was evidence of any strong linkage between the remanufacturing programs and the stockpile surveillance programs. Ideally, the scale and time-table of remanufacturing should be determined by the scale and time-table of warhead deterioration revealed by stockpile surveillance. Until now, clear evidence of warhead deterioration has not been seen in the enduring stockpile, but the plans for remanufacture still assume that deterioration is inevitable on the timescale of the old, arbitrarily defined "design lives" discussed in Section 2. We recommend that the plans for remanufacture be made as flexible as possible, so that remanufacture cost savings and enhanced reliability can be achieved as the findings of stockpile surveillance become available.

4 PRIORITIES FOR ESP/SLEP ACTION IN REMANUFACTURE

4.1 Status of Remanufacture

The nuclear weapons “complex” has made impressive accomplishments in establishing remanufacturing capabilities under the new constraints of budget, lost technologies, and safety and environmental concerns. Examples of accomplishments, which span the complex, include redevelopment of pit production capability which was lost when Rocky Flats was shut down, safety overhauls and introduction of robotic handling procedures at Pantex, reestablishment of CSA production under modern safety regulations, development of new manufacturing procedures for TATB and PZT-based fuzing, transfer of component manufacture (including tritium reservoirs) to the Kansas City Plant with greatly improved productivity, development of new production of neutron generators, installation of high-power computational capabilities at two of the production facilities, development of archival records on ongoing manufacturing procedures, and the beginning of common networking and data handling procedures. Of particular significance among these many accomplishments, we note the compilation and cross-correlation of old data from fabrication records and test records for pits; this compilation is being used in the development of new pit production and qualification procedures. We also note the coordination of work between Livermore and Y-12 on developing diagnostics for CSAs, and collecting data needed for life-time prediction during disassembly of decommissioned CSAs. These latter efforts are examples of the type of continuing ESP efforts that must be further developed and maintained in the next stages of remanufacture.

With these accomplishments in place, it is now reasonable to plan maintenance of the stockpile via partial or complete re-manufacture. At present, the complex is working on short-term planning, in which immediate needs of the stockpile will be addressed as efficiently as possible within the existing remanufacturing capabilities. The prioritization of stockpile maintenance needs is presently being made using ad-hoc procedures based on maintenance schedules and experience established prior to the test ban. The phase-in of maintenance schedules prioritized on the basis of scientific understanding and stockpile surveillance experience is the next challenge for the remanufacturing program. This is essential, first of all to ensure that stockpile readiness is maintained, and secondly to ensure the most efficient use of the limited resources available to maintain the stockpile.

4.2 Scheduling and Capabilities

The production rates of components at the various facilities are limited by one or both of two factors: i) the current existence of appropriate facilities and trained personnel, and ii) the capacities of new processes which are under development. Some examples of limiting factors are the number of cells available at Pantex, the rate of CSA remanufacture, the rate of neutron generator fabrication, the rate of tritium reservoir fabrication, and the rate of pit production. Short-term maintenance and remanufacture plans are being formulated around current capabilities, with branch points in decision-making scheduled as new information emerges from the enhanced surveillance program concerning stability of different weapon components. A significant decision branch point in the near future will determine the necessity of W76 rebuild, based on information on the stability of the HE to be obtained by the ESP. Such short-term decisions will have significant impact in the development of capacity, and thus the distribution of resources, which will not be easy to reverse once established. Therefore it essential that more of the information needed to develop long-term and coherent planning be acquired and placed into the context of decision making as rapidly as possible.

4.3 Enhanced Surveillance Data Gathering

Two subsystems which we perceive to be at the opposite extremes in their impact on scheduling of remanufacture are HE and pits. Based on current information, we consider HE to remain a questionable component in evaluation of stockpile readiness, whereas pits are now established as stable components in the stockpile. Thus planning for appropriate remanufacture regarding these two components frames the time scales of concern.

Accurate and extensive compilation of HE data, from old records (as was done for pits), from testing of HE components of decommissioned weapons, and from aging tests is needed urgently. Without this information, crucial short-term decisions will have to be made on a very conservative basis, possibly preventing other needed maintenance (or evaluation efforts), and almost certainly leading to wasteful allocation of scarce resources. Even prior to definition of new enhanced surveillance diagnostics for HE (which presumably are now under development), aggressive data acquisition designed to match and augment data in old records is needed.

For HE there is a well-defined series of qualification tests performed on each unit that is (and has been) shipped from Pantex. Repeating these measurements on a broad selection (e.g. different ages and different environmental experience) of HE from decommissioned weapons and of weapons under rebuild will allow the development of a time-dependent data set, as discussed in the following section. Immediate re-establishment of temperature-based aging studies on full weapons (AAU), now under a temporary halt at Pantex, is also essential. Because HE is a likely rate-limiting component in the stockpile, the accumulation of sufficient data to establish statistical trends in its performance should be an extremely high-priority concern.

Pits stand in contrast to HE in their impact on the stockpile. Because they are a crucial and expensive component, extreme care is required in reestablishing pit production correctly. The present pit-development program is demonstrating this care. On the other hand, because there is neither evidence nor physical reason to expect that pit aging on the present time scale has in any way degraded weapon performance, there is no reason to rush decision making as to future pit production rates. Development of serious *materials-science*-based criteria for evaluating pit readiness as a function of lifetime therefore can proceed on a longer-time scale than is needed for HE.

4.4 Statistical Lifetime Analysis

The continuing and expanded evaluation of weapons and components failure rates as a function of lifetime remains a serious need of the remanufacture program as discussed above. In the following we illustrate, with examples based on simple models, the potential use of lifetime data to inform decision making for remanufacture. The models are not intended to be definitive, because there is not yet (so far as we can tell) adequate data available to generate sufficiently realistic models. The models shown here are therefore meant to illustrate concretely the need for expanded collections of data, and the potential impact of this information on the remanufacture planning process.

4.4.1 Likelihood fits to aging data

We performed a maximum-likelihood analysis of aging data provided to us by the Sandia group [1]. This information consists of numbers of weapons sampled and numbers of "actionable findings"[*] observed, sorted by age of weapon in one-year bins. Our purpose was to use these data to estimate as accurately as possible the rate of actionable findings and, in particular, to look for any significant change in defect-rates with age (we specifically do not consider production-related defects).

In analyzing these data, we assume that the probability, p, of a defect being recorded as an actionable finding during a given inspection is a *smooth function* of the age in years, y, of the sample group being examined. Specifically, we assume:

$$p = a_0 + a_1 y + a_2 y^2 + a_3 y^4$$

where the a_n are parameters to be fitted to the data. Further, we assume these parameters are non-negative, implying that defect rates will only grow over time, in the same way for all types of weapons. The probability that r actionable findings are observed in a sample of n weapons in the age bin, y, is given by the binomial distribution,

$$f(r; n, p) = \frac{n!}{r!(n-r)!} p^r (1-p)^{n-r}$$

where p is the defect rate evaluated for the age, y, being studied.

Our likelihood function is the product over age bins of the individual binomial probabilities for the observed numbers of findings. The fitting parameters, a_n, are varied to maximize the logarithm of the likelihood function[†]

---

[*] Findings of defects or deviations from specifications sufficient to require official action, such as reporting and in-depth investigation. A detailed protocol exists to define actionable findings.

[†] This form correctly handles binomial statistics and corresponds (up to a factor of 1/2) to a χ^2 or least-squares fit when the r_i are reasonably large.

(up to an overall constant that does not influence the fit), given by:

$$\ln \mathcal{L} = \sum_i r_i \ln p_i + (n_i - r_i) \ln(1 - p_i)$$

where the summation is over all age bins, i, contributing to the fit; r_i is the number of actionable findings in the sample of n_i weapons examined in the given age bin and p_i is the actionable finding rate evaluated for the i-th bin.

The MS Excel tool, "Solver", was used to find fitting parameters that maximize $\ln \mathcal{L}$. Various fits were performed in order to study the stability of the results[‡].

The final results, shown in Figure 1, included data in the age range 5 to 32 years. Data from years 1 to 4 are well represented by the parameters determined from the older weapons, but were excluded from the fitting process to avoid possible biases (e.g. due to design or production errors) arising from the "youngest" samples. The fits consistently yielded linear solutions, where $a_2 = a_3 = 0$, presumably as a consequence of the positivity constraint. The best fit values for the other parameters are:

$$\begin{aligned} a_0 &= 0.002642\,\text{findings/trial} \\ a_1 &= 0.000355\,\text{findings/trial/year.} \end{aligned}$$

To estimate the errors on the fitted rate of actionable findings, the values of a_1 that change $\ln \mathcal{L}$ by 2 units (corresponding to a $\pm 2\sigma$ variation in likelihood) were found. Curves (straight-lines) for these parameters are included in Figure 1. A proper calculation of the covariance matrix for these fits is beyond the scope of this report, but we believe that the above procedure gives a reasonable estimate for the 90% confidence-level bounds. The two parameters, a_0 and a_1, are highly correlated; by using the slope parameter, a_1, to estimate errors, we should be conservatively setting confidence-level bounds for the oldest weapons under consideration.

[‡] We also performed fits with a likelihood function based on Poisson statistics. The results were indistinguishable from the binomial case.

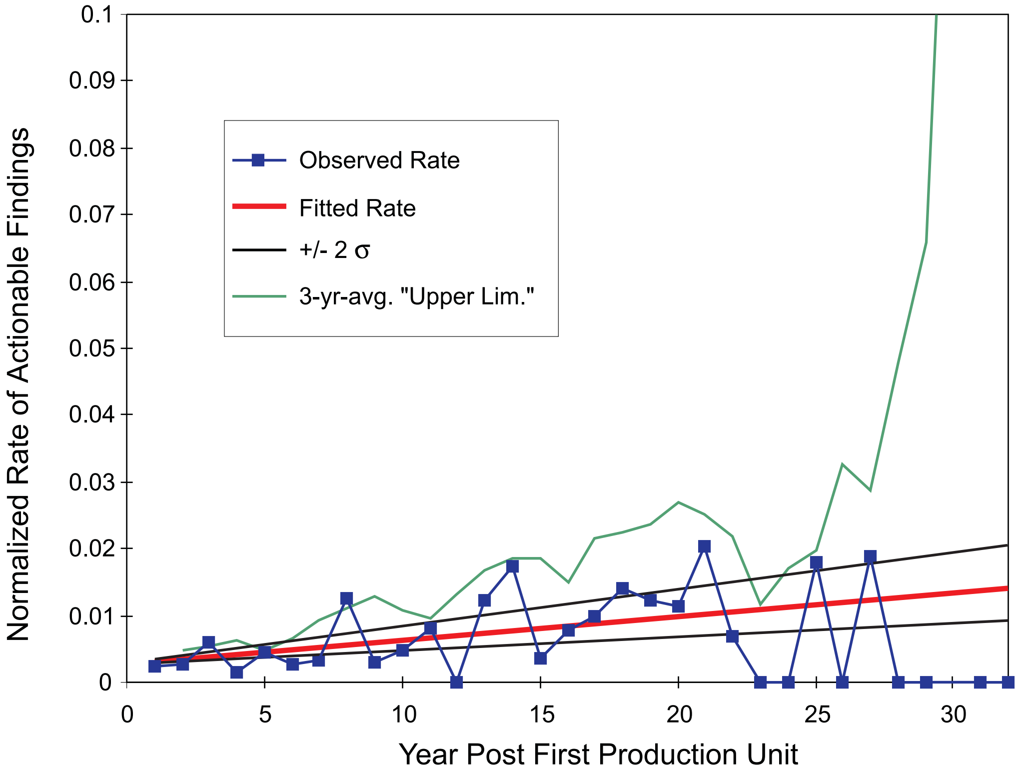

Figure 1: Summary of results on age-dependence of rate of actionable findings. The squares indicate the observed number of actionable findings[1] divided by number of samples, plotted against the cohort age. The line labeled “Fitted Rate” is the actionable findings rate versus age determined from the maximum-likelihood fits described here. The lines labeled “+/- 2 σ” indicate our estimate of the 90% confidence-level bounds for the rate actionable findings. The curve labeled “3-yr-avg. Upper Lim.” is the previously reported estimate[2] of the 90% upper limit on the rate of actionable findings, based on a three-year running average.

The results of our fit suggest a straight-forward picture of the aging process in these devices: a given weapon is a very complicated assembly consisting of large numbers of components, some of which are aging and may trigger actionable findings when examined. With many possible and nearly independent pathways leading to an actionable finding, the weapon, in this picture, behaves much like a sample of unstable particles: after a time, t, the fraction surviving is given by the exponential decay law,

$$f(t) = \exp(-\lambda t)$$

which is a consequence of the independent nature of the decays, as described by Poisson statistics. The parameter λ is the mean decay rate, or inverse of the mean-lifetime, $\tau = 1/\lambda$. In this picture, which we call the "Poisson model" of aging, the individual "decays" of components lead to a "build up" over time of actionable findings. Thus, the time dependence of the probability for actionable findings should have the form:

$$p(y) = 1 - \exp(-\lambda y).$$

In the limit of small λy, this reduces to the linear form, implied by our fits. Our fits also find a constant term, a_0, which can be interpreted as arising from some different, non-aging mechanism, such as "infant mortality" or defects that were hidden in post-production inspections[§]. Interpreted via this simple picture, which we believe to be plausible, the data suggest a constant defect probability of 1/4% and an aging lifetime of 2800 years. Taking the Poisson model literally, the data can be fitted with only one parameter, the mean-lifetime. In fact, such a model represents quite well the data for ages greater than 4 years (but not the younger data). The 90% confidence-level upper-limit for the mean findings rate in this case is 0.000765/yr, which is slightly above our "$+2\sigma$" curve given in the figure.

[§] Alternatively, the constant term can be interpreted as the "clock" for defects in the Poisson model starting 7 years before the weapon is produced

Also plotted in Figure 1 is the 90% confidence-level "upper limit", proposed in reference [2]. This limit was computed from a 3-year running average of the observed findings rate. It increases rapidly for ages greater than 23–27 years exactly because the oldest weapons exhibit virtually no flaws. In this interpretation, a rate of (near) zero findings is taken to mean that the true failure rate of the oldest weapons is unconstrained by observations, thus causing the rapid increase for the oldest weapons in the "upper limit" number of anticipated findings shown in Figure 1. As expected, the greater statistical power of the maximum-likelihood method yields a considerably more accurate estimate of the rate of actionable findings, particularly for the older weapons in the age range of up to perhaps 50 or 75 years. The basic assumption underlying our procedure—smoothness in the age-dependence of the underlying failure rates—is physically reasonable and gives no indication of significant increase, beyond a linear rise with age.

Our results should not be taken to mean that we have no concerns about aging of the stockpile [2]. Rather, we are not persuaded that there is any statistical evidence for substantial aging, *beyond* a Poisson-like behavior. Indeed, some components could have definite "wear-out" lifetimes that would lead to a rapid rise in specific types of actionable findings with age. Because of the small sample sizes of old weapons, sensitivity to possible non-Poisson aging is poor. For example, if we constrain the likelihood fits discussed here to their central values and ask how large the a_2 or a_3 terms could be, we find $a_2 < 1/(320\,\mathrm{yr})^2$ and $a_3 < 1/(133\,\mathrm{yr})^3$. Taking the a_3 term for illustration, if it should equal our current estimate of its upper-limit, then the projected findings rate for 30 year-old weapons would be increased by about 1% over the "normal" Poisson rate of 1-2% for that age group. To hope to detect such a change in rate—by observing, say, 16 defects when 8 are expected from the Poisson model alone—one should sample at least 800 weapons at or near 30 years of age, an impractical goal. In the data available to us, only 59 weapons in the stockpile with ages greater than 27 years have been tested and *no defects* were found. This result is fully consistent with the Poisson model discussed here, but lacks the statistical power needed to reveal departures from a smooth findings rate, as might be associated with some enhanced aging effect. Much larger samples of older weapons are needed to establish any such aging trend.

This analysis leads to two significant conclusions: 1) the findings versus age database must be kept up to date; and 2) there should be a selective emphasis on sampling older (rather than randomly chosen) weapons from the stockpile in carrying out the ESP.

4.4.2 Evaluations of steady-state remanufacture requirements

A strong need of the remanufacture planning process is the development of planning predictions for the needed rate of manufacture. The curve labeled "3-yr. avg. Upper Limit" in Fig. 1 with the implied cliff at an age of 30 years clearly does not provide a suitable basis for planning remanufacturing requirements. Planning predictions will have to be based on (and continually revised according to) the accumulated data from enhanced surveillance of the stockpile. As an example of such predictions, we can consider the simplest case where we have well-established statistical information, for instance about the lifetime $(1/\lambda)$ for a weapon or any component of a weapon.

As one case, we consider the simple result for a statistical lifetime obtained above. To predict the rate of remanufacture required to maintain a given level of stockpile readiness, consider a population of N_0 weapons, all created at the same time $t = 0$. Barring intervention, the number of weapons that one can statistically expect to be good at some time t later is just

$$N_{\text{good}}(t) = N_0 e^{-\lambda t} \quad .$$

The probability of a weapon failing is

$$p_{\text{failure}}(t) = 1 - N_{\text{good}}(t)/N_0 \quad .$$

Here we consider a stockpile started at $t = 0$ with $N_0 = 10,000$ weapons, and assume a decay rate of $\lambda = 0.001/\text{year}$ (comparable to the upper limit of our model in 4.4.1).

With this choice of λ we don't for a moment suggest that there is any experimental proof that a simple exponential decay at such a slow rate is valid far into the future. We apply it here only to illustrate how to extrapolate to lifetimes of up to perhaps twice the length of current data – i.e. to ∼60 years – in planning to maintain a steady-state stockpile of reliable weapons.

To maintain the stockpile and its remanufacture at steady state, beginning at year t_0, N_r of the oldest weapons are removed from the stockpile each year and replaced with an equal number of new ones. This leads to a "turnover" or "replacement" time defined by:

$$\tau_r \equiv \frac{N_0}{N_r} \ .$$

In this picture, there are three stages in stockpile age and reliability.

Original weapons: $0 \leq t < t_0$

$$\begin{aligned} \text{Average Age}(t) &= t \\ N_{\text{good}}(t) &= N_0 e^{-\lambda t} \end{aligned}$$

Original weapons being replaced: $t_0 \leq t < t_0 + \tau_r$.

$$\begin{aligned} \text{Average Age}(t) &= t + \frac{1}{2\tau_r}(t_0^2 - t^2) \\ N_{\text{good}}(t) &= N_0 \left\{ \left[1 - \frac{(t - t_0)}{\tau_r} \right] e^{-\lambda t} + \frac{1}{\lambda \tau_r} \left[1 - e^{-\lambda(t - t_0)} \right] \right\} \end{aligned}$$

Steady state remanufacture: $t \geq t_0 + \tau_r$.

$$\text{Average Age}(t) = \frac{\tau_r}{2}$$

$$N_{\text{good}}(t) \;=\; \frac{N_0}{\lambda\tau_r}\left(1-e^{-\lambda\tau_r}\right) \approx N_0\left(1-\frac{\lambda\tau_r}{2}\right) .$$

Figure 2 shows the three stages for $N_r = 100/\text{yr}$ and $400/\text{yr}$, corresponding to $\tau_r = 100$ and 25 years, for a remanufacture program starting $t_0 = 30$ years after the stockpile was created. Replacing only 100 weapons per year allows the stockpile to continue aging for another 70 years, with resulting decreases in the number of good weapons and increases in the failure probability. Steady-state values are only marginally less than the 100-year extrema. Replacing 400 weapons per year, however, produces immediate decreases in the average age and results in a young stockpile. Balancing remanufacturing costs against reliability would probably call for N_r between 100 and 400 for a 10,000 RV stockpile; or between 20 and 80 for a 2,000 RV stockpile under potential START III limits, with all of these values pertaining to the specific model and λ magnitude used here for illustrative purposes.

Notice that the failure probability is approximately given by:

$$p_{\text{failure}} \approx \frac{\lambda\tau_r}{2}$$

which suggests a simple algorithm for choosing the replacement rate for a given acceptable failure or "dud" rate when the decay rate λ is known:

$$N_r = \frac{\lambda N_0}{2p_{\text{failure}}} .$$

For the numbers used here ($\lambda = .001/\text{year}$, $N_0 = 10,000$ for the near term future – up to 60 to 80 years as illustrated in Fig. 2),

$$N_r = \frac{500/\text{year}}{p_{\text{failure}}(\%)} .$$

This example underscores the critical importance of developing the best possible predictive capability for failure of the components of the weapons. A steady state replacement schedule not only allows more efficient scheduling of

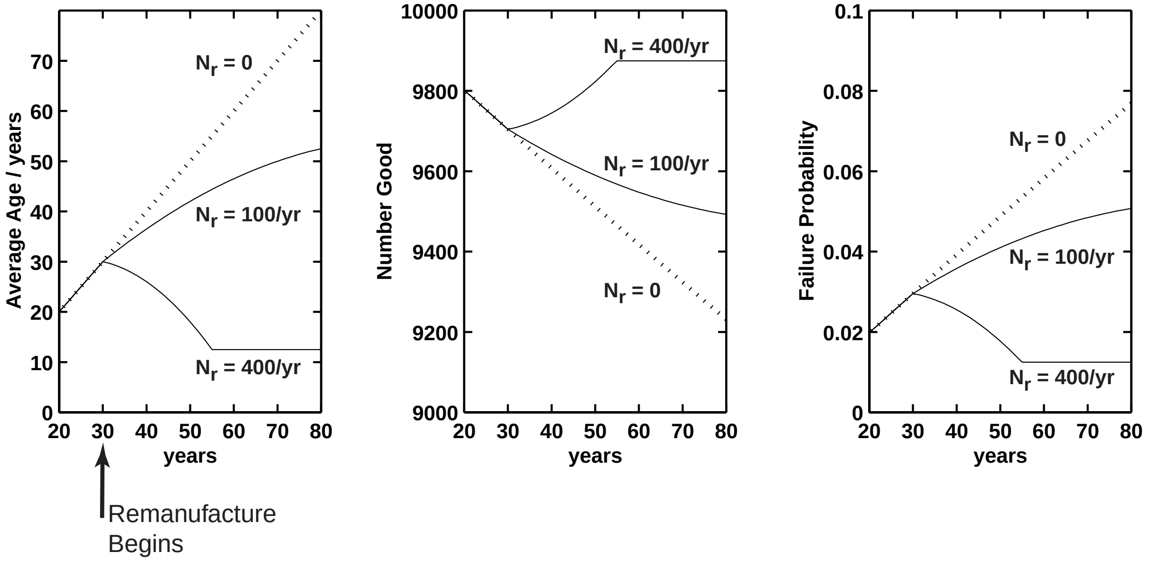

Figure 2: Sample calculation of stockpile statistics assuming that remanufacture starts at $t_0 = 30$ years, a decay rate of $\lambda = 0.001$/year and replacement rates of $N_r = 100$/year and 400/year for a 10,000 unit stockpile. Dotted lines are for no replacement, $N_r = 0$. Note that all curves depend critically on knowledge of λ.

remanufacturing resources, it also allows a lower failure rate to be maintained for the same net number of replacements over the chosen replacement cycle. However, to take advantage of a steady state remanufacture process, it is necessary to have detailed statistics on the failure rate of older weapons and their components, in order to determine whether the statistical decay rate becomes time dependent at long times (e.g. λ may change with age and there are likely to be thresholds for new failure mechanisms). This need demands continued aggressive sampling and meticulous record keeping on the properties of the aging stockpile. In addition, one can do much better in this endeavor if the aging mechanism is understood, so that the risks of maintaining somewhat older units in the stockpile can be modeled correctly.

Finally, further safety and efficiency benefits would accrue if weapons which are close to failure could be individually identified and removed from the stockpile through vigorous enhanced surveillance activity.

This analysis can be extended to take into account the replacement of individual components, each of which has its own (statistical) lifetime. This formalizes the recognition that already now, and increasingly so in the future, a weapon does not have a single “age” but is an agglomeration of numerous parts that have been produced (or remanufactured) at various times. In this sense, the “average age” of the stockpile does not continue to increase at an inexhorable, linear rate, precisely because of the impact of remanufacture (as well as LLC replacement).

5 MARGINS AND REMANUFACTURE

In certain cases, remanufacture of nuclear weapons components will have to be done with new technologies and no opportunity to test the assembled product as it is intended to be used. The prime example is pit remanufacture. Changes are planned in many aspects of the fabrication process, including the change from wrought to cast processes for the rough pit, and possible changes in physical attributes of the final machined pit. This creates a potential concern: Is it necessary for high confidence in the remanufactured weapon that the pit have as nearly as possible the same physical attributes as those tested underground in earlier years? Or can one circumvent this concern by other means?

Two possibilities for circumvention come to mind. The first is that a science-based program of experiment (including underground sub-critical studies) and simulation, and dealing with such questions as high-pressure equations of state, effects of forming and machining processes on the implosion process and the like, will provide the information (without underground nuclear tests) necessary for ensuring with high confidence that the final product will work as intended; this despite the possible introduction of new technologies, and consequent changed physical attributes relative to the original weapon. We believe that this is an important step, and urge that, in a few key areas such as pit remanufacture, the design laboratories and the production areas of the complex interact closely to implement a science-based remanufacture process.

The second mode of circumvention was discussed at some length in a previous JASON report [3]. In certain cases, slight changes in the attributes of a nuclear weapons component, such as those introduced by using new technologies, can be rendered unimportant by increasing the margin of performance of the weapon. By margin of performance, we mean the difference in primary yield which is expected from a normal weapon and the minimum primary yield which will drive the secondary to essentially full yield. The margin available to a specific weapon changes with time and circumstances, notably because primary yield is so sensitively dependent on the amount of tritium available in the gas system.

There are various means to enhance the margin without resorting to underground tests, for example, by relaxing stockpile-to-target sequence requirements (e.g., for survival in a hostile environment). But it seems clear that the most significant opportunity to enhance margin lies in the gas supply system. We will not go into great detail about enhancing gas supply here, but one obvious means is to shorten the tritium refill cycle time so that large excursions in the amount of tritium available do not occur.

We recommend that this question of the effect of margin enhancement on remanufacturing confidence be investigated in the only way now available: by a science-based remanufacturing study, in which large-scale calculations are made in an attempt to quantify the increase in margin due to, e.g., a better gas supply, and to estimate at least a reasonable and prudent bound on the decrease in margin from introduction of new manufacturing technologies.

6 KNOWLEDGE UTILIZATION & PRESERVATION

All units in the nuclear weapons complex expressed grave concern over the age distribution of their workforce. Due to budget reductions and resulting reduction in force, loss of experienced personnel has occurred without concomitant hiring of entry-level personnel (who would ordinarily have been trained by senior staff prior to their retirement). Thus, individual plants are not in a position to respond to any emergency which might require a sudden increase in production capability. Careful planning of future production rates, accompanied by a rate of hiring sufficient to sustain those production needs, is a serious planning requirement all across the complex. Meeting this planning need appropriately will be an additional benefit of developing a formal science-based remanufacture schedule.

JASON is aware of the knowledge preservation, archiving and data retrieval program of the DOE design laboratories. However, we do not know the extent to which similar programs are on-going in the manufacturing areas and urge that the fragile parts of warhead manufacturing, such as the lore and know-how on pit fabrication, be fully documented in order to retain the necessary information for reliable remanufacture. Each laboratory and plant should be consciously directed to archive and preserve in durable format the various steps involved in their particular part of the weapon production: primary, secondary, arming and fusing, high explosive fabrication/procurement, etc. For example, video tapes fully documenting the steps in the process from raw materials to finished product should become part of the archival material and record on weapon remanufacturing.

In particular, the “old timers” in the business, retired or near retirement, should be asked or supported in making videos on the general lore of nuclear explosive design, device fabrication and weaponization. The ultimate aim of this activity is to reduce the time on the learning curve in the event the country stops or greatly cuts back on nuclear explosive design and fabrication activity, but later is suddenly forced to renew the activity.

One possible test of this knowledge transfer would be to ask a group of “naive” scientists and technologists (e.g., recently graduated scientists and technologists) to refurbish/rebuild/remanufacture a device using existing facilities, but with no guidance other than that available through static documentation (i.e., no consultation with experienced personnel would be permitted). The quality of the result would provide an assessment of the success of knowledge transfer and perhaps highlight deficiences in the documentation.

References

[1] Data on Actionable Findings, kindly provided to us by Robert Paulsen of Sandia.

[2] SAND95-2751 (UC-700)

[3] Drell, S., JASON Report JSR-95-320, Nuclear Testing, November 1995.