
System-Level Flight Tests

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1 INTRODUCTION

System-level flight tests are an important part of the overall effort by the United States to maintain confidence in the reliability, safety, and performance of its nuclear deterrent forces. This study of activities by the Department of Energy in support of operational tests by the Department of Defense was originally suggested by Dr. Rick Wayne, Director, National Security Programs, Sandia National Laboratory/Livermore, and undertaken at the request of the Department of Energy, Defense Programs Division. It follows two 1997 studies by JASON [1] that focused on the Department of Energy's Enhanced Surveillance Program for the physics package – i.e. the nuclear warhead. Input was provided in a set of briefings extending over a two day period,¹ June 16–17, 1998 at the JASON Summer Study in La Jolla, CA. The schedule of briefings is given in Appendix A.

System-level flight tests provide data that are needed to assess the performance of the weapon systems that comprise the US nuclear deterrent. Measurements made cooperatively by the Departments of Energy and Defense on the Joint Test Assemblies (JTAs) provide unique opportunities to monitor the interactions and performance of sub-systems over the relevant operational flight conditions, and to search for failure modes not otherwise detectable.

System-level flight testing is not prohibited by the CTBT. Indeed, the need for such tests is largely independent of the CTBT, as they address the integrated performance of components and subsystems that cannot be probed by underground nuclear tests (UGTs). A system-level flight testing requirement was formally established as the JTA Program in 1963, but its origins reach back to the Operational Suitability Tests of the 1950s. In an

¹We also wish to acknowledge a very valuable tutorial on flight dynamics presented by Don Rigali of SNL on July 6.

era of strategic arms reductions, with little or no deployment of new launcher systems, system-level flight tests take on a new importance. Potential failures have been identified at the system level which would never have been uncovered by UGTs alone.

The special value of each system-level flight test derives from its being a review of the integrated performance of the delivery system and many functions of the warhead or bomb, in a realistic sequence from the launch of the delivery system to the arrival of the weapon at the target. The test includes the delivery system and a test unit version of the warhead or bomb.

The JTA measurements in flight environments have thus far been primarily limited to the functioning of the non-nuclear components, including restricted exercising of the gas-transfer systems, with the mass and moment of inertia properties of the nuclear explosive package (NEP) being mocked up in the instrumented flight tests. Recent flight tests without instrumentation provided limited data on the functioning of the NEP (with substitutes for special nuclear materials).

To remedy deficiencies of past JTAs, DOE and DOD are embarking on a program of High Fidelity Joint Test Assemblies (HFJTAs) that will be instrumented and have as realistic NEPs as possible, while not compromising the fidelity of the non-nuclear components. To achieve this goal, one will have to make judicious compromises between maintaining design fidelity and instrumenting the flight test units with new, validated, miniaturized diagnostic and telemetry equipment. The HFJTA program also faces the additional challenge of fewer opportunities for system flight tests than have been available in the past.

It would be wrong to look to HFJTAs to answer all questions concerning the performance of the weapon systems of the U.S. nuclear deterrent. They are not appropriate for completing development programs, or as substitutes for what can be measured in ground-based tests. HFJTAs will be most effective and valuable if an overall surveillance and life extension program is in place, clearly defining the objectives of flight testing, providing a clear process to prepare for flight tests by appropriate lab and ground tests, and including a well-defined plan for resolving any anomalies that appear during flight tests.

Flight opportunities will be seriously restricted in future years, in part because of budget limitations and in part because of potential treaty obligations. Under START II, the MX (10 RV) missile must be retired, and the MMIII (3 RV) missile will become a single-RV missile; no flight tests with MIRVed ICBMs will be permitted after the date START II is implemented (possibly by 2007). Program needs and priorities for HFJTAs must be oriented so that flight tests are reserved only for the most important system-comprehensive tests that cannot be accomplished by other means. It will be necessary, just as it was when UGTs ceased, to find convincing ways of supplementing full-function tests on the ground. This means that one must:

1. Define technical criteria and their level of priority so that a balance can be set within the HFJTA program between numbers of high-fidelity flight tests on war-reserve (or near-WA) systems of highly instrumented flight tests, and of highly instrumented ground tests of the behavior of critical components and their interactions.
2. Develop ways of testing the RV system, and also gravity bombs, in ground-based simulated operational environments that are as realistic as possible, without actual expenditures of ICBMs, SLBMs, gravity bombs or cruise missiles (CMs).

3. Make full use of components from flight and ground tests of Nuclear Explosion Packages (NEPs) slated for disassembly, including both NEPs that will be retired and those to be returned to the active stockpile.
4. Develop new cooperative modes of interaction between the joint DOD/DOE flight-test program and other components of DOE's stockpile stewardship program.

2 CONCLUSIONS AND RECOMMENDATIONS

Today, as much as ever, system flight tests are of great importance as the only experiments that provide direct experimental data on the performance of our war-reserve nuclear weapons systems. One relies on them to identify and mitigate possible failure modes from the overall weapon system during the stockpile-to-target sequence (STS), in the case of failures that cannot be identified with confidence under ground-based or otherwise simulated component tests. The system flight tests must therefore be planned, instrumented, and executed so that their results can be clearly interpreted, the causes of possible failures identified, and fixes confirmed.

To optimize the efficiency and effectiveness of the systems flight test program as one of the top-priority components of the U.S. Stockpile Stewardship and Maintenance Program, the present study leads to the following specific recommendations, beyond giving the program our general strong support. Insofar as the present report to DOE is concerned with DOD issues, our remarks can be taken as a recommendation for DOE to carry these issues to DOD.

The study:

- 1) Endorses the current efforts to develop Enhanced Fidelity Instrumentation (EFI). While useful for monitoring or diagnosing potentially serious problems, the new EFI will enhance our understanding of the overall functional and structural performance of the system. The new EFI program will include the development both of sophisticated, miniaturized new sensors, some of which could become part of the WR units, and of new telemetry capabilities. New EFI must be thoroughly debugged in ground tests, and very high confidence established that they

will not give rise to false positives, or false alarms, before being introduced into system-level flight tests.

- 2) Recommends the development of a strong ground-based program of testing that would complement and be fully integrated with the essential end-to-end flight testing, provide system-level tests that can be used to plan and analyze the results of flight tests, and help to develop remedies to any problems uncovered by the system-level tests.
- 3) Recommends exercise of all non-nuclear components under STS conditions as part of the HFJTAs. Should they malfunction, the weapon will fail.
- 4) Recommends strengthening the current JTA program structure through the establishment of a clearer and more rigorous process for evaluating the relative merits of higher-fidelity versus more data-intensive flight tests within the context of a strong program of ground-based testing.
- 5) Recommends expansion of the current plan, as described in the JTA Design Directive, to laying out a roadmap for the entire program, consistent with realistic budgets, cost/benefit trade-offs between ground- and space-based activities, and novel means of recovering data (e.g. optical links, relaying through a PBV, or other means). This effort should include ongoing awareness of advanced hardware development by NASA (e.g. New Millennium Program) and DARPA.
- 6) Recommends the formation of an independent advisory panel to oversee and review the plans, progress, and findings of the system-level flight test program in all its aspects, including the implementation of any proposed changes. It is an ever-important watch-dog role of such independent reviews to guard against changes that, while technically "sweet", cannot be justified on cost/benefit grounds, or that may lead to undesired loss of confidence in the performance of the upgraded

system. This panel should consist of individuals with sufficient independence and technical strength to provide objective evaluations from a perspective outside DOE's, and should report regularly to the responsible DOE, DOD, and military authorities. It is not intended that this panel would replace the current Laboratory and Project Officers Group (POG) structure for defining the execution of the program.

3 TECHNICAL ASPECTS OF THE SYSTEM-LEVEL FLIGHT TEST PROGRAM

Representatives of DOE AL, LANL, LLNL and SNL provided briefings on the current state of the system-level flight testing program. A plan is in place, outlined by the JTA Design Directive, and implemented by the JTA Steering Group and various Program Officers Groups in conjunction with the DOE AL Office. Based on these briefings, this report concludes that the ongoing success of the HFJTA flight program depends critically on two factors:

1. Development of the needed technologies for enhanced fidelity instrumentation (EFI);
2. Efficient exploitation of the limited number of available system-level flight tests that employ EFI to increase and sustain confidence in reliable end-to-end weapons performance.

It is imperative that the implementation of EFI continues to be appropriately as conservative and as cautious as possible, so as to avoid the possibility of introducing new unknowns into the functioning of any weapon system. A cardinal issue, the trade-off between fidelity of the test versus quantity and quality of the data obtained, is discussed in Section 4.

3.1 Enhanced Fidelity Instrumentation

3.1.1 Sensors

The briefings described a range of new technologies being developed for EFI. Figure 1 identifies the set of technologies that meets important needs, and the reasons these technologies are needed. This report strongly endorses sustained, adequate support for these programs. Each new technology must, of course, pass development and qualification stages before being incorporated into HFJTAs. It is essential that EFIs be fully proof tested so that one can have high confidence that they will not give rise either to false positives or negative results during system-level flight tests.

One vision of the JTA program focuses on the development of small, unobtrusive sensors that can be fielded on WR weapon systems as well as on high-fidelity JTAs. This minimizes the differences between WR systems and test assemblies, so that sensor packages will not degrade the fidelity of the testing.

An alternative vision of smart RVs relies on embedded sensors for detecting signs of aging as the weapon sits in the stockpile. Such RVs would have internal environmental sensors responding to evolved gases and other indications of the degradation of weapon reliability during normal aging.

One should strive to achieve maximum commonality between aging sensors and flight-test sensors called for in Figure 1. In fielding embedded flight-test sensors one quickly runs into limitations because of the lack of space, need for connections with telemetry, and the size and weight of transmitters and batteries. The problem becomes worse when both types of sensors (aging, and flight-test specific) are mounted in the same RV.

Needed Technologies for EFI

- 1. Smaller Sensors - NEP left in test unit**
- 2. Miniature, Power Efficient TM Components - can't use NEP space for TM**
- 3. More Efficient Power Sources - little space left for batteries**
- 4. Distributed TM System - can't use NEP space for TM**
- 5. NEP Instrumentation - not done previously - Working with LANL & LLNL**
 - a. Physical Parameters before event**
 - b. Pit Implosion Measurement**
- 6. Wireless Interface to Nuclear Can SubAssembly (CSA) - CSA container cannot be penetrated**
- 7. Measurement of Weapon Functions during pit implosion - not previously instrumented during explosive operation**
- 8. Higher Data Transmission Rates - more data during pit implosion which quickly destroys TM**
- 9. Position Measurement without radar transponder - can't use NEP space for TM**

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Figure 1: New technologies for EFI (D.E. Ryerson, Telemetry Technology Development Department 2664, SNL)

3.1.2 Telemetry

It is recommended that the program define a roadmap for telemetry, including estimations for future needs and plans to meet those needs in a unified way. The requirement to minimize changes to the flight vehicle substantially complicates telemetry. Weight, power and volume are all very limited. Also, there is understandable reluctance to adding new antennas to the RV. Good experimental practice and data should be brought to bear to validate any such change.

Future needs for increased bandwidth for advanced instrumentation might drive the program to consider the use of optical links rather than RF links. An optical link could transmit through the plasma sheath during re-entry. However, an optical link might require a new, small penetration through the RV shell, perhaps at the base.

Some years ago, it was pointed out [2] that a single-RV post-boost vehicle (PBV) could be developed to fly attached to the RV for a substantial part of the flight time, conducting needed mid-course maneuvers, near-terminal guidance, decoy deployment, and the like. While the time for developing such elaborate offensive functions has passed, it is still worthwhile to consider what could be done with a new PBV that would maximize the value of and opportunity for high-fidelity tests. In particular, the MMIII missile will be converted from a three-RV system to a single-RV system, and it will require modification of the PBV for the MMIII.

One suggestion is that any new PBV be made large enough to carry telemetry transmitters, most of the battery power for the on-RV sensors, six-degree-of-freedom position, velocity and attitude sensors (e.g., GPS, accelerometers, gyroscopes), and some thrusting capability. The new PBV would fly attached to the RV until shortly before re-entry, when it would

do its usual job of releasing the RV; then it would back off some distance, maintaining with its thrusters a separation large enough to avoid interference with the RV but small enough so that small battery-powered transmitters on the RV could continue to send data to the PBV for relay to the ground. These new PBV functions could be a part of the WR PBV, not simply an add-on for JTA flights. Because there would be substantially less intrusion into the RV itself, this could make it considerably easier to implement the vision in which every JTA flight is high-fidelity. As the development of a new PBV is a D)D function, the DOE should consult with DOD in this matter.

International treaty requirements substantially complicate the issue of telemetry. Our understanding is that no telemetry can be encrypted, and that data in all individual telemetry channels (though not their actual physical significance) must be readable by other countries, for example Russia. Thus, a risk/benefit analysis must precede the actual fielding of any particular channel in order to determine whether the knowledge gained by the US is worth the loss of knowledge to others, who may be able to infer technical information about the weapon from the channel. Also, we must be prepared to furnish technical information about telemetry itself (e.g. modulation scheme, channelization) to the Russians.

3.2 Ground-Test Component of the System-Level Flight Test Program

The greatest concern to arise in the present study is on the adequacy of the current ground-based testing as a necessary input for informed analysis of the HFJTA flights. Although all participants now put much thought into planning and analyzing the results of each flight test, this study did not find clear evidence of a complementary ground-based program combined with a rigorous evaluation process between potential contributions of ground- and

flight-tests. The value of a system-level flight testing program lies in the ability to exercise the integrated weapon system under STS conditions that cannot be reproduced in ground tests.

3.2.1 General Description of a Ground-Test Component

A ground-based experimental program should ideally include the following:

- 1) Archiving of flight-test data so that conditions of past flight tests can be (at least partially) reproduced, either in ground-based or in flight tests. It may also be possible to extract and compare valuable information from other (non-JTA) missile and rocket flight tests, which should be heavily instrumented and might provide useful information, especially of the early stages of flight.
- 2) Exploiting existing facilities or developing new facilities that reproduce in the laboratory the most critical or stressing aspects of an entire STS, as measured in flight tests. With some of the limitations of ground testing addressed below, the value of weapon-system testing is considerable even if it is not in an actual flight environment. Past records of flight tests are obviously essential for quantifying the dynamic responses of RVs, cruise missiles and bombs to STS stress, vibration, spin and temperature histories through laboratory experiments.
- 3) Exploring the limits of performance of weapon systems by means of ground-based experiments. One wants to know more than whether, or which, components no longer perform well enough. In order to understand how failures occur or what parameter changes lead to adverse effects, one also needs to know how far from failure individual compo-

ponents are and the rate at which these might be approaching critical states of non-operability.

- 4) Providing a diversity of means to make important measurements, and to make sure of the validity of what is being observed and of its interpretation.

These points are amplified in the following paragraphs.

A vigorous program of continual laboratory testing could be a valuable and relatively inexpensive adjunct to HFJTAs. Such ground-based tests should do more than just try to reproduce inflight conditions. Spins, accelerations, and heating could be exaggerated until components fail even though the needed stresses far exceed those encountered in flight. This would establish a database for determining the dependence of certain parameters on RV/NEP age, and perhaps identify which ones might be moving toward critical values. X-ray diagnostics, laser vibrometry and other potent diagnostic methods could be used. In addition, testing within space chambers with RV dynamics determined by an appropriate mounting could mimic the flight history of an RV before its weightless ($g=0$) coast phase. The latter phase could also be achieved for up to 30 second intervals inside suitably equipped high altitude aircraft, and for longer intervals in sounding rockets in free fall. Suitable aircraft exist in NASA's manned space program.

Ground tests are less expensive than missile flight tests, and could be repeated more often and with a larger sampling of RVs than can be expected for HFJTA flights. Moreover, ground instrumentation is free from the constraints on weight, volume, telemetry bandwidth and other limiting factors of flight tests. A variety of large ground-test chambers exist at present at NASA, NRL, Boeing, Hughes, and Lockheed facilities. If additional capabilities are required they could be constructed at one or more of the national laboratories. Well-instrumented environmental chambers to test the response

to heat, vibration, spin, etc. would likely be a good investment if existing ones are not adequate. The design, construction and use of imaginative new facilities should also be effective in the recruiting of talented young people into the program.

3.2.2 Relative Merits of Flight and Ground Testing

There are, of course, critical environments that cannot be simulated in ground-based or component tests. To achieve these, there is no substitute for end-to-end system-level flight tests. These critical environments are:

1. Boost phase;
2. Prolonged zero-g environment;
3. Re-entry environment with realistic temperatures, g-loads, and duration;
4. Very high-g environment such as suffered by bombs set for contact bursts.

Flight tests can create such environments not only singly, but in a realistically timed sequence, which is also important. A number of environments are impractical, if not impossible to simulate in the laboratory for a full-scale RV. These include, for example, aerodynamic drag or lift loads of 10s to many 100s of g for times of 10s of sec, and temperatures on the nose tip of 2000 K. In addition, ground-contact and penetration loads may be 10^4 g or more, with impact speeds greater than 3 km/sec. These loads and closing speeds are not directly attainable with rocket sled tests but require firing a rocket at a flyer plate, itself moving at high velocity. This scheme is not practicable for a full-scale RV. On the other hand, acceleration loads for aircraft-delivered

penetrator bombs are also very high, but are easily attained by dropping the weapon as it would normally be used.

Because of the limitations of ground testing there will be times when it is essential to test a system end-to-end, even though the critical subsystems under investigation could be thoroughly ground-tested. Such ground tests should still be carried out before flight tests, and should reproduce the above four critical environments as closely as possible.

Weapons scheduled for disassembly are good candidates for such ground tests. Every year, eleven of each type of stockpile weapon system are examined, the NEP of one of which is thoroughly disassembled and is therefore a good candidate to check for problems (e.g., aging effects) which could arise during the course of normal stockpile storage. Numerous other weapons, some of them representing types that are not scheduled to remain in the enduring stockpile, are also disassembled to meet treaty limits. A suggestion is that these weapons be subjected, after partial disassembly and certain other steps, to thorough system-level ground tests.² The actual tests performed will depend on whether the weapon is being retired or is intended to be returned to the active stockpile. For retired weapons of types remaining in the enduring stockpile, the primary and CSA can be replaced with high-fidelity test assemblies. All non-nuclear functions, such as arming, fuzing and detonator firing, can be tested with appropriate inputs mimicking those received from launch systems and environmental inputs. One could go so far as to detonate the high explosive, for example in one or two disassemblies each year. It is not clear how far one can go with weapons to be returned to the active stockpile, but there are no real barriers evident to system tests with JTA high-fidelity NEP components, after which the weapon would be reassembled with WR parts.

²The importance of taking advantage of studying these disassembled weapons, in more detail than is normally done, for signs of aging has been pointed out [1].

System-level flight tests are not intended to provide the primary surveillance of aging effects within the stockpile, as the latter is best done at the component or subsystem level on the ground. There is nevertheless an important synergy between the surveillance aspect of the Stockpile Stewardship Program and flight testing. Specifically, flight tests can provide invaluable confirmation that remanufactured components or any type of redesigned component of non-nuclear subsystems are not causing unanticipated degradation of overall system performance in operational environments. Sampling for flight tests should therefore not be on a random basis, but should be weighted either toward older units (in order to emphasize aging effects) or toward units containing remanufactured or redesigned (non-nuclear) components.

4 THE HIGH FIDELITY TRADE OFF WITH DATA RETRIEVAL IN SYSTEM-LEVEL FLIGHT TESTS

System-level flight tests provide two distinct but equally important types of information: 1) an integral test of the weapon system from launch through to the arming of the (inerted) nuclear device; and 2) data on the temperatures, accelerations, deflections and other aspects of the physical environment experienced by the components inside the warhead throughout the entire operational profile. There is an unavoidable tension between these two sets of objectives. For the first, the highest priority is to make as few changes to the system as absolutely necessary, the aim being to measure overall performance for a weapon system closely mimicking the war reserve (WR) unit. For the second, the goal is to extract the maximum amount of data possible from each test, which means the placement of large numbers of sensors and telemetry hardware inside the missile and RV, a process that necessarily requires changes to war reserve components. In either case, one modification that is always made is to remove the fissile material and replace it by non-fissile material, such as depleted uranium.

The present study was presented with the question of how one should choose in the tradeoff between these two objectives, fidelity of the test versus quantity and quality of data. It is concluded that there is no single choice that should be made, but that the best solution is to maintain a range of approaches between the two extremes. A well designed program should always include at least one of the highest-fidelity (potentially data poorer) tests for each weapon-system type over a multi-year cycle (say 3-5 years), the reason being that such tests are uniquely valuable. More data-rich tests, which are potentially lower in fidelity, should also be pursued but with great care that these are not duplicating studies that could be performed on the

ground, whether on components or the entire system. Indeed, these more data-rich flight tests should be planned and their results analyzed in the light of ground-based tests that have explored and exceeded the limits of performance of the system. Flight tests should not be used as a principal means of evaluating individual components, if for no other reason than that the statistics would be meaningless.

References

- [1] S. Drell *et al.*, JASON reports JSR-97-320 and JSR-98-320.
- [2] J. M. Cornwall, talk at the Symposium on Science and Society, AAAS Annual Meeting, 1990, New Orleans.

A System Level Flight Tests Presentation for the JASON Study

Tuesday, June 16,1998

9:00 A.M.	Introduction and Overview of Agenda	Rick Wayne, SNL
	<u>Policy and Background</u>	
9:20	<u>DOE Flight Test Design Directive</u>	Bob Lopez, DOE/AL
9:55	Historical Perspective of Flight Testing	Bob Peurifoy
	<u>Flight Test System Integration</u>	
10:55	<u>JTA Development Program from the Systems Perspective</u>	Russ Miller, SNL
11:30	Configurations, Diagnostics, Data and Impacts	John Duncan, SNL
12:15 P.M.	Lunch	
	<u>Requirements for Data and the Reasons</u>	
1:30	<u>Nuclear Explosive Package Data Needs</u>	Erwin Schwegler, LANL Dick Baxter, LLNL
3:00	Non-nuclear Data Needs	Russ Miller, SNL
3:30	Break	
	<u>Technology Development Activities</u>	
3:45	<u>Impact of New Requirements on Data System Architecture</u>	Art Hull, SNL
4:30	End day	

Wednesday, June 17,1998

9:00 A.M.	Measurement Technologies Being Developed	Dave Ryerson, SNL Ted Crawford, LANL Erwin Schwegler, LANL Dennis O'Brien, LLNL
12:15 P.M.	Lunch	
	<u>Summary</u>	
1:15	<u>Integrated JTA Program Plan</u>	Bob Lopez, DOE/AL
1:45	General discussion	All participants
	Answers to questions not adequate covered	
	Additional related topics if requested by JASONS	

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