DTRA National Ignition Facility (NIF)

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JASON was asked to address the utility of the National Ignition Facility (NIF) to the Defense Threat Reduction Agency (DTRA) mission of determining the effects on DoD systems of the X-ray environments produced by nuclear weapons. Many DoD systems, such as re-entry vehicles and satellites, have survivability requirements that cannot presently be tested. A modest joint research and development program by NIF scientists and DTRA should, within a few years, enable useful large dose-area testing of important DoD systems that cannot be performed with any other facility, existing or planned. The fidelity with which the X-ray sources that the NIF can produce will simulate a particular nuclear weapons X-ray environment requires detailed analysis. A much longer-term possibility is that the X-rays produced by high-gain fusion ignition capsules might provide a capability closer to that of UGT's, particularly in the 15-100 keV X-ray band. We conclude that DRTA should monitor developments in the NIF ignition campaign and open discussions with NIF scientists on the development of a high fidelity x-ray environment for large area testing, including addressing the neutron eradication question, when ignition has been achieved.

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Abstract

This report addresses the utility of the National Ignition Facility (NIF) to the Defense Threat Reduction Agency (DTRA) mission of determining the effects on DoD systems of the X-ray environments produced by nuclear weapons. Many DoD systems, such as re-entry vehicles and satellites, have survivability requirements that cannot presently be tested. This is because, since the cessation of underground tests (UGT's), available facilities cannot produce X-ray environments of sufficient intensity over a large enough area, or with the correct X-ray energy spectrum and pulse duration, to carry out all necessary tests.

We conclude that using the NIF laser beams to generate X-rays directly from underdense plasma targets could provide a valuable new capability for low-energy (≤15 keV) X-ray effects testing that would complement existing capability. A modest joint research and development program by NIF scientists and DTRA should, within a few years, enable useful large dose-area testing of important DoD systems that cannot be performed with any other facility, existing or planned. The fidelity with which the X-ray sources that the NIF can produce will simulate a particular nuclear weapon's X-ray environment requires detailed analysis.

A much longer-term possibility is that the X-rays produced by high-gain fusion ignition capsules might provide a capability closer to that of UGT's, particularly in the 15-100 keV X-ray band. However, source characteristics, including the level of simultaneous neutron irradiation, and when high-gain ignition might be achieved at the NIF are both uncertain. We conclude that DTRA should monitor developments in the NIF ignition campaign and open discussions with NIF scientists on the development of a high fidelity X-ray environment for large area testing, including addressing the neutron irradiation question, when ignition has been achieved.

1 EXECUTIVE SUMMARY

The Defense Threat Reduction Agency (DTRA) mission includes providing the capability to test the effects of nuclear-weapon-produced radiation environments on such Department of Defense (DoD) systems as re-entry vehicles and satellites. Although the survivability of a system involves its response to intense neutron as well as X-ray irradiation, this report is concerned with X-ray effects testing only. JASON has been tasked by DTRA to determine if the Armed Services and other DoD units, such as the Missile Defense Agency (MDA) can and should take advantage of the availability starting in 2009 of a new national asset with X-ray effects testing capability, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL).

The NIF offers two very different X-ray effects testing possibilities. The first is a near term (starting in 1-2 years) low-risk capability that would complement and could substantially enhance existing testing capability for the "cold" portion, ≤ 15 keV, of the X-ray spectrum. The second is a long-term possibility that assumes the NIF achieves high-yield (30-100 MJ or even more) fusion ignition.

The first capability would be obtained by directing the laser beams at high intensity onto specially designed "under-dense plasma" targets that would vary according to the specific subsystem and survivability requirement(s) being tested. It would not include any possibility of confounding effects due to the presence of neutrons. It is, therefore, expected that high fidelity[1] testing of particular systems in some specific X-ray dose, dose-rate and uniformity environments can be achieved by careful choice of the target material(s) and density (to adjust the X-ray spectrum and optimize its yield), and the laser intensity temporal profile. However, the actual X-ray environments that can be generated by the NIF must still be determined experimentally, and specific tests may still be most effectively carried out on other available test facilities, depending upon timing and cost constraints.

The second X-ray environment is possible only if and when the NIF achieves ignition and a fusion yield of several tens of MJ or more. In this case up to about 20% of the fusion yield might be converted to X-rays, a fraction of which will be useful for high fidelity weapon effects simulation. However, the natural X-ray pulse from an ignition target must be stretched and, for most test requirements, the neutron dose must be substantially reduced at the test object in order to have a high fidelity test. It is as yet unclear how best to accomplish those two necessities.

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[1] *High fidelity testing requires that the X-ray spectrum provide the same energy deposition spatial profile in a test object, with a time dependence that assures the same physical effects are induced, as the actual threat spectrum. In addition, there must not be confounding effects from other sources of energy or component damage, such as neutrons.*

Our principal finding is that within just a few years, the NIF lasers should be able to provide important X-ray effects testing capability that is not presently available to the nuclear weapons effects (NWE) test community by simply delivering the NIF laser beams at high intensity to under-dense plasma targets. Converting the 1-1.8 MJ of laser energy at a laser wavelength of 351 nm that will be available at the NIF in the 2010-2011 time frame into ≤ 2 keV X-rays with 30-60% efficiency in a low debris environment is one important possibility. Another would take advantage of perhaps 10% conversion efficiency to 10-15 keV X-rays, again anticipating a low debris environment. These capabilities would complement those that are available from such existing large-scale X-ray effects testing facilities as the Saturn and Z pulsed power machines at Sandia National Laboratories, Albuquerque. These two machines provide, for some purposes, satisfactory testing environments in the 2-10 keV range, and Saturn is commonly used for testing the effects of ~150 keV X-rays. Other facilities, such as Double Eagle, that are well known to the X-ray effects testing community, can also provide valuable capability in these portions of the X-ray spectrum.

A few years further in the future (after 2015), up to 3.4 MJ of green (527 nm) laser light may be available for X-ray effects testing. This could permit the production of useful x-ray environments with higher total X-ray energy and with the spectrum extending up to 20 keV. If X-ray generation efficiencies are as high as predicted by computer simulations, full threat-level testing in the lower photon energy ranges could be possible.

As a result, we recommend that DTRA initiate a modest experimental X-ray source development and characterization program in collaboration with NIF scientists beginning at a level of perhaps 2-3 FTE's. The goal of this effort would be to develop and accurately calibrate the highest priority x-ray environments for X-ray effects testing that can be produced by the NIF at the ~ 1 MJ laser energy level. The size and cost of this program would escalate as it transitions from research and development to testing of systems, as the latter will involve some facility engineering and operations requirements. Dedicated data acquisition facilities may also be needed.

DTRA's intention to involve university scientists in the effects testing program can benefit from the NIF X-ray source development program. Since it is unclassified research (and is not restricted to US citizens), university faculty and graduate students would be able to carry out fundamental X ray source and application science alongside NIF senior scientists as they develop the NIF laser-based X-ray source for weapon effects testing. Thus, this is a potential means to develop a new generation of scientists interested in X ray weapon effects testing.

The long-term possibility of producing a high fidelity test capability in the 15-100 keV X-ray energy range for meter-scale objects depends upon the NIF’s achieving high gain fusion ignition, an uncertain prospect at present. The issues of simultaneous neutron irradiation, X-ray pulse stretching and debris management while achieving the required X-ray fluence and spectrum in a practical experimental configuration remain to be addressed. Development of a credible conceptual design to convert the energy of a high gain fusion capsule into a high fidelity X-ray effects test environment of interest to the DoD is likely to involve a substantial program of computer simulations, and implementing it is likely to involve a major engineering project.

We recommend that DTRA should monitor developments in the NIF ignition campaign and open discussions with NIF scientists on the development of a high fidelity X-ray environment for large area testing, including addressing the neutron irradiation question, when ignition has been achieved.

2 INTRODUCTION

2.1 Background

The Defense Threat Reduction Agency (DTRA) mission includes responsibility for developing and maintaining the Nuclear Weapons Effects (NWE) testing capability of the Department of Defense (DoD). The goal of the NWE testing program is to determine the capability of such important military systems as re-entry vehicles and satellites to survive nuclear weapon-produced environments that they might encounter in the course of operation. Although the ability of a system to survive the effects of a nuclear explosion involves its response to intense neutron as well as X-ray irradiation, this report is concerned with X-ray effects testing only as neutron effects on systems are considered to be reasonably well understood from earlier testing using a combination of test facilities. In particular, DTRA has tasked JASON to determine if the Armed Services and other DoD units, such as the Missile Defense Agency (MDA) can and should take advantage of the availability starting in 2009 of a new national asset with X-ray effects testing capability, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL).

Ideally, a military system should be as resistant as possible, i.e., “hardened,” to the effects of radiation from a nuclear weapon explosion X-ray environment. To achieve a high level of radiation hardening requires that a system be designed to be immune to the effects of radiation, many of which were discovered only as a result of the X-ray effects testing program. Some of those discoveries were made in component or subsystem level tests that were carried out in laboratory facilities. However, others were found only in full system tests that were carried out using X-rays produced by underground nuclear explosions [1], a capability that has not been available to DTRA since 1992. Furthermore, budget limitations and priority changes have resulted in DTRA’s no longer supporting laboratory, “above-ground,” X-ray testing facilities based upon pulsed power machines. Some have been closed down (e.g., the Decade Facility) and others are to be maintained and operated by private enterprise for use by the Armed Services and other DoD agencies that have X-ray effects testing requirements [2]. For much of its X-ray facility needs, DTRA plans to rely on NNSA-supported facilities at the national laboratories. At present, the largest of these facilities are based upon pulsed power generators such as the Z-machine and Saturn at Sandia National Laboratories, Albuquerque (SNLA). Saturn, for example, operating as a source of ~150 keV X-rays produced by few-hundred keV electrons, is evidently a satisfactory facility for component, subsystem and even system-level testing of hardness to X-rays in that region of the nuclear weapon X-ray spectrum. However, at the present time, there are no X-ray sources capable of realistic testing of full system hardness to the so-called “cold” and “warm” portions of the X-ray spectrum below about 15 keV and between 15 and 100 keV, respectively.

Laser-based X-ray sources offer an alternative to pulsed power generator-base sources for X-ray effects testing. In recent years, the NNSA-sponsored OMEGA laser facility at the Laboratory of Laser Energetics, University of Rochester, has been used for X-ray source development experiments and small-scale effects tests. Based upon the OMEGA experiments, experiments in the 1990's on the NOVA laser at LLNL and computer simulations, the laser system at the NIF is projected to be capable of large dose-area product testing [3] in the "cold X-ray" spectral range (up to 15-, and perhaps 20-keV, depending upon the available laser energy) with a low debris and low electromagnetic noise environment. In anticipation of the use of the NIF for NWE testing, a large area (2.5 m by 1.5 m) "hatch" was included in the NIF target chamber at DTRA's expense to enable testing of ~1 m-scale DoD systems.

The context within which the present JASON study was undertaken includes two additional important elements. The first is a Defense Science Board (DSB) task force report that "encourages DoD to migrate to a modeling and simulation (code) based approach for „certifying' DoD systems" in the future, whether rebuilt with new components and subsystems or totally new [4]. Assuming this recommendation is followed, it will be essential for the models in the simulation codes, and the codes themselves, to be validated against a variety of experiments at small, intermediate and large scale. This point was also made in the DSB report. The second element is the DTRA experimental program plan provided to us [5] that is evidently intended to address the need for data from a variety of facilities for code validation as well as to develop the capability to use the NIF for X-ray effects testing.

Another DTRA goal described to us [6] is the development of a new generation of applied scientists interested in X-ray interaction with matter and, therefore, potentially interested in working in the DoD X-ray effects program, both on the experimental side and in modeling and simulation. At this stage, much of the work on X-ray source development at the NIF is expected to be unclassified and could provide an opportunity for bringing new people into the X-ray effects testing community.

Finally, it is important to bear in mind that there are two distinct categories of need for X-ray effects testing. First there are small and intermediate scale experiments. Some of these are intended to answer specific questions about how X-rays can damage specific components or subsystems, either directly by energy deposition or by induced electrical effects, while others are intended to address issues related to the interaction between two or more components and subsystems. The second category of tests are those that are intended to determine if major subsystems or even entire systems can meet the hardening requirements set for a weapon system or satellite. A common requirement for both is that the test environment must be "high fidelity," i.e., the X-ray spectrum must provide the same energy deposition and spatial profile in a test object, with a time dependence that assures the same physical effects are induced, as the actual threat spectrum, so that the test result will be a valid predictor of performance under a real threat. In addition, there must not be confounding effects from other sources of energy or direct component damage, such as neutrons.

While the full system tests place special requirements on the dose-area product and uniformity of the radiation environment, as we will discuss in Section 3, the smaller and intermediate scale experiments typically require less than 100 cm^2 of test area with a reasonably uniform dose. Thus, the large dose-area product capabilities projected for the NIF, to be discussed in Section 4, are not necessary for many of the experiments that the NWE test community wishes to perform.

To facilitate our study, we had briefings on the NWE testing requirements and programs of the MDA, the Air Force and the Army, as well as on the status of DTRA's NWE simulator program and on the importance of simulation fidelity. We also had a set of briefings on the capabilities of the NIF and on how it might be used to address DoD testing requirements. We wish to thank independent consultant Dr. Cyrus P. "Skip" Knowles and Chris Keane, Kevin Fournier and Larry Suter of LLNL, especially for taking the time to answer follow-up questions by e-mail and telephone calls.

2.2 The National Ignition Facility and its use for X-ray Effects Testing

By March of 2009, the NIF will be capable of delivering about 0.45 MJ of ultraviolet light in 96 laser beams at 351 nm wavelength, commonly called "blue," to the center of a 5 m radius test chamber. As the facility commissioning proceeds, the total laser energy in blue light delivered by NIF's full complement of 192 laser beams to target-chamber-center (TCC) will grow to 1 MJ or more in routine operation, with up to 1.8 MJ available for a limited number of tests.

The principal mission of the NIF in its first 2-3 years of operation is to use the blue laser light to induce fusion ignition in a spherical capsule containing fusion fuel, which consists of the hydrogen isotopes deuterium and tritium. Ignition is taken to mean that the fusion energy yield from the deuterium-tritium reactions is to be at least equal to the laser energy delivered to the target that includes the fuel capsule. Computer simulations suggest that a yield of 10-20 times the delivered laser energy can be achieved by the NIF operating in the blue by optimizing the target design and the laser temporal power profile.

The NIF laser system produces the blue light by frequency tripling the 1.055 μm wavelength infrared laser beam produced by the facility. (As such, the 351 nm light is often described as "3ω," where ω refers to the radian frequency of the "fundamental" 1.055 μm wavelength laser light.) It is also possible to modify the final optical components of the NIF to deliver up to 3.4 MJ of 527 nm light (frequency-doubled 1.055 μm light) to the TCC. This modification is presently planned to be implemented in 2015 because computer simulations predict that more than 100 MJ of fusion yield may be possible with ~ 3 MJ of 527 nm ("green") laser light. This possibility depends upon the not-yet-demonstrated control of laser-plasma instabilities that are expected to be more easily controlled with 351 nm laser beams. (This is the reason for the initial ignition campaign with 351 nm light even though the available laser power and energy is substantially less than at 527 nm.)

Further discussion of fusion-ignition on the NIF is beyond the scope of this report. However, we will discuss the potential value to the DoD of using NIF-ignition-driven X-ray sources for testing NWE survivability in Section 4.2.

DTRA's motivation to develop an X-ray NWE test capability on the NIF became strong with the cessation of underground nuclear explosions in 1992. As we have already noted, up until then, the "rad-hardness of a system," i.e., its ability to survive a specified intense radiation environment produced by a nuclear weapon, was determined using X-rays from underground explosions. In anticipation of the potential importance of having such a capability at the NIF, a large area (2.5 m by 1.5 m) hatch was included in the NIF target chamber at DTRA's expense to enable testing of ~1 m-scale DoD systems. Furthermore, the rest of the facility was designed and built with the expectation that NWE testing would be one of its important secondary missions. In the middle 1990's, an X-ray effects testing users group was formed for the NIF. This group estimated the x-ray environments of interest to the DoD that might be available using the NIF in two modes that will be discussed briefly in the next subsection and in more detail in Section 4.

Potential use of the NIF for X-ray effects testing should be considered in the context of other X-ray effects testing facilities available to the NWE testing community. DTRA maintained a set of NWE effects testing facilities for 4 decades (as DASA and DNA before the agency became DTRA) that are now either closed down or are to be maintained and operated by private enterprise for use by the Services and other DoD agencies. The remaining major U.S. X-ray effects testing facilities are the NNSA-sponsored facilities at Sandia National Laboratories, Albuquerque (SNLA), including the Saturn and Z pulsed power machines. (SNLA also operates the Hermes III facility, which is used for testing systems' survivability against the γ-ray component of the nuclear weapon environment.) Saturn is used effectively for ~ 150 keV X-ray effects testing using bremsstrahlung radiation produced by ~100 ns duration, multimegampere pulses of few-hundred keV electrons. The Z-machine can be used to produce $10^5 - 10^6$ J of ≤ 10 keV X-rays from plasma radiation sources driven by ~20 MA submicrosecond current pulses. For some X-ray effects experiments and for component and sub-system testing, it is possible that the Z-machine can provide an environment similar to that projected for NIF, assuming debris mitigation is carefully designed into the experiments/tests.

2.3 The NIF as an X-ray Source

The NIF offers two very different X-ray effects testing possibilities. The first is a near term (starting in 1-2 years) low-risk capability that would complement and could substantially enhance existing X-ray effects testing capability. It would be obtained by directing the laser beams at high intensity onto specially designed targets, creating so-called "underdense plasmas," which will be discussed in detail in Section 4.1. This mode of operation would not include any possibility of confounding effects due to the presence of neutrons, and experience to date in experiments on the OMEGA laser facility suggest that a low-debris test environment can be achieved. Thus, it is expected that this source can be designed to enable high fidelity testing of meter-scale DoD systems by careful choice of the target(s) and laser intensity temporal profile in perhaps as little as 2 years.

The second NIF X-ray environment is possible only if and when the NIF achieves ignition and a fusion yield of several tens to 100 MJ or even more. Up to about 20 percent of the fusion yield might be converted to X-rays, but the ignition-based X-ray pulse must be stretched and the neutron dose must be substantially reduced at the test object in order to have a high fidelity test for most DoD applications. Thus, this mode of operation could eventually enable realistic survivability testing of full meter-scale DoD systems; however, it must be considered long term with unknown probability of success because it requires that the NIF achieve ignition and high yield, and that a method be developed to stretch the X-ray radiation pulse and eliminate the neutron irradiation of the test object without excessive reduction of the X-ray intensity on the test object.

Both of these potential NIF X-ray sources will be discussed in more detail in Section 4.

2.4 The Charge to JASON in Summary and a Summary Response

2.4.1 The task summary statement

The charge to JASON includes a summary task statement, which we present here. A brief summary of our findings, conclusions and recommendations follows. A more detailed response to the task summary, as well as to the specific questions in our charge statement, is given in Section 5.

JASON task summary *- Evaluate the feasibility of DoD's using the National Ignition Facility (NIF) for high fidelity radiation effects testing in the near future and after ignition is achieved. JASON will make firm recommendations in line with the risks associated with return on investments as a principal focus within the study.*

2.4.2 Summary of findings, conclusions and recommendations

It was abundantly clear that not all X-ray effects testing requirements can be met by the simulators presently available to the DoD (nor could they have been met including the facilities that have been closed down recently by DTRA). For example, it has not been possible since the cessation of underground testing to achieve the necessary X-ray dose over a large enough area to determine if full DoD systems can meet current radiation hardening requirements in the cold (under 15 keV) portion of the spectrum, and there is very little capability to do even small scale experiments at high fluence levels in the 15-100 keV spectral range. (Requirements will be discussed in Section 3.)

Experiments have shown that directing high intensity laser beams onto appropriate underdense plasma targets can produce very useful sources for X-ray effects testing spanning the "cold X-ray" portion of the threat spectrum up to perhaps 13-15 keV. Scaling of experimental results from the NOVA and OMEGA lasers to the NIF suggests that the NIF lasers directed onto carefully chosen targets could provide higher cold X-ray dose-area product test environments than are available at any other NWE simulation facility, especially after 3.4 MJ of green laser light is delivered to the target chamber starting in 2015.

We recommend that DTRA should join with NIF scientists to develop and characterize underdense plasma x-ray sources of greatest value to the DoD testing community starting when the NIF laser system becomes operational in 2009. The joint effort can be initiated at the 2-3 FTE level, but the program cost will surely escalate as it transitions to testing because of the need to include facility engineering costs and dedicated data acquisition systems. Source characterization must include careful calibration of the full range of spectral components produced by the laser impinging upon a given target. It must also include determining the detrimental effects of stray laser light at all three wavelengths as well as the possibility that the debris problem may be more significant in NIF experiments than is anticipated based upon the OMEGA experiments.

We further recommend that this characterization program would be a good vehicle for DTRA to enable university scientists to become involved in the X-ray radiation effects program. The laser-driven X ray source characterization program is unclassified, which means that university faculty and students could work on fundamental X ray source science alongside NIF scientists on the world's most energetic laser. This opportunity could help to develop a new generation of scientists to work in the area of X ray radiation weapon effects testing.

In order to avoid surprises related to the cost to DTRA of carrying out tests on the NIF, it is important that DTRA and DOE/NNSA have a firm agreement in place as soon as possible that apportions in some reasonable way the costs of developing the source for each specific radiation environment needed by the DoD, for carrying out necessary facility engineering, and for operating the facility for tests. It is also important that DoD agencies compare the cost-effectiveness and schedule of using the NIF vs other simulation facilities, such as the upgraded Z-machine at SNLA, when such other facilities may also be able to meet the experiment or test requirements.

According to computer simulations, it is possible that an ignition-based X-ray source may enable testing in the 15-100 keV X-ray energy range, but very high yield, ~ 100 MJ, would be required, and the ultimate source characteristics cannot presently be specified. Also, if and when this capability may be achieved is uncertain. In our view, the use of a high yield fusion capsule as an X-ray source for weapon effects testing has not yet progressed to the point of a defensible conceptual design for a test configuration that would produce a high fidelity x-ray environment needed by the DoD test community. We, therefore, recommend that a conceptual design be developed at the ~1 FTE level by NIF staff scientists in anticipation of the achievement of ignition within the next few years. When that happens, DTRA can determine, based upon the credibility of the conceptual design, if a significant program is warranted to develop the NIF-ignition source for weapon effects testing. If so, DTRA can then initiate discussions with NIF scientists on developing a high fidelity X-ray environment for high fluence-area-product system testing, including addressing the neutron irradiation question.

Regarding the DSB-suggested goal of pushing toward a modeling and simulation-based capability to determining if a system design is adequately radiation-hardened, the data that are needed to validate the modeling and simulation codes will require a substantial experimental program. We believe that the success of this program will be facilitated if the components and subsystems used in experiments in the validation experiments, and eventually in the DoD systems, are designed to simplify the modeling and simulation and the validation process. We therefore recommend that DTRA endeavor to bring the appropriate people together in order to enable such a design process to be developed.

3 REQUIREMENTS

Military requirements for re-entry vehicles, satellites, sensor systems, etc., include survivability in radiation environments created by nuclear explosions that the systems could encounter in the course of their missions. These environments can include combinations of x-rays, gamma rays, neutrons, blast waves, and electromagnetic pulses (EMPs). The various insults induce various effects:

- The lowest energy range X-rays (<10 keV) deposit energy in the outer skin of a re-entry body or in reflective layers of sensor optics, causing surface blow-off. The blow-off, in turn, can cause mechanical damage, sharp acceleration of the body away from the blow-off or, in the case of a reflective layer, degraded reflectivity.

- Intermediate energy (10-100 keV) and high energy (≥100 keV) X-rays are absorbed by components inside a warhead, satellite or missile defense kill vehicle, inducing rapid local thermal expansions that in turn cause structural motion and permanent deformation, direct effects on electronic components (e.g., radiation-induced upsets) and radiation induced currents and electromagnetic effects (e.g., in cables and electronic subsystems).

- Neutrons react with nuclei throughout the warhead, producing gamma-rays through radiative-capture reactions and causing displacement damage, heating, and radiolysis.

- Gamma-rays react throughout the warhead causing transients electronic effects and dielectric breakdown.

- EMPs induce potentially damaging currents in cables and components.

- Blasts induce potentially damaging dynamic loads.

The X-ray environments that DoD systems must survive are quantified in DNA 6500H, “The Nuclear Warhead Modeling Handbook,” which is currently being updated, and MDA-STD-001, the High-Altitude Exo-Atmospheric Nuclear Survivability (HAENS) Standard for MDA.

It would be unreasonable to expect a laboratory facility to generate the complete threat environment that a full system is required to survive. Even the underground nuclear effects tests performed years ago exposed components and systems to environments that only approximated the DNA 6500H-defined threat environments. The goal is to combine theoretical analysis, modeling and computer simulation and sufficient testing to judge with high confidence whether components and systems can survive the defined threats.

This study addresses effects induced by X-rays, not by neutrons, gammas, EMPs, or blasts. X-ray effects arise from absorbed dose (i.e., deposited energy), which is a function of the total fluence incident upon the component of interest (cal/cm^2) and the distribution of the incident X-ray photons in energy, position, and time. The total fluence incident upon a component is the spectral integral of the incident spectral fluence (cal/cm^2/keV).

Different components in a system, such as a re-entry vehicle, satellite or kill-vehicle, see different fluences and spectra from a given postulated threat, as illustrated in Figure 1. The outer surface of a system (re-entry body or satellite, for example) sees the full intensity and complete spectrum of the X-rays that reach it. Inner components see intensity and spectra that have been "filtered" by the materials between them and the outside of the system. As a result, the deeper one goes into a system, the lower is the total fluence and the "hotter" is the spectrum, where "hotter" refers to higher average photon energy. (X-ray absorption rates tend to be higher for lower-energy X-rays, causing preferential filtering of the "colder" portion of the spectrum.)

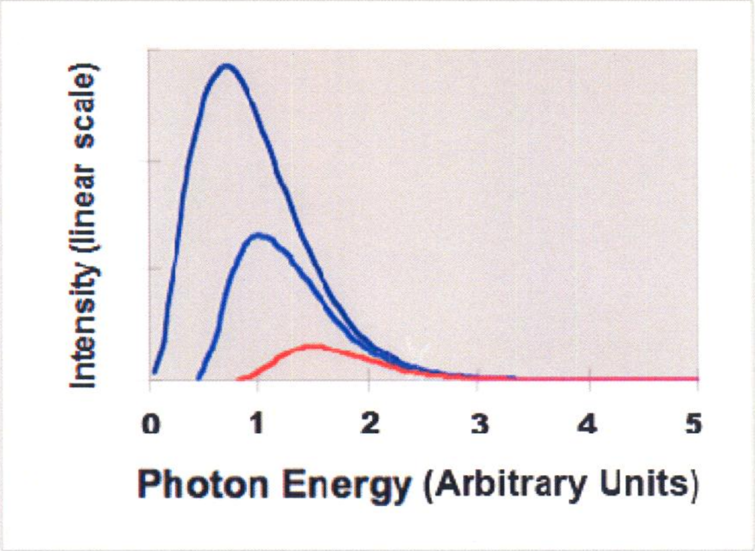

Figure 1. Illustration of different intensities seen by different components (arbitrary units) of a re-entry body. The upper curve is a blackbody spectrum, our illustration of the intensity that could be incident upon the outer surface (heat shield) of the body. The middle curve illustrates the resulting intensity incident upon the air frame. The heat shield has filtered out the low-energy photons. The bottom curve represents the intensity incident upon components inside the air frame. The air frame has further filtered the spectrum, shifting it to higher average energy but lower total intensity. *[Figure adapted from Ref. 7]*

If we consider the absorbed dose to various components that would be produced by the environments quantified in DNA 6500H, we could produce an "envelope" or bounding curve of fluence (cal/keV) as a function of photon energy (keV). Such envelopes have been produced, and two are shown in Figure 2, one for a system that must be very effectively hardened and the other for a system that requires about a factor of 100 less hardening. In a given energy range, the envelope fluence is the product of a fluence spectrum (cal/cm^2/keV) and an area appropriate for components in which the absorbed dose would be caused mostly by photons in that energy range.

If testing facilities could produce fluences as high as these envelopes with sufficient spatial uniformity and the correct temporal profiles, then they could subject components and systems to the same absorbed doses that they would receive in the defined threat environments. It is therefore desirable that for each energy range we have at least one test facility that can produce the intensity-area product defined by each envelope.

The Nation does not currently have test facilities that can produce intensity levels as high as the upper envelope shown in Figure 2 in much of the X-ray energy range below 100 keV, above which bremsstrahlung facilities such as Saturn can meet the requirement. This is particularly pronounced in the 10-100 keV range. Thus, a key question we address is whether NIF can help fill this gap and provide significantly improved capability to test components and systems with X-rays in this energy range.

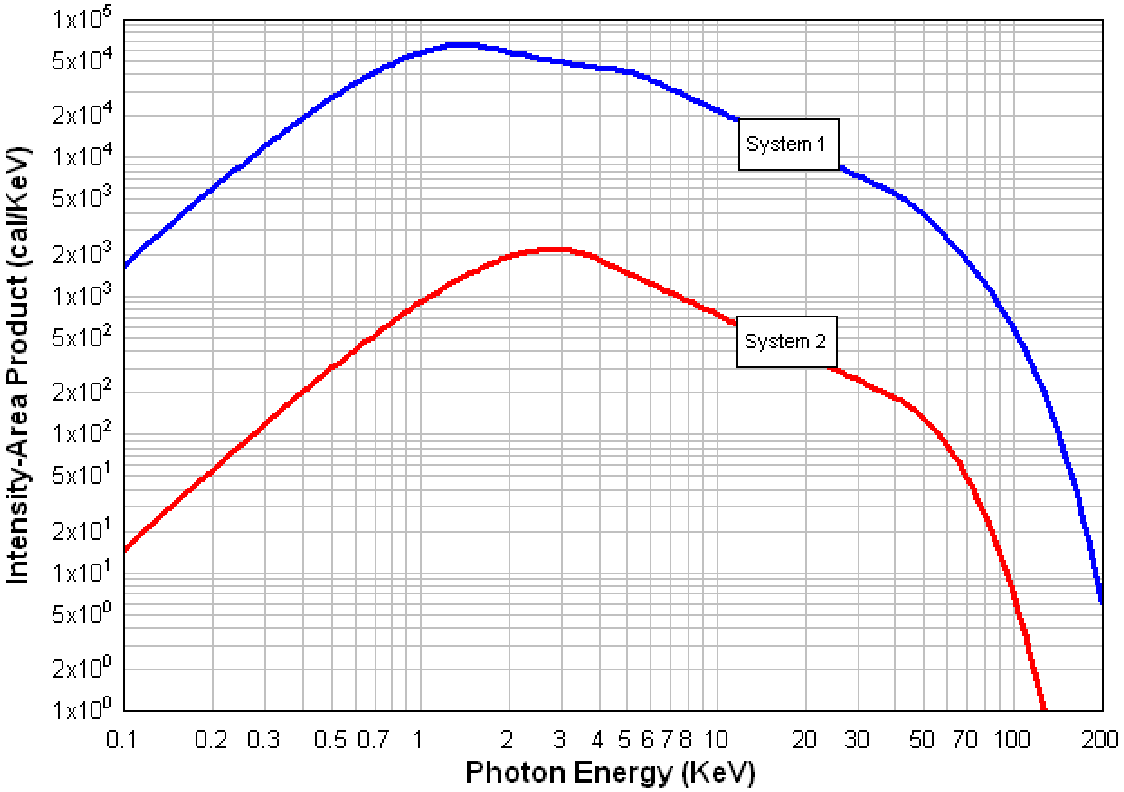

Figure 2. Generic envelopes of test environments. See text for explanation.

4 X-RAY GENERATION BY THE NIF, NEAR TERM AND LONG TERM POSSIBILITIES

4.1 X-ray Generation by Intense Laser Interaction with Underdense Plasmas

In the near term, the NIF facility can generate X rays with energies and intensities of interest to DTRA based on underdense, laser-heated plasmas. Underdense targets can convert several tens of percent of the laser pulse energy into X rays in the range ≤ 10 keV through nonlinear interaction of the high intensity electromagnetic waves of the laser with the plasma and subsequent highly ionized ion line, free-bound continuum and bremsstrahlung emission. As there are no nuclear reactions taking place, there are no confounding effects due to simultaneous neutron irradiation. These sources are particularly suited for X-ray effects testing in the cold portion of the spectrum as they can be efficient (~50% or more ≤ 3 keV and perhaps as high as 10% in the vicinity 10 keV) with proper choice of target material, plasma density and laser intensity.

For present purposes, an underdense plasma is defined as one for which the electron plasma frequency, $\omega_{pe} = (n_e e^2/\varepsilon_o m)^{1/2}$ is lower than the laser frequency $\omega = 2\pi c/\lambda$, where n_e is the electron density, e, m, c and ε_o are the electron charge, the electron mass, the speed of light and the permittivity of free space (MKS constant), respectively, and λ is the laser wavelength. Therefore, according to elementary plasma wave theory [8], the laser can propagate through the plasma, whereas it would be reflected if $\omega_{pe} \geq \omega$. The electron density at which $\omega_{pe} = \omega$ is called the critical density. For a 1 μm laser the critical density is 1.1×10^{21} /cm^3, and it scales as the inverse square of the wavelength. As such, the density for reflection of the 351 nm laser wavelength of initial NIF operation is about 10^{22}/cm^3. (For comparison, the gas density of 1 atmosphere of air at 0^o C is about 2.7×10^{19}molecules/cm^3 while solid density aluminum is about 6×10^{22} atoms/cm^3.) The earth's ionosphere is familiar underdense plasma for light and even for microwaves, but depending on the time of day, it can reflect radiowaves with wavelengths exceeding a few tens of meters.

A typical target for X-ray generation prior to irradiation by an intense laser beam is a high Z gas such as krypton, or a mixture of gases, such as krypton and xenon, at a pressure of about one atmosphere. The gas is contained in a thin-walled beryllium cylinder or a small balloon. One can also use aerogels doped with mid-to-high-Z elements like germanium. The aerogels can be made even lower mass-density than air. Targets of both types have been fabricated and tested, and they are relatively simple to make, especially in comparison with ignition targets (see Figure 3).

When a high-intensity laser pulse (>10^{14} W/cm^2) hits such a target, the leading edge of energy deposition in the target slows down relative to the speed of light as energy in the laser front ionizes the atoms and heats the electrons of the resulting plasma. This enables multiple ionizations of the atoms in the underdense plasma target and efficient absorption of the laser energy, effectively slowing down the speed of heating front propagation by the laser through the plasma. The highly ionized, but still underdense, plasma that results is relatively transparent to the laser. Therefore, the beam front can

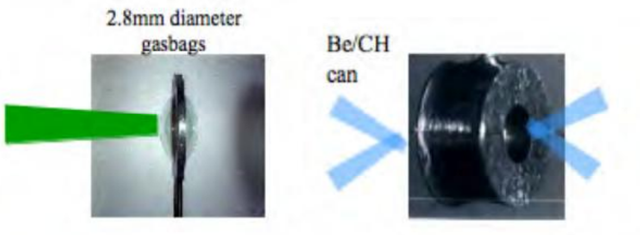

Figure 3. Examples of targets that become underdense plasma radiators when irradiated by high intensity laser beams. The "gas bag" on the left might be filled with ~1 atm of Kr + Xe, and the Be or CH cylinder on the right might be filled with a Ti or Ge-doped Aerogel. *[Modified from ref. 9.]*

Move forward as it uses its energy to convert more and more of the target material to hot plasma. There is sufficiently little material in the underdense plasma that the velocity of the "bleaching wave" exceeds the speed of sound in the unheated regions, and the whole target can be converted to underdense plasma before appreciable hydrodynamic expansion has occurred. Representative bleaching wave velocities in targets that convert laser energy efficiently to X-rays are of order 1 mm/ns. Therefore, a 1 ns laser pulse produces a ~1 mm long plasma radiation source.

The electrons of the underdense plasma have temperatures on the order of a few keV and densities 10-20% of the critical density for optimum X-ray production efficiency. Typical electron densities for 351 nm light are, therefore, about $10^{21}/\text{cm}^3$. Lower-Z elements in the target plasma, e.g., Ar, are fully ionized, but the higher-Z elements are only partially ionized. For example, a typical charge state of xenon might be near 44 (a neon-like xenon ion). As a result, collisions of the hot electrons with, for example, xenon ions can excite electrons from both the M shell (principal quantum number n=3) and the L shell (principal quantum number n=2), and energetic tail electrons can even produce holes in the K shell (principal quantum number n = 1). High energy X rays are produced as vacancies in these shells are filled by electrons in higher energy states, giving line radiation, or by unbound electrons, giving free-bound continuum radiation. The spectral fluence of the line radiation substantially exceeds the free bound continuum fluence from underdense plasmas and provides a very efficient way to convert the energy of hot electrons to high energy X rays.

If a laser-driven X-ray source starts out as a solid density target, the plasma generated by the laser at the solid surface is overdense (i.e., its electron density exceeds the critical density for the laser). Therefore, energy is coupled into the target poorly, generating plasma within it inefficiently and slowly enough that the bleaching wave moves subsonically. As a result, the un-illuminated material ahead of the plasma front is accelerated forward by the pressure of the plasma that is ablating and expanding off of the target surface back toward the laser. In that plasma, the electrons have temperatures comparable to those of underdense targets, but because of the rapid expansion of the ablation plasma, the electron density is much smaller and it does not radiate efficiently. This picture is very much like the process that causes implosion of an inertial confinement fusion (ICF) fuel capsule that is directly driven by a high-energy laser. A substantial fraction of the laser's energy is used to accelerate the un-illuminated material ahead of the ionization wave. This is highly desirable for ICF targets, but it means that the energy efficiency of ≥ 1 keV X-ray production starting from a solid density target is considerably lower than from an underdense plasma target. This is shown in Figure 4, in which the conversion efficiencies (CE) of laser energy into 4-8 keV X-rays by a Xe gas target and a solid CsI disk target are plotted vs electron density. (Cs and I are immediately above and below Xe in the periodic table.) These experimental results obtained using the NOVA and OMEGA lasers are also compared with computer simulations in Figure 4, showing that good agreement is obtained using 2D computer simulations. This suggests that the physics of X-ray production from initially solid density and initially ~ 1 atmosphere high Z gas targets is reasonably well understood. Please see Ref. 9 and references therein for further information about these experiments.

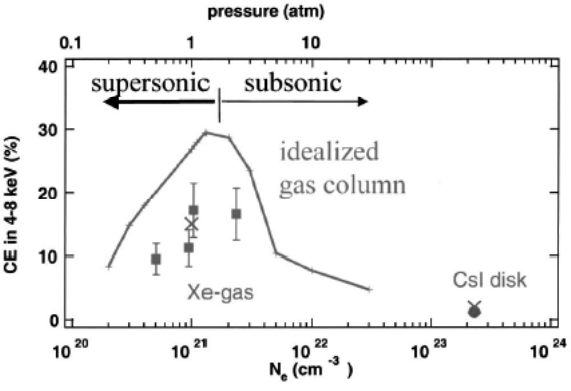

Figure 4. Conversion Efficiency (CE) of laser energy into X rays in the 4-8 keV energy band as a function of the electron density in the plasma of the target. The experimental results were obtained with the NOVA and OMEGA laser systems delivering 35 and 20 kJ, respectively, to the target. The plasma density was varied by changing the initial gas pressure over the range 0.5-2.5 atm. The X symbol marks the calculated CEs of the 1 atm Xe and CsI disk targets using a 2 D simulation. *[From Ref. 9]*

In summary, there has been high-quality modeling and good validation experiments on underdense plasma targets as sources of high-energy x rays. While there may be surprises as these experiments are scaled up to the much higher drive energies expected from NIF, it is our judgment that the physics is well enough understood that the relatively high X-ray production efficiencies projected for the NIF by the proponents of underdense plasmas, as shown in Figure 5, will be delivered within a factor of two. Clearly the essential next step is to determine if the calculations of conversion efficiency of laser energy into > 1 keV X rays shown in Figure 5 for the NIF lasers converging on an underdense plasma target will be borne out by experiments at the higher energies and laser intensities that are available at the NIF.

Another characteristic of underdense plasma targets is the very small mass of the target, including the holder. As such, in the experiments on OMEGA, the target is essentially vaporized. This resulted in a very low debris areal mass density even a few cm away from the initial position of the target, which has been projected to approximately 0.1 μg/cm^2 at 1 m at the NIF [10]. While it remains to be demonstrated that the OMEGA results for low debris mass will be repeated with the NIF, it seems very plausible that careful target and target holder design can enable this to be the case even at a factor of 10 or more higher power and energy on target. This would be a highly desirable characteristic of an X-ray source intended for cold X-ray experiments, code validation and large fluence-area-product weapon system testing.

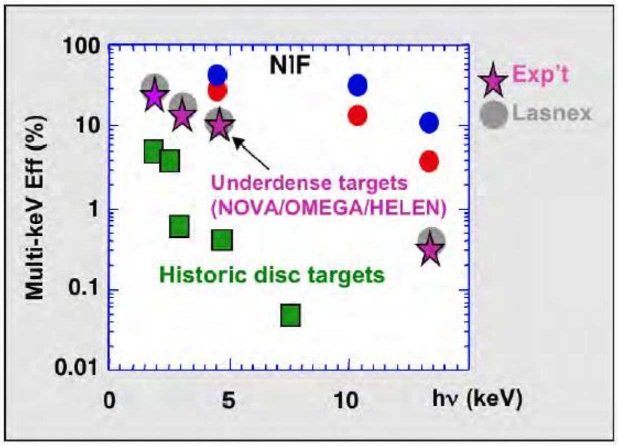

Figure 5. Summary of experimental results on CE as a function of x-ray energy band with disk (solid) targets and underdense plasma targets together with LASNEX calculations (gray circles). Also shown are LASNEX code predictions of conversion efficiency vs X-ray energy band for NIF operating at 351 nm driving optimized targets with 60 TW for 2 ns (red circles) and with 300 TW for 6 ns (blue circles). *[From Ref. 11]*

4.2 X-ray Source Based upon High Gain Fusion Ignition

The energies released by an ignited fusion fuel capsule, potentially in the range of several tens to 100 MJ or even more after a few years of operation of the NIF with up to 3.4 MJ of green light, would seem to be attractive as a source of X-rays. Unfortunately, there are major obstacles to turning this energy to useful (X-ray effects testing) purposes. Eighty percent of the energy produced by deuterium-tritium fusion is released as 14 MeV neutrons. Because of their long mean free paths (equivalently, their small interaction cross-sections) their energy can be deposited only in large masses of matter. For example, their scattering cross-section on protons is 0.7 barns and on carbon is about 1.4 barns, giving 0.12 cm^2/gm as the attenuation coefficient in solid density CH_2. Thus, 9 cm of paraffin or polyethylene absorb less than 20% of the neutron energy (taking into account the maximum energy transfer to protons of ½ and to C of 1/13, and the fact that 37% of the neutrons do not scatter at all in that 9 cm). This matter will not be heated even to 1 eV and so will not produce any X-rays.

Another consequence of the small interaction cross-section of 14 MeV neutrons is that they require a very thick (several tens of cm) shield if their fluence on a test object is to be reduced by two or more orders of magnitude. Such a thick shield of even a low-Z material would be an even more effective X-ray shield, precluding direct X-ray exposure of a test object shielded from the neutrons.

Because 14 MeV neutrons travel at 5.2 cm/ns, they arrive very soon after the X-ray pulse if they are not stopped, and their effects (if not completely shielded) would generally be impossible to separate from those of the X-rays of interest. This is a problem that did not arise in underground tests because the great yield of a nuclear explosion meant that the test object could be many hundreds of m from the explosion. This distance affords both temporal separation of the neutrons and the possibility of mechanical closure of the line of sight before they arrived.

The remaining 20% of the fusion yield is released as 3.5 MeV alpha particles. In hot hydrogen plasma, most of them stop in an areal density of 0.3 gm/cm^2, as a result of which the electron temperature of the burning plasma rises and quickly reaches tens of keV once fusion power density exceeds bremsstrahlung radiation power density in an ignition target (at about 4 keV). The X-ray emission by this plasma has been calculated by Suter [11] to be up to 16% of total yield. The portion that escapes the laser entrance hole (~0.2 steradians) would constitute a potent X-ray source if it weren't for the neutron flux that would also impinge upon the test object. The hohlraum walls are normally thick enough to degrade the dose that would be delivered to a test object by a large factor, but the neutron fluence would not be reduced. Other calculations carried out by LLNL scientists indicate that seeding the outer layers of fuel with a small amount of gold would reduce the fusion yield by a factor of roughly 2, but the radiation would be substantially enhanced, especially above 10 keV. Thus, in this case, the neutron to x-ray energy deposition ratio would be reduced by a factor of 5, but the neutrons would still be there close behind the X-rays. For most DoD requirements, this would still be unacceptable.

Thus, it appears that there is no choice but to shield the test object from direct irradiation by the neutrons and try to scatter the 16 MJ of X-rays per 100 MJ of total fusion yield from a fusion fuel capsule. Figure 6 shows a notional design of how a high fidelity x-ray effects test might be done with a very high yield ignition source [12].

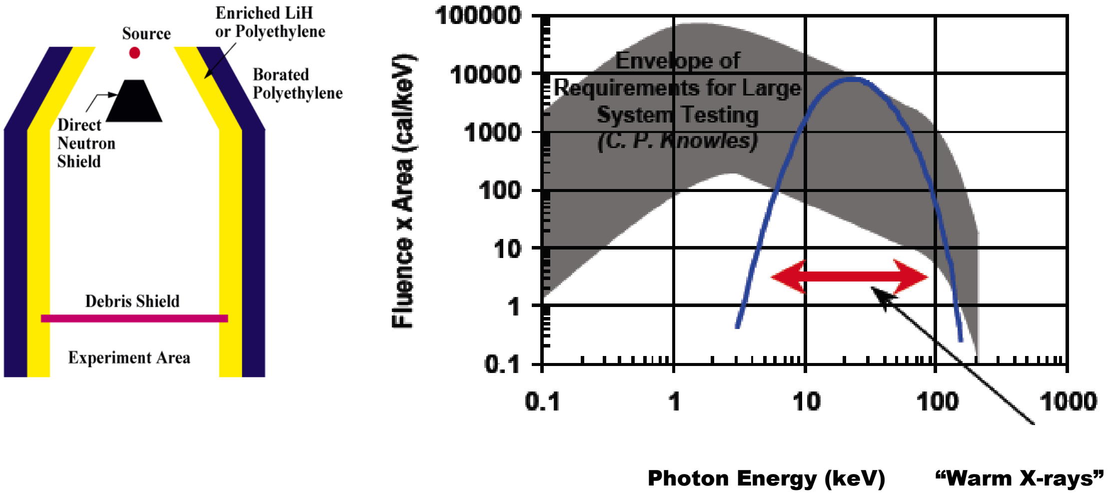

Figure 6. At left is a notional design of a configuration to scatter a substantial fraction of the X ray energy from a high yield ignition target so that it can irradiate a 1 m – scale test object in the "experiment area" with greatly reduced neutron dose. Analysis done in the 1990's suggested that 660 MJ of total ignition capsule yield would be required to reach the blue curve as a test spectrum, thereby meeting the top-level requirement in the "warm X-ray" energy range (see Fig. 2). *[Modified from Ref. 12]*

Suppose that as much as 10% of the x-ray energy produced by fusion alpha particles is scattered into the downward 2π steradians and provides the field of X-rays that irradiate a test object hidden behind the neutron shield, as illustrated in Figure 6. Assuming 16% of the yield is in X-rays, and then 1.6 MJ per 100 MJ of yield would be the effective new source 2-3 m away from the 1 m scale test object in order to have reasonably uniform irradiation. Then at least 150 MJ of yield would be required to have the same source strength as can be achieved, according to LASNEX, by directing the 3.4 MJ green laser beams on an underdense target. This crude argument suggests that only for D-T fusion yields >> 100 MJ would ignited capsules be useful as X-ray sources for X-ray effects testing. This is consistent with the calculation noted in Figure 6 caption that 660 MJ would be needed to enable pulse stretching and neutron elimination and still have enough X-ray fluence on the test object behind the neutron shield to meet requirements in the 15-100 keV X-ray range. This will be the region of the X-ray spectrum in which test capability will be lacking even assuming the best X-ray CE for the green laser beams using under dense plasmas.

5 CONCLUSIONS AND RECOMMENDATIONS (Responding to Task Questions)

5.1 Task Summary and Summary Response

JASON task summary - Evaluate the feasibility of DoD's using the National Ignition Facility (NIF) for high fidelity radiation effects testing in the near future and after ignition is achieved. JASON will make firm recommendations in line with the risks associated with return on investments as a principal focus within the study.

Summary response

The NIF lasers could provide important high fidelity X-ray effects testing capability starting within 1-2 years that would complement the testing and model-validation capability available from such existing large-scale X-ray effects testing facilities as the Saturn pulsed power facility. Some of the anticipated capability for ≤ 2 keV photon energy range X-ray effects testing using the near-term 1-1.8 MJ (351 nm) laser energy level has not been available for important DoD systems from any laboratory ("above ground") weapon effects simulation facility. An important point here is achieving "simulation fidelity:" the test must produce the same energy deposition profile in a test object, with a time dependence that assures the same physical effects are induced, as the actual threat spectrum, with accuracy sufficient to make the test a valid predictor of performance under the real threat. In addition, there must not be confounding effects from other sources of energy.

An X-ray source in the 3-10 keV range is another potentially useful source for testing and experiments. However, in this range, the upgraded Z-machine may offer comparable capability for some applications, assuming the debris is adequately eliminated.

A modest size research and development program (starting at 2-3 FTE's for perhaps 2 years) carried out jointly by NIF and test community scientists is required to develop and characterize X-ray sources produced by the NIF laser for various particular X-ray weapon effects test requirements. As the joint program moves from research and development to system testing, the cost will escalate as the need grows for special-purpose facility engineering and operations. There may also be significant costs associated with providing dedicated data acquisition facilities for some of the tests, although there is the possibility that these costs could be shared with other facility users requiring a large number of high bandwidth data channels. This appears to us to be a low-risk opportunity to develop an important range of test capabilities for the DoD. A few years further in the future (after 2015), the possibility of up to 3.4 MJ of green laser light's becoming available for X-ray effects testing promises a significant enhancement of the range of environments that will be accessible to the DoD nuclear weapon effects testing community at the NIF.

As the source development and characterization experiments are said to be entirely unclassified, we suggest that this element of DTRA's X-ray effects testing program would be a good vehicle by which to introduce university scientists in the program in order to foster the development of a new generation of scientists interested in the interaction of X-rays and matter.

By contrast, nuclear weapon effects testing that depends upon ignition of a fusion fuel capsule by the NIF, especially X-ray effects testing without the potentially confounding effects of a large neutron flux, is difficult to assess at present. Assuming ignition (defined as fusion energy out equal's laser energy into the hohlraum) is achieved in a timely manner, we first note that considerably greater yield than the NIF laser energy is required to generate a useful ignition-based x-ray source. For example, exploratory calculations done by LLNL scientists more than 10 years ago estimated that ignition capsules that would have yielded a few 10's of MJ, if "clean," can be seeded with high Z material(s) and made into a useful X-ray source at the cost of reduced fusion yield. Neutrons are not eliminated in that approach, but are substantially reduced in dose ratio relative to the x-rays. Much more yield (>>100 MJ) and a complicated configuration, proposed so far only at the notional level, are required to greatly decrease the neutron-to-x-ray dose level and to fill in the "missing slice" of the x-ray threat spectrum between 15 and 75-100 keV that has not been available for test since the cessation of underground tests. While this would be of great value to the test community, a many-year research and development effort by NIF scientists is needed to achieve high yield ignition. If and when it becomes clear that several tens to 100 MJ of fusion yield might be achieved at the NIF, then DTRA involvement in developing a useful X-ray environment for X-ray effects simulation is warranted. {Note: LLNL scientists have no plans to develop seeded sources (or any other X-ray enhanced sources) for X-ray effects testing without significant DoD participation.}

5.2 Responses to Specific Task Questions

1. a) Can the NIF deliver a radiation pulse to a test object with adequate simulation fidelity?

   Recent experimental results and simulations suggest that the NIF laser beams impinging upon carefully designed underdense plasma targets will be able to produce X-ray environments of interest to the nuclear weapons effects test community in the DoD. The dose-area product projected to be available for testing large area objects with X-ray spectra that will give good simulation fidelity for specific testing purposes will meet some of the survivability requirements for important DoD systems. Programmatically important X-ray environments up to perhaps 13 keV are projected to be available for high fidelity, for system-scale object tests within just a few years. Test environments could reach perhaps 20 keV when the facility is modified to be capable of delivering 3.4 MJ of green light to the center of the target chamber (presently planned for 2015). The possibility of driving runaway electrons in a thin walled hohlraum also makes possible ~100 keV bremsstrahlung sources at the NIF. However, it is not clear why there would be an advantage of doing this at the NIF and not using, for example, Saturn.

The radiation pulse produced by a NIF ignition target may be useful for x-ray effects tests only if the test will not be spoiled by the presence of 14 MeV neutrons. Only very preliminary designs have been developed so far for a high fidelity X-ray effects testing configuration using NIF ignition capsules that substantially reduces the neutron dose seen by the test object.

b) What is the "natural" output of the NIF, both using the lasers directly to generate radiation pulses and the energy produced when the NIF has achieved ignition (long term), and how must it be modified?

The natural output of the NIF laser X-ray source will depend upon the laser target. Intermediate and high Z gas targets near 1 atm pressure and doped low mass-density aerogel foams are both excellent targets for intense laser beams if the goal is to produce ≥ 1 keV X-rays efficiently. Both kinds of targets can be tailored to produce spectra and intensities of interest to the test community to meet different requirements. The efficiency of conversion of laser energy into X-rays is projected to range from ~60% in ≤ 2 keV X-rays to ~10% near 10 keV. The spectra produced by efficient radiators (such as Kr and/or Xe gas, or Ge-doped aerogel foams) are line-dominated, although they do have a continuum component. Dose rate as well as dose requirements can be met by varying the arrival time of different laser beams on their target(s). The physics of X-ray emission from these targets appears to be well enough understood that actual yield efficiencies at the NIF are likely to be reasonably close to the high values quoted above.

The energy output from D-T fusion is 80% in 14.1 MeV neutrons and 20% in 3.5 MeV He nuclei. The total fusion energy from an ignition capsule is largely released in a sub-ns burst. Conversion of much of the neutron energy into x-rays requires a large volume of material, but a good deal of the energy in the He nuclei can be converted into x-rays by absorbing their energy in a mid- or high-Z material that radiates over a time of the order of 1 ns (~1 keV radiation). High fidelity testing requires that the pulse be stretched and the neutron dose be substantially reduced. The ratio of allowed neutron dose to X-ray dose depends upon the test object or system, and so the required modifications to the natural output pulse must be worked out for each test object.

2. a) What are the technical difficulties, specifically debris mitigation as well as others that must be addressed and overcome to provide the various desired test

environments from an ignition-capsule-driven radiation pulse?

This cannot be addressed adequately until there is more than a notional design of how the energy from an ignition capsule would be converted into X-rays for testing an object. However, LLNL's debris experts claim that the debris field from an ignition capsule (even one seeded with high Z elements), absent a neutron absorber and x-ray pulse stretching structure, can be directed away from the test object. This claim is based upon their plans to direct the worst of the debris field away from vulnerable objects that are inside the vacuum chamber. However, they do use a shield of fused silica to protect the focusing lenses from debris. Unfortunately, tests that require 1-2 keV (or lower) X-ray energies do not permit more than a few mils (or less) of Be or plastic to be placed in front of the test object.

b) For example, what are the physics and engineering challenges to elimination/mitigation of neutrons, stretching the radiation pulse and conversion of the fusion energy to the desired radiation spectrum?

Any material in the target chamber that will be vaporized, liquefied or blown off a radiation converter, target support structure or scatterer is a potential hazard to the test object (as well as anything else in the test chamber). Therefore, the challenge can be summarized by saying that as much of the energy as possible must be absorbed in materials that retain their integrity. At 7 Cal/cm^2 averaged over the 5 m radius target chamber wall per 100 MJ of yield, of which a minimum of 20% is in soft photons, energetic ions and target debris, the problem is clearly severe for anything placed, for example, 2 m from the source where the angle-averaged fluence is about 44 Cal/cm^2/100 MJ. If the X-ray scattering structure in the notional design for a high yield ignition X-ray test configuration, Figure 6, is far enough away to insure it is not going to be a hazard, it is not clear that an adequate dose can be delivered to a test object hidden behind a neutron shield. The answer to this question requires a point design that is studied in detail.

3. Are the NIF capabilities (laser-generated x-rays as well as after ignition is achieved) better in some effects-testing dimension(s) than existing pulsed-power-based radiation effects simulation facilities?

The capability of the NIF laser-driven X-ray source to deliver sub-keV and 1-2 keV photons for testing is expected to be better, assuming the debris field proves to be as low as it has been in OMEGA experiments and tests. This is because plasma radiation sources (PRS's) such as z-pinches on the Z-machine (Z) and Saturn have problems extracting such photons from the load regions of the pulsed power machines for irradiation of large area test objects. For ≥ 3 keV X-rays, the situation is more complicated. PRS's on Z may yield comparable X-ray radiation sources to that which the NIF laser will be able to produce in the 3-10 keV range, but ~50% of the dose may be lost due to shielding the object from debris. However, we note that if a test requires that the copious quantities of ≤ 2 keV photons produced by an underdense plasma source be removed from the test environment, the NIF laser-driven source may also have to tolerate a substantial reduction in available dose over a given system-scale area. Absent substantial further improvement of the upgraded Z-machine's capability to generate radiation in the 10-15 keV band, NIF should also be able to produce larger radiation fluence-area products in that warm X-ray region than Z.

In all spectral ranges, the NIF facility has the benefit of a 5 m vacuum chamber within which to place the system to be tested, whether it is to be close to or a few meters from the source (which will be at or near the center of the chamber). The multi-square meter port would enable large objects to be placed in a large external chamber even further from the source than 5 m. However, it is our understanding that the coupling between the main target chamber and the external chamber is to be limited to a 1 m diameter aperture.

High yield (>100 MJ) ICF ignition may be the only way to access the "missing slice (from 15 to 75-100 keV) of the threat spectrum, although an approach involving colliding plasmas (the Ring Accelerator Compression Experiment - RACE), was presented to us as part of an earlier JASON study on X-ray simulation [13]. As far as we know, that device was not investigated beyond its 1989 level of maturity.

It is conceivable that the energy released from a ~100 MJ yield ignition capsule can be converted with a few percent efficiency into an x-ray radiation spectrum that will provide a test environment that approximates the actual threat spectrum of a nuclear weapon in space or the upper atmosphere. For integrated tests of a re-entry vehicle (RV), a satellite or some other important DoD system, it is likely that the configuration would have to minimize neutron dose during the X-ray pulse while maintaining some of the softer X-ray spectral components to have a high fidelity test. The configuration would also have to stretch out the pulse to avoid dose-rate effects (for example, in electrical subsystems within an RV) that would not occur in an actual threat X-ray pulse. If all of this can be accomplished, which is by no means certain, and then a very useful source for X-ray effects testing would be available to the Armed Services and MDA. Because no detailed designs exist and even the most optimistic designers of NIF ignition experiments don't expect to achieve ~100 MJ of fusion yield in less than 10 years, we suggest that DTRA should wait until at least 1-2 MJ of fusion yield is achieved. In the meantime, LLNL scientists might develop a conceptual design for using fusion yield to generate a useful X-ray simulation environment. This would enable DTRA to decide if a useful ignition-based X-ray test environment is possible once the prospects for very high yield ignition can be better evaluated.

4. Will there be any special debris mitigation requirements to assure the <u>facility</u> will suffer negligible "extra" damage as a result of the conversion of fusion ignition

energy to the appropriate x-ray radiation spectrum?

LLNL scientists have stated that they have a "validated simulation tool NIF ALE-AMR [that] provides a state-of-the-art tool to address debris issues for ignition sources [with a test object present in the chamber] or more complex geometries." The latter refers to configurations that greatly reduce the neutron flux seen by a test object while still enabling it to be subjected to a high fluence, high spectral fidelity X-ray simulation environment. The simulation tool would be applied to the complete test configuration when one reaches a state of maturity beyond conceptual design. In the meantime, they do not expect test objects to damage the facility at the relatively large source to test object distances that would be used. (The test object is supposed to survive the real threat environment.) Nor do they expect debris from the ignition target or shrapnel from x-ray scattering structures to affect the target.

5. What DoD-specific diagnostic suite might be necessary to enable the NIF to be used for high fidelity radiation effects testing? The analysis will include examination of inherent risks to successful creation of a diagnostic suite.

For the NIF laser-driven X-ray source, a calibrated soft X-ray spectrometer is needed to enable accurate depth-dose calculations to be carried out for specific test objects. Although high absolute calibration accuracy (better than 10%) is needed, there is no particular risk here as the necessary diagnostic systems have been built elsewhere (e.g., the NOVA and OMEGA facilities).

6. a) What DoD-specific design and/or operational capability will be necessary for expanding the National Ignition Facility (NIF) for high fidelity radiation effects testing? The analysis will include examination of inherent risks toward implementing recommendations toward creating new operational capabilities.

Evidently NIF laser pulse energy, the number of beams to be used, the pulse shape of the beams and the delay of one beam relative to another are all under the control of the system operator already. Special requirements on focusing beams further than 3 cm from target chamber center, however, could not use existing focal point adjustment capability. Special requests, such as mixing a few green (532 nm) beams focused on a target 20 cm from chamber center using the 351 nm focusing lenses together with 351 nm beams delivered to a target at chamber center would likely require some extra preparation and special operating procedures.

A screened room with high bandwidth data acquisition channels close to the test chamber may be needed to provide adequate bandwidth, i.e., short cable runs, for signals collected from test objects. Additional high bandwidth cabling from inside to outside the test chamber may be needed beyond what is in place already for ignition and high-energy-density science experiments at the NIF. Accurate spectra will be needed, as was already noted, perhaps with ~1 ns time resolution.

Laser timing and pulse shapes needed for tests will be specific to the X-ray effects testing community, but should be well within the range of pulse shapes that can be produced by the NIF lasers. If a large test object is open to the main target chamber vacuum, mutual compatibility must be assured. Other issues will surely arise when LLNL facility engineers and scientists and members of the first DoD organization to bring a major test object to the NIF get together to discuss each other's needs and requirements. There is no reason to doubt that all of these things can be done for the laser-based X-ray source. As for the cost to DTRA to do this, it is our understanding that a Memorandum of Understanding is being drawn up between DTRA and DOE/NNSA that will determine financial responsibility for different aspects of preparation for X-ray effects testing on the NIF.

For X-ray effects simulation based upon a high yield ignition target, a pulse-stretching/neutron stopping structure must be designed that permits laser access, doesn't lead to damage of the test object or laser optical systems, and doesn't damage the test chamber. The NIF team seems confident that this can be done, but it is not clear how thoroughly this has been considered so far.

S/RD testing will be no problem. In fact, stockpile stewardship physics experiments are planned for the facility in the very first year of operation.

b) What additional computer simulation capability might be needed to design the structures needed to convert the natural radiation from an ignition target to a suitable test source?

LLNL scientists state that their need to do the very same thing for underground tests (UGTs) means that they already know how to do this. It is not clear that the computer capability used 20 years ago to design a converter of 10^{13} J of mostly fission energy from a UGT to an X-ray environment suitable for DTRA's DoD clients can be used for the problem at hand. This could turn out to require a considerable effort in terms of code development and configuration design and optimization. A high fidelity, full system test environment with adequate uniformity may not be possible without, for example, placing the test object in a chamber that is beyond the 5 m boundary of the present NIF target chamber. As we have already noted, this possibility is built in to the NIF chamber even for large test objects. The cost of implementing it would depend upon the size of the required appendage to the test chamber. We do not consider this a major concern at present as the future availability of a high-yield ignition-based X-ray effects testing source at the NIF is uncertain.

c) What special NIF operational procedures might be required to carry out a weapon effects test vs a normal ignition test? - - See answer to part a.

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