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Title: Pulsed Power Science and Technology: A Strategic Outlook for the National Nuclear Security Administration (Summary)

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Pulsed Power Science & Technology: A Strategic Outlook for the National Nuclear Security Administration (Summary)

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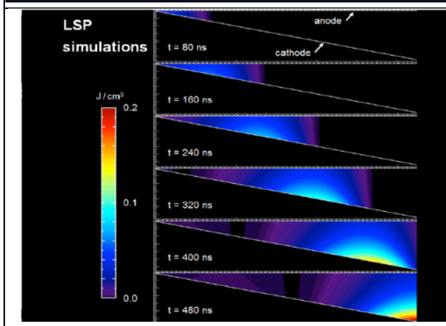
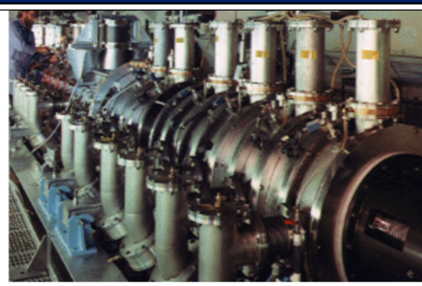
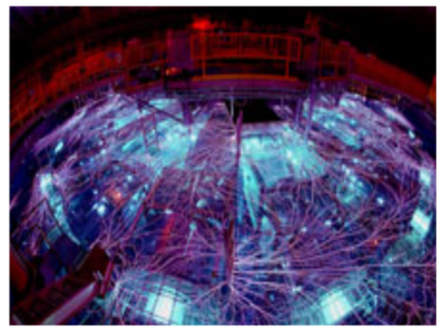
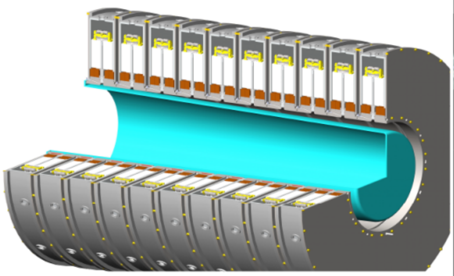
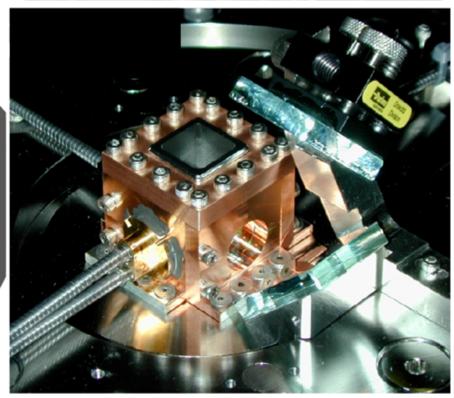
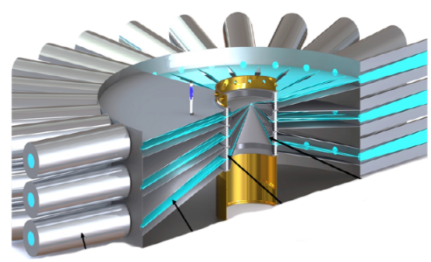


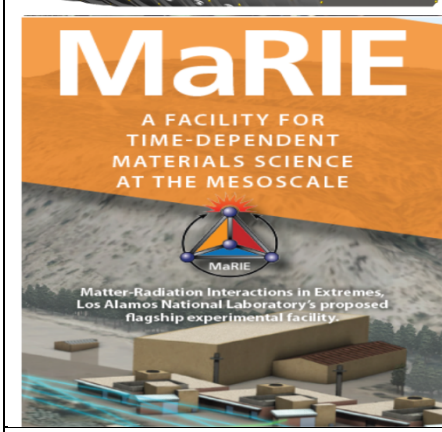


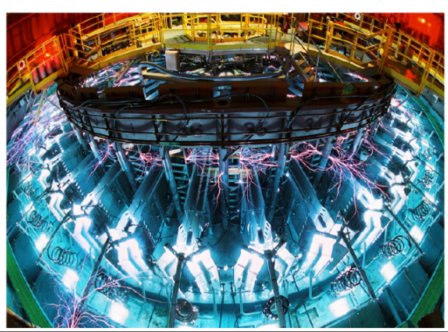


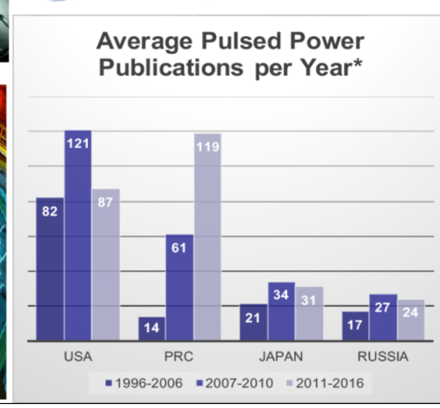












Introduction

Major advances in pulsed power technology and applications over the last twenty years have expanded the mission areas for pulsed power and created compelling new opportunities for the Stockpile Stewardship Program (SSP). This summary document is a forward look at the development of pulsed power science and technology (PPS&T) capabilities in support of the next 20 years of the SSP. This outlook was developed during a three month long tri-lab study on the future of PPS&T research and capabilities in support of applications to: (1) Dynamic Materials, (2) Thermonuclear Burn Physics and Inertial Confinement Fusion (ICF), and (3) Radiation Effects and Nuclear Survivability. It also considers necessary associated developments in next-generation codes and pulsed power technology as well as opportunities for academic, industry, and international engagement. The document identifies both imperatives and opportunities to address future SSP mission needs.

This study was commissioned by the National Nuclear Security Administration (NNSA). A copy of the memo request is contained in the Appendix. NNSA guidance received during this study explicitly directed that it not be constrained by resource limitations and not attempt to prioritize its findings against plans and priorities in other areas of the national weapons program. That prioritization, including the relative balance amongst the three focus areas themselves, must of course occur before any action is taken on the observations presented herein.

This unclassified summary document presents the principal imperatives and opportunities identified in each mission and supporting area during this study. Proceeding this area-specific outlook, we discuss a cross-cutting opportunity to increase the shot capacity on the Z pulsed power facility as a near term, cost effective way to broadly impact PPS&T for SSP as well as advancing the science and technology to inform future SSMP milestones over the next 5-10 years. The final page of the summary presents two timelines that couch the opportunities discussed here in terms of the broader strategic timelines encapsulated in the fiscal year 2017 Stockpile Stewardship Management Plan (SSMP). The detailed foundation for this document, along with additional opportunities, can be found in a corresponding classified document, which is available upon request.

Summary List of Principal Imperatives and Opportunities

The list below summarizes the principal imperatives and opportunities from the study. The remainder of this summary document explains these in more detail. The detailed foundation for this document, along with additional opportunities, can be found in a corresponding classified document, which is available upon request.

- Key Recommendation
  - Pursue an increase to the capacity of the Z facility to 250 experiments per year

- Dynamic Materials Imperative
  - Complete the development of a next-generation containment system for use on Z that would enable reaching about 5 Mbar with improved power flow

- Dynamic Materials Opportunities
  - Near-term improvements to Z dynamic materials capabilities
  - Development of an optimized system for actinide experiments
  - Development of small, flexible drivers for deployment at other national facilities
  - Continued refinement of high-explosive pulsed power systems

- Thermonuclear & Inertial Confinement Fusion Opportunities
  - Mature the required pulsed power driver engineering and technology needed to achieve 10-30 MJ yields within the next 20 years
  - Establish a combined experimental and computational program in driver-target coupling (power flow physics)

- Nuclear Survivability and Radiation Effects Research Imperative
  - Revitalize the Saturn and HERMES-III pulsed power facilities

- Nuclear Survivability and Radiation Effects Research Opportunities
  - Improve sources for warm (10-100 keV) x-rays and high energy (>1 MeV) neutrons
  - Pursue development of combined hostile environments (photons and neutrons)

- Supporting Pulsed Power: Imperative
  - NNSA, in consultation with laboratory staff, should establish clear rules of engagement for import/export control and classification in the areas of pulsed power science & technology to enable productive relationships with academic, industry, and international partners

- Supporting Pulsed Power: Opportunities
  - Create academic programs on both new and existing intermediate-scale pulsed power facilities
  - Augment current efforts to develop experimentally validated models

Key Recommendation: Increase shot capacity on Z

The "Z" facility at Sandia National Laboratories is the world's most powerful pulsed power machine. Up to 22 MJ of electrical energy can be compressed into current pulses with 100 to 1000 ns duration, for a peak electrical power of 80 TW and a peak current of 26 MA. This current can be used to create a large magnetic pressure (26 MA at a radius of 1 mm produces a 100 Mbar pressure, or 100 million times atmospheric pressure), which can be used to create high energy density conditions in the laboratory akin to those created on large laser facilities such as the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL). Z supports ICF, Science, and Engineering-related research and development programs in high energy density physics relevant to nuclear weapons.

Emerging from this study is that pursuing an increase in the capacity of the Z facility, to around 250 experiments per year over the next four years, would facilitate the progress in dynamic materials, inertial confinement fusion, thermonuclear burn, radiation effects and nuclear survivability physics. This information would be important for reducing present uncertainties associated with areas of capabilities identified as future opportunities. Some corresponding investments in modernizing sub-systems dating back to the mid-1980s will be needed to sustain this shot rate and keep it viable and relevant through at least 2025.

As the first step in increasing the shot capacity on Z we recommend the establishment of a Z shot rate enhancement study similar to that recently conducted for the National Ignition Facility. This study would be supported by experts from both within NNSA and external to NNSA with experience operating experimental facilities similar to Z. Further opportunities related to Z are discussed in the following sections.

Dynamic Materials Experimental Research

Mission Overview & Current Capabilities

Material models, validated with accurate data in relevant regimes, are a key input to the simulations underlying the NNSA approach to assessments of both stockpile weapon systems and potential threats posed by improvised nuclear devices (INDs). The dynamic response of materials is most important during the "cold" stages of a nuclear weapon implosion before ionization into plasma has occurred and where materials may still retain strength. Material compressibility and strength is governed to a large degree by its microstructure, impurities, and composition. Within the next 20 years, Life Extension Programs (LEPs) and the United States Strategic Command's "3+2" future stockpile vision to develop interoperable warheads (IWs) will require decisions on whether to reuse, remanufacture, or replace nuclear weapon components. Natural aging or remanufacture of weapon materials is likely to alter their grain size and structure, impurity levels, and densities. For this reason, the FY17 SSMP calls for significant progress to be made in understanding materials by 2023-2024, as illustrated in by the timeline shown in Figure 1.

Understanding the importance of material changes on hydrodynamic performance requires both modeling and a combination of both integrated and focused-physics experimental capabilities. Hydrodynamics tests at LANL's DARHT and LLNL's Site 300 Contained Firing Facility and subcritical experiments at the Nevada National Security Site, including those planned to use the future Enhanced Capabilities for Subcritical Experiments (ECSE), are integrated tests of weapon performance. Small-scale, precision experiments will be necessary to help quantify performance impacts and interpret results from the more integrated hydro-test and subcritical experiments. Pulsed power is one of several technologies in use today to perform focused and small-scale experiments since it can create pressures, densities, and strain rate conditions that complement those using other techniques (e.g., gas-gun driven plate impacts, laser-driven shocks/compressions, and static compression cells). The magnetic pressure created by pulsed power can be used (1) to accelerate very high velocity impactors to collide with and drive strong shocks into a sample, (2) to directly compress a sample without creating shocks, (3) to generate complex trajectories through temperature-density phase space by shocking a sample and then slowly ramping it to higher pressure, and (4) to produce one-dimensional radial implosions. Pulsed power also contributes to the diagnosis of subcritical experiments by providing high-energy (>1 MeV) radiographic imaging capabilities. As such, it plays a direct role in the ECSE project, which had CD-0 in 2014 and is scheduled to be completed in 2024. (As an ongoing project, the needs of the ECSE were not directly discussed during this study at the request of the NNSA.)

Presently, all pulsed power driven experiments conducted with hazardous actinide samples use the Z facility at SNL. Smaller pulsed power facilities are also used to study surrogate materials, high explosives, polymers, and powders. Examples include the Veloce driver at SNL, the PHELIX facility at LANL, and high-explosively driven systems like the LLNL Full Function Generator. In all cases, precise control of the loading and unloading conditions as a function of time is critical to obtaining data of sufficient quality to validate material models.

The existing pulsed power facilities in the United States have several limitations and constraints for meeting the mission needs for dynamic materials data. These include: (1) difficulty in achieving the peak sample pressures desired for specific applications, (2) difficulty containing the hazardous materials, which if released could shut down operations for an extended time, (3) limited access for diagnostics, (4) a high annual demand for experimental programs using the facilities (e.g., Z), and (5) producing, characterizing, and assembling actinide samples with carefully controlled impurity levels, microstructure, and processing.

Imperatives and Opportunities

As seen in Figure 1, materials and subcritical experiment data obtained before or during the 2023-2027 IW-2 concept and feasibility studies could affect designs being considered for that system. With that timeframe as a guide, four opportunities to exploit the unique capabilities of pulsed-power drivers for dynamic material investigations have been identified.

Near-term improvements to Z dynamic materials capabilities The three biggest challenges for conducting materials research on Z today are (1) safely containing the hazardous actinide material, (2) creating the desired time-dependent magnetic pressure drive on a sample in the presence of losses, and (3) diagnosing the material conditions, such as its phase. All of these challenges are interrelated for actinide experiments because the existing containment system on Z is only authorized for use at moderate pressures (up to about 3 Mbar), it constrains the power flow in a way that affects and limits the temporal pulse shape of the magnetic pressure, and it severely limits diagnostic access. Therefore, **there is a near-term imperative to complete the development of a next-generation containment system for use on Z that would allow us to reach about 5 Mbar with improved power flow.**

If a next-generation containment system cannot be developed, it will severely restrict Z's ability to contribute to the entire classes of weapon issues and address Nuclear Counter Terrorism program questions.

Development of an optimized system for actinide experiments **There is an opportunity to build a high-pressure, high-capacity pulsed power system optimized for materials research that could validate accurate, phase aware models for actinides (e.g., Pu, U, and potential IND compounds) at high pressures (>5 Mbar) with sample loading time scales in the microsecond range.** To accomplish this, the facility must include diagnostic capabilities for measuring the sample density, temperature, and the location of phase transition boundaries. Additional experiments on the facility would be aimed at surrogates, other nuclear weapon materials (e.g., high explosives, polymers, compacted powders), and the development of physics models. To take advantage of this facility, a corresponding enhanced national capability for sample production will be needed, particularly for actinides. The timeline in Figure 2 outlines a best-case scenario for completing such a facility, which has CD-0 beginning in 2018 and operations beginning in 2023, thereby providing it with the maximum opportunity to impact milestones, IW-2 activities, production decisions, and subcritical experiments in the mid-2020s as noted above, as well as contributing to timely data collection for IND needs.

Development of small, flexible drivers for deployment at other national facilities The NNSA and Department of Energy have begun making investments in high-quality diagnostic capabilities at various national facilities such as the Advanced Photon Source-Dynamic Compression Sector (APS-DCS), the Linear Coherent Light Source (LCLS) and eventually MaRIE,. **There is an opportunity to collocate smaller pulsed power systems at these facilities to drive material samples and take advantage of the ability of these facilities to precisely diagnose key material properties.** These data could then play a significant role in developing improved physics models for the NNSA.

Continued refinement of high-explosive pulsed power systems To obtain material compressibility data at extreme pressures (~30 Mbar) or high-precision shock-driven materials data at even higher pressures (~100 Mbar) will require high-explosively driven pulsed power (HEPP). While the shot rate of HEPP experiments has always been much lower than laboratory pulsed power facilities, the number of data points needed at these extreme pressures is low. **To preserve the opportunity to collect such data with HEPP, some expertise and capability would need to be sustained within the NNSA in parallel with facility-based pulsed power platforms.**

Thermonuclear Burn Physics and Inertial Confinement Fusion (ICF)

Mission Overview & Current Capabilities

Pulsed power has played a significant role in the national ICF program for decades. Magnetic Direct Drive (MDD) is the principal approach being pursued today because of the favorable energy coupling to the target and budgetary considerations although indirect (x-ray) drive concepts are also of interest. The main MDD approach being studied on Z today is Magnetized Liner Inertial Fusion (MagLIF), a magneto-inertial fusion approach uniquely well suited to pulsed power.

ICF applications include nuclear weapon physics studies, weapon effects simulation, and isotope production. Certain fundamental processes are qualitatively common to both laboratory ICF and thermonuclear processes in weapons, including radiation transport and containment, implosion physics, interfacial instabilities and mix, the compression and burn of fuel, opacities, equations-of-state, computational modeling, thermonuclear ignition, and neutron/charged-particle transport. ICF systems can potentially be used as neutron or x-ray sources for the investigation of radiation vulnerability and hardening of military systems and components outside of the primary or secondary portions of a warhead. Participants in this study briefly reviewed the SSP benefits of achieving various yield outputs from today's ~10 kJ yields available in the complex to the high yields (>100 MJ) referred to in the ICF portion of the FY17 SSMP (see 2018 milestone in Figure 1).

A key observation of this study is that to better inform the design and assessment of future stockpile options, it is important to produce a robust platform that generates 10-30 MJ of thermonuclear fusion yield in the laboratory during the next 20 years, on the path to advancing the science, engineering, and technology to produce >250 MJ yields in the future.

The national ICF program has undergone considerable scrutiny in recent years. A major review of the national program in 2015 led to several key observations and actions including:

Shot opportunities on Z should be increased. The MDD Program should dedicate more opportunities for understanding and optimizing the power flow in the driver-target coupling, and understanding the scaling of MagLIF performance as a function of design parameters such as current, fuel preheat, magnetic field, fuel density, liner aspect ratio, and liner material over as large a range as possible at the Z facility. There should also be more experiments that pursue alternative concepts to MagLIF. Additional ICF resources should be prioritized to the MDD effort to build a stronger cadre of designers, experimental physicists, and diagnosticians.

In part in response to this review, NNSA released the ICF Framework document in May 2016, which led to changes in the FY17 SSMP milestones in FY20 and FY22 as shown in Figure 1. At the present rate of effort for ICF experiments on Z (about 65 shot days and roughly 50 shots per year), it is unlikely that adequate progress will be made on MagLIF, let alone on the alternate concepts recommended.

Opportunities

While it is unclear today whether 10-30 MJ yield is achievable with pulsed power, it is imperative that the science and technology expertise be preserved and research continue. With sufficient investments it is likely that the feasibility of pulsed power to meet the long term mission could be established within the next 10 years. The first investment recommendation is the increase in Z shot capacity, noted above, to advance target science. The aforementioned increase in the overall shot capacity of Z to 250 shots per year could be consistent with an increase in ICF shots to about 100 per year, with the remainder divided between Science program and Z Fundamental Science program experiments. A one-hour increase in the daily shot window would also substantially increase the likelihood of getting an ICF experiment each day (the present rate is about 4-4.5 shots per five days, with the vast majority of experiments occurring within 60 minutes of the end of the shot window).

Two additional investment opportunities are to (1) mature the pulsed power driver engineering and technology required to achieve 10-30 MJ yield, and (2) establish a combined experimental and computational program in driver-target coupling (power flow physics).

Such investment would also significantly strengthen the major program review in FY22 in the SSMP to assess the facility investments needed to meet future stockpile stewardship requirements.

In the same way that a single test and demonstration beamline was constructed prior to building the 192 beams of the National Ignition Facility, construction of a pulsed power test and demonstration module would be a minimum step required prior to building any large-scale facility. Linear Transformer Driver (LTD) architecture is one possible configuration believed to be capable of delivering 10-30 MJ fusion target yields. This architecture is considerably different from Marx-capacitor-bank systems like the present Z facility, and would require substantially more (and considerably smaller) capacitors assembled in annular “cavities” that would surround a water-insulated central conductor as part of a “module”. Many (~90) modules would supply electrical energy to a central target region, roughly analogous to the way the 192 beams of the National Ignition Facility supply optical energy to a central target region. The timeline in Figure 2 outlines a best-case scenario for completing a 25-33 cavity demonstration Z-next module by FY22, which would provide the best opportunity to impact the FY22 facility review in the FY17 SSMP. For reference, the longest water adder demonstrated to date used five LTD cavities in series, and that module used older-generation cavity technology relative to the current state of the art.

Nuclear Survivability and Radiation Effects Research

Mission Overview & Current Capabilities

Evaluation of the survivability of non-nuclear-explosive-package components is critical to the certification and assessment of the evolving stockpile. This evaluation requires data to validate codes used to model neutron and radiation effects on weapon components. . Current facilities that provide key data on survivability and radiation effects include HERMES, Saturn, the Annular Core Research Reactor, the Ion Beam Laboratory, NIF, and Z.

The 30-TW Saturn pulsed power facility was converted from the PBFA-I facility in 1987, and has been in operation since that time. It is primarily used to drive high-voltage diodes to produce >100 keV x rays for a period of 15-20 ns as a weapon effects simulator. It is also capable of studying plasma radiation sources for <10 keV x rays. The High-Energy Radiation Megavolt Electron Source (HERMES-III) built in 1988 is the world’s most powerful pulsed power gamma simulator. A 19 MeV, 30 nanosecond electron beam generates MeV-energy gamma rays for testing large military hardware (e.g., tanks). It fired its 10,000th shot in July 2015. Saturn and HERMES-III primarily support NNSA Engineering research programs and are also experimental testing platforms for Directed Stockpile Work in support of Stockpile Modernization.

This study included key participants from a concurrent effort to develop a Warhead Hostile Environment Survivability Plan (WHESP). Observations and needs considered as part of the WHESP that are directly relevant to pulsed power informed this study and are detailed in the full document. The needs are informed by our present understanding of the threats, but these may evolve in the near future as the capabilities of other nations improve.

Imperatives and Opportunities

In order to better evaluate radiation threats to the survivability of the nuclear deterrent, it is important to revitalize and improve upon historical pulsed power capabilities for nuclear survivability and radiation effects research.

The near-term imperative due to the advancing age of historical capabilities is to revitalize the Saturn and HERMES-III pulsed power facilities.

These facilities currently provide unique and important capabilities for hot (~0.1-1 MeV) x-rays and gamma rays (>1 MeV), respectively, but are nearly 30 years old. Figure 2 proposes a Saturn refurbishment project be executed in 2021-2023, a time period where facility usage is predicted to be at a minimum based on the LEP and certification needs outlined in the FY17 SSMP. If not completed during this time period, there will be increasing risk to certification activities after 2023 until such a refurbishment can be completed.

To better meet possible future needs of the evolving stockpile, two opportunities are highlighted:

Improve sources for warm x-rays and high energy neutrons There is an opportunity to improve the ability of Saturn to produce warm x-rays (0.02-0.1 MeV) by lowering its operating endpoint voltage. The timeline in Figure 2 includes a study in 2017 to evaluate technology upgrades for Saturn that could achieve this, which could be implemented by 2024. There is also an opportunity for HERMES-III to serve as a high-energy neutron source using ion-beam target interactions. A three-year Laboratory Directed Research and Development project has been initiated at SNL to study this possibility, with the study being completed in 2019 as shown in Figure 2.

Pursue development of combined hostile environments There is an opportunity to create unique combined hostile environments that should be evaluated and considered for the 10- to 20-year time frame. One option is the possibility of coupling a new pulsed power gamma-ray source to the Annular Core Research Reactor, which produces epi-thermal (low-energy) neutrons. A second option is to look at combined 14 MeV neutrons plus warm (10-100 keV) x-ray platforms on a more powerful version of the Z facility ("Z-next"), assuming that it appears to be a promising approach for generating 10-30 MJ within the next 20 years as stated above. The timeline in Figure 2 suggests that such a study could be completed by 2023, by which time the ICF facility investment likelihood would be clearer. Such combined hostile environment capabilities could be used to validate predictive capabilities for weapon design needs for a responsive stockpile, as outlined in the FY17 SSMP plan for 2030.

Supporting Pulsed Power: Personnel, Technology, Codes, Academia, & Industry

In order for the U.S. National Laboratories to continue to be recognized as world leaders in pulsed power science and technology 20 years from now, personnel expertise, state of the art technology and modeling capabilities and strong integration with academia and industry, and strategic engagement with international partners must be present.

Meeting the current and future needs implied by this overarching vision will require investments that sustain pulsed power expertise, advance pulsed power technology in collaboration with industry, develop new predictive computational tools, and engage the academic community. It is therefore imperative that the NNSA works with the national laboratories to establish clear rules of engagement in PPS&T to enable productive relationships with academic, industry, and international partners.

The national expertise base within the NNSA for pulsed power technology development is narrowly concentrated within a few small pockets today. A larger set of expertise exists outside of the NNSA, largely sponsored by the Department of Defense (DoD), but the scale of DoD pulsed power applications is considerably smaller than the high-power NNSA facilities. The NNSA does not presently support pulsed power technology and engineering development—the limited academic funding in this area all comes from the DoD, and consequently the overwhelming majority of students trained in this area find ready employment within the DoD complex.

Academic researchers using pulsed power for physics research have access to several ~0.1 MJ pulsed power facilities at various universities, and there is an academic program on the 22 MJ Z machine. Extrapolating physics platforms and diagnostics over this scale is challenging. **There is an opportunity to create academic programs on additional existing (e.g., Saturn) and future NNSA facilities as a way to ameliorate this issue and increase interactions between laboratory and academic researchers.**

Suggestions for improving academic funding are included in the full manuscript.

Modeling pulsed power systems is complex and capability gaps exist in today's codes that if addressed would hugely benefit the design of any new system as well as the ongoing research efforts in all areas. The major impact would come from experimentally validated models that can accurately predict the effect of very low density plasma that naturally evolves from the surface of components on power flow to the target. **Increasing the shot rate on Z would provide an opportunity to substantially augment current efforts to develop experimentally validated models, which would benefit the SSMP milestones in FY20 and FY22.**

The timeline in Figure 2 outlines a best-case scenario for model development under this scenario. This includes phased improvements in power-flow modeling capability to contribute to the credible physics scaling SSMP milestone in FY20 and the FY22 facility investment decision milestone. It also includes improved, "extended" magneto-hydrodynamics models in FY21 for target coupling, which would feed into future facility investment decisions presently scheduled in FY22. In order to achieve this, several specialized high-fidelity physics codes would be highly beneficial to help validate physics models that can be used in larger integrated codes.

The integrated outlook detailed in this document provides a compelling vision that would continue to improve the stewardship of our nuclear deterrent, aid in nuclear counterterrorism efforts, and facilitate the continued maturation of pulsed power science and technology. U.S. leadership in pulsed power science and technology is threatened today by the growing investments and progress made by China. One leading indicator of this growth is that China is now publishing about 119 professional journal articles on average per year in PPS&T, compared to about 87 articles per year from the United States over the same time period. However, investing in these imperatives and opportunities during the next ten years should help preserve U.S. preeminence in this area. Taken together, these opportunities would represent a substantial investment. The degree to which they can be pursued will depend upon available funding and relative priorities within the broader SSP. The determination of these priorities is beyond the scope of this study. The authors of this document have not considered the merits of these investments over other priorities in the SSP. The scenarios and activities outlined in Figure 2 are included for the purpose of highlighting how the opportunities presented here might be able to support the future as outlined in the FY17 Stockpile Stewardship Management Plan, but have not been approved for funding on those time scales by the NNSA complex.

Figure 1: Selected milestones from the FY17 Stockpile Stewardship Management Plan (SSMP) that various elements of this PPS&T strategy could contribute to.

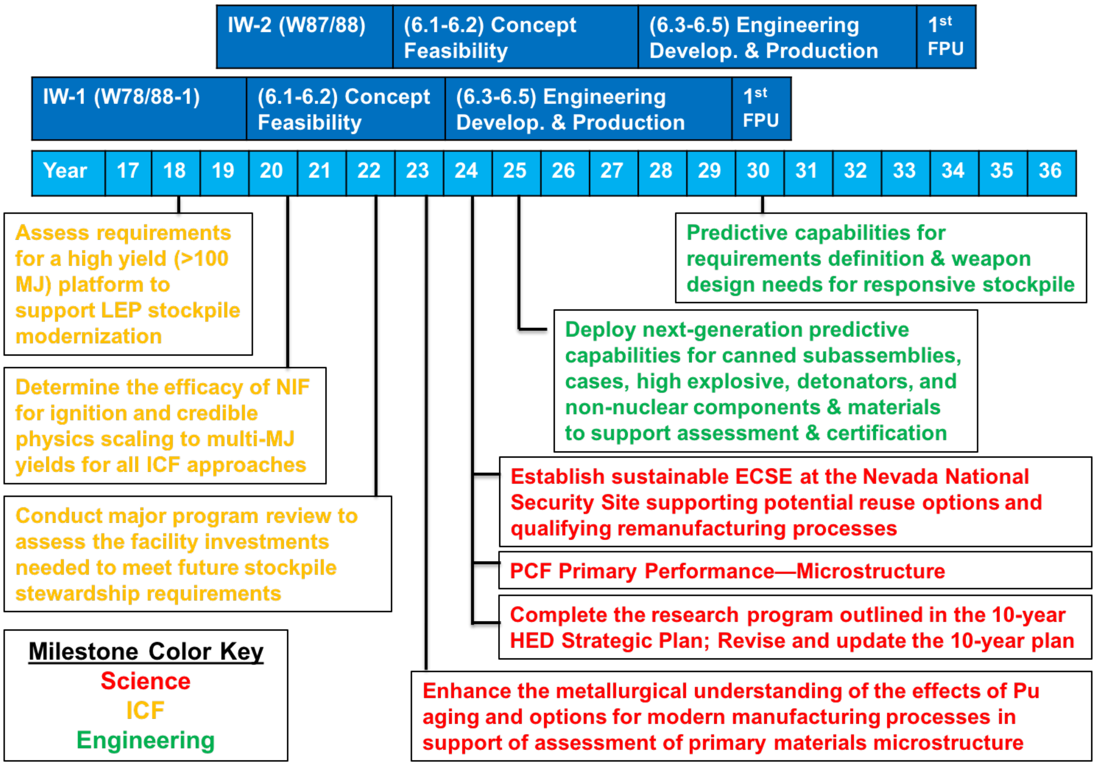
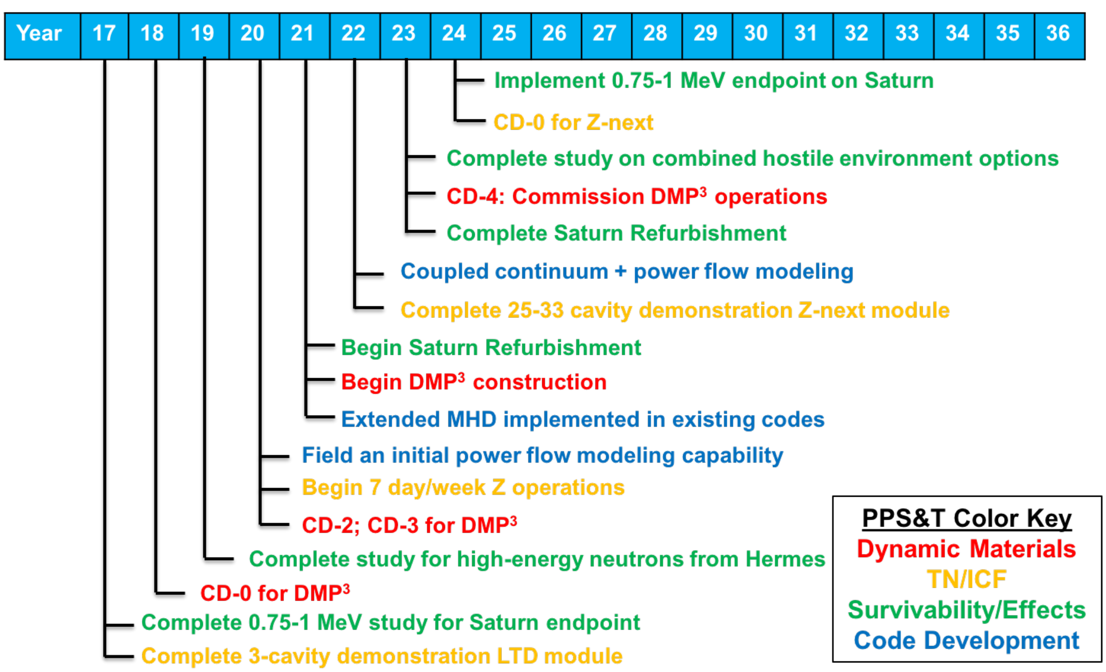


Figure 2: An aggressive hypothetical timeline for selected elements from this PPS&T strategy intended to illustrate how these elements could contribute to the SSMP milestones above. NNSA guidance explicitly directed that this study not attempt to prioritize these elements against other plans and priorities in the SSMP. Adopting all of these elements would require changes to ongoing program efforts and significant new investments.



Appendix A: NNSA Request

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

NNSA National Nuclear Security Administration

May 13, 2016

TO: J. STEPHEN ROTTLER
DEPUTY LABORATORIES DIRECTOR AND EXECUTIVE VICE PRESIDENT
SANDIA NATIONAL LABORATORIES (SNL)

CHARLES P. VERDON
PRINCIPAL ASSOCIATE DIRECTOR FOR WEAPONS & COMPLEX INTEGRATION
LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)

ROBERT B. WEBSTER
PRINCIPAL ASSOCIATE DIRECTOR OF WEAPONS PROGRAM
LOS ALAMOS NATIONAL LABORATORY (LANL)

FROM: KEITH R. LECHIEN
DIRECTOR, INERTIAL CONFINEMENT FUSION (ICF)
NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)

RALPH F. SCHNEIDER
DIRECTOR, RESEARCH AND DEVELOPMENT (R&D)
NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)

SUBJECT: Developing a strategic plan for pulsed power science and technology capabilities for high energy density physics applications for the Stockpile Stewardship Program (SSP)

NNSA has long recognized the importance of pulsed power science and technology (PPS&T) to high energy density physics (HEDP) mission applications for the SSP, and, having personal scientific roots in PPS&T, we well understand the need for a clear, mission-driven, prioritized vision for the future. NNSA requests a prioritized tri-laboratory, mission-driven plan for capability investments, and recommendations for NNSA's Stewardship Science Academic Programs (SSAP) to meet the PPS&T-related aspects of HEDP mission applications over the next two decades.

This plan must provide continued support for three principal HEDP mission applications:

- dynamic material properties (DMP),
- nuclear survivability and radiation effects science (RES), and
- thermonuclear burn (TN) physics and inertial confinement fusion (ICF).

It must also include the development of next-generation of codes for PPS&T physics design.

Recent efforts (*i.e.*, the Ten-year High Energy Density (HED) Science Strategic Plan and the national 2016 Inertial Confinement Fusion Program Framework) have defined clear HEDP requirements in most of these areas; however, identifying the PPS&T capabilities that must be developed necessitates an extended analysis of the *mission* requirements.

1) Dynamic Material Properties

Dynamic materials science requirements derive from two NNSA constituencies: 1) Defense Programs (DP) managed by the Science Program, and; 2) Defense Nuclear Nonproliferation (DNN) and Nuclear Counterterrorism (NCT) managed by DNN Research and Development. There are existing scientific plans and roadmaps, and some future scientific needs are described by Mission Need Statements of the Dynamic Compression Sector (DCS) and the Matter-Radiation Interactions in Extremes (MaRIE) facility. It is important for this plan to enable high-hazard DMP experiments (such as with plutonium) to be conducted safely and without risking serious, adverse consequences to a facility or to the Stockpile Stewardship Program. Therefore, the tri-laboratory plan should include:

- An assessment and recommendations for optimization of the science program for executing the DNN/NCT materials roadmap that builds upon the many years of success DP's Dynamic Plutonium Experiments effort.
- A requirements definition and rough order of magnitude cost for an inherently safe, high-fidelity pulsed power driver capable of complex loading and unloading, with simultaneous pressure and temperature measurements, x-ray diffraction, and other advanced diagnostics that fits within the existing NNSA facility footprint.
- An assessment of the cost and risk avoidance to DP and DNN/NCT that would be afforded by the pursuit the aforementioned capabilities.

2) Nuclear Survivability and Radiation Effects Science

X-ray and neutron sources are under development at Z, Saturn, HERMES, and the NIF that meet near-term requirements for life extension programs (LEPs). Evolving requirements for nuclear and non-nuclear components, however, must be captured in a manner that is conducive to assessing PPS&T needs. In addition, the 2015 Review of NNSA's ICF/HED portfolio identified the need to strengthen the integration between the "stove-pipes" of the HEDP community and the radiation effects science and hostile environment communities. Therefore, the tri-laboratory plan should include:

- Documentation of the x-ray and neutron source requirements that are implied by the long-term nuclear survivability and hostile environment requirements.
- A requirements definition for the PPS&T capabilities needed to meet those requirements.

3) Thermonuclear Burn Physics and Inertial Confinement Fusion

The TN and ICF missions have clear requirements for multi-megajoule fusion yield, as articulated in the Laboratory Directors' January 20, 2015 letter on the importance of HED science. Developing credible evidence for physics scaling to multi-megajoule yields for the three major ICF approaches is the core component of the ICF Program Framework and is directly dependent upon experimental opportunities on existing facilities. TN and ICF research opportunities on Z are quite limited, and all are focused on "direct-drive" due to resource limitations, with the magneto-inertial fusion community poised to conduct less than half as many experiments over the next five years as compared to both the indirect and direct drive laser inertial fusion communities. The 2015

Review of NNSA's ICF/HED portfolio stated that shot opportunities on Z should be increased and "resources prioritized to the [magnetic direct drive] MDD effort to build a stronger cadre of designers, experimental physicists, and diagnosticians." Therefore, the tri-laboratory plan should include:

- A cost-benefit analysis to achieve more TN/ICF opportunities on Z through additional operational shifts.
- An evaluation of whether the number of DMP experiments on Z could be reduced in favor of TN/ICF as part of the assessment of new capabilities supporting the DMP mission mentioned above.
- An assessment of the utility of x-ray driven capsules using recently developed sources on Z for SSP applications.
- An assessment of the mission need for "high-yield" fusion capabilities, and a summary of the potential implications for PPS&T capabilities.

4) Next-Generation Codes for PPS&T Physics Design

Advancing computational capabilities are a key part of the next-generation PPS&T strategy. For decades, the nuclear security enterprise has used reduced-physics fluid codes to make simulations tractable; this is an historic artifact of the limitations of older computer architectures. Simulations of a wide variety of three-dimensional and kinetic effects require fundamentally new computational platforms that are fully relativistic, fully electromagnetic, and massively parallel to take advantage of the latest generation of computer clusters that are available today or in the near future. Therefore, the tri-laboratory plan should include:

- An assessment of capabilities needed both for pulsed power technology (*e.g.*, driver-target coupling) and for magneto inertial target physics.

5) Academic and industry engagement in PPS&T

The tri-laboratory plan should also include a description of a credible path for ensuring a pipeline of future pulsed power scientists through the SSAP. Finally, the plan should identify the industry partners capable of co-developing components, conducting research and development, and leading production-scale manufacturing activities for modular pulsed power technologies.

Dr. Bryan Sims is the NNSA point of contact for this effort (bryan.sims@nnsa.doe.gov). By May 18, please provide Dr. Sims the name of a single point of contact from each laboratory. The plan shall be submitted to NNSA by August 18, 2016.

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