Linked Neutronics and Hydrodynamics Calculations for the Z Pinch Driven Target of X-1

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ABSTRACT

Linked neutronics and hydrodynamics calculations have been performed for X-1 targets using the radiation hydrodynamics computer code BUCKY and the neutronics code ONEDANT. Target neutronics calculations were performed taking into account the varying configuration during the burn as well as the distributed material densities and fusion neutron source profile. The energy spectrum of neutrons emitted from the target varies during the burn with a softer spectrum produced in early time intervals. Neutrons emitted from the target carry 69.22% of the fusion energy with 28.3% carried by the x-rays and debris. A small fraction of 0.03% is carried by gamma photons and 2.45% is lost in endoergic reactions. Full coupling of the neutronics and hydrodynamics calculations is essential for making consistent predictions of the partitioning of the target energy between x-rays, ion debris, neutrons, and gamma photons and an accurate estimate of the net target yield by accurately accounting for the endoergic energy losses and energy deposited by neutrons.

I. INTRODUCTION

X-1 is a concept for a large pulsed power machine that could produce intense x-ray pulses with wire array z-pinches.[1] The produced x-rays will provide unique applications in areas of x-ray damage, high-energy physics, inertial confinement fusion (ICF), and radiation effects simulation research. X-1 will have the capability to drive z-pinches to currents of ~60 MA producing x-ray yields of ~16 MJ. A fraction of this x-ray energy would be sufficient to ignite high yield ICF capsules.[2] Three target concepts have been considered. These are dynamic hohlraums, z-pinch driven hohlraums and static wall hohlraums. A detailed discussion of these concepts is given in reference 2. In this paper, we consider only the static wall hohlraum target concept. In this target concept, x-rays would be fed to a cylindrical hohlraum from both ends. The hohlraum would create the proper symmetry for the implosion to ignition of the ICF capsule producing large fusion yields (200-1000 MJ). The blast resulting from the explosion would be confined inside an aluminum target chamber submerged in a water tank for shielding purposes. An experiment chamber concept is shown in Fig. 1.

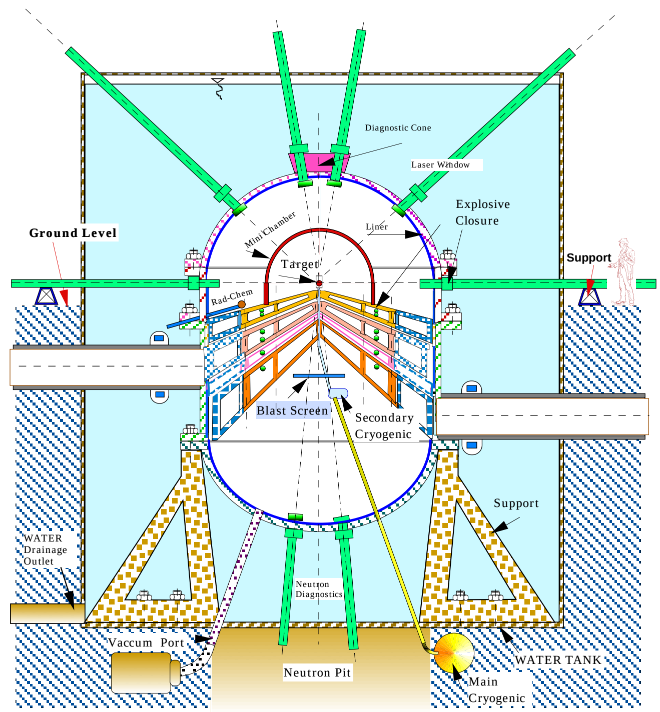

Fig. 1. X-1 experiment chamber concept.

Following DT fusions, 14.1 MeV neutrons and 3.5 MeV α particles are produced. The whole energy of the α particles will be reabsorbed in the target. In addition, a fraction of the neutrons' energy will be reabsorbed in the target following interactions of the fusion neutrons with the extremely dense target. The energy reabsorbed in the target is carried by x-rays and target debris. Accurate determination of the characteristics of the radiation emanating from the target during the burn is critical to understanding the target chamber behavior. This involves performing capsule implosion and burn calculations using radiation hydrodynamics computer codes. The capsule hydrodynamics calculations yield the target configuration and material composition that vary during the burn. Hence, linking the target neutronics calculations to the hydrodynamics calculations is essential.[3] We have developed an automated linkage between the one-dimensional radiation hydrodynamics code BUCKY-1[4] and the neutron transport code ONEDANT.[5] In this paper, we utilize this calculation tool to determine the characteristics of radiation emanating from the X-1 target.

II. TARGET DESCRIPTION

The X-1 target we have considered consists of a beryllium-oxide ablator cryogenic capsule enclosed in a helium filled gold hohlraum. The cylindrical hohlraum is attached on either end to wire array z-pinches, which supply the hohlraum with x-rays. The beryllium-oxide shell consists of two layers: an outer shell of BeO and an inner shell of $Be_{98}O_2$. The beryllium-oxide layers are designed to use a given radiation temperature pulse shape to produce a properly timed set of shocks. As the beryllium-oxide shells are heated by the hohlraum x-rays, the opacity changes due to the ionization of the oxygen atoms. When oxygen becomes fully ionized, the bound-free and bound-bound atomic transitions no longer occur, the opacity drops and the radiation is allowed to pass. By carefully adjusting the geometry of the two beryllium-oxide layers, an efficient implosion is achieved. The cryogenic DT fuel is compressed to a high ρR assembly, with the inner fuel heated to the point of thermonuclear ignition. A burn wave propagates through the compressed fuel, burning 30% of it.

III. CAPSULE IMPLOSION AND BURN CALCULATIONS

In our analysis, we have assumed a radiation temperature history in the hohlraum peaking at 275 eV. The assumed radiation temperature history is shown in Fig. 2 as a function of time after the z-pinch begins. Then, we have simulated the implosion and burn of the X-1 capsule with the 1-D computer code BUCKY.[4] BUCKY is a 1-D Lagrangian radiation hydrodynamics computer code, with flux-limited multigroup radiation diffusion and thermonuclear burn. Neutrons are produced during the burn, which deposit some energy back into the fuel. BUCKY uses only a simple escape probability method for the re-absorption of neutron energy. The capsule geometry has been adjusted to give a good implosion and thermonuclear yield. The implosion is shown in Fig. 3, where Lagrangian zone boundaries are plotted versus time. The best initial capsule geometry can be seen in Fig. 3. The target reaches peak compression, ignites and burns at ignition time, about 157 ns after the z-pinch begins. The burn time was divided into 10 time intervals to provide target information for the neutronics calculations. The time at the midpoint of each of these intervals measured from start of the z-pinch is given in Table 1. The mass density profiles at selected time intervals during the burn are plotted in Fig. 4 as a function of radial distance from the center of the capsule. The densities get lower as one approaches the end of the burn. The fusion power profiles are shown in Fig. 5. It is clear that at early times during the burn, the fusion neutrons are generated in a small region at the center of the capsule. As time elapses, the expanding target results in spreading the neutron source over a larger volume. The information in Figs. 4 and 5 represent important input for the target neutronics calculations.

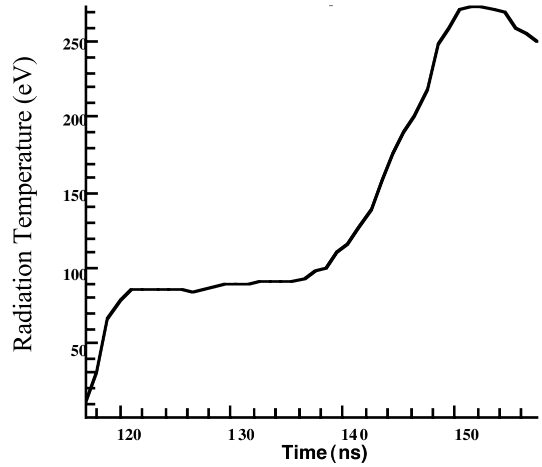

Fig. 2. Hohlraum radiation temperature history on surface of X-1 capsule.

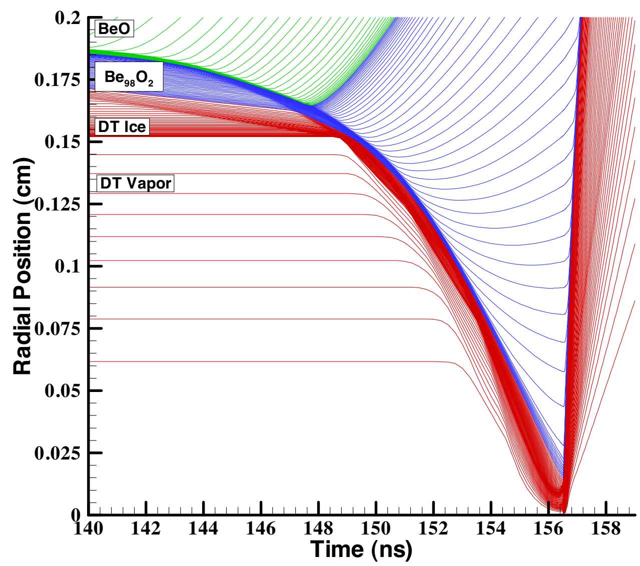

Fig. 3. Positions of Lagrangian zone boundaries plotted against time since start of z-pinch implosion.

Table 1. Times at Midpoints of Time Intervals

Interval	Time (ns)
1	156.450
2	156.475
3	156.500
4	156.505
5	156.510
6	156.515
7	156.520
8	156.525
9	156.550
10	156.595

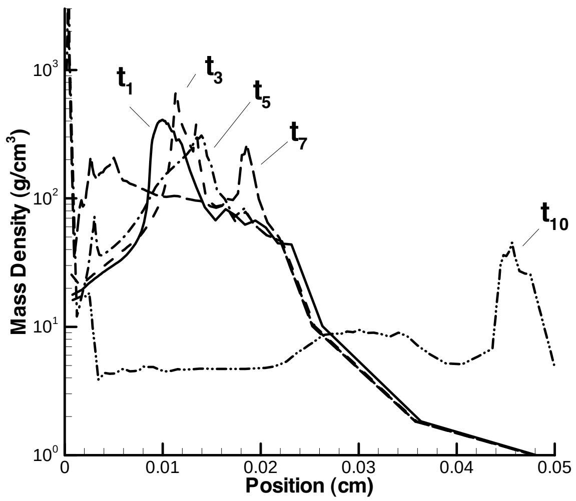

Fig. 4. Mass density profiles in capsule near ignition time.

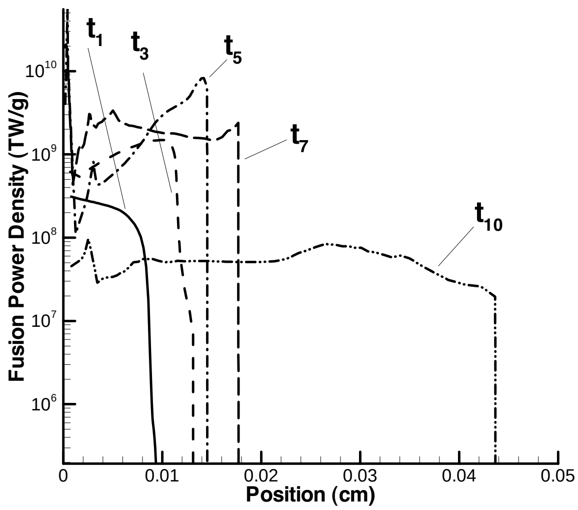

Fig. 5. Fusion power density profiles near ignition time.

IV. TARGET NEUTRONICS

In a DT fusion reaction one 14.1 MeV neutron and one 3.5 MeV alpha particle are produced. The DT fuel is heated and compressed to extremely high densities (> 100 g/cm^3) before it ignites. Although the target radius is very small, the fusion neutrons will have a significant probability for interaction with the dense fuel before emanating from the target. The neutron interactions with the fuel and other target constituents result in significant softening of the neutron spectrum. In addition, neutron multiplication occurs as a result of (n,2n) and (n,3n) reactions yielding more than one neutron being emitted from the target for each DT fusion. Gamma photons are also produced from neutron interactions with the target constituents. The energy deposited by the neutrons and gamma photons heats the target. This energy and the whole energy of the α particles produced in the DT fusion ultimately take the form of radiated x-rays from the hot plasma and expanding ionic debris.

Neutronics calculations have been performed for the X-1 target using the ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system.[5] The target is modeled in one-dimensional spherical geometry. In addition to the DT fuel and the $Be_{98}O_2$ and BeO shells, the neutronics model included a 25 μm thick gold layer at a radius of 2 cm to represent the hohlraum. BUCKY output has been post-processed to provide fusion burn and density profiles at ten selected times during the burn in a format adequate for the ONEDANT neutronics calculations. In this manner, the target neutronics calculations were performed taking into account the varying configuration during the burn as well as the distributed material densities and fusion neutron source profile. Neutronics calculations have been performed for the ten time intervals during the burn using the target specifications determined by BUCKY. The results were combined, weighted by the percentage of the yield produced in each time interval, to determine the time-integrated overall target neutronics parameters.

The total number of neutrons emitted from the target per DT fusion is 1.064. This value is larger than unity because of neutron multiplication resulting from interactions of neutrons with the dense DT fuel. Neutron multiplication is much smaller (1.014) during the final time interval due to the reduced density. The neutrons emanating from the target carry a total energy of 12.18 MeV per DT fusion implying that the average neutron energy is 11.45 MeV. The neutron energy spectrum gets harder in the final stages of the burn due to the lower density. Figure 6 shows the energy spectra for neutrons emitted from the target during the first, fifth, and tenth time intervals. The time integrated energy spectrum is also given. It is interesting to note that only 66.4% of the neutrons emitted from the target are uncollided 14.1 MeV neutrons. Neutron target interactions lead also to gamma generation. For each DT fusion reaction, 0.0024 gamma photons are emitted as a result of neutron-target interactions with an average energy of 1.97 MeV. The gamma energy spectrum is given in Fig. 7.

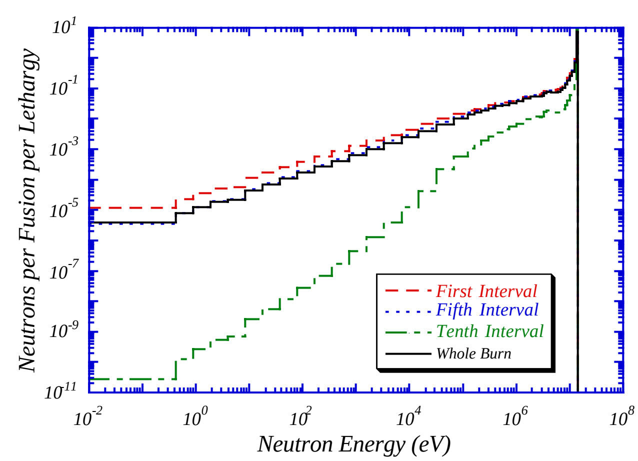

Fig. 6. Energy spectrum of neutrons emitted from target.

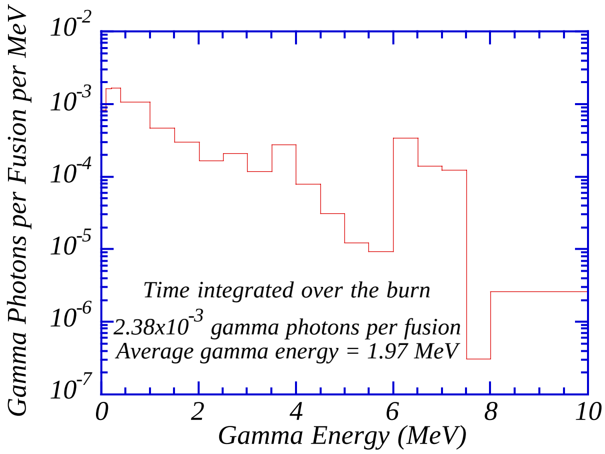

Fig. 7. Energy spectrum of emitted gamma photons.

The fraction of neutron energy reabsorbed in the target is given in Table 2 for the different time intervals. It is clear that the fraction of neutron energy redeposited is much lower during the final stages of the burn due to the reduction in the DT density. Almost all of the energy is deposited in the DT fuel zone. The results obtained from the neutronics calculations are compared to those resulting from the simple escape probability model used in BUCKY. In general, the simple neutronics model in BUCKY tends to underestimate the energy redeposited by neutrons.

Table 2. Neutron Energy Reabsorbed in the Target

Interval	% of yield	% of Neutron Energy Reabsorbed	
		Neutronics	Hydrodynamics
1	0.36	13.57	12.94
2	1.10	13.64	13.06
3	6.92	14.79	12.50
4	19.93	14.36	12.20
5	21.38	11.99	11.08
6	11.86	10.26	9.21
7	7.91	9.39	7.72
8	13.24	9.35	6.59
9	13.55	4.55	3.61
10	3.75	1.65	1.28
Total	100	10.50	9.05

The total energy redeposited by neutrons as obtained from the neutronics calculations is 1.48 MeV compared to 1.27 MeV per DT fusion predicted by BUCKY. This slightly impacts the x-ray and ion debris yield determined from the hydrodynamics calculations. The energy deposited by gamma photons is only 100 eV/DT fusion. When the 3.5 MeV energy carried by the alpha particle emerging from the fusion reaction is added, a total energy of 4.98 MeV per DT fusion is found to be carried by x-rays and target debris following the microexplosion. Performing an energy balance for the target indicates that 0.43 MeV of the energy is lost in endoergic reactions per DT fusion. This represents about 2.5% of the target fusion yield and will impact the energy partioning and the net target yield. The detailed partitioning of the energy produced from the target is listed in Table 3.

Notice that currently the neutronics calculations are only linked to the hydrodynamics code by utilizing its results. However, the hydrodynamic code uses only a simple escape probability method for the re-absorption of neutron energy and does not account for endoergic losses resulting from neutron target interactions. It is therefore important to have full coupling between the two calculations where the hydrodynamics code also utilizes the neutronics results. Full coupling of the neutronics and hydrodynamics calculations allows making consistent predictions of the partitioning of the target energy between x-rays, ion debris, neutrons, and gamma photons and an accurate estimate of the net target yield by accurately accounting for the endoergic energy losses and energy deposited by neutrons.

Table 3. Energy Partitioning from X-1 Target

Neutrons	69.22%
Gamma photons	0.03%
x-rays and debris	28.3%
Endoergic loss	2.45%

The improvement in target neutronics calculations by linking to the hydrodynamics calculations involved accounting for the variation of target parameters with time during the burn and the spatial variation of mass and fusion power densities (Figs. 4 and 5). In the past, target neutronics calculations were performed for a single target configuration during the burn with uniform mass densities in each of the target zones and uniform fusion neutron source in the DT fuel zone. The results of this paper clearly indicate that the neutronics features of the target vary considerably during the burn. Hence, picking a single target configuration during the burn for the neutronics calculations might lead to significantly different results as clearly indicated by the results in Fig. 6 and Table 2. We assessed the impact of the spatial variation of mass and fusion power densities by performing two calculations using the target configuration at the fifth time interval. In the first one, the detailed spatial distribution obtained from BUCKY was used. In the second one, uniform mass densities corresponding to the volume-averaged values were used in each of the four capsule zones. In addition, the 14.1 MeV neutron source was assumed to be uniform in the DT fuel zone. Table 4 compares the neutronics results for these two cases. The calculation using uniform distributions tends to underestimate neutron target interactions since it does not properly account for the extremely large mass and fusion power densities at the center of the fuel zone. This results in underestimating neutron multiplication and spectrum softening. This leads also to overestimating target neutron yield and underestimating the gamma, x-ray and debris yields. However, the differences are small implying that the improvement in target neutronics achieved by linkage to the hydrodynamics calculations is contributed primarily by accounting for temporal variation of target features during the burn. Including the detailed spatial distributions of mass and fusion power densities adds a second order refinement of the results.

Table 4. Neutronics Results for Fifth Time Interval with Detailed Spatial Distribution of Densities and Source Compared to Results with Uniform Distributions

	Uniform	Distributed
Neutron multiplication	1.052	1.076
Energy carried by neutrons (MeV/fusion)	12.09	11.98
Average energy of neutrons (MeV)	11.50	11.13
% of neutrons @ 14 MeV	66%	62.3%
Emitted gamma per fusion	$1.5x10^{-3}$	$2.5x10^{-3}$
Energy carried by gamma (MeV/fusion)	0.0017	0.0042
Average gamma energy (MeV)	1.12	1.97
Absorbed neutron energy (MeV/fusion)	1.63	1.65
Absorbed gamma energy (MeV/fusion)	$2.2x10^{-5}$	$1.2x10^{-4}$
Endoergic losses (MeV/fusion)	0.374	0.466
Fusion Energy Partitioning:		
Neutrons	68.71%	68.07%
Gamma Photons	0.01%	0.02%
X-rays and Debris	29.15%	29.26%
Endoergic Losses	2.13%	2.65%

In the future, the coupling between BUCKY and ONEDANT will be enhanced by including the generated helium, hydrogen and other species in the neutronics model. Of particular interest is the production of helium from the DT fusion reactions. Since each DT fusion produces a helium nucleus and the burn fraction is about 30%, large amounts of helium will be produced. The amount of helium in the target will be increasing from zero at the start of burn to a maximum value at the end of the burn. We performed calculations to assess the impact of the helium on the target neutronics parameters. The preliminary results indicated that the additional helium results in a slight impact on the neutron energy spectrum and the target energy partitioning. This issue will be fully addressed after the coupling between BUCKY and ONEDANT is fully implemented.

V. SUMMARY

Capsule implosion and burn calculations have been performed for X-1 targets using the radiation hydrodynamics computer code BUCKY. For these calculations, a radiation temperature history peaking at 275 eV is assumed to drive a fusion capsule. The geometry of the layers has been optimized to provide correct shock timing during the implosion. BUCKY output has been post-processed to provide fusion burn and density profiles at ten selected times during the burn in a format adequate for neutronics calculations. Target neutronics calculations were performed taking into account the varying configuration during the burn as well as the distributed material densities and fusion neutron source profile. The energy spectrum of neutrons emitted from the target varies during the burn with a softer spectrum produced in early time intervals. Neutron interactions with the target constituents result in 1.064 neutrons and 0.0024 gamma photons emitted from per DT fusion. These neutrons and gamma photons have average energies of 11.45 and 1.97 MeV, respectively. The total neutron energy reabsorbed in the target is 1.48 MeV per fusion. Performing an energy balance for the target indicates that neutrons emitted from the target will carry 69.22% of the fusion energy and 28.3% will be carried by the x-rays and debris. A small fraction of 0.03% is carried by gamma photons and 2.45% is lost in endoergic reactions. It is important to have full coupling between the two calculations where the hydrodynamics code also utilizes the neutronics results. Full coupling of the neutronics and hydrodynamics calculations allows making consistent predictions of the partitioning of the target energy between x-rays, ion debris, neutrons, and gamma photons and an accurate estimate of the net target yield by accurately accounting for the endoergic energy losses and energy deposited by neutrons.

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REFERENCES

1. G.E. Rochau, et al., "Systems Analysis and Engineering of the X-1 Advanced Radiation Source," Fusion Technology, 34, 825 (1998).

2. R.E. Olson, et al., "Indirect-Drive ICF Target Concepts for the X-1 Z-Pinch Facility," Fusion Technology, 35, 260 (1999).

3. J. MacFarlane, M. Sawan, G. Moses, P. Wang, and R. Olson, "Numerical Simulation of the Explosion Dynamics and Energy Release from High-Gain ICF Targets," Fusion Technology, 30, 1569 (1996).

4. J.J. MacFarlane, G.A. Moses and R.R. Peterson, "BUCKY-1 – A 1-D Radiation Hydrodynamics Code for Simulating Inertial Confinement Fusion High Energy Density Plasmas," University of Wisconsin Fusion Technology Institute Report UWFDM-984 (1995).

5. R.E. Alcouffe et al., "DANTSYS 3.0, One-, Two-, and Three-Dimensional Multigroup Discrete Ordinates Transport Code System," RSICC Computer Code Collection CCC-547, Contributed by Los Alamos National Lab, August 1995.