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Radiochemistry: A Versatile Diagnostic for the NIF Ignition Campaign

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The purpose of this paper is to provide quick, clear, concise information about radiochemical diagnostics for the NIF program. Radiochemistry is perhaps the most versatile, flexible and dynamic of all nuclear diagnostics because it provides quantitative data on multiple capsule performance parameters such as mix, asymmetry of implosion, shell and fuel ρR, yield, neutron spectral information, high energy neutron information, fill tube jets, charged particle stopping, and the fission yield of the hohlraum by employing a variety of nuclear reactions on materials either present naturally in the capsule or specifically doped into the capsule. The choice and location of the doped material, together with the specific nuclear reaction used to produce a measurable product nuclide or ratio of nuclides, provides significant diagnostic information on the performance of the capsule during the experiment. The nature of the experiment, design of the capsule including fuel(s), and desired diagnostic information would dictate the radiochemical dopants used on any given shot—not all reactions would be possible nor monitored on any given experiment. Some of this diagnostic information is obtainable with other diagnostics, for example, the neutron yield is measured using Cu-activation pucks or nTOF. The unique niche of radiochemistry, for which few other measurements are currently planned, is the quantification of ablator/fuel mix. This diagnostic can supply complementary information on ablator ρR, asymmetry and unique information on mix—three of the four important concerns of the ignition campaign. This paper will not discuss the additional nuclear chemistry and physics possible by utilizing radiochemistry collection and similar nuclear reactions.

Definition of terms:

Collection fraction: The fraction of the total debris that is collected for analysis usually measured by comparing the amount of some isotope collected to the initial amount of that isotope in the capsule. Sometimes called the bomb fraction or collection efficiency.

Detector: An element or isotope specifically doped into the capsule (or already present) that will undergo nuclear reactions to produce a product for analysis.

Product: The result of a nuclear reaction on a detector whose production rate is proportional to diagnostically important information. Minimum detectable amounts are indicated in Table 1 of Appendix I.

Tracer: An isotope specifically doped into the capsule, preferably co-loaded with the detector, but possibly placed nearby, used to determine the collection fraction.

Diagnostic information: Quantitative amount of ablator/fuel mix
Detectors: ^{18}O, ^{79}Br, ^{127}Xe
Tracers required: Ne, Kr, Xe
Detector location: Uniformly distributed in the innermost ablator layer
Nuclear reactions used: ^{18}O(α,n)^{21}Ne; ^{79}Br(d,2n)^{79}Kr; ^{127}I(d,2n)^{127}Xe
Products: ^{21}Ne (stable); ^{79}Kr($t_{1/2}$ = 1.455 d); ^{127}Xe ($t_{1/2}$ = 36.4 d)
Ratios measured: ^{21}Ne/^{18}O; ^{79}Kr/^{79}Br; ^{127}Xe/^{127}I
Possible interferences: ^{21}Ne background in target chamber
Best simulations: 2D Be/Cu and 2D CH capsules by Cerjan
Minimum capsule yield diagnosable: ~60 kJ (DT); ~1 MJ (HTD)

Brief description:

This measurement utilizes the difference in range between the 3.5 MeV alpha-particles produced in DT fusion and the up-scattered deuterons produced by 14 MeV neutron knock-on reactions to probe the extent of the ablator mixing into the fuel. Since knock-on deuterons have a longer range and are produced more or less uniformly throughout the fuel, the (d,2n) reactions occur deeper into the ablator material including ablator that was not mixed into the fuel. Because the alpha-particle range is shorter, and the alpha-particles are mostly produced in the hot spot, the (α,n) reaction is very sensitive to mixed ablator material. Indeed, if ablator material is mixed into robustly burning material and the burn is NOT perturbed, the production of the alpha reaction product is higher than in non-mix cases. However, in nearly all mix scenarios, because the higher-Z material mixing into the fuel actually does perturb the burn, namely it cools the fuel and less alpha-particles are produced, the production of the alpha reaction product drops significantly and much faster than the yield of the capsule is dropping. A comparison of the ^{21}Ne/^{18}O ratio with one of the deuteron-induced ratios, such as ^{127}Xe/^{127}I, enables quantification of mix as shown in Table A. This effect has also been shown for double shell capsules [1] even though the capsules ignite in different manners; double shells are volume ignition and the point design capsules are hot spot ignition.

Table A: Radiochemical isotopes produced and ratios to loaded detector isotopes for various Be/Cu point design capsule implosions as a function of mix length at the ablator/fuel interface. The initial loading of ^{127}I and ^{18}O were 1×10^{14} and 1×10^{15} atoms, respectively.

Mix length (μm)	Yield (MJ)	^{127}Xe	^{21}Ne	^{127}Xe/^{127}I$_L$	^{21}Ne/^{18}O$_L$
0	25.22	1.02×10^{10}	2.08×10^{11}	1.02×10^{-4}	2.08×10^{-4}
10	14.01	3.44×10^{9}	7.02×10^{10}	3.44×10^{-5}	7.02×10^{-5}
20	3.19	2.73×10^{8}	1.09×10^{9}	2.73×10^{-6}	1.09×10^{-6}
30	0.65	3.05×10^{7}	5.50×10^{7}	3.05×10^{-7}	5.50×10^{-8}

[1] J. Colvin, C. Cerjan, R. Hoffman, M. Stoyer, and P, Amendt, *"Radiochemical Tracers as a Mix Diagnostic for the Ignition Double-Shell Capsule"*, submitted to Phys. Plasmas (2008).

Diagnostic information: Capsule asymmetry during implosion
Detectors: ^{126}Xe [^{124}Xe, ^{134}Xe]
Tracers required: Xe (maybe ^{134}Xe)
Detector location: Uniformly distributed in the innermost ablator layer
Nuclear reactions used: ^{126}Xe(n,2n)^{125}Xe; ^{126}Xe(n,γ)^{127}Xe [^{124}Xe(n,2n)^{123}Xe; ^{124}Xe(n,γ)^{125}Xe; ^{134}Xe(n,2n)^{133}Xe; ^{134}Xe(n,γ)^{135}Xe]
Products: ^{125}Xe ($t_{1/2}$=17.1 h); ^{127}Xe ($t_{1/2}$ = 36.4 d) [^{123}Xe ($t_{1/2}$ = 2 h); ^{125}Xe ($t_{1/2}$ = 17.1 h); ^{133}Xe ($t_{1/2}$ = 5.243 d); ^{135}Xe ($t_{1/2}$ = 9.1 h)]
Ratios measured: ^{127}Xe/^{125}Xe [^{125}Xe/^{123}Xe; ^{135}Xe/^{133}Xe]
Possible interferences: if use ^{126}Xe will interfere with ^{127}I(d,2n)^{127}Xe mix diagnostic; if use ^{134}Xe fission from hohlraum will interfere
Best simulations: 2D Be/Cu and 2D CH capsules by Cerjan
Minimum capsule yield diagnosable: ~60 kJ (DT); ~150 J (HTD)

Brief description:

This measurement utilizes the differences in locations and densities of ablator material induced by various reasonable and expected perturbations due to asymmetries in the implosion (P2, P4, P6, …) coupled with differences in the neutron spectrum (most notably the lower energy downscattered ~6—10 MeV neutrons) to provide information on the possible asymmetry mode. When coupled with external neutron yield measurements or charged-particle-induced product ratios, a dominant mode can be uniquely identified. This diagnostic provides a snapshot of ablator material location and density at peak burn time.

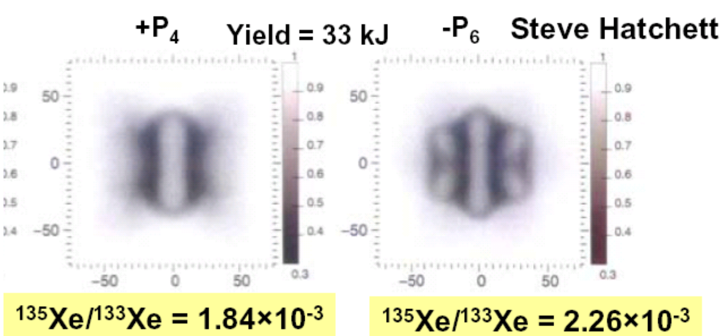

Fig. A: Simulated ARC images by Steve Hatchett for two capsules with identical yields of 33 kJ but suffering from different asymmetries and the calculated Xe radiochemical ratios for each case showing a 20% difference.

Table A: Comparison of radiochemical ratios for four different asymmetry modes showing the unique fingerprint obtained by using multiple ratios.

Ratio	P6 -0.0097	P6 -0.0145	P4 0.0190	P4 0.0285
^{21}Ne/^{18}O	1.59E-07	1.72E-09	5.74E-07	1.71E-09
^{127}Xe/^{127}I	5.44E-07	7.27E-09	8.99E-07	8.41E-09
^{135}Xe/^{133}Xe	1.43E-03	2.26E-03	1.40E-03	1.84E-03
^{127}Xe/^{126}Xe			2.39E-02	3.52E-02
Yield (MJ)	0.87705	0.0339743	1.21456	0.0330379

Diagnostic information: Ablator ρR (or amount of ablator remaining at peak burn time)
Detectors: ^{65}Cu [^{70}Ge;^{76}Ge]
Tracers required: Cu [Ge]
Detector location: Graded dopant in Be ablator [CH ablator]
Nuclear reactions used: $^{65}Cu(n,2n)^{64}Cu$ [$^{70}Ge(n,2n)^{69}Ge$; $^{76}Xe(n,2n)^{75}Ge$]
Products: ^{64}Cu ($t_{1/2}$=12.7 h) [^{69}Ge ($t_{1/2}$ = 1.63 d); ^{75}Ge ($t_{1/2}$ = 1.38 h)]
Ratios measured: $^{64}Cu/^{65}Cu$ [$^{69}Ge/^{70}Ge$; $^{75}Ge/^{76}Ge$]
Possible interferences: production of ^{64}Cu from $^{63}Cu(n,\gamma)^{64}Cu$ [^{75}Ge from $^{74}Ge(n,\gamma)^{75}Ge$]
Best simulations: 1D Be/Cu capsules by Spears (1D Omega capsules by Haan, Tipton) [none]
Minimum capsule yield diagnosable: ~200 kJ (DT); ~800 J (HTD)

Brief description:

This measurement utilizes the high 14 MeV neutron fluence at peak burn time coupled with the remaining ablator material location at that time to quantify the amount of remaining material. Cu that has been ablated is located at a larger distance from the hot spot and lower ρR than the remaining ablator material and consequently undergoes fewer (n,2n) reactions. The $^{64}Cu/^{65}Cu$ ratio is directly proportional to ablator ρR × Y. A comparison of Cu activation for several simulations of the Be/Cu point design capsules with differing amounts of ablator remaining, varied within the expected variances for NIF implosions, is shown in Table A.

Many factors which degrade the yield of an ICF capsule are modeled, but the relative proportions of each are not well constrained because of gaps in our understanding of the physics. Sufficient capsule diagnostic information is required to constrain the modeling efforts and one measurement that both ICF and HEDP programs would like is the ablator shell ρR at peak burn time. Ablator thickness during the implosion has been measured for some capsules. The shell ρR is normally measured by monitoring the high energy protons (14.7 MeV) from D + ^{3}He reactions in flight and measuring the broadening or shifting of the emitted particle's "birth" energy. This proton measurement utilizes a surrogate capsule with $D^{3}He$ fuel and suffers from uncertainties due to energy losses exiting the capsule, low abundance of the reaction, and ablator blow-off, which is hard to quantify. Additionally, as the ρR increases, eventually charged particles are slowed significantly or stopped in the capsule and the diagnostic becomes not viable. Neutrons are more penetrating, and thus a neutron based diagnostic will be viable to higher ρRs.

Table A: ^{64}Cu production as a function of ablator thickness. The "thinner ablator" case may not be distinguishable from nominal because of expected 5-7% uncertainties on the measured atom ratio.

Implosion	Yield (MJ)	^{64}Cu (atoms)	$^{64}Cu/^{65}Cu$	$(^{64}Cu/^{65}Cu)$/nominal
Very thin ablator	6	3.870E+08	2.545E-09	5.623E-06
Thinner ablator	12	6.609E+13	4.346E-04	9.602E-01
Nominal	14	6.884E+13	4.526E-04	1.000E+00
Thicker ablator	12	9.410E+13	6.188E-04	1.367E+00
Very thick ablator	0.2	1.807E+11	1.188E-06	2.625E-03

<u>Diagnostic information:</u> Fuel ρR
<u>Detectors:</u> ^{38}Ar
<u>Tracers required:</u> Ar
<u>Detector location:</u> Uniformly distributed throughout fuel
<u>Nuclear reactions used:</u> $^{38}Ar(n,2n)^{37}Ar$
<u>Products:</u> ^{37}Ar ($t_{1/2}$=35 d)
<u>Ratios measured:</u> $^{37}Ar/^{38}Ar$
<u>Possible interferences:</u> Ar background in target chamber
<u>Best simulations:</u> 1D CH or glass OMEGA capsules by Haan
<u>Minimum capsule yield diagnosable:</u> ~1e12 neutrons (DT); UK (HTD)

<u>Brief description:</u>

This measurement utilizes the 14 MeV neutrons produced in DT fusion coupled with the location and density of the fuel at peak burn time to quantify the average ρR of the fuel using the (n,2n) nuclear reaction. As can be seen from Table A, the $^{37}Ar/^{38}Ar$ ratio is proportional to the fuel ρR of two sets of direct drive non-cryo capsules, with yields around 10^{13} neutrons. Corrections for volume effects might be expected, since the detector is positioned within the burning fuel where the neutrons are being produced rather than external to the production region. Such corrections have not been made to the calculations shown in Table A. It should be noted that the maximum amount of ^{38}Ar allowed in a capsule without affecting the burn has not been determined.

Table A: Fuel ρR and ^{37}Ar production compared between several direct drive OMEGA capsules. Note that the $^{37}Ar/^{38}Ar$ ratio is proportional to the fuel ρR × Y for at least two capsule designs.

Capsule	Ablator	Yield (14 MeV neutrons)	Fuel ρR (mg/cm^2)	$^{37}Ar/^{38}Ar$*	K‡ (× 10^{23})
DD Non-Cryo	Glass	3.2×10^{13}	6.6	1.1×10^{-8}	5.4
DD Non-Cryo†	Glass	3.9×10^{13}	6.8	1.4×10^{-8}	5.4
DD Non-Cryo	CH	6.7×10^{12}	13.8	5.7×10^{-9}	6.2
DD Non-Cryo	CH	9.1×10^{12}	14.6	8.2×10^{-9}	6.2

*~1 at% ^{38}Ar loaded in fuel region of capsule
†Significant production of ^{38}Cl, ^{35}S, and ^{39}Ar from (n,p), (n,α) and (n,γ), respectively
‡K =($^{37}Ar/^{38}Ar$)/(Y•ρR)

Diagnostic information: Yield
Detectors: ^{126}Xe; ^{134}Xe (various others will also work)
Tracers required: Xe [various]
Detector location: Uniformly distributed in inner part of ablator
Nuclear reactions used: ^{126}Xe(n,2n)^{125}Xe; ^{134}Xe(n,2n)^{133}Xe
Products: ^{125}Xe ($t_{1/2}$=17.1 h); ^{133}Xe ($t_{1/2}$ = 5.243 d)
Ratios measured: ^{125}Xe/^{126}Xe; ^{133}Xe/^{134}Xe
Possible interferences: may interfere with mix diagnostic, neutron rich Xe produced from fission in hohlraum [none]
Best simulations: 2D Be/Cu and CH capsules by Cerjan
Minimum capsule yield diagnosable: ~1 kJ (DT); ~100 J (HTD)

Brief description:

This measurement utilizes the 14 MeV neutrons produced during DT fusion. The production of the (n,2n) product is proportional to $\rho R \times Y$, thus if ρR is known by another measurement, the yield of the shot is proportional to the measured ^{125}Xe/^{126}Xe or ^{133}Xe/^{134}Xe ratio (shown in Table A for a variety of Be/Cu implosions with differing asymmetries).

Table A: Comparison of ^{133}Xe production for a variety of Be/Cu capsule calculations degraded by imposed laser asymmetries with varying amplitudes and Legendre mode. Note the correlation of the ^{133}Xe/^{134}Xe ratio with yield as plotted in Fig. A.

Calc. No.	Asymmetry	Y (MJ)	^{133}Xe/^{134}Xe
1	P6	0.0609	5.38E-05
2	P4	0.0623	5.83E-05
3	P2,P4,P6,P8	0.097	9.58E-05
4	P6	0.129	1.36E-04
5	P4	0.155	1.73E-04
6	P6	1.096	1.18E-03
7	P4	1.857	1.93E-03

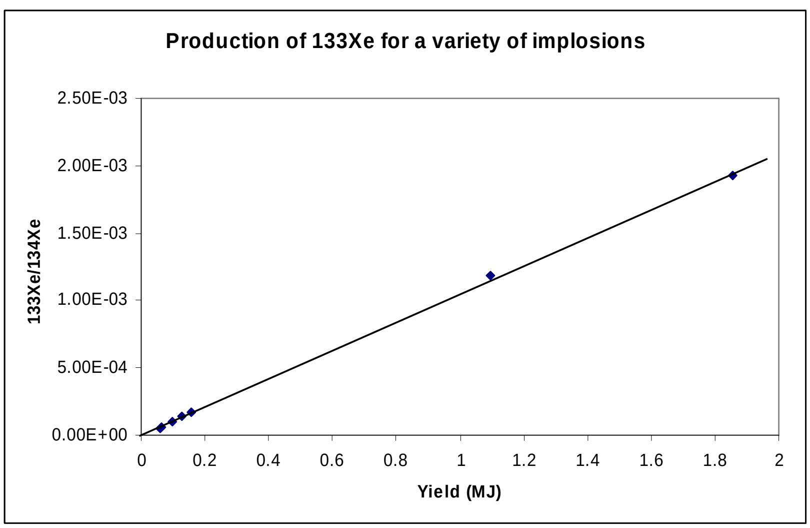

Fig. A: Production of (n,2n) reaction product with yield for the capsules in Table A.

Diagnostic information: Neutron spectral information
Detectors: various threshold (n,2n) detectors or combinations of (n,p), (n,α), and (n,2n)
Tracers required: various
Detector location: Innermost part of the ablator or external hockey pucks
Nuclear reactions used: ^{81}Br(n,p)^{81}Se; ^{81}Br(n,a)^{78}As; ^{81}Br(n,2n)^{80}Br in ablator;
^{58}Ni(n,2n)^{57}Ni; ^{197}Au(n,2n)^{196}Au; ^{65}Cu(n,2n)^{64}Cu external foils
Products: ^{81}Se ($t_{1/2}$=18.5 m); ^{78}As ($t_{1/2}$=1.5 h); ^{80}Br ($t_{1/2}$=17.7 m); ^{57}Ni ($t_{1/2}$=35.6 h);
^{196}Au ($t_{1/2}$=6.2 d) ; ^{64}Cu ($t_{1/2}$=12.7 h)
Ratios measured: ^{81}Se/^{81}Br; ^{78}As/^{81}Br; ^{80}Br/^{81}Br; ^{57}Ni/^{58}Ni; ^{196}Au/^{197}Au
Possible interferences: UK
Best simulations: None
Minimum capsule yield diagnosable: UK (DT); UK (HTD)

Brief description:

This measurement utilizes several nuclear reactions, each with differing thresholds, to roughly measure the time-averaged energy spectrum of neutrons at the detector location, either internal or external to the capsule. By comparing the activation ratios for multiple reactions with one another, one can determine the fractions of activation that occurred in different energy regions. Two ideas are discussed here, namely using detectors internal to the capsule and monitoring a variety of nuclear reaction products, and using external foils. The concept is illustrated for the three external foils but could be extended to additional foils easily. Three threshold (n,2n) reactions are shown in Fig. A. The thresholds for the (n,2n) reactions on ^{197}Au, ^{65}Cu and ^{58}Ni are approximately 9 MeV, 10 MeV and 12.5 MeV, respectively. When combined with higher threshold reactions as discussed in the next section, quantification of higher energy neutrons may be possible.

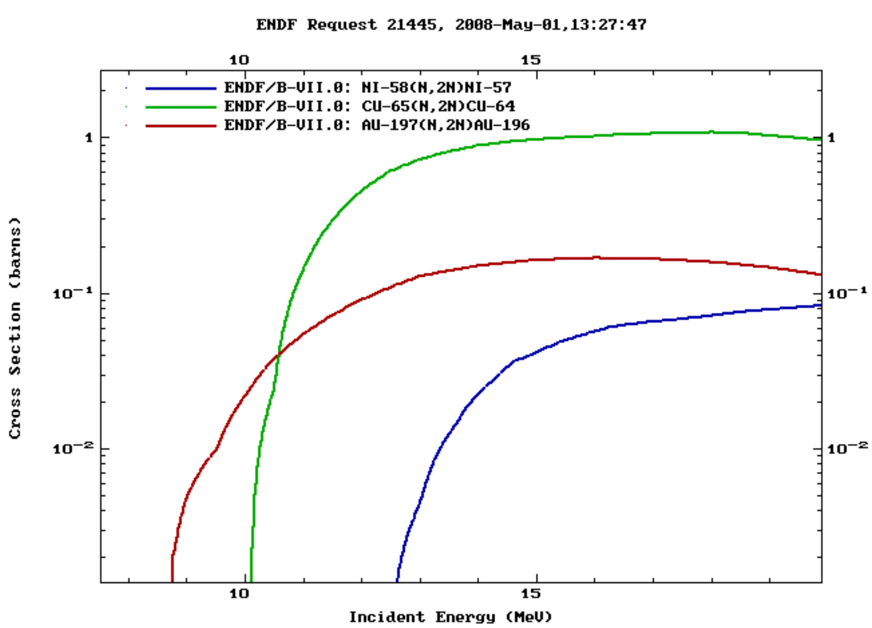

Fig. A: A comparison of ENDF/B-VII evaluated (n,2n) cross-sections for ^{58}Ni (blue), ^{197}Au (red) and ^{65}Cu (green) targets.

Diagnostic information: Quantification of high energy neutrons
Detectors: ^{12}C [^{206}Pb]
Tracers required: none
Detector location: External hockey pucks
Nuclear reactions used: $^{12}C(n,2n)^{11}C$ (threshold ≈ 22 MeV) [$^{206}Pb(n,3n)^{204m}Pb$ (threshold ≈ 15.5 MeV)]
Products: ^{11}C ($t_{1/2}$ = 20.36 m) [^{204m}Pb $t_{1/2}$ = 1.12 h]
Ratios measured: $^{11}C/^{12}C$
Possible interferences: Other activities with 10-20 min. half-lives like ^{13}N
Best simulations: None
Minimum capsule yield diagnosable: ~5 MJ (DT); UK (HTD)

Brief description:

This measurement utilizes large amounts of material placed external to the capsule (such as at the target chamber wall or in a re-entrant tube) and threshold (n,2n) or (n,3n) reactions which only occur with higher energy neutrons. The natural abundance of ^{206}Pb is significant at 24.1% indicating that a natural Pb hockey puck may be used. The ^{205}Pb produced from (n,2n) reactions is long-lived ($t_{1/2}$ = 1.5e7 y) and does not emit gamma-rays and thus will not interfere with the counting of the Pb hockey puck following a shot. The cross-sections for $^{12}C(n,2n)^{11}C$ and $^{206}Pb(n,3n)^{204m}Pb$ are shown in Fig. A.

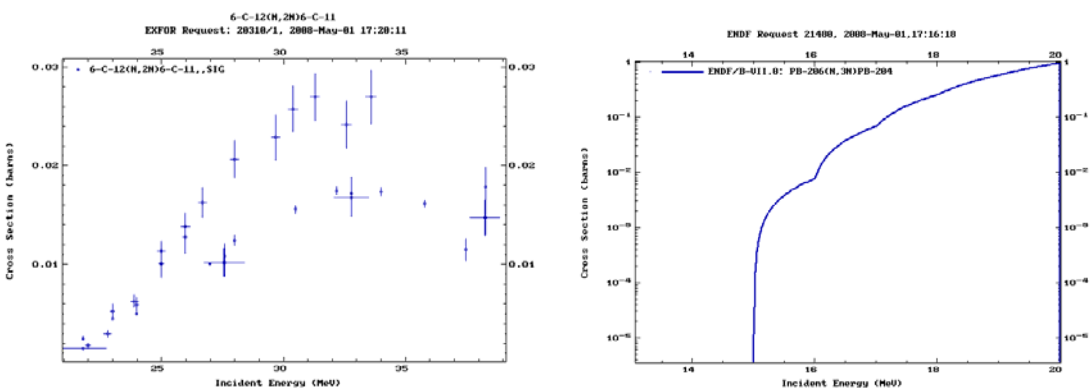

Fig. A: Comparison of the threshold $^{12}C(n,2n)^{11}C$ (left) and $^{206}Pb(n,3n)^{204m}Pb$ (right) reaction cross-sections. The $^{12}C(n,2n)^{11}C$ cross-section is measured data and indicates a threshold of about 22 MeV. The $^{206}Pb(n,3n)^{204m}Pb$ cross-section is from ENDF/B-VII and has a threshold of about 15 MeV. Both are suitable for measuring higher energy neutrons. At 18 MeV the (n,3n) cross-section is about 100 mb. The $^{12}C(n,2n)^{11}C$ cross-section peaks around 30 MeV at ~25 mb.

Diagnostic information: Quantification of jet caused by fill tube
Detectors: ^{48}Ti, ^{79}Br
Tracers required: V,Kr
Detector location: Around mouth of fill tube on innermost part of ablator
Nuclear reactions used: ^{48}Ti(d,2n)^{48}V; ^{79}Br(d,2n)^{79}Kr
Products: ^{48}V ($t_{1/2}$ = 15.98d); ^{79}Kr($t_{1/2}$ = 1.455 d)
Ratios measured: ^{48}V/^{48}Ti; ^{79}Kr/^{79}Br
Possible interferences: None; interferes with mix diagnostic potentially
Best simulations: None
Minimum capsule yield diagnosable: UK (DT); UK (HTD)

Brief description:

This measurement utilizes a spatially loaded detector around the base of the fill tube and knock-on deuterons to quantify the amount of ablator material jetted into the fuel as a result of hydro motion of the fill tube. If no material is jetted, then the (d,2n) reaction will produce a certain amount of ^{48}V or ^{79}Kr because the deuterons have ranges long enough to interact with ablator entrained material. However, the ^{48}V or ^{79}Kr production will increase as material is jetted into the fuel. The knock-on deuterons are less sensitive to the cooling of the fuel than other shorter-ranged charged particles are, thus any enhancement of ^{48}V or ^{79}Kr production should be proportional to mix of the fill tube jetted material (this material has gotten closer to the hot spot). Some calculations show approximately 20-30 ng of CH material is jetted into the hot spot, and even that Ge, which was doped in the interior of the CH ablator and is expected to be completely blown off at peak neutron production time, still makes it into the hot spot.

<u>Diagnostic information:</u> Charged particle stopping
<u>Detectors:</u> ^{18}O
<u>Tracers required:</u> O, Ne
<u>Detector location:</u> Uniformly loaded in fuel
<u>Nuclear reactions used:</u> $^{18}O(\alpha,n)^{21}Ne$; $^{18}O(n,2n)^{17}O$
<u>Products:</u> ^{21}Ne (stable); ^{17}O (stable)
<u>Ratios measured:</u> $^{21}Ne/^{18}O$; $^{17}O/^{18}O$
<u>Possible interferences:</u> background Ne and O in target chamber; interferes with mix diagnostic potentially
<u>Best simulations:</u> None
<u>Minimum capsule yield diagnosable:</u> UK (DT): UK (HTD)

<u>Brief description:</u>

This measurement compares the production between a charged-particle induced reaction and a neutron-induced reaction to look for enhancements or suppression of the charged-particle reactions. Other charged-particle reactions could be used—by comparing α, d, t, p induced reactions normalized to neutron-induced one might be able to say something about charged-particle stopping powers in plasmas. This is the least developed idea amongst the ignition radiochemical diagnostics.

Diagnostic information: Fission yield of the hohlraum
Detectors: ^{238}U
Tracers required: Multiple, Kr, Xe
Detector location: Hohlraum
Nuclear reactions used: $^{238}U(n,f)$
Products: multiple fission products, ^{87}Kr ($t_{1/2}$ = 1.27 h); ^{88}Kr ($t_{1/2}$ = 2.84 h) ; ^{138}Xe ($t_{1/2}$ = 14.1 m); ^{135}Xe ($t_{1/2}$ = 9.1 h)
Ratios measured: various
Possible interferences: None
Best simulations: None
Minimum capsule yield diagnosable: ~10 kJ (DT); ~800 J (HTD)

Brief description:

This measurement utilizes the 14 MeV neutron-induced fission of ^{238}U from the hohlraum and multiple fission products to determine the fission yield of the hohlraum. The expected production of fission products from a 1.2 MJ yield is shown in Figure A.

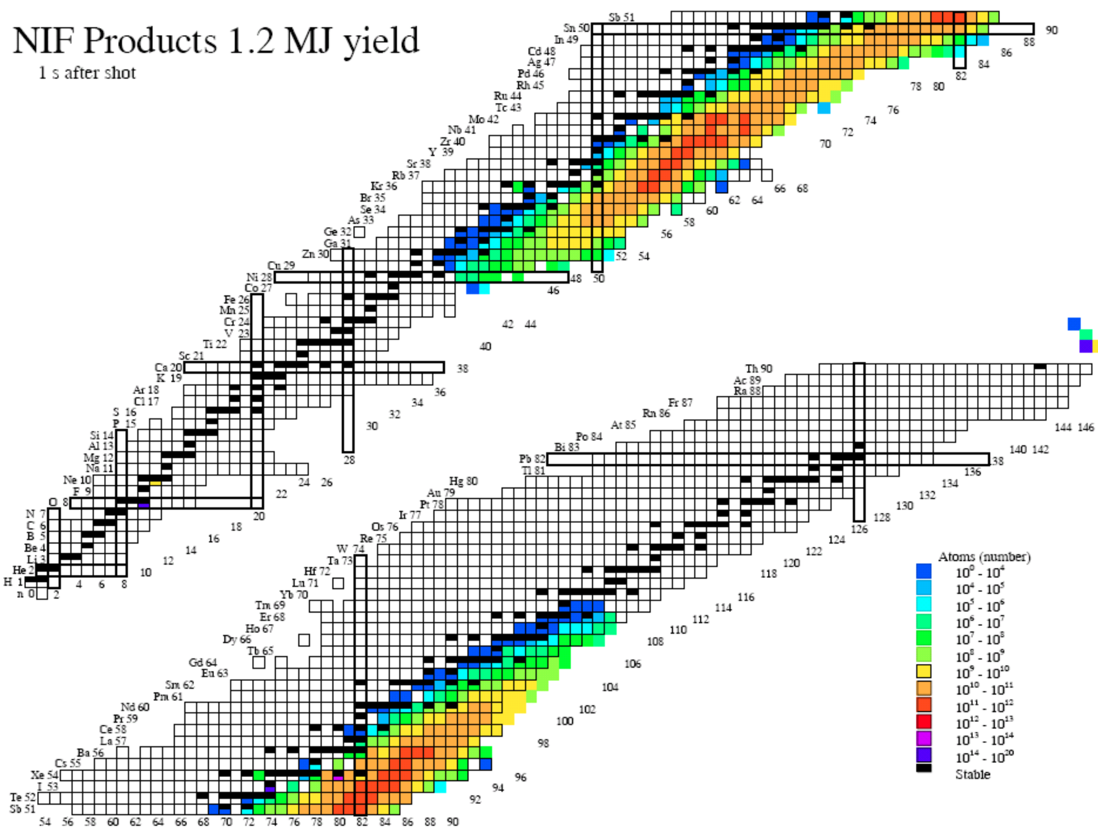

Fig. A: Chart of the nuclides showing the production (in numbers of atoms) of the fission products from 14 MeV neutrons on the ^{238}U in the hohlraum.

Appendix I

Table 1: Minimum detectable and quantifiable (with ±5% uncertainty) amounts of products for the various reactions discussed in the diagnostic information pages.

Nuclide	No. atoms needed for 5% determination*
^{11}C	1×10^{6}
^{21}Ne	1×10^{6}
^{37}Ar	1×10^{6}
^{48}V	1×10^{6}
^{57}Ni	1×10^{6}
^{64}Cu	1×10^{6}
^{69}Ge	1×10^{6}
^{75}Ge	1×10^{6}
^{78}As	1×10^{6}
^{81}Se	1×10^{6}
^{80}Br	1×10^{6}
^{79}Kr	5×10^{5}
^{85}Kr	2×10^{7}
^{87}Kr	1×10^{6}
^{88}Kr	1×10^{6}
^{123}Xe	1×10^{6}
^{125}Xe	1×10^{6}
^{127}Xe	1×10^{6}
^{133}Xe	7×10^{5}
^{135}Xe	1×10^{5}
^{196}Au	1×10^{6}
^{204m}Pb	1×10^{6}

*red values are default rule-of-thumb and need further evaluation