LLNL-TR-414096

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Chamber Clearing First Principles Modeling

G. Loosmore

June 22, 2009

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Gwen Loosmore
6/22/2009

Chamber Clearing First Principles Modeling

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Introduction

LIFE fusion is designed to generate 37.5 MJ of energy per shot, at 13.3 Hz, for a total average fusion power of 500 MW. The energy from each shot is partitioned among neutrons (~78%), x-rays (~12%), and ions (~10%)[1]. First wall heating is dominated by x-rays and debris because the neutron mean free path is much longer than the wall thickness. Ion implantation in the first wall also causes damage such as blistering if not prevented. To moderate the peak-pulse heating, the LIFE fusion chamber is filled with a gas (such as xenon) to reduce the peak-pulse heat load. The debris ions and majority of the x-rays stop in the gas, which re-radiates this energy over a longer timescale (allowing time for heat conduction to cool the first wall sufficiently to avoid damage).

After a shot, because of the x-ray and ion deposition, the chamber fill gas is hot and turbulent and contains debris ions. The debris needs to be removed. The ions increase the gas density, may cluster or form aerosols, and can interfere with the propagation of the laser beams to the target for the next shot. Moreover, the tritium and high-Z hohlraum debris needs to be recovered for reuse. Additionally, the cryogenic target needs to survive transport through the gas mixture to the chamber center. Hence, it will be necessary to clear the chamber of the hot contaminated gas mixture and refill it with a cool, clean gas between shots. The refilling process may create density gradients that could interfere with beam propagation, so the fluid dynamics must be studied carefully.

This paper describes an analytic modeling effort to study the clearing and refilling process for the LIFE fusion chamber. The models used here are derived from first principles and balances of mass and energy, with the intent of providing a first estimate of clearing rates, clearing times, fractional removal of ions, equilibrated chamber temperatures, and equilibrated ion concentrations for the chamber. These can be used to scope the overall problem and provide input to further studies using fluid dynamics and other more sophisticated tools.

Overview

The current LIFE chamber (as of 5/5/2009) relies on hot-spot target compression at 13.3 Hz. The chamber itself has an inner radius of 2.5 m, with 48 beamports of 0.192 m diameter[2] intersecting the chamber. The chamber is filled with 4.1 μg/cc of xenon gas to reduce the peak-pulse heat load on the first wall while providing an acceptable level of interference with laser propagation[3].

---

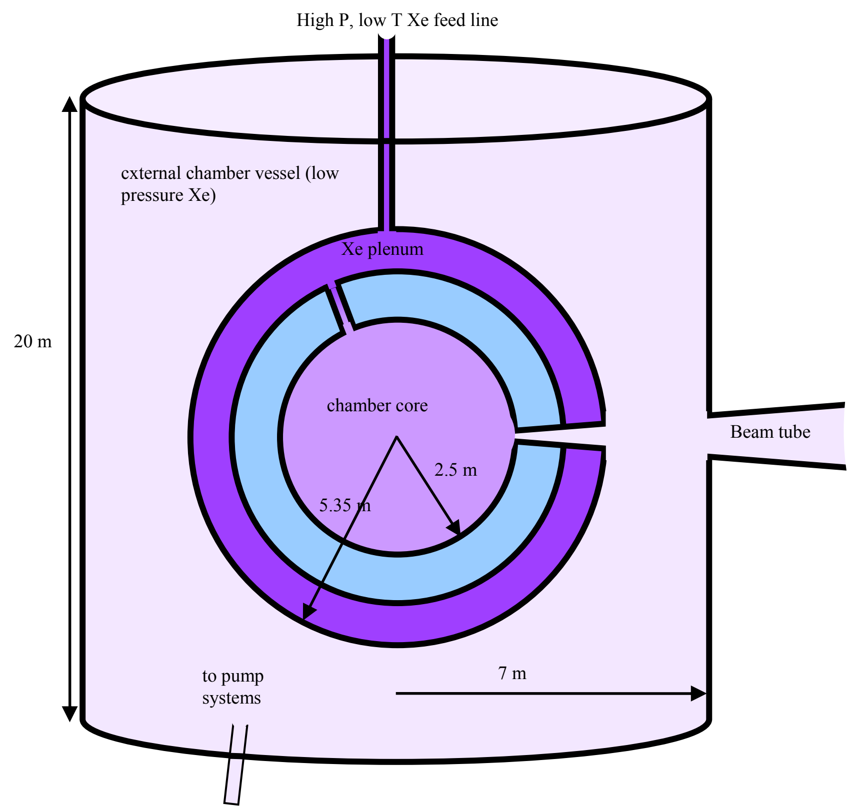
[1] Partitioning fractions are from Peter Amendt's rad hydro simulations.
[2] The beamtube could be broadened: 0.192 m is the size of the beam at the point of intersection with the chamber wall.
[3] (JL's analysis shows that this gas level should reduce a 3 ω beam by 10%. The fast ignition igniter beam, on the other hand, is expected to tolerate as much as 6 μg/cc xenon, based on expectations of stripped electrons interfering with the beam. Xenon is expected to go to a +10 state, which means that 4 μg/cc could produce 1.83 e-/cc, based on SW's work, the igniter beam can tolerate as much as 3e-17 e-/cc.

The 37.5 MJ shot is expected to produce 3.9 MJ of ions and 4.4 MJ of x-rays[4]. The majority of the x-rays are expected to be absorbed by the xenon, forming an ionized hot ball of plasma[5] that will radiate x-rays over a longer timescale. Most of the ions will stop in the xenon. H, D, and T ions from the capsule will be sufficiently energetic to impact the wall directly, as may some individual hohlraum ions that fail to thermalize.

The sudden heating of the xenon gas (or a central sphere thereof) creates a blast wave of material moving towards the chamber wall. When the blast wave impacts the chamber wall, it will reflect inward, recompressing and reheating the gas, so there will be a series of pressure pulses before equilibration. These pulses force the debris-contaminated hot gas up the beamtubes. As this gas vents it will cool and recombine. The debris atoms may coalesce into aerosols as they cool. The beamports and optics may need protection from the pressure pulses, the hot gas, and aerosols[6].

The high temperatures in the chamber after a shot (even after recombination) will create a high pressure environment, and the gas will tend to vent through the beamtubes. If the pressure outside the chamber is held sufficiently low, then the venting will occur at sonic velocities (i.e. via choked flow). It is assumed that this venting process will provide the primary clearing mechanism for the chamber. A series of pumps will be used to pump down the volume external to the fusion chamber to provide the low pressures needed for choked flow. The following schematic diagram illustrates the design.

Figure 1: A schematic look at the fusion chamber core, beamtube, and larger external chamber vessel



[4] See brief note entitled LIFE Target Details 4_24_09.docx
[5] Bucky calculations suggest a central ionized core with decreasing charge state towards the chamber wall
[6] We need to protect optics and beamtubes. The final optic is a Fresnel lens in the path of the gas.

The chamber core (the fusion chamber) is shown to be penetrated by a beamtube (in actuality there will be 48) and a xenon fill plenum. The chamber vents through the beamtube to the external chamber vessel where the xenon pressure is low. The external chamber vessel will be pumped down and the xenon cooled and cleaned for refilling.

For the purpose of analysis, it is useful to treat the problem as having two distinct phases, before and after recombination/equilibration. Answers to the following questions may facilitate analysis and solution of the chamber clearing problem.

Relevant Chamber Clearing Scientific Questions

Before equilibration:

1. How long until the chamber gas recombines and equilibrates?
2. How much material is flushed up the beamtubes by blast/shock waves, before recombination and equilibration?
3. What are the properties (temperature, pressure, composition) of the hot gas moving up the beamtubes?
4. What is the resulting impact on the beamtubes and optics?
5. How does continuous pumping of cool xenon impact these issues?

After equilibration:

6. What are the properties (temperature, pressure, composition) of the equilibrated gas?
7. What is the state of the debris ions and under what conditions do aerosols form?
8. Where should the xenon fill ports be located, what size and orientation should they have, to maximize venting?
9. What chamber debris concentration, density gradient, temperature can be tolerated?

Some relevant timescales are shown in the following table.

Table 1: Relevant timescales

Event	Timescale after shot [s]
X-ray absorption by xenon (chamber fill gas)	~10 ns (speed of light)
Target x-rays (not absorbed) impact first wall	~10 ns (speed of light)
Target debris (ions) impact first wall	10s to 100s of us[7]
Pressure pulse first impacts first wall	~ ms
X-rays re-radiate from xenon and impact first wall	ongoing
xenon charge state cools to ~ 1eV	~ ms
Heat transfer from hot gas to wall	us to ms
Aerosol formation	?
Choked flow time constant	0.35 s (see below)
Next shot	0.075 s

[7] Estimating ion velocity from 1/2 mv^2 assuming overall ion energy split evenly among ions

A Leaky Tank Model: Free Batch Expansion of a Compressible Fluid

Some general understanding of the problem can be gained by considering a simplified model of the reactor, where there is no fill gas, and the venting occurs analogous to the discharge from a punctured overpressurized tank. This model, which is taken from Bird Stewart and Lightfoot (BSL), p. 480[8], considers only the forced egress of the hot chamber gases under the influence of the high pressure developed as a result of the temperature spike. Models described later in this paper will extend this analysis.

The chamber is modeled as a large, stationary, insulated tank, and the beamports are represented as independent convergent nozzles. The maximum venting flow rate occurs under choked flow, in which further reductions in external pressure will not increase the flow velocity. This analysis applies to an equilibrated situation. The following assumptions are made[9]:

- The gas is ideal
- The venting is frictionless
- The flow is adiabatic (the chamber walls are insulating)
- The beamports can be treated independently, so that the total vent area is additive
- Flow through the beamports can be modeled as quasi-steady
- No significant velocities are present except very near the beamports
- Fluid properties are homogeneous in the chamber

BSL presents equations for the maximum flow rate from the chamber, i.e. for choked flow conditions. During choked flow, further decreases in the pressure outside the chamber do not result in increased flow rates, as the sonic velocities at the orifices will not permit the pressure wave to transmit upstream. In other words, choked flow occurs for pressure ratios above a critical level, specifically when:

$$\left(\frac{p_2}{p_1}\right)_{crit} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

where p_2 represents the external pressure, p_1 the internal chamber pressure, and γ the ratio of the heat capacities (C_p/C_v), which is 1.67 for a monoatomic gas. Because the internal pressure falls over time with venting, it will be necessary to reduce the external pressures over time, to match the reductions in internal chamber pressure and maintain the critical ratio for choked flow.

The chamber density falls as:

$$\rho_1(t) = \rho_0\left(\frac{t}{C_t}+1\right)^{\frac{2}{1-\gamma}}$$

where ρ_0 is the initial chamber density, and the time constant C_t is given by:

---

[8] Similar equations and derivations can be found in other compressible flow treatments.
[9] Several of these assumptions are questionable for the existing chamber design.

$$C_t = \frac{\frac{V}{A}\left(\frac{2}{\gamma - 1}\right)}{\sqrt{\gamma \frac{p_0}{\rho_0}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}}$$

Here V represents the chamber volume and A the beamport area available for venting. The temperature of the gas can be computed by recognizing that for a reversible adiabatic change of an ideal gas:

$$PV^{\gamma} = \text{constant}$$

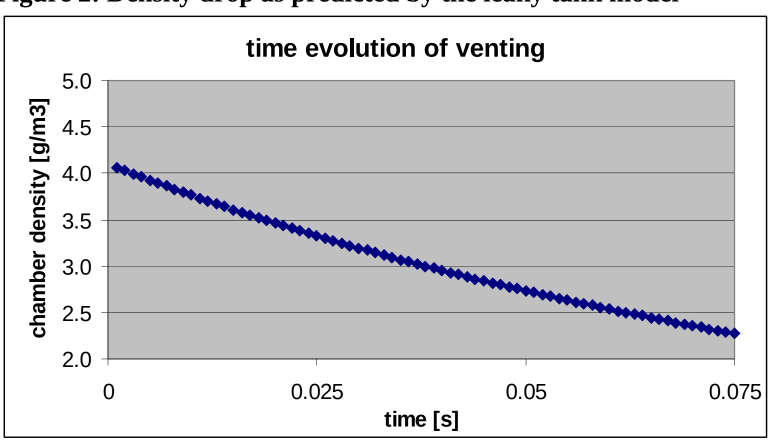
which, with the ideal gas law, yields:

$$T_1 = T_0 \left(\frac{\rho_1}{\rho_0}\right)^{\gamma - 1}$$

For the noble gases under consideration, $\gamma > 1$, and the chamber clears more quickly with smaller values of C_t. This time constant increases with chamber volume and decreases with increased vent area, but it also decreases with increased temperature (through the increased pressure term in the denominator). In practice, the initial chamber density is prescribed by the fill gas needed to protect the first wall (and by any additional hohlraum debris). For the purpose of this analysis, the pressure is computed using the ideal gas law.

For the chamber described earlier, the chamber volume is 65.45 m3. The total area available for venting if all beamports are open is 1.39 m2, 1.8% of the total internal area of the chamber wall. Xenon has a specific heat ratio of 1.666 and a molar mass of 131.3 g/mol. With the initial gas density of 4.1 g/m3 and an assumed initial post-shot temperature of 5000K, the initial post-shot pressure is 1298 Pa. The critical choking pressure ratio is 0.49, and the time constant is 0.346 s. The time evolution of the chamber density is shown below:

Figure 2: Density drop as predicted by the leaky tank model



In this analysis, in 0.075 seconds (i.e. before the next shot), the chamber “naturally” vents roughly 45% of the gas. In that time, the gas is assumed to cool adiabatically, which brings the temperature from 5000 to ~3300K, using the equations above. As the pressure in the chamber falls, the external pressure needed for maintaining choked flow drops from 630 to 350 Pa.

The actual post-shot temperature is unknown. If we increase the temperature to 10,000K, the venting will proceed more quickly. In this circumstance, approximately 55% of the gas is vented by 0.075 s. An initial temperature of 15,000K leads to venting of approximately 60% of the gas within that time period.

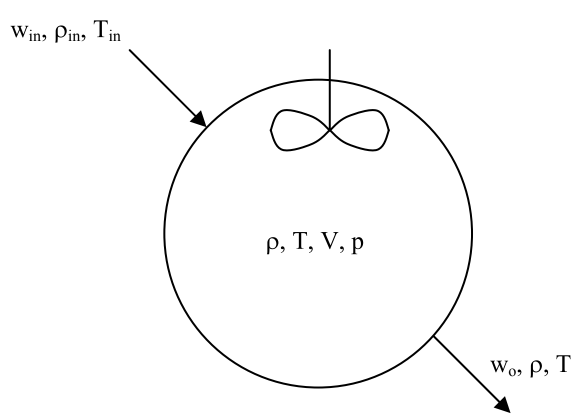
Modeling Inflow and Radiative Cooling: A Simple Fully-Mixed Reactor Study

Introduction and Assumptions

The previous analysis from BSL does not consider the effects of either inflowing cool xenon or heat transfer from the gas to the walls. These effects can be modeled in a simplified fashion for a fully-mixed spherical reactor. As in the BSL approach, this formulation assumes the plasma has recombined and the gas temperature and density have equilibrated within the chamber. The gas is assumed to be ideal. Pressure pulses are not considered or modeled. The following assumptions are made:

- The chamber dimensions are as above (2.5 m radius chamber, beamports have 0.192 m diameter, and so on).
- Gas vents through the beamports, and dedicated fill tubes come from a xenon plenum to fill the chamber with cool xenon gas.
- The chamber is instantaneously and continuously well-mixed, so that the fill gas blends immediately, and the vented gas has the same properties as the gas within the chamber.
- No gas velocities develop within the chamber.
- Gas enters and leaves the chamber at the sonic velocity appropriate for the temperature of that stream (choked flow conditions). I.e., as the cool fill gas mixes into the chamber, the velocity of the venting gases drops.
- The gas is composed entirely of xenon (debris from the hohlraum is neglected).
- The gas radiates to the chamber wall either not at all, or with the emissivity of a black body.

Figure 3: The fully-mixed reactor model



This analysis will allow an exploration of the effect of various parameters on the temperature evolution within the chamber and the amount of gas and debris that clears before the next shot.

The added mass from target debris is neglected in this analysis. Best-guess LIFE targets will provide ~0.4 g of material (primarily lead), whereas the chamber contains ~270 g of xenon gas at 4.1 ug/cc. Overtime, if the chamber is not fully vented, debris will build up in the chamber, but preliminary calculations indicate there should be less than a factor-of-10 increase in the debris mass even for very small fractions of gas vented (see the section on debris below).

The fill gas temperature and density are assumed to be constant throughout the filling process. Typically, the fill gas temperature is taken as 293K (room temperature), but this can be changed. The density ρ_{in} is chosen to ensure that the final chamber gas density is 4.1 ug/cc at shot time. (Note that xenon has a density of 5.9 kg/m3 at STP.) The plenum itself and fill gas tube are not included in the analysis, so the properties of fill gas are assumed to be valid at the inlet to the chamber. The inlet mass flow rate w_{in} [M/T] is given by:

$$w_{in} = \rho_{in} u_{s,in} A_{in}$$

where A_{in} is the area of the fill tubes, and $u_{s,in}$ is the sonic velocity of the fill gas at the fill temperature. This assumes a sufficient pressure in the fill tubes to attain this maximum fill velocity. Generally, the sonic velocity is computed as:

$$u_s = \sqrt{\frac{\gamma RT}{MW}}$$

where MW is the molecular weight and R the gas constant. Because the reactor is fully mixed, the outlet flow rate is a function of the chamber conditions:

$$w_o = \rho u_{s,o}' A_o = \rho u_o A_o$$

where A_o is the total beamtube area available for venting, and the outlet sonic velocity is modified (as in the BSL model) to account for the differences between the "nozzle" conditions and the main chamber:

$$u_o = u_{s,o}' = u_{s,o} \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

The equation of continuity (mass balance) is:

$$\frac{d(\rho V)}{dt} = w_{in} - w_{out}$$

The equation of energy can be written:

$$\frac{d\left(\rho V\hat{U}\right)}{dt} = w_{in}\left(\hat{U}_{in} + \frac{p_{in}}{\rho_{in}}\right) - w_{out}\left(\hat{U} + \frac{p}{\rho}\right) - q^{"}A_{sph}$$

where $\hat{U}$ is the internal energy per unit mass and q" is the radiative heat flux. In principle, convective heat transfer could also be parameterized and added to the model. Here, for simplicity, radiation is modeled using the following equation for the heat transfer between a nongray gas and black enclosure:

$$q^{"} = \varepsilon\sigma T^{4} - \alpha\sigma T_{w}^{4}$$

where T_w is a fixed wall temperature, σ is the Stefan-Boltzmann constant, ε is the gas emissivity, and α is the gas absorptivity for the radiation from the wall. For this model, the emissivity and absorptivity are assumed to be equal. Additional issues pertaining to radiative heat transfer in the xenon are discussed briefly below.

For an ideal gas:

$$d\hat{U} = C_{v}dT$$

and for a monoatomic ideal gas:

$$\hat{U} = \frac{3}{2}\frac{N_{a}kT}{MW}$$

where Na is Avogadro’s number.

By substitution, an equation can be derived for the time rate of change of temperature within the chamber:

$$\frac{dT}{dt} = \frac{1}{\rho VC_{v}}\left\{\left[w_{in}\left(\frac{3}{2}\frac{N_{a}kT_{in}}{MW} + \frac{RT_{in}}{MW}\right) + \varepsilon\sigma T_{w}^{4}A_{sph}\right] - \left[w_{in}\left(\frac{3}{2}\frac{N_{a}kT}{MW}\right) + w_{out}\left(\frac{RT}{MW}\right) + \varepsilon\sigma T^{4}A_{sph}\right]\right\}$$

The first term (in square brackets) represents the source of energy that serves to increase the temperature; the second term represents the energy loss that serves to drop the temperature in the chamber. Note the presence of the inlet flow w_{in} in both the sink and source terms. For low fill temperatures and high chamber temperatures, the fill gas serves to reduce the overall energy, i.e. the w_{in} sink term is greater than the source of energy due to the fill gas. As the chamber temperature drops, eventually the fill gas provides a net source of energy that acts against further reduction in chamber temperature.

A first-order finite difference approximation[10] is used to compute the chamber temperature over time from the energy equation and the chamber density from the continuity equation. The timestep size is computed dynamically as a function of the source and sink terms, to minimize the temperature increment in any given timestep. The user can specify fill gas temperature and density, vent and fill areas, chamber radius, initial temperature and density, wall initial temperature and thickness, whether to run model with radiation, and what emissivity to use.

Debris Fraction and Long-Term Concentrations

The debris fraction, i.e. the fraction of post-shot material that remains at the time of the next shot, can be estimated from the fraction of the original chamber gas vented. Because the reactor is assumed to be fully-mixed in this model, then some of the cool xenon fill is vented immediately upon mixing. In this way, the debris fraction cannot be computed by comparing the volume of gas vented to the chamber volume. The fraction of chamber mass removed in an incremental timestep Δt is given by:

$$\frac{\rho u_o A_o \Delta t}{\rho V} = \frac{u_o A_o \Delta t}{V}$$

where the mass density ρ is treated as constant over a timestep. For this chamber design, the overall mass in the chamber remains approximately constant over time, as cool xenon replaces the vented hot xenon gases from the chamber. Immediately after a shot, the debris in the chamber rises to a value of mass *M* in the chamber. This mass vents with the hot gases and is not replenished in the cool xenon stream. In the first timestep Δt_1, the fraction of the debris mass removed in a timestep is:

$$\frac{u_{o,1} A_o \Delta t_1}{V} M$$

thus, the fraction remaining is:

$$\left(1 - \frac{u_{o,1} A_o \Delta t_1}{V}\right) M$$

The fraction remaining after the second timestep, Δt_2, is given by:

$$\left(1 - \frac{u_{o,2} A_o \Delta t_2}{V}\right)\left(1 - \frac{u_{o,1} A_o \Delta t_1}{V}\right) M$$

and so forth. This debris fraction is solved for iteratively within the model. In order to compute the steady-state actual mass accumulated, the buildup from multiple shots must be considered. The following analysis assumes that the debris vents freely from the chamber with the gases (either does not aerosolize or the aerosol particles also follow streamlines and vent). Let the debris mass in the chamber just before shot "n" be given by M_{n-1}, with the mass density given by

[10] Currently implemented in Excel

C_{n-1}. Each shot adds an incremental mass Δm of debris, and the volume of vented chamber gas between shots is ΔV. Before venting, the mass density in the chamber after shot "n" would be:

$$C_n' = \frac{C_{n-1}V + \Delta m}{V}$$

The venting process will remove $C_n'\Delta V$, so the overall chamber density before shot "n+1" becomes:

$$C_n = \frac{C_n'V - C_n'\Delta V}{V} = C_n'\left(\frac{V-\Delta V}{V}\right) = \left(\frac{M_{n-1}+\Delta m}{V}\right)\left(\frac{V-\Delta V}{V}\right)$$

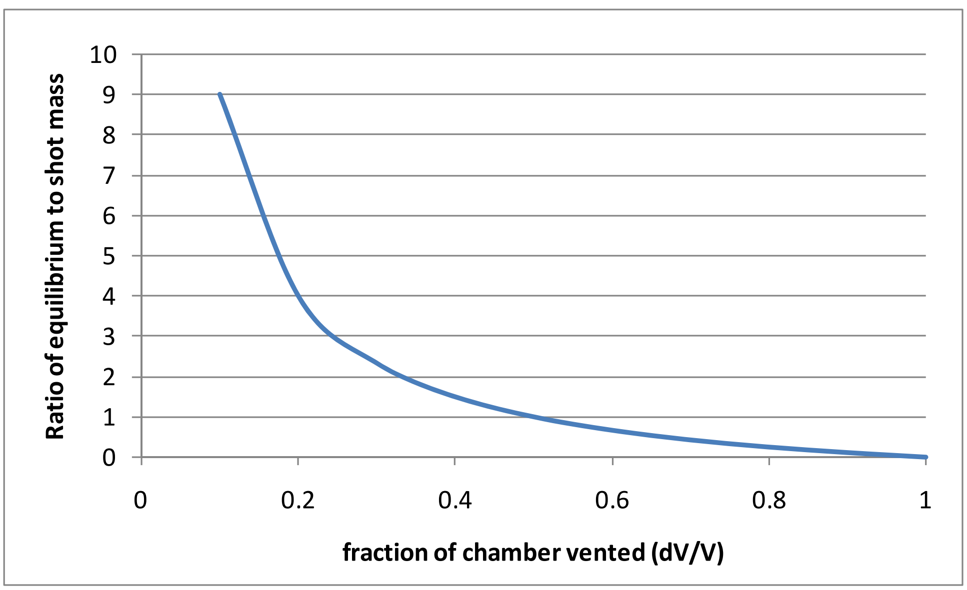
In the limit, assume that the mass density goes to a steady-state value, such that $M_n \approx M_{n-1}$, and the equilibrated chamber debris density (for $\Delta V/V \leq 1$) is:

$$C = \frac{M}{V} = \left(\frac{\Delta m}{\Delta V}\right)\left(1-\frac{\Delta V}{V}\right)$$

Hence the ratio of equilibrium to shot mass can be estimated from:

$$\frac{M}{\Delta m} = \left(\frac{V}{\Delta V}\right)\left(1-\frac{\Delta V}{V}\right)$$

Figure 4: Equilibrium debris



When half of the chamber gas is removed, the equilibrium debris mass in the chamber rises to the mass that is supplied each shot. Larger vent fractions reduce this quantity proportionally.

Radiation

The radiation from the hot xenon will be a dominant source of heat transfer soon after the shot, when much of the xenon gas is highly ionized. Because xenon is a monoatomic noble gas, once the electrons and ions have recombined, very little radiation will occur (there are no vibrational or rotational excitation modes). At the point of recombination, radiation of a pure xenon gas will "stall". Preliminary calculations suggest that this occurs at a xenon temperature of roughly 1 eV. However, the xenon emissivities and opacities are not well known at these (relatively low) temperatures; this is an active area of research. It may be that the debris ions (such as lead) are still radiating significantly at that temperature. If so, these debris ions may provide a cooling channel: collisions with hot xenon atoms will re-ionize the lead atoms, which will radiate this energy to the wall. This needs to be investigated and quantified.

The wall temperature rise is approximated here[11] by estimating the depth *d* of heat conduction within a timestep, as:

$$d^2 = 2\kappa\Delta t$$

where κ is the conduction heat transfer coefficient in [m2/s] and Δt is the timestep; energy from the radiation flux is deposited evenly within that layer to determine the wall temperature for the next timestep. Because the wall temperature is expected to be much lower than the gas temperature for most of the process, the radiation from the wall to the gas is not significant. A conservative approach is to neglect radiation in the absence of validated emissivity data.

Fully-Mixed Reactor Model Results

The fully-mixed reactor model has been used to estimate the debris fraction remaining and chamber gas temperature at shot time for different parameter sets and assumptions. For these purposes, it is assumed that the equilibration takes ~1 ms, so the "next shot" occurs in 74 ms.

In the base case, the 2.5 m radius chamber starts with 4.1 ug/cc at an initial temperature of 5000K. Venting proceeds through the 48 beamports of area 0.029 m2 (corresponding to a diameter of 19.2 cm). It is assumed that the wall starts at an initial temperature of 873K, the fill gas at an initial temperature of 293K, and that the fill gas tube has an area equal to one beamtube. The fill gas has a sonic velocity of 176 m/s, and the chamber sonic velocity is initially 410 m/s. In this case, a fill gas density of 0.4 kg/m3 is required to maintain the chamber density at 4.1 ug/cc at the next shot time (this corresponds to a pressure about 6 times higher in the fill than in the chamber at initial conditions). Here, the debris fraction remaining is 0.57, implying that 43% of the original chamber volume and debris mass have been vented. Assuming no radiation from the gas to the wall (or vice versa), the final temperature of the gas is 2960K.

Consider a case with the same input values but with radiation included, with a bulk emissivity[12] of 1e-3. In this case, the gas cools more quickly, reducing the exit sonic velocity and thus the outlet flow rate. The debris fraction remaining is therefore slightly higher, at 60%. A lower density of fill gas is needed, 0.36 kg/m3, to maintain the proper chamber density. The chamber

---

[11] This is a very crude parameterization for scoping the wall radiation effect; users are referred to RadHeat for more sophisticated assessments

[12] Note that CO_2 and H_2O can have emissivities on the order of 0.1, but we expect monoatomic xenon to be orders of magnitude smaller without vibrational and rotational modes. The debris ions may help.

temperature in this case is 2290K. Note that an emissivity value of 1e-4 has very little effect; the debris fraction remaining in this case is again 57%, and the final chamber temperature is 2850K.

Returning again to the base conditions, if the initial temperature is 10,000K instead of 5000K (i.e. roughly 1eV), the chamber sonic velocity increases to 580 m/s initially. Because more vents at this higher velocity, the debris fraction remaining drops to 47%. An inflow density of 0.53 kg/m3 is needed to maintain 4.1 ug/cc at shot time. The final chamber temperature is again cut roughly in half, to 4830 K.

Again using 5000K as the initial chamber temperature, but doubling the vent area (increasing the beamtube diameter to 27 cm), the debris fraction drops to 36%. Here a fill density of 0.7 kg/m3 is required to restore the initial chamber density. The final chamber temperature drops to 1980K. Using 10,000K as the initial temperature with the doubled vent area requires a fill density of 0.9 kg/m3; here the debris fraction drops to 25% and the final chamber temperature is 2860K.

The model predicts no effect from changing the fill area, other than requiring a proportional change in the fill density to match the lost mass. In other words, the same amount of cool fill gas is used in these cases, which means that the same volume is vented and same final temperature attained.

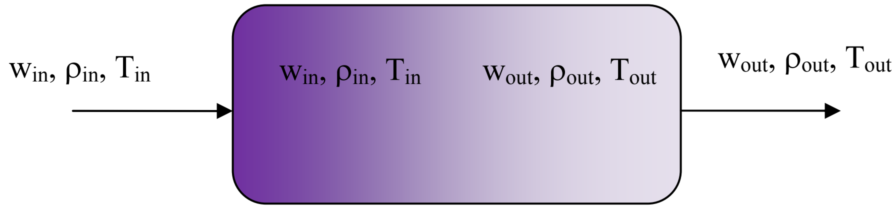
If the initial gas density is reduced, but the temperature and vent areas stay the same, then the outflow rate scales down proportionately, but the *fraction* removed stays the same. Hence, there are no gains, in this model, from a reduction in the initial gas density.

Modeling Inflow and Venting: A Simple Flow Through Reactor Study

Depending on the actual vent/fill configuration, the chamber dynamics during the vent/fill process may be better approximated with a flow-through model in which the two fluids do not mix. This model is a good approximation for a portion of a pipe, for example, in which material comes in one end, flows through, and exits the other end. In this case, there would be no drop in temperature due to mixing (except in a shallow interface between the cool fill gas and the hot venting gas, which is neglected here). For the treatment here, it is assumed that the fluids do not mix until the very end of the simulation (i.e. the time of the next shot), at which point they mix instantaneously (to provide an estimate of the final temperature). This flow-through type of regime could be considered as providing the most optimistic estimate of the removal of hot gases from the chamber, but this design could lead to dramatic density gradients that could interfere with beam propagation.

The flow-through chamber is illustrated below, using a rectangular shape for illustration.

Figure 5: Schematic of flow-through reactor



As in the fully-mixed reactor, the gas vents at the sonic speed in the hot gas. However, the gas doesn't cool during the flow-through process, so this speed remains inflated relative to the fully-mixed case, allowing more rapid venting.

As a comparison, consider the scenario where 48 beamtubes are used for venting. The sonic velocity in the 5000K chamber gas, modified for the compression effect, is 410 m/s, resulting in a total flowrate of 570 m3/s, or 2.3 kg/s (at the chamber density of 4.1e-3 kg/m3). Given that xenon has a density of 5.9 kg/m3 (xenon at STP), and with a sonic velocity for fill of 176 m/s, a fill area of ~2.2e-3 m2 is needed. For this scenario, 64% of the hot gas vents in 74 ms. The combination of the cool fill gas with the remaining hot gas yields an overall final chamber temperature of 1975K. The analogous scenario in the fully-mixed case would yield a final chamber temperature of 2900K, with only 43% of the initial chamber gas vented. If the vent area is increased by a factor of about 1.6 (increasing the diameter to 24 cm), then the mass flow rate becomes sufficient to completely vent the chamber in 74 ms.

Table 2: Results of fully-mixed reactor study

ρ_{init}	T_{init}	A_{vent}	ε	ρ_{fill}	T_{fill}	A_{fill}	% debris remaining	T_{final}
4.1 ug/cc	**5000 K**	**1.39 m2**	**0**	0.4 kg/m3	293 K	0.029 m2	57%	2960K
4.1 ug/cc	5000 K	1.39 m2	**1e-3**	0.36 kg/m3	293 K	0.029 m2	60%	2290K
4.1 ug/cc	5000 K	1.39 m2	**1e-4**	0.4 kg/m3	293 K	0.029 m2	57%	2850K
4.1 ug/cc	**10000 K**	1.39 m2	0	0.53 kg/m3	293 K	0.029 m2	47%	4830K
4.1 ug/cc	5000 K	**2.78 m2**	0	0.7 kg/m3	293 K	0.029 m2	36%	1980K
4.1 ug/cc	**10000 K**	**2.78 m2**	0	0.9 kg/m3	293 K	0.029 m2	25%	2860K
4.1 ug/cc	5000 K	1.39 m2	0	0.2 kg/m3	293 K	**0.058 m2**	57%	2960K
4.1 ug/cc	5000 K	1.39 m2	0	0.8 kg/m3	293 K	**0.014 m2**	57%	2960K
2.0 ug/cc	5000 K	1.39 m2	0	0.2 kg/m3	293 K	0.029 m2	57%	2960K

Table 3: Results of flow-through reactor study

ρ_{init}	T_{init}	A_{vent}	ε	ρ_{fill}	T_{fill}	A_{fill}	% debris remaining	T_{final}
4.1 ug/cc	**5000 K**	**1.39 m2**	0	5.9 kg/m3	293 K	2.2e-3 m2	36%	1975K
4.1 ug/cc	5000 K	**2.2 m2**	0	5.9 kg/m3	293 K	3.5e-3 m2	0%	293 K

Conclusions

The flow-through reactor design provides a much reduced temperature (and increased debris fraction remaining) relative to the fully-mixed design, as long as the density gradient between the fluid can be minimized (or kept from the beam path). If the LIFE chamber can be engineered to force a flow-through type of design, then beam propagation and target injection may be greatly facilitated. At this time, the constraints on temperature, debris, and density gradients engendered by beam propagation and target injection are not known. Even in a fully-mixed regime, the beamports can be opened to speed chamber clearing. The neutronics effects of this change require further study. The models described here presuppose an equilibrated gas at ~1 ms post shot. Rad/hydro simulations are needed to better quantify the initial temperature of such a gas and, indeed, whether and when such a condition comes about. The loss of material from the chamber due to the initial blast waves is not included here. Methods to remove heat from the vented gas and to recycle the target constituents and xenon need to be designed.