Princeton Plasma Physics Laboratory

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A Concept for a Low Pressure Noble Gas Fill Intervention in the IFE Fusion Test Facility (FTF) Target Chamber

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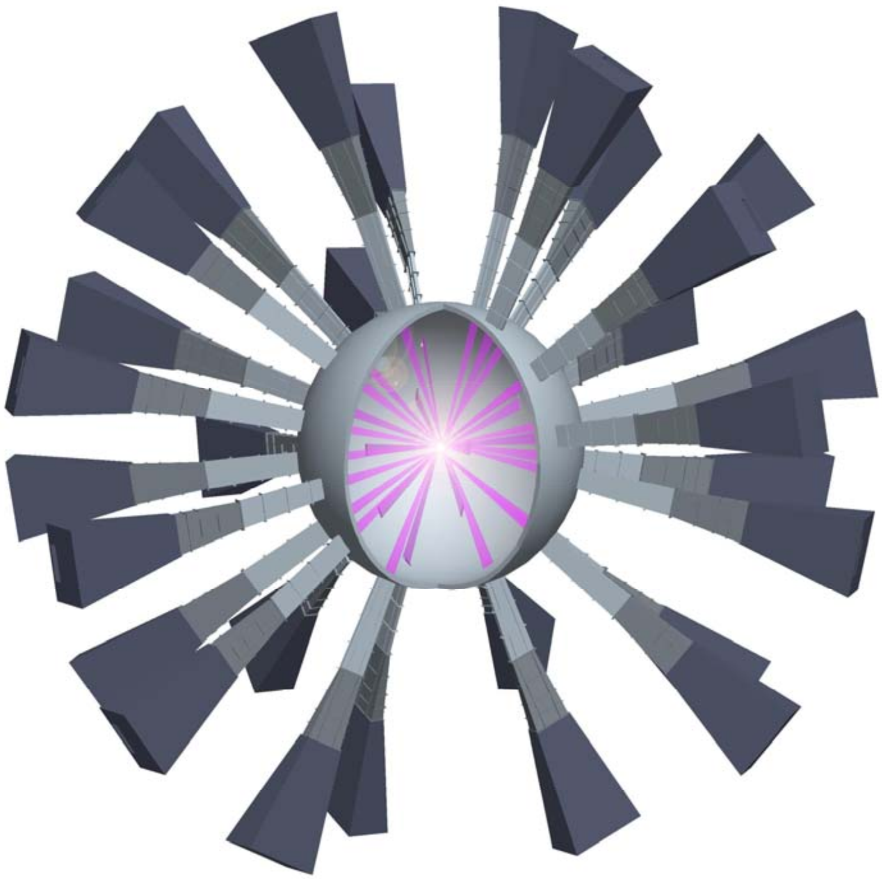

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List of Acronyms

CGPS – chamber gas processing system
COTS – commercial off the shelf
FTF – Fusion Test Facility
FRS – fuel recovery system
MI – magnetic intervention
TM-DP – turbo molecular-drag pumps

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Abstract - An engineering evaluation has been initiated to investigate conceptual engineering methods for implementing a viable gas shield strategy in the Fusion Test Facility (FTF) target chamber. The employment of a low pressure noble gas in the target chamber to thermalize energetic helium ions prior to interaction with the wall could dramatically increase the useful life of the first wall in the FTF reactor[1]. For the purpose of providing flexibility, two target chamber configurations are addressed: a five meter radius sphere and a ten meter radius sphere.

Experimental studies at Nike have indicated that a low pressure, ambient gas resident in the target chamber during laser pulsing does not appear to impair the ability of laser light from illuminating targets[2]. In addition, current investigations into delivering, maintaining, and processing low pressure gas appear to be viable with slight modification to current pumping and plasma exhaust processing technologies[3,4].

Employment of a gas fill solution for protecting the dry wall target chamber in the FTF may reduce, or possibly eliminate the need for other attenuating technologies designed for keeping He ions from implanting in first wall structures and components. The gas fill concept appears to provide an effective means of extending the life of the first wall while employing mostly commercial off the shelf (COTS) technologies. Although a gas fill configuration may provide a methodology for attenuating damage inflicted on chamber surfaces, issues associated with target injection need to be further analyzed to ensure that the gas fill concept is viable in the integrated FTF design[5].

In the proposed system, the ambient noble gas is heated via the energetic helium ions produced by target detonation. The gas is subsequently cooled by the chamber wall to approximately 800°C, removed from the chamber, and processed by the chamber gas processing system (CGPS). In an optimized scenario of the above stated concept, the chamber wall acts as the primary heat exchanger. During removal, gas is pumped through the laser ports by turbo molecular-drag pumps (TM-DP). For the purpose of reducing organic based lubricants and seals, a magnetically levitated TM-DP is being investigated with pump manufacturers. Currently, magnetically levitated turbo molecular pumps are commercially available. The pumps will be exposed to thermal loads and ionizing radiation (tritium, Ar-41, post detonation neutrons). Although the TM-DP's will be subjected to these various radiations, current designs for similar pumping devices have been hardened and have the ability of locating control electronics in remote radiation shielded enclosures[4]. The radiation hardened TM-DP's will be

required to operate with minimal maintenance for periods of up to 18 continuous months. As part of this initial investigation for developing a conceptual engineering strategy for a gas fill solution, commercial suppliers of low pressure gas pumping systems have been contacted and engaged in this evaluation. Current technology in the area of mechanical pumping systems indicates that the development of a robust pumping system to meet the requirements of the FTF gas fill concept is within the limits of COTS equipment[3,4].

Introduction

The Fusion Test Facility is a proposed next step in the development of a viable IFE direct drive power reactor for the generation of electrical energy. This progenitor device is designed to be a high repetition (5 Hz) ignition facility producing approximately 150 MW of fusion energy[6,7]. The FTF reactor will be used to test various components and materials for future use in fusion power reactors. The production of 14 MeV neutrons generated by the FTF will produce a considerably high level of transmutations in various test components. Such experimental operations and testing are needed to develop the next generation of components and materials in both the IFE and MFE arenas. The FTF would employ modular krypton fluoride (KrF) lasers as the driver for igniting direct drive targets.

One important area of concern in the FTF is reducing the effects of the high energy (3.5 MeV) He ions on the surfaces of the first wall for the currently proposed spherical target chamber radius of 5 meters (chamber volume of 523,600 liters and a surface area of 3,141,600 cm^2). A chamber with a radius of 10 meters, (4,188,800 liters and 12,566,400 cm^2 respectively) is also examined. Figure 1 illustrates the various ions present in the target chamber after the target reaction. Due to the abundance and energy of the He ions, they are considered to be most detrimental.

Target Reaction Ion Energy Distribution[8]

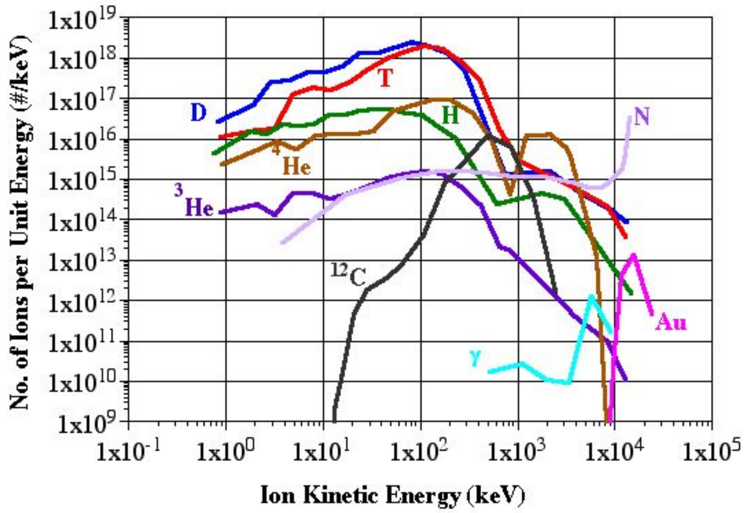

Figure 1. Number of ions predicted to be present within the FTF target chamber per unit energy.

Studies conducted under the direction of the HAPL program have shown that post-detonation energetic helium ions can drastically reduce the useful life of a dry first wall in an IFE reactor due to the accumulation of implanted helium. For the purpose of attenuating energetic helium ions from destructively interacting with first wall components in the FTF target chamber, several concepts have been advanced. These include magnetic intervention (MI), deployment of a dynamically moving first wall, use of a sacrificial shroud, renewable liquid surface, designing the target chamber large enough to mitigate the damage caused by He ions on the chamber walls, and the use of a low pressure noble gas resident in the target chamber. It is proposed that employing a low-pressure noble gas in the target chamber to thermalize energetic helium ions prior to interaction with the wall is an attractive option. The principal benefit of this concept is the simplicity of the design which employs no moving parts, no reactor internal elements, and the utilization of modified existing technologies for pumping, cooling, and processing the ambient noble gas. Although the gas load in the system would be increased over other proposed methods, the use of a "gas shield" may provide a cost effective method of extending the life of the first wall.

Evaluated Modes

This study evaluated three operating modes of the gas fill concept with consideration of plasma exhaust processing efficiencies, gas recycling, thermal loads, flow regimes, and operational processes. The three selected gas fill operating modes include[9]:

[1] Slow gas flow: A resident gas flowing at a low rate of removal and processing. In this mode, the majority of the thermal load resident in the gas is removed by the first wall, thus the first wall serves as the principle heat exchanger.

[2] Intermediate gas flow: An intervention gas flowing at velocities of approximately 10 m/s with heat removal via an external heat exchanger. After being removed, the gas is cooled, processed, and returned to the target chamber for additional service.

[3] Rapid gas flow: An intervention gas at velocities of about 50 m/s. In this scenario, the gas is consistently removed from the chamber, cooled, processed, and returned for additional service. In this configuration, the possibility for laminar flow, by means of an injected gas stream, is evaluated to aid with target injection.

After evaluation, it was concluded that an optimized slow gas flow would provide the best configuration. The rapid gas flow approach is determined not to be advantageous for the following reasons: cylindrical geometry would be necessary if laminar flow was to be attempted, but the gas stream would still be turbulent with a Reynolds number that exceeds the maximum value for laminar flow[10]; the incoming flow would be heated by rapidly moving alpha particles expanding outward isotropically; the large amount of gas needed to be cooled and re-circulated would not be practical. The intermediate gas flow approach is not advantageous for the following reasons: it is a complicated hybrid solution that does not optimize heat and plasma exhaust removal. This process would require excessive pumping and a high processing rate, additionally most of the heat would be removed by the wall. The slow gas flow proved to be the most advantageous for the following reasons: the heat would be removed directly by the first wall and would require minimal chamber gas processing.

For this initial evaluation, we consider relatively inexpensive Ar gas (see figures 2 and 3) as a primary fill medium. In this operating scenario, the argon gas is heated via interaction with the high energy helium ions and other reaction products. This thermal energy is then transferred to the first wall and removed by the first wall cooling system. After the gas is cooled to approximately 800°C at the chamber wall, it is removed for processing via pumps located at the laser ports. The efficient recycling of fuel and fill gas back into the FTF operations cycle is critical for a cost effective operation. The factors that impact the optimal gas density and pumping rate are target injection heating and positioning concerns, the lifetime of the wall, and the allowable levels of impurity gases and tritium in the argon.

Target Interactions in an Ambient Gas

During 2003, an experimental campaign was undertaken at Nike to evaluate the effects of an ambient, low pressure noble gas on the ability of the KrF lasers to focus on and illuminate a target. These experiments at NRL indicate that the use of a low pressure ambient gas in the target chamber will not impede the ability of KrF laser light to illuminate the target. These observations have also been confirmed by calculation. As a result of these experimental results from Nike, an ambient gas fill solution for extending the life of the first wall in the FTF appears plausible.

Fill Gas Selection: Argon

Several inert gases were considered during the selection process for the gas fill in the FTF target chamber which include; helium, neon, argon, krypton, and xenon. The varying ability of these five inert gases at a density of 8 g/m^3 to attenuate high energy alpha particles is illustrated in figure 2.

Projected Range for Alpha Particles[11]

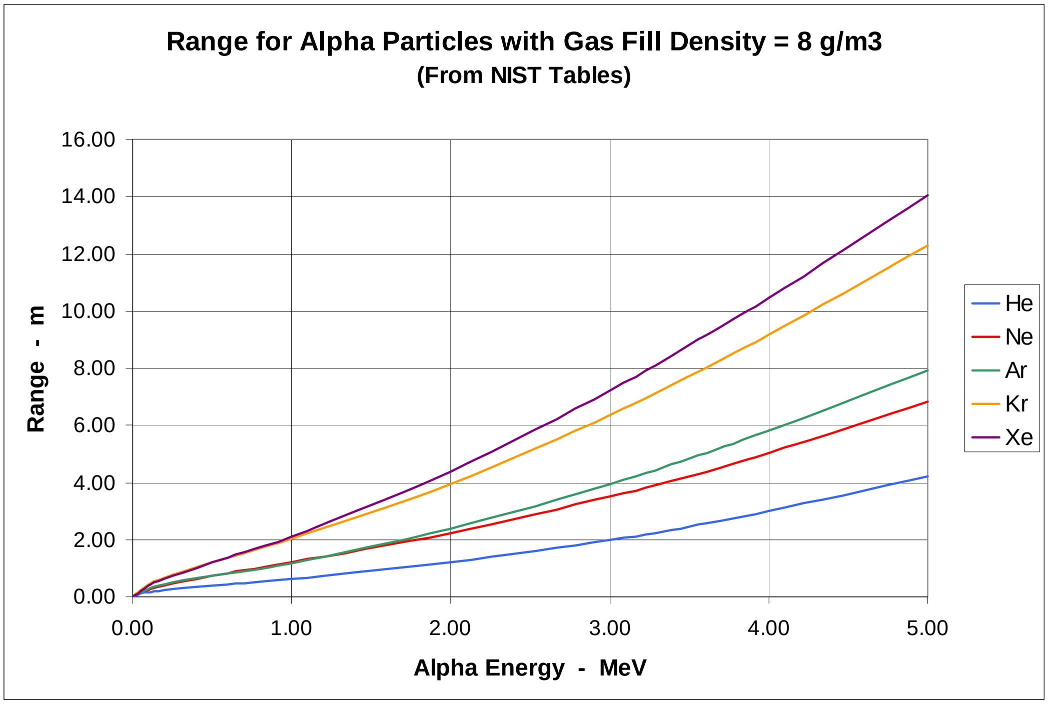

Figure 2. Projected range for alpha particles of various energies with an inert gas density of 8g/m^3 for helium, neon, argon, krypton, and xenon.

For this evaluation, argon was selected for analysis as the ion intervention chamber fill gas for the following reasons: argon is readily available at a reasonable cost, it has been tested for effective laser path interaction, argon is a good carrier gas for pumping operations, and standard industrial methods for processing argon are well established. The employment of argon as the fill gas in the target chamber vessel is calculated to be 523,000 torr-liters at a nominal density of 2.34 g /m^3 (1 torr ST). The ability of argon gas at various densities to attenuate high energy alpha particles is shown in figure 3. Here, the projected range of alpha particles within the target chamber is plotted as a function of their energies. Table 1 depicts the percentage of thermalized alpha particles for various densities and chamber radii.

Range for Alpha Particles with Argon Gas Fill

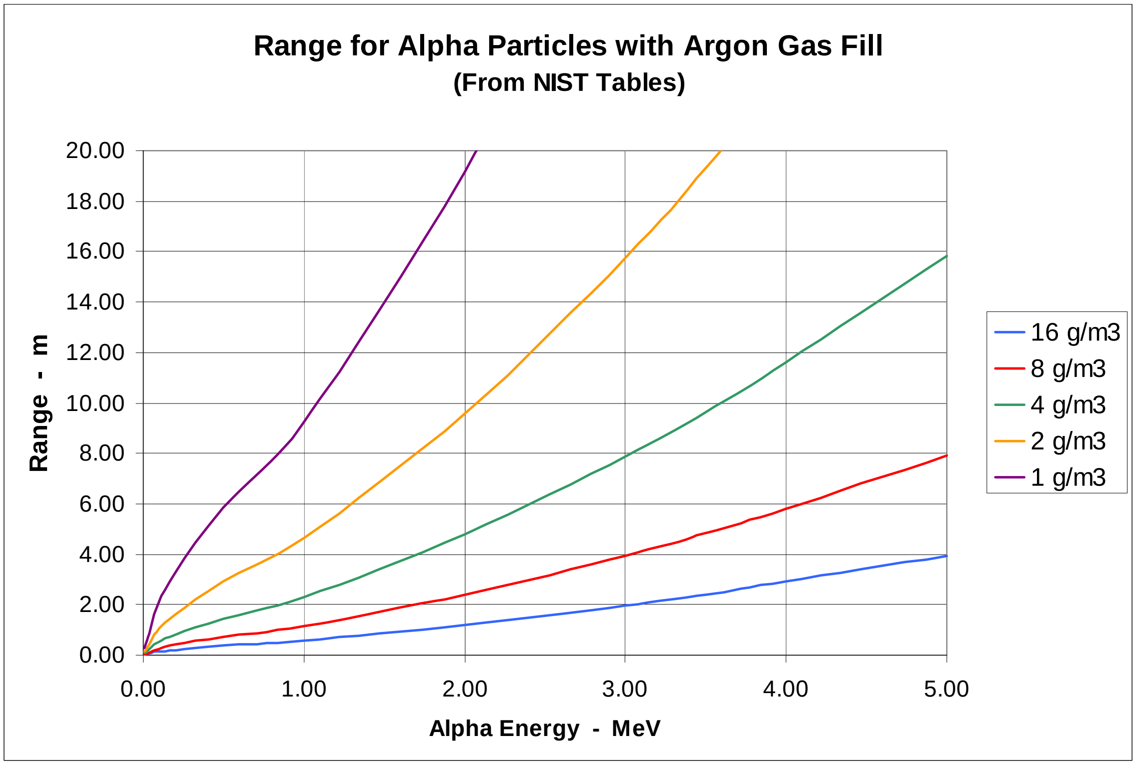

Figure 3. Projected range for alpha particles of various energies when an inert gas fill (argon) is present within the target chamber. Various densities of the argon gas fill are plotted.

Fraction of 3.5 MeV Alpha Particles Thermalized

Radius	Density	Pressure	Thermalized Fraction
m	g/m^3	torr at ST	%
5	2.00	0.85	25.89
5	2.34	1.00	30.29
5	4.00	1.70	51.77
5	4.68	2.00	60.68
5	7.68	3.28	99.42
10	2.00	0.85	51.77
10	2.34	1.00	60.57
10	3.86	1.65	99.91

Table 1. Percentage of 3.5 MeV alpha particles thermalized prior to making contact with the first wall given a specific target chamber radius and Ar density.

Intervention Gas Temperature

For the purpose of determining the temperature of the intervention gas, an estimate is presented based on the reaction energy, gas density and wall temperature yields. For a 5 m radius target chamber (150 MW FTF configuration) the peek average intervention gas temperature is estimated to be on the order of ~ 10,000°K. This is well below the ionization energy for argon which is ~ 160,000°K.

In a larger chamber (10 m radius) the average intervention gas temperature is reduced by a factor of 2 to 3. It is expected that once the FTF target chamber configuration is better known, a dynamic intervention gas model can be developed.

Intervention Gas Parameters

Total Reactor Power	MW	150
He Ion Fraction	%	20
He Ion Power	MW	30
Repetition Rate	Hz	5
He Ion Energy per Detonation	MJ	6
Radius	m	5
Volume	m^3	523
Argon Specific Heat	J/g*K	0.52
Surface area	m^2	314.00
Power density at wall	w/m^2	95,541
Argon Density	g/m^3	2.34
Argon Mass	g	1224
Chamber Wall Temperature	°C	~ 800
Total Average Gas Temperature	°K	~ 10,000

Table 2. Intervention Gas Parameters.

Fill Gas Flow Regime Evaluation

As stated in the task and scope section of this report, three gas fill operating scenarios (low gas flow, intermediate gas flow, and rapid gas flow) are evaluated[12].

In the low and intermediate gas flow operating modes (approximately 1 – 5 m/s and 10 m/s respectively), the majority of the thermal load resident in the ambient Ar gas, resulting from post detonation heating, is transferred to the first wall via conduction. Since having a low or intermediate flow present in the chamber would not significantly decrease the thermal load delivered to the chamber wall, a driven flow at these speeds is not considered to be beneficial.

In the 50 m/s configuration, gas would be removed from the chamber, cooled, processed, and returned back to the chamber for additional service. The achievement of laminar flow would be desirable because the gas stream might aid target injection. However, calculations regarding the Reynolds number of Ar in this configuration indicate that laminar flow would not be achievable. The feasibility of achieving laminar flow is limited by physical constraints. Such a flow in the context of a 5 m radius target chamber may be approximated by flow in a 5 m radius cylinder. Using this approximation, the Reynolds number was determined to be 9696 which is well above the 1100 required for laminar flow (Table 3). Based on this calculation, it is unlikely that laminar flow will be achievable in any configuration[10,13].

Estimated Reynolds Number

Density ρ (g/cc)	2.34E-06
Group speed v (cm/s)	5000
Diameter d (cm)	1000
Temperature (K)	10,000
Viscosity μ (g/cm*s)	1.21E-03
$Re = \rho\ v\ d / \mu$	9696

Table 3. Estimated Reynolds number for 50 m/s Ar flow in a 5 m radius cylinder.

Consequently, it appears that the most viable gas fill scenario is an optimized "low" flow. In the optimized mode, there is no driven flow inside the chamber. Only a natural, radial flow due to target detonation is present. In this mode, the first wall is equipped with an active cooling system that maintains the wall temperature at approximately 800ºC. The ambient gas, along with post detonation products are then removed from the target chamber and directed to the CGPS where they are processed to reclaim un-expended fuel products and remove non-useful components from the chamber fill gas. After processing, the recovered shield gas is recycled back to the target chamber for additional service. The optimal pumping speed and throughput for this configuration are determined by the percentage of resident impurities and tritium levels in the shield gas.

Optimized Flow Rate

The pumping system must be capable of removing sufficient chamber gas at a rate to maintain a sufficiently low percentage of impurities, including tritium, in the argon fill gas. Figure 4 illustrates the percentage of impurities in the chamber gas for various intervention gas densities as a function of exhaust volume rate. For the purpose of keeping the percentage of impurities low, only relatively low pumping rates are required. Figure 5 shows the amount of tritium retention in the target chamber as a function of exhaust rate.

The computation to determine the concentration of reaction products in the intervention gas is based on the mass flow equilibrium state between target material input and chamber exhaust output. In this equilibrium state, for any given exhaust rate, the concentration of reaction products in the exhaust volume will have a mass equal to that supplied by the detonation of the target. In order to maintain mass equilibrium, the intervention gas must also be replenished at the same rate that it is exhausted. Both the mass and particle concentration can be calculated in equilibrium, but since the alpha attenuation factor is dependent on particle concentration, that is the value plotted (see following figures). Once the equilibrium concentration for all the materials is computed, the quantity of retained tritium is readily determined.

Effectiveness of Exhaust in Clearing Reaction Products from Chamber

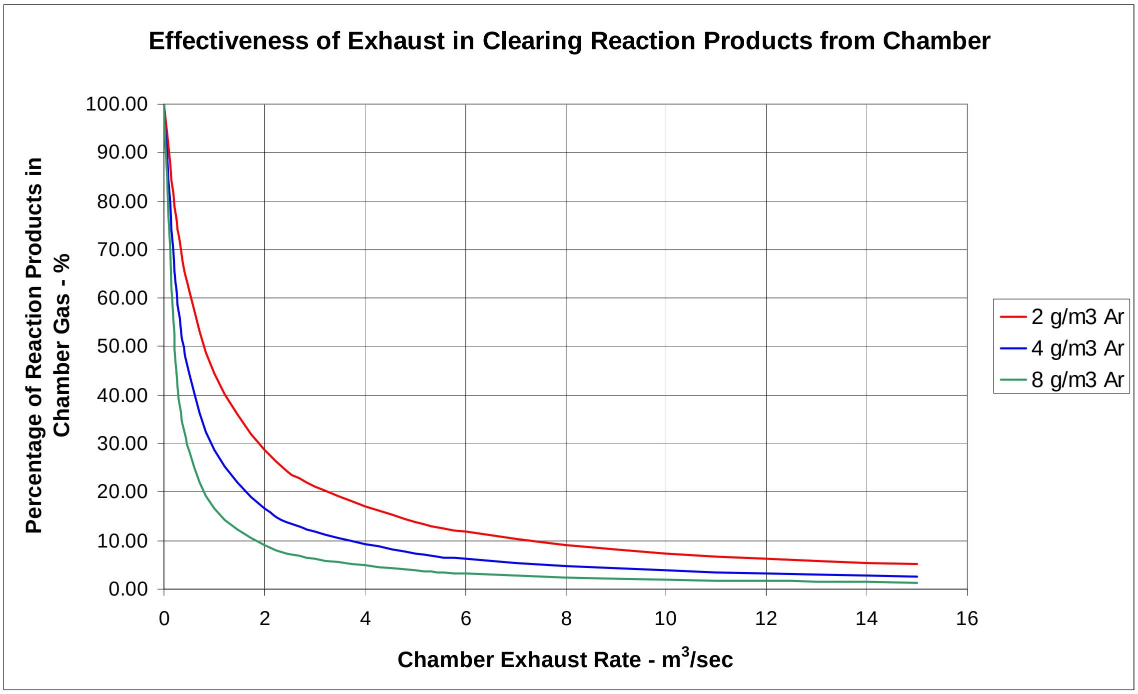

Figure 4. Resident impurity levels for different shield gas densities as a function of exhaust volume rate.

Chamber Tritium Retention as a Function of Exhaust Rate

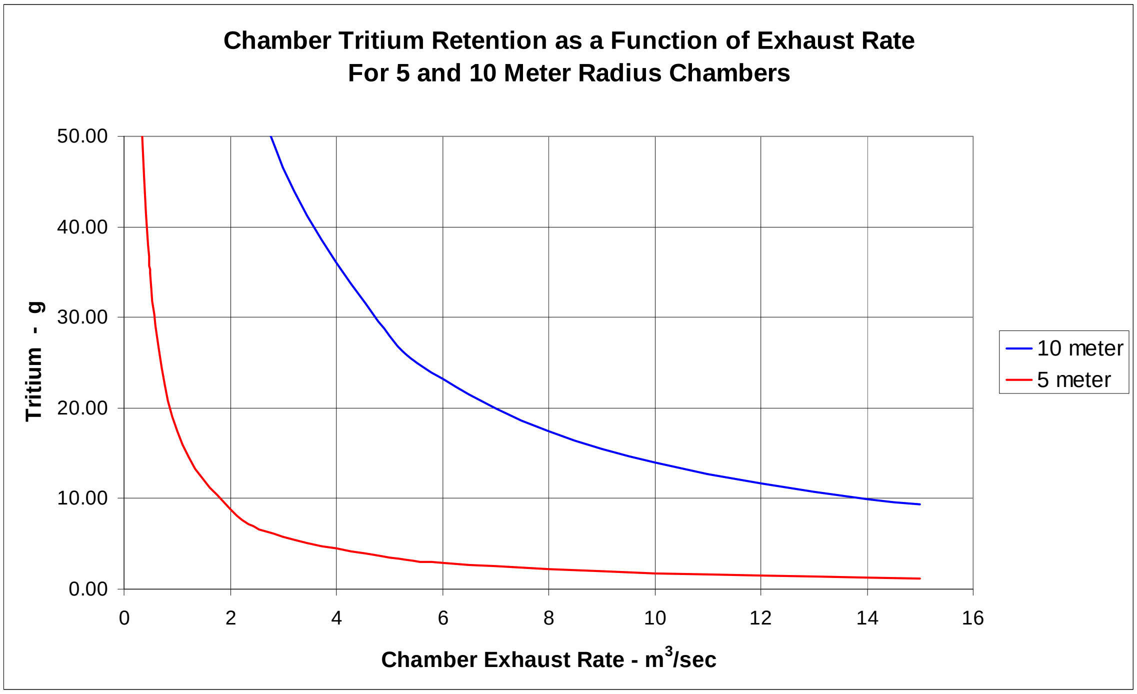

Figure 5. Tritium retention in the target chamber as a function of exhaust rate.

Pumping System

A critical component to the success of a gas intervention concept is the ability to effectively pump the chamber to remove components of reaction as well as the ability to handle heated and activated intervention gas from the target chamber. The design must also utilize COTS products in order to be economically efficient. To minimize organic-based lubricants and seals that are incompatible with tritium, a magnetically levitated TM-DP is under investigation. The viability of magnetically levitated, radiation hardened TMP/ drag pump hybrids with pumping speeds up to 5,000 L/s is being investigated with the commercial vacuum pumping industry. Interactions with industry representatives have shown promise. Two existing low-pressure gas pumping platforms have been identified as possible candidates for use in the FTF target chamber pumping system.

The pumps will be exposed to radiation from tritium, Ar (Ar-41), and low levels of post detonation neutrons. Therefore, the pumps must be radiation hardened and fitted with metal seals. Issues associated with processing radioactive and high temperature gases over prolonged periods of time have been addressed by the commercial sector in other applications with similar requirements to those of the FTF vacuum pumping system[4]. Additionally, the ability to remotely locate pump electronics in a shielded enclosure and to fabricate the pumps with metal seals is available with COTS equipment.

Mass Flow Diagram

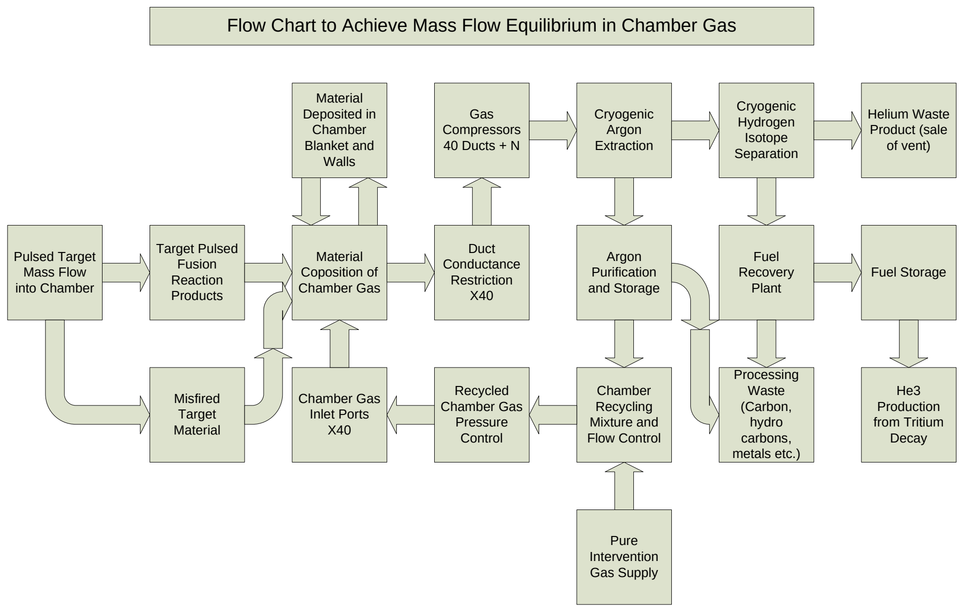

Figure 6. Mass flow within the FTF target chamber, the chamber gas processing system, and the fuel recovery system.

Chamber Gas Processing System

Post detonation pre-processing is necessary to prevent Ar from entering the fuel recovery system. In order to accomplish this, an additional processing stage to the previously designed fuel recovery system (FRS) has been conceptualized. This addition is referred to as the chamber gas processing system (CGPS). This facility would use a two-stage cryo-separation system, in line with turbo-molecular drag pumps, to remove Ar from the effluent gas stream before it enters the receiving analysis portion of the fuel recovery system. In order to achieve the required separation, each cryogenic stage would be comprised of several cryogenic units. This will ensure timely recycling of the argon intervention gas and allow for more efficient processing of hydrogen isotopes.

In this configuration, effluent will pass through the first cryogenic separation stage, at liquid nitrogen temperature (77ºK), which will remove

Ar as well as most impurities, such as trace amounts of oxygen, in the gas stream[14,15]. In order to minimize the expenditure of Ar, gas trapped at this stage will be purified of contaminants and recycled. Hydrogen isotopes, nitrogen, and helium will not condense at this temperature and will pass to the next stage. After the first cryogenic separation stage, the remaining effluent will pass through the second stage, at liquid helium temperature (4.2ºK), to remove any nitrogen and all hydrogen isotopes from the gas stream. Helium will pass through the cryogenic column; hydrogen isotopes, however, will condense onto the cryogenic surface. At this point, only helium will remain in the gas stream. Meanwhile, hydrogen and any nitrogen from the second cryogenic separation stage will enter the receiving and analysis system, a portion of the fuel recovery system. As a result, a highly concentrated mix of hydrogen isotopes and trace amounts of nitrogen progresses to the fuel recovery system. This high concentration will lead to an improvement in hydrogen adsorption efficiency by the Pd-Ag permeators, greatly reducing the number of permeator cycles necessary to withdraw all hydrogen isotopes from the gas stream. Thus, the cryogenic separation system will not only allow for the fast recycling of Ar, but will also expedite the progress of target materials through the fuel recovery cycle. The resulting purified argon would be stored for return to the target chamber in order to maintain the correct intervention gas density. Optimizing the gas processing system will allow for continuous and reliable operation. A diagram of this process is depicted in Figure 7.

Chamber Gas Processing System

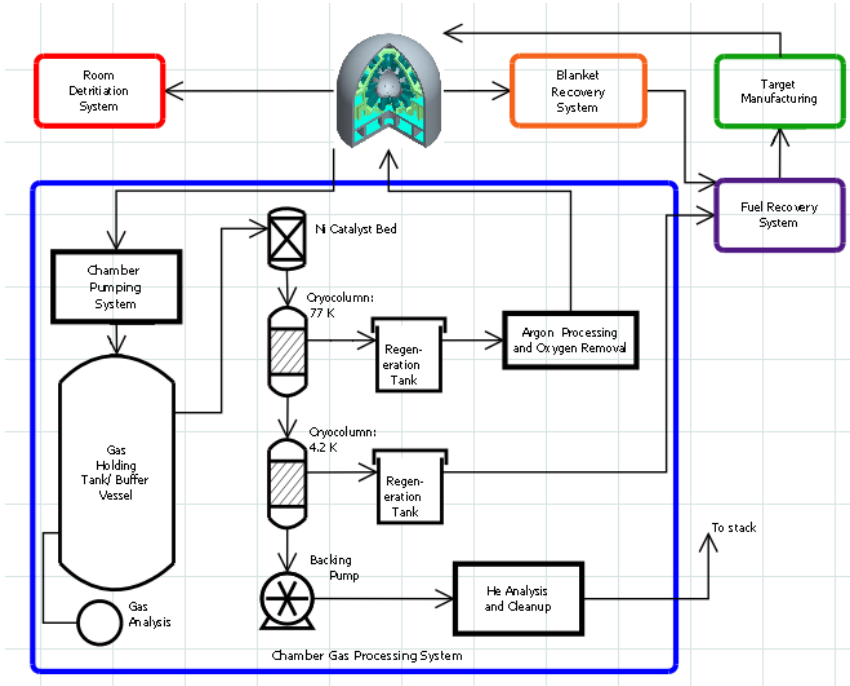

Figure 7. Chamber gas processing system.

Conclusion

An engineering study has been undertaken to evaluate operational gas fill parameters, pumping system requirements, and the associated chamber gas processing system required to employ a low pressure noble gas as a dynamic shield against post detonation helium ions in the FTF target chamber. The use of an intervention gas in the FTF target chamber is a possible solution for extending the life of the first wall. The strength of the gas fill concept is simplicity. This concept provides a solution that requires no moving or internal chamber parts, nor does it necessitate a significant redesigning of the target chamber. The gas being evaluated for this purpose is argon. Argon is a relatively inexpensive gas and provides good ion stopping properties. Studies at Nike show that, at low pressures, a noble gas resident in the target chamber does not appear to impede the ability of KrF laser light from illuminating direct drive targets. An evaluation regarding the fill gas flow was the main focus of this study. After analyzing three selected operating scenarios, it was determined that an optimized low gas flow would be the most advantageous. In addition, the requirements of a chamber gas processing system (CGPS) have been addressed. This system utilizes cryogenic separation to remove reaction products from the argon gas.

As part of this engineering evaluation, commercial suppliers of mechanical pumping systems have been contacted to assess the current state of low pressure pumping systems for the FTF operational environment. These commercial off the shelf products appear only to require minor modifications. Issues associated with target injection need to be further analyzed to ensure that the gas fill concept is viable in the integrated FTF design.

Engineering Tables

Isotopes of Argon[16]

Isotope	Natural Abundance	Half-life	Decay Medium	Decay Energy (MeV)	Decay Product
^{36}Ar	0.34%	^{36}Ar is stable with 18 neutrons			
^{37}Ar	Syn	35 d	ε	0.813	37Cl
^{38}Ar	0.06%	^{38}Ar is stable with 20 neutrons			
^{39}Ar	Trace	269 y	β−	0.565	39K
^{40}Ar	99.60%	^{40}Ar is stable with 22 neutrons			
^{41}Ar	Syn	109.34 min	β−	2.49	41K
^{42}Ar	Syn	32.9 y	β−	0.6	42K

Table 4. Various types of argon isotopes that exist. Several of these isotopes are unstable and therefore undergo radioactive decay. Ar-41 is of particular interest because it has a relatively short half-life.

Reference Data: ^{40}Ar

Parameter	Value	Units	Notes
Standard Atomic Weight	39.95	g/mol	
Density	1.784	g/l	(0°C, 101.325 kPa)
Melting point	83.80	K	
	−189.35	oC	
	−308.83	oF	
Boiling point	87.30	K	
	−185.85	oC	
	−302.53	oF	
Triple point			83.8058 K (189°C), 69 kPa
Critical point			150.87 K, 4.898 MPa
Heat of fusion	1.18	kJ/mol	
Heat of vaporization	6.43	kJ/mol	
Specific heat capacity	20.786	J/mol-K	(25oC)
Thermal conductivity	$17.72x10^{-3}$	W/m-K	(300 K)
Speed of sound	609	m/s	(gas, 1073 K)

Table 5. Relevant reference data regarding ^{40}Ar including density, atomic weight, specific heat capacity, and thermal conductivity.

NIST ASTAR Stopping Range of 3.5 MeV Helium Ions in Argon Gas[11]

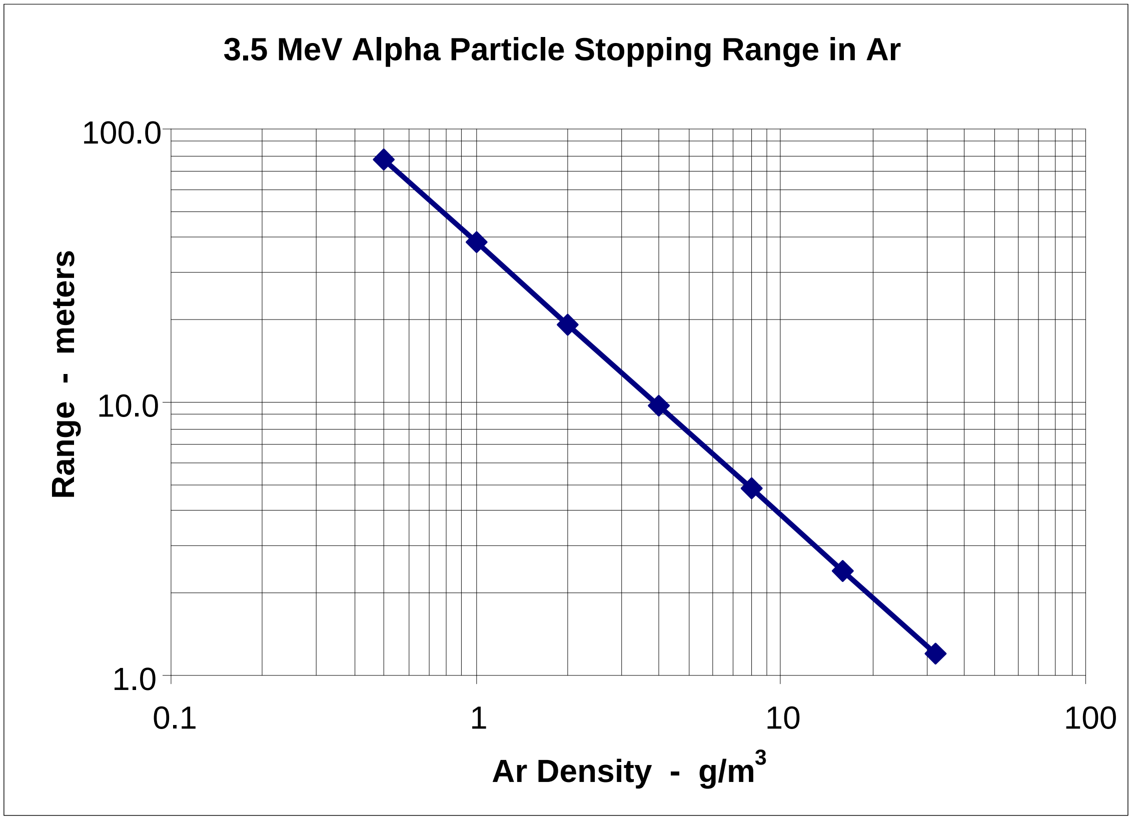

Figure 8. Stopping range of 3.5 MeV alpha particles in argon gas as a function of argon density.

Gas Load and Density of Argon at 1 Torr*

Chamber radius =	5	10	m
Volume of spherical chamber =	523.5	4,188.0	m3
Volume =	5.235E08	4.188E+09	cc
Volume =	523,500	4,188,000	liters
Gas load in spherical chamber at 1 torr =	523,500	4,188,000	T-L
1 standard T-L =	3.52E+19	3.52E+19	particles/T-L
Total number of argon atoms in chamber =	1.84E+25	1.47E+26	
Total number of argon atoms per cc =	3.52E+16	3.52E+16	particles/cc
Avogadro's number =	6.022E+23	6.022E+23	particles/mole
Moles of argon per cc =	5.845E-08	5.845E-08	moles/cc
Molar mass of Ar =	40	40	gm/mole
Argon density =	2.34E-06	2.34E-06	gm/cc
Mass of Argon in Chamber =	1,224	9,799	gm

Table 6. Gas load and density of argon at 1 torr ST for chambers of 5 m and 10 m radius.

Temperature and Pressure Rise for 6 MJ Helium Input Energy*

Chamber radius =	5	10	m
Argon atoms in chamber =	1.84E+25	1.47E+26	
Helium input energy =	6.00E+06	6.00E+06	J
ergs/joule =	1.00E+07	1.00E+07	
ergs =	6.00E+13	6.00E+13	
ergs/atom =	3.26E-12	4.08E-13	
Boltzmann constant (K) =	1.38E-16	1.38E-16	erg / K
E =	3/2 KT	3/2 KT	erg-K
T =	(2/3)*E/K	(2/3)*E/K	
T =	1.57E+04	1.97E+03	K
PV =	nRT	nRT	torr- m3
For constant volume and density, T1/P1 =	T2/P2	T2/P2	
P2 =	(T2/T1)*P1	(T2/T1)*P1	
P1 =	1	1	torr
T1 =	3.00E+02	3.00E+02	K
T2 =	1.57E+04	1.97E+03	K
P2 =	52.3	6.6	torr

Table 7. Calculations for argon temperature and pressure rise for chambers of 5 and 10m radius at 1 torr and 6 MJ.

Chamber Wall Power Density*

Chamber radius =	5	10	m
Chamber surface area =	314	1,256	m2
Chamber surface area =	3,141,000	12,564,000	cm2
Argon thermal energy (30 MW) =	30,000,000	30,000,000	W
Chamber wall power density =	9.6	2.4	watts/cm2

Table 8. Chamber wall power density for chambers of 5 and 10 m radius for 30MW input power.

*Does not include laser ducts.

Throughput of Ar

Assumed pumping speed =	10,000	400,000	L/s
Throughput of Argon =	10,000	400,000	T-L/s
Throughput of Argon =	23.38	935.24	gm/s
Throughput of Argon =	84,171	3.37E+06	gm/hr
Throughput of Argon =	185.56	7,423	lb/hr

Table 9. Gas throughput loads at pumping speeds of 10,000 and 400,000 L/s at 1 torr for a low and intermediate flow configuration.

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