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RISK ASSESSMENT OF HIGH DENSITY PLASMA EXPERIMENTATION

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Abstract- ***In the field of plasma technologies a significant portion of the design and developmenttime is devoted to ensure safety. High voltages, currents, temperatures, and pressures encountered among a range of plasma technologies can lead to unnecessary risksfor the people and the environment. There is no method for systematic and easy safety verification of any particular plasma device. The challenge of structuring a universal methodology for any particular plasma device is due to the fact that there are different plasma devices with different specifications and configurations. Although there exist different manuals for safe operation of specific plasma units, as well as the ranges of safe operation, however, in terms of the design for safe operation, there is a lack of comprehensive methodologies for safety design and verification of plasma experimentation. There are risks that stem from the sources of high pressure equipment, vacuum equipment, high voltage and high current equipment. In this work, an approach to risk assessment of plasma devices is demonstrated based on functional modeling, which is used to compare the performance of two case studies in terms of risks and safety breaches, particularly the performance of induction electrode-less fluorescent lamp (IEFL) fixture and a high pressure plasma device. The results of the two cases showed ability to assess risks in different plasma technologies, which made the proposed methodology more relevant for risk assessment and hazard tracking for a range of plasma devices.***

Keywords: Dense Plasma; Plasma Safety Simulation; Plasma Instability Tracking; Equivalent Model.

PACS:52.75.Hn, 52.59.Hq.

INTRODUCTION

The Energy Safety and Control Lab at University of Ontario Institute of Technology (UOIT) is involved in researching dense plasma phenomena, and in developing scientific equipment for plasma analysis, in collaboration with Hydrogen Omni Power Energy (HOPE) Innovations. A feasibility study conducted at UOIT on current plasma technologies and experimental configuration proposed by HOPE led to further investigation of plasma properties for safe operation. The methods for plasma simulation, radiation detection, control and cooling systemswere evaluated and chosen in preparation for the experimental stage at UOIT. The work presented herein analyzes and evaluates the risks associated with the plasma sources and plasma experiments, as well as hazard prevention in the dense plasma experimentation.

The research performed at UOIT is aimed to highlight the most prominent aspects of dense plasma (DP) and its application to fusion energy generation. In order to perform accurate analysis of DP in experimental setting, the guiding functional model of the experiment had to be made in order to track the multitude of phenomena, including safety and the hazard propagation. The fusion technologies in particular are a global engineering challenge that can lead to a clean, sustainable, and inexpensive energy supply. Thefusion energy has the advantage of fuel abundance in the world and in space. It is commonly perceived that in an accident situation, a fusion reactor is much safer than any current fission reactors. However, despite this opinion there are risks associated in activating any DP rigs (DPR). The DP phenomenon requires vacuum machinery, high voltage units, explosive gases, and may result in dangerous radiation. Indeed, it is possible to stop the reaction simply by shutting off the energy supply to the reactor; the unstable plasmas quickly dissipate and do not affect the surrounding systems. There is a level of neglect that is rooted in the assumption that the resulting unstable plasmas will not lead to expensive damages. Such assumption is incorrect and in order to prevent the damages associated with DP phenomenon, in the respectful applications, a systematic need for a safety protocol and hazard prevention is in order. Perhaps, the decommissioning phase of a fusion reactor would be much shorter than that of a fission reactor, and most of the materials would be able to be reused for other fusion reactors [1]. There is no reason to assume, however, that the operation of DPRs is without hazards. The safety associated with the high voltage and vacuum equipment as well as the explosive gases applies primarily to the DPRs. The process of achieving fusion is nested with difficult problems of containing extremely high temperature reactions, maintaining high purity of fuels, and preventing plasma instabilities that run the reactions to null. Consideration of risks, hazards, and the safety parameters of the DP equipment is essential for creating a device that will allow for proper operation regardless of what the plasma phenomena is needed for.

The work presented herein starts with an overview of the existing plasma technologies and their practical importance. The bulk of these technologies are designed based on the materials that do not necessarily encompass plasma

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technologies in particular. Specifically, when it comes to planning for the safety of the plasma devices, there is no particular methodology that solely concerns with making sure that the device will be safe. For this reason, the approach via the multiphysics modelling is considered in this work, to make the approach to safety planning more elegant and comfortable to the engineers who would like to quantify the safety of their designed plasma device. In fact, as a result of the multiphysics approach and experimental observations, it was possible to notice and deduct some of the prominent risks and hazards associated with the plasma technologies. Based on such observations an equivalent model for a general plasma device was created in order to track where and why certain risks and hazards occur. The two cases for the IEFL fixture and a plasma experiment were used to verify the use of the tool for the purposes of safety verification.

LITERATURE REVIEW

Plasma Technologies

It is worthwhile to highlight some of the most prominent applications of dense plasma phenomena prior to discussion of the related safety parameters. Some of the high end neutron generators use the dense plasma to produce high fluxes of elementary particles at rates reaching up to 6×10^{16} neutrons per discharge [2]. Furthermore, in the scientific research the use of analysis tools that utilize plasma to detect specific parameters ofmatter are becoming more common place, primarily due to the speed and the compactness of such tools. For example, the gas analysis, the surface analysis, the catalyst analysis, the plasma cleaning, and the vacuum analysis are becoming significantly relevant in the chemical and the integrated chip industriesdue to compactness and the associated speed [3]. In aerospace industry, the use of plasma for the testing of material robustness in abrupt temperature changes in the environment is fairly common among the leading manufacturers [4]. Also, the use of dense plasma for propulsion is an active field of research [4], and it is in use on most of the artificial satellites [4]. In the area of electrical engineering, the use of material processing via plasma for the micro-chip manufacture is a trusted industrial method that is improving on ongoing basis, andtowards the nano-scale devices [4]. The area of communications and radar technologies is also benefitting from the plasma phenomena for the makings of compact and precise transmitters and receivers [5]. In daily lives the use of dense plasma is also evident in arc lighting and among the construction sites for welding and cutting of the metals [6,7]. It is expected that within near future the dense plasma technologies would be employable for the exhaust cleaning [8], since, already the use of dense plasma exists in power plants that convert rubbish to synthetic gas, and then to electrical power [9,10]. Such technology is also in use in the developing field of the enhance oil recovery process [11,12]. Of course, despite such a list of dense plasma applications, the ultimate milestone among the many engineers and scientists is the fusion power generation, which is deemed to bring the new energy revolution when its means come to fruition [13].

Risk-Assessments for Plasma Technologies

Evidently, the dense plasma rigs (DPRs) range from the high luminescence arc lighting to the state of the art fusion devices, and the number of plasma applications is growing. Hence, the safety and hazard prevention for DPRs is of prime importance. The existing safety regulations for the DP equipment, such as the plasma cutters, are primarily the procedures for safe work in the environments that employ plasma cutters or welders [14,15]. Also, the majority of technologies, currently existing on the market and that use plasma phenomena, are designed so that the end user will not be able to access the working circuits, or, without breaking a warranty seal. Plasma is, after all, an extremely hot gas and improper handling of it is bound to cause accidents with high risk to the people and their environments. A practical and integrated framework for the DPRs is in order, based on the independent protection layers and fault prevention methodologies. The safety rules and requirements for DPRs are designed into such systems as the safety control layer [16]. As per IEC61508 standard, the industrial facilities have to make a proper implementation of the safety verification techniques in order to provide a safe atmosphere for operation [17-20]. It is of key importance for the DPR unit design to meet the verification process for all validated safety requirements [21,22]. At the temperatures higher than 3,000 K, the atoms in matter begin to achieve the state of plasma. In the plasma, the electrons of the atoms will no longer be bound to the nuclei, and the formedplasma is a suspension of the negatively charged electrons and the positively charged nuclei, or ions [23]. The quasi-neutral state behaves similar to metals, due to the raised energy potential on the particles composing the plasma. Hence, the plasma is capable of carrying electric currents and is influenced by electromagnetic forces. The hazards pertaining to plasma phenomena include the electrical charge dissipation, heat dissipation, and possibly explosions, especially when the dense plasma phenomena take place in a confined volume. Current international efforts in the development of the fusion reactors are the best example of strict compliance with the safety requirements, mainly due to the nuclear background of the involved researchers and the expense of the testing units [13]. However, in the nano-manufacturing processes also reap the benefits of plasma technologies, and, in due manner, follow the safety protocols and risk prevention procedures to prevent any accidents resulting from the plasma processes and the consequential products [24]. In both of these highly advanced research areas the physics associated with plasma plays a key role in predicting the risks and understanding the hazards.

Multiphysics Modeling Framework of Plasma Experiment

The theory ofdense plasma modelling stems from fluid dynamics, heat transfer, electrodynamics, and circuit analysis. The limited map, shown in Figure 1, demonstrates the different branches of plasma phenomena [25]. This figure is a portion of a larger study intended for a multiphysics modeling of plasma systems. During the research the authors were involved in the creation of the physics simulation program that is based on the formulations relevant to each specific branch in the plasma phenomena. The focus of formula based simulation was to compute and to evaluate the theoretical behaviour of plasma in conditions leading to atomic fusion. The purpose of such models was to initially develop a dynamical representations of the plasma under different one-dimensional conditions, without compromising the realism as much as possible

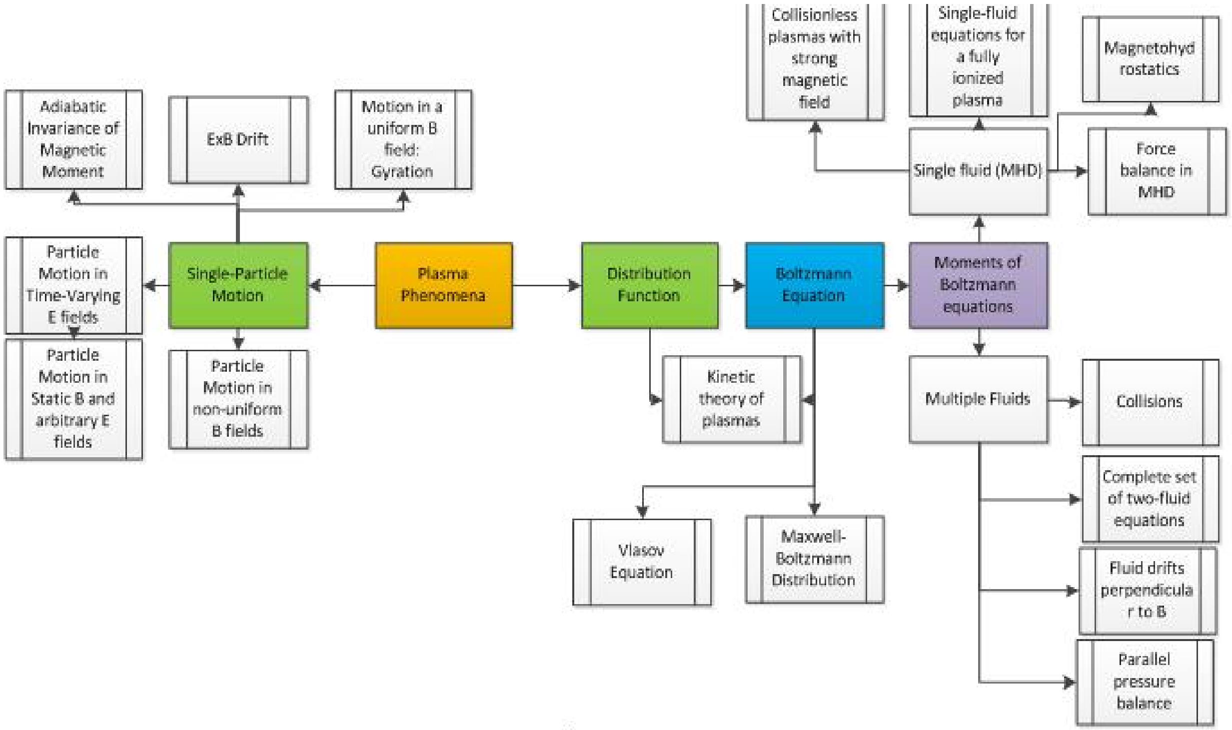

Figure 1: The multiphysics modelling of plasma phenomena [25].

The experimental setting for the dense plasma was created by keeping in mind the interrelationships of plasma phenomena conditions.Its representation is shown as a functional model in Figure 2

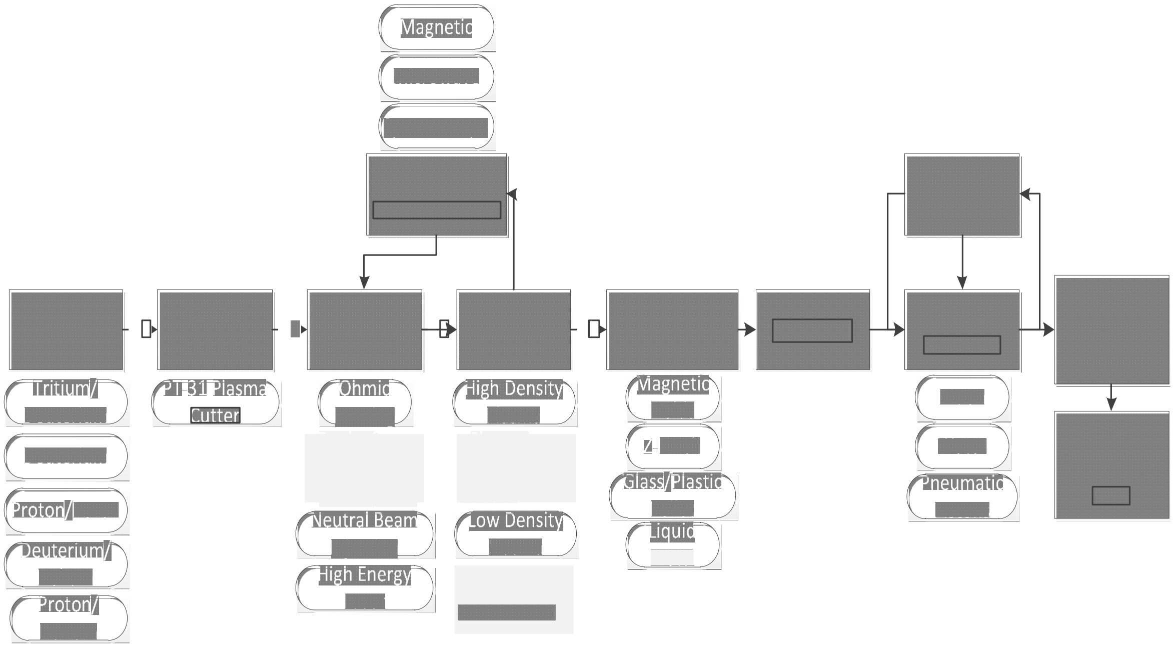

Figure 2: Experimental setting functional model for a fusion device.

The Y terms represent the changes in temperature, Coulomb forces, mass flow rate, inter particle distance (cross-section), and the plasma density.In the existing experiment, the plasma is generated via the electric arc torch and then it is emitted as a jet through a nozzle. The cathode is connected to a power supply, and when in operation, the cathode discharges electrons in the form of an arc. This arc travels to the anode, and heats the gas within its pathway, ionizing the atoms. Hence, plasma is formed and then projected outwards by the continuous flow of working gas, via the pressure generation and the intrinsic magneto-motive force. The method depicted in this experimental setting is non-transferred, that is, a DC discharge has limited produced heat; unlike transferred method, where the anode is outside of the nozzle.

Ideally, the goal of DP research is to achieve the ultimate energy goal of the self-sustaining fusion reaction. Such goal is aligned with the intentions of the Energy Safety and Control Lab and the authors of the current work. Fusion reactions and dense plasma phenomena in general create an enormous amount of heat, which needs to be monitored and controlled. Relaiblediagnostics are crucial in DPRs. The most used diagnostics methodologies include the magnetic, microwave, and the spectroscopic.

Although, the use of magnetic diagnostic varies depending on the type of dense plasma reactor, there are essential requirements pertaining to plasma. Magnetic diagnostics measure the basic equilibrium parameters such as current, the position of plasma, its shape, and any magnetic fluctuations happening during operation. This diagnostic operates in electromagnetic spectrum ranging from 100 Hz to a few MHz [13].

The microwave diagnostics are placed in three categories. The first is reflectometry, which measures the phase shift of an injected resonance wave with respect to plasma, and, consequentially, helps to determine the position of plasma. The other method is electron cyclotron emission (ECE), which is used to measure the temperature of the electron radial profile. The amount of energy released due to black body radiation is proportional to this temperature. Lastly, interferometry is used to measure the difference between the wave packet sent through the plasma and a wave that is sent through the vacuum. This diagnostic provides a line-averaged plasma density along the path of the injected wave. These diagnostics are applicable in the range from 1 GHz to 3 THz [13].

The electromagnetic wave length in plasma ranges between 10 nm to 10 µm, and, therefore, it is be possible to investigate the Bremsstrahlung spectrum as well as the radiation fromthe minute impurities that may be present in the plasma, hence, the use of spectrometry in DP research is essential. It is possible to determine the electron temperature, plasma rotation, the Doppler shift, as well as the plasma density using the spectrometry [13]. Also, in combination with the laser induced fluorescence and the Fourier Transform Spectroscopy it is possible to selectively analyze the minute properties of plasma on a quantum level.Radiation is a major loss in plasma, therefore it can be used forthe diagnostic procedures to measure the acceleration of plasma particles and their interactions with electric and magnetic fields [26]. However, the integration of the detectors into the DP experimental setup presents the challenge of the intense heat of the plasma, which may damage the detector. The detector window must be placed a safe distance away from the plasma channel to prevent damage.

The experimental setup is a configuration of two plasma sources facing each other. The conductors leading to the plasma torches are the high current carriers. The nozzles of the plasma generators as well as the leads of these generators are insulated near the gap space between the nozzles. The block diagram for the experiment is shown in

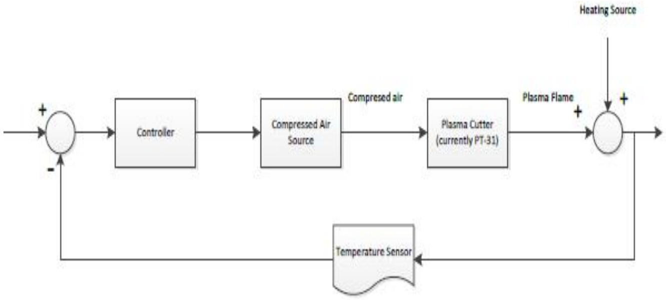

Figure 3: Basic block diagram for the process control.

Experimental setup was conducted to investigate the plasma created from plasma torch setup. Figure 4, below, depicts the experiment in a working mode.

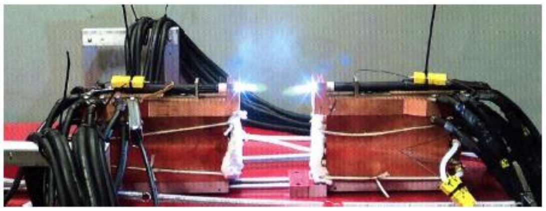

Figure 4: HOPE experiment [27].

The experiment involves two plasma torches controlled by computers to create a plasma field in the volume between, known as the plasma space.

Safety Assessment Framework of Plasma Experiments

The use of plasma technologies varies from the micro- and nano-scale devices [4] to the large facilities such as the ITER Tokamak [28]. Hence, the scale of the device utilizing plasma comes into play depending on its particular purpose. For instance, most of the fluorescent lights available for commercial and residential facilities are capable of reaching the electron temperatures equivalent to the temperatures near surface of the sun [25]. Despite this, due to the low pressures inside the plasma chamber, and, hence, the low level of particles available for ionization, the plasma inside such lighting fixtures does not present a significant threat. This does not reduce the dangers of the materials associated with the lighting fixtures. However,if a fluorescent fixture is broken, or shatters due excess power and cracks, then the sharp shards, the halide vapor, and a possible blast, do present a threat to human health and environment. Therefore, although the plasma confined in the fluorescent lamp is not necessarily dangerous, the materials and the systems associated with its function may pose as a hazard. Taking this example as an analogy for other applications, it is worth noting that the larger scale of the plasma employing devices the more likely is that they will have accommodating materials and systems that are not safe when breached. That same fluorescent light may be made to be entirely robust and leak proof, in fact, it may be the designed to be the most safe device. Nonetheless, such design will not be entirely safe from human creativity and the human ability to hurt themselves. For this reason, most of the devices have to have the layer of protection that warns to not misuse the object, for the purposes unintended in the original design, as well as, to be built in a fool-proof manner. This is the very top layer of protection against the misuse, the core of protection against the misuse of devices utilizing plasma is the emergency shut-down system that stops the entire process when a notion of a disaster is within the safety limits. The other layers of safety for the plasma devices are between the core and the top, and their number is directly proportional to the complexity of the device.

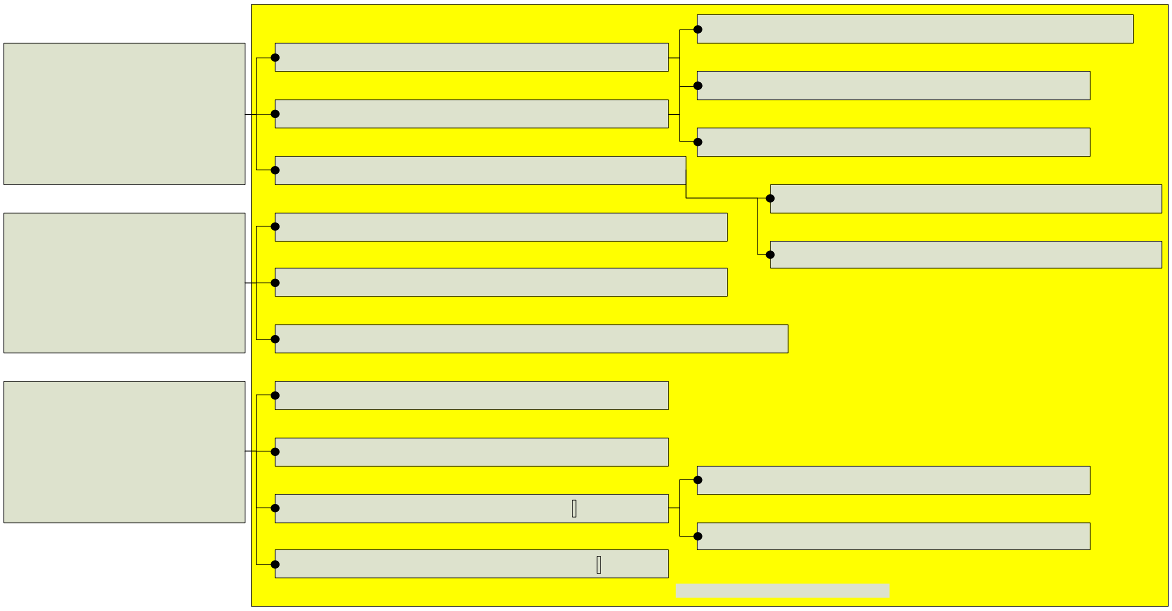

Figure 5. The DPR subsystems and the associated fault predictors.

Each fault predictor and hazard process variable can be linked with a particular hazard that may occur in a DPR system. Most significant hazards have been identified by the authors based on the existing works in the field of applied plasma technologies, primarily as the result of literature review. Such hazards are presented in Figure 6 and the associated fault predictors leading to the specific hazard are identified for each one. For instance the explosion hazard presented in the figure may occur as a result of single, or a combination of, fault predictors. Justifiably, the explosion will occur for certain when the voltage (V) and current (I) supplied to the DPR’s discharge systems (DS), and electrostatic confinement systems (ECS), exceeds the intended rated values, the chamber pressure (P) exceeds rated levels, the excessive gas diffusion (GD) occurs through the chamber walls, the chamber has a large number of connection points (CP), the chamber is made of fragile materials (CM), the shielding thickness (ST) is thin, and electric discharge

The layer of protection for devices like plasma welding and cutting equipment is usually a certificate of competence in operating such devices. This certificate typically prevents un-trained personnel away from the equipment that requires previous knowledge and experience of the device under consideration [14,15].In the work presented herein, it is assumed that the equipment designed for the applications utilizing plasma is made for the purpose of avoiding any hazardous outcomes; that is, the devices under study may be utilizing the technologies with associated risks, as is the case with the halide inside the fluorescent lights, but under normal operating conditions their risks are negligible.

The authors recognized that the plasma units have a hypothetical composition of three subsystems making up a DPR: power supply, gas system, and system cooling. The corresponding fault predictors and the associated hazard process variables for each sub-system are presented in Figure 5.

elements (EDE) are quickly consumable. However, the extent of any particular hazard, such as the explosion, depends on the safety limits of a particular DPR unit; a plasma display must certainly not present an explosion hazard, whereas, the fast pyrolysis of rubbish by plasma incurs the inevitable micro-explosions in the refinement process.

Understandably, the presented hazards are fairly generic for any particular DPR. However, for the purposes of the current work it was essential to identify the key hazards, and not necessarily the consequential hazards. Certainly, an excess of electromagnetic interference and microwaves will lead to malfunctioning electric equipment and present some health risks, which, in their own right, are the hazards; preventing the electromagnetic interference and microwaves will cease such consequences to begin with. Therefore, by keeping the level of abstraction for the presented hazards and the associated fault predictors as is, will ultimately lead to preventing the consequential hazards of any DPR.

Figure 6. The DPR hazards with the leading hazard predictors/factors

Risk and Hazard Assessment of Plasma Experimentation

As evident from Figure 6, there are several hazards in the existing experimental setup that must be protected against. Table 1, below, lists some of the most common issues possible in dense plasma (DP) research. In order to apply the precautions, the safety systemshave to be redundant, independent and relevant on multiple safety levels.

Table 1.Risks, hazards, and prevention strategies in dense plasma research

#	Risk	Hazard	Prevention
1	Temperature too high	Could damage containment or melting or excess fusion reactions	Emergency cooling system on standby and Several temperature measuring devices
2	Voltage too high	Plasma source/head-piece damage	• Temperature gage in closed feedback • Material used for head-piece has to withstand high temperature • Cooling system for head-piece in standby
#	**Risk**	**Hazard**	**Prevention**
3	Over pressure in Containment	Rupture of containment	• Containment made to withstand very high temperature • Pressure gage • Pressure relive valves
4	Impurities/ particulate in containment	Disturbance/ Unwanted reactions	Vacuum and purging system
5	Plasma overload	Uncontrollable/runaway fusion	Provide limited fuel and stabilize the plasma via confinement
6	Corrosion in plasma source	Malfunction of head-piece elements	Regular change of the head-piece elements
7	Fuelling line malfunction	No fuel	Regular maintenance of machine and a standby back-up machine
8	Electric bolt mis-fire	Low temperatures	Focussing and confinement mechanism
9	Fuel pellet* wrong size	Fusion not occurring as planned	Policy to check fuel in accordance to standards
10	Power Outage	Malfunction of control device or possible shutdown	Backup system /power for emergency systems
11	Fuel proportions incorrect	Fusion not occurring as planned	Policy to check proportions
12	Leakage of coolant	Loss of cooling accident	Gage to check coolant level and a sealed coolant system
13	Leakage of fuel	Loss of fuel	Measured at regular intervals, regular checking for leakages, and a sealed confinement unit
14	Leakage of catalyst	Slowdown of fusion and loss of catalyst	Gage to determine the catalyst level and a sealed confinement system
15	Temperature too low	Loss of fusion reaction	Temperature measuring devices and sensors to indicate temperature, as well as insulation to prevent excessive heat losses
16	Malfunction of controls	Loss of control	Regular system inspection and more than two of three logic for system robustness
17	Damage done to plasma source	Loss of fusion and unwanted results	Regular inspection and protective layer surrounding the source element to protect it from external harms

*Note: No radioactive sources with activity higher than that from a conventional smoke detector are used throughout the research.

Procedures and Strategies for controlling runaway reactions and instabilities. Furthermore, by mapping out a range of possible faults, their causes, and the prevention strategies it is possible to apply the safety precautions to the DP systems of varying scale. Based on anticipated risks, it is possible to size a particular system that employs dense plasma and meet the minimal safety requirements while attaining the requirements. Currently, some of the most prominent safety requirements for safe research in DP area are as follows:

- Have the means to mitigate the negative impacts of DP occurrence (such as stray neutrons and x-rays) by employing protective shielding
- The equipment must handle the high pressure and high temperature environment
- Multiple safety systems are implemented to prevent malfunctions
- The system must contain of failsafe safety devices
- Power supplies for safety systems must be present and maintained at regular intervals
- Means for controlling DP occurrence must be present
- Means and procedures for containment must be present
- Impurities must not lead to safety breach
- The DP testing rig must have limiters for maximum gas injection
- Power outage shall not result in an unsafe operation
- Means to prevent and detect leakage must be present
- Control devices are well calibrated, reliable, and robust in case of safety breach
- Shutdown systems are fully functioning and upon deactivation of the acting components of the test rig, the safety systems of the rig remain in a functional state.

The implementation of these safety rules is foundational when designing any DP systems.

Risk Estimation Model for DP Experimentation

Structure of the Risk Estimation Model

In this section we present an option for evaluating the risks associated with two specific plasma generation units. By using the knowledge of DPR subsystems and the associated fault predictors, the hazards, the hazard predictors/factors, as well as the risks, we intend to use an abstract approach for estimating the risks in DPR by building a model in MATLAB/Simulink. For the first case of simulation we will use a case of aninduction electrode-less fluorescent lamp (IEFL) in order to see whether the model makes sense in respect to the available data [29]. In the second case we will present a hypothetical scenario along the lines of the HOPE experiment. At the current time,the plasma devices that are considered in our research operate at the currents below 100 kA. Based on this value, we assumed that such devices have sufficient shielding to prevent excessive electromagnetic radiation and any possible neutrons generated in the process of electric discharge in a deuteron atmosphere. Based on the work of Vikhrev and Korolev[2], it is expected that the approximate amount of neutron per single 100 kA pulse will be in the range of the 10^5 neutrons, and, hence, would not result in significant radioactive hazards [2].

For the purposes of safety verification it was assumed that the bulk plasma properties of the plasma devices can be represented by an equivalent circuit, compromised of a resistive component connected in series with an inductor, and a capacitor connected in parallel to the series circuit. The electromagnetic properties of plasma are expressed in terms of its maximal resistance, inductance and capacitance. The thermal properties of plasma are expressed in terms of the properties of the working gas and its thermal qualities. The specific operating conditions for the two scenarios are presented in Table 2. For the IEFL device a 70 Watt lighting fixture investigated in [29] and [30] is taken as a unit under investigation. Whereas for the HOPEexperiment, the data is obtained directly [27]. Unlike the setting demonstrated in Figure 4, it is intended to analyze the safety of plasma confined by a steel chamber. A 60 centimeter stainless-steel tube with an outer diameter of 12 millimeters and an internal diameter of 4 millimeters is assumed to be the confining chamber for the modified case of HOPE experiment. It is assumed that plasma behaviourcan be approximatedby a blackbody with an emissivity factor of 5%. In the current case, the model is entirely internal and does not take into account any outside noise, although, it is intended to be included in the future research. The space occupied by the devices is assumed to have enough air circulation to maintain a uniform room temperature of 293.15 K.

Table 2. Design Parameters of the Case Studies.

Design Parameters of the Chamber	IEFL	HOPEExperiment
Electromagnetic Properties		
AC Voltage Source [V]	1200 [30]	800 [27]
Operational Frequency [Hz]	250’000 [30]	DC[27]
Current Source [A]	Induced to 0.066	20,000 [27]
Plasma Resistance [Ohm]	18181.81 [30]	90 (at breakdown) [25]
Plasma Capacitance [pF]	400 [29]	1.38×10^{-16}[25]
Plasma Inductance [uH]	0.4244 [29]	3×10^{-5} [25]
Plasma Relative Permeability	1	1
Cross-Sectional Area [m^2]	2.1237×10^{-3} [30]	1.2566×10^{-5} [27]
Length of Plasma Section [m]	0.1335 [30]	0.1 [27]
Equivalent Number of Turns for the current carrier	18 [29]	2 [27]
Gas/Thermal Properties		
Specific heat at constant pressure Cp [J/(kg*K)]	1040[31]	1007 [32]

Table 2. Design Parameters of the Case Studies (continue…)

Specific heat at constant volume Cv [J/(kg*K)]	1039[31]	719.3 [32]
Dynamic viscosity	$5.62/10^7$ [31]	1.983×10^{-5} [32]

[s*Pa]		
Initial Pressure [kPa]	33.015[31]	620.5
Initial Temperature [K]	293.15	293.15
Occupied Volume [m^3]	$6.5762/10^4$	7.53982×10^{-6}
Plasma Mass [kg]	$1.4511/10^6$ [32]	7.53982×10^{-6} [32]
Radiation Coefficient [$W/(m^2*K^4)$]	$5.103/10^8$ [32]	5.103×10^{-8} [32]
Enclosing Surface Area [m^2]	0.4404	7.564955×10^{-3}
Internal Convective Heat Transfer Coefficient [$W/(m^2*K)$]	Irrelevant due to near vacuum [For more rigorous calculations becomes necessary]	91.1 [32]
Chamber Properties		
Chamber Material	Glass	Steel
Mass [kg]	0.185 [32]	0.4724 [32]
Thickness [m]	0.001	0.004
Thermal Conductivity [W/(m*K)]	1.38 [32]	60.5 [32]
Specific Heat [J/(kg*K)]	745 [32]	434 [32]

Figure 7 shows the conceptual model for dense plasma rig unit, as modeled within Matlab/ Simulink. This model is made of an “electromagnetic state of plasma” component and a “thermal and gas properties of plasma” component, shown in Figures 8 and 9 respectively.

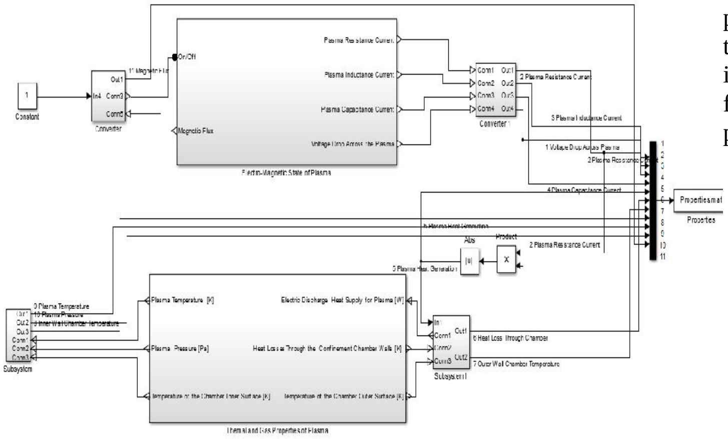

Figure 7. The conceptual model of the dense plasma rig unit.

Figure 8 showsa potential electromagnetic equivalent circuit used with the dense plasma, which is modeled within Matlab to enable the accurate evaluation of the risk scenarios associated with DPR experimentation.

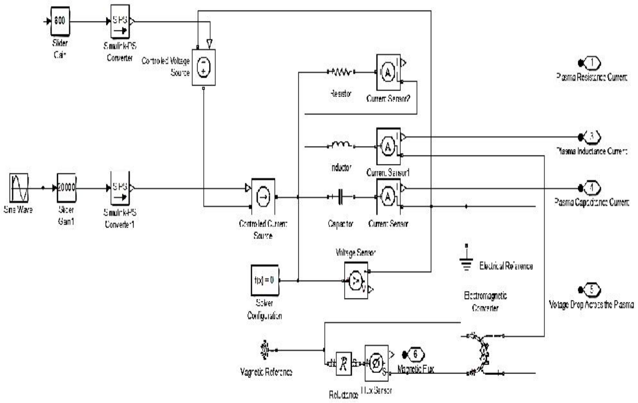

Figure 8. The electromagnetic equivalent circuit of the of the dense plasma.

Figure 9 shows both the thermal and gaseous settings of the plasma confinment chamber, and it is used to evaluate risk scenarios associated with thermal and gas systems of the plasma setup. These models use the multiphysics modeling to predict and evaluate the risks associated with plasma devices and setups.

The properties provided in Table 2 are used directly within the Simulink model, since, these are the design parameters of the plasma devices under consideration. Once these properties are assigned, the plasma device simulation would be activated via the “run” command in Simulink, and provide the operational qualities of the device. The operational qualities include the voltage drop across plasma, currents in the series circuit and the curent in the parallel capacitor, the magnetic flux, the heat generation by plasma via the ohmic heating, the overall sensible temperature of the plasma, the pressure within the chamber, the heat loss through the chamber, and the temperatures of the chamber’s inner and outer walls. Using these results with respect to the fault and hazard predictors presented in Figures 5 and 6, it is possible to evaluate the overall safety of the plasma device.

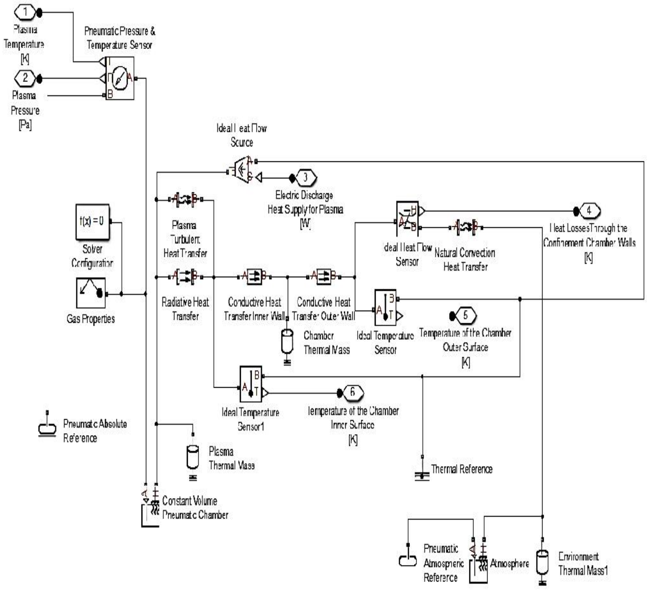

Figure 9. The thermal and gaseous setting of the dense plasma confinement chamber.

The risks of the plasma devices are evaluated based on how close the results of simulation match with the corresponding safety ranges assigned by the designers of the plasma devices. The reason for this is that any system designed for a particular plasma device will have its own safety limits, as should be apparent per discussion in Section 2.1. Hence,for the two case studies the safety limits are derived from the original design documentations as well as the reference materials pertaining the material properties [33]. The safety limitsfor two cases are listed in Table 3.

Table 3. Design Safety Limits of the Case Studies.

Design Parameter	IEFL	HOPE Experiment
Maximum Plasma Voltage Drop [V]	1200	1.8×10^{6}
Maximum Series Circuit (R&L) Current [Amp]	0.066	20000
Maximum Parallel Capacitance (C) Current [Amp]	0.066	20000
Maximum Magnetic Flux [Wb/cm]	1×10^{-7}	1×10^{-7}
Plasma Heat Generation [W]	70	3.6×10^{10}
Heat Loss Through the Chamber [W]	40	3.6×10^{9}
Chamber Outer Wall Temperature [K]	343	400
Chamber Inner Wall Temperature [K]	343	2750
Plasma Sensible Temperature [K]	1600	6.6×10^{5}
Plasma Pressure [kPa]	42	6.54×10^{5}
Bursting Pressure [kPa]	101	9.8×10^{5}

Results of the Risk Estimation Model

A set of results was obtained after assigning the accompanying properties outlined in Table 2 into the Simulink models for the IEFL case, and then for the HOPE experiment case. The results of the simulation with the respect to the designated safety values are presented in Table 4 as ratio of the results to the safety limits.For the IEFL case an hour of operation was tested for any particular breaches in the safety. In case of the hypothetical HOPE experiment, however, after 6 milliseconds of operation it became apparent that a breaching safety is inevitable.

The voltage excess ratio is useful for risk estimation when the system under consideration might have some internal storage or a static anomaly. Nonetheless, in the current cases it does present much use besides pointing out that human contact with the voltage sources should be avoided. A likewise argument also applies to the current ratios. From Table 4 it is evident that due to the minimal values of the risk associated values, the ratios of design parameter breach, the operation of the IEFL device has minimal risks. On other hand, in case of the hypothetical case of the HOPE experiment it should become apparent that the system has risks of excessive temperature and a potential to explosion as a result of a chamber rapture. In order to prevent such risks a material change, an auxiliary heat removal unit, and, possibly, alternative operational setting could be used in order to prevent any risks.

Table 4. Risks associatedwith the Case Studies.

Design Parameter	IEFL	HOPEExperiment
Voltage Excess Ratio	0	0.06
Series Circuit (R&L) Current Ratio	0	0.06
Parallel Capacitance (C) Current Ratio	0	0
Magnetic Flux Ratio	0	0
Maximum Allowable Heat Generation Ratio	0	0.0035
Maximum Heat Loss Ratio	0	0
Maximum Outer Wall Temperature Ratio	0.755	3.63
Maximum Inner Wall Temperature Ratio	0.11	193
Sensible Temperature Ratio	0	0.802
Pressure Ratio	0	1.71
Bursting Pressure Ratio	0	1.14

Furthermore, going back to Figures 5 and 6 it will become apparent that in case of the hypothetical HOPE scenario, it may be worthwhile to see whether the alternative materials diffuse any of the gas through the chamber walls, or perhaps the fault predictors associated with the system cooling have to be altered in a manner that will minimize the risks. However, admittedly the hypothetical experiment case may not be well defined in its initial confinement design. Firstly, the hazard of explosion needs to be mitigated in order to see what other possible design refinements may be necessary. Nonetheless, the purpose of the model was to see the risks of the plasma devices and at its current stage it allows for the use in quick and relatively methodology for estimating the safety of a particular plasma device.

CONCLUSION

The approach to risk assessment of plasma devices in terms of the equivalent structure methodology has a potential to become a convenient tool in estimating the risks of plasma devices and plan for the safe operation of such devices. The equivalent structure allowed to evaluate the performance of two case studies in terms of risks and safety breaches, particularly the performance of induction electrode-less fluorescent lamp (IEFL) fixture and a high pressure plasma device, a hypothetical experiment. The results lead to the risk assessment and hazard tracking within the definitions of conventional plasma devices. The stark contrasts of the case studies is understandable in the current work, due to the major differences. Nonetheless, the methodology presented herein can help in mitigating any dangers in future plasma devices by being implemented during the design process.

In this work, detailed review and analysis of plasma settings and experimentations are studied and used to provide a foundation to assess risks associated with plasma devices.In order to achieve the stated target, a multiphysics modeling framework is proposed based on two case studies, one for dense plasma setting conducted with the collaboration with

HOPE Innovations, and the other was for Induced Electro-Fluorescent Lighting (IEFL). In order to provide a systematic risk assessment framework, physical system model is developed, and associated with properties of the different components and operation used in each setup.

The work presented herein analyzes and evaluates the risks associated with the plasma sources and plasma experiments, as well as hazard prevention in dense plasma experimental and practical rigs. The result of the work done by the authors in regard to the safety and risk assessment of the high density plasma experimentation is primarily meant to make a foundation for the design of future generation plasma devices. The results of simulations are appropriately fit as the outlines for designing the DPRs.

In the future work on the equivalent model risk and hazard prediction, it is intended to implement a dynamic algorithm that will alter the design parameter in order to adjust the required safety limits.

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