Process Safety Management in Plasma Experiment and Generation System

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Abstract

The Experimental Plasma Generation System (EPGS) is proposed for studying and investigating the plasma behavior in vacuum conditions and under the influence of the varying boundary conditions. Furthermore, (EPGS) is intended to verify the computational models with the physical data. The safety design of EPGS takes into consideration the target safety system design, input parameters, output parameters, measurement techniques, and the fault propagation scenarios with respect to the Process Safety Management (PSM) via the IEC 61508. Also, the design of the Target Real Time Safety System (TRTS) for EPGS will be explained in relation to its primary experimental functions. The TRTS will be simulated using Simulink, with errors randomly generated at key cracking points, and the shut down procedure will be executed based on the deterministic algorithm for the Real Time Safety Verification (RTSV). In the nutshell, the cumulative outcome of the current work is to provide a design for plasma experimentation device that will have scalable properties in both the physical parameters, as well as the safety parameters.

Keywords—IEC 61508, PSM, plasma safety simulation and management, plasma device design, safety oriented design.

Highlights:

- Engineering design of proposed experiment of plasma generation system (EPGS)
- Safety analysis of EPGS
- Apply IEC61508 on safety design of plasma devices
- Simulation of EPGS safety system using Simulink

1. Introduction

Plasma safety and handling may become an increasingly important topic for future manufacturing and energy industries. It is, therefore, important to consider, evaluate, and analyze the risks that will be encountered when the plasma devices are implemented on a large scale. The current work dwells on the matter of plasma safety in the experimental environment and aims to provide a design option for conducting plasma experiments on a small scale, in order to extrapolate to large scale systems and industrial applications. It is certain that the risks are inevitable no matter the situation or design, however, it is possible to reduce certain risks and to prevent hazards by both making wise design decisions and by the rigorous collection of experimental data. The Process Safety Management (PSM) is a framework governed by the good design practices for the purpose of safe maintenance, integrity, and hazard prevention of the systems, materials, and energy related practices, it can therefore act as a guideline to achieve safe designs of plasma devices [1]. Furthermore, the PSM is in close cohesion with the IEC 61508, an internationally recognized standard for the safe operation of the Equipment Under Control (EUC), where the control systems are based on the proper operation of Electrical/Electronic/Programmable Electronic Systems (E/E/PES) safety related systems and external risk reduction facilities. The Plasma Experimentation and Generation System (EPGS) will be largely based on the principles of PSM and the IEC61508 standard. The reason for designing EPGS is to create an experimental setup for performing small scale plasma experiments and for studying the plasma behavior under a variety of different conditions such as the plasma pressure, the electron density, plasma propagation velocity, plasma laser interactions, and plasma electron interactions. The implementation of PSM via the use of IEC 61508 for the design is in due to the convenience for the novel design of EPGS.

1. 1. Objective and Purpose

The objective of the current work is to give the highlights of PSM and IEC 61508, and to apply them to the design of the EPGS. The purpose of conducting the PSM using the IEC 61508 is to minimize the risks and hazards of the designs that are their initial stages of conception, to make a set of rules for the safe operation, to create a list of possible risks and hazard, and to present a function that highlights the probability of risk associated with a particular operation of a device. Currently the main objective is to work with parameters that will be defined for EPGS and to use them in order to define the safety measurement, to make deterministic algorithms for the Real Time Safety Verification (RTSV), and to define the protection and safety barriers for EPGS. The creation of the probabilistic algorithm for plasma instabilities is achievable through the experimentation, and therefore only the deterministic algorithm will over-ride the probabilistic algorithm in this work. Firstly, the overview of the EPGS design will be conducted, then the design of the target safety system for EPGS will be provided. The input and the output parameters, as well as the possible measurement techniques for the safe operation of EPGS will be highlighted so as to demonstrate the fault propagation scenarios for EPGS in accordance with the design requirements. Also, the safety limits, measurement, protection/barriers as well as the algorithm for real time safety verification in deterministic way will be defined.

1. 2. Literature Review

Human made devices tend to fail depending on the degree of complexity and quality of the design. The more complex a device, the more likely that some part of it will fail and the tracking of such failure will be made all more complex, and time consuming, unless, of course, there is a well-defined fault prevention system in place [2]. Certainly, if the failures are expected as a result of intentional design, or as a feature leading to prevention of a bigger failure, then accounting for such feature makes it an important part of the design. However, there are failures that occur not by intention and lead to malfunction, and these are in the focus when dealing with fault prevention in the design stage. In the case of the plasma devices the capacity for failure is in relationship with the main objective of plasma generation [3]. The fact that plasma devices incorporate the effect of electromagnetic systems and thermo-fluidic systems is critical during the design stage, especially in the field of plasma safety [4]. Furthermore, this fact is generally accepted on the grounds that any new design can be evaluated as the sum of its composing parts [5]. This approach is not wrong, though, it may lead to missing the net effects of plasma such as the generation of microwaves, residual charge carriers, and a spectrum of other effect entirely dependent on the purpose of the plasma device [6]. Indeed, the large portion of the plasma devices that exist in the market are oriented on singular use and have a limited scope of operation [7]. However, in the nearby future it is very likely that the technological growth of humanity will demand ever-growing complexity from the plasma devices [8]. This statement may seem obscure, as it may be hardly noticeable what effect the plasma devices have on the daily lives of people. To support this statement, however, it is worth-while to point out that the manufacturing of the digital devices is highly dependent of the plasma vapor deposition processes [9,10], the medical facilities utilize plasma disinfectant chambers for keeping sanitary environment [11], the success of the military operations may rely on the effectiveness of the communication networks, and radars, that operate via the plasma effects [12], and the energy production in the near future will be able to prevent the effects of pollution [13] and possibly tap the nuclear fusion [14] and propel humanity to the exploration of the solar system [15]. The approach of the plasma technology utilization is definitely not going to be singular as it will involve a multitude of orchestrated events actuated by systematically organized parts. Perhaps, this is a future outlook on the state of future technology overall, and it is certain that there will be an ever necessary elegance. However, the reciprocity of plasma with the design will inevitably lead to essential application of the safety principles and the enforcement of the risk accountability [16]. This is not to say that the foundations of safety-oriented design currently implemented for the novel technologies is irrelevant, though it is reasonable to expect that alterations and the inclusions of new sections particular to specific technological developments will be accumulated as more and more complex devices enter the growing demand of humanity for expanding its capabilities.

1. 3. Engineering Design of Plasma Experiment

EPGS is an enclosed chamber that contains two plasma generators facing each other. EPGS includes a vacuum pump, 3 electron beam generators, laser and optics systems, high voltage generator, high current generator, and a set of diagnostic tools for the analysis of the plasma and its dynamics. The objectives of EPGS include the studies of the plasma modes, plasma generation options, stability, methodologies for control, novel diagnostic methods, interaction of plasma with materials, plasma mixing, and the plasma wall interaction. It is worth-while to highlight some of the key components of EPGS in order to understand the how EPGS meets its objectives. The pictures below will point to the specific components of EPGS as well as highlight the points where a risk of safety breach is possible.

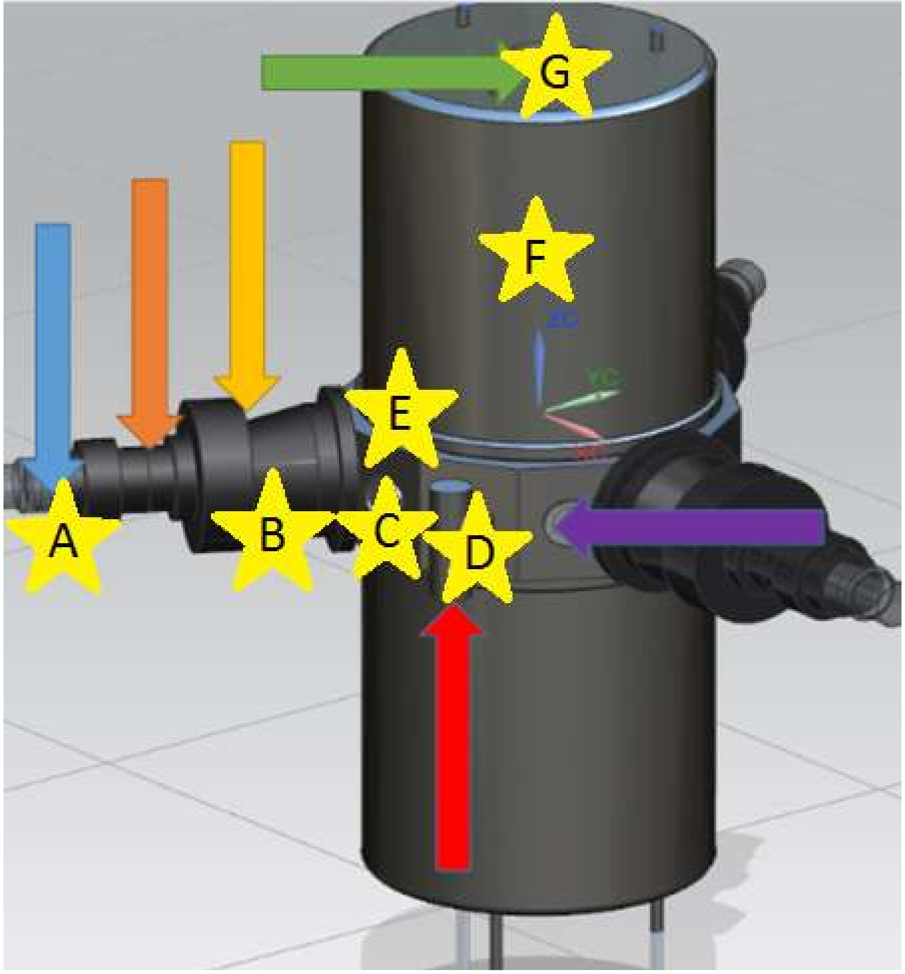

Figure 1: An over-all view of EPGS

The potential safety breach risk points of EPGS are indicated by stars: (a) Hot, HV area, e- generation; (b) Magnetic field for e- trajectory control; (c) View-port dislodging/cracking, possible leakage area, explosion/implosion hazard (EIH); (d) Possible Leakage Area (PLA), EIH; (e) PLA, EIH; (f) Chamber Strain; (g) View-port dislodging/cracking, PLA, EIH; Components: Blue Arrow->Electron gun; Orange Arrow->Hysteresis magnetic coil; Yellow Arrow->Control magnetic coil; Red Arrow->Vacuum pump connection valve; Violet Arrow->Quartz view-port; Green Arrow->Quartz window for high power laser light.

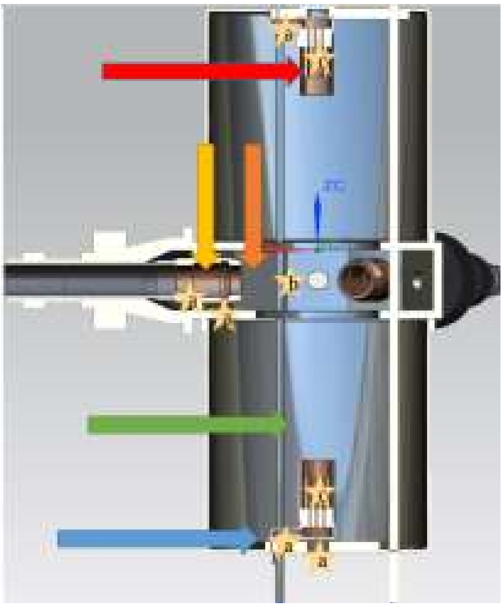

Figure 2 : EPGS cross-section

In figure 2 the cross-section of EPGS is presented to showcase the internal components. Some of the additional potential safety breach risk points for EPGS include: (a) PLA and quartz cracking points, EIH; (b) Charge accumulation and X-ray area; (c) Plasma gas puff instabilities, irregular generation, mismatched timing of plasma discharge/gas release, EIH; Components: Blue Arrow->Chamber retention plate; Orange Arrow->Female copper coupler; Yellow Arrow->Male copper coupler (e-gun is rigidly glued to this portion); Red Arrow->Plasma generator unit; Green Arrow->1 of 3 threaded rods holding the assembly intact.

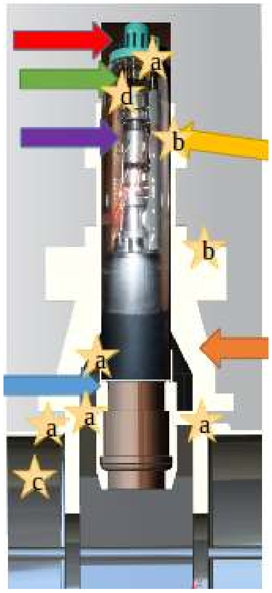

Figure 3: Electron-gun cross-section

Figure 3 is a detailed view of the electron gun component. The possible safety breach risk points for electron gun assembly are: (a) PLA and quartz cracking points, EIH; (b) Current supply for the magnetic coil control; (c) High voltage area for charge accumulation; (d) Thermo-ionic e- generation, hot area. For the electron gun assembly the components are: Blue Arrow->Male Copper Coupler (e-gun is rigidly glued to this portion); Orange Arrow->Precision magnetic coil for electron trajectory control; Yellow Arrow->Hysteresis magnetic loop for stray electron control; Red Arrow-> Connection point of the electron generation and static control; Green Arrow ->Thermo-ionic electron generation; Violet Arrow >High-Voltage electron trajectory selector .

Figure 4 is a close-up view of the plasma generator. The plasma generator components are presented in figure 4 by the color-coded arrows. Safety breach risk points of the plasma generator are indicated by stars: (a) PLA and quartz cracking points, EIH; (b) Current supply for the magnetic and theta coil control; (c) Laser beam input area (plasma laser coupling); (d) Plasma discharge area, hot zone; (e) Puff pre-mixing zone (possible cause for instabilities). The overall design of EPGS is therefore summarized in the pictures above, though these designs act more as sketches to get the idea of what a potential, final design may look like and what safety-related issues need to be considered.

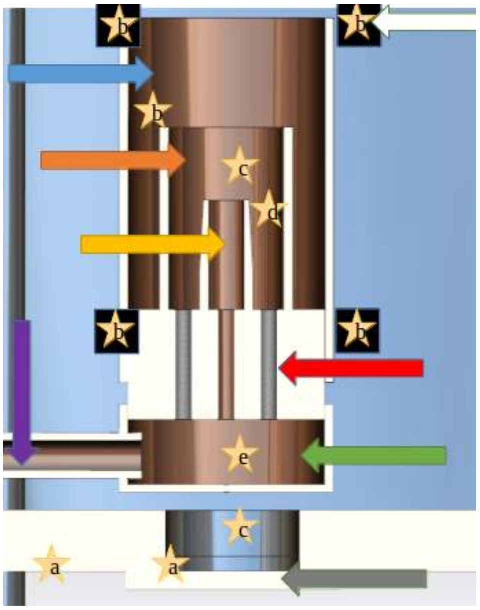

Figure 4: Potential-plasma generator cross-section. Components Blue Arrow->Theta-pinch flat coil; Orange Arrow->Large Electrode (Alternate Polarities Possible); Yellow Arrow->Small Electrode (Alternate Polarities Possible); Red Arrow->Isolator Puff Control mount for the conductors; Green Arrow-> Working gas supply pre-puff chamber; Violet Arrow->Working gas supply tube; Grey Arrow->Quartz window for laser beam source; White Arrow->Additional coils for plasma circulation control.

2 Brief Outline of PSM

It needs to be stated that the process safety needs to be implemented in the very early stages of the engineering design. The PSM is achieved by outlining clear instructions for operation and maintenance in order to verify the asset integrity and to prevent any major incidents. Leadership and culture are the center of safety management for the reason that active leadership for the safe practices exemplifies the importance of maintaining a safe environment [17]. Upon establishing the safety leadership, the appropriate information needs to be provided for the engaged parties to have competence in PSM. The demonstration of full competence in the process involvement to enables the involved parties to take timely actions in order to prevent hazardous events. Hence, the preventive actions depend on the risk awareness, which is essential for PSM implementation, since, unaware persons may lead to the corruption of the PSM systems unknowingly.

The common aspects of PSM are as follows: 1.Hazard Identification (noting the possible risks of equipment operation); 2. Equipment Integrity (ensuring that there are no broken components in the system); 3. Chemical Hazard Data (providing the documentation and labeling for the chemicals involved); 4. Inspections and Audits (regular checking of the system performance); 5. Documentation Systems (a maintained and regular track record of the system operation with specified times and operation procedures).

There are four fundamental pillars of PSM. Pillar 1: Commit to Process Safety: a. Process Safety Culture; b. Accountability: Objectives and Goals; c. Compliance with standards, codes, and regulations; d. Active involvements of engaged parties; e. Stakeholder Outreach. Pillar 2: Understand Hazards and Risks: a. Process Safety Information and Documentation; b. Hazard Identification; c. Risk Analysis. Pillar 3: Manage Risk: a. Operating Procedures; b. Safe Work Practices; c. Design quality assurance; d. Safe design implementation at the design stage of the processes; e. Asset Integrity and Reliability; f. Maintenance; g. Contractor Management; h. Training and Performance Assurance; j. Management of Change; k. Pre-Start-up Safety Review; l. Conduct of Operations; m. Emergency Planning and Response. Pillar 4: Learn from Experience: a. Incident Investigation; b. Measuring and Metrics; c. Periodic Safety Audits; d. Management Review and Enhancement of Process Safety; e. Knowledge; f. Trade Secrets. Having the knowledge of PSM is crucial when approaching a novel design, and albeit its evident and straightforward structure it is important to follow it thoroughly.

2.1 Outline of IEC 61508

The knowledge of PSM makes it obvious that zero risk is impossible even when all the safety precautions are in place. The safety must be implemented from the very start of the design process because it helps the designer to plan for the end-user safety and to minimize the non-tolerable risks. IEC 61508 is intended for safety engineering and management from the very conception and to the decommission by considering the aspects of the system itself (i.e. the human factors and the safety cases/proofs are not part of the standard)[18]. IEC 61508 helps in implementing the safe design and it is composed of 7 sequential and integrated parts: 1. Development of the Overall Safety Requirements (General); 2. Realization phase for E/E/PES safety-related systems requirements; 3. Realization phase for safety-related software requirements; 4. Definitions and abbreviations; 5. Examples of methods for the determination of safety integrity levels (SILS); 6. Guidelines on the application of Parts 2 and 3; 7. Overview of techniques and measures.

Parts 1 through 3 are critical for the safety design of new E/E/PES and EUCs. Part 1 (General Requirements) defines the activities to be carried out at each stage of the overall safety lifecycle, as well as the requirements for documentation, conformance to the standard, management and safety assessment. Part 2 (Requirements for (E/E/PES) Safety-Related Systems) and Part 3 (Software Requirements) interpret the general requirements of Part 1 in the context of hardware and software respectively. Parts 4 through 7 are guidelines and examples for development and are primarily suited for evaluating the potential designs [19]. It is important to note that IEC 61508 is not just a technical guideline, but a fully implementable version of PSM intended for the E/E/PES and corresponding EUCs. The risk reduction is achieved via the "Safety Function", which are based on the understanding of the risks associated with the system and understood through the implementation of IEC 61508 [20]. In order to develop the safety functions the following steps need to be taken: 1. Identify and analyze the risks; 2. Determine the tolerability of each risk; 3. Determine the risk reduction necessary for each intolerable risk; 4. Specify the safety requirements for each risk reduction, including their SILs; 5. Design safety functions to meet the safety requirements; 6. Implement the safety functions; 7. Validate the safety functions.

According to IEC 61508, the purpose of the overall safety life-cycle is to force safety to be addressed independently of functional issues, thus overcoming the assumption that functional reliability will automatically produce safety. Phases 1 and 2 indicate the need to consider the safety implications of the EUC and its control system, at the system level, when first they are conceived. In Phase 3, the risks are identified, analyzed, and assessed against tolerability criteria. In Phase 4, safety requirements for risk-reduction measures are specified. In Phase 5 these are translated into the design of safety functions, which are implemented in safety-related systems, depending on the selected manner of implementation. Phases 6, 7, and 8 provide the overall planning of Operation and Maintenance, Safety Validation and Installation and Commissioning, respectively. Phases 9, 10, and 11 need to showcase the realization of Safety Related E/E/PES, Other technology safety related systems, and the external risk reduction facilities, respectively. In Phases 12, 13, and 14 outline the process of carrying out the functions of installation and commissioning, safety validation, and operation and maintenance, to be on the overall systems, regardless of the technologies of the safety-related systems. Phases 15 and 16 cover later modification and retrofit of the system and decommissioning, respectively. Given that EPGS will be primarily based off the existing technologies it will be evaluated on the principles of the components. The installation of EPGS is similar to the pressure vessel and has the perceived hazards of implosion, electric shock, EM radiation, X-ray radiation, gas dissipation, explosion, heat, audible noise, and laser light.

2.2 Target Safety System Design

To manage the hazards and to maintain the equipment integrity the safety system has to take care of the possible risks of EPGS. Certain risks can only be reduced by considering the specific design features, while other risks can be prevented by placing warning systems. Since most of the hazards/risks have been identified in the EPGS Design Overview section, it is worthwhile to focus on them as well as the electronic portion of the relevant components. The identified risks and the possible alleviation techniques are as follows: 1. Hot area needs to be cooled and be ventilated to prevent hot-spots, proper labeling; 2. HV area in case it is non-isolatable then it needs to be shielded and labeled; 3. Magnetic field interference proper shielding from outside is the best option; 4. View-port dislodging/cracking, possible leakage area, explosion/implosion hazard can only be prevented by employment of quality seals and flanges; 5. Chamber strain is eased by the means of structural confinement (threaded support rods); 6. Charge accumulation and X-ray areas need to have shielding and labeling; 7. Plasma gas puff instabilities, irregular generation, mismatched timing of plasma discharge/gas release can prevented only by the proper selection of quality components and good control systems; 8. Laser beam input area (plasma laser coupling) has to be labeled and handled with care like the rest of the devices associated with EPGS;

The above techniques are the passive methods for assuring the safe operation of EPGS. It should be evident that the use of active components would add an unnecessary layer of risk, since the active components would require a source of energy that can fail and, consequentially compromise the whole system.

3 EPGS Inputs and Outputs

It is necessary to consider the key inputs and outputs of EPGS in order to understand the safety precautions that may have to be taken when operating.

The key input parameters into EPGS include: 1.Electricity (110 V, 5 A for the electron guns and 230V, 50 A for the plasma generators, also auxiliary power needs to be provided to lasers, vacuum pump, control systems, and diagnostics); 2. Working gases such as Helium or Argon are preferable, since, the use of gases like hydrogen and oxygen has a higher risk of explosion; 3. Laser light may be introduced into the plasma to yield the wake-field acceleration effects as well as for the diagnostic purposes [21]; 4. Accelerated electrons will provide a unique approach to controlling the plasma instabilities in the plasma [22]; 5. RF signals and RF heating are utilized for energizing the plasma as well as the diagnostics purposes;

The key outputs of EPGS are as follows: 1. Diagnostic outputs such as the plasma temperature, pressure, polarization, signal absorptivity, propagation velocity, as well as the auxiliary data like the vacuum pressure, the puff feed rate, and the x-ray count (for safe operation the sensor will detect when to shut the system down); 2. EM radiation may be produced and create some interference; 3. X-rays are possible, although minute, their alleviation is preferable for the lab operation; 4. Heat dissipation will occur at certain points on the equipment and it is best to keep track of the high heat areas and cool them; 5. Auxiliary charge accumulation may occur, so the system needs to be grounded after the conduction of each experiment in order to prevent charge interferences;

The key controls of EPGS in its current design stage are the availability of resources and proper engineering, whereas, the key mechanism are the vacuum pump and the plasma generators. The IDEF0 makes a fairly inclusive description of the overall composition of EPGS in its safety oriented design structure.

4 Measurement Techniques

Since the vast majority of outputs from EPGS is the measurements of the plasma parameters it is necessary provide an insight on what they are. The parameters to be measured include plasma temperature, pressure, polarization, signal absorptivity, propagation velocity, the vacuum pressure, the puff feed rate, and the x-ray count. The measurement of the plasma temperature, pressure, and polarization will be conducted by the use of the CCD sensors, polarization filters, and the diode IR lasers. The signal absorptivity will be conducted by placing a small antenna array to supply the signals at one corner of the setup and receive them at the other end (on either side of the two opposing chambers). The propagation velocity can be estimated using high speed cameras in combination with the signal absorptivity antennas and the CCD sensors. The vacuum pressure will be read using the pressure gauge for achieving medium vacuum, as well as a Penning cell, in order to measure the high vacuum. The puff feed rate will be determined by the operation of the precision solenoid valves, based on the opening and closing times. Lastly, the x-ray count will be determined using miniature isolated PV cells connected to signal amplification circuit. In order to monitor the plasma behavior these devices will mostly act as active components, and hence relying on these components for the safety maintenance will not be essential but will greatly assist in making deductions about the state of the experimental setup.

5 Fault Propagation Scenarios

The most likely fault propagation scenarios for EPGS can be currently be identified as follows: 1. Cracked port-hole window –> Breach of vacuum system –> Contamination of the chamber systems –> Oxidation –> Malfunctioning of plasma generator and thermal ionization components –> Possible overheating and explosion; 2. Magnetic field interference from outside sources –> Electron path interference –> Plasma instabilities –> Damage to electronic components and diagnostic systems; 3. Charge accumulation –> Plasma gas puff instabilities –> Irregular generation –> Mismatched timing of plasma discharge/gas release –> Damage to electronic components and diagnostic systems

Other fault propagation scenarios may have similar conditions as outlined in the work on risk assessment of high density plasma experimentation [23].

5. 1. Safety Measurement for EPGS Design

The measurements of safety in EPGS are not the same as the measurement techniques, as they relate more to the observation of plasma. Nonetheless, the measurement of plasma properties and the measurement of the safety of the system are not separable concepts and act in collaboration during the EPGS operation. The key parameters for the safety measurement are the chamber pressure, temperature, the strain on the chamber walls, and the x-rays generated in the process of plasma activity. The pressure inside the chamber determines whether the chamber will collapse, or explode based on the amount of available gas, measured via the pressure gauge and a Penning cell. The temperature of the chamber outside surface determines the amount of heat released in the process of plasma creation and will be measured via a thermo-couple. The heat generated can be dangerous for operation of auxiliary systems and it may be a cause the un-necessary strain due to the metal expansion. In the lieu of the pressure and temperature measurement, the strain at the chamber walls depends on the strain of the chamber walls it can be estimated for how long can the chamber be utilized; after a certain number of operational runs the fatigue may cause the wear to the chamber. The chamber wall strain is simply measured via the strain gauges. Lastly, the x-rays generated are measured via a photo-voltaic detector system. The amount of x-rays generated can be dangerous if it is above the medical maximum, so only a certain amount of runs can be performed at a time depending on the amount of x-rays produced.

5. 2. Protection and Safety Barriers for EPGS

The protection and safety barriers guard the user from the possible mishaps that may occur as a result of lack of awareness either when around the device or during its use. First and foremost, the frame structure of EPGS has to be solid enough to maintain the mechanical integrity of the structure during its various stages of operation. In addition to the safety measures there is a need to make simple and obvious indicators that light up when the chamber passes through the specific stages of operation: Green: vacuum pump activated for chamber cleansing; Yellow: the auxiliary systems such as the magnetic field generators, the electrostatic systems , the lasers, and the diagnostics are on stand-by; Blue: the plasma puff is released, the laser beam is on, the electrons are projected onto the plasma collision region, and the diagnostic systems are fully engaged; Red: the system is idle and there is an internal error due to the breached safety measurement settings; operation is unsafe either for the experiment or the staff; and, the system is open for maintenance without procedure of proper shut-down.

There needs to be a physical barrier between the people in the lab and the experiment, possibly, a 1/4 inch plexi-glass barrier with a secure lock, to avoid any possible malpractice. The computer connected to the experiment needs to have an access code available only to the staff specifically devoted to the operation of EPGS. Following through with implementation of these barriers and encouraging the safety leadership is practice that will reduce the chances of risk and prolong the operational usefulness of EPGS.

5. 3. Deterministic Method for RTSV

The deterministic algorithm for the real time safety verification is based on the safety measurement, barriers, and the operational performance of EPGS. The algorithm is broken down into the three stages, corresponding to the specific stages of operation.

Green Stage: 1. Activate system and control circuits; 2. Activate the Vacuum Pump; 3. Measure Pressure of Vacuum and the strain of the chamber walls; 4. Does the chamber wall strain exceed the maximum? (if Yes: Abort); 5. Does Vacuum meet the pressure requirements? (If No: Redo 3).

Yellow Stage: 1. Activate the diagnostics check protocol; 2. Measure the parameters of the chamber at inactive conditions and compare to the known values; 3. Are all systems functional? (If No: Abort); 4. Activate electron projection system to the idle setting; 5. Warm up the laser to be in stand-by mode; 6. Activate the magnetic systems for the plasma generator; 7. Measure magnetic field strength; 8. Does magnetic field strength meet the experimental requirements? (If No: Abort); 9. Activate the diagnostic systems to full alert; experiment imminent; 10. Pre-charge the gas puff chamber by shutting off the chamber valve and activating the gas inlet valve; 11. Shut off the gas valve.

Blue Stage: 1. Prepare the plasma generation circuit for full engagement; 2. Plasma generation and puff release is simultaneous; the chamber puff valves are activated on opposing ends of the chamber and the gas is energized moments after the puff release; 3. Generated plasma may either be a spheroid or an arc spanning the length of the chamber; 4. The passive antenna array measures the RF of the plasma; Plasma is un-interrupted; 5. Are plasma parameters within the expected operation range? (If No: Abort); 6. Plasma collision imminent, engage the electron projection systems on the plasma; 7. Measure the X-ray flux; 8. Is the X-ray flux within a safe operational range (i.e. below the medical maximum)? (If No: Abort); 9. Visual acquisition diagnostics are fully engaged; 10. Optional: Fully engage the laser system for laser plasma interaction effects; 11. Optional: Activate the magnetic systems for plasma control; 12. Plasma collision occurs: (a) Measure plasma frequency, magnetic field, and absorptivity; (b) Measure the chamber wall temperature using the thermocouples; (c) Measure the laser light scattering and polarization from the plasma collision; 13. Derive the plasma properties from the gathered data and prepare for the next experiment.

Currently the main objective is to work with the previously defined parameters and use them in order to define the safety measurement, to make deterministic algorithms for RTSV, and to define the protection and safety barriers for EPGS. The creation of the probabilistic algorithm for plasma instabilities is only achievable through the experimentation, and, therefore, the deterministic algorithm takes precedence.

6. Design of the Target Real Time Safety System

Unlike a vast majority of the safety designs implemented for preventing disasters, as in case of dams, nuclear reactors, and the grid systems, the EPGS is not subjected to harsh environmental conditions that can occur spontaneously and lead to a disaster. The nature of EPGS is to be an experimental unit for observing the plasma behavior under controlled conditions. In order to maintain the controlled conditions, however, a high degree of prudence needs to be maintained in order to have quality data from experimentation. If one of the system components is not able to function properly then the system has to shut-down and re-calibrated before further operation. The implementation of various operational conditions on plasma can lead to certain plasma instabilities, if the experiment is intended for such a purpose, and the system on its own must not fail both structurally and performance-wise.

The Target Real Time Safety System (TRTSS) for EPGS has eleven (11) key systems, with four of the systems having unit clones, and each one of these systems have corresponding capacities for failure: Chamber Structure System: Quartz Mirror Cracking, Steel Chamber Failure, Possible Leakage, Explosion/Implosion Hazard (EIH); Vacuum Pump System: Remote Relay Activation Failure, Valve Failure, Rotary Vane Pump Failure; Gas Puff System (2 units): Premature Release, Clogging (Valve Failures), Gas Leakage, EIH; Plasma Generation System (2 units): Current Leakage, Conductor Abrasion, Premature Arcing, Magnetic Hysteresis; Magnetic Control System (2 units): Conductor Failure, Magnetic Field Hysteresis, External Magnetic Interference, Current Mismatch; Electron Projection System (3 units): Projection Distortion, Chamber Cracking, Thermoelectric Wire Failure, Over-Voltage Ringing Hazard; Laser System: Cooling Failure, Laser Tube Degassing, Electronic

System Malfunction RF Heating System: Self-Interference, Reverse feedback failure, Static Interference; X-Ray Detection System: Random Gamma Detection, Irreversible Sensor Failure; Diagnostic System: Chamber Thermocouple Failure, Diagnostics Optics Misalignment, Pressure Gauge Failure, Magnetic Sensor Malfunction, EM interference; Camera System: CCD Failure.

At any one of the above systems, and their clones, the occurrence of any one of the listed failures is a good indication that the experiment needs to be either halted or the system check has to be performed to track down the particular location of the failure. If any one of the failures is not detected, after the rigorous system checking prior to the experiment, then the experiment can be launched with confidence that the experiment data is clear of possible interference due to the structural and/or performance reasons. Each system has to be checked for the corresponding faults from the respective failure modes and that can only be made by having the dynamic monitoring system that can observe the failure modes and simply shut down the system if the calibrations are not performed. In essence the TRTSS for EPGS is a shut-down system that will not allow for the experiment to run unless the failure modes are removed. The reason for this simple, yet effective strategy, has to do with the value of the clear and precise data from the experiments conducted in EPGS [24]. If this strategy is ignored then the purpose of EPGS is null.

6.1. TRTSS Simulation

The EPGS TRTSS is simulated using Simulink modeler. The system’s respective capacities for failure are mapped to the components of the system. The failures are simulated using the uniform random generators operating in the range between 0 and 1, with 1 representing 100% failure. The assumption that the failure occurrence is random is far-fetched for most of the systems implemented in EPGS, however, the risk of having incorrect data as a result of any of the failures will undermine the purpose of the experiments that need to be conducted using EPGS. In order to account for the various failures due the extensive periods of use time the best suited modifier for the random number generator is the sample time setting, which, at best, can accommodate the different periods of wear to a small extent. For the sake of the simulation purposes the sample time settings on the failure mode generators have been set to 0.1 seconds.

The fault propagation scenario for EPGS that will be modeled using Simulink is the following:

Cracked port-hole window –> Breach of vacuum system –> Contamination of the chamber systems –> Oxidation –> Malfunctioning of plasma generator and thermal ionization components –> Possible overheating and explosion

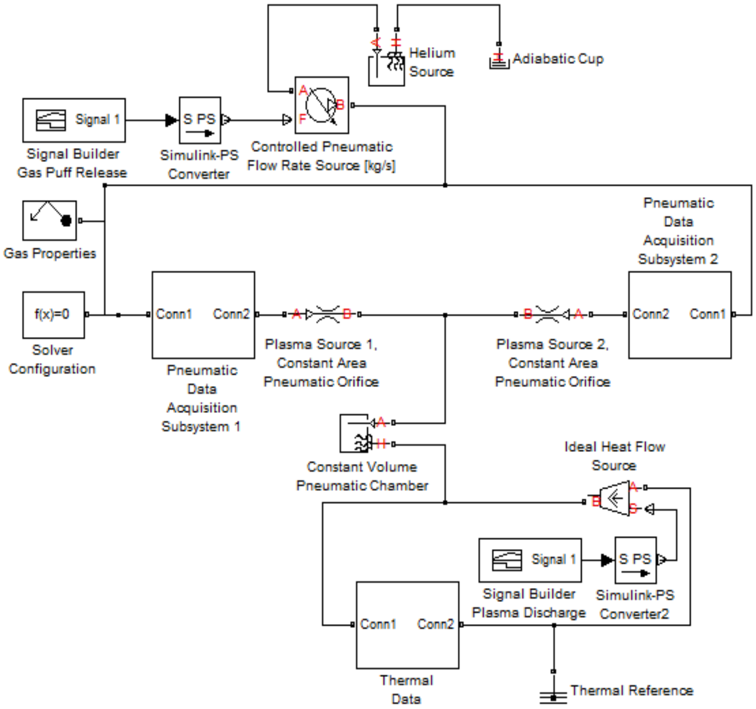

Figure 5: Ideal Case of the EPGS operation without the violation of the system integrity via the cracks.

Figure 7 shows the Simulink model of EPGS at ideal conditions. The other scenarios, listed in section 9, require the MHD modelling of plasma within the plasma chamber and will be made in the course of future work using ElmerFEM. The following figures show the Simulink model of EPGS subcomponent blocks such as the pneumatic and thermal data acquisition subsystems and the fault occurrence subsystem.

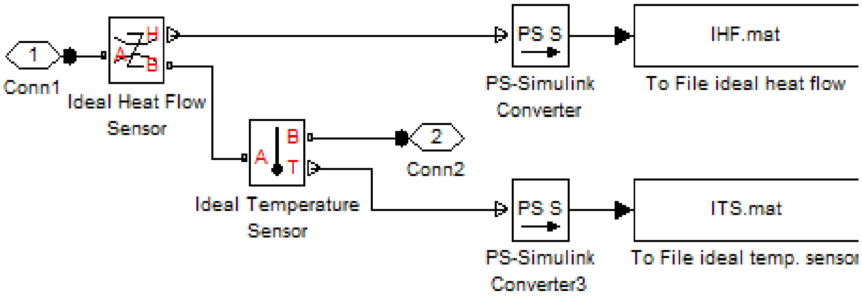

Figure 6: Thermal Data Acquisition Subsystem.

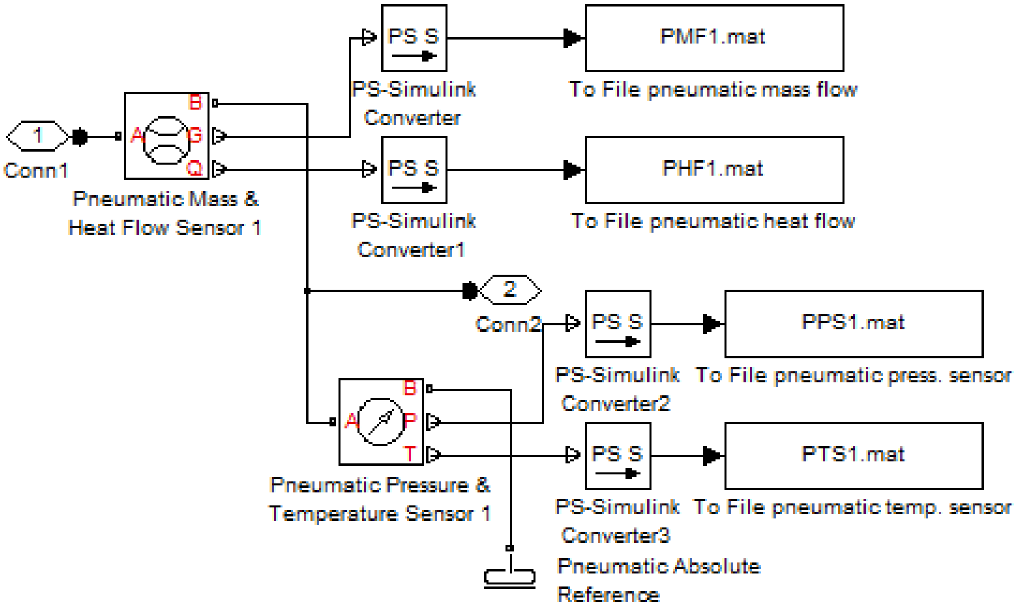

Figure 7: Pneumatic Data Acquisition Subsystem.

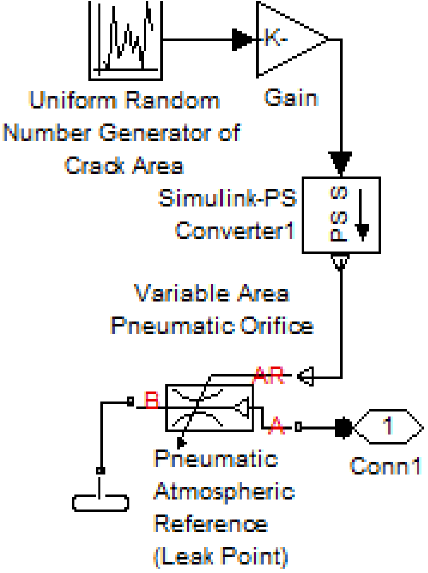

Figure 8: Failure due to cracking of the chamber/loss of integrity.

The simulations will be made using Helium as the working gas. The reason for using Helium is that it is a non-explosive element that is the closest in its properties to hydrogen; Helium would be preferred to be used in the actual experiment during its operation to reduce any risks, though Argon is a much more economic option that will be most likely utilized for testing and calibration. The amount of helium injected will be only between 1 μ gram/ms and 1 gram/ms. For the simulation purposes it is assumed that 1 gram/ms is released from both ends of the plasma generator to have maximum load conditions. The net amount of heat added into the system is assumed to be at the maximum plasma generation load of 12.05 kW (110 V, 5 A for the electron guns and 230V, 50 A for the plasma generators). The duration of the experiment is only 4 seconds. The cracks are modeled as a variable area pneumatic orifice with a discharge coefficient of 0.9 and a minimum area of 1e-12 and a maximum area of 1e-6. The two plasma source discharge orifices are 5e-6 with the discharge coefficient of 0.5. The primary method of heat transfer is the radiation heat transfer, with the area exposed being 0.3 and the radiation heat transfer coefficient of 4e-8, for vacuum conditions.

The first simulation is conducted under the assumption that no cracks occur at all. In this case the temperature of the chamber does not increase and the discharge elements reach a maximum temperature of roughly 842 K, which is hardly a temperature that can cause the meltdown of the plasma generators likely to be made of tungsten (with the melting temperature around 3695 K, a metallurgical safety limit for the EPGS' plasma generators). Furthermore, the ideal conditions of the EPGS simulation support the main concept of safety verification prior to experimentation in order to acquire legitimate data. The pressure within the chamber during the ideal case is shown in the figure below. At 2 seconds the gas puff is released into the chamber, indicated by the spike in pressure, and raises the overall pressure in the chamber as a consequence.

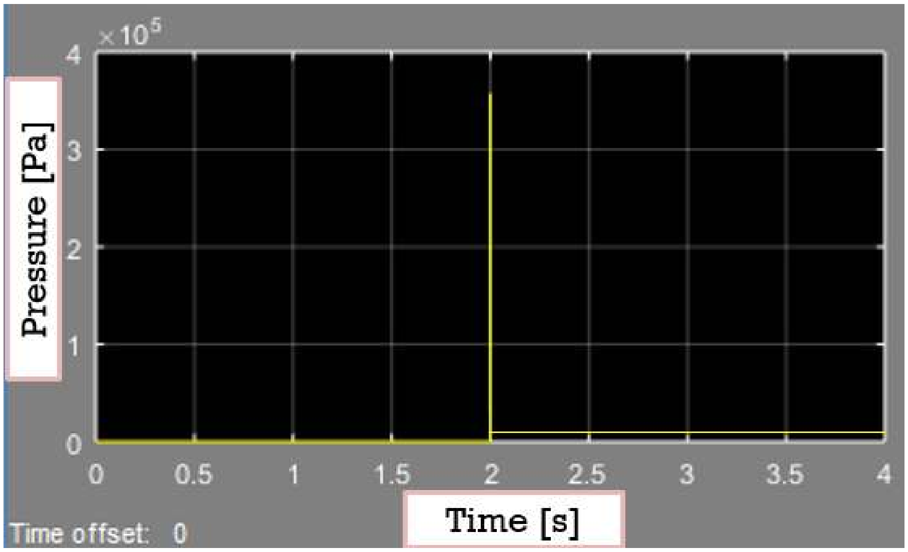

Figure 9: Pressure (y-axis) inside EPGS during ideal plasma generation stage over time (x-axis)

The next simulation assumes that the cracks happen at random throughout the structure of EPGS and at random intervals. The creation of this simulation is made by adding a subcomponent system that creates an orifice opening at random prior to and during the plasma discharge. The outcome is quite evident by the fact that the chamber gradually loses vacuum and the pressure within the chamber rises prior to the plasma puff release. This in effect leads to the contamination of the chamber by the atmospheric particles and may result in irregular formation of the plasma discharges and the oxidation of the internal components. Furthermore, the main mechanism driving the acceleration of the plasma puffs is the high vacuum, meaning that due to the pressure rise from cracks, the effectiveness of the puffs will be diminished. In the regards to the temperature of the plasma generators, it drops to around 500 K as a result of the cracks. The temperature drop is an indicator that the number of particles intended for the ionization has increased and the net effect of the uniform plasma generation is made obsolete. It’s worthwhile noting that while the extremely high temperatures are not good for the integrity of the plasma generators, the low temperatures during the plasma generation are also a bad sign of the experiment malfunction. The last figure shows the pressure inside the EPGS chamber when cracks randomly occur throughout the experiment, note the rising slope. From the start there is a continuous leakage and at 2 seconds the gas puff, the spike in pressure, makes some contribution to the rising pressure, although at this point the contaminants will affect the plasma generation.

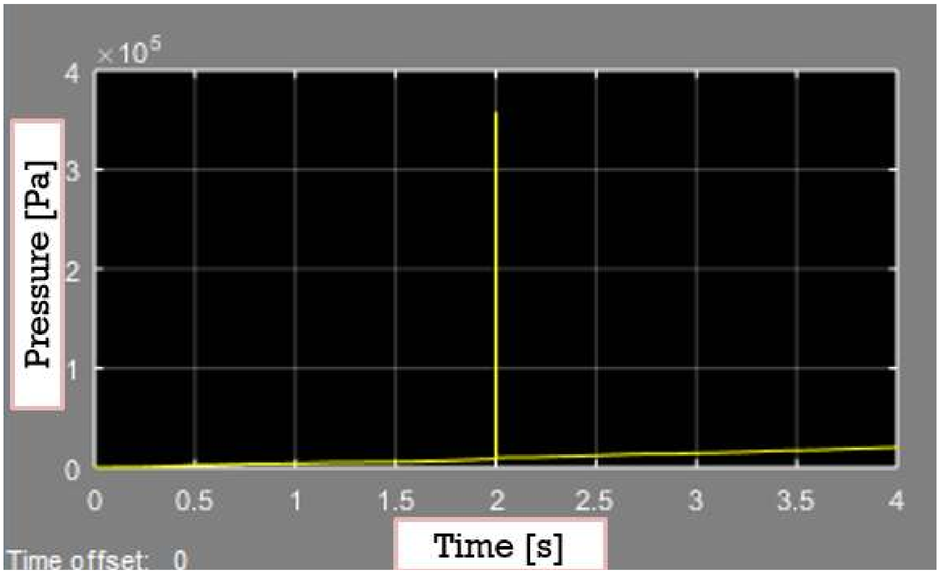

Figure 10: Pressure (y-axis) inside EPGS during faulty plasma generation stage due to cracks over time (x-axis).

The conglomerate representation of the system failures presented is not a fair representation of the system in operation. In fact, making the decision of running the plasma simulation on statistics rather than the experiments a very risky method, and can lead to very skewed and in-precise data. Meanwhile, assigning risks to plasma phenomena are counter-productive, since the experiments that will be conducted in EPGS will be only made below the maximum rated power of the device in order to have presentable data and clean experimental record, and not to test the extreme performance ranges of the device. The plasma instabilities and interactions will be observed as long as the device operates below the rated levels and it will be possible to deduct the effects of these instabilities by scaling the observations and not the loads on the system itself. Keeping in mind the previous figure for the system failure, for the same run it is best to have the connection to the EPGS subsystems and the critical points of interest and make direct sensor connections to obtain the readings for the system status provide them to the experimenter and not allow for the experiment to run until after the failures are removed.

7. Conclusions

In case of the EPGS there is no current method to reduce the dynamic failures. It is best to keep the experiment error free and prevent the failures before they have a chance of occurring by pre-checking the system operation before each run by having a monitoring system that checks the system status and indicates where a possible failure may occur prior to the experimentation. If any of the experimental scenarios include the unstable behaviors that may occur due to the plasma nature it is best to take the precautions by adjusting the plasma controlling parameters to the safe operation range for sustaining the plasma instabilities but without going beyond the extent of the EPGS operational range. As a final note, TRTSS serves more as the system checker before the conduction of the experiment and it works in line with the deterministic algorithm for the real time safety verification algorithm. This approach is in-line with the philosophy that the best safety strategy is the avoidance of the failure from the start.

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