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Qualitative Reliability Issues For In-Vessel Solid And Liquid Wall Fusion Designs

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ABSTRACT

This paper presents the results of a study of the qualitative aspects of plasma facing component (PFC) reliability for actively cooled solid wall and liquid wall concepts for magnetic fusion reactor vessels. These two designs have been analyzed for component failure modes. The most important results of that study are given here. A brief discussion of reliability growth in design is included to illustrate how solid wall designs have begun as workable designs and have evolved over time to become more optimized designs with better longevity. The increase in tolerable heat fluxes shows the improvement. Liquid walls could also have reliability growth if the designs had similar development efforts.

I. INTRODUCTION

This paper presents an initial study of qualitative reliability aspects for solid wall PFC and liquid wall protection schemes for magnetic fusion reactor vessel protection and heat removal. Reliability issues pervade both design approaches; nearly every design trade-off issue affects reliability or has a reliability influence. Reliability is affected by material choices, mechanical design, fabrication techniques, construction techniques, and operating strategy. Reliability goals influence, or are influenced by, the system operation, maintenance downtime, component replacement frequency, and operational lifetime. Since there has not been an engineering design effort for liquid wall systems, this paper dwells on qualitative reliability aspects. Component reliability is traditionally thought of as a statistical discipline using quantitative values; nonetheless, there are important qualitative aspects of reliability. Qualitative reliability is examining system or component failure modes (the manner in which failures occur).

The solid wall PFC armor tile approach has been under consideration and in use at existing fusion experiments for many years. In the past, individual armor materials (graphite, beryllium, etc.) were used. Now, the fusion program has stopped searching for one material that will meet all first wall and divertor in-vessel needs. Mixed materials and layered materials are under consideration for fusion designs such as the Fusion Ignition Research Experiment (FIRE).

Reasons for exploring the liquid wall concept have been discussed by Abdou[1], Moir[2], and Morley[3]. Abdou has suggested that the liquid wall concept will accommodate high power densities where surface heat fluxes are over 2 MW/m^2, and these systems could also have a high power conversion efficiency of over 40%. Abdou also states that the design should have a high availability, where the mean time between failures (MTBF) is greater than 43 times the mean time to repair (MTTR), or 97.8% availability, which he asserts is needed for an economically attractive power plant. Abdou points out that the liquid wall, being an electrically conducting shell, will improve plasma stability and plasma confinement. The liquid wall is also believed to offer increased disruption survivability, somewhat reduced waste volume, and faster maintenance. Moir stated that the self-renewing thick liquid layer (0.5 m of Flibe or 1.6 m of lithium) allows longer irradiation lifetime of the vacuum chamber, less irradiation of the chamber walls to allow shallow land burial, and if fast moving, the liquid can remove a considerable radiative surface heat flux. Morley discussed the thin liquid film wall for divertors. The benefits were protection of the underlying surface from erosion and blistering, continual replenishment of the liquid surface, large heat removal capability, and reduced heat penetration to the structure. Morley also added these benefits: elimination of the complications of armor tile attachment, the possible reduction of tritium inventory trapped in immobile armor materials, and the possible elimination of beryllium as a plasma facing material.

Solid wall designs offer their own advantages. An important fact to realize is that solid walls have improved their reliability and service life; they are more erosion-resistant and can now tolerate high heat fluxes up to and beyond the conditions envisioned for the International Thermonuclear Experimental Reactor (ITER). These conditions were 0.5 MW/m^2 for the first wall in normal operation (3 MW/m^2 in transients) and 5 MW/m^2 for the divertor in normal operation (up to 20 MW/m^2 in transient conditions).[4] Neutron irradiated carbon fiber composite monoblocks[5] have shown good integrity under electron beam irradiation testing up to 25 MW/m^2. Solid wall systems operating with a high temperature liquid metal coolant can also attain high power conversion efficiency, such as the Advanced Reactor Innovation and Evaluation Study - Advanced Tokamak (ARIES-AT) design.

Solid wall designs have matured to become more reliable to withstand the forces encountered in service, including vibration, electromagnetic-induced forces, thermal stresses, and other plasma-induced forces from normal operation and, more importantly, disruptions. In past decades, solid walls were believed to need frequent changeouts due to wall surface erosion and neutron irradiation, but low activation materials and PFC surface refurbishment via chemical vapor or plasma spray deposition allow longer residence times. The ITER experiment design called for a 6-month divertor replacement every 3.3 calendar years in the basic performance phase, and first wall module maintenance would be infrequent; that is, less frequent and less time consuming than the divertor.[4] Future power plant designs, such as the ARIES-AT study, suggest short outages for wall module replacement, perhaps 4 days/year.[6] A total downtime for ARIES-AT was estimated to be less than 40 days per year, which is greater than 89% plant availability.

The solid wall modules require remote handling for their replacement in maintenance outages. State-of-the-art remote handling technology has grown in the past three decades to meet such challenges of moving 4 ton and larger modules.[7] The Joint European Torus (JET) had a complete divertor replacement in 1998. It was very successful, showing how remote handling equipment can meet maintenance needs.[8] The ARIES-AT design calls for less downtime than JET required. Both liquid and solid wall design approaches would require some level of remote handling technology, and the technology is maturing to meet future needs.

While solid wall designs use passive components (pipes, mechanical mounts, plates, welds, brazes, etc.) with low failure rates, the large population of components presents the possibility of frequent failures. Several fusion programs around the world have been investigating methods to increase the reliability of joints and in-vessel flow paths. Candidate solid first wall and blanket designs have had reliability assessments[9] that show first wall designs achieving 90% availability values, and combined first wall/blanket systems reaching the mid- to high-eighty percent availability range. The ARIES designs show that solid walls with low afterheat materials could reach higher availability values.[6]

Fission and fossil-fueled power plant experiences have shown that there can be a “stair-stepping” availability growth as a plant operates.[10] Similarly, as any first wall/blanket system operates, it is quite possible that a reliability growth campaign would increase the operational availability to such competitive levels. Reliability can improve as the plant staff repairs weaknesses (recognized from operation) in replacement modules or parts prior to their installation in the machine, operates the system in the most beneficial manner (high coolant purity, most benign plasma shut down, strict rates of warm-up and cool-down, etc.), and takes other steps to enhance system availability. It is important to recognize that all power generating stations have gone through a reliability growth period. Current performance of solid walls (or liquid walls) can improve, but the high reliability of matured technologies cannot be immediately reached.

II. CONCEPTUAL DESIGN OVERVIEWS

The solid wall design considered here is the familiar modular design described earlier, using carbon, beryllium, or tungsten armored heat sinks. The coolant channels may be SiC tubes as in the ARIES-AT design. The liquid wall design of most interest here is the gravity and momentum driven flow (GMD) design; it is chosen since it is representative of the design concept. The GMD design is a thick liquid layer (0.5 to 1 m) of lithium, lithium-tin, or molten salt Flibe on a solid wall substrate, flowing at high velocities (10 to 15 m/s) from inlet nozzles at the top of the reactor to collection nozzles at the bottom. The other liquid wall design is the convective liquid flow first wall (CLiFF), where a thin, flowing layer of liquid (i.e., 2 cm) faces the plasma. Behind the substrate wall is a thick layer of liquid for shielding and heat removal.[11]

III. QUALITATIVE RELIABILITY COMPARISON

The comparison was performed by examining what ways the major components in each system could fail, and how those failures might affect the system. A failure modes and effects style of analysis was used, considering the major components to be found in either system.[12] The most important findings of the reliability study are given below, in order of their importance.

A. Coolant pumping

In solid walls, the large, thick in-vessel wall modules protect the vacuum vessel. Even in off-normal heating and cooling conditions, there are no concerns about vessel integrity. Any thermal or radiation damage is expended within these modules. Some solid wall designs use low afterheat materials (SiC afterheat reduces in a few minutes) so that decay heat is small and there is no need for active decay heat removal cooling. If a module were damaged by decay heat, it is designed for replacement. In liquid wall designs, maintaining the liquid wall layer is crucial to protecting the substrate and the vacuum vessel. Providing assured pumping is very important during plasma operation. If the liquid wall surface heat flux is as high as stated (up to 2 MW/m^2) then the vacuum vessel cooling system [e.g., double walled vacuum vessel with annular cooling] probably could not remove enough heat to prevent wall damage if the liquid wall flow was lost in part of the machine. Basically, the Loss of Flow Accident (LOFA) would leave the vessel unprotected. The LOFA could lead to damage of the permanent structure (the substrate plates and possibly the vacuum vessel inner wall) before the plasma could be shut down. For this reason, the liquid wall availability is driven by the coolant pump reliability rather than the in-vessel component reliability. The damage in a liquid wall LOFA would be difficult and potentially costly to repair since vacuum vessels are not currently designed for repairability. Therefore, the liquid wall system pumps must be very high reliability for investment protection. The flow loop might use redundant units (each sized for 100% flow), with independent power sources (non-trivial power requirements for such large pumps) and controls. The pumps would need continuous, redundant monitoring to detect any off-normal trends. The multiple pumps and instrumentation would increase the inspection burden over the solid wall system; fortunately the items to inspect are ex-vessel. A plasma shutdown system that does not generate runaway electrons or lead to very high heat loads would be needed for the liquid wall design to help protect the vessel walls. Pump trips are unlikely events, but the possibility of damage is high; therefore, some form of design precautions must be taken.

B. Vacuum quality

Current machine operations have demonstrated that solid wall systems can maintain reasonable vacuum cleanliness. The wall cooling system is designed to accommodate baking to drive out water vapor and other gases. The tokamak can also perform glow discharge cleaning and other techniques as part of commissioning to begin an operating run. There is erosion and sputtering of PFC surfaces during operation, so low atomic weight materials are used to reduce plasma energy losses. The coolant is contained, so from a purity perspective, the focus is on maintaining cleanliness of heat transfer surfaces, reducing tube plugging from oxide or other material buildup, and keeping pumps and instrumentation clear of foreign material. A standard purification system should suffice for this application, as it has for tokamak experiments and a variety of power plants. Liquid wall designs may also require vacuum vessel cleaning prior to coolant flow, but it is unknown how the electrical insulation coatings would respond to glow discharge cleaning or other in-vessel cleaning techniques. There may be no effect, or perhaps the surface could be slightly damaged. When the coolant does flow, there is a concern about a large-scale vacuum distillation effect in lithium releasing impurities into the plasma. Vacuum distillation is a laboratory process sometimes used for purifying liquid metals. The vacuum level in the laboratory processes is in the 0.1 to 1 Pa range.[12] Therefore, since the vacuum vessel base pressure would likely be in the 1E-05 Pa range, it is reasonable to expect some level of impurity liberation as the liquid metal coolant flows through the vacuum vessel. Therefore, to operate the liquid wall machine and achieve high availability, the liquid metal must be very pure. A robust coolant purification system is needed to treat a large percentage of the coolant as it flows around the system. Any equipment failures in the coolant purification system would likely lead to increased impurities in the vacuum chamber; enough degradation would lead to a forced outage to re-establish vacuum purity. Adding additional purification cold traps to the piping system increases the amount of equipment for inspections, maintenance, and adds more pressure boundary components. The liquid wall will also have some coolant evaporation, termed lithium frost,[13] as well as sputtering. Operating the liquid lithium in fusion conditions (such as at the Current Drive Experiment-Upgrade at PPPL) is an important step to quantify the coolant purity issue, and verify that the wall can operate and be available for plasma operation.

C. Nozzle reliability

An important nozzle reliability issue raised by the liquid metal wall designers is that the nozzles must be "dripless". The only analogy for solid walls would be a pinhole leak that jetted coolant toward the plasma periphery. Nozzle wear is an important issue; if the nozzle mouth area were to increase due to flow-induced erosion from the 10 to 15 m/s flow velocity and the slight expansion expected when the liquid traverses from low pressure flow to vacuum flow, the nozzles might require replacement. There would be downtime for replacement and pre-operational testing of the replacement unit. A related issue is nozzle alignment; nozzles would have to be checked periodically to assure proper wall coverage.

If the flow nozzles in the liquid wall system were required to oscillate for wall coverage, this would mean a moving component in the vacuum vessel. Past types of in-vessel diagnostics (retractable probes, etc.) have shown that moving parts in a vacuum have poor reliability. Lubricating oils typically do not function well in vacuum due to their vapor pressure, so greases have been used for diagnostics and remote handling equipment. The best approach for reliable oscillating nozzles would be units lubricated and driven by the flowing coolant.

D. Maintenance downtime

Another issue with solid versus liquid wall reliability is the downtime for refurbishment and component replacement. During the 1980's, the solid wall components tested in high heat flux electron beam apparatus would fail before completing a test series.[12] There has been a concerted effort to improve the reliability and service life of these mock-ups, including feedback from field experience in operating tokamaks. The actively cooled wall armor modules can now withstand entire test series of repeated high heat flux pulses without degradation or failure. Advances in high temperature materials and in braze joining, together with design simplification, have led to reliability growth for these units. Future designs like ARIES-AT are projecting even simpler designs, so that replacement would be less frequent than in the past, and the downtime would be reduced. In-vessel module inspections may still be needed, and these could increase downtime. Plant availability estimates, for example the ARIES-AT design, have risen to the 80 to 90 percent range.[6]

The liquid wall system design would still require in-vessel inspections for nozzle, vane, and substrate wall integrity, and possibly refurbishment of the electrical insulation coating on the substrate wall. In-vessel instrumentation may require periodic cleaning and calibration. Abdou has suggested that a first wall/blanket availability should be 97.8% or greater for an economically competitive power plant; and that the simple liquid wall designs show promise of meeting such values. For a calendar year, this allows only 8 days of scheduled plus unscheduled first wall/blanket outage. Consider that half the time should be set aside for unscheduled outages. Assuming around-the-clock operation, extensive remote inspection equipment, parallel path inspection of pump internals and the vacuum vessel components, parallel paths with other system inspections, sectorized maintenance, and any other possible time-saving steps, four days is a short time. The inspection outage should fully inspect the vessel interior, verify coating effectiveness, perform operational checks of nozzles, replace any worn nozzles, recondition the vacuum vessel and vacuum system, and flow liquid coolant for pre-operational conditioning. Such effort might be possible to achieve by a large, seasoned plant operations staff having excellent outage planning, good procedures, and a matured plant. Liquid wall designs could have the reliability growth that would allow them to potentially meet this restrictive time interval.

E. LOVAs

This issue is the availability impact from an air ingress event. If the vacuum vessel were to suffer an extremely unlikely breach failure that allowed air into the vessel (i.e., a loss of vacuum accident or LOVA) during plant operation, the solid wall design would react by having a plasma disruption. The PFCs would be hot and would react with the oxygen in air until the walls were cooled. The wall cooling system would be intact unless the plasma disruption damaged some parts of the system. Even with damage and possible air-PFC reactions, the wall modules could be repaired and the surfaces refurbished. In a liquid wall system, the ingress air would be exposed to a very large surface of liquid metal. The coolant could be quickly drained to a holding tank to minimize any chemical reactions with the inrushing air; but some provision for decay heat removal must be in place. The heat release from the chemical reaction with air is very high for some liquid metals, especially lithium. It is possible that the heat released could damage the machine interior (flow vanes, nozzles, substrate wall coatings, and perhaps the substrate wall itself). In addition, there would be some downtime for repairs and for coolant purification. The valves to the coolant holding tank would need to be quite reliable, since an inadvertent drain event would damage the machine.

F. LOCAs

This issue is consideration of extremely unlikely ex-vessel pipe failures. In the solid wall design, an ex-vessel pipe failure (loss of coolant accident or LOCA) without plasma shutdown leads to in-vessel tube overheat and probably burnout. The result is mobilization of both radioactive materials (tritium, activated corrosion products, activated dusts) and hazardous chemical dusts with potential release to the environment. In the solid wall system, the LOCA coolant inventory would be limited to one flow loop. In the liquid wall system, after air pressure equalizes in the vacuum vessel, it may be possible that more coolant from other loops could flow out of the break via gravity unless the design precludes such an event. No matter what the specific design, the coolant would likely have to be drained to the holding tank to minimize chemical reactions with ingress air. In the liquid wall design, accident progression is faster than the solid wall design. The breach allows air directly into the vessel. The releases to the reactor building would be hot coolant, coolant-air combustion products, released tritium from the coolant, and any activated impurities. If the liquid layer thickness is eliminated by the LOCA flow before the plasma can be shut down or disrupts, substrate wall damage would likely occur, giving the same downtimes discussed above.

G. Helium pumping

Another vessel cleanliness issue is vacuum pumping. Typically, liquid helium cryopumps are chosen for magnetic fusion use since they are very clean (no pump oil or lubrication concerns), operate without difficulty in magnetic fields, and have good pumping capacity for most gases. However, these pumps have a very low capacity for pumping helium. In solid wall designs, the excess deuterium and tritium from each gas puff fueling help to entrain helium ashes into the vacuum pumps and cryotrap[14] it in the vacuum pumps. There is a concern that the liquid walls will take up the D and T into solution and these gases would not be available for cryotrapping helium ash. Vaporized lithium may perform the same entrainment function as the D and T. The lithium frost might swamp the cryopump. Testing can determine if frost poses a concern for a liquid wall power plant. If cryopumps are unacceptable, then effects of coolant vapor on other types of vacuum pumps must guide pump selection.

H. Natural circulation

The liquid wall design allows coolant to flow in a vacuum. Natural circulation flow is not possible from the top of the vacuum vessel to the bottom under vacuum conditions regardless of how the ex-vessel portion of the flow loop is designed or configured. Natural circulation has been regarded as a beneficial passive safety feature, and it allows relaxation of reliability requirements on the coolant pumps. The liquid wall design could take advantage of low afterheat materials so that decay heat removal was not needed in the design; the pump system is already given extra requirements for functionality in normal operations. If high afterheat materials were used, then a decay heat removal system would be needed. Perhaps a vacuum vessel annular cooling system could be designed to allow natural circulation decay heat removal.

V. CONCLUSIONS

The main contrast in system design approaches is trading the large solid wall modules with their cooling passages (such as the SiC passages in the ARIES-AT design), headers, and mounts for a simple, open surface. Wall modules are traded for a small number of flow nozzles, flow vanes, and electrically insulated substrate plates. This trade-off initially appears to be very positive since the number of components and their complexity are greatly reduced. However, the in-vessel availability of the liquid wall system is simply shifted from passive component wall modules to the active pump component.

Quantitative reliability comparisons cannot be made until an engineering effort is made to design the ex-vessel system for liquid walls. Qualitatively, the liquid wall design approach would likely use the same types of ex-vessel equipment as solid wall designs using the same coolant. A first approximation of liquid wall availability would be the availability of a single high temperature pump. Prudent ex-vessel system design could potentially result in high system availability values.

Table 1 shows how this initial list of important features compared between designs. The comparison highlights these reliability issues; some can be changed by design. Other issues may be altered by feedback from testing. The liquid wall idea should be investigated for its merits, and for possible use in conjunction with solid walls, as in the Advanced Limiter-divertor Plasma-facing Systems task.[15]

Table 1. Comparison of Features

Feature	Solid wall	Liquid wall
Coolant pumping	+	/
Vacuum quality	+	?
Nozzle reliability	/	?
Maint. downtime	-	+
LOVAs	-	-
LOCAs	-	-
Helium pumping	+	?
Natural circulation	+	-

legend: **+** is good, **/** is neutral, **-** is poor, **?** is unknown

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