IFE Chamber Technology Testing Program In NIF and Chamber Development Test Plan

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ABSTRACT

Issues concerning chamber technology testing program in NIF involoving: criteria for evaluation/prioritization of experiments, engineering scaling requirements for test article design and material selection and R&D plan prior to NIF testing were addressed in this paper. In order to maximize the benefits of testing program in NIF, the testing in NIF should provide the experimental data relevant to DEMO design choice or to DEMO design predictive capability by utilizing engineering scaling test article designs. Test plans were developed for 2 promising chamber design concepts. Early testing in non-fusion/non-ignition prior to testing in ignition facility serves a critical role in chamber R&D test plans in order to reduce the risks and costs of the more complex experiments in NIF.

I. Introduction

One important class of issues concerning a testing program in any given facility is directly related to the development of the test articles. It is generally necessary prior to testing inside the facility that these test articles be developed to the point where there is a high degree of confidence in their design and operation so that no unexpected defects are present which might jeopardize the machine's operation. Another set of issues is associated with the validation of the test plan and testing parameters to ensure that the testing mission can be achieved, and engineering design integration of the test module interface with the test facility systems (such as final optics and reactor chamber in the National Ignition Facility (NIF)). Resolution of testing program issues is required before a decision to move forward with test program implementation can be made.

As ITER serves as a fusion testing facility for magnetic fusion energy (MFE) nuclear technology component testing, so the comprehensive inertial fusion environmental conditions in NIF provide opportunities for inertial fusion energy (IFE) chamber technology testing. The main objective of testing in ITER is to provide DEMO relevant integrated performance test data in a fusion environment. However, such a goal for chamber technology testing in NIF might not be achievable because its integrated performance is evaluated in an enclosed scaled test article where all of the interrelated factors can only be simulated. In particular, the repetition rate limitation associated with any presently envisioned chamber protection scheme cannot be addressed. Consequently, in order to maximize the benefits of a testing program in NIF, the goals of testing need to be clearly defined. In other words, is testing to provide the experimental data for code benchmarking, or serve as a preliminary basis for design concept evaluation? Such a distinction will have an impact on the experimental test article design.

The objective of this paper is to address issues concerning the chamber technology testing program in NIF. Specifically, issues regarding: (1) criteria for evaluation and prioritization of IFE technology testing in NIF, (2) engineering scaling requirements for test article design and interaction with the NIF machine, and (3) the R&D needs prior to constructing and performing IFE technology experiments on NIF, are addressed. Experiments for the chamber protection schemes now envisioned for testing on NIF will require extensive R&D before a detailed definition of NIF test articles can be accomplished. Since these R&D needs are considered as part of the overall chamber development program, they will be addressed as a part of the chamber development test plans.

II. Criteria for evaluation and prioritization of IFE chamber technology testing in NIF

Diverse experiments for addressing issues concerning IFE chamber protection methods have been proposed for testing in NIF[1]. These include: (1) gas dynamics experiments to determine the efficiency of gas in attenuating soft X-rays and debris, while minimizing shock loading on the first wall and the interference of the gas fill with laser or ion-beam propagation and the use of cryogenic targets, (2) liquid interaction experiments to examine the effects of liquid interactions with neutrons, X-rays and debris on the integrity of the liquid wall protection scheme and (3) hi-rep mini-chamber experiments to provide a relevant simulation of protected-wall IFE chamber clearing with single shot and multi-shot bursts. The proposed experiments span a number of reactor chamber types: gas-filled chamber, thin film wetted wall and thick liquid walls.

A set of criteria for the evaluation and prioritization of these experiments needs to be developed. Such an evaluation scheme should include the following issues: (1) relevancy of test data to evaluation of a DEMO design option, (2) value of test data for the validation of a DEMO design code, (3) maturity of concept/material choice, (4) test section cost, (5) material compatibility with NIF systems, (6) overall risk to NIF operation, (7) residual activation/toxicity and disposal, (8) machine down time required and (9) the ability to be implemented simultaneously with other tests. Certainly, these criteria need to be expanded and defined in a more quantitative way, and doubtless other criteria need to be added, before a useful method of evaluation/prioritization can be established.

An underlying assumption is that the development pathway of IFE technology would involve a DEMO reactor prior to a commercial reactor. DEMO relevancy and engineering scalability must be determined from specific performance parameter requirements of a DEMO chamber component. Such DEMO goals and performance requirements are useful not only in evaluating the experiments, but also in designing the experimental setups. Several techniques have

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been developed to determine DEMO's goals and requirements for fusion energy application. Within these, the "roll-back" technique is currently recommended by the utilities and adopted in the MFE community[2]. This technique, based on the experience in the fission industry with scaling up from pilot plants to demonstration plants and then to commercial units, requires that the technology and/or design changes from a DEMO to a prototype commercial reactor should be small. This technique, then, emphasizes the need to use a power reactor concept in determining the design options adopted and the data-base needed for design of the DEMO plant.

However, it must be recognized that the state of the art for IFE chamber technology is not advanced enough to select a reactor chamber design option, nor is it possible at this time to assure that any of the presently proposed concepts will eventually prove viable. There is a lack of experimental data and of experimental verification of computational predictions. Moreover, no one chamber concept is appropriate for the entire range of yields and repetition rates, or for all drivers. It is therefore difficult to develop a common set of chamber performance parameter requirements.

Recognizing this deficiency, it is judged more beneficial to define a range of DEMO performance parameters, utilizing previous design studies as horizons, similiar to the data-base needed to design DEMO. Under this assumption, an example set of DEMO performance parameter ranges, taken from IFE reactor chamber design studies, is compiled in Table 1 in order to provide some consistent basis for guiding chamber technology testing in NIF.

Returning now to the list of evaluation criteria, we see that they all basically fall into the general categories of benefit, risk, and cost. Obviously a test which is to provide DEMO relevant data should receive a high priority in NIF testing. However, if test information directly relevant to a DEMO design choice cannot be obtained for a given concept, the test which appears to provide experimental data which improves/validates predictive capabilities receives a high priority.

In addition to the use of engineering scalability for measuring a test's benefits, compatibility also plays an important role in determining the priority and feasibility of experiments. The compatibility issues involve whether the introduction of an experiment or experimental medium in NIF would lead to degradation of physics performance (e.g. the gas-fill experiments) or to lifetime reduction of NIF components (e.g. laser optics and/or reactor chamber). For example, lead was used as the working fluid in the Prometheus wetted wall concept. However, the use of this material in NIF might complicate chamber cleaning and maintenance. Thus, the selected fluid material for the film flow experiment should not only achieve the testing goal with prototypical film flow characteristics but also be compatible with the NIF device.

Moreover, an ill-developed experimental setup might cause failures in the NIF chamber, which would then have a significant impact on NIF operation and availability. A mature design that would entail little risk (especially one that could be conducted with other experiments in the same shot), would receive a higher priority. A broader and deeper examination of the complex benefits and risks of IFE chamber technology testing in NIF is needed.

III. Test article design engineering scaling requirements and interaction with NIF machine

As discussed in the previous section, in order to maximize test benefits, the test article design should be based on engineering scaling so that important DEMO relevant phenomena can be reproduced under NIF reduced testing conditions. In this section, as an example, such an engineering scaling law is applied to the film flow experiment proposed to be tested in NIF to determine the material choice and test location. Similar scaling is required for the HYLIFE thick liquid jet concept which has doubtless been addressed by others.

Experiments in NIF were defined [1] to address the following areas concerning film flow wetted-wall protection concepts:

1) Synergistic effects of radiation and impulsive loading on the porous structure–if the wall surface is a liquid, it can ablate and be reestablished without damage. However, the underlying structure is still eventually limited by the pulsed mechanical stresses due to the reaction forces resulting from fast ablation.

2) Hydrodynamic response of liquid metals to fast energy deposition–specifically the disassembly of liquids into droplets in response to instantaneous impulse and to isochoric heating and the reestablishment of the film after the explosion

These experiments require a film to be established on a plate (or a sleeve) which is prototypical of a first wall panel of a film-protected cavity. One of the key nondimensional parameters governing the characteristics of vertical falling film and of liquid droplet size is the surface tension number (N_σ) defined as

$$N_\sigma = \frac{\sigma}{\rho} \left[\frac{2}{\upsilon^4 g}\right]^{1/3}$$

where σ is the surface tension coefficient, υ is the kinematic viscosity and ρ is the liquid density. For the liquid metals, the values of the surface tension number are appreciably higher than those of room temperature water and of machine oil, as shown in Table 2. If the liquid metal is not suitable for NIF, the alternative might be hot water in which the surface tension number approaches that of lead, due primarily to the reduction in viscosity as temperature increases. The use of hot water, however, may not be suitable due to high vapor pressure. For flibe, on the other hand, the surface tension number is very small. Notice that even cool water has a surface tension number ten times higher than that of flibe (66% LiF) at 500 ^{o}C.

The experimental test article can be inserted into the chamber through a manipulator tube or be mounted on a reduced size chamber such as a mini-chamber. However, to be reactor relevant, the experimental test article must be set at a distance from the target where a prototypical reactive impulse on the film and substrate from the vaporized gas can be produced. In Table 3 the calculated impulse is listed as a function of distance between the NIF target and test film for water and lead under a X-ray yield of 0.9 MJ. These calculations suggest that a prototypical impulsive load relevant to Prometheus is achievable if an experimental water film test can be set at about 0.75 m away from the target and at 1 m away for lead film. The calculated results also indicate that vapor will leak out of the end of the manipulator tube if a debris shield was not employed. This vapor will deposit on the surface of optics debris shield and on the chamber walls.

The mini-chamber concept was introduced to serve as a baffle system in which a frost system can trap the debris, ablated material and shrapnel, reducing damage to the NIF final optics. The concept provides a better defined and highly instrumentable geometric configuration that makes cavity gas code benchmarking more straightforward.

If a debris shied can be used through which the X-ray spectrum is transmitted but ablated material cannot escape, it is possible, that the use of the manipulator tube has the possibility of completely sealing off the working liquid from the rest of the test cavity. The entire flow loop can be enclosed with only power and instrumentation leads exiting the test volume. This fact allows the use of more reactor relevant materials in the ablation impulse tests. The mini-chamber, while it might allow a more fully integrated test of cavity gas evaporation/recondensation, does not seem likely to allow multiple tests to be run simultaneously.

IV. Chamber Development Test Plan: R&D needs prior to IFE technology experiments on NIF

Two essential elements shall be simultaneously considered in the chamber development test plan: a chamber driver interface program and a chamber research development program. The chamber-driver interface program addresses issues associated with the compatibilities of the chamber protection scheme with the beam propagation mode. For example, if the ballistic mode is required for heavy-ion beam propagation, then a large area (about ~1 m diam.) openings must be provided through the first wall. This complicates the design of the film flow protection scheme since the interior walls of these beamlines have to be protected. This issue is somewhat relaxed if a self-formed transport channel propagation mode can be used. Experimental data in this area are necessary to determine the physics constraint imposed on the design concept feasibility.

In order to optimally resolve the issues and develop a chamber in a timely matter whose feasibility and attractiveness can be predicted with adequate certainty, the methodology of the test plan developed in the FINESSE study is adopted here for chamber research development[3]. As presently envisioned, an effective chamber research development test plan involves three stages, each requiring planning in different degrees of detail: (1) a non-fusion/non-ignition test bed program, (2) a NIF testing program and (3) an inertial fusion test facility program. As shown in Figure 1, the types of experiments in various stages can be classified, based on the degree to which environmental conditions (e.g. X-ray, debris blast, neutrons) and the physical elements of the chamber are present or simulated, as: basic, separate effects, multiple interaction efects, partially integrated, and integrated tests. The nature of the information sought gradually shifts from fundamental, scientific data to empirical, design related data which will be required to support integrated testing in a fusion environment. However, it should be noted that the engineering feasibility of a chamber technology cannot be validated until a fully integrated, scaled chamber is tested in an inertial fusion test facility. (Here, the engineering feasibility is defined as the demonstration of a prototype system at a level of performance such that the system can be applied to a DEMO reactor without significant technical obstacles.) The tests performed in the non-fusion/non-ignition facilities and in NIF provide experimental data for concept evaluation–both the elimination of undesirable concepts and the addition of new, innovative concepts.

Given our current understanding of the issues for the most promising chamber protection concepts, it is possible to specify in detail the experiments and facilities required for the near term. However, the characteristics of experiments performed beyond the next several years will depend on the results of near term testing and also on future developments in chamber design. For the purpose of planning experiments, we have attempted in this study to select two designs: a thin wetted wall protection concept such as the Prometheus design and a thick liquid jet like HYLIFE II.

A. *Thin film protection (Prometheuss concept)*

A test plan for the thin film protection system, as shown in Figure 2, involves a number of parallel near-term tests in which most separate or multiple issues are investigated in non-fusion test facilities and a fusion test facility where integrated cavity responses are simulated. The issues addressed here include: film flow thickness and drainage, flow around obstructions, film flow injector development, film flow stability and response to impulsive loading. The objectives are to characterize film flow profiles in relevant geometries with and without impulsive loading and develop instrumentation techniques. An evaluation will be conducted prior to testing in NIF to determine the practicality of the concept based on the results of non-fusion experiments. If the concept is indeed promising, a partially integrated testing can then be carried out in NIF to verify design features with the maximum number of environmental conditions possible (as discussed in the previous section). However, fully integrated testing is needed because uncertainties in cavity behavior will not be resolved without combining film thermal hydraulics, vapor dynamics and condensation and transient structural mechanical response.

B. *Thick liquid jet (HYLIFE-II Concept)*

Development issues related to the thick liquid jet concept include: (1) steady vertical jet alignment, (2) oscillating jet feasibility, (3) material compatibility, (4) industrialization of flibe, (6) isochoric heating response and blast venting, and (7) tritium recovery and control. The test sequence shown in Figure 3 structures the experiments according to the test program phases with initial emphasis on understanding the liquid jet behavior, developing the moving component for an oscillating jet and investigating material compatibility in a non-ignition/non-fusion environment. These tests are organized according to their level of integration, from basic properties, to phenomena in separate and multiple effects tests, and to concept verification in an inertial fusion test facility. As the non-fusion/non-ignition tests results become available, a major evaluation can be conducted to determine the feasibility of the concept and to guide future experiments. If the results favor the concept as proposed, further tests can be conducted in NIF to address the disassembly of liquid in response to instantaneous isochoric neutron heating and the dynamics of vapor venting.

C. *Modeling requirements*

The testing program should be accompanied by a strong complementary program of model development in order to understand the test results and to improve predictions of the chamber behavior. This will in turn reduce the number of required future experiments. One of the primary difficulties of the chamber model development lies in a large number of interactive effects in a complex three-dimensional chamber geometry.

Table 4 summarizes the areas in which model development is most needed for the IFE chamber. Although significant code development has been done for radiation heat transport, gas dynamics and isochoric heating, further development on these areas geared toward complex chamber geometries and including nonequilibrium interface transport is needed. Additionally, code modeling of condensation/chamber clearing involving gas venting and interaction of vapor shock with droplet sprays is needed.

Table 4. Example Chamber Technology Model Development Needs

Multi-dimensional radiation heat transport
Interfacial heat and mass transport
Liquid stability and fragmentation
Vapor dynamic venting and condensation

V. Conclusion

In order to maximize the benefits of the testing program in NIF, testing in NIF should provide the experimental data relevant to DEMO design choice or to DEMO design predictive capability by utilizing engineering scaling test article designs. These tests, which provide experimental data relevant to DEMO design choice should receive the highest testing priority. The catch is that it is presently impossible to define a DEMO to a satisfactory degree. It is found that the key requirements for the engineering feasibility of a chamber protection scheme, for instance, must be addressed in an inertial fusion environment prior to DEMO. Test plans have been developed for 2 promising chamber design concepts. Early testing in non-fusion/non-ignition prior to testing in an ignition facility serves a critical role in chamber R&D test plans in order to reduce the risks and costs of the more complex experiments in NIF.

The issues concerning chamber technology testing in NIF which were discussed suggest the need for an IFE Technology Testing Working Group for NIF. Such a group would be able to: define the criteria for evaluation/prioritization of experiments to a workable degree, provide an interface with NIF designers regarding test port requirements, establish important engineering scaling requirements for test article design and material selection and identify necessary R&D before an NIF test article design can be finalized and prepared for testing.

Acknowledgments

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Table 1. Summary of DEMO/Reactor Chamber Performance Parameters Space (Heavy-Ion)

Parameter	Value
Total Target Yield (MJ)	350 - 700
Repetition Rate (Hz)	3.5 - 7
X-Ray Energy (MJ)	70 - 140
Debris Energy (MJ)	35 - 70
X-ray Fluence (J/cm^2)	> 50
Ion Fluence (J/cm^2)	> 20
Peak Pressure (GPa)	>30
Impulsive Pressure (Pa-s)	> 20
Neutron Heating (J/g)	> 100
Cavity E/V (J/cm^3)	> 0.5

Table 2. Surface Tension Number of Liquid Fluid

Liquid	T °C	ρ g/cm3	μ g/cm-s	σ dyn/cm	N_σ
Lead	450	0.4	0.02059	438	21475
Lithium	500	0.484	0.0034	349.0	67900.0
Flibe LiF+BeF$_2$ (66% +34%)	500	1.98	0.15	200	317
Cool water	10	1.0	0.0129	75.0	3140.0
Room temperature water	20	1.0	0.01006	73.4	4280.0
Pressurized hot water	90	0.970	0.0032	61.7	16400.0
Oil, machine light	20	0.903	0.8666	36.475	5.42

(ρ = density, μ= viscosity, σ = surface tension)

Figure 1 Types and Roles of Experiments and Facilities for IFE Chamber Technology Testing
(Near term foucs: IFE chamber technology testing in non-fusion and non-ignition devices)

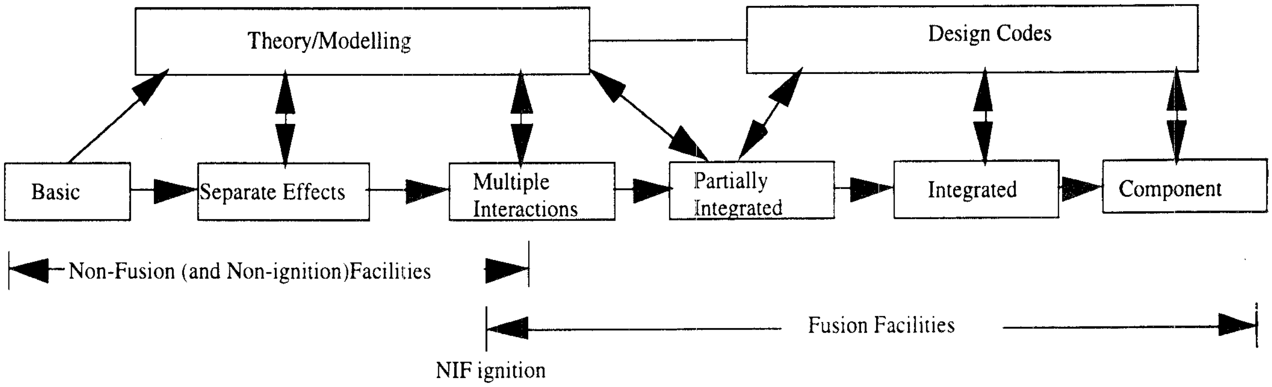

Figure 2 Example Test Sequence for Major Thin Flow Tasks (Prometheus Chamber Concept)

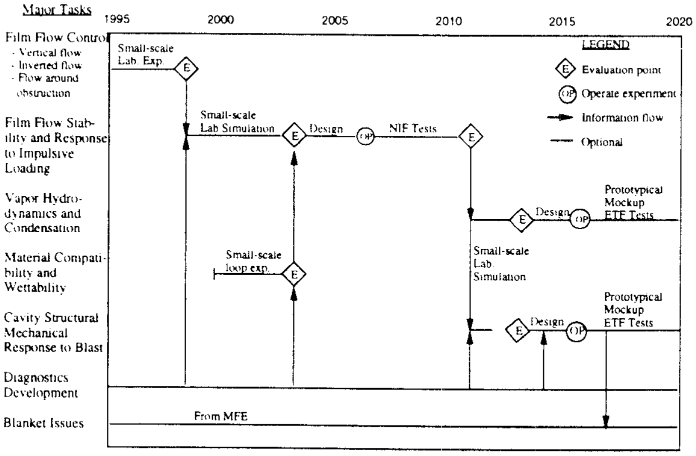

Table 3 Reactive Impulse of Vaporized Vapor for Different Experimental Set-ups (Vapor in chamber = 1 mtorr, NIF X-ray energy 0.9 MJ, Film panel = 0.25 m x 0.25 m)

Parameter	Water		Lead	
Distance (target to test film), m	0.75	1.0	0.75	1.0
Mass vaporized, g	0.356	0.188	1.3	0.845
Reactive impulse, Pa-s	23.	11.75	50.5	28.4
Vapor velocity, m/s	4080	3903	2400	2100

Figure 3 Example Test Sequence for Major Thick Liquid Jet Tasks (i.e. HYLIFE II Chamber)