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This paper provides an overview of one option for LLNL's LIFE power plant design with a focus on the fusion nuclear science and technology aspects. The design is based on 132 MJ yield indirect-drive targets ignited by a diode pumped solid state laser that delivers 2.2 MJ on target at a pulse rate of 8.3 Hz for the first market entry plant (MEP) and 16.7 Hz for subsequent first generation commercial plants (FCP). The chamber first wall is steel which is protected from direct exposure to target x-ray and ion emissions by a Xe fill gas at ~6 μg/cm^3. Reduced activation ferritic martensitic steel is proposed for the MEP while commercial plants will utilize higher strength, more radiation damage tolerate steels such as ODS, which can also operate at higher temperature for improved thermal efficiency and overall plant economics. Liquid Li is the primary coolant and tritium breeding material. An intermediate loop with molten salt as the working fluid transports power to a Rankine steam cycle; the estimated gross electric power conversion efficiency is 45% for the MEP and 47% for the FCP.

Keywords: inertial fusion energy, power plant, chamber, breeder

1. Introduction

In 2009 the US DOE conducted a study of research needs for magnetic fusion energy (MFE), and one of the primary thrust areas was harnessing fusion power [1,2]. This thrust dealt with the science and technology development needs primary related to the topic of fusion nuclear technology including the following areas: closing the fusion fuel cycle; power extraction; material science; safety and environment; and reliability, availability, maintainability, inspectability (RAMI). These topics are also important to the development and commercialization of inertial fusion energy (IFE), and in this paper we review key aspects of LLNL's Laser Inertial Fusion Energy (LIFE) power plant design with a focus on these aspects [3-8]. The international community also continues R&D on IFE. Key efforts include the HiPER program in the EU [9] and the KOYO-F fusion reactor design and laser inertial fusion test (LIFT) experimental reactor study in Japan [10, 11].

Figure 1 is a schematic of the fusion operations building of the LIFE power plant showing the laser system (only the top laser beams are shown), the fusion chamber, and primary-to-intermediate heat exchangers. LIFE makes maximum use of available technologies and industrial capabilities in order to shorten the time to market. As discussed in more detail below, the design achieves a tritium breeding ratio high enough to close the fuel cycle (with significant margin); it uses Li as the primary coolant/tritium breeder and a commercially available power cycle with high efficiency for power extraction and conversion; the fusion chamber for the first plant is fabricated using near-term, reduced activation ferritic martensitic (RAFM) steel; the design includes features to minimize the tritium inventory for improved safety; and both the laser and chamber are comprised of modular components for easy replacement to improve availability

Key parameters of the first LIFE plant, the Market Entry Plant (MEP), and the first generation of commercial plants (FCP) are given in Table 1. Both plants use the same laser and target with 2.2 MJ on target producing a predicted yield of 132 MJ per pulse. The MEP operates at 8.3 Hz giving a fusion power of 1100 MW and thermal power of 1320 MWt; it is intended to be the first fully integrated demonstration of IFE. The FCP operates at twice the pulse repetition rate and power level. The scale up from the MEP is straight forward since the FCP will use the same fuel target design, and the same heat transfer system and power conversion components but with twice the number, e.g., four primary loops instead of two.

Table 1. LIFE plant parameters.

	MEP	**FCP**
Laser energy on target, MJ	2.2	2.2
Target yield, MJ	132	132
Pulse repetition rate, Hz	8.3	16.7
Fusion power, MW	1100	2200
Thermal power, MWt	1320	2640
Chamber material	RAFMS	ODS
First wall radius, m	6.0	6.0
Neutron wall load, MW/m^2	1.8	3.6
Surface heat load, MW/m^2	0.63	1.26
Tritium breeding ratio	1.05	1.05
Primary coolant	Li	Li
Intermediate coolant	Molten salt	Molten salt
Chamber outlet temp., ºC	530	575
Conversion efficiency, %	45	47
Gross power, MWe	595	1217
Laser electrical power input, MWe	124	248
In-plant power load, MWe	34	64
Net electric power, MWe	437	905

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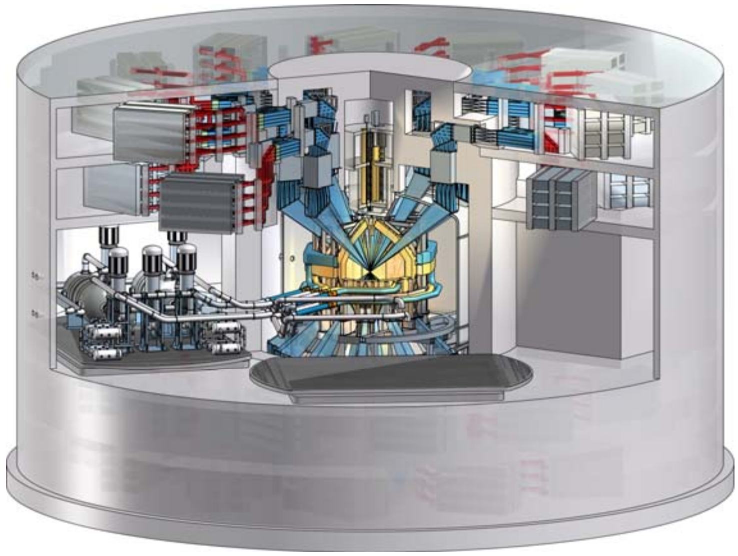

Fig. 1. Schematic of the LIFE Fusion Operations Building showing the modular laser, fusion chamber and primary-to-secondary heat exchangers.

2. Closing the fusion fuel cycle

The tritium breeding material for LIFE is liquid Li, which also serves as the first wall and blanket coolant. Lithium is an attractive choice for LIFE: low density (and thus reduced structure mass required for support), very good tritium breeding performance which eliminates the need for ^{6}Li enrichment and/or neutron multipliers such as Be), and high affinity for tritium, which we view as a positive more than an negative as explained in the following.

2.1 Tritium breeding performance

The tritium breeding ratio (TBR) for LIFE can be as high as ~1.4. In the early stages of fusion power deployment where startup inventory is needed for new plants, it may be desirable to run LIFE in a high TBR mode in order to supply T to new plants. In a more mature fusion power economy, the TBR will be adjusted to a point closer to unity with just enough extra to cover decay and any losses (which will have to be extremely small). Therefore, we have included a liquid Sn region in the LIFE blanket to reduce the TBR and increase the blanket energy gain via neutron multiplication and (n,γ) reactions. With the Sn blanket, the TBR is reduced to 1.05 (to account for uncertainties in the estimates) and the overall energy multiplication for the blanket (i.e., total thermal power to fusion power) is 1.2.

2.2 Tritium recovery

High gain ICF targets are calculated to achieve 20-30% burn of injected DT fuel. The unburned DT is recovered from the chamber gas exhaust, which is mostly Xe that is used to protect the first wall from damage by x-rays and ions emitted by the target burn. A preliminary conceptual design for the recovery system has been completed, but we are currently evaluating potentially more attractive options [12].

An advantage of Li's high affinity for T is that the permeation through coolant pipes and heat exchanger wall is minimized. On the other hand, the high affinity requires a robust system for extracting T from Li. Our baseline approach is the molten salt extraction system developed and demonstrated at bench scale by ANL in the 1970's [13]. The ANL work demonstrated extraction down to 1 wppm, but by adding additional stages we propose operating LIFE at 0.1 wppm. At that level, the entire tritium inventory in the blanket and primary coolant loops is expected to remain <100 g for the FCP.

2.3 Challenges and R&D needs

A key step in closing the fuel cycle is to demonstrate ignition and high gain target performance leading to a high fuel burn fraction. Continued work is needed on cost effective and energy efficient methods for recovering DT from the chamber exhaust. The design of the plant must emphasize the safe use of Li in order to minimize the possibility of a Li spill and fire. Engineering controls are factored into the plant design, but Li metal reactivity and corrosion require further R&D. The ANL work on the molten salt tritium extraction process was an important first step leading researchers to conclude that the process "should be feasible." Tritium recovery, however, is such a critical operational and safety requirement for the plant that significant additional R&D will be needed to prove the applicability of this technology for fusion. A redemonstration and scale-up of the molten salt extraction process will be required. Continued R&D on alternative approaches for T extraction is also necessary.

3. Materials and power extraction

Material choices and power extraction are closely inter-related. About 26% of the fusion energy released on each pulse is in the form of x-rays and energetic ions. To prevent ion damage and overheating, the first wall of the LIFE chamber is protected by a low density (6 μg/cm^3) of Xe gas. The gas is dense enough to absorb all the ions and most of the x-rays but does not significantly degrade the transport of laser energy to the target (~2% loss). The heated gas then re-radiates to the first wall over a much longer time, thus reducing the peak heat flux and pulsed temperature rise at the first wall surface [14]. A typical temperature response is illustrated in Fig. 2. Without the gas fill, the energy pulse width would be on the order ns, and the temperature rise large enough to melt steel.

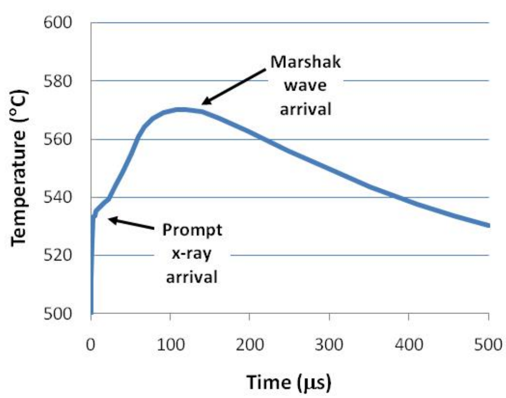

Fig. 2. Typical temperature response of the steel first wall. The fill gas reduces the first wall heating by spreading out the energy pulse from the target.

While shrapnel from targets and mounting materials may be an issue for current ICF experiments [15], we do not expect it to present a threat to the IFE chamber first wall. A multi-axis tracking system provides a go/no-go decision based on the target orientation and position only a couple cm from target chamber center. If the laser is fired, there is a high degree of certainty that the beam energy will enter the hohlraum. Our analyses indicate that the beam energy is sufficient to vaporize the target including the hohlraum, creating atomic-level debris rather than shrapnel even if the target does not ignite. If the beams are not fired the target passes through the chamber and impacts a liquid Pb pool in the sump at the bottom of the chamber.

The Market Entry Plant uses RAFMS [16] with peak blanket outlet of 530 C. Radiation damage lifetime is uncertain, but there is high confidence the material can maintain its functional integrity to at least 10-20 dpa. The MEP operates at 1100 MW of fusion power (1320 MW thermal) and has a 6.0 m radius first wall. Under those conditions the wall accumulates ~10 dpa per full power year. The first wall could operate for 2 to 4 years, depending on the duty factor, before reaching 20 dpa.

A key difference between IFE and MFE is the pulsed nature of IFE which results in much higher peak neutron fluxes for the same integrated fluence [17,18]. Modeling and a limited number of experimental studies have specifically examined pulsed irradiation [19-23]. Whether or not the pulsed source has a significant impact on the resulting cumulative radiation damage and materials properties is still uncertain. Clearly more R&D, including modeling and experiments, is needed.

One possible approach to addressing pulse neutron damage is to use the first high average power fusion device to test materials. We propose using the MEP as an accelerated materials damage testing facility. A reentrant testing assembly would be used to place material sample (for example of advanced ODS steel) at ~3 m from chamber center. At that radius damage rates would be 4x larger and 20 to 40 dpa could be achieved in less than 1 year. The plan is that materials tested in the MEP would then be qualified for use in subsequent commercial plants. These advance materials would not only have longer damage lifetimes (perhaps 150 dpa or more) but could also operate at higher temperatures leading to improvements in the power conversion systems efficiency. In this way, it will be possible to bypass the need for a dedicated materials irradiation facility such as the International Fusion Materials Irradiation Facility (IFMIF).

4. Power Cycle

LIFE uses a supercritical steam cycle for power conversion; this was chosen because it is a proven technology with good overall performance. The cycle incorporates a molten salt intermediate loop to provide additional T barrier to the environment and also to eliminate the possibility of Li/water reactions in the event of a steam generator tube failure. The key power conversion system parameters for the MEP and first commercial plants are given in Table 1. The MEP with a chamber outlet temperature of 530 ºC has a gross conversion efficiency of 45% and net electric power of 437 MWe after accounting for laser power requirements (248MWe) and in-plant power needs (e.g., feedwater pumps, primary and secondary loop pumps and T extraction systems pumps). The FCP uses a more capable ODS steel and the outlet temperature is increased to 575 ºC. The FCP operates at twice thermal power of the MEP; this along with higher outlet temperature yields a net power of 905 MWe.

Over the next decade, efficiency improvements (to 50% or more) may be possible by going to supercritical steam cycles that are currently being developed worldwide, or through the use of advanced gas cycles currently in the R&D phase.

5. RAMI

An important design philosophy for LIFE has been to include modularity and other features to enhance availability and ease of maintenance. Figure 3 illustrates the modular nature of the LIFE chamber. A complete LIFE chamber consists of 12 modules that are not physically connected other than via the surrounding support structure. The coolant headers surround the chamber and support structure and are design for rapid connection/disconnection from the primary coolant feed loops.

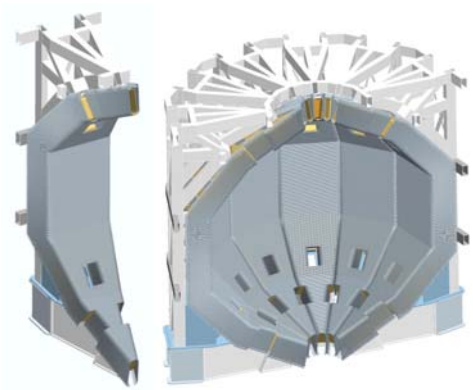

Fig. 3. The LIFE chamber is constructed of independent modules, which are supported by an exterior steel structure.

The chamber is designed for rapid replacement and repair. In fact we propose that the entire chamber is removed and replaced as a unit. One reason this is possible is that the chamber is not the vacuum vessel. Rather it is mounted inside a separate large vacuum chamber (see Fig. 4). The chamber is mounted on a rail system that is used to transport it from the vacuum chamber to the remote maintenance bay when replacement is needed. A new chamber is then moved via rail into place, coolant lines are attached, vacuum door closed and sealed and the system is up and running again. We estimate that this could be accomplished in about 2 weeks, which would have a very small impact on the plant availability.

Although not the topic of this paper, the laser system is also based on a highly modular design. The required laser energy is delivered using 384 beam boxes, which can be removed for repair/maintenance while the plant continues to operate (as long an no more than one box in each group of 8 does not require repair at the same time).

6. Summary

As with all IFE chambers, the LIFE chamber must deal with the short-range emissions from the target, which includes x-rays and energetic ions. The LIFE approach is to use a low density Xe fill gas to absorb the ions and most of the x-rays thus spreading out the delivery time (and thus peak heat load) to the first wall. The LIFE chamber is modular and is located within a separate vacuum chamber. This configuration was chosen to allow rapid maintenance since the radiation damage life of near-term reduced activation ferritic/martensitic (RAFM) steels cannot be accurately predicted at this time. The first LIFE plant will also be used as a materials test facility to provide high neutron doses to candidate materials such as ODS steel which is proposed for subsequent plants. Liquid lithium is used as the first wall and blanket coolant and tritium breeder. Lithium's attractive features include low mass density (leading to lower chamber mechanical loads), good heat transfer characteristics, good tritium breeder capability, and affinity to retain tritium. The high tritium solubility greatly reduces tritium permeation and helps limit the site inventory. A molten salt tritium extraction technique, previously demonstrated at Argonne National Laboratory, is the baseline tritium recovery approach. To avoid the possibility of Li contact and reaction with water, the LIFE design includes an intermediate heat transfer loop using a molten salt similar to the heat transfer salts used in the solar thermal industry. The power conversion cycle is based on the steam Rankine cycle that has a well-established industrial based. The thermal conversion efficiency for the first generation commercial LIFE plant with a chamber outlet temperature of 575 ºC is estimated to be about 47%.

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