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CONFINEMENT FUSION SYSTEMS

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(INVITED PAPER)
THE MATERIAL IMPLICATIONS OF DESIGN AND SYSTEM
STUDIES FOR INERTIAL CONFINEMENT FUSION SYSTEMS

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The major material requirements for inertial confinement fusion (ICF) reactors will be presented. These requirements will be defined by first describing the environment created from the process of generating energy with ICF, and then analyzing the ICF reactor concepts which have been designed to cope with this hostile environment.

In comparison to magnetic fusion energy (MFE) systems, ICF systems have three features which significantly influence material requirements. First, there is the disadvantage of designing first-walls and blanket structures which can survive the pulsed radiation environment. This combination of cyclical stresses, high energy neutrons, and high fluxes of charged particles and x-rays produces an environment never before faced by material scientists. Second, there is the advantage of a fusion driver which is decoupled from the reactor environment. For example, no large magnetic fields are present in the vicinity of the reactor. Therefore, liquid lithium may be more attractive as a coolant and tritium breeding medium. Finally, fusion chamber vacuum requirements are much lower for ICF systems. This means that liquid metals can be used as first-wall protectors.

The differences are apparent in recent ICF reactor conceptual designs. Recent conceptual designs include:

- (1) A liquid lithium cooled blanket with a lithium wetted first-wall.
- (2) A liquid lithium cooled blanket with a magnetically protected first-wall.
- (3) A liquid lithium cooled blanket with a dry sacrificial liner.
- (4) An Li_2O cooled blanket with a buffer gas protected first-wall concept (SOLASE).
- (5) A liquid lithium cooled blanket with a fluid first-wall concept (HYLIFE).

A brief discussion of these ICF reactor concepts will be given focusing on the operational parameters which influence key material requirements.

With one exception (SOLASE), all the above ICF reactor concepts use liquid lithium for blanket cooling and tritium breeding. In addition, the wetted wall and fluid wall concepts use liquid lithium in the vacuum chamber for first-wall protection. It is evident that liquid lithium could play a large role in ICF reactors. Therefore, a significant portion of this paper will be devoted to the material problems associated with containing and flowing liquid lithium in the pulsed radiation environment of the ICF reactor. Preliminary investigations indicate that ferretic steels may be the structural materials of choice for ICF reactors which use liquid lithium.

Materials Problems Associated With Flowing Liquid Lithium
in a Pulsed Radiation Environment

Materials problems that must be considered under this heading include mechanical and thermal loads, liquid lithium corrosion, radiation damage, and synergistic effects. Materials must retain adequate strength, ductility, and dimensional stability under cyclic stresses while exposed to the degrading effects of molten lithium and radiation. To the material selection criteria of mechanical strength, lithium compatibility and resistance to radiation damage, we can add that criteria of fabricability, low cost and limited use of scarce or imported elements for this applications.

Although corrosion in liquid lithium is similar to that in liquid sodium, lithium is generally considered more corrosive than sodium. The principle types of liquid-metal corrosion include:

1. Simple dissolution,
2. temperature-gradient mass transfer,
3. concentration-gradient or dissimilar metal mass transfer,
4. intergranular penetration,
5. impurity reactions, and
6. alloying between liquid metal and solid metal.

The variables that can influence the type and severity of liquid-metal corrosion on a given type of material include the following:

1. Temperature and temperature gradients
2. cyclic temperature fluctuation,
3. flow characteristics,

4. impurity levels in the liquid metal and the container material,
5. ratio of metal surface area to liquid volume,
6. surface condition including grain size, finish, etc. of the container material,
7. number of materials in contact with the same liquid metal,
8. stress and stress gradients, and
9. heat treatment.

The general effects of lithium on ferrous alloys can be summarized as follows:¹

1. High temperature, temperature gradients and chemical activity gradients promote dissolution and mass transport,
2. corrosion rates increase with the nickel content of stainless steel alloys,
3. carbon and nitrogen impurities in lithium accelerate corrosion,
4. stresses and flow increase corrosion rates,
5. lithium may react with carbides and promote cracking along grain boundaries,
6. chromium depletion in stainless steels may result in nickel dissolution from the chromium depleted (nickel rich) regions adjacent to grain boundaries, and
7. the use of extra low carbon steels and stabilized grades will effectively decrease corrosion by lithium.

Since many of the materials which have shown excellent corrosion resistance, such as pure iron and refractory metals, have limitations

related to their mechanical properties, and fabricability or availability, it is necessary to study many of the available commercial alloys. For ICF applications, low alloy ferritic steels appear very attractive. These alloys do not contain nickel and have much lower chromium concentrations than austenitic stainless steels. Chromium is an element that may be difficult to obtain in quantity in the U.S. by the turn of the century and any nickel dissolved in lithium and flowing through a high neutron flux will activate to form ^{58}Co and ^{60}Co . These low alloy steels offer excellent economy as well as excellent properties for pressure vessel construction. The most common steel is 2.25 Cr-1.0 Mo which is used extensively in this country for heat exchangers and steam generators. The version of this steel stabilized with Nb is used in Europe and Japan in both fossil and nuclear systems.

The radiation from an ICF pellet can be divided into two broad categories: 1) Penetrating radiation consisting primarily of a spectrum of high energy neutrons strongly peaked at 14 MeV and representing about 70% of the pellet yield and the more energetic x-rays; 2) Short range radiation consisting of low energy x-rays and energetic debris (unburned fuel, alpha particles and pellet materials). The extremely large heat load imparted by the short range radiation is such a severe materials problem that most ICF reactor concepts deal with it by protecting the chamber structural materials from direct exposure. The use of replenishable fluids, sacrificial liners and diverting magnetic fields all reduce the heat load to the chamber structural walls.

With the exception of the fluid wall concept, HYLIFE, these measures do not protect reactor materials from neutron damage. The two neutron damage parameters generally discussed are the helium production rate and the atomic displacement rate. Helium accumulation can result in a loss of ductility while displacement damage can lead to dimensional instability due to void swelling.

Although little is known about the effects of neutron radiation on ferritic steels, the available data suggests that they are more resistant to both helium embrittlement and swelling than austenitic stainless steels.²⁻⁴ In addition, the rate of helium production is lower in ferritic steels than austenitic stainless steels due to the absence of nickel which has a much higher cross section for (n,α) reactions than iron.

A great deal of R&D is required to quantify the effects of flowing liquid lithium and radiation on candidate materials for ICF applications. The variables that affect the corrosion of ferrous alloys have been identified but we have only begun to understand exactly how these variables affect the corrosion mechanisms and rates. Quantifying the mechanisms, kinetics and effects of these variables and determining appropriate scaling laws will require a series of lithium corrosion experiments. Research must proceed from static testing and thermal loops to systems that reasonably simulate operating conditions such as pumped loops containing stressed specimens.

The radiation damage environment presents unique materials problems. While the time-averaged neutron damage rates can be simulated in fission reactor testing, the instantaneous damage rates in ICF reactor may be up

to 10^8 times greater.⁵ New pulsed-irradiation test facilities will be required to do meaningful experiments on the effects of such high rates.

In both corrosion and radiation damage testing priority should be given to the low alloy ferritic steels since current evidence indicates that in both cases they are less susceptible to degradation than austenitic stainless steels. Lower cost ferritics also use smaller quantities of scarce materials.

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Description of HYLIFE

In the HYLIFE converter concept pulsed fusion energy is converted to steady thermal power by means of an array of flowing liquid lithium jets.¹ The array consists of four hundred 30 cm diameter jets and provides the equivalent of at least one meter of protection to the chamber structural materials, shielding them from direct exposure to the x-rays, debris and high energy neutrons emitted by the fusion pellet. The concept is unique in that the energy conversion blanket is inside the first structural wall. The liquid lithium also serves as the primary coolant and fertile material for tritium breeding. The majority of the fluid circulates at nearly constant temperature ($\sim 500^{\circ}\text{C}$) while less than 10% of the total flow is diverted to heat exchangers for power conversion. Less than 1% of the gross electrical power is required to circulate the lithium. The beams are focussed from 60 meters and penetrate the chamber through windowless apertures.

The major features of the HYLIFE concept are:

1. The chamber can be operated with pulsed thermonuclear yields of several thousand megajoules and power densities approaching those of a LWR.
2. No replacement of the first structural wall or blanket structures is required.
3. Common ferritic steels can be used for the reactor structure.

4. The combination of the fluid blanket and ferritic steels reduces the induced radioactivity and biological hazard potential by more than an order of magnitude compared to other concepts.
5. The laser driver and pointer/tracker system for hitting the pellets are in a separate less expensive building, away from the radiation environment.

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