OVERVIEW OF MATERIALS R&D IN LASER INERTIAL FUSION ENERGY (IFE)

N.M. Ghoniem (UCLA), L. Snead (ORNL), J. Sethian (NRL)

US Fusion Materials Science Program

Strategic Planning Meeting

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Presentation Outline

- IFE Features & Radiation Environment;
- Statement of Objectives;
- Key Science and Technology Challenges;
- Framework and Integration Logic;
  - Approach;
  - On-going Activities;

General Features

	IRE	ETF	Power Plant
Driver Energy, (MJ)	0.1	1-2 MJ	2-4
Yield, (MJ)	0	50-200 MJ	150-450
Repetition Rate	Burst Mode ~ 1000 shots @~ 5 Hz	5-10 Hz for hours	5-15 Hz, continuous
wall radius (m)	3 or 0.4[b]	2-5	6.5

Chamber Radiation Environment

Neutrons	0	$\phi_{14} = 3\times10^{13}$ n/cm^2-shot	$\Phi_{14} = \sim10^{14}$ n/cm^2-s; $\Phi_{fast} = 8\times10^{14}$ n/cm^2-s; $\Phi_{tot} = 10^{15}$ n/cm^2-s; ~15 dpa/y; 3700 appm
Gamma-rays	0	Negligible	He/y Negligible
X-rays (J/cm^2)	1.0^c	0.6-1.0	0.4-1.2
Ions (J/cm^2)	< 1.0^c	18-28	8-24

Optics Radiation Environments

Optics stand-off	10 (0.2)[d]	20	30
Neutrons	0	ϕ_{14} = 2-8×10^{11} n/cm^2-shot	F_{14} = 5×10^{12} n/cm^2-s; F_{fast} = 9×10^{12} n/cm^2-s; F_{tot} = 10^{13} n/cm^2-s; D_n = 3×10^9 Gy/yr, SiO2 transmutation: He=69appm, H=28,C=54, Mg=15, Al=4 appm/y
Gamma-rays	0	0.7-3 Gy/shot	~10^9 Gy/y
X-rays (J/cm2)	1.0[c,d]	14-56	19-76
Ions(J/cm2)	< 1.0[c,d]	.3-1.1	0.4-1.1

STATEMENT OF OBJECTIVES-1

- **Development of Material Systems and Components for High Average Power Density Laser Optics;**
  - **Develop both reflective and transmissive optics;**
  - **Investigate effects of laser, X-ray, neutron and ion/debris;**
  - **Critical issue for transmissive optics : degradation of transmissivity as a result of color center formation;**
  - **Considered materials : SiO_2, CaF_2, MgF_2 and Al_2O_3;**

STATEMENT OF OBJECTIVES-2

- **Critical issue for reflective optics: degradation of the Laser-Induced Damage Threshold (LIDT) by surface deformation mechanisms;**

- **<u>Considered material systems</u>: FCC metals (e.g. Cu & Al), BCC metals (e.g. Mo & W), SiC, Layered structures and innovative design concepts ;**

- **<u>Design objective:</u>**
  - **Minimize (or compensate for) gross structural deformation by gravity, thermal and mechanical loads;**
  - **Control microscopic surface deformation caused by material defects.**

STATEMENT OF OBJECTIVES-3

- **Development of Reliable Chamber Structures and Components for the IFE Dry-wall Concept;**
  - **Key Issues:**
    - **Pulsed neutron damage;**
    - **Intense X-ray effects;**
    - **Effects of repetitive thermomechanical shock Loading.**
  - **Material Systems : engineered high-temperature composites, with variants of C/C, C/SiC, SiC/SiC; (2) Refractory alloys (W & Mo); ODS Ferritics; Layered structures.**

FRAMEWORK & INTEGRATION LOGIC

- **"Cradle-to-Grave" approach;**
- **Balanced Mix between:**
  - **Fundamental understanding of mechanisms;**
  - **Integration of material and design concepts;**
  - **Data-base generation for IRE and ETF.**
- **Experiments:**
  - **Collection of a database;**
  - **Motivated by theoretical ideas and concepts;**
- **Theory & Modeling:**
  - **Validated by experiments within the program;**
  - **Advanced models of structural performance and reliability.**

The SIX Research Thrust Areas

IRE & ETF Materials & Design Data Base
IRE & ETF Optical Systems Materials Evaluation
Development and Testing of FW and Structural Materials
Unique IFE Materials Science for FW & Structures
Surface Modification Science & Technology
Materials Impact on Safety, Economics & the Environment

SOMBRERO Basics

Geometry:

Cylinder with two cones @ the ends;

⇒ Mono-Axial Geometry;

⇒ Panel Shape?

(manufacturing + maintenance + analysis problems);

⇒ Panel locking?

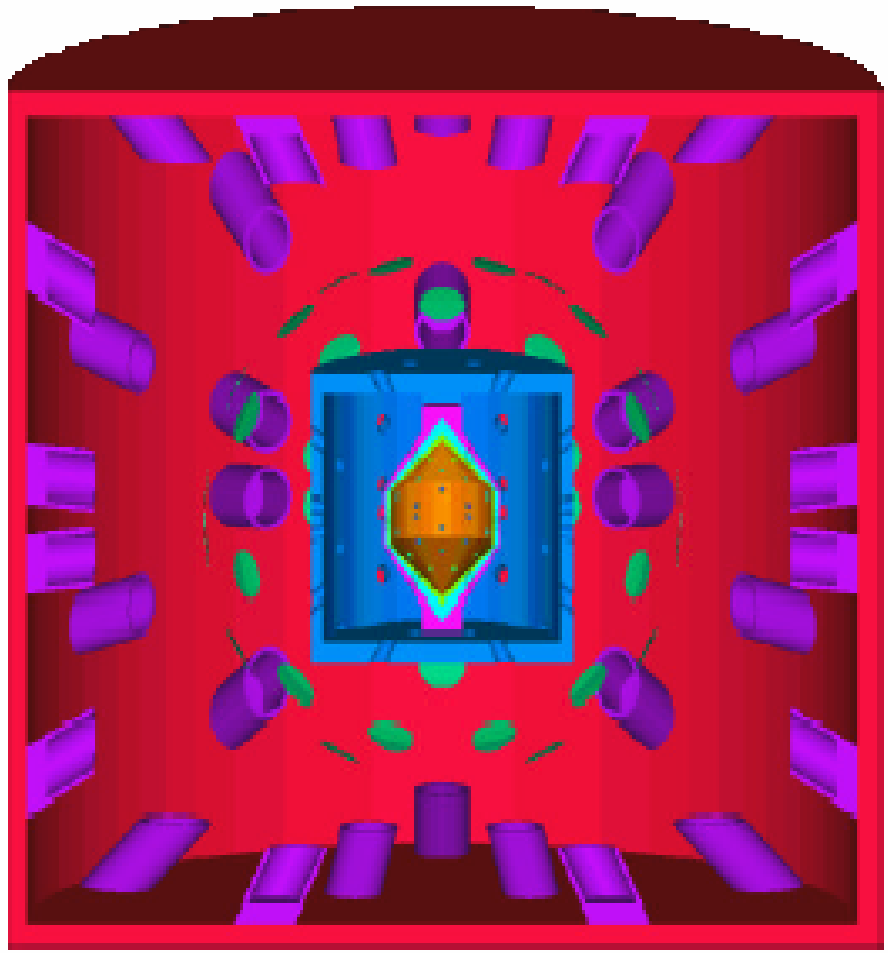
(NO weldings, threaded joints);

Cooling:

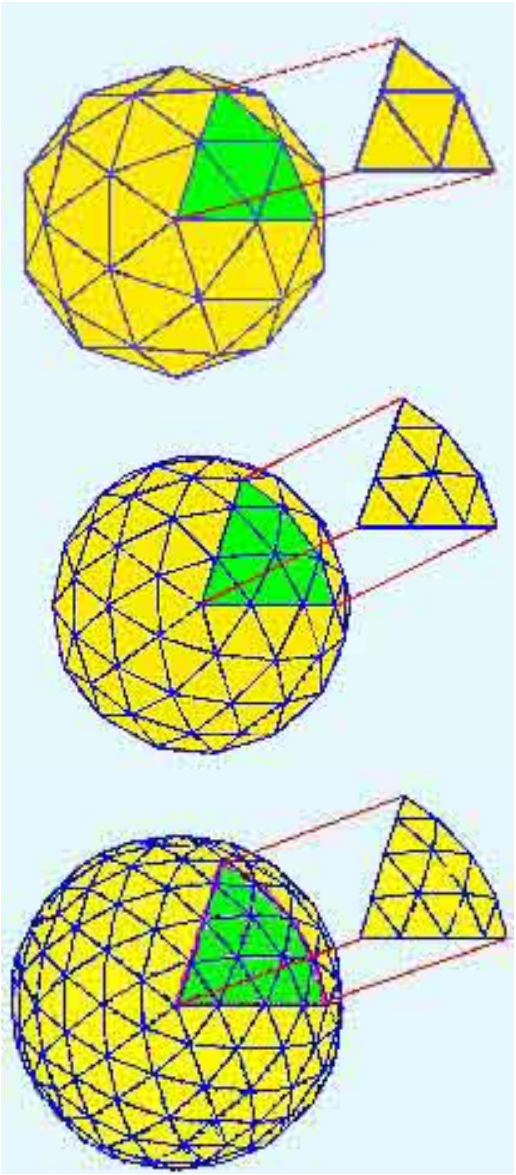
Flowing from the top to the bottom;

⇒ Leakage prevention?

Model of a DPSSL-modified SOMBRERO target building includes final optics and neutron dumps



From SOMBRERO to **UCLA's Design: Spherical Geometry**



2nd Frequency:

20•4=80 Faces;

All Equal Faces

3rd Frequency:

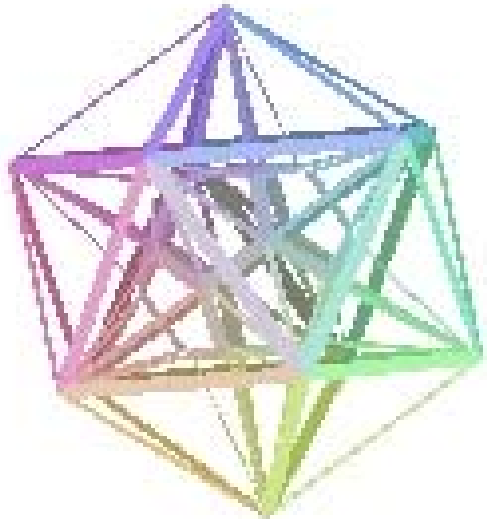
20•9=180 Faces;

2 different Faces

4th Frequency:

20•16=320 Faces;

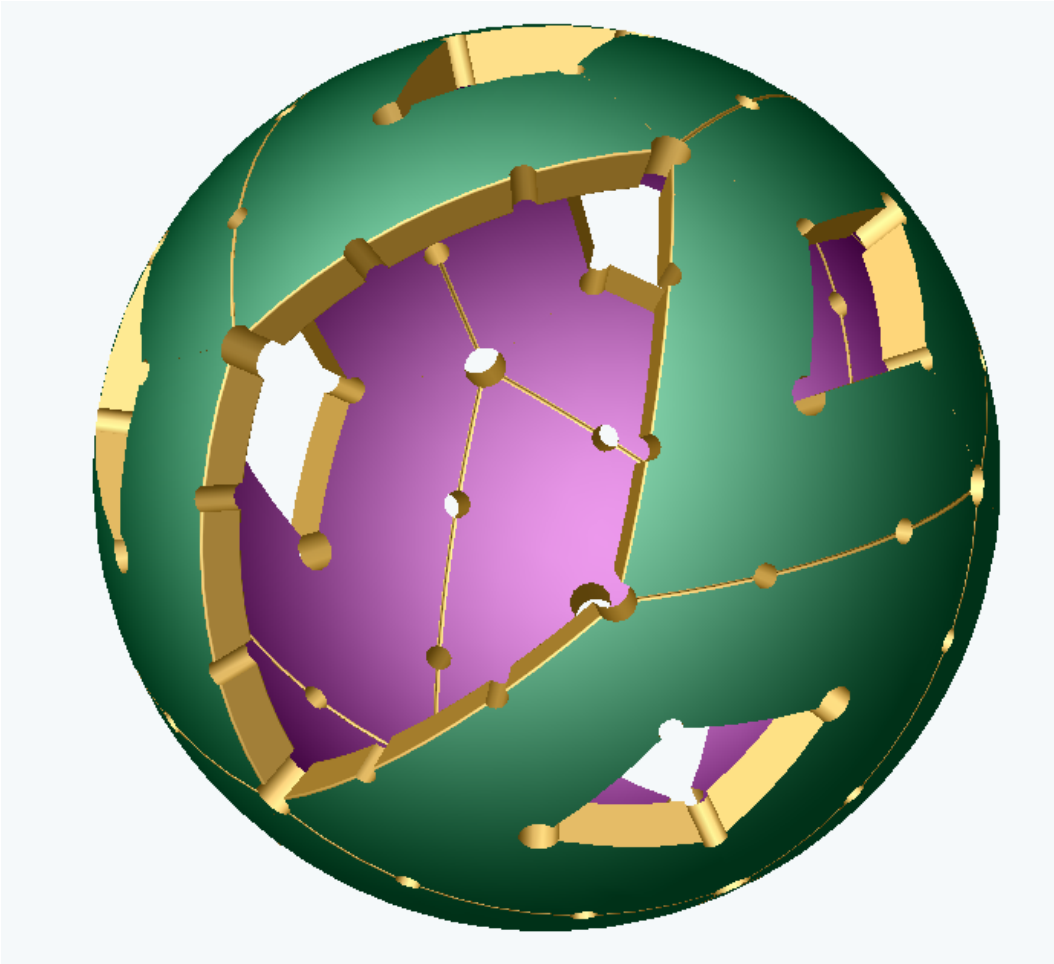
5 different Faces



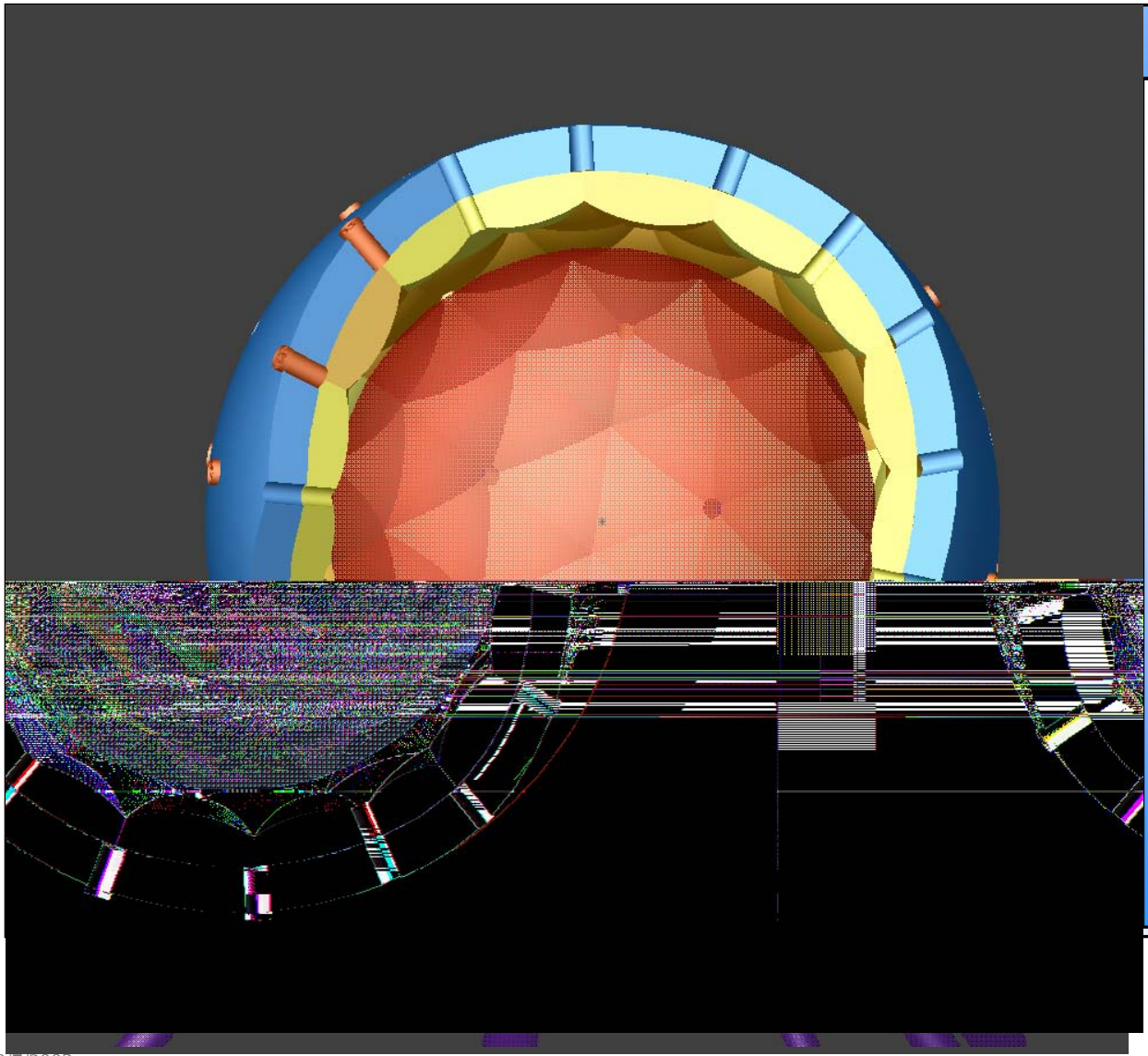
Icosahedron:

20 Faces

Mechanical Design-I



UCLA's Design of IFE Chamber

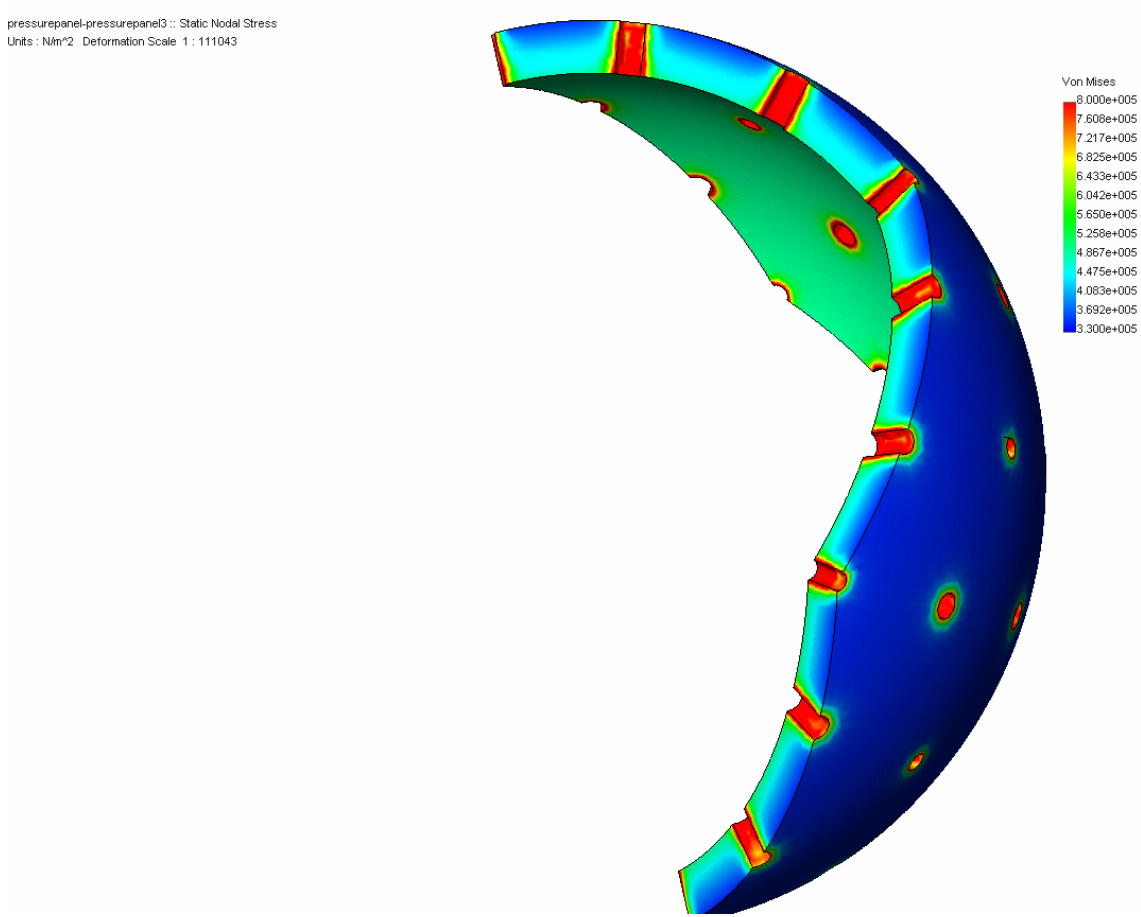


- The explosion creates pressure waves and thermal gradients with spherical geometry.

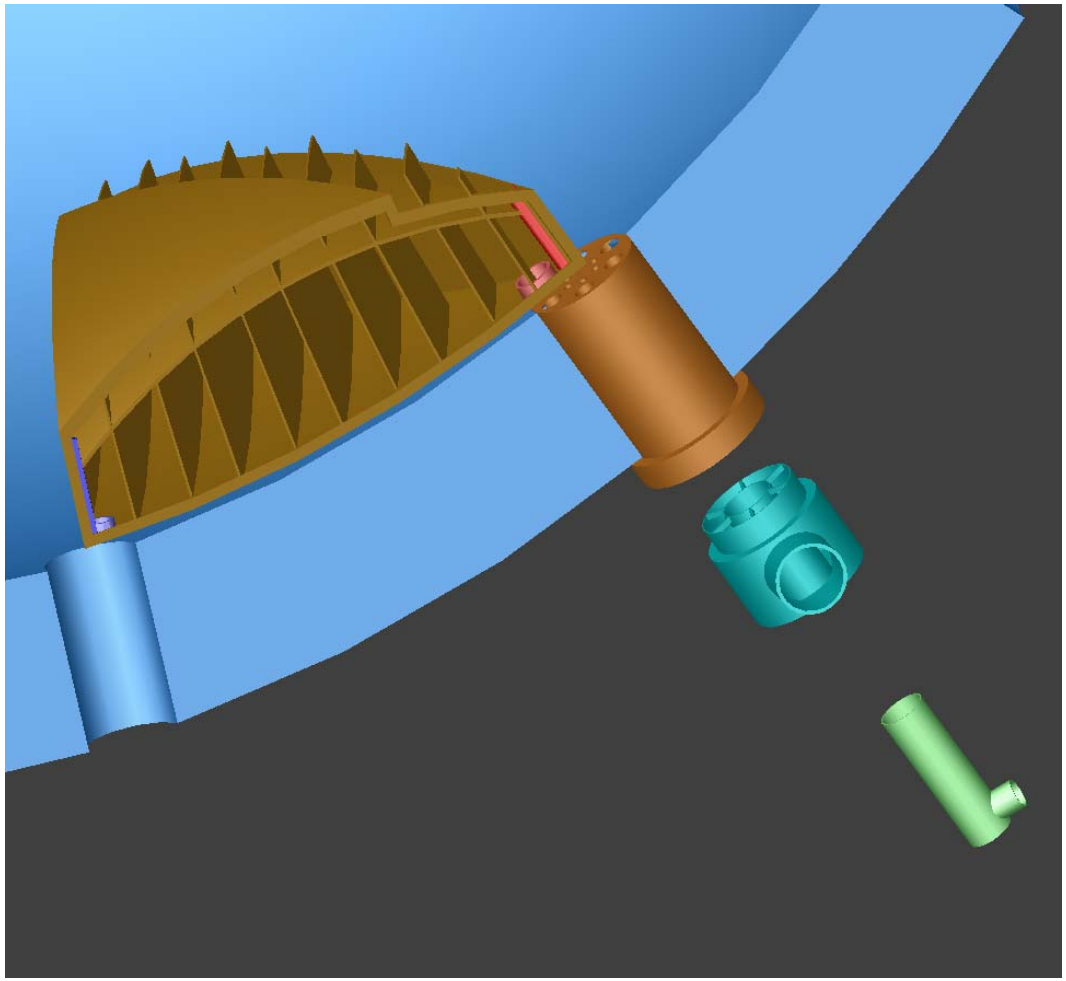
power is 2000MW.

Design of IFE Structural Materials is Challenging

- Stress analysis on the chamber structure is performed using FEM techniques.



UCLA's Design of IFE Chamber



- The cooling pipes also serve as mounts for each panel.

enter trough pipes from outside the chamber

Thermomechanical Loading

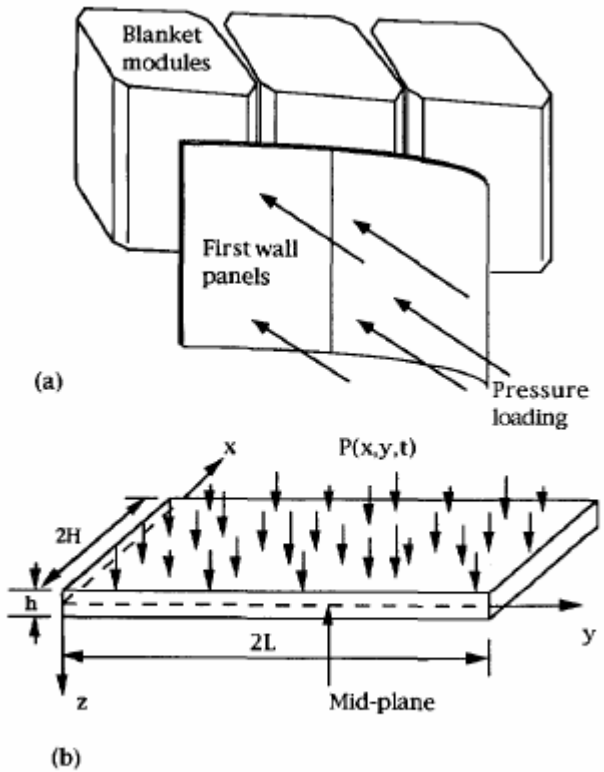
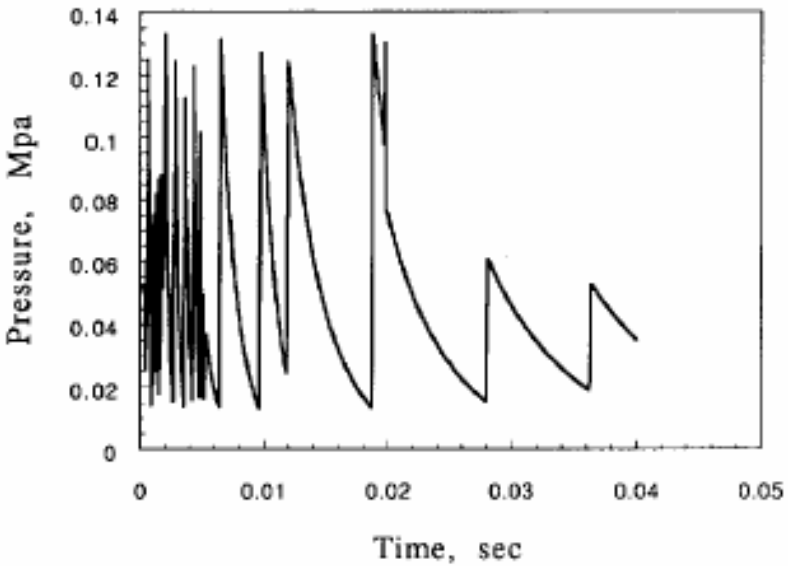
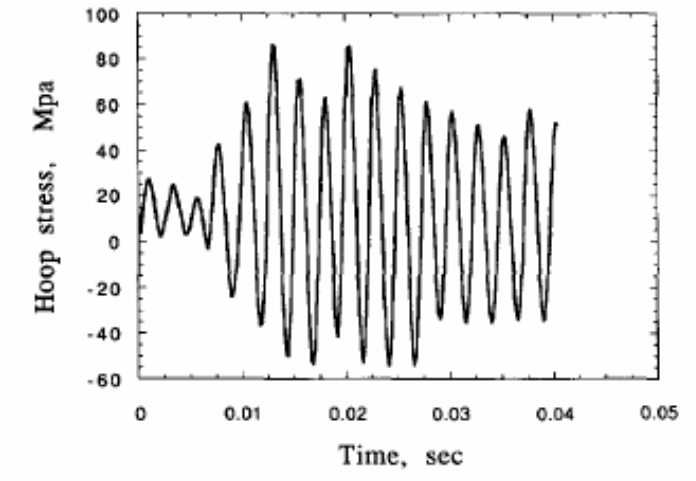


Fig. 5. Schematic of (a) the first wall/blanket configuration and (b) the plate model of the PROMETHEUS first wall.



FW stress depends on geometry and temperature/ pressure ratio



Spherical Shell

Plate – Pressure only

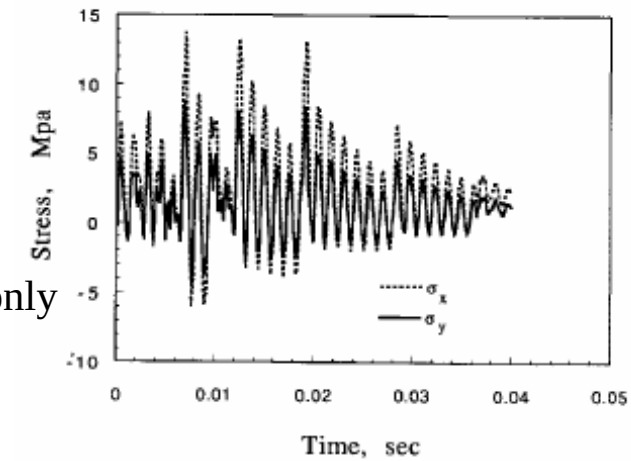


Plate – Pressure & Temperature

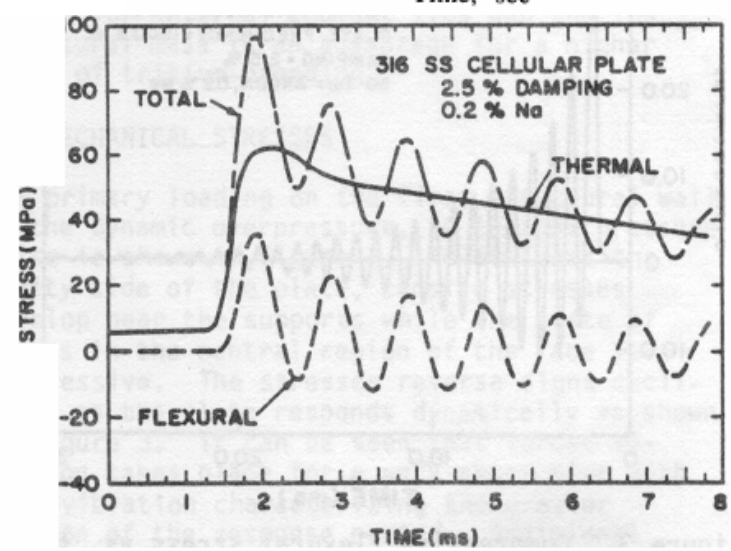


Figure 8. Combined compressive stress vs. time.

Modeling Approaches

- Engineering (S-N-P):
  - Linear Life-fraction rule: $\sum_{j=1}^{i} \frac{n_j}{N_j} \geq 1$
  - Non-linear Damage: $\sum_{j=1}^{i} \left(\frac{n_j}{N_j}\right)^m \geq 1$
- Fracture Mechanics (Paris-Erdogan Law)

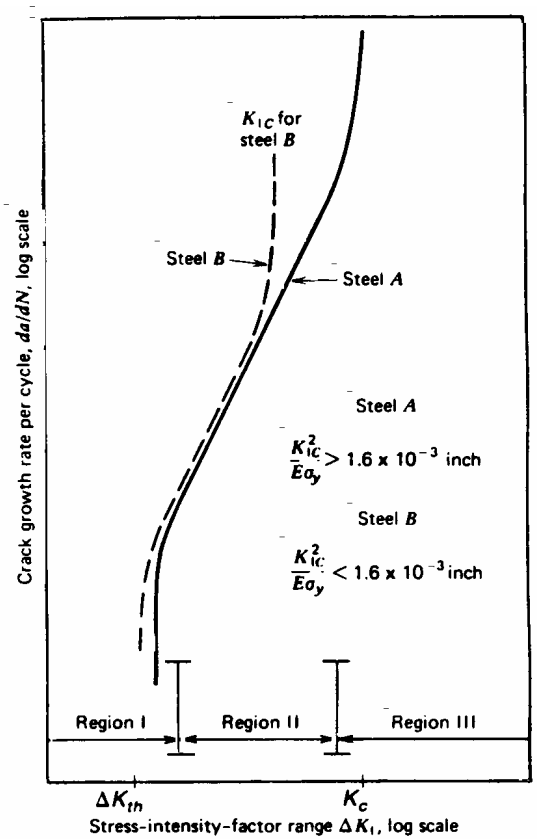
$$K = C\sigma\sqrt{\pi a}$$

$$\Delta K = K_{\max} - K_{\min}$$

$$\frac{da}{dn} = C_{PE}(\Delta K)^n$$

- Micromechanics: (Dislocation Dynamics & Micro-crack mechanics.

Paris Law



IGURE 8.23. Schematic representation of fatigue crack growth in steel. (See ef. 67.)

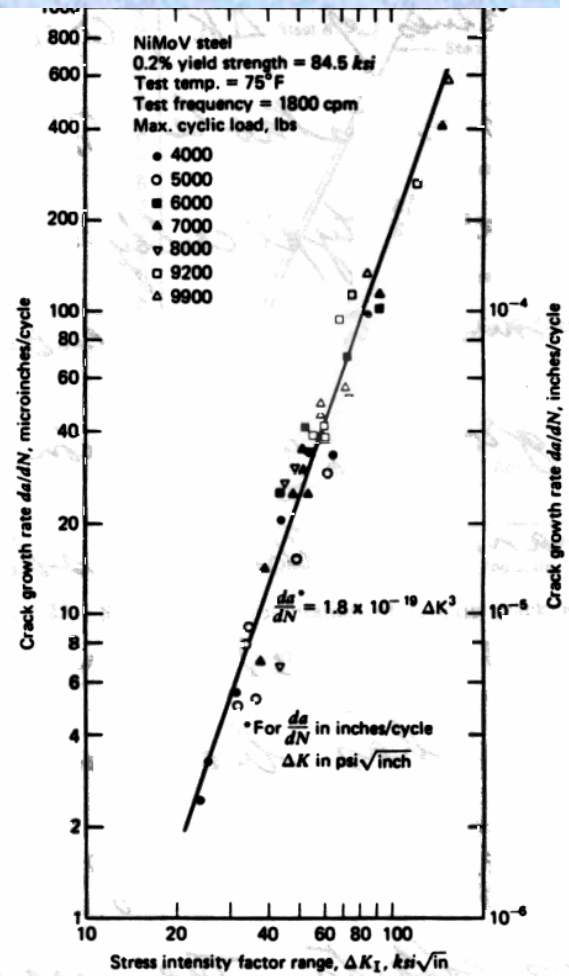


FIGURE 8.22. Crack growth rate as a function of stress-intensity range for Ni-Mo-V steel. (From ref. 66, copyright Society for Experimental Stress Analysis, 1971; reprinted with permission.)

Experimental Needs

(1) S-N-P

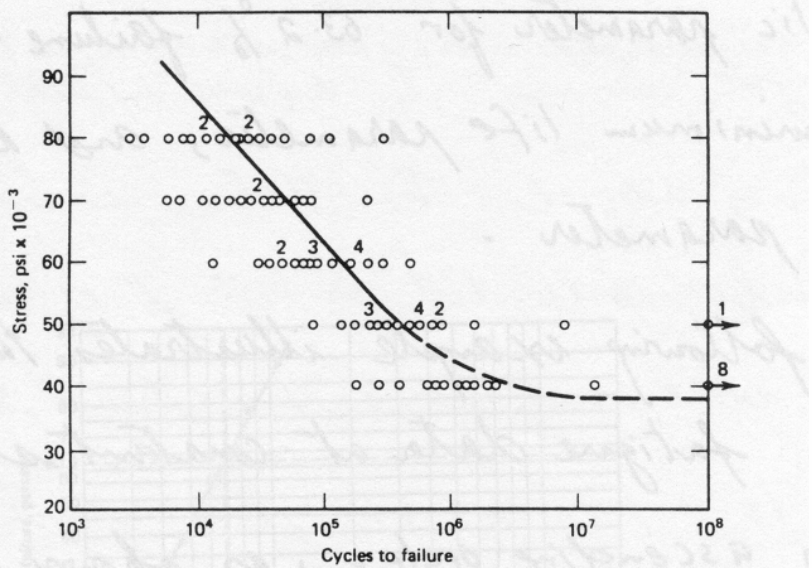


FIGURE 10.2. Fatigue data for constant stress level testing program plotted on standard *S-N* plot. (After ref. 1)

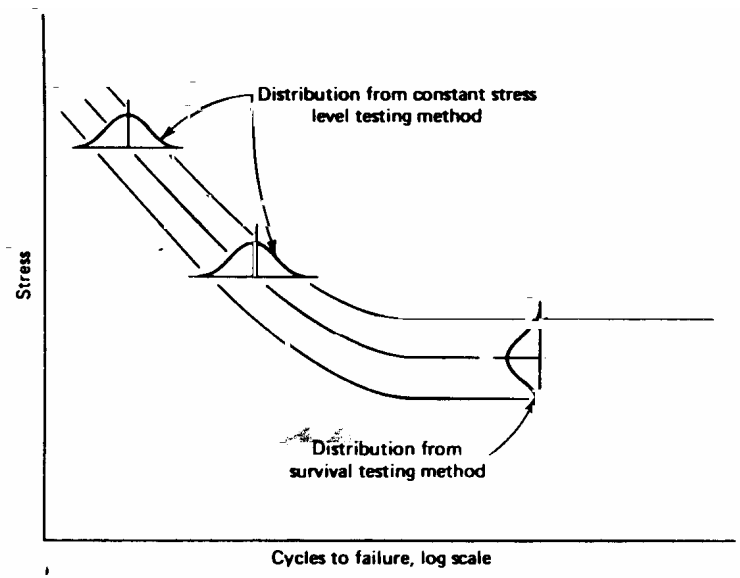


FIGURE 10.6. *S-N-P* curves determined by using constant stress level method in finite life range and survival method in infinite life range.

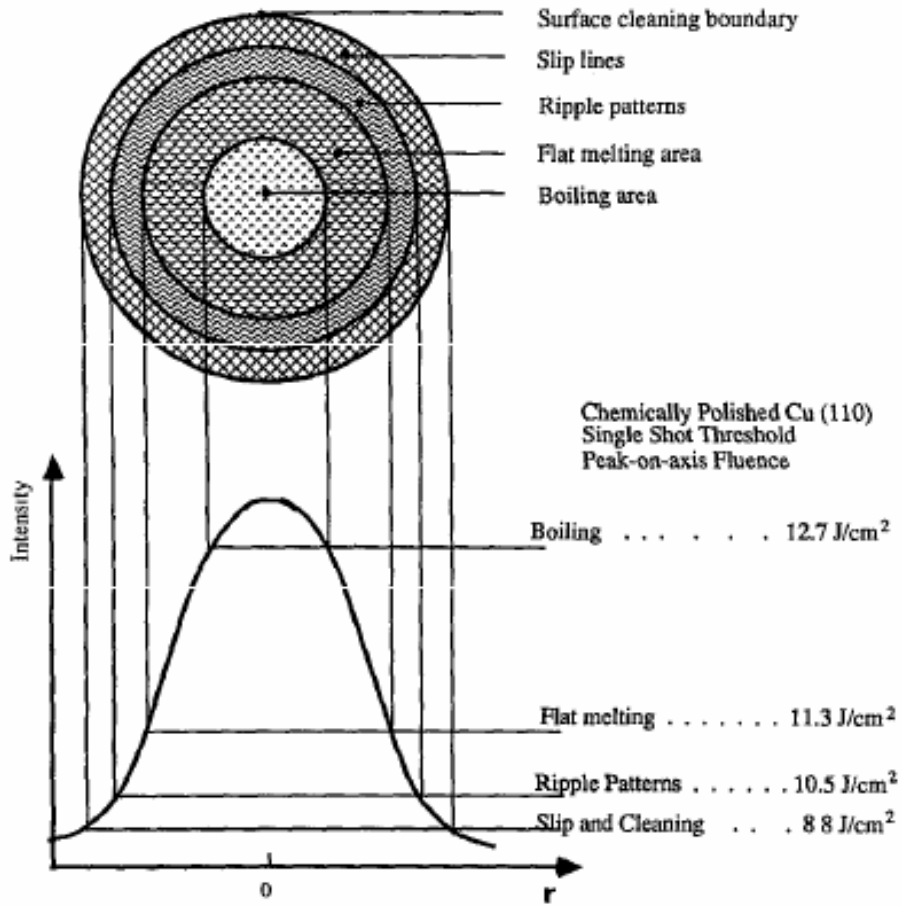
(2) da/dn

(3) Threshold Fracture toughness (bulk & interface)

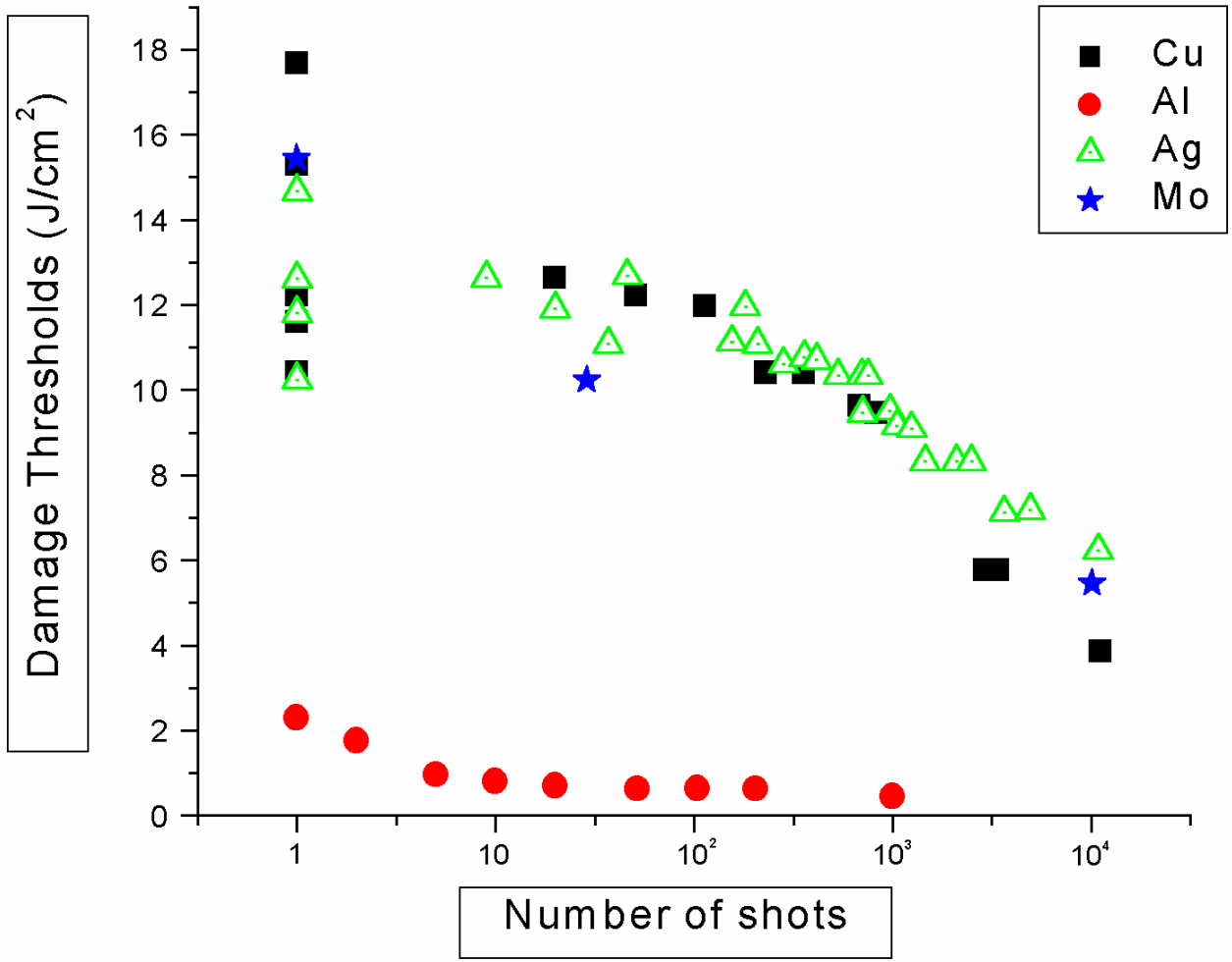
LASER OPTICS

- Eliminates the use of a crystal for the fusion chamber
- Easier fabrication methods
- Cost effectiveness
- Versatility
- Longer lifetime

Experimental Data for Polished Cu



Data for Multi Pulse Damage

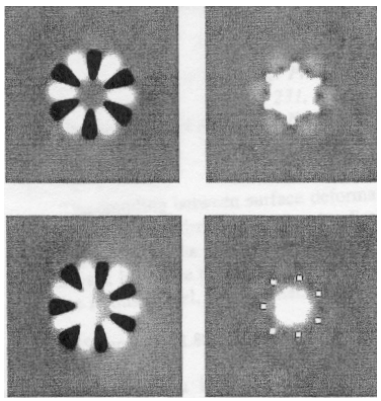


SURFACE DEFORMATION MECHANISMS

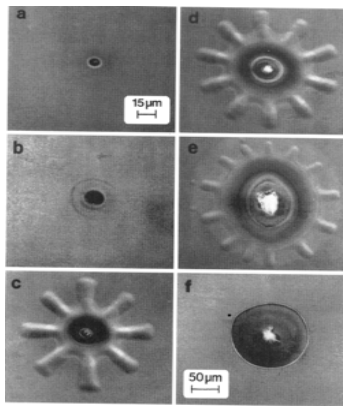
- **Single Shot Effects on LIDT:**
  - Laser Heating Generates Point Defects
  - Coupling Between Diffusion and Elastic Fields Lead to Permanent Deformation
- **Progressive Damage in Multiple Shots**
  - Thermoelastic Stress Cycles Shear Atomic Planes Relative to one Another (Slip by Dislocations)
  - Extrusions & Intrusions are Formed when Dislocations Emerge to the Surface

SINGLE-SHOT EXPERIMENTS & MODELING

Focused Laser-induced Surface Deformation

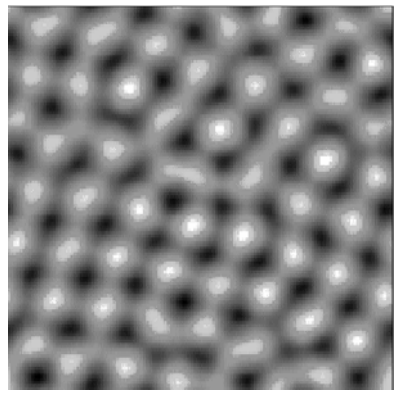


Computer Simulation



Experiment

Uniform Laser-induced Surface Deformation



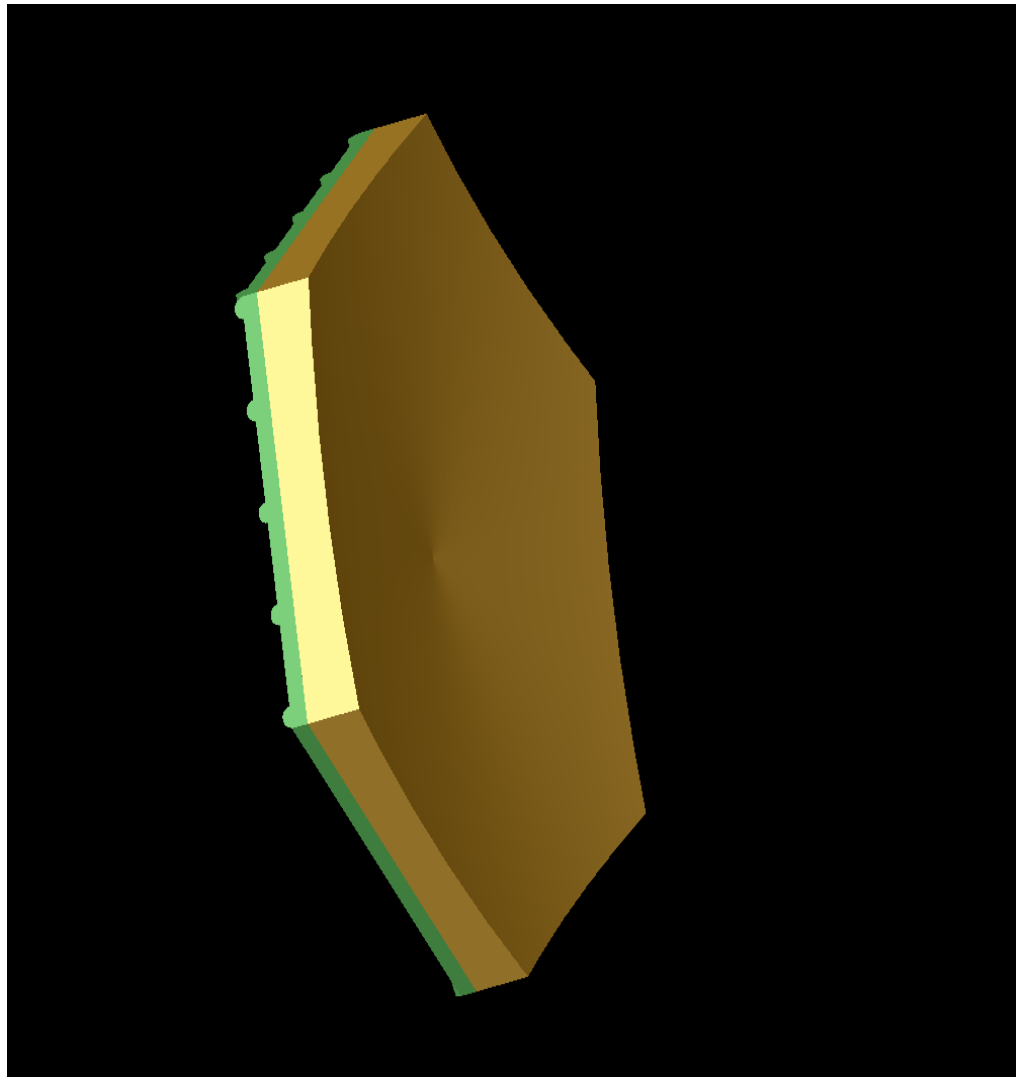
Computer Simulation

Focused laser-induced surface deformation (Lauzeral, Walgraef & Ghoniem, **Phys. Rev. Lett. 79, 14 (1997) 2706**)

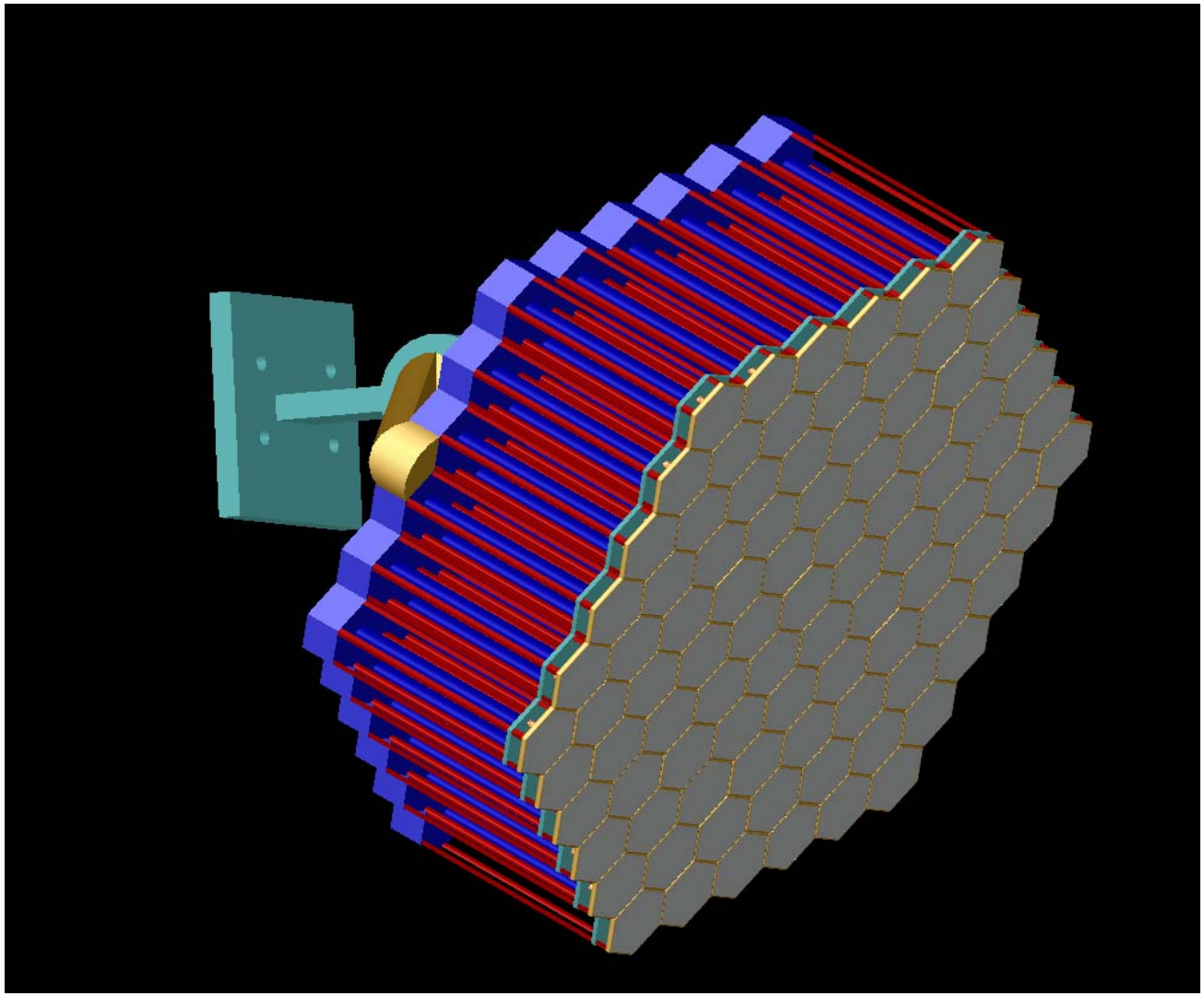
(Walgraef, Ghoniem & Lauzeral, **Phys. Rev. B, 56, 23, (1997) 1536**)

Front view of basic unit

- Top layer- e-Beam Al
- Second layer-CVD-SiC
- Third Layer: SiC Foam
- Fourth layer- composite face sheet;
- Fifth Layer: SiC Foam;
- Back Face: Web-reinforced Structure.



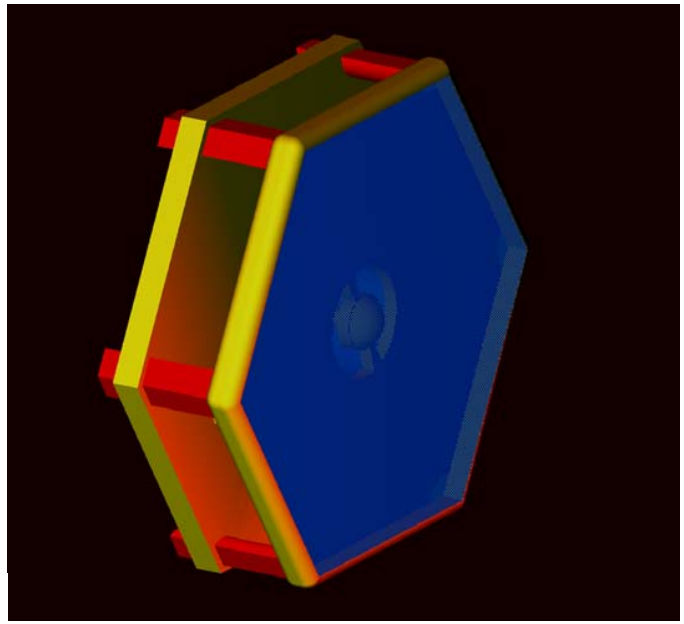
Assembly of entire structure

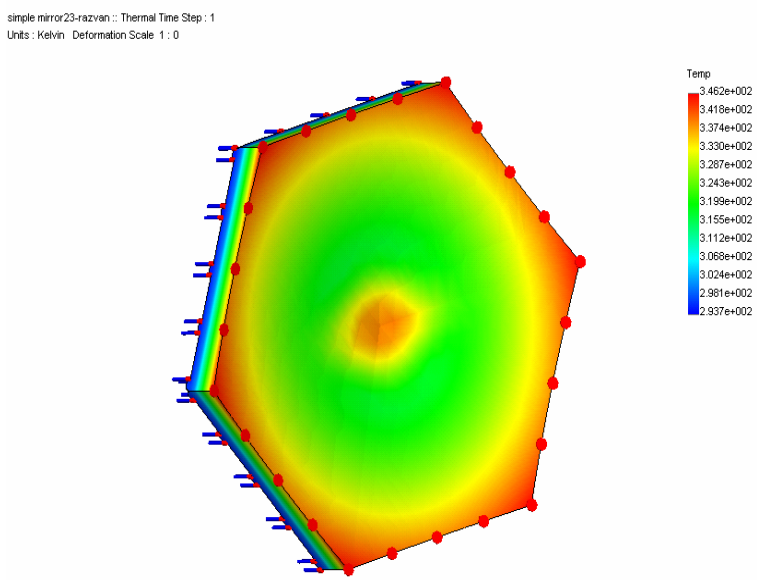


Thermal loads and stresses

$$Q = 10 \frac{W}{cm^2}$$

- Cooling system needs to remove 740 W per mirror
- Mass flow rate of coolant .018 Kg/s
- Working temperatures of the coolant 290K to 300k
- Water as possible coolant





Unique IFE Environment

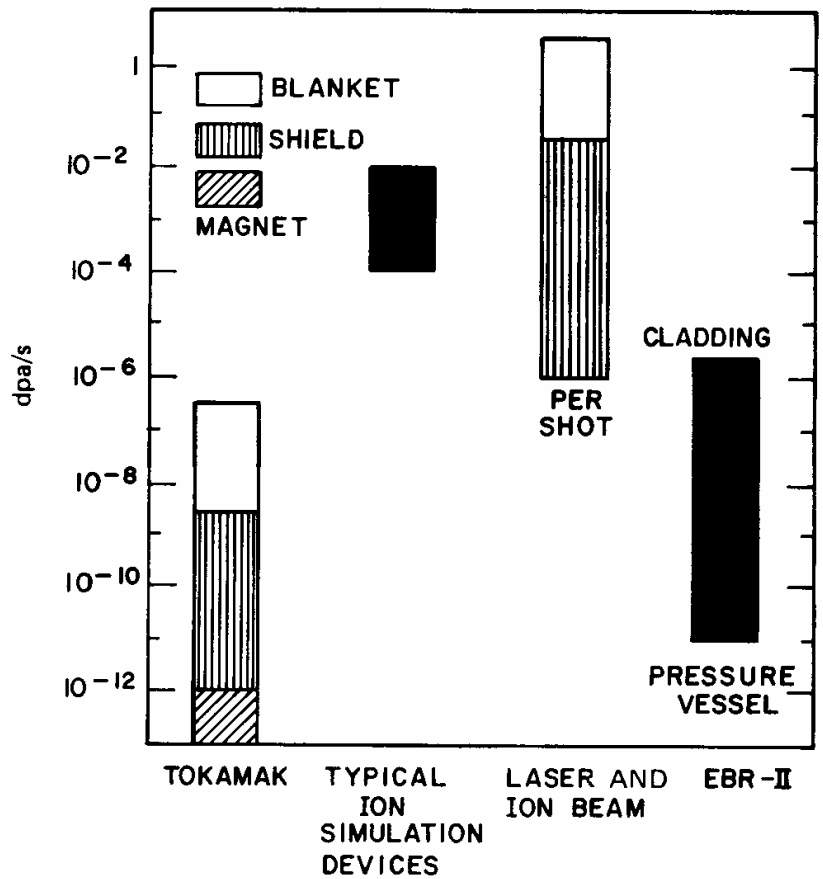


Fig. 1. Instantaneous displacement damage rates in deuterium-tritium/controlled thermonuclear reactor (D-T/CTR) first walls and simulation facilities.

Integration of Materials and Chamber Design

Materials-by-Design Knobs:

(1) Alloying and Composition.

(2) Multi-function Materials (e.g. Layering)

(3) Composite Architectures.

Chamber Design Knobs:

(1) Size and Shape.

(2) FW Constraints.

(3) Coolant/ FW system.

(4) Buffer Gas Pressure & Evacuation.

(5) Temperature & Required Efficiency.

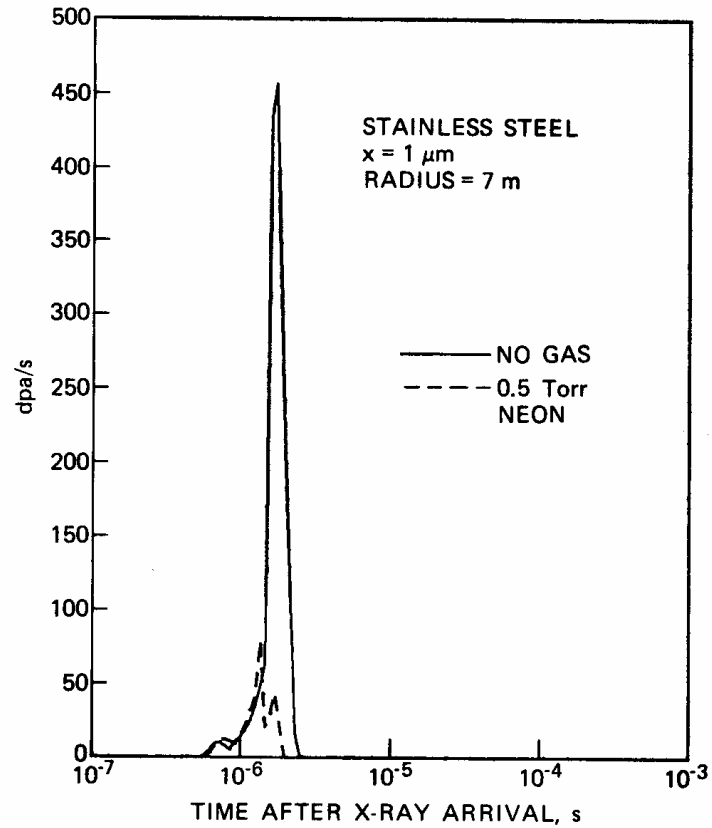


Fig. 10. Effect of a 0.5-Torr neon buffer gas on the instantaneous displacement damage rates at $x = 1\ \mu m$ (Ref. 19).

Unique Structural Phenomena - Void Swelling Experiment

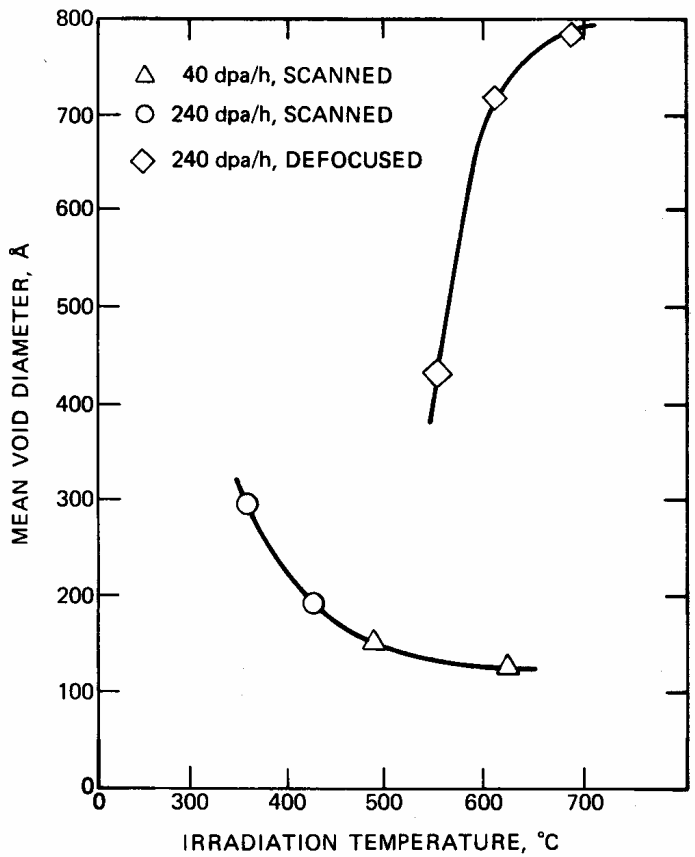


Fig. 13. Experimental results of self-ion irradiated nickel for steady defocused and scanned beams (Ref. 39).

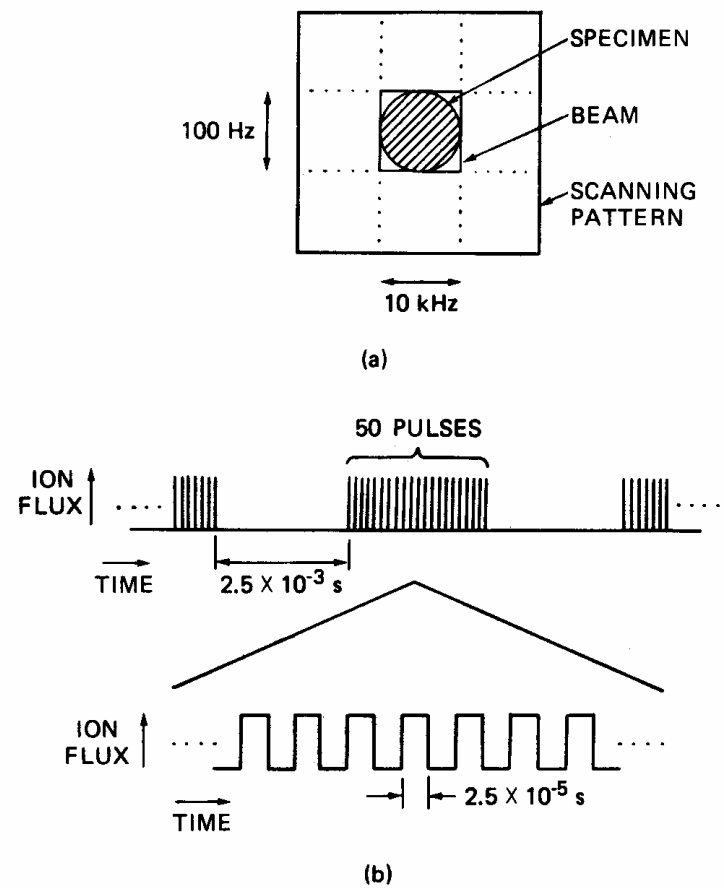


Fig. 14. Time structure of the ion beam in the NRL experiment (Ref. 39): (a) idealized scanning pattern and (b) idealized ion flux.

Unique Structural Phenomena - Void Swelling Theory

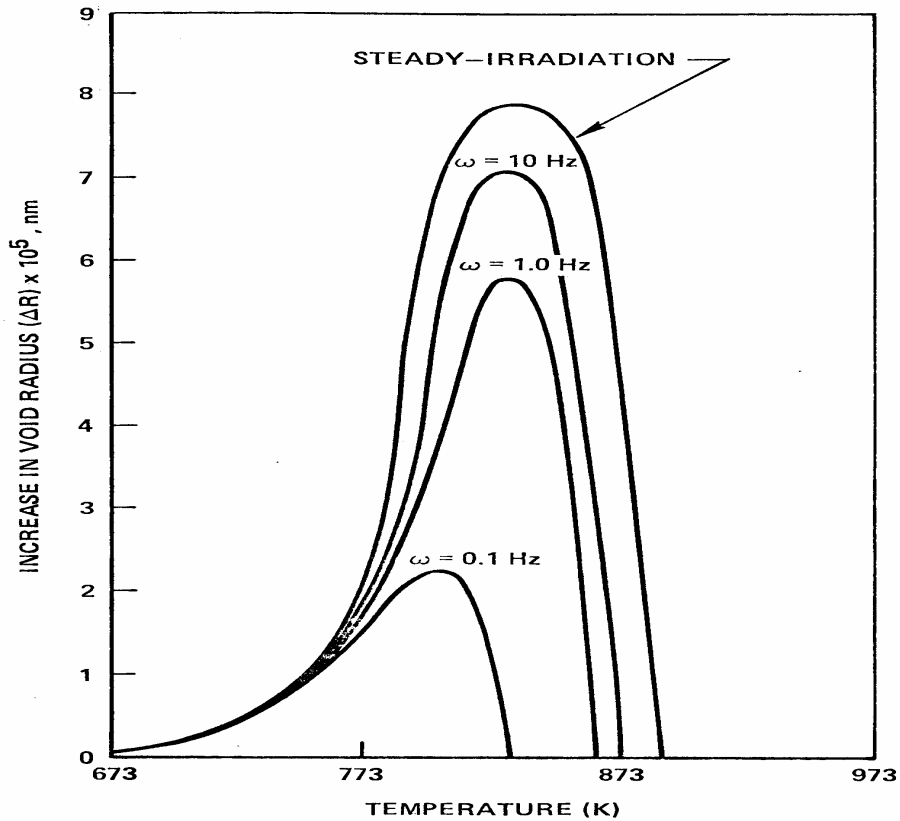


Fig. (3): The increase in the average void radius as a function of irradiation temperature for various pulsing frequencies. $R_c(0)$ = 10 nm, T_{on} = 10^{-7}sec, Z_i = 1.08, and average dose rate = 10^{-6} dpa/s.

Conclusions

- Very challenging scientific and technical issues for IFE materials require a dedicated, self-consistent and integrated R&D approach.
- Augmentation and focusing of on-going activities have been recommended;
- A detailed R&D plan has been worked-out, with many participation opportunities from the community.