The Need for Neutron Radiation Damage Information from the Viewpoint of the Fusion Reactor Designer

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Prepared for the International Conference on Radiation Test Facilities for the CTR Surface and Materials Program, Argonne National Laboratory, 15-18 July 1975.

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by

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Abstract

An analysis of the type and amount of data required for the design of the near term experimental power reactors and fusion engineering reactor facilities is given. It is shown that design data is required on a much shorter time scale than the actual operation of the particular reactor systems. Given the present schedule of the U.S. to a demonstration power plant in 1997, data up to 10^{21} n/cm^2 (14 MeV) is required by FY 81 on structural materials, probably austentic steels. Information on carbon at high temperatures (1000-2000°C), modest displacement values (1-10 dpa) and high helium contents (~1000 appm) is also required. The operational characteristic of neutron multipliers (Be compounds) solid breeders (Li compounds) and superconducting magnet materials during 14 MeV neutron irradiation must also be understood by the early 1980's if the EPRs or FERFs are to operate by the late 1980's. Emphasis on in situ testing and proper simulation techniques is also stressed.

I. Introduction

It is now very evident that once the plasma physics problems are solved, the next most serious roadblock to economical fusion power is the degradation of materials properties in the intense environment of a D-T fusion reactor. Put another way, we may be successful in producing and confining a reactor grade plasma, but we may not be able to take full advantage of its benefits because of material failures induced by the high energy neutrons released from the D-T reaction. Prudent engineering will force us to set strict lifetimes on the reactor components which must allow for a sufficient safety margin. This in turn will probably mean that many of the reactor components will not last the full lifetime of the reactor and will have to be changed at intervals on the order of a few years. The replacement of highly radioactive, and in many cases, brittle components will undoubtedly be done remotely and appropriate measures must be taken to provide adequate long term storage facilities. The time involved in replacement will reduce the plant availability factors and have an adverse effect on the economics. The continual replacement of reactor components also will represent a significant operational cost as well as increasing inventory costs.

It is easy to conclude from the above scenario that any improvement in the materials performance will have a significantly beneficial effect on the economical and environmental costs of fusion power. Therefore vigorous programs must be started now to understand how this new environment will modify the behavior of CTR materials and how we may ameliorate those detrimental effects. Obviously, one must understand the fundamentals of the radiation damage but, given the current timetable to a fusion demonstration power reactor (DPR) in the late 1990's, it is clear that both fundamental studies and engineering testing will have to take place at the same time. This point clearly requires emphasis because we will only investigate the engineering requirements in this paper. It is understood that an aggressive and rigorous fundamental research program is a vital part of the overall fusion program until the end of this century.

It is now convenient to divide the discussion up into two parts: first, what is the time frame in which engineering information is needed, and second, what are the materials, properties, and level of effort required for the safe design of both near and long term reactors? The reader is referred to an associated paper outlining some specific ways in which we can satisfy the needs of the designer, at least in the near term.[1]

II. Time Frame in Which Engineering Information is Required

Figure 1 is an approximate summary of the current U.S. plans to build a D-T burning DPR of the tokamak class by the end of the century. Similar, but slightly delayed schedules would apply to the mirror, laser or theta pinch concepts should they prove to be more attractive than the tokamak. We will consider only the tokamak plan here but the results would also apply to the other systems with appropriate time delays. Table 1 summarizes the major features of the tokamak systems as best they can be perceived at this time.

The U.S. program is based on having the Princetom Large Torus (PLT) operating in FY-76 to test plasma scaling parameters and heating methods. Shortly thereafter the Poloidal Divertor Experiment (PDX) will examine the questions of impurity control and particle removal. Next the Doublet-III will explore the advantages of a non-circular plasma cross section and extend plasma scaling laws. All of these devices are hydrogen machines and do not face any problems of radiation damage.

Table 1

Summary of U.S.A.E.C.-DCTR Proposed Fusion Devices in the 1980-2000 Period-Tokamaks

Device	Current MA	Fuel	Magnets	Breeding	Wall Loading MW/m^2	Plant Factor	Power Disposition
PLT	1-2	H_2	Cu	No	-	-	-
PDX	?	H_2	Cu	No	-	-	-
D-III	1-2	H_2	Cu	No	-	-	-
TFTR	2-3	D-T	Cu	demonstrate	~0.1	10^{-4}	dump
EPR-I	~5	D-T	S/C[a]	?	0.1-0.2	0.1-0.5	electricity?
FERF-I	?	D-T	S/C	?limited	~1	~0.5	dump?
EPR-II[b]	5-10	D-T	S/C	Yes	~0.5	~0.5	electricity
FERF-II[b]	?	D-T	S/C	probably some	~2	~0.7	dump?
DPR[b]	10-15	D-T	S/C	Yes	~1	~0.7	electricity

[a] S/C = superconducting

[b] estimated by author

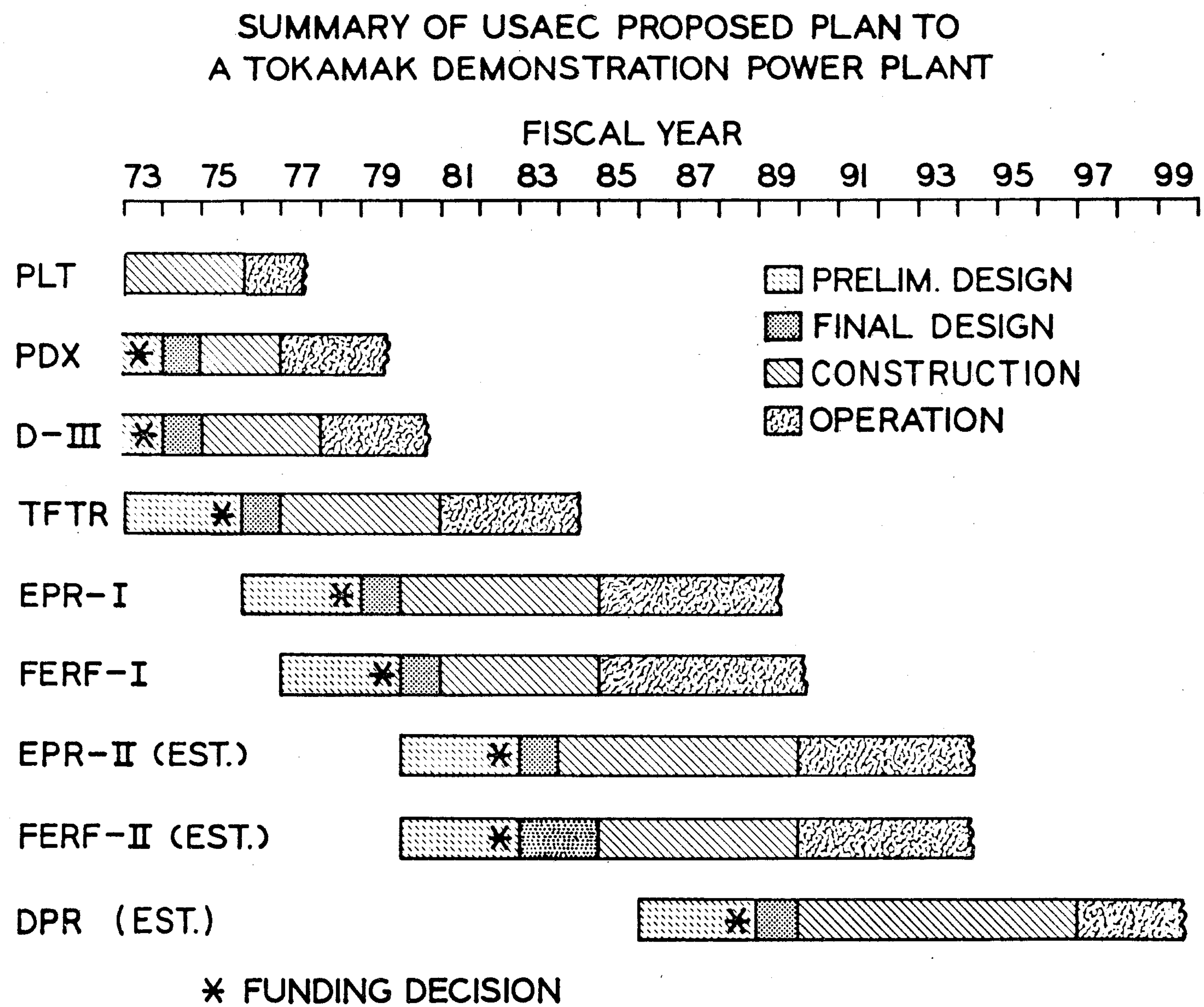

SUMMARY OF USAEC PROPOSED PLAN TO
A TOKAMAK DEMONSTRATION POWER PLANT
FISCAL YEAR
73
75
77
79
81
83
85
87
89
91
93
95
97
99
PLT
PDX
D-III
TFTR
EPR-I
FERF-I
EPR-II (EST.)
FERF-II (EST.)
DPR (EST.)
PRELIM. DESIGN
FINAL DESIGN
CONSTRUCTION
OPERATION
* FUNDING DECISION

Figure 1

The Tokamak Fusion Test Reactor (TFTR) is the first U.S. device which will use a mixture of D and T but the number of "shots" per year will be only on the order of 1000. The integrated uncollided 14 MeV neutron current will be on the order of 1×10^{16} n/cm^2/year which is high enough to induce significant amounts of radioactivity but not high enough to cause any real damage. The use of D and T in this device will be started ~FY 82.

The first reactor for which engineering data on bulk neutron damage is required are the Experimental Power Reactor (EPR-I) and the Fusion Engineering Research Facility-I (FERF-I). The EPR-I would be designed to advance both plasma physics (scaling laws, heating, fueling, burn control, impurities, etc.) as well as to advance reactor technologies such as remote disassembly and assembly, limited tritium breeding, tritium containment, use of superconducting magnets, limited electrical production, etc. The object of the FERF-I would be mainly to test materials to high neutron fluences typical of the demonstration power reactor (DPR). The FERF-I will itself experience significant radiation damage problems and it now appears that the design of this reactor will have to be without the benefit of data generated in even a quasi-typical CTR environment.(1)

The EPR-II and FERF-II reactors would be advanced versions of their predecessors designed to <u>confirm</u> the design of the DPR which is to operate in the late 1990's. Unfortunately, they will not be able to impact the DPR design since they will not have operated before construction of the DPR the DPR begins.

It is reasonable to assume that the last time that a designer can make meaningful changes in a given reactor is when construction actually begins. With that criteria, we see that the design of the reactors must be completed as follows:

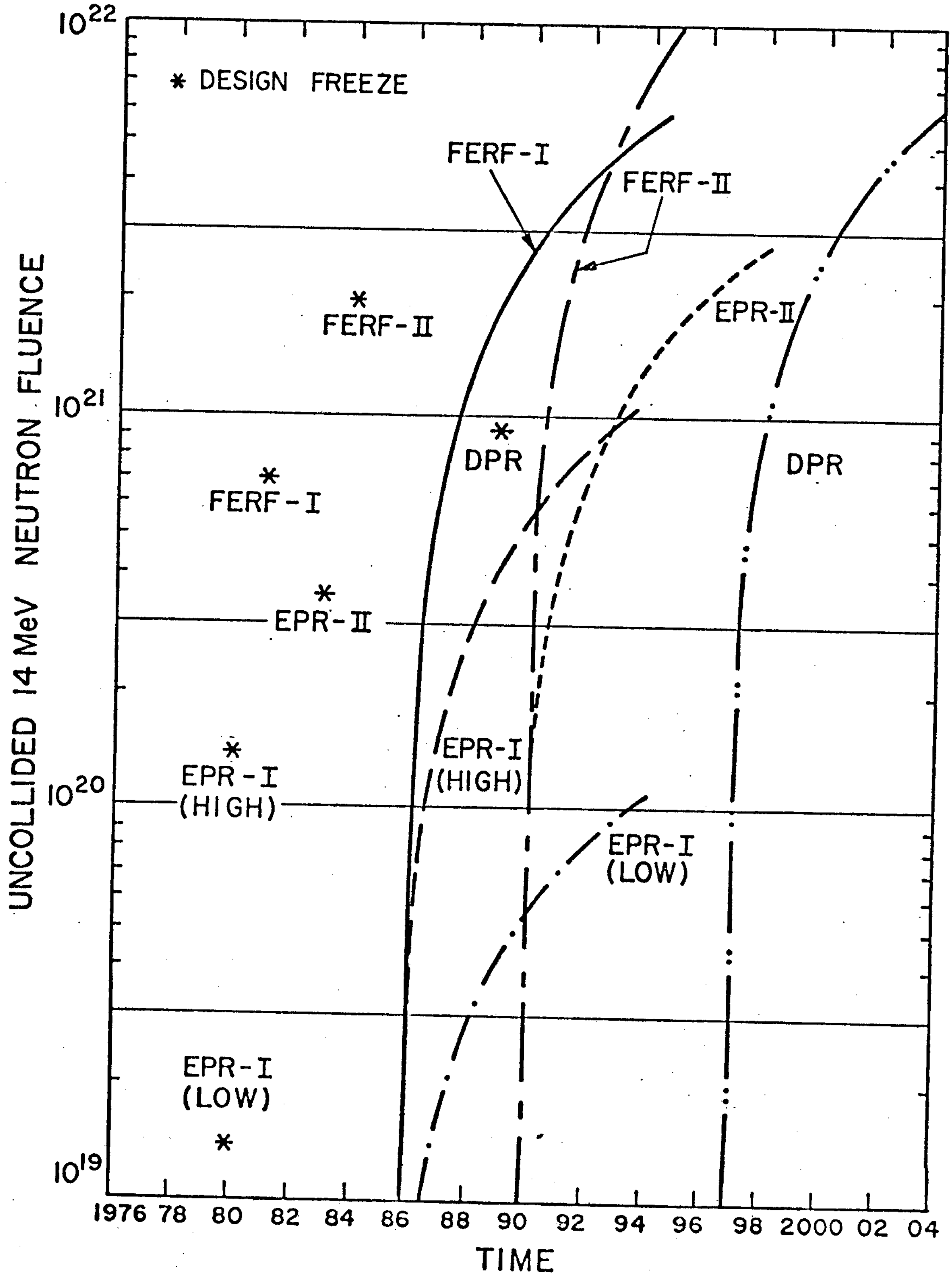
EPR-I	End of Fiscal Year - 1980
FERF-I	End of Fiscal Year - 1981
EPR-II	End of Fiscal Year - 1983
FERF-II	End of Fiscal Year - 1984
DPR	End of Fiscal Year - 1989

It is apparent from this brief analysis that the first four reactors (EPR-I, FERF-I, EPR-II, and FERF-II) must be designed without information generated in a realistic D-T plasma environment. Various ways of accumulating this information are discussed in other papers of this conference, i.e., fission reactors, solid targets, liquid targets and gaseous targets.[1-2]

Another way of looking at the time constraints is given in Figure 2 from reference 1. The accumulated uncollided 14 MeV neutron fluence is given for the five devices discussed and the stars indicate when the design information must be available for each of the reactors. Here we see more clearly that the need for 14 MeV neutron damage increases from $\sim 1 \times 10^{20}$ n/cm^2 in FY 1980 to 7×10^{20} n/cm^2 in FY 81, 1×10^{21} n/cm^2 in FY 82, 1.3×10^{21} n/cm^2 in FY 83 and 2×10^{21} n/cm^2 in FY 84. More detailed analysis of this situation is given elsewhere[1] but it is worthwhile to note here that such demands may be greater than any present or future simulation technique can satisfy. On the other hand, once the FERF-I is operating it will be able to supply the information for the design of the DPR (I and II?) and, along with FERF-II, could supply data for the design of the commercial power reactors (CPRs) of the early 21st century.

III. Estimate of Level of Damage in Potential CTR Materials for Near Term Fusion Devices

We will limit our discussion here to only those reactors which will require information from simulation devices. Any prediction of the design of these reactors is very risky at this time but it is felt that enough general



* DESIGN FREEZE
FERF-I
FERF-II
EPR-II
DPR
EPR-I (HIGH)
EPR-I (LOW)
UNCOLLIDED 14 MeV NEUTRON FLUENCE
10^{22}
10^{21}
10^{20}
10^{19}
1976 78 80 82 84 86 88 90 92 94 96 98 2000 02 04
TIME

FIGURE 2

features are understood to make order of magnitude estimates. Table II is constructed following this approach and it lists the probable primary and secondary structural materials, liners, reflectors, breeders, shield materials, magnet materials and neutron multipliers for the "near term" reactors

The next order of business is to establish the approximate operating conditions for the materials listed in Table II. Again this requires considerable speculation but since all of the designs must be completed by the 1980-1984 time period it is probably safe in assuming that no drastically new technologies will be employed. Table III gives the estimated temperature, fluence, displacement damage, gas bubble formation, and stress information for the materials in Table II.

The EPRs are expected to run hotter than the FERFs because they need to generate electricity either as a proof of principle or semi-continuously. The FERFs can be total energy consumers and therefore will probably be run as cold as possible to minimize radiation damage problems. The one exception will be the carbon liners which will be quite hot if they are in the plasma chamber and reradiate their energy to the first walls.

The accumulated 14 MeV neutron fluences have already been given and the calculated dpa rate (assuming back scattered spectra similar to a UWMAK system) is given for the stainless steel. We can see that dpa rates are in the modest range of 1-14 dpa/year. This is equivalent to fast fission neutron displacement damage of 2.1×10^{21} to 3×10^{22} n/cm^2.

The fourth column lists the helium gas production rates for steel, carbon and for some reactors Be and $LiAlO_2$. The helium production rates in the steel are quite high ranging from 20 to 200 appm per year. This would require very high fast neutron fluences (10^{23} to 10^{24} n/cm^2) to produce the same level of helium although thermal reactors would require considerably

Table II

Probable Materials in the Near Term D-T Fusion Reactors

Reactor	Primary Structural Material	Secondary Structural Material	Liner	Reflector	Breeder	Neutron Multiplier	Shield	Magnet
EPR-I	Steel	Al alloy	C	C	Li, LiAl	Be	Pb, B_4C	TiNb, Cu
FERF-I	Steel	Al alloy	C	Steel	None	None	Pb, B_4C	TiNb, Cu
EPR-II	Steel	V alloy	C	C	Li, $LiAlO_2$	Be	Pb, B_4C	TiNb, Cu
FERF-II	Steel	V alloy	C	Steel	None	None	Pb, B_4C	TiNb, Cu

Table III

Estimated Operating Conditions for the Solid Materials in Near Term Fusion Reactors

	Temp°C[(a,b)]	Maximum $\phi t(14MeV)yr^{-1}$	Maximum dpa/yr^{-1} (c)	Maximum appm He/yr
EPR-I	200-600	1.4×10^{20}	1	20 (SS) 250 (C) ~250 (Be) ~750 ($LiAlO_2$)
FERF-I	50-200	7×10^{20}	5	100 (SS) 1200 (C)
EPR-II	300-600	3.5×10^{20}	2	50 (SS) 600 (C) 700 (Be) ~1900 ($LiAlO_2$)
FERF-II	50-200	2×10^{21}	14	300 (SS) 3400 (C)

(a) Temperature for first wall and breeding zone

(b) Carbon liner temperatures will probably exceed 1000°C and in the case of thick neutrons shields may approach 2000°C.

(c) Approximately the same for steel and C lower values.[3] High levels of helium in carbon, Be, and solid breeders may also be troublesome especially if the helium collects into bubbles which promote swelling.

Now that we have a feeling for the time in which data is required, the possible materials to be used and an estimate of the operating conditions, we can address the question of just what type of data is required.

IV. Specific Information to be Sought by Designers of Near Term Fusion Reactors

A. Structural Materials

This class of materials is probably most important because it forms the containment shell for the plasma, coolant, breeding, and shielding materials. Any fracture of the structural members could be catastrophic with respect to release of radioactivity, danger of explosions or implosions, and destruction of expensive equipment. Failure of the breeder, liner, reflector, or magnet materials is serious, but has very few of the health and safety problems associated with a structural failure.

The reactor designer will require that at the very least, the dimensional and mechanical properties of the structural material be known (or in hand) through the first year of operation. This requires information from other areas such as corrosion, surface damage and compatibility which we will assume is available from laboratory tests in a non-radioactive environment.

The dimensional information needed includes such phenomena as

1. reduced thickness due to neutron sputtering
2. void induced swelling
3. swelling due to the formation of internal gas bubbles
4. swelling due to the transmutation of the base metal to other solid elements which have a larger specific volume.

The last three properties can cause components to warp or restrict coolant channels such that temperature excursions are possible. Non-uniform swelling can also cause severe stresses and strains to build up to the point that premature failure is experienced.

There are many mechanical properties which are of importance to a safe reactor design and a few of these are listed below

1. tensile strength (yield and ultimate)
2. ductility (uniform and total elongation at failure)
3. creep rate
4. creep-rupture life
5. fatigue life
6. fracture toughness

It will be very important for the reactor designer to know the response of CTR blanket structures to both fast and slow strain rate applications because both are present in such systems. Startup in Tokamak systems may take place in 10-100 seconds whereas pulsed systems such as the theta pinch and laser systems may produce large pressure pulses 1-10 times a second. The repeated application of these pulses can also present a problem with respect to fatigue. For example, if the EPR-I can achieve a 100 second cycle time and if it runs only 50% of the time, then the structural materials will experience ~150,000 cycles per year. A theta pinch system with a 10 second cycle and 50% plant factor would experience 1,500,000 cycles per year and a laser system which fires only one pellet per second (50% of the time) would experience 15,000,000 cycle per year. Clearly, the effect of irradiation on the fatigue life will be a very important factor even in near term devices.

The long term creep rate will also be critical in the higher temperature regions of the EPR's. The effect of D-T irradiation on in-reactor creep must be known as well as the effect of a large number of reactor cycles on the creep-rupture life.

Finally, fracture toughness of the structure is important to know, especially because of the large vacuum chambers and the danger of implosions. The measurement of this property, especially under realistic radiation, coolant, and stress conditions may prove to be extremely difficult.

It is important to stress two points about the amount and nature of data required for adequate reaction design. First of all, the information should be gathered in situ. Properties such as creep rate, rupture life or fatigue life are quite different if measured out of a reactor after irradiation opposed to in reactor measurements. Such tests are considerably more difficult and expensive, but absolutely essential for safe design.

The second point to emphasize is that designers will want many data points covering a wide range of operating conditions so that they can make more meaningful extrapolations. Not only would this be required of the primary structural metal but it may also be required of a backup alloy as well. Such a philosophy can multiply the number of data points required for a good structural analysis by an order of magnitude. This is particularly important to recognize when the amount of in situ testing volume is limited. Another way to evaluate the usefulness of various testing facilities is to calculate the cost of in situ data points per unit of fluence. This sometimes makes lower flux-larger volume sources more valuable than high flux-small volume devices.

B. Carbon Liners and Reflectors

The interesting feature of the carbon protector concepts[4,5] is that they will run at very high temperatures (1000-2000°C). From past experience with fission neutron irradiated carbon at 1000-1200°C,[6] it may be concluded that the damage rate is considerably reduced as the temperature is increased. However, one is never sure about such a prediction until it is experimentally verified, (for example, remember voids in metals?). The production of large quantities of helium gas internal to the carbon may also complicate this prediction. In any case, considerable dimensional testing of carbon irradiated with 14 MeV neutrons is required for all the near term reactors. These studies need to be performed on various types of carbon such as pyrolytic carbon, carbon or graphite cloth and nuclear grade bulk graphite to name just a few.

The concern about the neutron damage to the graphite reflector of the EPRs stems from the expectation that considerable dimensional changes will occur if the reflector operated at 600-800°C and displacement damage will be equivalent to 10^{22} n/cm^2 (fission). This latter number corresponds to about 5 years in EPR-I and 2.5 years in EPR-II. Again, the effect of high helium contents may make the dimensional changes even more severe.

C. Breeding Materials

There are two major problems that are known at this time for this class of materials. The first has to do with the high helium production rate. For every tritium atom produced, there is a corresponding helium atom. This is no problem in liquid lithium, but it could cause considerable swelling in solid breeding materials. For example, if one attempted to breed with $LiAlO_2$ in EPR-I or II, the corresponding helium concentration would be ~1000-2000 appm after one year. Such high helium contents in materials which have low thermal conductivities (high temperature gradients) are likely to cause considerable swelling and possible restructuring of the breeder material. This would tend to increase the stresses on cladding material and may induce premature failure.

The second problem might be radiation enhanced sintering of solid breeder materials. Most of these systems rely on small particle size (10's of micron diameter) to allow the tritium to be released without building up a large inventory. If the particles sinter together, the diffusion pathlengths for the tritium is increased and the tritium inventory may rise dramatically.

There is very little information on high fluence damage in solid breeders and if such systems were to be used in EPR's, a wide range of experimental conditions must be examined.

D. Neutron Multiplier

The only practical neutron multiplier in fusion reactors is beryllium. This element undergoes the following reaction

$$^{9}Be\ (n,2n)\,^{8}Be \rightarrow 2\ ^{4}He \qquad E_{th} = 1.85\ MeV$$

Therefore, the production of large amounts of helium gas is unavoidable in a CTR spectrum. The helium gas then collects into bubbles and can cause considerable swelling. The magnitude of this swelling is important to know so that containment structures are not overstressed. It is also important because it will determine the bulk density of the Be required before irradiation.

There has been some work on Be for fission reactor application and Figure 3 shows the calculated swelling as a function of bubble size and gas content for temperatures which might be typical of EPR operation.(7) Note that if the bubble size exceeds 1000-10,000 Å, "break away" swelling occurs. If the Be in EPR-II were to last the anticipated lifetime of the reactor, 5-10 years, then methods for keeping the bubble size below 1000 Å must be developed.

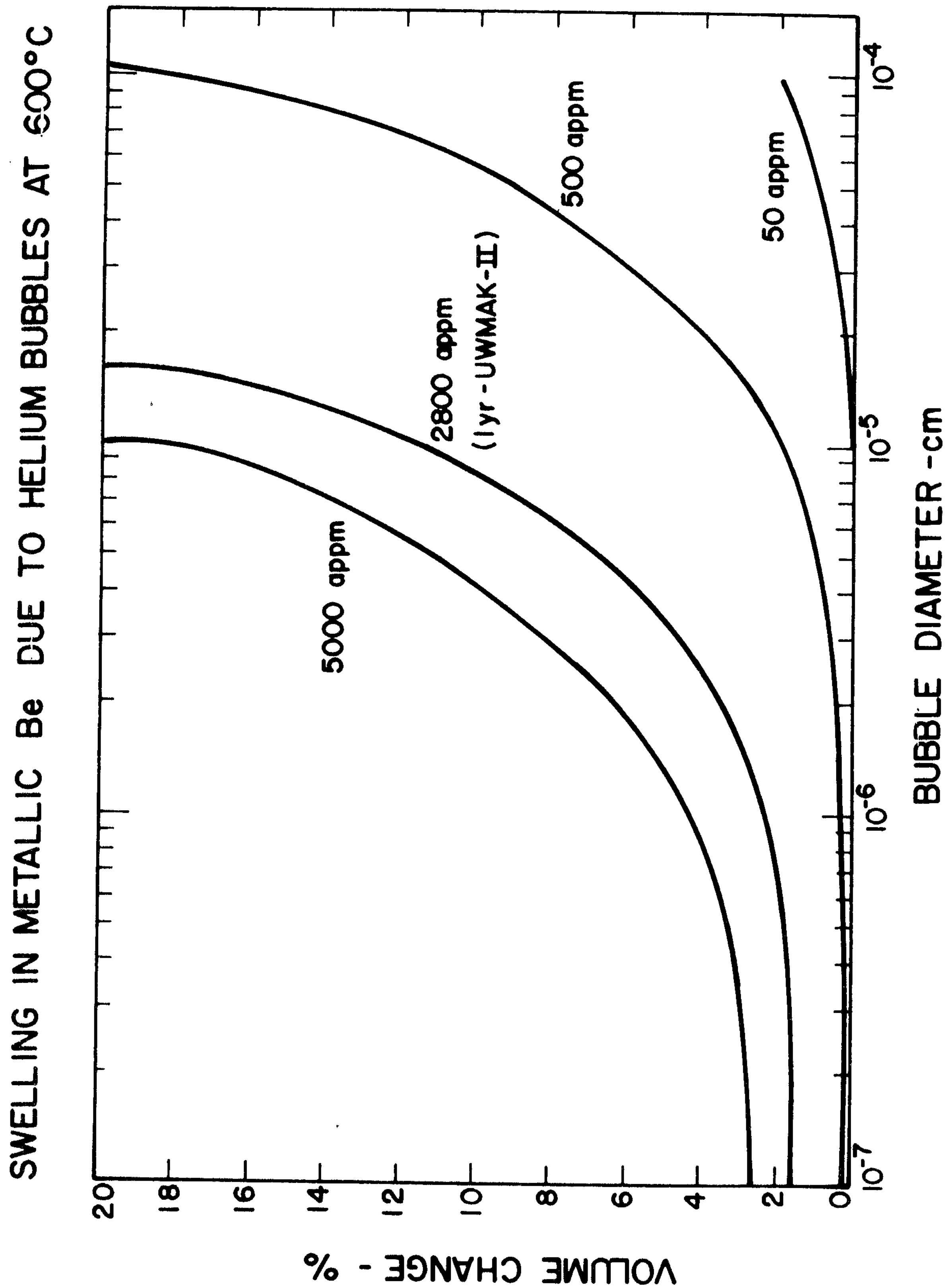

SWELLING IN METALLIC Be DUE TO HELIUM BUBBLES AT 600°C
VOLUME CHANGE - %
0
2
4
6
8
10
12
14
16
18
20
BUBBLE DIAMETER -cm
10^{-7}
10^{-6}
10^{-5}
10^{-4}
5000 appm
2800 appm
(1yr-UWMAK-II)
500 appm
50 appm

Figure 3

E. Magnet Materials

The design of the blanket and shield for D-T fusion reactors is very much a tradeoff between the level of nuclear heating (and radiation damage) produced in the magnet and the increased cost of thicker blanket-shield combinations and larger magnets. Obviously, one could reduce the nuclear heating to insignificant levels by using massive shields, but such a move may prove too costly. Therefore, it is vital to know what level of damage is tolerable in magnet materials such as the:

superconductor (i.e. TiNb)
stabilizer (i.e., Cu or Al)
electrical insulators (i.e. phenolics)
thermal insulation (i.e. mylar)
and structural support (i.e, 304-316 SS)

There is very little information available on these materials at cryogenic temperatures. Furthermore, designers will undoubtedly require data collected in situ at ~4°K on the electrical or magnetic properties because irradiation at room temperature, or irradiation at cryogenic temperatures then post irradiation testing outside the reactor, is known to give results atypical of the real damage state. The most serious reactor to consider in this regard are the FERFs because they will undoubtedly be required to run at high plant factors which will not allow significant time for magnet warm up to anneal out the damage.

An estimate of the required information for the EPR's and FERF's can be made assuming the following thresholds for damage[8]

TiNb	0.05 dpa
Cu Stabilizer	10^{-4} dpa
Electrical Insulation	3000 Mrads (~3 x 10^{-3} dpa)
Thermal Insulation	120 Mrads (~3 x 10^{-4} dpa)
Structural Support	~10^{-2} dpa

Given a dpa rate of 14 per year and assuming a 10 year magnet lifetime we see that designs for the near term reactors must attenuate the neutron displacement damage by a minimum of 5 x 10^{-7} without magnet warm up, or, by 1 to 2 x 10^{-6} with magnet warm up a few times during the plant lifetime. As a rule of thumb, 1 dpa corresponds to roughly the damage incurred by an uncollided 14 MeV neutron fluence of 2 x 10^{20} n/cm^2 and its back scattered spectrum. This means that in situ testing on several magnet components needs to be conducted for a 10^{19} n/cm^2 neutron exposure.

F. Electrical Insulator and Other NonStructural Materials

It is difficult to predict what information will be required here because relatively few designs have specified the function or environment for electrical insulators or other non-metals. Certainly, there will be a need for electrical insulators for the injectors in tokamak and mirror but they may well be positioned outside the major radiation damage zone. The one exception to this observation is the insulation on the first wall of the theta pinch reactors which must withstand 100 kV/cm during very fast pulsing conditions. In situ electrical resistance measurements on Al_2O_3, MgO and Y_2O_3 at high temperatures during neutron fluxes of 10^{13}-10^{14} n/cm^2/sec (14 MeV) must be obtained. Fluence accumulations of 10^{20}-10^{21} uncollided 14 MeV neutrons/cm^2 must be achieved, understood and result in the selection of a radiation damage resistant material.

One last point to mention with respect to materials and that is the problem of neutron damage to mirrors for laser devices. These mirrors must retain a high degree of reflectivity under rather severe radiation exposures (essentially equal to those on the metallic first wall.) It will be necessary to test mirror materials (probably coated with materials like GaAs or CdSe) at moderately high temperatures to 14 MeV neutron fluences of 10^{20}-10^{21} n/cm^2.

VI. Relevant Simulation Tests

There are three key questions that must be asked of any data coming from irradiation facilities which purport to simulate CTR irradiation environments.

1. Does the test simulate the primary knock-on atom (PKA) spectrum typical of a complete (14 MeV and back scattered neutrons) CTR neutron spectrum?

2. Does the test produce transmutation products (both gaseous and solid) with the proper ratio to displacements?

3. Does the test produce displacements at a rate which is typical of the CTR environment?

The first question is especially important for damage processes which depend on the displacement spikes rather than total displacements. For example, this may be the case for void nucleation, precipitate formation or precipitate dissolution. Electron irradiation can produce sufficiently high dpa levels in CTR materials but can only displace one or two atoms per collision. This is contrasted to the 10^3-10^4 atoms displaced per neutron collision in a CTR spectra.

The second point is especially important for processes which depend on the interaction of displaced atoms (or vacancies) with foreign atoms such as gaseous transmutation products (H,He) or solid transmutation products such as Si in Al, Zr in Nb, Ti in V, etc. It is also known that gaseous atoms can have a dramatic effect on the nucleation of voids (increasing the rate) and that solid impurities generally tend to reduce the nucleation rate by trapping the point defects. Fission reactors (with the exception of helium generation of nickel containing alloys in thermal reactors) cannot produce the proper ratio of transmutation products to displaced atoms thereby may not be able to provide valid simulation results. Figure 4 is an example of the helium/dpa ratio produced in several CTR materials in a CTR and EBR-II environment. In some materials, there are 3 orders of magitude difference between the ratio in fusion reactors and the ratio in fission systems. Prior doping with transmutation products is not always an acceptable way to get around this difficulty. High initial concentrations of impurity atoms can bias the microstructure such that the proper defect configuration is never reached. Accelerator studies with heavy ion bombardment can be coupled with simultaneous hydrogen or helium injection to overcome this problem, but no one has yet been able to simultaneously inject the proper amount of solid impurity atoms.

Finally, the rate at which damage is found is also very important. Accelerated studies by their very nature are performed at higher displacement rates than normal. It is known that higher damage rates increase the probability of recombination of interstitials and vacancies, lowering the supersaturation level and thereby reducing void formation and growth at a given temperature. Figure 5 shows what the typical instantaneous displacement rates might be in tokamaks, mirrors, theta pinches and laser systems. These rates also vary significantly from the blanket to the shield and to the magnet. For tokamak and mirrors, the rates are generally modest in comparison to fission reactors and they become quite low as one progresses to the outer portions of the reactor. The rates in the theta pinches are increased because of the pulsed burn for only ~100 ms in a 3-10 sec cycle period. The rates are highest

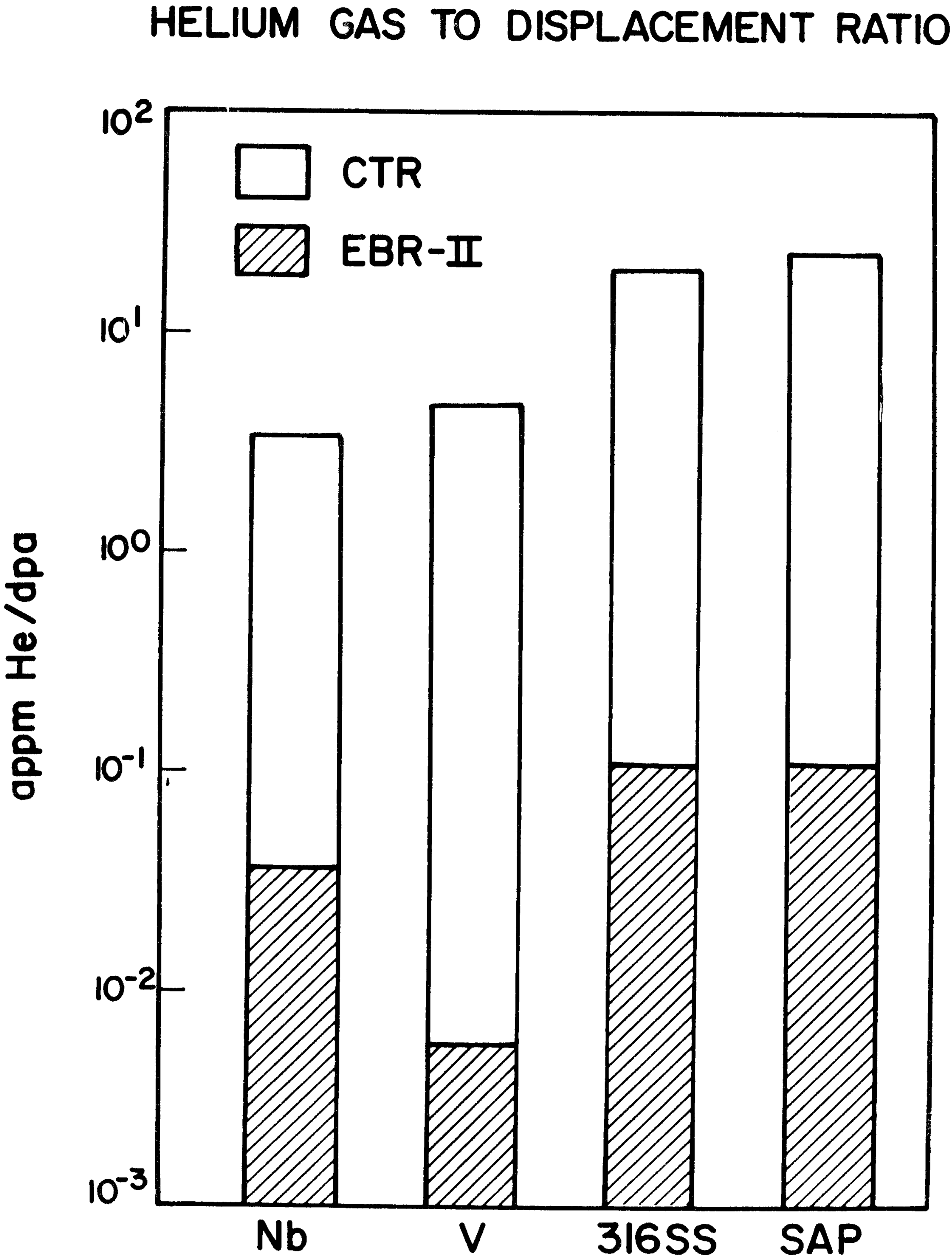

HELIUM GAS TO DISPLACEMENT RATIO
CTR
EBR-II
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
appm He/dpa
Nb
V
316SS
SAP

Figure 4

INSTANTANEOUS NEUTRON DISPLACEMENT RATES IN DT CTR FIRST WALLS

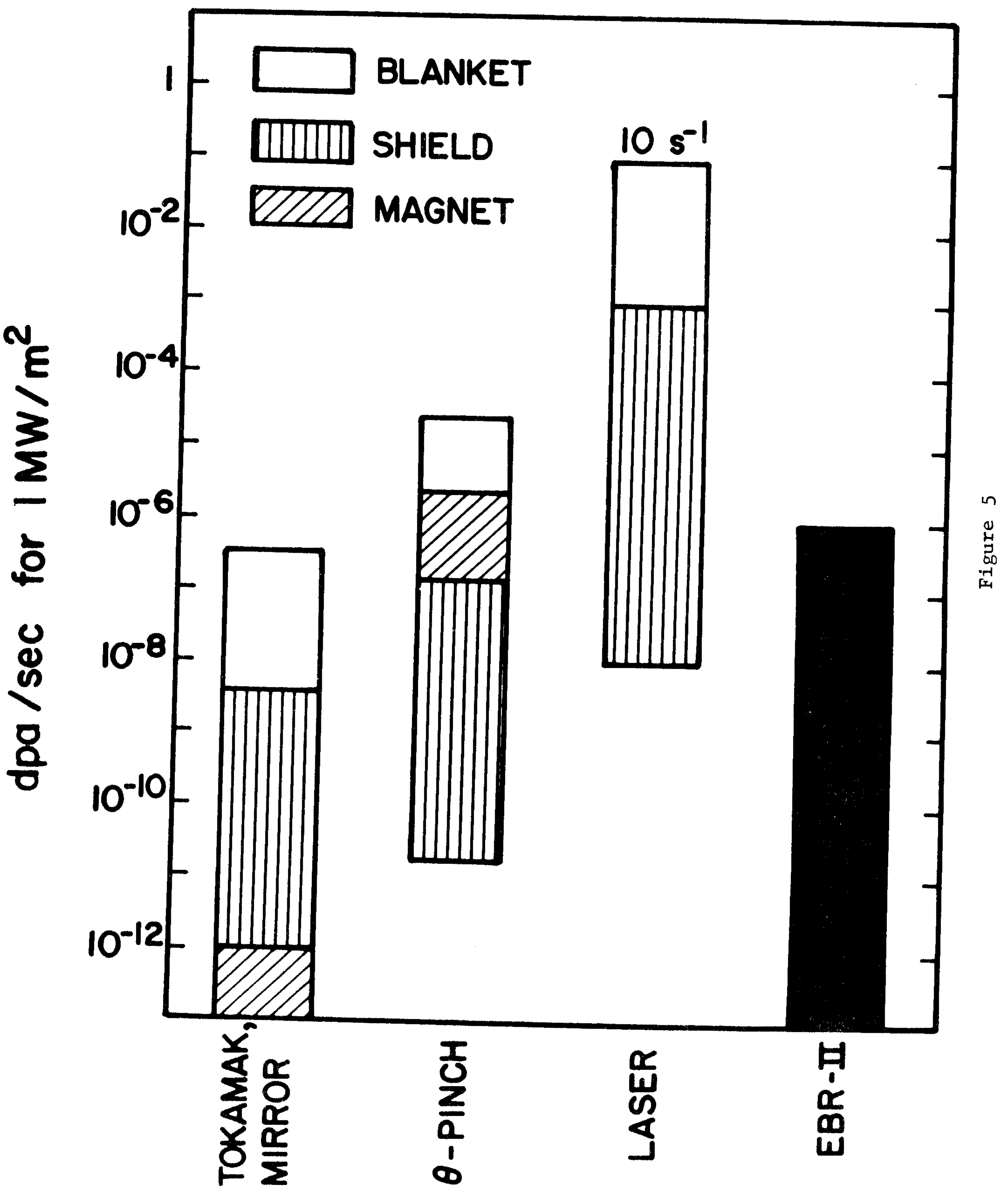


Figure 5

for laser systems because the neutrons are produced on a nano second scale and neutrons are slowed down on a microsecond scale. Hence, very high ($\sim 10^{-2}$ to 10^{-1} dpa/sec) damage rates are incurred instantaneously even though the time averaged dpa rate per year is about the same for tokamaks and mirrors.

The designers of the pulsed systems will need to know the effect of these high damage rates on physical and mechanical properties of CTR materials. Special facilities such as pulsed accelerators may be necessary to tailor the displacement rates to more realistic values. Finally, it will be very difficult to use pulsed sources to simulate steady state damage in tokamaks or mirrors and vice versa, steady state damage in the tokamaks and mirrors may not be at all typical of the damage incurred in pulsed systems at the same damage level.

VI. Conclusions

The need for CTR materials radiation damage information is becoming quite critical for the design of the Experimental Power Reactors and FERFs which are expected to operate in the period 1985-1990. Design decisions on these reactors will have to be essentially complete by FY 80 - FY 84. This means that considerable information must be gathered on structural, reflector, liner, breeder, neutron multiplier, magnet and insulating materials in the 1975-1980 period. This data must be collected in a realistic environment which means heavy emphasis will be placed on in situ testing, and duplication of the proper PKA spectrum, transmutation product to displacement atom ratio and displacement rates. The number of data points required will be quite large for design purposes and secondary materials will have to be tested in parallel to insure a timely solution. All of this adds up to a very difficult period in the latter half of the 1970's and failure of this effort could mean significant postponement of the operation of the first demonstration power reactor well into the 21st century.

Acknowledgement

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