NEED FOR AND REQUIREMENTS FOR NEUTRON IRRADIATION FACILITY FOR FUSION MATERIALS TESTING ‡

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ABSTRACT

The construction and operation of an intense 14MeV neutron source is essential for the development and eventual qualification of structural materials for a fusion reactor demonstration plant (DEMO). Because of the time required for materials development and the scale-up of materials to commercial production, a decision to build a neutron source should precede engineering design activities for a DEMO by at least 20 years. The characteristic features of 14MeV neutron damage are summarized including effects related to cascade structure, transmutation production, and dose rate. The importance of a 14MeV neutron source for addressing fundamental radiation damage issues, alloy development activities and the development of an engineering data base is discussed. From these considerations the basic requirements and machine parameters are derived.

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1. Introduction

The realization of safe, economical and environmentally sound fusion energy is an ultimate goal for fusion research. In the course of attaining this goal, one of the most challenging problems is the development of fusion reactor materials. Particularly, it has long been recognized that the first wall and blanket structural materials will be exposed to a very high fluence of high energy neutrons and that the development of materials which can be used under such severe conditions is a key issue for fusion reactor development.

For research and development of materials for high fluence irradiation performance and of testing of potential materials, an intense fusion neutron source is a pressing need for material scientists and engineers as an essential tool. Engineering test reactors such as ITER and FER cannot be used for high fluence testing. Their relatively low 14MeV neutron fluxes would necessitate exposure times on the order of tens of years, which exceeds the lifetime of the first wall and blanket structure of these next-step machines. Therefore, the idea of utilizing fusion reactors instead of an intense neutron source contains a self-inconsistency1).

The history of developing the intense neutron source for fusion materials development, especially from the standpoint of international cooperation will be described in another paper2). In the present paper, we will summarize the characteristic features of radiation effects in materials irradiated with 14MeV neutrons. Updated knowledge of radiation effects with high energy neutrons will provide a clearer view on the need for and requirements of the intense neutron source and will give a basis for considering the suitability of such a source.

Major inputs to this paper come from independent recent studies, within the past one or two years, carried out in the United States, Europe and Japan3, 4, 5).

2. Fusion Neutron Radiation Effects on Materials

The first wall and blanket structural materials in a future fusion reactor will be used under the severest conditions among the various materials used for the permanent or semi-permanent components of the reactor. Neutron wall loading is an important parameter used to define the operating conditions for the materials. Typical values of the neutron wall loading for the current design of fusion devices ranges from 0.5 - 2MW m^{-2}. The thermal wall loading depends on the neutron wall loading and on details of the design but the usual values are of the same order of magnitude as the neutron wall loading. 1MW m^{-2} of neutron wall loading corresponds to an incoming 14MeV neutron flux from the plasma of 4.43 X 10^{17} neutrons m^{-2} s^{-1}. However, the actual neutron flux at the first wall position is dependent on the materials configuration in the blanket: usually the total neutron flux at the first wall is roughly an order of magnitude higher than the incoming 14MeV neutron flux. Not only the flux but the spectrum of neutrons also depends on the detailed configuration of the materials, and hence is design-dependent. If we use the concept of the neutron spectrum at the first wall in the discussion of a neutron source, we have to define a reference design of the fusion device and a benchmark spectrum at the reference position of the device. In any case, the high energy region of the spectrum and in particular, the fraction of 14 MeV neutrons plays an important role in creating atomic displacements and in transmutation reactions.

Table 1 summarizes the conditions of first wall structural materials for various fusion devices, showing estimated cumulative lifetime neutron wall loadings, corresponding lifetime displacement damage levels and the amount of helium production for austenitic stainless steels. For comparison, the maximum achieved conditions with a D-T neutron source, RTNS-II, are also given. Here, we would like to make a few remarks:

(1)Even if the lifetime displacement levels are low for near term machines, there are still some new problems associated with a large component such as a first wall structure. Securing the integrity of a large scale permanent component of a reactor receiving a displacement dose exceeding 1 dpa will be a new experience in nuclear technology. This will be easily understood if we consider that radiation embrittlement is still an important issue in pressure vessel steels for light water reactors.which receive less than 0.01 dpa during their service lifetime of 30 - 40 years.
(2)It should be pointed out that the next-generation machine such as ITER will be constructed from existing materials having a well-established fabrication technology. These materials however will not satisfy the more demanding requirements of the DEMO environment and entirely new materials, probably having reduced activation characteristics, will be required. A recent comprehensive study$^{6)}$ in the U. S. concluded that at least 5-8 years operating experience with an intense 14 MeV neutron source will be required before a realistic assessment can be made of the environmental and economic potential of fusion as a major energy source. If construction of a DEMO as the next stage of commercialization appears justified at that point, the development of a design data base for prototypic commercial materials and integrated component testing in an Engineering Test Reactor would probably require a further 8-10 years. Since the design and construction of a 14MeV neutron source will require say 5 years, it appears that a decision to build a 14MeV neutron source should precede building a DEMO by at least 20 years.
(3)The world's largest 14MeV neutron source is the RTNS-II, which has been shut down for a few years. With this machine, the practically attainable damage level for almost continuous operation

for one year is about 10^{-2} dpa, which is four to five orders of magnitude less than the damage level expected for a commercial fusion reactor. Further development of fusion as an energy source can not be justified without making an appropriate investment for materials development to bridge the enormous gap between our current experience of 14MeV neutron damage and what will be required for a DEMO.

Nearly all of the materials and components of a fusion reactor will be required to be subjected to neutron irradiation testing. For some materials of important components, the necessary test conditions to be completed before a DEMO reactor can be designed are shown in Table II[1, 7]. Among those materials listed, radiation damage in first wall and blanket structural materials will be the severest for the DEMO reactor and beyond[8]. However, even for the near-term machines such as FER, NET and ITER, radiation effects in some materials other than the first wall structural materials will also be important. For example, in graphite, irradiation to 1 MW y m^{-2} which corresponds to a total neutron fluence of about 1 X 10^{26} n m^{-2} will produce displacement damage of 9 dpa and 2175 at.ppm of helium[3]. The effect of irradiation in various kinds of graphite under this irradiation condition on structural integrity, thermal conductivity, fracture toughness and so on has not been studied owing to the lack of a 14MeV neutron source facility. Even with fission reactor irradiations, which produce much less helium, the irradiation database exceeding 1 dpa is very limited. Most of the data available are for irradiations below 5 X 10^{26} m^{-2} for E>50 keV[9]. Even for the most common structural alloys such as austenitic stainless steels, the irradiation data base below 300 C in an aqueous environment to a dose range exceeding 1 dpa is very limited.

The point to emphasize is that although is is extremely unlikely that the introduction of an intense 14MeV neutron source will be timed to meet these near term objectives, radiation damage studies are still very important for materials for near term applications. However if a rapid decision is taken to implement the neutron source, it could also make a contribution to the characterization of some materials for ITER$^{4)}$.

3. Characteristic Features of Radiation Effects with 14MeV Neutrons

The major characteristic features of radiation effects produced by 14MeV neutrons are twofold; (1)cascades produced by high energy knock-ons, and (2)large nuclear transmutation rates including high helium production rates.

3.1. Effects related to high energy cascades.

Figure 1 shows the maximum PKA energies for 1MeV and 14MeV neutrons for various elements. It should be pointed out that subcascade energy is typically a few tens to several tens of keV so that the damage produced by fission neutrons is mostly in single (sub) cascades, whereas that produced by fusion neutrons is composed of multiple subcascades. The cascade is a region containing a high density of point defects, and the probability for the point defects to escape from recombination, in other words the defect production efficiency*, the freely migrating defect production efficiency and the clustering efficiency depend on the structure of the cascade. The subcascade structure produced by energetic heavy ions which simulate energetic PKAs is shown in Fig.2. A number of calculational or experimental investigations have shown that the defect production efficiency and the freely migrating defect production depend on PKA energy. Examples are shown in Fig. 3[10, 11]. As shown in the figure, both efficiencies decrease considerably at higher PKA energies. this implies that even if the dpa values are the same for the two kinds of radiation environments, the effective dpa is less for the radiation giving higher PKA energies. For a better irradiation correlation, one should determine the appropriate correlation parameters dependent on PKA energies rather than relying on a single parameter of dpa. The correlation parameters may be different for different property changes; for example, void swelling and irradiation creep rates may be most adequately related to freely-migrating defects. Since PKA energy spectrum is determined by neutron energy spectrum, it is important in evaluating the neutron sources to consider how closely the neutron spectrum gives the PKA spectrum for fusion reactor materials. In this connection, the effect of high energy tails for some of the proposed neutron sources should be carefully evaluated.

3.2. Effect of helium and other transmutants

Among the various kinds of transmutants, helium is the most important one because it is well known that helium has a pronounced effect on microstructural evolution, in particular, void formation.

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* Slightly different definitions have been made by different investigators.

Figure 4 shows the effect of the mode of helium introduction on void formation[12]. In some exceptional cases, void swelling differs by an order of magnitude in the presence of helium. For example, if one compares Fig 4 (a) and (d), swelling is 18 % in the case of (a), whereas it is only 1 % for the case of (d) at the same displacement level of 70 dpa.

Helium is known to assist void nucleation. However, if a large number of cavities are formed by helium, they enhance the sink density and sometimes cavities can not grow beyond a certain critical radius depending on the number of helium atoms in the cavity and on the sink strength of various other sinks. Thus in such a case, helium suppresses void swelling. Helium is also known to enhance interstitial loop formation. There are several factors which determine the incubation fluence of void swelling. One of these factors is helium; a change of swelling rate from the incubation stage to a steady state void swelling regime is considered to be due to a transition from a gas-driven bubble regime to a bias-driven void growth regime. However, the incubation fluence seems to depend also on other microstructural variables such as dislocation density and on microchemical factors such as radiation-induced segregation and precipitation. All of these factors are also affected by the presence of helium. Therefore, it is very difficult to predict what the incubation fluence would be in the fusion reactor environment. The effect of helium on radiation-induced or enhanced precipitation or on phase stability has also become evident. Modification of the mobility of point defects by helium trapping may be one of the possible mechanisms.

Helium causes high temperature embrittlement in most of the materials irradiated with neutrons, particularly at low strain rates. This can be a major problem even in fission reactor irradiated materials, in which the helium generation rate is one or two orders of magnitude less than in the fusion neutron case. Helium is also known to cause low temperature embrittlement in some metals.

By utilizing fission reactors or accelerators, the effect of helium may be studied independently as shown in Table III. However, the simultaneous generation of helium, hydrogen and solid transmutants together with displacement damage can only be simulated by a fusion neutron source. Therefore, helium, hydrogen and solid transmutant production rates relative to dpa rate are the crucial factors to be considered in evaluating a neutron source.

The effect of hydrogen has not been clearly understood yet. Recent simulation studies with dual beam accelerators indicate that the effect of hydrogen on microstructural evolution and on embrittlement does exist, but is has not been quantified yet. However, hydrogen effect seems to occur at relatively low temperatures; below 300 C in pure nickel, below 400 C for austenitic stainless steel, for example. It should be noted that these are ITER relevant temperature ranges.

The effect of some of the other transmutants has been discussed, for example, vanadium production in stainless steels. However, no experimental studies to assess the impact of solid transmutants have been performed. Further studies will be needed both theoretically and experimentally in the future.

3.3 Effect of dose rate

In a fusion reactor, the displacement rate will typically be (3-10) x 10^{-7} dpa s^{-1}. This is a dose rate typically obtained using the most advanced materials testing reactor. In "simulation" studies with heavy ion accelerators, much higher dose rates, exceeding the fusion reactor case by a factor of 10^3-10^4 have been utilized. Such an accelerated irradiation, sometimes produces completely different microstructural evolution. Even among different neutron irradiations, it has recently been pointed out that the dose rate effect is important. Figure 5 shows the overwhelming role of dose rate on swelling[13)].

For materials development, accelerated irradiation testing is desirable but it should be such that the data can be extrapolated to the actual operating condition of the materials. In other words, the neutron source must have the potential to study the dose rate effect over a wide range.

4. Need for the Study of Radiation Effects to High Fluences.

One of the strongest incentives for the high energy intense neutron source is to understand the behavior of materials at high fluence, to develop materials which can be usable up to a high fluence and to establish (a high fluence) materials database for the first wall and blanket materials of a DEMO reactor. A 14MeV neutron source must be sufficiently flexible to accommodate three types of research and development activities,

(1) fundamental studies
(2) alloy development activities
(3) development of an engineering database.

The objective of the fundamental studies is to develop a basis for predicting materials behavior in a fusion environment from the very beginning of defect production to the very high fluence expected in a commercial fusion reactor. The methodology of predicting materials behavior in a fusion environment to a high fluence region may be by constructing models from basic data and by calibrating the models from experiments using an appropriate, well-defined neutron source. More specifically, the present effort is focused on linking RTNS-II data with equally well defined fission reactor data, and in the near future, extending the established correlation to high fluence will be required.

The purpose of the alloy development phase is to define the physical and mechanical property changes during irradiation through various stages of developmental alloys. This is an iterative process involving modifications to alloy compositions and will require a long time, say five years for one research cycle. The neutron source must have the capability of accelerated irradiations: a study of dose rate effects must be carried out to ensure the validity of the higher dose rate data. In order to handle a large specimen matrix, because of the large number of variables involved, the establishment of small specimen test techniques is required. It should also be noted that new phenomena could evolve at high fluences owing to radiation-induced segregation and to chemistry changes resulting from nuclear transmutations.

In the engineering database phase, measurements of physical and mechanical properties for prototypic commercially produced candidate materials must be obtained at least to a DEMO lifetime fluence.

For fusion reactor development, it seems obvious that irradiation testing of blanket components will be necessary. This will require very large volumes and flux levels, rather than fluence, as high as the actual fusion environment. There has been some discussion of whether the neutron source should be capable of accommodating the irradiation testing of large scale components[14)] but it seems to be more sensible to consider a different type of fusion nuclear technology testing machine such as ITER. In any case, one should recognize that none of the facilities can do the entire job by itself.

The argument given above also relates to irradiation volume issues. For fundamental studies for calibrating damage models, typical specimens are of pure metals and model alloys, and mostly mini-sized. Recent size dependence studies have shown that bulk tensile properties can be obtained if the size of the minimum section of the specimen is larger than ten times of the grain size. The irradiation conditions of neutron flux and temperature must not vary too much over the specimen volume. Because of the application of small specimens, accurate results can be obtained, for example, with RTNS-II, which has a very steep flux gradient of 30 %/mm near the source point. If the research objective is materials development for high fluence using developmental alloys or to obtain a materials database for candidate materials, use of the standard sized specimens is preferable. However, one should also recognize that in some of the mechanical property testing such as fracture toughness, sometimes the valid specimen size becomes very large and we have to compromise by setting a certain limiting value for the homogeneiety of damage over the specimen volume. In the case of large component testing, one has to require a large volume and an appropriate flux gradient which is not much different from the actual fusion device in question. In other words, the materials testing is to obtain design-independent data, whereas component testing is usually design-dependent. The need for a high fluence capability is also different for the two kinds of research objectives.

The time structure of the neutron flux is also of concern because some of the proposed neutron sources are essentially pulsed sources. For materials irradiation studies, steady state sources are preferable. Pulsing affects microstructural evolution in a complex manner depending on alloy composition, temperature and pulse frequency$^{3)}$. European studies indicate that the pulsing frequency should be more than 100 Hz with a ratio of beam time over cycle time greater than 0.5$^{4)}$ if pulsed operation is unavoidable. However, the criteria must be determined by the characteristic time constants of various solid state processed which strongly depend on temperature.

5. Neutron Source Requirements for Fusion Materials Testing

From the discussions given above, the factors for evaluating the suitability of the source for materials testing may be summarized as follows:

(1) Neutron spectrum,

This is very important because, first, it determines the primary recoil spectrum, which strongly affects radiation-induced property changes and secondly it determines nuclear transmutations. The neutron spectrum should produce a primary recoil spectrum similar to that of a fusion reactor and nuclear transmutations which are not much different from those produced by fusion neutrons.

A pure 14 MeV spectrum is superior because various fusion reactor spectra can be tailored from the pure D-T spectrum.

In some of the proposed neutron sources the effect of the high energy tail beyond 14MeV must be evaluated. However nuclear data for high energy neutrons especially above 20MeV are scarce and the method of evaluating the nuclear data in the energy range must be developed.

(2) Flux and fluence,

A high fluence capability, at least to a DEMO fluence will be required. To achieve the DEMO fluence within a reasonable time of 2-3 years the displacement rate must be greater than $6X10^{-7}$dpa/s. Here, continuous operation of the source or a very high source availability is assumed possible.

(3) Irradiation volume,

For alloy development and for establishing the database for some candidate materials, an irradiation volume greater than $10^{-3}m^3$ is required. This is determined by the number of materials to be examined, or broadness of experimental matrices, the types of experimental set-ups and the necessity of in-situ instrumented experiments.

(4) Flux gradient,

This is closely related to the irradiation volume and is dependent on the progress and limitations of specimen miniaturization,and the requirement of homogeneiety of radiation damage within the test section of the specimens. In some cases, temperature gradients within the specimens will limit the size of the specimens.

(5) Accessibility,

Precise temperature control is essential for irradiation studies. Easy set-up or removal of the specimens without breaking the specimens is a necessary pre-requisite. In-situ experiments requiring even larger access space are considered absolutely necessary$^{4)}$. Perturbation of the irradiation environment by the specimens must be minimal. The neutron source is desired to provide a "benchmark" field, which is relatively unaffected by loading the materials in the irradiation position. In some kind of neutron sources, the effect of the magnetic field or of electrostatic potential must be assessed.

(6) Time structure of the neutron flux,

A continuous or at least quasi-continuous operation with high duty cycles is considered mandatory. Repetition time greater than time constant of solid state processes in the materials under study would introduce unacceptable complexity and uncertainty into the observed radiation effect which would lead to difficulties in analyzing the results.

(7) Upgrading capability,

Since improvements in machine technology would give additional flexibility to the source, a capability for upgrading is desirable, for example, to accommodate higher fluence testing needs and to examine dose rate effects over a wider range and so on.

(8) Neutron source as an integrated facility,

The neutron source is not merely a combination of accelerator and target. It should be an integrated facility for materials research with target cells, shielding, research and service hot cells, ancillary hot laboratories and so on. The importance of these additional parts of the facility to the materials research and to the total cost of the facility should be fully recognized.

6. Concluding Remarks

(1) The materials research program should precede the plasma machine program by at least ten years. While the plasma community is discussing the next generation machine, materials scientists and engineers must be considering the DEMO.

(2) The important characteristic features of the fusion neutron environment are two-fold. One is the effect of cascades produced by high energy PKAs and the other is that of nuclear transmutations. Both effects are determined by the neutron spectrum.

(3) The neutron spectrum of the source should give PKA spectra and nuclear transmutations simulating those obtained in materials placed in a fusion environment. A high fluence capability at least to a DEMO fluence is essential. This determines the minimum requirement of the flux assuming continuous or quasi-continuous operation of the source. Irradiation volume is also of great concern for alloy development and for obtaining an engineering database. Other requirements such as flux gradient, accessibility, time structure of the neutron flux, capacity for upgrading are also important. Finally, it is pointed out that construction of the irradiation cells, hot laboratories, shielding, safety and other ancillary facilities must be given adequate consideration.

(4) The capability for large scale integrated component testing is desirable but it should not be an essential factor in the source evaluation. This kind of testing is important for the study of design-

dependent materials performance in a fusion environment and will probably require a different type of facility.

(5) The neutron source should provide a "benchmark" irradiation field which is relatively unaffected by experimental set-ups. In this regard it is important to develop an international consensus on the type of fusion neutron environment which should be used as a reference.

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Figure Captions

Figure 1. Maximum primary knock-on energy produced by 1 MeV and 14 MeV neutrons for various elements. Range of subcascade energy is also shown. Above this range, the cascade may be composed of multiple subcascades.

Figure 2. Subcascade structure in gold produced by energetic heavy ions at 120K, simulating cascade produced by energetic PKAs.

Figure 3. (a) Defect production efficiency in copper as a function of a cascade parameter, $T_{1/2}$, which is a kind of average PKA energy9); (b) Free interstitial production efficiency experimentally obtained in Ni-Si alloy and by computer simulation in iron10).

Figure 4. Voids produced by dual ion bombardment at 900K to 70 dpa in an austenitic alloy. (a) No added gas; (b) Simultaneous injection at 20at.ppm He/dpa; (c) Pre-injection of 1400 at.ppm He at room temperature. (by N. H. Packan and K. Farrell, ref. 11.)

Figure 5. (a) Void size as a function of dpa in pure nickel. "Predicted" size-dose relations are shown for various dose rates; (b) Void swelling as a function of dpa. The broken lines are the "predicted" swelling-dose relation according to (a). (ref. 12)

Table 1. Damage Parameters For An Austenitic Stainless Steel First Wall In Various Fusion Reactors

Fusion Device	Integrated Neutron Wall Loading, MW y/m^2	Displacement Damage Level dpa	Helium Production at.ppm
FER	0.3	3	45
NET	1	10	150
ITER (Physics)	1	10	150
(Technology)	3	30	450
DEMO	10	100	1500
Commercial Reactor	40	400	6000
Maximum achieved condition with RTNS-II	10^{-3}eq. 1×10^{19}n/cm^2(14MeV)	10^{-2}	0.2

Table II. Critical issues and range of conditions for the different classes of materials (ref. 6)

Materials application	Critical issues	Range of conditions
Plasma interactive/high heat flux components	Rate of erosion and redeposition Thermal conductivity change Fatigue Tritium permeation rate	Neutron ≥14 MeV, up to 200 dpa Plasma particle 0.01 to 1 keV, up to $10^{30}/m^2$ Heat flux: up to 5 MW/m^2
Blanket structural	Mechanical, microstructural and dimensional changes Tritium permeation rate Compatibility with breeder materials	Neutron ≥14 MeV, up to 200 dpa Temperature up to 700 °C
Tritium breeding	Tritium release behaviour Structural integrity. Compatibility with structural materials and coolants Development and evaluation of neutron multipliers	Neutron 0.1–10 MeV. Burn-up ratio: up to 15% Temperature 400–900 °C
Superconducting magnet	Critical temperature, critical field, critical current. Fabrication and mechanical stability. Stability of coils.	Radiation doses relatively small Not a critical issue
Special purpose	Mechanical and dimensional changes Electrical conductivity and dielectrical property changes.	Neutron up to 100 dpa

Table III Simulation techniques for fusion neutron irradiation effects

Utilization of fission reactors

(1) Nickel trick (for Ni-bearing alloys): $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$

  a) Spectral tailoring technique

  b) Isotope tailoring technique

  c) Injector foil technique

(2) Copper triple reactions: $^{63}Cu(n,\gamma)^{64}Cu \xrightarrow{\beta} {}^{64}Zn(n,\gamma)^{65}Zn(n,\alpha)^{62}Ni$

(3) Iron double reactions: $^{54}Fe(n,\gamma)^{55}Fe(n,\alpha)^{52}Cr$

(4) Boron trick: $^{10}B(n,\alpha)^{7}Li$ reaction

  a) $^{10}B/^{11}B$ isotope tailoring

  b) Continuous ^{10}B supply technique

(5) Tritium trick: $^{3}T \xrightarrow[12.3y]{\beta} {}^{3}He$

  a) Static method

  b) Dynamic helium charging experiment (DHCE)

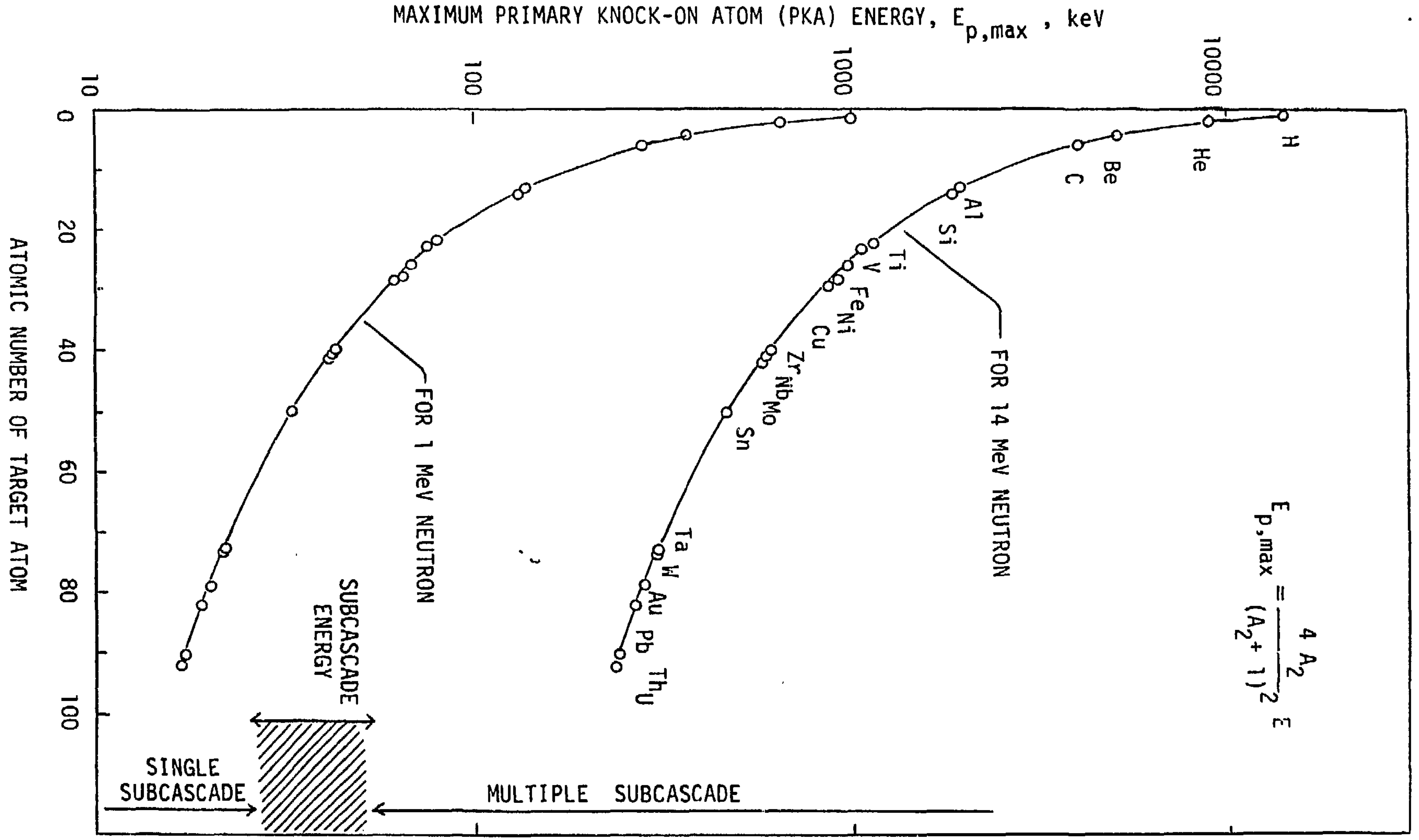
Fission reactor coupled with charged particle accelerator

Utilization of accelerators

(1) Helium pre-implantation

(2) Dual beam ot triple beam irradiation

(3) Light ion irradiation: e.g. 20 MeV deuterons.


MAXIMUM PRIMARY KNOCK-ON ATOM (PKA) ENERGY, $E_{p,max}$, keV
10
100
1000
10000
ATOMIC NUMBER OF TARGET ATOM
0
20
40
60
80
100
H
He
Be
C
Al
Si
Ti
V
Fe
Ni
Cu
Zr
Nb
Mo
Sn
Ta
W
Au
Pb
Th
U
FOR 1 MeV NEUTRON
FOR 14 MeV NEUTRON
$E_{p,max} = \frac{4 A_2}{(A_2 + 1)^2} E$
SUBCASCADE ENERGY
SINGLE SUBCASCADE
MULTIPLE SUBCASCADE

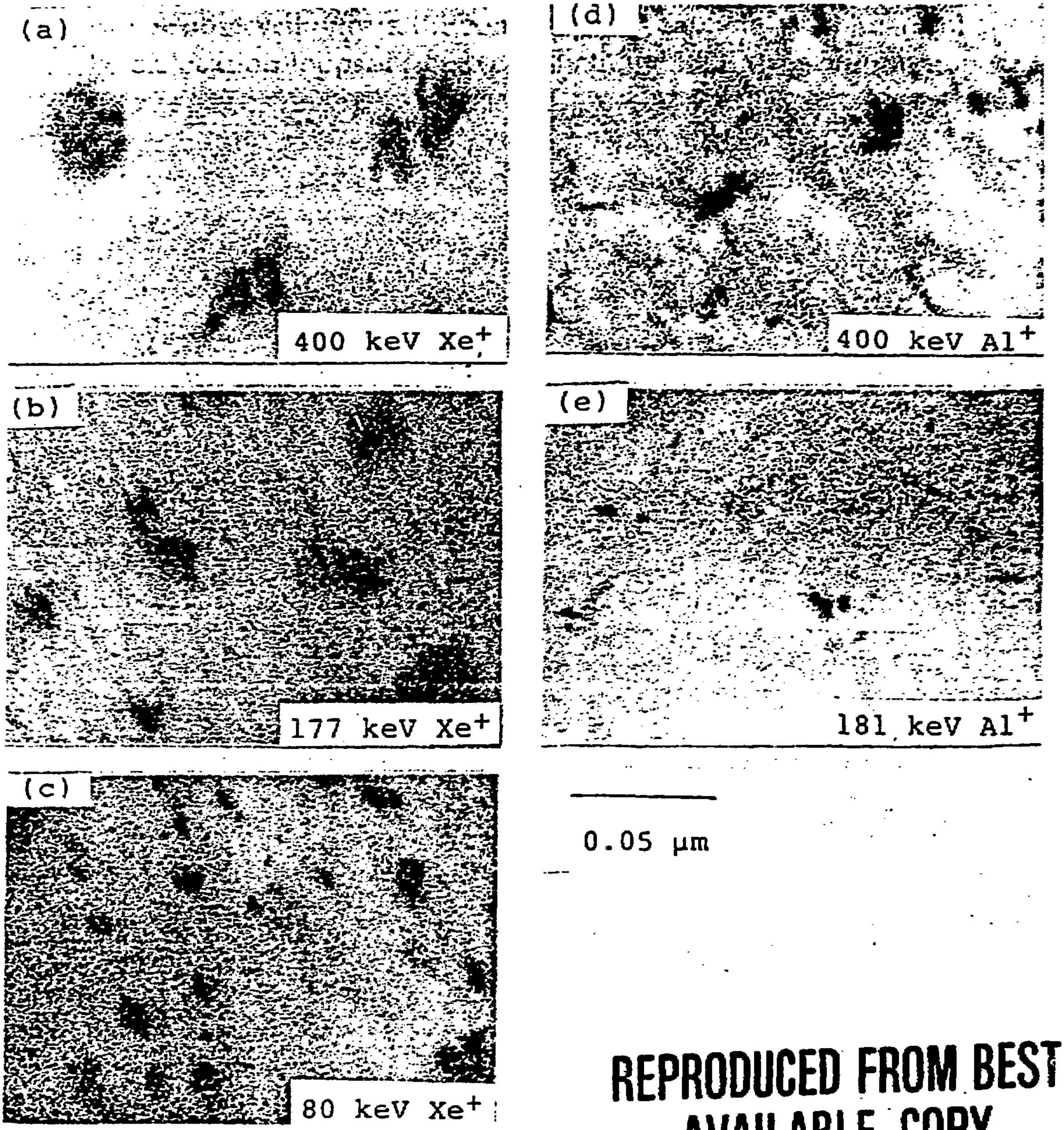
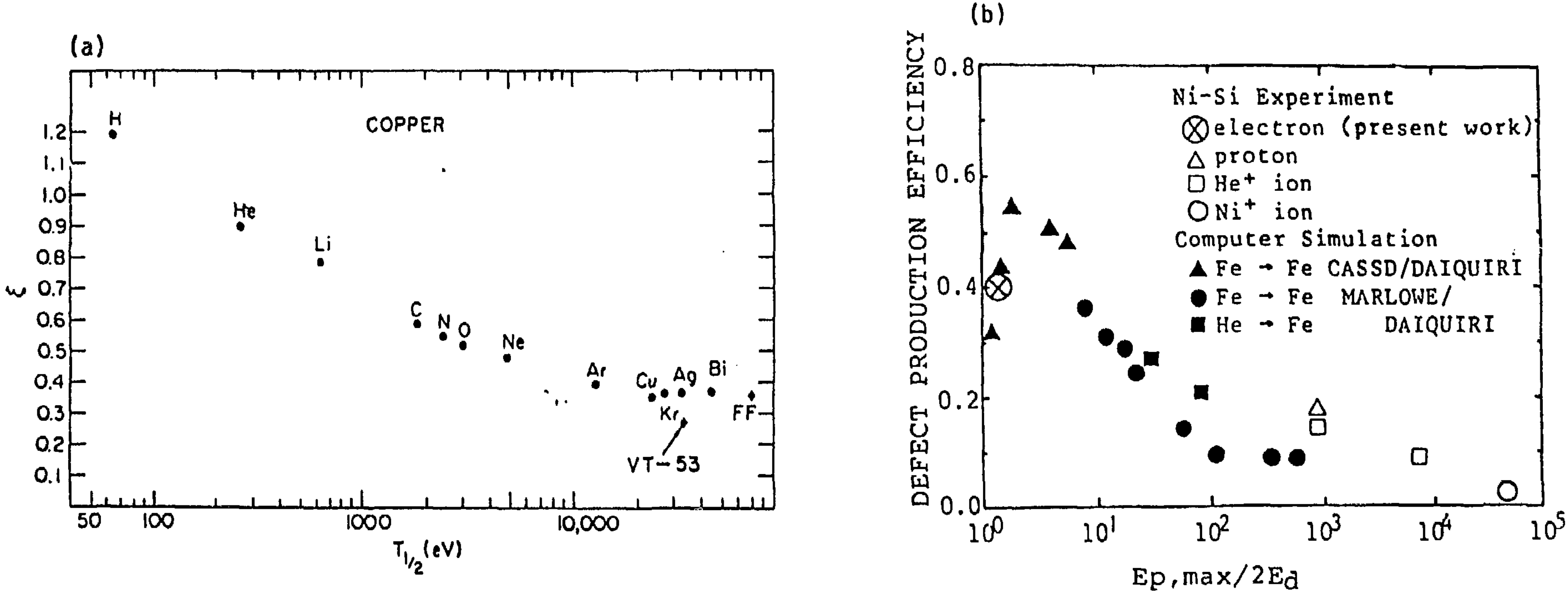


Fig. 2


(a)
COPPER
ε
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
H
He
Li
C
N
O
Ne
Ar
Cu
Ag
Bi
Kr
FF
VT-53
50
100
1000
10,000
$T_{1/2}$ (eV)
(b)
DEFECT PRODUCTION EFFICIENCY
0.8
0.6
0.4
0.2
0.0
Ni-Si Experiment
⊗ electron (present work)
△ proton
□ He+ ion
○ Ni+ ion
Computer Simulation
▲ Fe → Fe CASSD/DAIQUIRI
● Fe → Fe MARLOWE/
■ He → Fe DAIQUIRI
10^0
10^1
10^2
10^3
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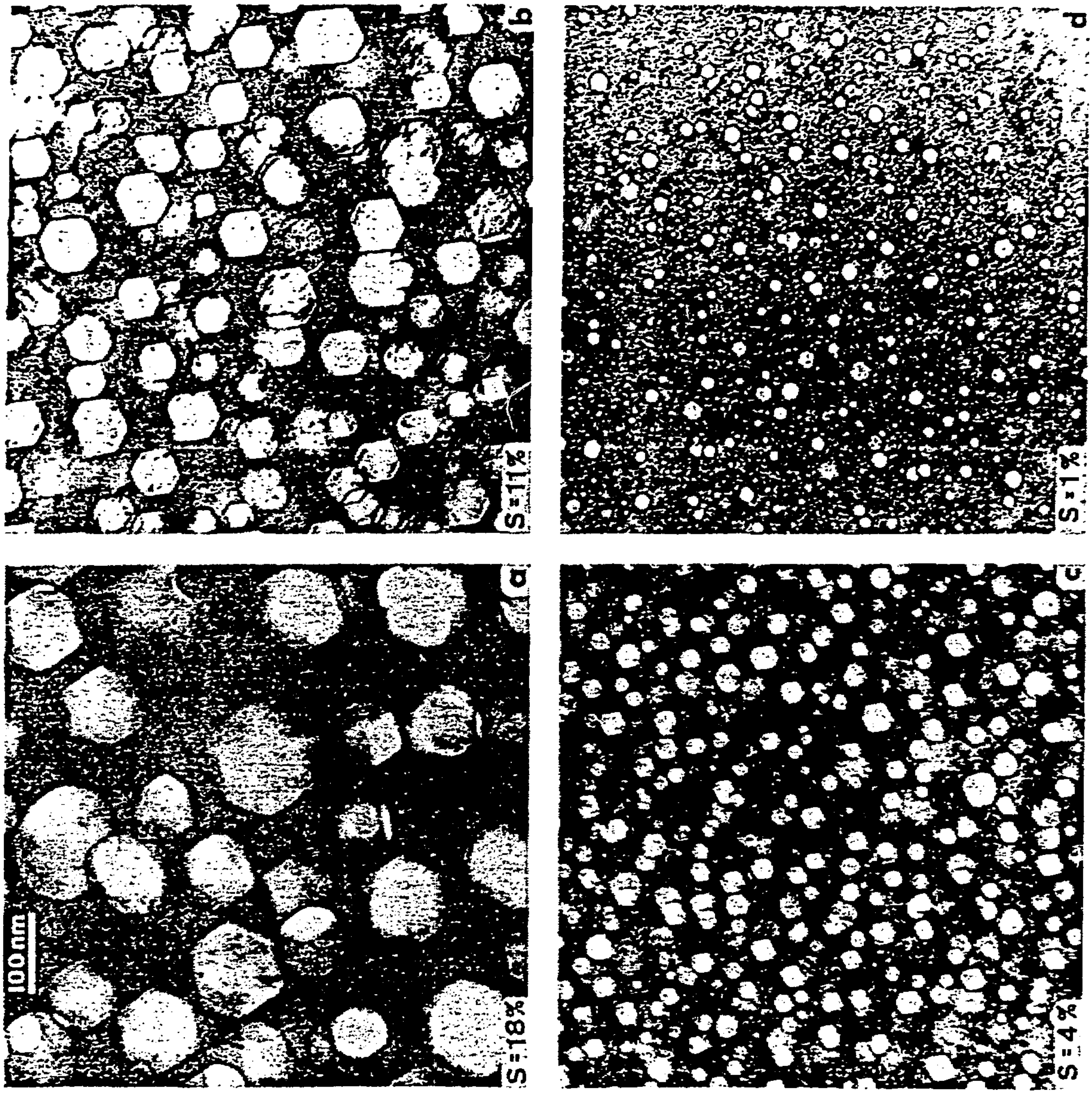
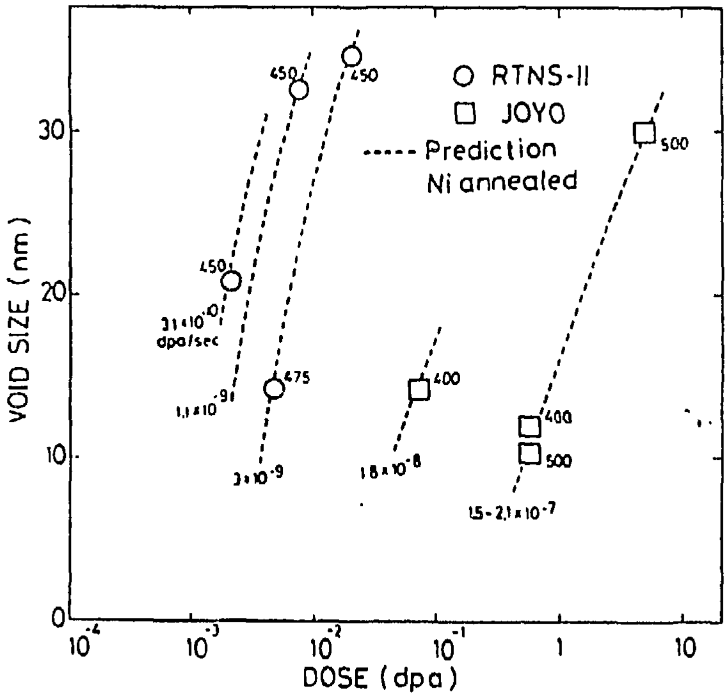
10^5
Ep,max/2Ed

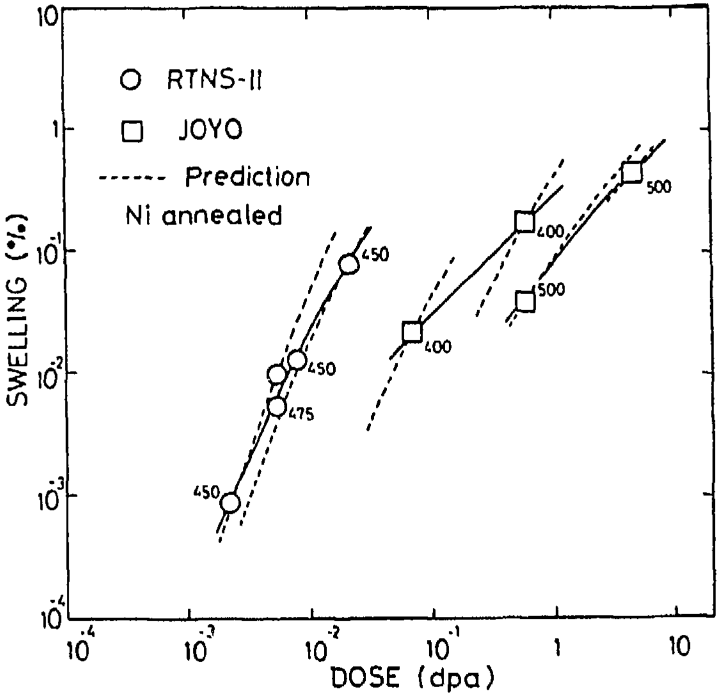
Fig. 3


b
S=11%
d
S=1%
a
100 nm
S=18%
c
S=4%

(a)


RTNS-II
JOYO
Prediction
Ni annealed
VOID SIZE (nm)
DOSE (dpa)
0
10
20
30
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
450
450
450
475
400
400
500
500
3.1×10^{-10} dpa/sec
1.1×10^{-9}
3×10^{-9}
1.8×10^{-8}
$1.5-2.1\times10^{-7}$

(b)


RTNS-II
JOYO
Prediction
Ni annealed
SWELLING (%)
DOSE (dpa)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
450
450
450
475
400
400
500
500