BR8920362

ISSN 0101-3084

CNEN/SP

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PUB
V

PUBLICAÇÃO IPEN 232

DEZEMBRO/1988

SÃO PAULO

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SÃO PAULO – BRASIL

Série PUBLICAÇÃO IPEN

INIS Categories and Descriptors

B22.60

B24.60

ALPHA PARTICLES
CEMENTS
COPPER ALLOYS
IRON ALLOYS
PHYSICAL RADIATION EFFECTS

IPEN - Doc - 3106

Aprovado para publicação em 03/11/88.

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RADIATION EFFECTS ON METALS, ALLOYS, AND CEMENT(*)

G.Lucki e V. Sciani

ABSTRACT

High - energy particle irradiation of materials brings as a consequence changes in their atomic structures that alter the electrical, magnetic and mechanical properties which are the most important characteristics for practical applications of metals and alloys. A review is made on experimental results of in-pile (IEA-RI reactor) and CV-28 cyclotron irradiated materials. Resistivity measurements on CuPd an FeNi alloys showed different behaviour during fast neutron irradiation. While CuPd had almost coincidental relaxation curves, FeNi presented a distinguishable short and long-range ordering with the critical order-disorder temperature at 515ºC. Vacancy supersaturation curves of FeNiSi (49-49-2 at.%),FeNiCr (49-95-49,95-0,1 at.%), FeNiMo (50-50 at.% + 50 ppm) and pure FeNi (50-50 at.%), determined by means of the Magnetic After Effect are presented as an effective pre-selection method of nuclear materials before the destructive stage of void formation and swelling. A displacement of damage peak from 480 to 500 and 570ºC was detected on pure AISI 321 stainless steel and with 0,05 wt.% and 0,10 wt.% of Nb additions by means of resistivity and micro-hardness. Ultrasound techniques applied to fast neutron irradiated portland cement paste (fluence 7,2 x 10^{18} n/cm^2) showed a 24% decrease in its dynamic elasticity modulus. Helium diffusion on Au, Ag and Al foils irradiated in cyclotron was studied, suggesting a vacancy mechanism for single He atom diffusion. Embrittlement by Alpha particle implantation in cyclotron - to simulate in-pile (n, α) reaction-was measured by high temperature creep on AISI 316 stainles steel.

EFEITOS DA RADIAÇÃO EM METAIS, LIGAS E CIMENTO

RESUMO

A irradiação de materiais com partículas de alta energia tem como consequência mudanças na sua estrutura

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(*) Trabalho apresentado no 4th. International Symposium on Radiation Physics , em São Paulo, de 03 a 07 de Outubro de 1988.

atômica o que altera as suas propriedades elétricas, magnéticas e mecânicas; as quais formam o conjunto das características mais importantes para as aplicações práticas de metais e ligas. No trabalho é feita uma revisão dos resultados experimentais de materiais irradiados no caroço do reator IEA-R 1 e no cíclotron CV-28. Medições da resistividade em CuPd e FeNi evidenciam comportamentos diferentes durante a irradiação com nêutrons rápidos. As curvas de CuPd eram praticamente coincidentes, enquanto as isotermas de FeNi mostram a ordenação de curto e longo alcance, com a temperatura crítica da transição ordem-desordem a 515ºC. Curvas de supersaturação lacunar de FeNiSi (49-49-2% at.), FeNiCr (49,95-49,95 - 0,1% at.), FeNiMo (50-50% at.+50 ppm) e FeNi (50-50% at.) determinadas por meio de EFEITO MAGNÉTICO PROTERIOR são apresentadas como um método efetivo de pré-seleção de materiais nucleares antes do estádio destrutivo da formação de cavidades e do inchaço. Deslocamento de picos de dano, de 480 para 500 e 570ºC foi detetado no aço inox AISI 321 puro e com adições de 0,05% e 0,10% em peso de Nb, por meio da resistividade e microdureza. Técnicas ultrassônicas apiicadas a pasta de cimento Portland irradiado (com fluxo entegrado de 7,2x10^{18}n/cm^{2}) mostraram um decréscimo de 24% no módulo de elastícidade dinâmico. Difusão de He em chapas finas de Au,Ag e Al foi estudada, sugerindo um mecanismo lacunar para a difusão de átomos do gás. Experimentos de simulação para simular a reação (n,α)em reatores foram realizados para estudar a fragilização do aço inoxidável AISI 316 implantado com partículas alfa no cíclotron, por meio de fluência em altas temperaturas.

1. INTRODUCTION

Reactor components are exposed to high fluences of energetic particles which produce changes in their atomic structure.These desturbances,consequently,influence the electrical,magnetic and mainly mechanical properties (e. g. hardness,strenghth,ductility and dimensional stability) which are the most important characteristics for practical application of metals and alloys. Whereas some changes may be considered as "beneficial" effects (1) (2) in metals and alloys, most of them are destructive justifying the expression "Radiation Damage" for the influence of radiation on materials.

Considering the irreversible trend trowards the development of nuclear technology and uses of nuclear energy, it becomes evident that Radiation Damage in reactor components must be seriously considered for a safe and economic operation of present fission reactors, and mainly, on fusion reactor of the future. Therefore it is essential to acquire a fundamental understanding of radiation damage effects and develop radiation-resistant materials.

An interesting comparison can be made on the vulnerability of metals and other materials, by following example: the core components of a fast breeder reactor are exposed to a fast neutron flux of approximately $10^{15} n/cm^2$. sec., which results in about 300 displacements per atom (dpa)after 10 years of operation,practically destroying the original structure.Another irradiation time cumulative effect is the swelling in present reactor stainless steels, which is a technologically unacceptable disturbance. Plastics desintegrate at much lower doses ($\sim 3.10^{-4}$dpa),and 10^{-12}part of the above mentioned dose would develop pathological processes in bio-tissue leading to the destruction of a living organism.The catastrophic effect of radiation on organic material is due to the fact that a replacement of an atom by another element alters the chemical nature of the material. By contrast, a random exchange of atoms between different, lattice sites has no macroscopic effect on pure metal and disordered alloy for relatively small doses, since an appreciable part of the absorbed radiation energy goes into electronic excitation and does not produce structural changes in metallic materials, other than heat.This is not the case of ionic conductors,semiconductors and insulators whose physical properties are strongly influenced by electronic excitation.

The radiation damage study consists of two major, not completely overlaping, fields:basic research on pure materials and technological studies (data collection) on commercial reactor materials.Research workers are interest ed in basic properties of point defects and structure changes,performing experiments at low-temperature, low-dose irradiations using elaborate methods to determine the atomic behavior of interstilials and vacancies. Very pure metals and single crystals are used as samples with one kind of predominant defect present, in order to obtain reproducible results. On the other hand, nuclear engineering, to design and construct advanced reactors, must face technological challenges like radiation-induced swelling, enhanced embrittlement and creep of commercial alloys, and needs data on the behavior of these materials after several years of reactor service at high doses and temperatures. In the last decade a convergence of both fields has been noted and is due to great advances recently made in determining the structure and basic properties of point defects in pure metals with the research presently turning to defect aglomerates in dilute and concentrated alloys, and mainly to the development of simulation techniques (charged particle irradiation) used to characterise commercial materials with regard to their radiation resistance. In spite of the convergence of basic and technological researches, many results and their theorical understanding are still confined to model materials of structures much simpler than those of commercial alloys. Therefore, the macroscopic property changes in reactor materials are only qualitatively understood with many open questions regarding detailed mechanisms leading to embrittlement,swelling, radiation-enhanced diffusion, etc., however the ecquired knowledge is sufficient to identify the areas where radiation damage in structural materials can endanger the safe and economic operation of reactors.

Regarding the structural materials requirement,the following considerations must be made.At present, commercially available power reactors are the following three types: (LWR)- light-water reactors, and to a much smaller degree, the (HTR) high- temperature reactors and,(HWR)heavy-water reactors,which rely on the rare U-235 isotope as fuel. For this reason other types of nuclear energy sources are being developed in several countries one of them the liquid-metal fast-breeder reactor (LMFBR), to make available a proven and environmentally safe commercial reactor in the next decade, which would greatly increase the effective uranium resources, since it "burns" both U-238 an U-235 isotopes. Another type of reactor is the controlled thermonuclear fusion reactor whose practical feasibility has not yet been demonstrated,but in last years such progress has been achieved that researchers are strarting to analyse the technological and economic aspects of fusion reactors where material considerations are of paramount importance (3). Since here only irradiation-induced property changes will be discussed,references (4,5 and 6) are suggested for further informations on different types of reactors.

In boiling an pressurized-water reactors where the core structure-consisting of fuel cladding,pressure tubes, grid plates, control rods, etc - is exposed to fast-neutron fluxes of order of 10^{13}n/cm^{2}. sec and temperatures around 300ºC, the radiation damage normally is the life-time limiting factor. The most important radiation effects are low-temperature embrittlement, irradiation creep in stainless steel and Zircaloy, and less frequently an increased hydrogem adsorption and corrosion produced by radiolysis.

Due to their high safety relevance, the thermal reactor pressure vessel deserves great attention.The pressure vessels are generally made of low-ferritic steels welded by special processes and, during thir life-time, are exposed to fluences in the range of 10^{18} - 10^{19} n/cm^{2} (fluxes up to 10^{11} n/cm^{2}.sec), at temperatures below 300°C. Low-temperature embrittlement may occur, shifting the ductile-brittle transition temperature into the operating range (20 - 300°C) of reactor pressure vessels(7) as shown in Fig. 1.

The diminished toughness(8) of the irradiated material may lead to spontaneous crack propagation and fracture of the reactor containment vessel; with catastrophic consequences. Due to this, extensive investigations have been carried out and should proceed intensively in the future to make available a broad data base to allow reliable technological predictions. In parallel, surveillance samples of material are irradiated in the neighborhood of the reactor core and tested before the pressure vessel atains the corresponding fluence. If the control of technological problems has been achieved (only apparently), the physical understanding, on atomistic scale, has not yet been quantitatively determined.

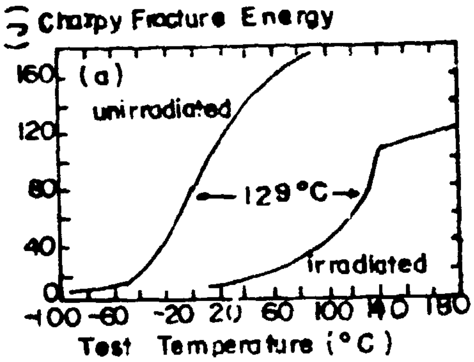


Fig.1-Ductile to brittletransition shift of Ni-Mo-Cr reactor pressure vessel steel after irradiation with $1.25\times10^{20} n/cm^2$ (7).

It is a known fact that the irradiation hardening and embrittlement in pressure-vessel steels is a consequence of point-defects aggregation (vacancies and intersticial atoms), however the role of impurity atoms and other microstructural defects in stabilizing and affecting these clusters in commercial alloys is far from being completely unterstood. Gas-cooled high-temperature reactor (HTGR), have concrete vessel, fuel contained in graphite coating, and oly a few metallic structural components, reason why no serious radiation damage problems in metallic components are expected, with the exception of control rods. These operate at higt temperatures ($\sim 950^{\circ}C$) and are exposed to fluences which could cause high-temperature embrittlement. Considerable radiation damage effects like , volume change, thermal conductivity, and mechanical properties are expected to occur in the graphite coating, but are not discussed in this paper.

In contrast with LWR, the LMFBR operate with liquid sodium cooling at temperatures up to 700ºC, fluxes exceeding 10^{15}n/cm^2 sec and high mechanical stresses (~100 MPa), which lead to material deteriorations that limit the lifetime of many components below economicaly desirable values . The most representative parameters related to radiation damage problems in fast-breeder and fusion reactors, are compiled in Table 1.

The operating temperature of LMFBR is limited by structural material available which is an austenitic stainless steel. The power density level determines the neutron flux, helium production rates, stress levels and fuel expansion. These conditions combined, lead to following destructive effects, in decresing order of deterioration: - swelling by void growth - irradiation creep - high temperature embrittlement and radiation enhanced diffusion. Investigations are being caried out,on world-wide scale, to develop radiation-resistant materials whose properties vary within certain limits established by engeneering requirements, as shown in Table 1.

In spite of the difference in physical concept of LMFBR and thermonuclear fusion devices, there are some similarities in the radiation damage problems for the structural materials in both systems. In analogy to the core of a LMFBR, the first wall and blanket materials sorrounding the plasma are exposed to high temperatures, intensive mechanical stresses and fast neutron fluxes higher than 10^{14} n/cm^2, depending on the wall energy loading which varies from 1 MW/m^2 to 7 MW/m^2 for different fusion reactor designs. However, it is already known that the neutron energy spectrum will be considerably higher than in a fission reactor due to the 14MeV neutrons produced by fusion. These will yield a strongly anhanced Helium production by (n, α) reaction leading, as a consequence, to high - temperature embrittlement.

Table I. Anticipated Structural Material Requirements for Future Reactor Systems (after Ref. (9)).

PARAMETER	UNIT	FAST BREEDER (steel)	FUSION REACTOR
Temperature	^{o}C	300-600	300-500(steel) 500-1000(refract)
Maximum instantan displacement rate	dpa/s	$\sim 10^{-6}$	$3x10^{-7}-10^{-4}$(magnetically confined) 1-10(inertially confined)
Avarange displacement rate	dpa/year	~50	10 - 30
He production	appm/year	~10	200-600(steel), 25-150(refract.)
No. of power cycles	$Year^{-1}$	~10	$10-10^{5}$(magnetically confined) $10^{7}-10^{9}$(inertially confined)
Stress level	MPa	60-120	60-200
Maximum permissible:			
Volume change(lifetime)	%	<5	< 10
Creep strain (lifetime)	%	<1	<1
Ductility(elongation)	%	<1	<1-

For the evaluation of the critical radiation damage problems, several simulation techniques have been introduced, with the inicial aim of producing high damage rates for swelling studies after charged particles implantation. Very high swelling rates were achieved by the implantation with heavy ions (5MeV) - 10^4 greater than in a typical fast breeder reactor, but with the handicap of a very limited damage range ($1\mu m$) allowing only TEM observations on very thim samples.

Light ions, like p, d and α , with energies from 5 to 30MeV are suitable for homogeneous damage production in 25 to 100 μm thick samples apropriate for bulk mechanical properties measurement like: creep, fatigue, stress-strain curves, etc., but limited to a reduced damage rate of approximately 10^{-5} dpa/sec(10). With α implantation the highest app He/dpa rates ($\sim 10^4$ appmHe/dpa) can be achieved for simulation studies of He embrittlement in materials(11). The high - voltage electron microscopy (HVEM) is especially useful as a simulation technique since it permits the observation of structure changes during the radiation damage generation with fast electrons (~1MeV). Some of the more important simulation techniques are listed on Table 2. In the last decade several laboratories have developed techniques of simulating neutron-damage phenomena through charged - particle bombardment. Although the first radiation damage experiments date from 1965 the simulation studies started at Radiation Damage Division - IPEN in 1984 on cyclotron implantations and the results obtained have shown that simulation techniques can provide fast, inexpensive and useful information about many aspects of radiation damage problem. Particularly, basic studies, as well as technological characterization for material development programs would be unthinkable without the use of simulation techniques.

Table II. Characteristic Features of Different Simulation Techniques (10).

PARTICLE; ENERGY RANGE;	ADVANTAGES	DISADVANTAGES	MAIN FIELD OF APPLICATION
Heavy ions(self ions); 2-5 MeV Van de Graaf	Extremely high damage rates(100 dpa in 3 hours);	Very small ranges(1μm) inhomogeneous damage,surface effects, unknown distribuition of high stresses	TEM investigation of swelling by void formation;screening of swelling resistant alloys
Light ions(p, d,α)5-30MeV; cyclotrons	Somewhat higher damage rates than reactors;homogeneous damage in ~100 m thick samples; mechanical tests possible	Limited to 5 dpa; damage structure different from n-damage	Simulation of "inpile" mechanical properties changes(irradiation creep, fatigue, embrittlement, influence of stress on swelling).
Electrons; 0.2 - 3MeV HVEM	High damage rates;production and observation of defect structure simultaneously	Very thin layers(surface effects) and small areas (stresses);damage structure very different from neutrons(single Frenkel pairs)	In-situ observation of the build up of damage structure: dislocation loops,voids, cluster complexes, etc.

2. EFFECT OF RADIATION ON CRYSTAL LATTICE

The macroscoscopically observed radiation damage phenomena are a consequence of two elementary interactions between the bombarding particles and the lattice atoms:

a) Neutrons,ions and electrons with incident energy E transfer a recoil energy T to the atoms; if T > Td (Td-treshold energy) creating a Frenkel pair (vacancy-intersticial)

b) Transmutation nuclear reaction produce considerable concentrations of foreign atoms within the material,such as Helium gas due to (n, α) reaction plying an important role in the mechanical stability under fast-neutron irradiation.

The primary event, when the primary knock-on atom (PKA) is produced, is characterized by the probability of transfering a recoil energy T to the atom, i. e. by the differential cross-section d σ (T,E). For ions, dσ/dT is given by the Rutherford cross-section proportional to $(ET^2)^{-1}$ showing that small energy transfers are favored. Fast neutrons have a contrasting behavior with d /dT almost constant for small (10^2eV) and medium (10^4eV). The maximum transferable energy, for non relativistic particles is given by:

$$T\ \max = \frac{4\ M\ m}{(M + m)^2} \qquad (1)$$

where: M - mass of lattice atom

m - mass of the incident (bombarding) particle

The fundamental problem of Radiation Damage can be summarized by the following equation:

$$C_d = \int_0^{E\max} \int_0^{T\max} v(T)\ \frac{d\ \sigma(T,E)}{dT}\ \frac{d\ \emptyset\ (E)}{dE}\ dT\ dE = \sigma_d \cdot \emptyset \quad (2)$$

where: C_d - displacement rate

v - damage, function (averange number of atomic displacements produced per PKA with recoil energy T - is zero for $T < T_d$.)

$\emptyset$ - fluence (integrated flux)

σ_d - displacement cross-section

The comparison of damage structures - cascade size distribuition due to different incident particles - can be made by means of eq. (3):

$$C_d' = 1/\sigma_d \emptyset \int_0^{T'} \int_0^{Emax} v\ (T)\ d\ \sigma(E,T)\ d\ \emptyset\ (E) \qquad (3)$$

where: C_d' - fraction of displacements produced by primary recoil atoms with $T < T'$

C_d' is showm in Fig. 2 for diferent bombarding particles in Ni. The recoil energies for which, e.g., half of the atomic displacements are produced, are:

~ 50 e V for 1 MeV electrons
~ 5 KeV for 13 MeVα-particles
50 KeV for 5 MeV Ni - ions
~100 KeV for 1 MeV neutrons

The physical meaning of this curves (Fig.2) can be explained as follows: the steepness of the curves indicates the energy range of recoils with siginificant contribuition to the damage: For exemple:

- fast neutrons produce recoils in a narrow energy range- between 10^4 and 10^5 eV - meaning that the majority of Frenkel pairs is distributed in large cascades.
- α - particles, have all recoil energies - from 100 eV to 1 MeV contributing equally to the damage yielding a broad spectrum of cascades containing a variable number (up to thousands) of defects.

3. RADIATION DAMAGE STUDIES AT THE INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES - IPEN-CNEN/SP.

Radiation Damage research started at IPEN-CNEN/SP in 1965 as a consequence of technical cooperation between

Brasil and France, in a group denominated GRESIL (short for Grenoble-Brasil). In 1970 the group grew to a departamental status - Materials Science and Technology Dept. In 1976 the Radiation Damage Division was created , performing the radiation Damage Studies on the compact cyclotron and reactor.

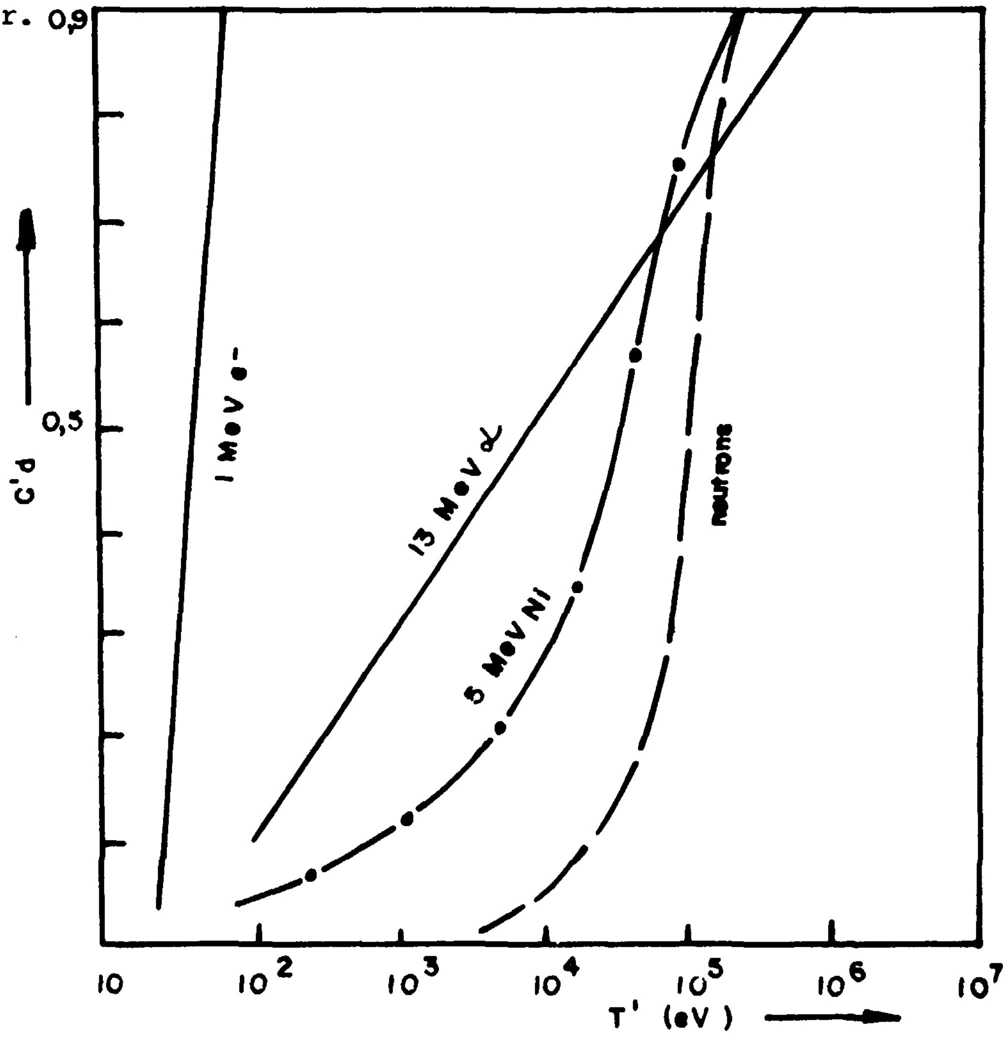


Fig.2. Function C'd calculated for Ni irradiated by different particles (10).

In what follows, only the most important experiments will be mentioned. In 1965 the first work was performed an order- disorder transformation on Cu - Pd (50-50 at% and FeNi Mo (49-49-2%) using an "in-situ" irradiation device (Fig. 3) which allowed the study of isothermal kinetics under enhanced diffusion conditions, at high temperatures and controlled atmosphere by means of electrical resistivity.

3.1 Electrical Resistivity

Cu Pd and FeNi alloys showed different behaviour under irradiation (13). While Cu Pd had almost coincident relaxation curves (Fig. 4), FeNi (Fig. 5) presented distinguinshable short and long range order with the critical order-disorder transition at $T_c = 515 \pm 5$ºC.

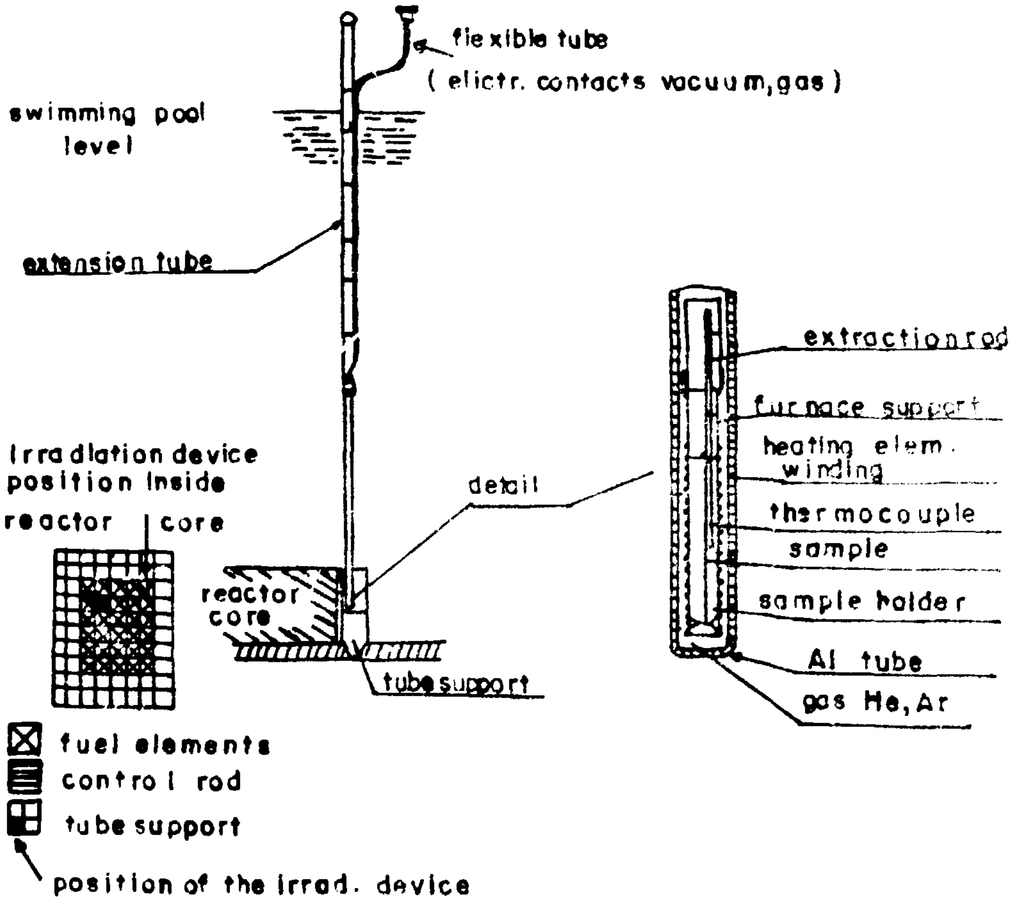


Fig.3. Irradiation device for "in-situ" resistivity measurements.

The order formation on Cu Pd could only be detected by means of X - Ray diffraction. Computer analysis of the relaxation curves suggests the existence of two predominant processes - nucleation and growth of ordered domains.

3.2 Magnetic Methods

With the aim of establishing characterization methods of nuclear materials, basic research theory and techniques (solid state physics) and applied techniques (irradiation and mettalurgy) were used to find some practical proceedures. This is the case of supersaturation curves, determined by means of the Magnetic After Effect (MAE), which makes feasible a cheap and rapid pre-selection of more adequate materials before the destructive stage of void formation and swelling are atained. Since vacancy supersaturation is a necessary condition for the formation of voids, the metal or alloy with the lowest supersaturation is initially a more suitable material for nuclear environments.

The relaxation time constants τ are inversely proportional to the vacancy concentration C_v,

$$\frac{1}{\tau} \alpha C_v \qquad (4)$$

The supersaturations is defined as the ratio between the vacancy concentration under irradiation $C_{v\ irrad.}$ and the thermal vacancy concentration C_v,

$$S = \frac{\tau}{\tau irrad} = \frac{C_{virrad}}{C_v} \qquad (5)$$

giving on Fig. 6 the supersaturation curves for FeNi (50-50 at%), FeNi Mo (50-50 at% + 50 ppm) and FeNi Cr (49,95-49,95 - 0,1 at%).

An example of the improvement (" beneficial effect") (1) (2) of the magnetic properties after irradiation on si and Mo doped FeNi alloy can be seen in Figs 7 and 8.

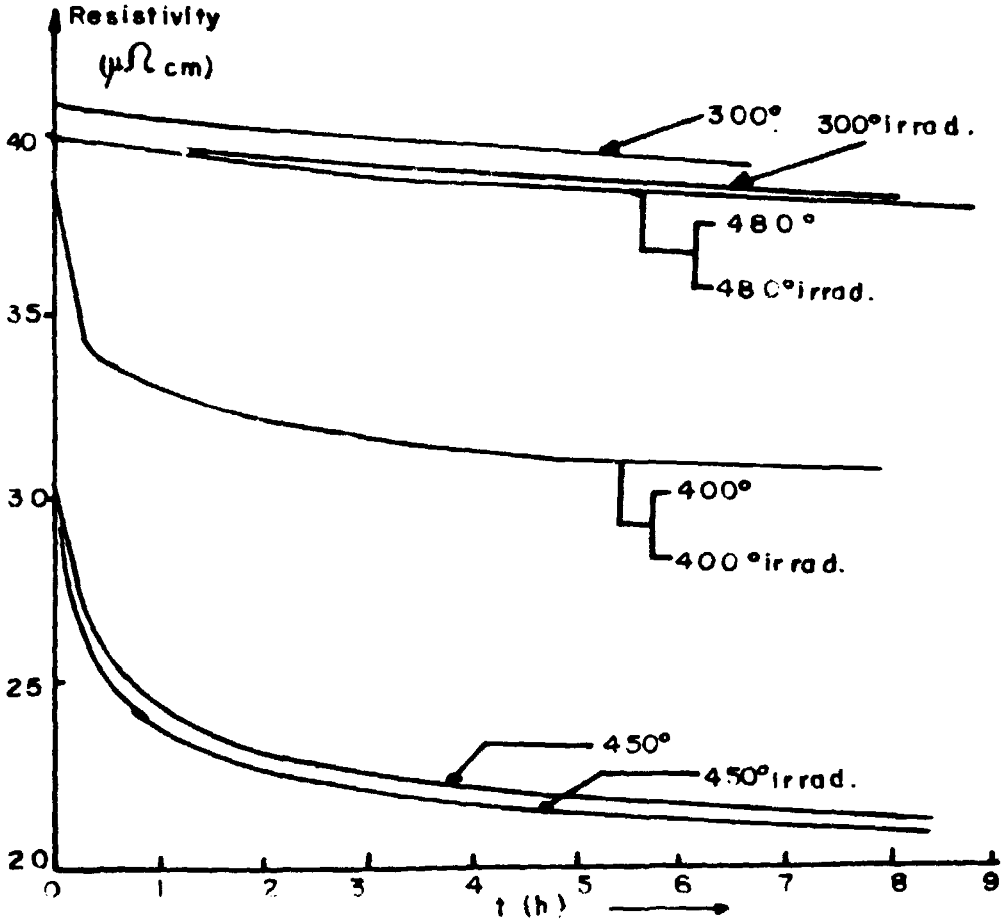


Fig.4. - CuPd ordering with and without irradiation.

In fact the small dose ($4.10^{17} n/cm^2$) fast neutron irradiation enhanced the short range ordering of the alloys increasing their ferromagnetic character and turning them more "trustful" for technological applications (e.g. - as servomechanisms). Of course, higher doses will destroy that order.

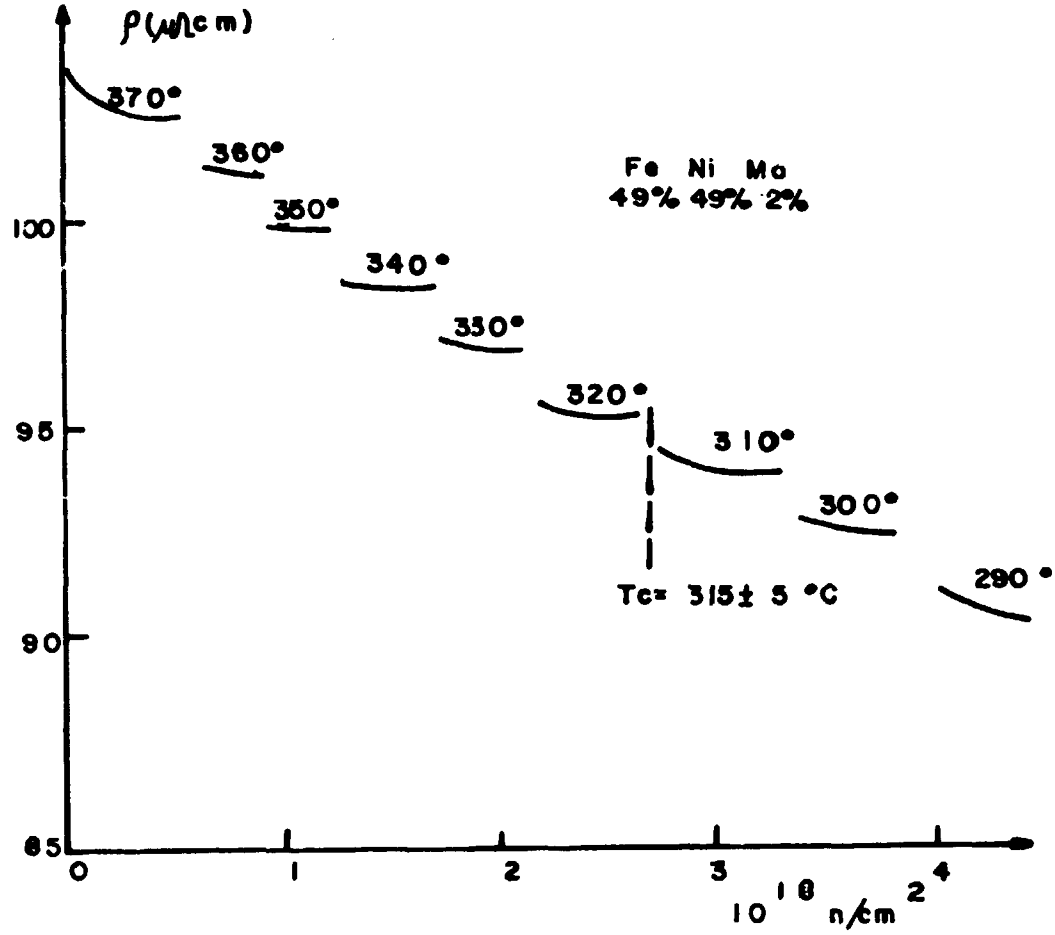


Fig.5 - Order-disorder transition T for Fe Ni Mo

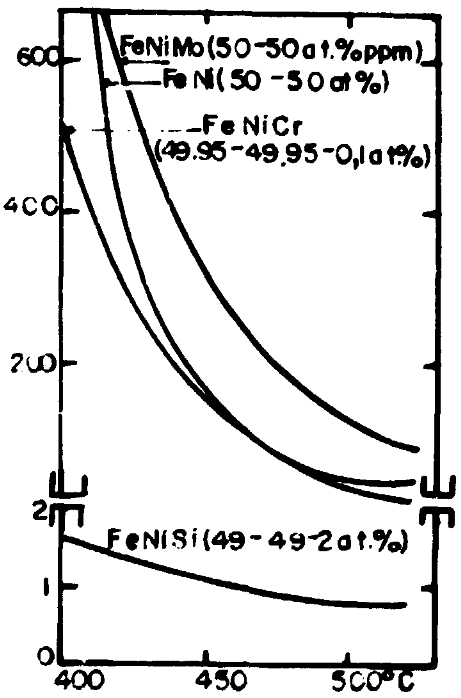


Fig.6. Vacancy supersaturation in FeNi alloys (59).

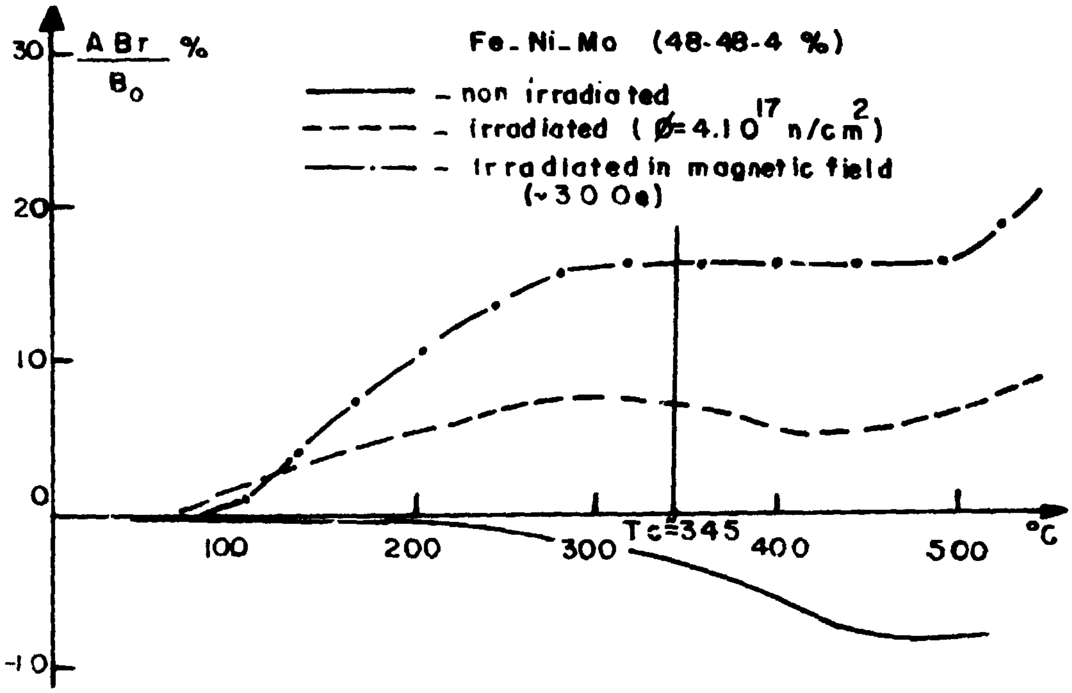


Fig.7 - Remanence variation of FeNiMo alloy after isochronal annealings.

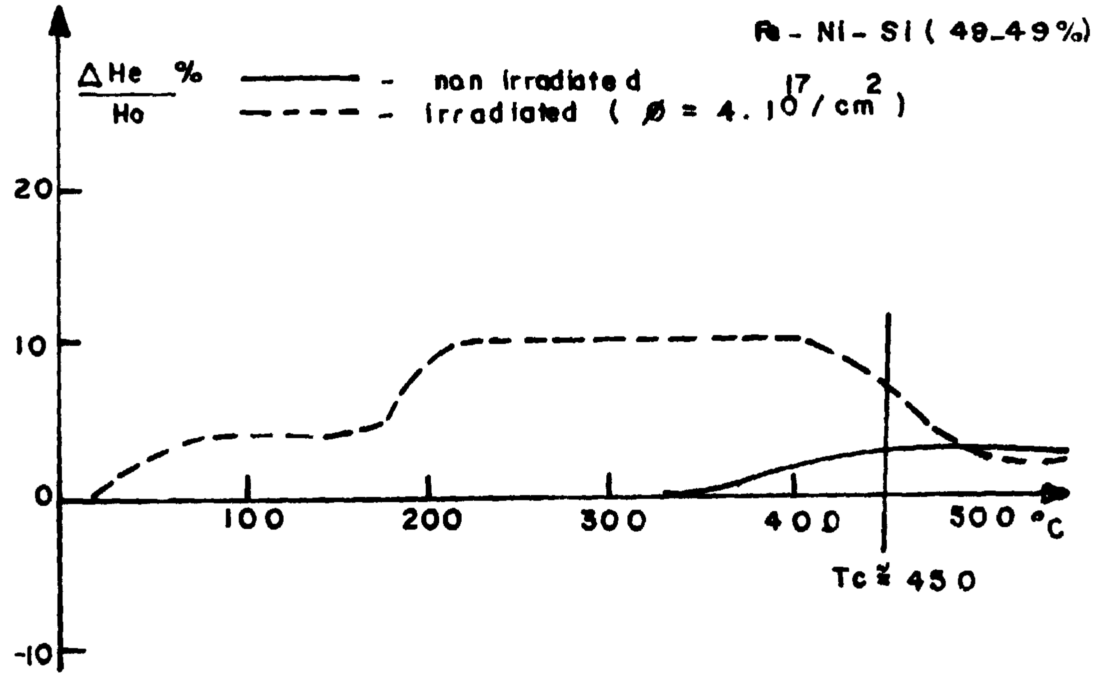


Fig.8 - Coercitivity variation of FeNiSi, after isochronal annealings.

3.3 Mechanical Methods

3.3.1 Microhardness (46) (54)

The purpose of this experimental series is to make a contribuition to the technology of fabrication and characterization of special stainless steels with Niobium additions by means of microhardness (and electrical resistivity) studies-before, during and after - fast neutron irradiation. Effects of radiation in a wide range of temperature in austensitic stainless steel type AISI 321 with 0.05 and 0.10 wt.% Nb were investigated after neutron irradiation with fluences about $10^{17} n/cm^2$ employing Vickers microhardness technique which is sensitive to microstructure changes produced by irradiation, as well as, thermal and mechanical treatments.

The results indicate the existence of radiation damage peaks around 480ºC for the material without Nb additions; around 500ºC with 0.05 wt.% Nb and around 570ºC with 0.1 wt.% Nb, as shown in Fig. 9. No microhardnes variation was detected on non-irradiated material (Fig. 10)

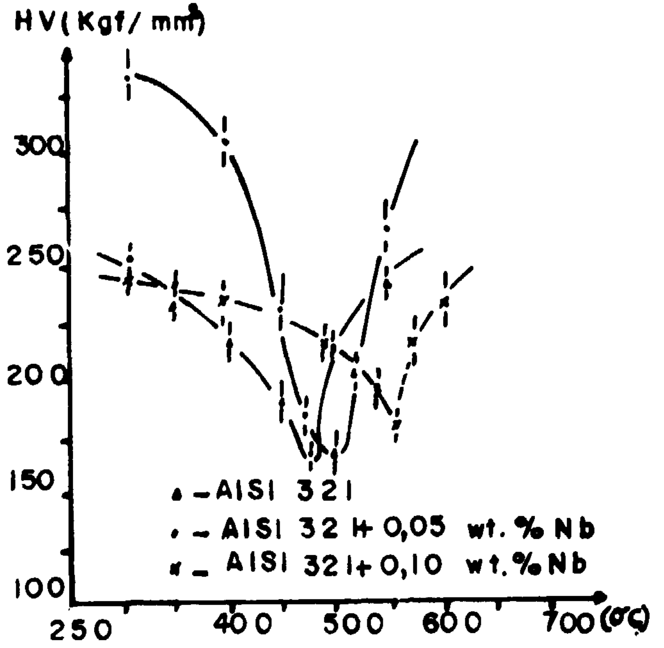


Fig.9-Variation of microhardness with irradiation temperature and composition.

The results were confirmed by means of electrical resistivity (Fig.11) The inversion of damage peaks is attribuited to the niobium carbide precipitates formed at grain boundaries. A displacement of the damage peaks to higher temperatures as a function of increased Nb addition was observed and can be considered as result of practical significance in nuclear materials selection.

3.3.2 Ultrasound (65) (69)

The scope of using ultrasonic technique is to study the fast neutron radiation effects and temperature on Portland cement, through the evaluation of the Dynamic Elasticity Module (Ed). Two methods were used:

a) Resonance Frequency and

b) Pulse Velocity on non irradiated, as well as, samples irradiated to afluence of 7,2 $10^{18} n/cm^2$ (E ≅1 MeV), at a temperature of 120±5°C due to gamma haeting. To eliminate the thermal effect this temperature was simulated in a microwave oven on the non irradiated samples, with the same number of thermal cycles of the irradiated samples. The measurements were performed in saturated state (relative humidity-100%) for the sake of

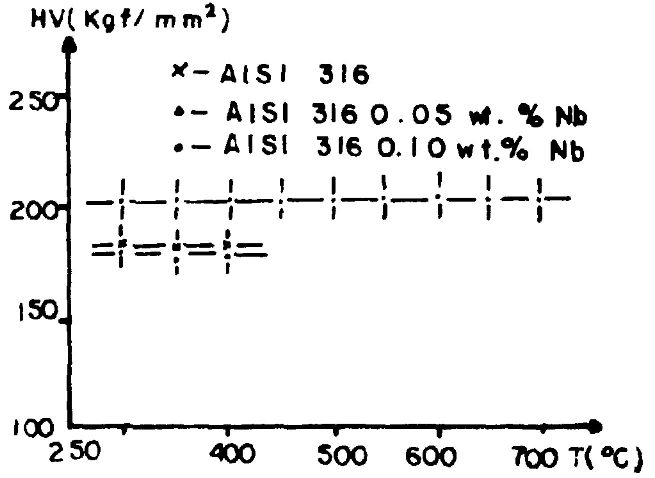


Fig. 10- Microhardness vs. annealing temperature for the non-irradiated material.

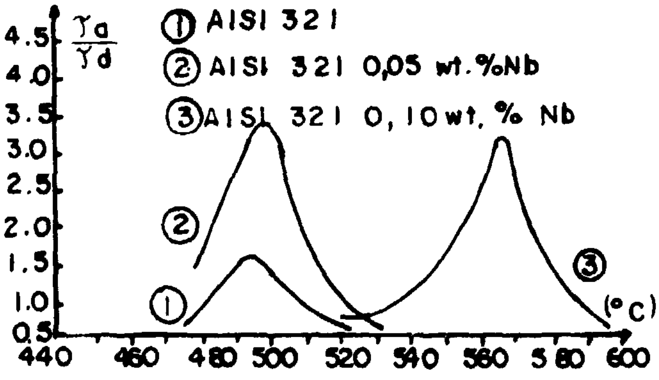


Fig. 11- Variation of the ratio between the relaxation time constant after $(\tau_a)$and during (τ_a)irradiation respectively, with temperature.

comparison and showed a general decrease of Ed on both types of samples, allowing the distinction of the radiation effect in spite of the predominant thermal influence.

	Irradiated samples	non irradiated samples
Resonance Frequency Variation:		
ΔEd(Fr)	- 24%	- 17%
Pulse Velocity Variation:		
ΔEd (Vp)	- 28%	-18%

Although from these data it is not possible to describle the interaction of fast neutron irradiation with a complex structure like cement, the radiation damage is evidenced by the smaller recovery of the dynamic elasticity module Ed , showing that the mechanical properties of cement are changed even by small irradiation doses.

3.4 Simulation Experiments

The importance of simulation experiments has been described in the introduction as an effective technique for materials characterization.

3.4.1 Gas Release (53)(63)

Helium has been homogeneously introduced in Au, Ag and Al foil as room temperature by α implantation in a CV-28 cyclotron to simulate (n,α) reaction. After implantation Helium release was observed during isothermal and linear heating experiments.

It is assumed that after room temperature implantation all He atoms are trapped in vacancies, i.e., in substitutional positions. Mobility may be regained by two diffusion mechanisms:

a) interstitial diffusion between two vacancies (substitutional positions) and,

b) vacancy mechanism assumed to operate in most substitutional alloys. For this case the activation energy H_V is located in the following range (accordingly to the five frequencies model) (75).

$$Q^{sd}_{2V} - E^F_V \leqslant H_V \leqslant Q^{sd}_V \qquad (6)$$

where: Q^{sd}_{2V} - activation energy for self-diffusion by divacancies

E^F_V - formation energy of a vacancy

Q^{sd}_V - activation energy for self-diffusion

The activation energy obtained through gas release clearly favours the vacancy mecanism for single atom He diffusion as can be seen in Table 3.

Table 3. - Experimental activation energies (gas release) compared with calculated values for vacancy mechanism. (Q^{SD}_{2V}, Q^{SD}_V(73) and E^F_V(74)).

metal	vacancy mechanism		experimental values
	$Q^{SD}_{2V} - E^F_V$ (eV)	Q^{SD}_V (eV)	H_{He}(eV)
Au	1.42	1.76	(1.70 0.13)
Ag	1.06	1.76	(1.51 0.12)
Al	0.92	1.28	(1.40 0.11)

3.4.2 Stainless Steel Embrittlemen by Alpha Particle Implantation in Cyclotron (66) (70).

The critical consequence of He gas,produced by (n,α)reaction,is the fast degeneration of the mechanical properties of metals and alloys. For this reason the study of this detrimental effect becomes important in:

a) seleçtion of more adequate materials, through the characterizaton of presently available materials,and
b) search for new,more radiation-damage resistant alloys.

Two experimental series weres were performed in the Radiation Damage Division at IPEN-CNEN/SP on AISI 316 atinless steel, by means of creep measurements, in different conditions of; applied stress, temperature, He implanted doses and fast neutron irradiation.Creep $\dot{E}$ is a parameter strongly dependent on temperature and activation energy E_a (of order of self-difusion), and is defined by:

$$\dot{\varepsilon} \ \alpha \ \exp -(E_a \ / \ kT) \qquad (7)$$

The first experimental series consisted of ten samples, 100 um thick, with 50% coldwork. Three samples (I-1,2 and 5) were fast neutron irradiated inside the IEA-R1 reactor core with a fluence of $1,7.10^{18} n/cm^2$; four samples (AI-1,2,3 and 4) were homogeneously He implanted at concentrations of 5 and 26 appm in CV-28 cyclotron and the rest (samples 20, 25 and 29) were control samples. The creep behaviour of samples is visualized in Figs.12 and 13.

In Fig. 12, the neutron irradiated samples, except for the lower rupture point, have almost coincident creep behavior. On the other hand, in Fig. 13, a marked difference can be seen on He implanted samples by the decrease in rupture time and ductility,showing that embrittlement occurs even by small He concentrations.

The second experimental series consisted of ten samples with a 100 MPa applied stress, divided in two lots:

1 st. - 7 samples annealed during 2 hours at 1,050ºC in vacuum batter than 10^{-5} Torr.
2 nd. - 3 samples 20% coldworked after the annealing

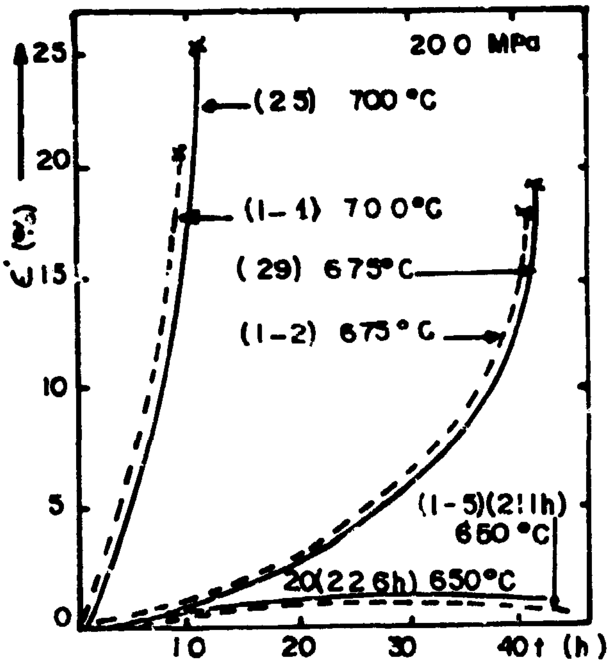


Fig.12-Creep behaviour of control samples (20,25 and 29)and fast neutron irradiated samples (I-1, 2 and 5)

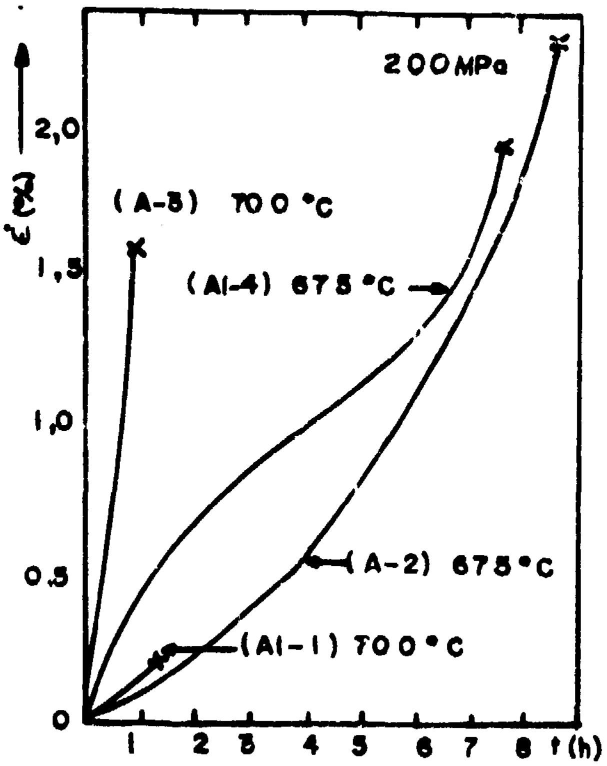


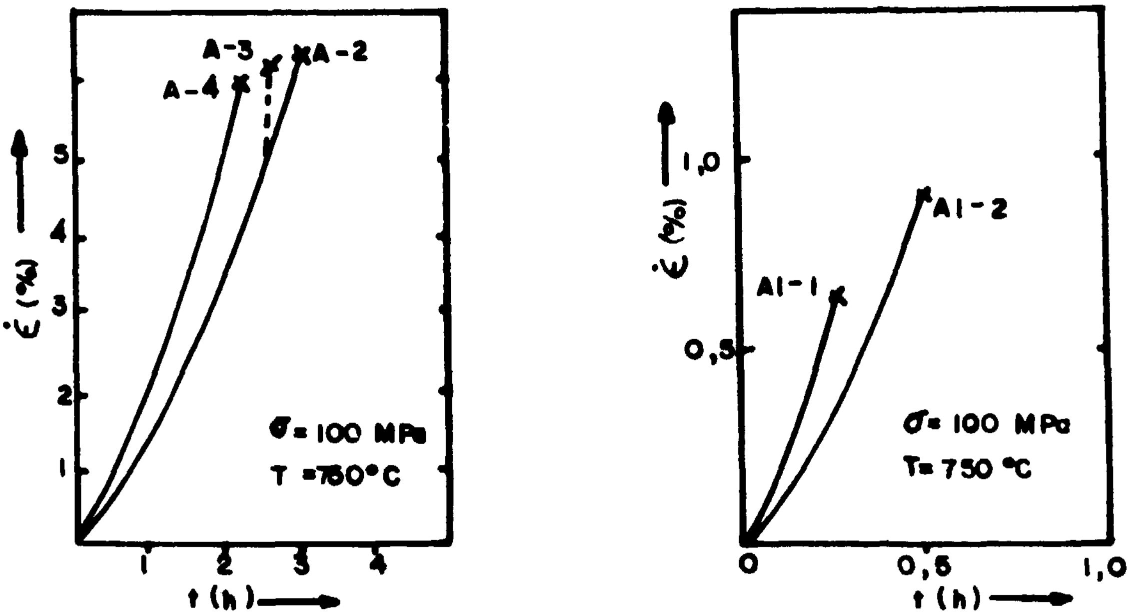
Fig.13-Creep curves on cyclotron implanted samples-with 5 appm (AI-3,4)and 26appm(AI-1,2)of He.

Two annealed (AI-1,2) and one cold-worked (DI-3) samples were implanted with 26 appm He in cyclotron. The results of creep measurements can be seen in Figs. 14 and 15.

The analysis of the results ahows that:

- approximately,a factor 2 deformation (to rupture) decrease, and a factor 10 increase in rupture time on 20% coldworked samples (D) in comparison do the annealed samples (A).
- the implantation of 26 appm of He (samples AI-1,2 and DI-3) has a great effect on the reduction of rupture time (t_r),if compared with the coldworked samples (D-2,3,4); approximately a factor 4 t_r derease for (AI-1,2) and a factor 2 tr decrease for (DI-3).

All the above mentioned results offer an experimental evidence of the intense embritlement due to the preence of He in the materials structure.



a) b)

Fig.14- Creep curves: a)annealed samples - b)annealed and 26 appm He implanted samples.

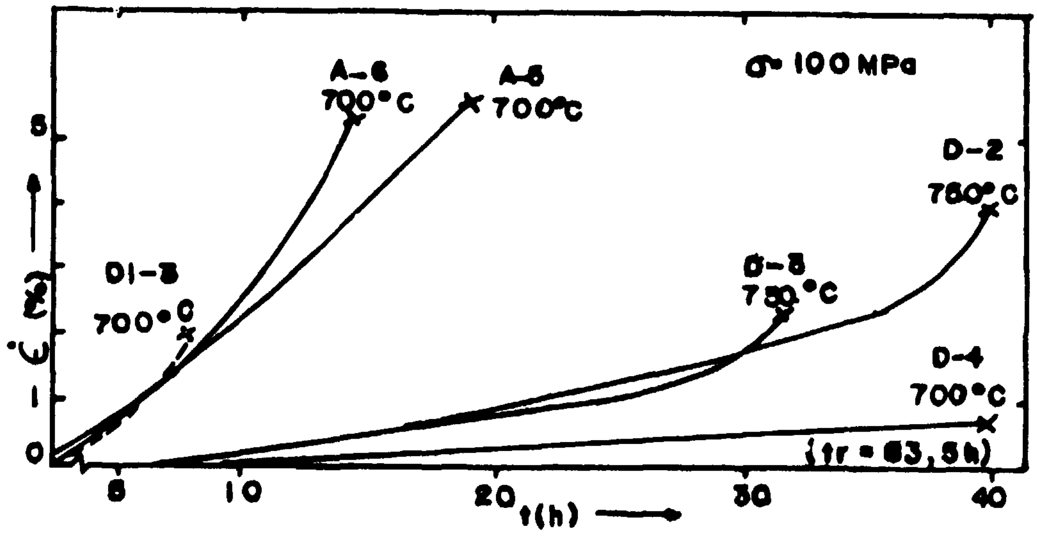


Fig.15- Creep behaviour on samples: annealed (A-5,6) - coldworked (D-2,3,4) - coldworked and 26 appm He implanted (DI-3).

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