SOLID STRUCTURE RESEARCH LABORATORY
INSTITUTE OF ATOMIC ENERGY
NATIONAL NUCLEAR CENTER
REPUBLIC OF KAZAHSTAN

Agreement 5462 U 0015-35

LA-SUB--96-106

INVESTIGATION OF HIGH PURITY BERYLLIUM FOR THE INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

TASK 002

DETERMINATION OF MICROSTRUCTURAL CHARACTERISTICS AND CREATION OF TECHNICAL PROJECT FOR IRRADIATION EXPERIMENTS, CLEARING BEHAVIOR OF BERYLLIUM MATERIALS UNDER CONDITIONS, CLOSE TO THERMONUCLEAR REACTOR.

FINAL REPORT

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Almaty, 1995

ABSTRACT

The report includes a description of experimental abilities of Solid Structure Research Laboratory of IAE NNC RK, a results of microstructural characterization of A-4 grade polycrystal Beryllium produced at the Ulba metal plant and a technical project for irradiation experiments. Technical project contains a detailed description of five proposed experiments, clearing behavior of Beryllium materials under the influence of irradiation, temperature, helium and hydrogen accumulation. Complex irradiation jobs, microstructural investigations and mechanical tests are planned in the framework of these experiments.

LIST OF PARTICIPANTS

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CONTENTS

1. BACKGROUND

Present work is based on the agreement 5462U0015-35 dated 21 november 1994 between the Regents of the University of California and the Science Technical Center of Controlled Thermonuclear Fusion of the Republic of Kazahstan.

The purpose of agreement is to determine some characteristics of polycrystal beryllium material and to create technical project for reactors experiments, clearing behavior of beryllium materials under conditions, close to TNR.

According to TASK 002 of agreement it is necessary to develop technical project, including description of technical parameters and conditions of experiments, description of experimental methods, list of existing and needed equipment for the performance of experiments, price-list of each proposed experiment on the following themes: sample preparation and examination in TEM, sample irradiation it cyclotron by alpha-particles (up to 500 appm He), and sample irradiation in tandem accelerator by protons (up to 1000 appm H) with damage level about 30 dpa, plastic properties investigation of irradiated and not irradiated beryllium.

During agreement performance a possibility has arised to extend possible work relatively to the agreement conditions.

Therefore, we decided to present more complete information about our abilities and to give detail description of some possible experiments in the framework of future collaboration. Acquaintance with this possibilities could help to get clear notion about our laboratory and to choose experiments for the continuation of collaboration.

2. INFORMATION ABOUT SOLID STRUCTURE RESEARCH LABORATORY (SSRL)

2.1. INVESTIGATIONS PERFORMED IN SSRL

Solid Structure Research Laboratory (SSRL) of the Institute of Atomic Energy, National Nuclear Center of the Republic of Kazahstan (IAE NNC RK) has been performing investigations in radiation physics of solids, including radiation effects in reactor materials, for last 20 years.

Main directions of investigations are the following:

1) Basic research on the initial radiation damage in metals under charge-particle and neutron irradiation; clarification of damage character depending on energy and mass of bombarding particles (and primary knock-on spectra); study of cascade damage [1-5].
2) Interactions between radiation defects and gas impurities (helium, hydrogen). Microstructure evolution under irradiation and during post-irradiation annealing, correlation between microstructure and physical and mechanical properties of materials [6-13].
3) Phase transformations in reactor materials (stainless steels and alloys) doped with helium [14-23]:
4) Simulation of fusion reactor radiation damage using ion accelerators, development of irradiation techniques [24-26].

2.2. PERSONNEL.

The project main technical staff are the members of staff of the Solid Structure Research Laboratory:

Sergei Petrovich Vagin, a cand. of phys. and math. sci., the laboratory head, a qualified specialist in the field of radiation material science and electron microscopy, the project leader.

Bekmuhamed Dzharmuhamedovich Utkelbayev, cand. of phys. and mat. sci., the deputy of the laboratory head, a qualified specialist in the field of radiation material science and electron microscopy, a coordinator of all experiments, a performer of structural studies.

Peter Vasilievich Chakrov, a scientific researcher, qualified specialist in the field of radiation material science, electron microscopy and electrochemical treatment of materials, a performer of TEM and SEM-studies and material irradiation at the cyclotron.

Andrei Albertovich Loktionov, a cand. of phys. and mat. sci., a senior scientific researcher, a qualified specialist in the field of radiation material science, a performer of cyclotron and reactor irradiation.

Valentina Pavlovna Poltavtseva, cand. of phys. and mat. sci., a specialist in the field of radiation material science, a performer of material mechanical tests and cyclotron irradiation.

Nigmet Kospanovich Kospanov, an engineer, a specialist in equipment, a performer of SEM studies and reactor irradiation.

Nadezhda Alexandrovna Pyatiletova, an engineer, a specialist in equipment, a performer of metallography studies and microhardness measurements.

A support staff (8 persons) is used in the Project: two engineers, four technicians, two laboratory assistants.

All the data concerning the personnel staff are presented in Appendix 1. The main technical staff takes part in the Project all the time.

The support staff is used for execution of definite jobs: engineers are expected to design and to adjust target and ampule devices, technicians are to prepare the target and ampule devices for irradiation and to fulfil irradiation as well, laboratory assistants are to prepare specimens for TEM and SEM studies.

2.3. DESCRIPTION OF EXPERIMENTAL ABILITIES.

1.2.1. ISOCHRONOUS CYCLOTRON U-150 M.

At the isochronous cyclotron U-150 M (fig.2.1) the sample bulk doping by helium and/or hydrogen is fulfilled, as well as formation of various damage profiles through the specimen surface and depth with specially devised irradiation techniques and devices applied.

Technical characteristics:

Accelerated ion mass	1-4 amu;
Ion energy	7-60 MeV;
Energy spread	1 %;
Ion beam current	up to 50 μA;
Number of experimental channels	4.

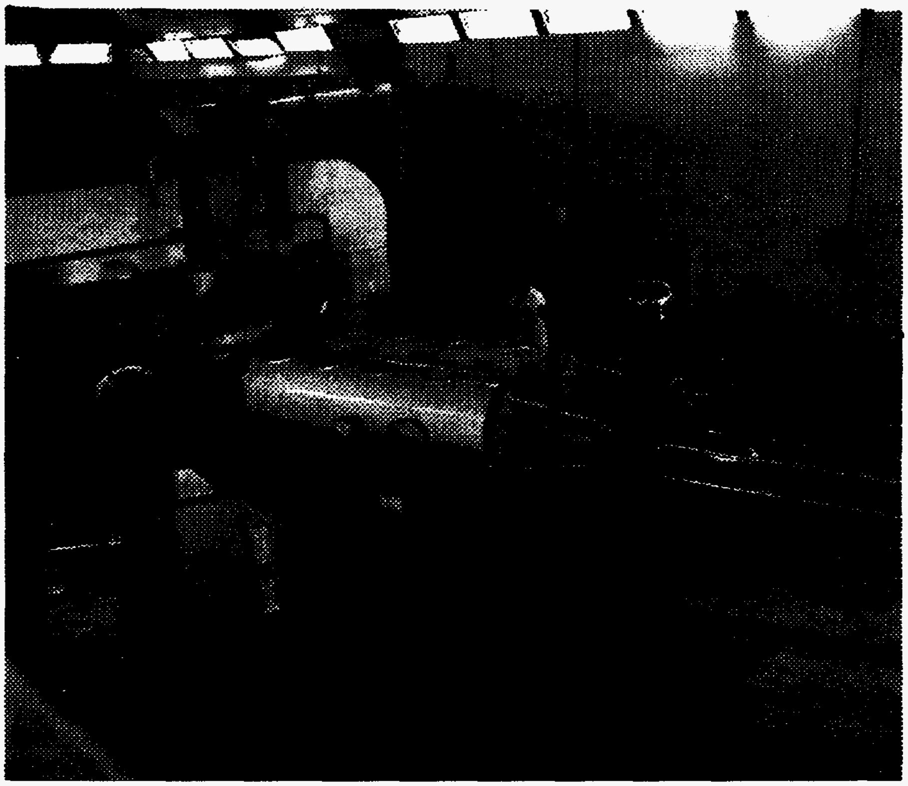

Fig.2.1. Isochronous cyclotron U-150 M.

2.3.1.1. Homogeneous ion doping

Homogeneous doping through the sample thickness is caused by moving of wedge stopping filter in front of samples, while the samples are motionless and fixed on bulk copper plate, which is heated to high temperatures by inside heater (fig.2.2).

Technical parameters of homogeneous volume doping of samples by helium and hydrogen atoms:

Damage degree	up to 0.01 dpa;

Sample thickness	
doped with helium	up to 1.2 mm,
doped with hydrogen	up to 6.5 mm;
Implanted atoms concentration	up to 100 appm;
Temperature	20-800 °C.

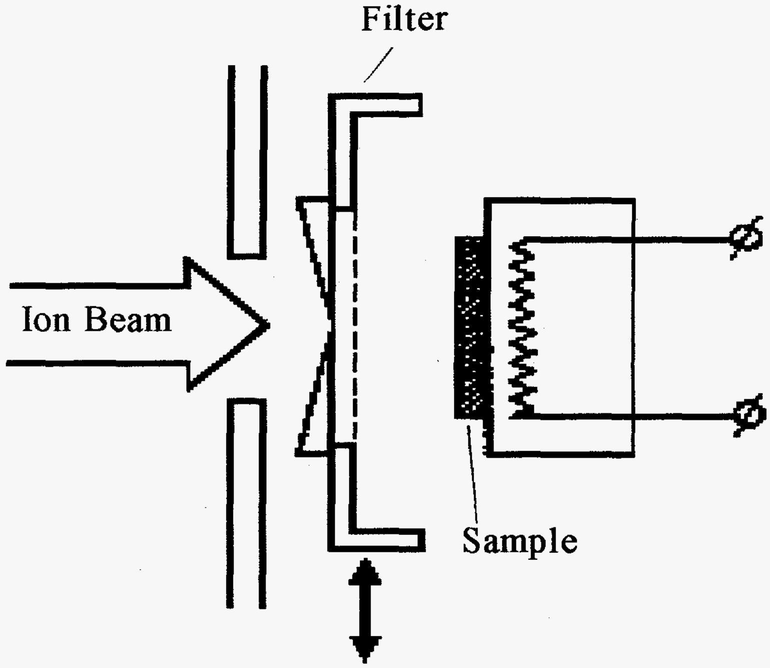

Fig.2.2. Irradiation technique for homogeneous ion doping.

2.3.1.2. Expanded profiles formation

For the formation of "expanded" damage profiles, including straggling zone, on the surface of irradiated sample, metal foil bended according to assigned law is used (fig.2.3).

Following parameters of irradiation are reached by using this technique:

Profile "expansion" coefficient	up to 100;
Incident particle energy:	
alpha-particles	20-50 MeV;
protons	7-30 MeV;
Impurity concentration/damage degree ratio	0-2000 appm/dpa.

This technique enables to investigate on the single sample defect structure and material properties (by metallography, measurement of microhardness and lattice parameter, etc.) at various values of impurity concentration/damage degree ratio and different spectra of primary knock-on atoms.

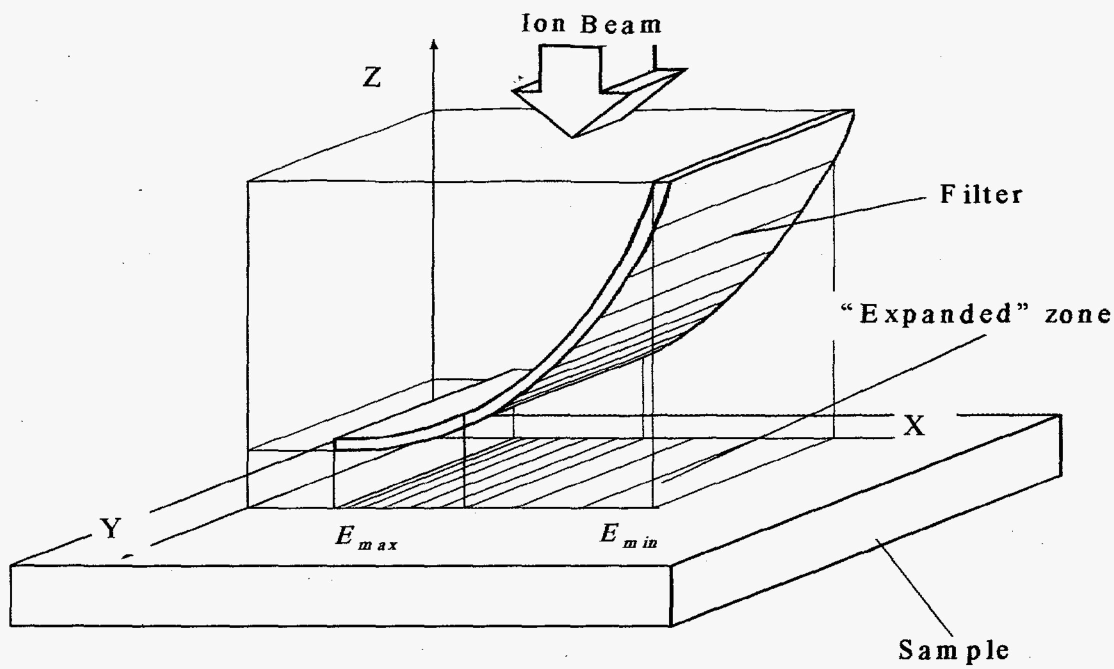

Fig.2.3. Irradiation technique for expanded profiles formation.

2.3.1.3. Formation of separate doped zones in the sample

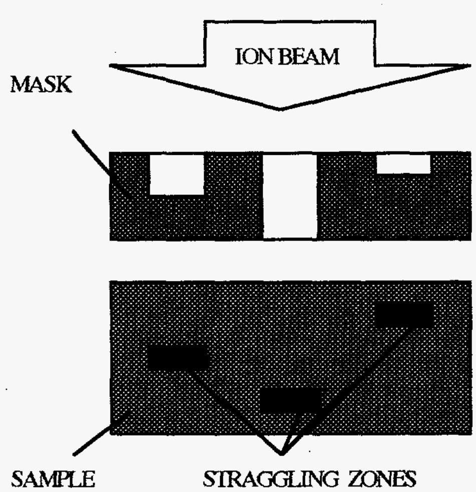

Fig.2.4. Irradiation technique for the formation of separate doped zones in the sample.

Irradiation of bulk Beryllium samples for metallography and mechanical tests is realized with use of stopping filters and masks, which provides doped zones formation at different depths in the sample and their spacial separation on the surface. As a result, there is non-irradiated region near any irradiated region of the sample. Depending on the material grain size, the dimensions of opened rectangular or round "windows" in the masks are chosen (fig.2.4). Usage of such geometry irradiation allows to study a formation of bubbles in doped zone, hardening of irradiated material, inclination to blister formation, and in case of brittle fracture (irradiated layer breaking off) - to determine critical parameters of the irradiation.

2.3.1.4. Formation of periodically arranged regions of implantation

For study of high gas impurity concentration influence on material structure by TEM methods, another irradiation technique is used. It consists in cylindrical stopping filters placing in front of the sample (fig.2.5).

Technical characteristics:

Filter diameter	10-100 μm;
Particle energy	7-60 MeV;
Impurity concentration	up to 1000 appm.

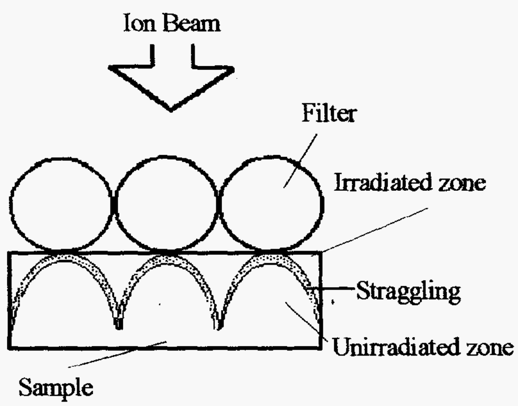

Fig.2.5. Irradiation technique for the formation of periodically arranged regions of implantation.

2.3.2. HEAVY ION ACCELERATOR UKP 2-1

Heavy ion accelerator UKP 2-1 (fig.2.6) is a tandem accelerator with two independent accelerating tracts and oilless pumping system. Due to high energy stability and wide accelerated mass range it allows to carry out precision nuclear-physical measurements of radiation damage and impurity concentration profiles in near-surface layers of material by Rutherford backscattering, nuclear reactions, ion channeling and PIXE methods. Besides this, the accelerator allows to carry out high-dose irradiation experiments with material damage degree about dozens of dpa.

Accelerator technical characteristics:

Accelerating voltage	0.05-1.0 MeV;
Accelerating voltage stability	0.015 %;
Accelerated mass range	1-250 amu;
Ion beam current for:	
hydrogen	up to 100 μA,
heavy ions	about 1 μA;
Focal spot size	0.01 mm;
Scanning area	30x30 mm^2.

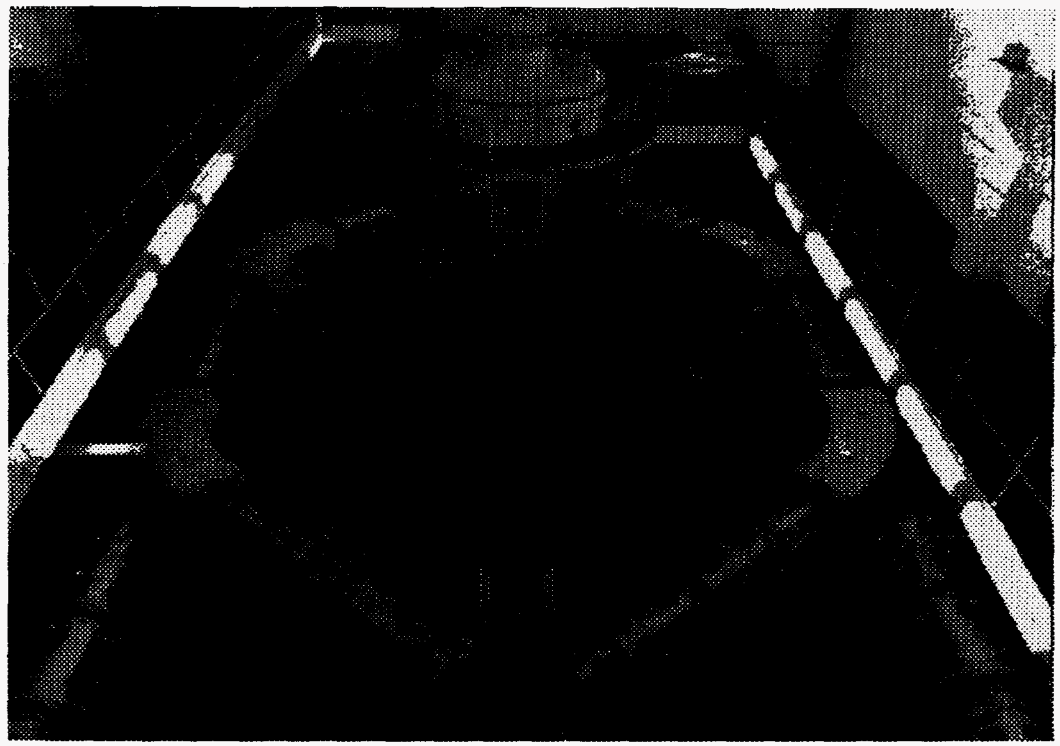

Fig.2.6. Heavy ion accelerator UKP 2-1.

Study of high-dose irradiation effects on the structure and properties of materials is carried out with use of this accelerator. Application of special techniques makes possible TEM-study of a defect structure along ion range in the material ("cross-section").

Modified device for a homogeneous ion doping is used as a target chamber for irradiation. Besides this, a universal target chamber is used, allowing simultaneous damage formation by ion irradiation and nuclear-physical measurements of damage and concentration profiles.

Irradiated surface analysis by SEM and optical metallography allows to determine main irradiation parameters resulting in fatal changes of sample surface, and to estimate a possibility of radiation-enhanced and thermal restoration of large-scale surface damage (blisters, cavities and so on) by intensive proton beam.

2.3.3. NUCLEAR REACTOR **IGR**

Pulse uran-graphite self-stopping thermal neutron reactor IGR has the following technical characteristics:

Power at the pulse mode	10 GW;
Maximum energy release	5.2 GJ;
Fuel temperature	<1400 K;
Coolant	is absent;
Neutron flux density at the pulse mode	$0.7x10^{17}$ n/cm^2 s.

Central experimental channel diameter is 22.8 cm. Ampule devices allow to realize irradiations in hydrogen or nitrogen environment. High reactor reactivity (3.4%) provide minimum neutron pulse as short as 0.12 s. Pulse heating of samples up to near-melting temperatures is possible.

2.3.4. NUCLEAR REACTOR **EWG 1 M**

The EWG.1M reactor - an advanced EWG.1 reactor - is a research water-cooled heterogeneous thermal nuclear reactor with light-water moderator and coolant and beryllium reflector. The reactor core includes 30 water-cooled technological channels installed in three-circular row cells. An equivalent diameter of the core is 0.548 m, height is 0.8 m. In the central part of the reactor there is an experimental loop channel with a diameter of 0.164 m surrounded by beryllium displacer, in which it is possible to locate an apparatus including one or some tested fuel assemblies or containers with irradiated material samples. In the beryllium moderator 12 rods of the reactor reactivity compensation system are mounted. Core surrounding reflector has 10 regulating drums, which are the operating members of the reactor control and safety system.

Technical characteristics:

Reactor modification	EWG.1	EWG.1M
Power, MW	720	72

U-235 loading,kg	6.7÷15.9	4.6
Fuel	(U,Zr,Nb)C	U,Zr/Zr
Fuel temperature, K	3400	390
Coolant	$H_2.N_2$	H_2O
Coolant temperature, K	3100	370
Thermal neutron flux density in the core, n/cm^2s	$3.5x10^{15}$	$3.5x10^{14}$

The reactors described above are disposed at the former Semipalatinsk nuclear testing site and belong to the Institute of Atomic Energy NNC RK.

In the territory of Kazakhstan there is an industrial fast neutron reactor (BN-350), situated in Aktau town and used for electric power production and for distillation of Caspian Sea water. This reactor does not belong to National Nuclear Center, but there is a possibility of high-dose irradiation of beryllium samples in it at neutron flux density about 10^{16} n/cm^2 s. Exposition in the central channel, where neutron flux and energy are maximum, allows to produce in beryllium samples radiation damage degree up to 30 dpa in a reasonable amount of time.

2.4. METHODS OF INVESTIGATION

Following basic methods of investigation are used in SSRL:

1. Transmission electron microscopy (TEM) and techniques of TEM-specimens preparation including "cross-section" techniques allowing observation of the whole damaged zone in the single specimen.
2. Scanning electron microscopy and optical metallography.
3. Tensile tests and microhardness measurements.
4. X-ray diffraction.
5. Precision automatically controlled annealing of samples in vacuum and inert environment.

2.4.1. TEM-SPECIMEN PREPARATION TECHNIQUE

Initial processing of bulk Beryllium samples for TEM-specimen preparation includes electric discharge cutting, mechanical grinding and electrochemical polishing resulting in 3 mm diameter disks with thickness about 0.2 mm. Specially modified device for visual control of surface quality "in situ" during electrochemical polishing, "ELIPOVIST", is used for choice and adjustment of electrolyte composition and polishing conditions.

Final thinning of TEM-specimens is realized by one-side jet electrochemical polishing in the original device with automatic switching off at the initial stage of specimen perforation.

Cross-sectioned TEM-specimens will be prepared by using a novel technique, which is less complicated than wide-known methods.

2.4.2. TEM METHODS TO BE USED

At the first step of research, study of beryllium microstructure includes determination of grain size, grain shape, grain orientation and peculiarities of dislocation structure.

This will be attained by photographing, processing and analysis of bright-field images of microstructure and corresponding diffraction patterns. Dislocations identification will be performed by standard method using the vanishing criterion $\mathbf{g} \times \mathbf{b}=0$, where $\mathbf{g}$ is the reflection vector and $\mathbf{b}$ is the Burgers vector. Defocused images method D-2-1/2 will be used for estimating of strains in matrix.

At the further microstructural study of irradiated samples the regularities of evolution of dislocation structure, voids, bubbles and impurities distribution are to be determined depending on irradiation and post-irradiation treatment conditions. In some cases "in situ" experiments with specimen heating in TEM can be carried out.

Since the Beryllium is a material with a relatively low impurities solubility, a secondary phases precipitation on grain boundaries, dislocations and in the matrix is to be expected. These precipitates have significant influence on the plastic properties of material. Therefore a study of irradiation effect on impurities redistribution and secondary phases formation is desirable. Unfortunately, subcontractor do not possess an apparatus for high resolution microprobe analysis. It could be expedient to conduct such experiments jointly with LANL.

2.4.3. TENSILE TESTS AND MICROHARDNESS MEASUREMENTS

For measurements of mechanical characteristics of beryllium (tensile strength, ductility, microhardness) tensile tests in the "INSTRON-1195" facility at various temperatures (20-800 °C) in vacuum ($3x10^{-3}$ Pa) with deformation rates $10^{-2} \div 10^{-4}$ s^{-1} and microhardness measurements by Vickers method in the PMT-3 device with indenter loading of 50-200 g are planned.

2.4.4. METALLOGRAPHIC METHODS

Metallographic study includes sample surface grinding and polishing, chemical etching for microstructural features visualization, and image recording using "NEOPHOT-2" optical microscope and/or "REM-200" scanning electron microscope. Due to large focus depth, SEM will be used also for the analysis of fractured surfaces of samples after mechanical tests, including quantitative relief measurement by means of stereophotography.

It is reasonable to study impurities and their segregation effect on the fracture mode using high-resolutional SEM with microprobe analysis.

For study of large-scale surface damage and swelling in the irradiated zone, profilometry method will be applied allowing to detect relief roughnesses with accuracy of 100 nm.

2.4.5. X-RAY DIFFRACTION

Precision measurements of lattice parameter in different grade beryllium samples, and determination of lattice periods of secondary phase particles will be performed in "DRON-3" X-ray diffractometer with copper, iron, or cobalt anode.

2.4.6. POST-IRRADIATION ANNEALING TECHNIQUE

For study of defect structure evolution as a result of post-irradiation annealing, special device is used, which includes small electric furnace with resistive heater and thermocouples, situated in the vacuum volume, and precision automatic temperature controller. The device provides temperature stability about 1 % in the range of 50-800 °C at residual pressure of 10^{-3} Pa. There are a possibilities of annealing in the inert environment (Ar) and programmed step by step temperature variation.

3. MICROSTRUCTURAL CHARACTERIZATION OF POLYCRYSTAL BERYLLIUM MATERIAL.

3.1. INTRODUCTION

Polycrystal Beryllium of (A-4) grade, produced by hot pressing at Ulba metal plant, was taken as a sample for study.

Its purity turned out to be not very high, as it is clear from undermentioned results, but this fact has enabled to test a suitability of our experimental techniques and methods more completely.

Grain size in analyzed samples was too large for the obtaining of any statistical information about grain size and grain shape by transmission electron microscopy (TEM). Therefore such information was obtained with use of optical metallography, while TEM-study was focused at the analysis of matrix defect structure.

3.2. SPECIMEN PREPARATION AND EXPERIMENTAL PROCEDURE.

3.2.1. OPTICAL METALLOGRAPHY.

Bulk beryllium cylinder with diameter of 17 mm was sliced by electric discharge cutting into plates with thickness about 0.4 mm. Plates was mechanically grinded and polished using fine polishing powder. Polished plates was subjected to chemical etching in boiling 10 % solution of HOOCCOOH in water during 2 minutes in order to visualize crystal grain boundaries.

Etched polished sections of beryllium samples were studied in Neophot-2 optical microscope. Structure images with magnifications from 100 to 400 were recorded onto photoplates. Measurements were carried out on photographic prints with total magnification of 400.

3.2.2. TRANSMISSION ELECTRON MICROSCOPY.

Bulk beryllium cylinder with diameter of 17 mm was sliced by electric discharge cutting into plates with thickness about 0.4 mm. Plates were mechanically grinded up to 0.2 mm thickness. 3 mm diameter disks were cut from grinded plates in electric discharge device in order to avoid sample deformation. TEM-specimens were prepared from 3 mm diameter disks by one-jet electrochemical polishing in a mixture of $HClO_4$ (200 ml), C_2H_5OH (700 ml) and $C_3H_8O_3$ (100 ml) at room temperature, 20 V, and 5 mA. This solution was chosen from a lot of possible and known from literature compositions taking into account experimentally tested quality of polishing and accessibility of reagents.

TEM-study of beryllium samples was carried out in JEM-100 CX and EM-125 transmission electron microscopes at accelerating voltage of 100 and 125 kV and magnifications from 1000 to 100000. Microstructure images and corresponding diffraction patterns were recorded onto photoplates. Diffraction pattern distances were measured directly at photoplates. Sizes, distances and densities of microstructural features were measured at magnified photographic prints.

3.3. RESULTS OF MICROSTRUCTURAL STUDY.

3.3.1. OPTICAL METALLOGRAPHY RESULTS.

Fig.3.1 shows a typical photograph of etched polished section of beryllium sample.

The material consists of polygonal grains with size ranging from about 2 to 50 μm without any preferential orientation. Size distribution of grain sections obtained using a series of micrographs is presented at fig.3.2. An average grain size value determined from histogram is equal to 8.5 μm.

3.3.2. TEM RESULTS.

Low magnification micrograph of Be sample structure is shown at fig.3.3. One can see a lot of second phase inclusions, visible as black spots. Volume content of second phase was estimated to be about 1 %, using low magnification TEM-images.

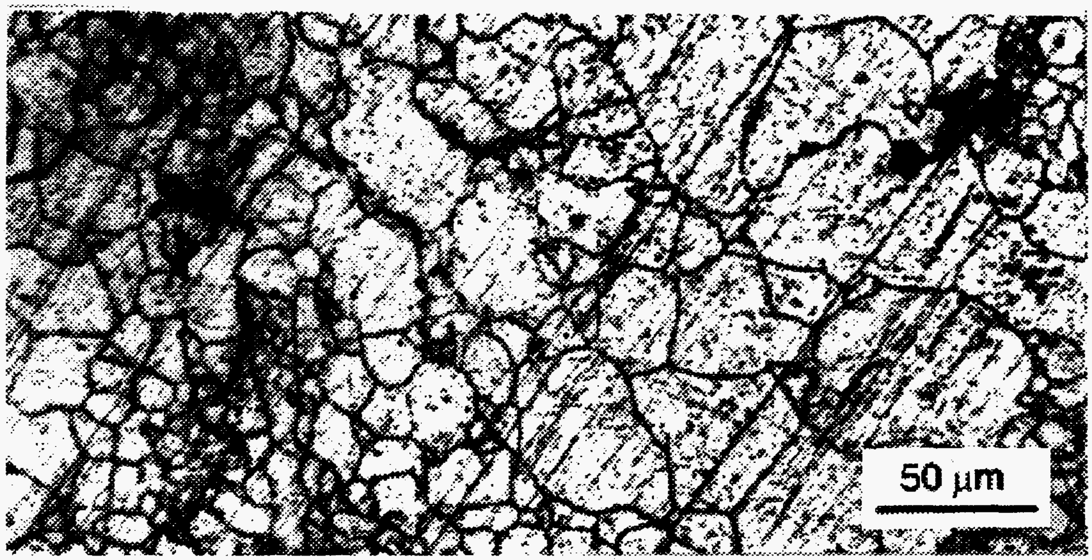

Fig.3.1. Optical micrograph of etched polished section of A-4 beryllium sample.

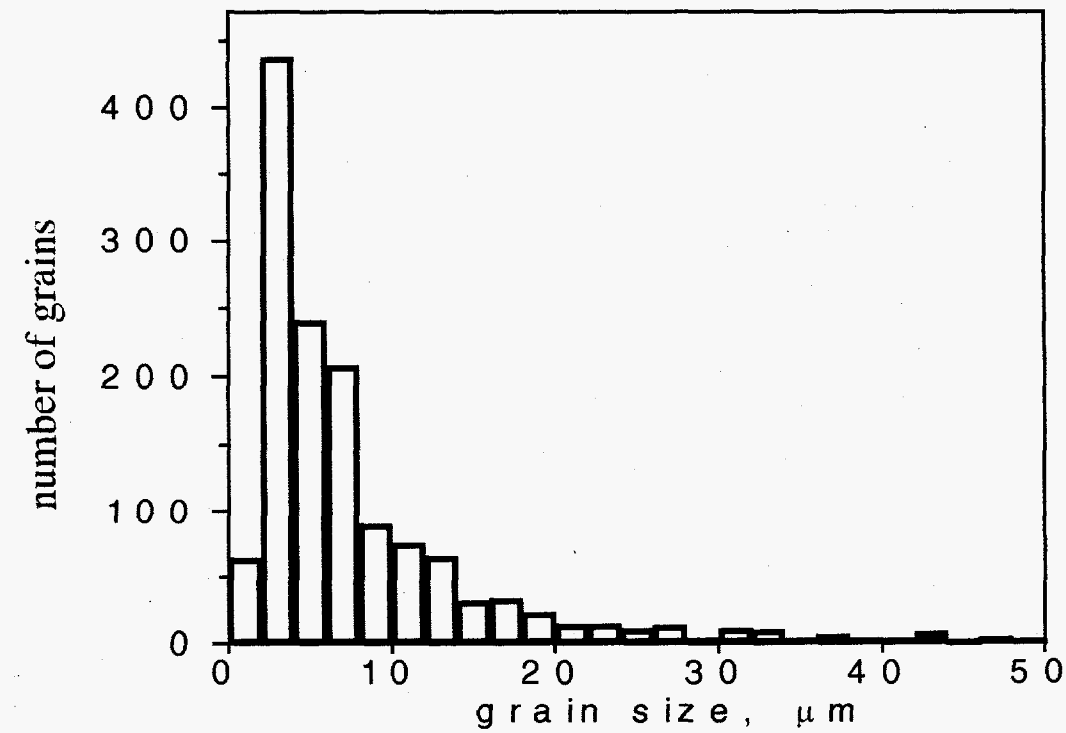

Fig.3.2. Histogram showing grain size distribution in A-4 beryllium.

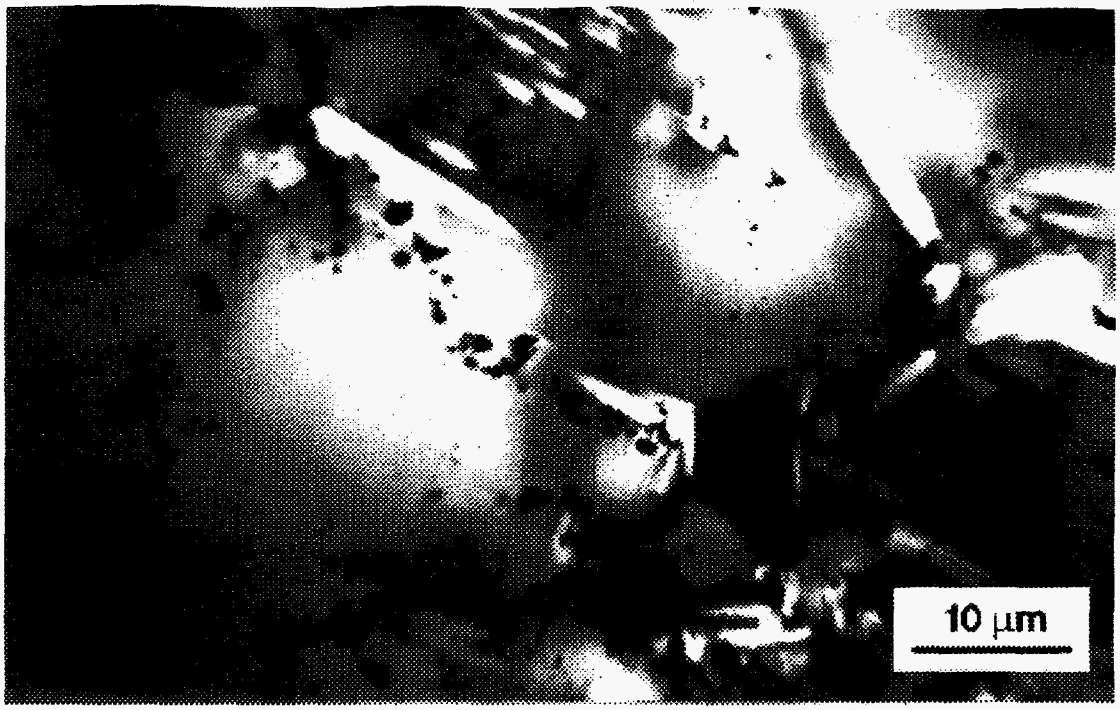

Fig.3.3. Low magnification TEM image of A-4 beryllium microstructure.

Specimen thickness was determined by stereophotography and its mean value for large areas at low magnification proved to be about 1 micron. Inclusions are situated near grain boundaries and randomly in grain matrix (see fig.3.4), in the latter case their size being somewhat smaller, as a rule . Fig.3.5 presents size distribution of inclusions calculated using a series of micrographs at magnification of 20000. Shape of particles was close to prismoidal, and mean value between largest and least dimensions of single particle was taken as particle size. As it is seen from histogram, size of inclusions ranges from about 50 nm to 1300 nm with average value 450 nm.

Nature of inclusions was determined by means of electron diffraction, using matrix reflections for calibration. Lattice distances determined from diffraction patterns are well coincident with known distances for beryllium oxide, BeO. Dark field images in the BeO reflections show bright contrast of inclusions (see fig.3.6). It some occurrences oxide particles form conglomerates with diameter about 1000 nm, as shown at fig.3.7.

Presence of BeO phase is confirmed by X-ray diffraction, which shows well-defined series of BeO reflections. Some additional non-identified weak reflections were found by X-ray diffraction, but any other than BeO second phase inclusions were not identified by electron diffraction.

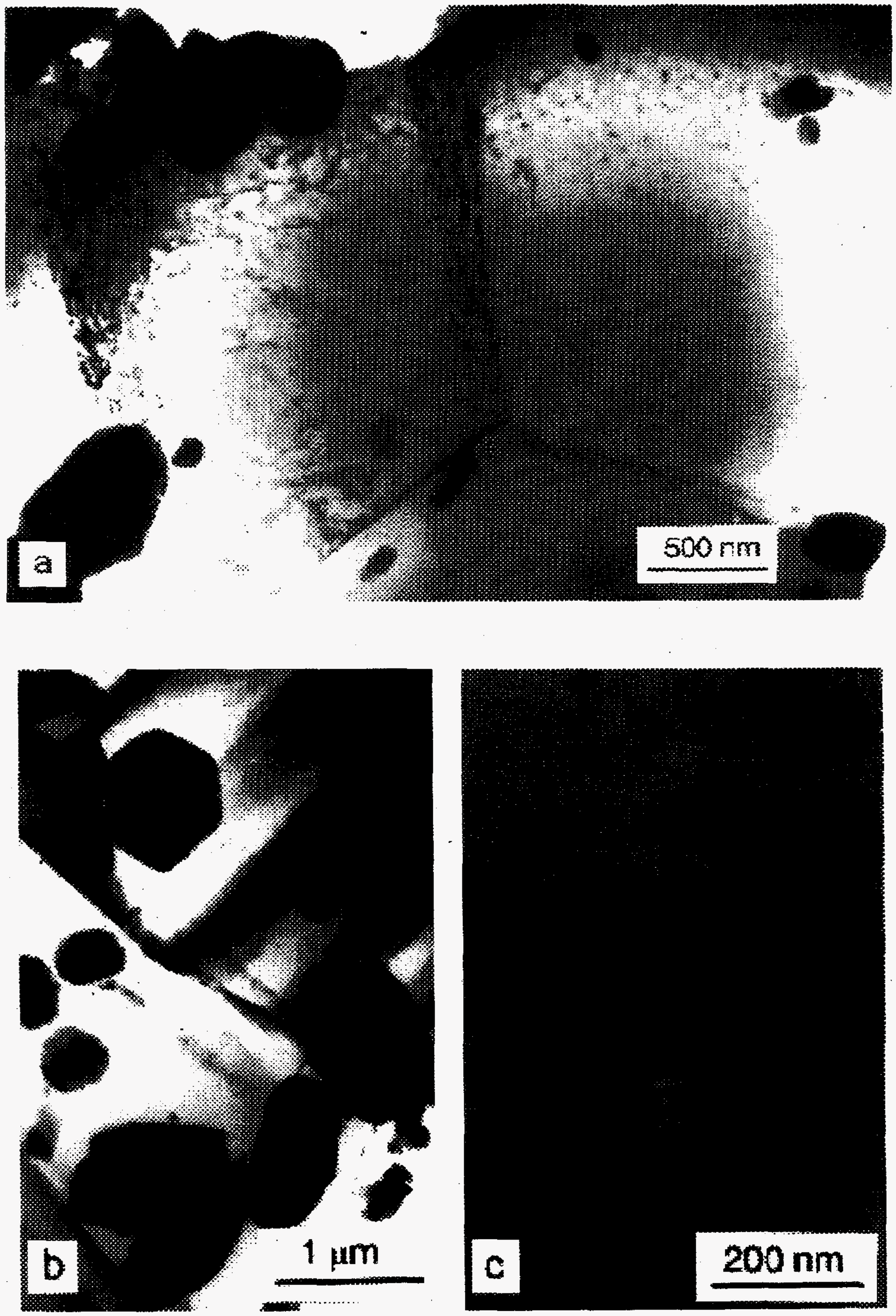

Fig.3.4. Second phase inclusions in A-4 beryllium: a) 40000 magnification; b) large particles near grain boundary at 20000 magnification; c) small particles in matrix at 100000 magnification.

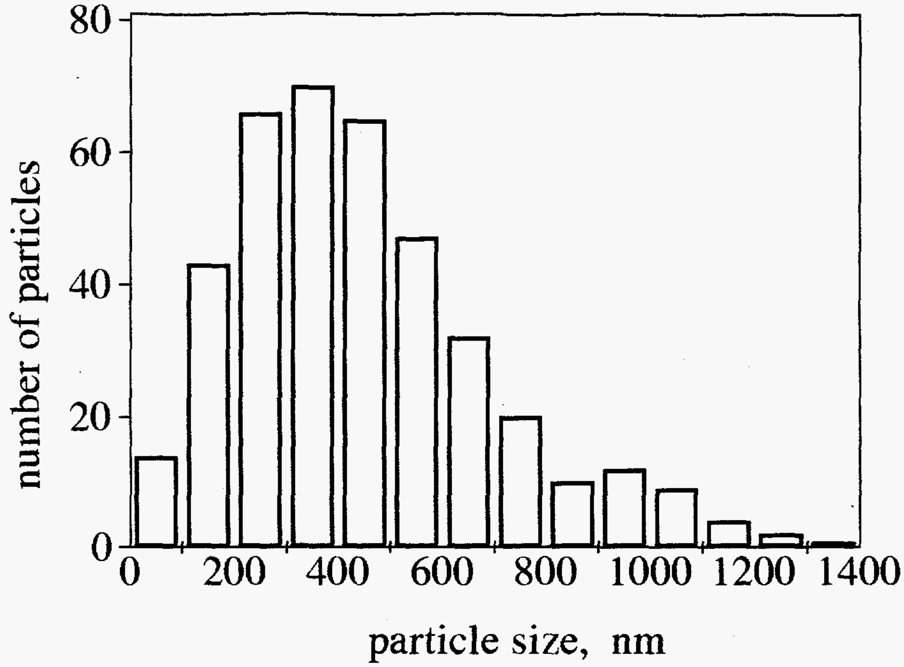

Fig.3.5. Histogram showing size distribution of second phase particles in A-4 beryllium.

It was found that intercrystalline interfaces in analyzed samples are well-formed grain boundaries, notwithstanding the material have been produced by hot pressing. Disorientation of adjacent grains is compensated by a network of grain boundary dislocations (fig.3.8). No cavities were observed in the samples, including near-boundary regions.

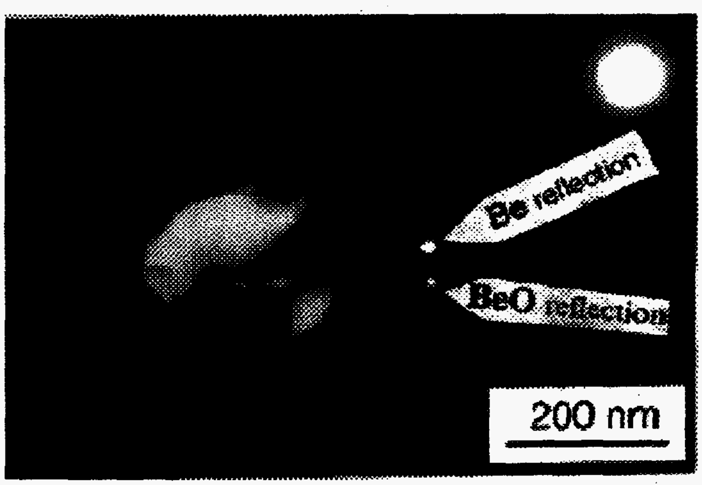

Fig.3,6. Dark field image of inclusion in BeO reflection.

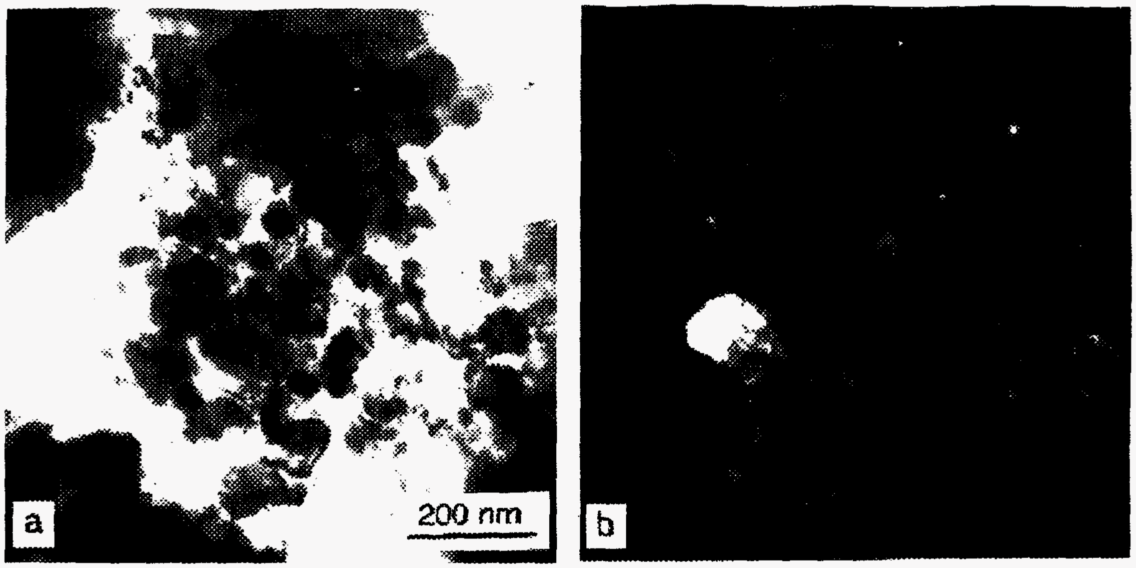

Fig.3.7. BeO particles conglomerate in A-4 beryllium: a) bright field; b) dark field image in BeO reflection.

Fig.3.8. Grain boundary in A-4 beryllium.

Besides oxide particles, linear dislocations and small dislocation loops were found in the grain matrix (fig.3.9), with average dislocation density about $2x10^9$ cm^{-2}, as was estimated by random secant lines method. For a calculation of specimen thicknesses, the "extinction contours" method in a two-beam diffracting conditions was applied. Dislocation density is not uniform in a grain volume. In most cases crystal grains are divided by dislocation walls onto slightly disoriented blocks (fig.3.10).

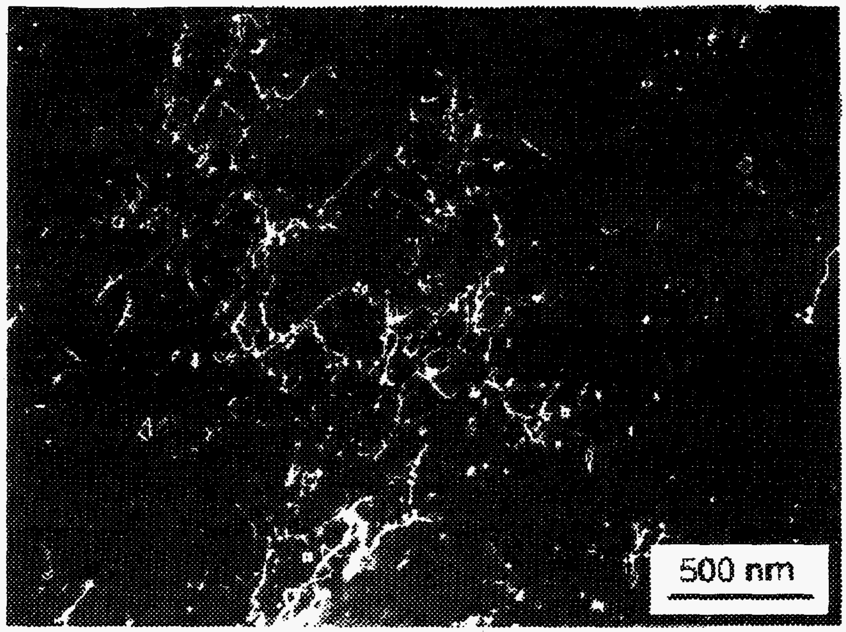

Fig.3.9. Dislocations and dislocation loops in matrix, dark field image.

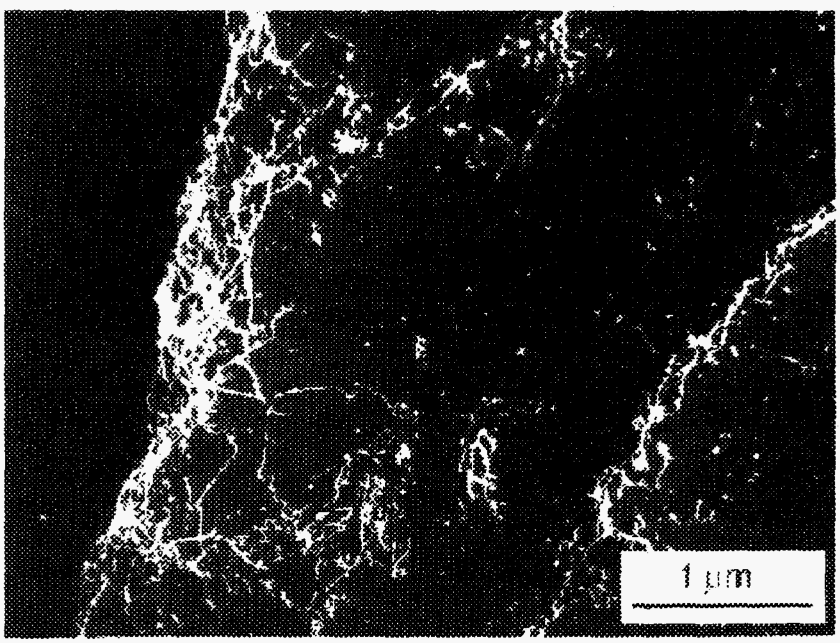

Fig.3.10.Dislocation walls in matrix, dark field image.

3.4. SUMMARY.

The aforesaid results show that sufficiently complete information about microstructure of polycrystal beryllium material can be obtained by means of transmission electron microscopy in combination with optical metallography and X-ray diffraction. The material analyzed in the present study is a polycrystal beryllium with an average grain size about 8.5 μm, well-formed grain boundaries and without cavities. Dislocation density in grain matrix is $2\ 10^{9}\ cm^{-2}$, taking into account dislocation walls. High contents of BeO inclusions (about 1 % by volume) with average diameter of 400 nm was found in the material.

4. TASK FORMULATION FOR THE DEVELOPMENT OF THE PROJECT FOR THE EXPERIMENTS ON INVESTIGATION OF BERYLLIUM MATERIALS BEHAVIOR UNDER CONDITIONS, CLOSE TO THERMO-NUCLEAR REACTOR (TNR).

When choosing the materials and making an attempt to construct the first wall of the thermo-nuclear reactor, a number of the problems related to the studying the properties of beryllium under conditions of He and H atoms accumulation, intense radiation and temperature influence are left unsolved, as well as the task of production of Be coatings satisfying numerous requirements, called "TNR conditions".

One of the specific problems related to this type conditions and requiring a definite solution is the clearing up of the complex effect of gaseous impurities, radiation defects and the temperature on the physical-mechanical properties of beryllium and real beryllium products. Such problem can be divided into a number of sections:

- structural and phase stability of Be and Be coatings under the intense radiation influence;
- gaseous swelling and gas-filled bubble behavior in Be and Be coatings under thermal and reactor irradiation influence;
- variation in the Be mechanical properties under the conditions of He and/or H atoms accumulation;
- variation of the mechanical properties of Be-substrate interface.

5. POSSIBLE EXPERIMENTS

5.1. EXPERIMENT A

The experiment objective is investigation of structural stability and gaseous swelling of plasma-spraied beryllium.

TASKS

TASK A1. To create in the Be samples the inner helium- and hydrogen-doped zones with the concentrations of 10, 100, 200, 500, 1000 appm He and/or 30, 300, 600, 1500, 3000 appm H by alpha-particle and proton irradiation.

TASK A2. To execute post-irradiation thermal annealing of Be samples with various contents of He and/or H at the temperatures 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours accompanied by specimen surface profilometering.

TASK A3. To prepare specimens by Be sample cutting, grinding, mechanical polishing, electrochemical polishing and etching. To study the specimen structures by transmission and scanning electron microscopy, and optical metallography.

TASK A4. To measure the microhardness of Be specimens with various contents of He and/or H along the bombarding particle ranges after annealing at 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours.

TASK A5. To carry out the processing and analysis of the data of profilometry, microstructure studies and measurements of Be sample microhardness after implantation of He and/or H atoms and post-irradiation annealing.

TASK A6. To prepare a final report, describing all completed task activities.

EXPECTED RESULTS:

- The Be samples having interior closed He and/or H doped zones with concentrations of 10, 100, 200, 500, 1000 appm He and/or 30, 300, 600, 1500, 3000 appm H are to be produced.

- The Be specimens with various He and/or H atoms contents, annealed at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours are to be obtained. The data on sample surface profile measuring are also to be obtained.

- The experimental data on the defect structure and gaseous bubble evolution during post-irradiation annealing of the Be specimens with closed He and H zones are to be obtained by transmission and scanning electron microscopy, and optical microscopy.

- The experimental data on microhardness measuring along the bombarding particle ranges in Be specimens with various He and/or H contents after annealing at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours are to be obtained.

- A final report on the results of structural, profilometric and metallographic studies, measurements of microhardness of the annealed Be samples having closed zones with various contents of He and/or H atoms is to be prepared.

EXPERIMENT DESCRIPTION

The beryllium samples having the dimensions 40x7x1 mm^3 are irradiated by 23 MeV alpha-particles and/or 7 MeV protons in the isochronous cyclotron U-150 M trough a thick mask with the holes of a diameter 3 mm. As a result, the closed gaseous zones shaped as the disks of a diameter 3 mm and a thickness up to 100 μm are produced in the material interior. A set of samples is irradiated in order to produce the zones with He concentrations of 10, 100, 200, 500, 1000 appm and/or H concentrations 30,300, 600, 1500, 3000 appm. The irradiation temperature is 100 °C. The irradiation conditions, the specimen number and the required cyclotron time are presented is Table 1a (Appendix A). It should be noted that a part of the samples, irradiated by alpha-particles, later are re-irradiated by protons too. As a result we shall have three groups of samples with the closed zones which will contain the helium, hydrogen and helium plus hydrogen atoms. Further, the irradiated samples will be subjected to the annealing at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours accompanied by specimen surface profilometering.

For the observation of Be microstructure along bombarding particle ranges and microhardness measurements, the annealed specimens are sliced, grinded and polished in cross-section. After specimen chemical etching, investigation of gaseous bubble development in the doped zone is carried out by TEM, SEM and optical metallography methods.

Microhardness measuring is carried out along ion range, including the straggling zone.

TASK SCHEDULE

The experiment is performed during 2 years(see Table 1a, APPENDIX A). The task A1, related to Be samples cyclotron irradiation, will be carried out during the first quarter of the first year of the project activity. Irradiated sample annealings, according to the task A2, are executed during the second and third quarters. The tasks A3, A4, related to microstructure studies and microhardness measurements, are made each during a half of year. The tasks A5 and A6 are carried out during the last quarter of the second year.

FINANCIAL INFORMATION

Total cost of the experiment comprises \$ 113883. The first year of project activity requires \$ 69399, whereas the second year costs \$ 44484. Total financial information on each item of expenditures is presented in Tables 3a, 4a and 5a (Appendix A).

5.2. EXPERIMENT B.

The experiment objective is the investigation of behavior of the mechanical properties and microstructure of plasma-spraied Be versus the implanted He and/or H atom concentrations and the implantation temperature.

TASKS

TASK B1. To implant Be tensile specimens by He atoms up to concentrations of 10, 100, 200, 500 appm and by H atoms up to 30, 300, 600, 1500 appm at 100, 500 and 800 °C.

TASK B2. To perform tensile tests of Be specimens at 20, 500, 800 °C after He and H implantation up to various concentrations at various irradiation temperatures.

TASK B3. To carry out SEM investigations of the fracture surfaces of the tested Be specimens with various contents of He and H atoms.

TASK B4. To carry out TEM investigations of Be specimens with various contents of He and H atoms after mechanical testing.

TASK B5. To prepare a final report on the results of mechanical testing and microstructure investigation of the Be samples implanted by He and H atoms.

EXPECTED RESULTS:

- The Be tensile specimens implanted by He atoms up to the concentration of 10, 100, 200, 500 appm and H atoms up to 30, 300, 600, 1500 appm at various temperatures are to be produced.

- The basic mechanical properties of Be samples versus the concentrations of He and H atoms and implantation temperature are to be cleared up.

- The basic regularities in variation of the Be specimen fracture nature versus the concentrations of He and H atoms and implantation temperature are to be determined.

- The basic regularities in Be microstructure changes after mechanical testing versus the concentrations of He and H atoms, the implantation and mechanical testing temperature are to be obtained.

- A final report on the results of mechanical testing and TEM investigation of the Be samples implanted by He and H atoms up to various concentrations at various temperatures is to be prepared.

EXPERIMENT DESCRIPTION

The tensile specimens with the dimensions 40x7x0.2 mm^3, prepared at LANL, are implanted gomogeneously through the volume by He atoms up to the concentrations of 10, 100, 200, 500 appm and by H atoms up to the concentrations of 30, 300, 600, 1500 appm using alpha-particle and proton irradiation at 100, 500 and 800 °C in the isochronous cyclotron U-150 M. The implantation conditions, the specimen number and the required cyclotron time are presented in Table 1b (Appendix B). A part of samples is irradiated successively both by alpha-particles and by protons. As a result, we are to obtain three groups of irradiated samples: with helium, with hydrogen and with helium plus hydrogen atoms.

The irradiated and unirradiated samples will undergo tensile testings at deformation rates of $10^{-2}\div10^{-4}$ s^{-1} at 20, 500 and 800 °C up to the fracture. By tensile diagrams, the material strength and ductility limit will be determined as an average values of the parameters obtained in three identical tests.

The investigation of nature of Be specimens fracture will be done by SEM technique. After SEM investigations the disks of a diameter 3 mm are cut from the fractured samples. TEM-specimens are prepared from these disks. As a result of TEM investigation of Be specimens the qualitative and quantitative data on dislocation densities, gaseous bubbles and particles, their distributions within matrix and along grain boundaries will be obtained.

SCHEDULE

The proposed experiment is to be performed during 18 month (see table 2b, Appendix B). Task B1 will be completed during the first two quarters. Tasks B2, B3, B4 and B5 are to be carried out per quarter during the next 4 quarters.

FINANCIAL INFORMATION

The experiment cost consists of the participant payments during 18 months (APPENDIX 1), equipment cost, material cost, travel cost, government taxes and overhead. Total cost of the experiment B comprises $ 245861 (See Table 3b, 4b, 5b, APPENDIX B).

5.3.EXPERIMENT C

The experiment objective is the investigation of Be-substrate interface behavior depending on the He and/or H concentration under pulse reactor irradiation.

TASKS

TASK C1. To prepare the samples and the target devices for cyclotron irradiation, to determine the conditions for sample implantation by He and H atoms.

TASK C2. To perform the implantation of Be-substrate plates by He atoms up to He concentrations of 10, 100, 200, 500 appm and/or by H atoms up to 30, 300, 600, 1500 appm at 100, 500 and 800 °C.

TASK C3. To carry out the calculations of the reactor power and the specimen temperatures at neutron fluxes of $1x10^{16}$, $5x10^{16}$, $1x10^{17}$, $5x10^{17}$ n/cm^2 s and to choose the irradiation regimes for pulse reactor testing of the Be-substrate samples.

TASK C4. To perform the reactor tests of Be-substrate plates with various contents of He and/or H atoms for interface strength.

TASK C5. To carry out slicing, mechanical grinding and polishing, electrochemical treatment of the Be-substrate samples with He and/or H after reactor tests and to investigate the Be-substrate interface by methods of transmission, scanning electron microscopy and optical microscopy.

TASK C6. To measure the microhardness within the interface region of Be-substrate samples with various contents of He and H after reactor testing .

TASK C7. To perform processing and analysis of the results of reactor testings, microstructure studies and the measurements of microhardness for the Be-substrate samples with various contents of He and H atoms.

TASK C8. To prepare a final report on task performance.

EXPECTED RESULTS:

- The Be-substrate samples implanted at 100, 500 and 800 °C by He atoms to the concentrations 10, 100, 200, 500 appm and/or H atoms to the concentrations 30, 300, 600, 1500 appm are to be produced.

- The neutron flux, the required reactor power, and the sample temperature are to be calculated, and the irradiation régimes for pulse reactor testings of the Be-substrate samples with various contents of He and H atoms are to be chosen.

- The Be-substrate samples with various contents of He and/or H atoms, tested in the reactor at neutron fluxes 1×10^{16}, 5×10^{16}, 1×10^{17}, 5×10^{17} n/cm^2 s are to be obtained.

- Critical reactor irradiation conditions for fracture of the Be-substrate samples along the interface are to be determined (resource testing).

- The polished sections of the Be-substrate samples with various contents of He and H after reactor testings are to be prepared. Structural investigation of the Be-substrate interface is to be carried out by TEM, SEM and optical microscopy methods.

- The Be-substrate interface microhardness data for the samples with various contents of He and H after reactor testings are to be obtained.

- The final report on the results of reactor testings, structure and metallographic studies and measurements of microhardness of the Be-substrate interface for the samples with various contents of He and H atoms is to be prepared.

EXPERIMENT DESCRIPTION

The Be-substrate samples with the dimensions 40x7x1.5 mm^3, having the Be layer of a thickness about 1 mm, are irradiated in cyclotron by 50 MeV alpha-particles and 30 MeV protons in such way that the interface is implanted by He atoms up to the concentrations 10, 100, 200, 500 appm, and by H atoms up to 30, 300, 600, 1500 appm at 100, 500 and 800 °C.

For reactor testing the most of samples are implanted at 100 °C by He up to 100 appm and by H up to 300 appm (see Table 2C, Appendix C). Successive irradiation by alpha-particles and protons will allow to produce three groups of the samples: with He, with H and with He+H.

Before reactor testing, the ampoule device parameters are determined is such manner that the sample temperature varies from 800 to 1100 °C at neutron fluxes $1x10^{16} \div 1x10^{17}$ n/cm^2 s and various neutron pulse frequencies and intensities.

Reactor testings are carried out at neutron fluxes $1x10^{16}$, $5x10^{16}$, $1x10^{17}$, $5x10^{17}$ n/cm^2 s with 13 tests per each flux value (see Table 3C, Appendix C). Total test number is 52. After each testing investigation of irradiated samples is carried out in order to determine the state of the Be-substrate interface.

After reactor testings the fracture surfaces of all fractured samples are studied by SEM technique. The rest specimens are cut in the cross section and, after mechanical grinding, polishing and/or electrochemical treatment, the region of Be-substrate interface is investigated by TEM, SEM, optical microscopy, and microhardness measurement methods.

Basing on all obtained results of reactor testings, post-reactor structural studies and microhardness measurements, a conclusion on the stability of the Be-substrate interface under conditions close to TNR is made, the critical parameters of irradiation resulting in material fracture are determined.

SCHEDULE

This experiment is performed during three years. Preparation and execution of cyclotron sample implantation by He and/or H atoms (Tasks C1 and C2) are expected to be completed during the first three quarters. In the fourth quarter of the first year the parameters of reactor testing (Task C3) are calculated; during the first half of the second year all reactor testings are to be performed (Task C4). During the second half of the second year structural investigations of samples after reactor testings (Task C5) are carried out. Microhardness measurements are performed in the first half of the third year (Task C6). During the third quarter of the third year accumulation, processing and analysis of all experimental data concerning the properties of the Be-substrate interface are to be done (Task C7).

The project activity is completed at the fourth quarter of the third year by the final report on the results of reactor testing of the Be-substrate samples implanted by He and H.

FINANCIAL INFORMATION

The experiment cost consists of a participant payments, equipment expenditures, material purchase, travel cost, government taxes and overhead. Participant payments comprise $ 190 daily (Appendix 1).

Participants will work 110 days per year, so total annual participant payments comprise $ 22800. The equipment cost is composed of the cyclotron rent ($ 98000), a price of a microhardnessmeter ($ 10000), a price of a computer, a printer, a xerox ($ 5800) and a payment for reactor irradiation ($ 122500). Expenditure for working materials (abrasives, chemical reagents, photomaterials and stationery) requires annually $ 1300. The Travel cost comprises $ 20000. The overhead comprises 10% of the sum of the payment lost, the equipment cost, the material cost and the travel cost. The total cost of the experiment comprises $ 384032, including $ 159214 during the first year, $ 179784 during the second year, and $ 45034 during the third year.

Complete financial information for each item of expenditures per each year is given in Tables 4c, 5c, 6c and 7c (Appendix C).

5.4. EXPERIMENT D.

The experiment objective is TEM investigation of the defect structure and gaseous bubble evolution during post-irradiation thermal annealing of Be samples implanted by He and H atoms up to high concentrations.

TASKS

TASK D1. To carry out Be samples implantation by He atoms up to the concentrations 100, 200, 500, 1000 appm at 100, 500 and 800 °C.

TASK D2. To carry out Be sample implantation by H atoms up to the concentrations 300, 600, 1500, 3000 appm at 100, 500 and 800 °C.

TASK D3. To carry out the annealing of the samples with He and/or H at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours.

TASK D4. To prepare TEM-specimens from the samples with He and/or H annealed at 300, 500, 700, 900, 1100 °C.

TASK D5. To carry out TEM investigation of microstructure of the Be specimens with various contents of He and/or H atoms, annealed at 300-1100 °C during 0.1-1000 hours.

TASK D6. To perform processing and analysis of the results of TEM investigations of the Be specimens after He and/or H implantation and post-irradiation annealing, to prepare the final report.

EXPECTED RESULTS

- The Be samples implanted by He atoms up to the concentrations 100, 200, 500, 1000 appm at 100, 500 and 800 °C are to be produced.
- The Be samples implanted by H atoms up to the concentrations 300, 600, 1500, 3000 appm at 100, 500 and 800 °C are to be produced.
- The Be samples with He and/or H, annealed at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100 and 1000 hours are to be produced.
- The TEM-specimens from the Be samples, implanted by He and/or H and annealed at 300-1100 °C during 0.1-1000 hours, are to be produced.
- The TEM investigation of microstructure of the specimens with various contents of He and/or H atoms, annealed at 300-1100 °C during 0.1-1000 hours, is to be performed.
- Processing and analysis of the results of TEM investigation of Be specimens after He and/or H implantation and post-irradiation annealing are to be carried out. The final report is to be prepared.

EXPERIMENT DESCRIPTION

The Be samples (36 disks of a diameter 3 mm) are irradiated by 1 MeV alpha-particles and protons in heavy-ion accelerator UKP 2-1 at 100, 500 and 800 °C in a special target device. The set of samples is irradiated up to He concentration 100, 200, 500, 1000 appm and/or H concentration 300, 600, 1500, 3000 appm with a doped layer thickness about 1 μm .

The irradiated samples annealing is performed in vacuum at 300, 500, 700, 900, 1100 °C during 0.1, 1, 10, 100, 1000 hours. Further, TEM-specimens are made from these samples by jet electropolishing technique.

TEM investigation of objects is aimed, mainly, to obtaining quantitative and qualitative information about evolution of gaseous bubbles, dislocation structure, second-phase particles and impurities redistribution in the material. Application of the specific irradiation technique gives a possibility to study at one TEM-specimen at once three zones: the zone irradiated "by shooting through", the straggling zone and unirradiated part of a specimen, making significantly easier the comparative structural study.

SCHEDULE

The experiment D is performed during 2 years (see Table 10, Appendix D). The tasks D1, D2 are carried out during the first and second quarters of the first year respectively. The task D3, related to long-termed post-irradiation annealing, is executed during the third and fourth quarters of the first year. The task D4 is executed during the first quarter, D5 during the second and third quarter, D6 during the fourth quarter of the second year.

FINANCIAL INFORMATION

To perform the experiment D, $ 91784 is required, including $ 46970 during the first year and $ 44814 during the second year. Complete financial information concerning each item of expenditure every year is presented in Tables 3d, 4d and 5d (Appendix D).

5.5. EXPERIMENT E

The experiment objective is TEM study of phase-structural transformations in Be with various He and H contents irradiated by protons up to 1, 5 and 30 dpa at 500 and 800 °C.

TASKS

TASK E1. To carry out the Be samples implantation by He atoms up to the concentrations 10, 100, 200, 500, 1000 appm at 100 °C.

TASK E2. To carry out the Be samples implantation by H atoms up to the concentrations 30, 300, 600, 1500, 3000 appm at 100 °C.

TASK E3. To perform 1 MeV proton irradiation of the Be samples with various He and/or H contents up to 1 and 5 dpa at 500 and 800 °C.

TASK E4. To perform 1 MeV proton irradiation of the Be samples with various He and/or H contents up to 30 dpa at 500 and 800 °C.

TASK E5. To prepare TEM-specimens from the samples with various He and/or H contents , irradiated by 1 MeV protons up to 1, 5 and 30 dpa at 500 and 800 °C.

TASK E6. To carry out TEM investigation of microstructure of the Be specimens with various contents of He and/or H,irradiated by 1 MeV protons up to 1, 5 and 30 dpa at 500 and 800 °C.

TASK E7. To carry out processing and analysis of the results of TEM investigation of the Be specimens after He and/or H implantation and proton irradiation up to 1, 5 and 30 dpa at 500 and 800 °C.

TASK E8. To prepare the final report on the results of microstructural studies of Be with various contents of He and/or H atoms, irradiated by 1 MeV protons up to 1, 5 and 30 dpa at 500 and 800 °C.

EXPECTED RESULTS:

- The Be samples implanted by He atoms at 100 °C up to concentrations 10, 100, 200, 500, 1000 dpa are to be produced.
- The Be samples implanted by H atoms at 100 °C up to concentrations 30, 300, 600, 1500, 3000 dpa are to be produced.
- The Be samples with various contents of He and/or H atoms , irradiated by 1 MeV protons up to 1 and 5 dpa at 500 and 800 °C are to be produced.
- The TEM-specimens are to be prepared from Be samples with various contents of He and/or H atoms, irradiated by protons up to 1, 5 and 30 dpa at 500 and 800 °C.
- The quantitative and qualitative data are to be obtained as a result of TEM investigation of microstructure of Be with various contents of He and/or H atoms, irradiated by protons up to 1, 5 and 30 dpa at 500 and 800 °C.
- Processing and analysis of the results of TEM study of phase-structural transformation in Be with various He and H contents, irradiated by protons up to 1, 5 and 30 dpa at 500 and 800 °C are to be carried out, a final report is to be prepared.

EXPERIMENT DESCRIPTION

The Be samples (36 disks of a diameter 3 mm) are irradiated by 1 MeV alpha-particles and protons in heavy-ion accelerator UKP 2-1 at 100 C in a special target device. The set of samples is irradiated up to He concentration 10, 100, 1000 appm and/or H concentration 30, 300, 3000 appm with a doped layer thickness about 1 μm . Then the samples implanted by He and/or H atoms are reirradiated by intense proton beam up to 1, 5 and 30 dpa at 500 and 800 °C. TEM-specimens are prepared from irradiated samples by jet electrochemical polishing.

TEM analysis of irradiated Be specimens is aimed mainly to the obtaining of qualitative and quantitative information on the evolution of gaseous bubbles, dislocation structure, impurities redistribution and secondary phase particles formation.

SCHEDULE

The experiment E is performed during 2 years. Each task is carried out during one quarter (see Table 1e, Appendix E).

FINANCIAL INFORMATION

To perform the experiment E, $ 94960 is required, including $ 50146 during the first year and $ 44814 during the second year. Complete financial information concerning each item of expenditure every year is presented in Tables 4e, 5e and 6e (Appendix E).

5.CONCLUSION

As a result of present agreement tasks performance, and looking through similar works executed in the framework of the ITER program by member states, as well as taking in mind the possibilities available and the existing experimental base, we propose the following formulation of the project on investigation of Be and Be coatings: "Complex simulation of fusion reactor radiation and thermal effect on the beryllium structure and properties".

The project aim is to study the beryllium (Be coatings) structure and properties under the conditions simulating radiation and thermal effect in TNR, to determine the critical parameters needed for choice of engineering and technological solutions related to creation of the first wall of ITER. A performance of the proposed tasks allows to solve the following problems:

- swelling of beryllium deposited onto a substrate by plasma spraying or another technique, variation of its physical mechanical properties in presence of gaseous impurities, grain-boundary effects: embrittlement, cracking etc.;

- investigation of the beryllium-substrate interface behavior under conditions of intense irradiation and gaseous impurities accumulation;
- study of temperature cycling effect on a Be coating and its behavior under neutron irradiation accompanied by accumulation of gaseous impurities and radiation defects;
- phase-structural transformations in Be under the conditions of simultaneous effect of high-level damage and high concentrations of He and H atoms.

The experimental base available at NNC RK allows to perform the proposed experiments on volume doping of bulk Be samples and their radiation heating under conditions close to TNR. The list of proposed experiments is incomplete due to limited report volume. The description of the experiments on simulation of the complex effect of He and/or H atoms on various properties of Be and Be coatings under intense proton and neutron irradiation and thermocycling has suffered the most.

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APPENDIX 1

Technical Staff.

Name	Area of project expertise	Scientific rank	Daily rate
Vagin S.P	Leader of the project	Cand.phys. math.sci.	30
Utkelbayev B.D.	Co-ordinator of experimental jobs, TEM-study	Cand.phys math.sci.	25
Chakrov P.V.	TEM-study, irradiation of samples	-	25
Loktionov A.A.	Cyclotron and reactor irradiation	Cand.phys. math.sci.	20
Poltavtseva V.P.	Mechanical tests, irradiation of samples	Cand.phys. math.sci.	20
Kospanov N.K.	SEM-study, irradiation of samples	-	10
Pjatiletova N.A.	Optical metallography, preparation of specimens	-	10

Support Staff.

Personnel	Number of persons	Area of project expertise	Daily rate
Engineer	2	Development of cyclotron and reactor irradiation methods	10
Technician	4	Cyclotron and reactor irradiation	5
Laboratory Assistant	2	Preparation of TEM- and SEM-objects	5

APPENDIX 2

Destination, size and number of samples for implantation.

Destination	Size of samples	Number of samples per irradiation	Implantation rate, appm/hour He	Implantation rate, appm/hour H
Study of structure	Diameter of 3 mm and thickness of 0.2 mm disks	36	0.18	0.09
Mechanical tests	Plates of 40x7x0.2 mm^3 size	3		

APPENDIX 3

Costs of irradiation jobs.

Irradiation facility	Cost
Isochronous cyclotron U-150 M	50 USD/hour
Heavy ion accelerator UKP 2-1	20 USD/hour
Nuclear reactor IGR	4000 USD/test

APPENDIX A

Table 1a. Technical Schedule.

Year	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
First	TASK A1	TASK A2	TASK A3	TASK A3
Second	TASK A3	TASK A4	TASK A5	TASK A5

Table 2a. Implantation parameters, number of samples and required cyclotron time.

Gaseous impurity concentration	Irradiation temperature, °C	Number of samples	Cyclotron time, hours	
10 appm He		16	1	
100 appm He		16	7	
200 appm He		16	15	
500 appm He		16	36	
1000 appm He		16	72	
	100			327
30 appm H		16	1	
300 appm H		16	11	
600 appm H		16	22	
1500 appm H		16	54	
3000 appm H		16	108	

Table 3a. Financial information (First year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Cyclotron irradiation	16350	-	-	-	16350
-Microhardness-meter	10000	-	-	-	10000
-Computer, printer	5800	-	-	-	5800
EQUIPMENT TOTAL	32150	-	-	-	32150
MATERIALS					
-Abrasives	-	200	-	-	200
-Chemical reagents	-	200	-	-	200
-Photo-materials	-	500	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	100	1000	100	100	1300
TRAVELS	-	-	-	-	-
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	3966	841	751	751	6309
TOTAL COST	43626	9251	8261	8261	69399

Table 4a. Financial information (Second year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT	-	-	-	-	-
EQUIPMENT TOTAL	-	-	-	-	-
MATERIALS					
-Abrasives	200	-	-	-	200
-Chemical reagents	200	-	-	-	200
-Stationary	100	100	100	100	400
MATERIALS TOTAL	500	100	100	100	800
TRAVELS	10000	-	-	-	10000
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	1791	751	751	751	4044
TOTAL COST	19701	8261	8261	8261	44484

Table 5a. Summary cost of EXPERIMENT A.

BUDGET ITEM	FIRST YEAR	SECOND YEAR	TOTAL
PAYMENTS TO PARTICIPANTS	22800	22800	45600
EQUIPMENT	32150	-	32150
MATERIALS	1300	800	2100
TRAVELS	-	10000	10000
GOVERNMENT TAXES	6840	6840	13680
OVERHEAD	6309	4044	10353
TOTAL COST	69399	44484	113883

APPENDIX B

Table 1b. Technical Schedule.

Year	First quarter	Second quarter	Third quarter	Fourth quarter
First	TASK B1	TASK B2	TASK B3	TASK B3
Second	TASK B4	TASK B5	-	-

Table 2b. Implantation parameters, number of samples and required cyclotron time.

Gaseous impurity concentration	Irradiation temperature, °C	Number of samples	Cyclotron time, hours	
10 appm He	100	12	6	
100 appm He		30	180	
200 appm He		12	108	
500 appm He		12	270	
30 appm H		12	8	
300 appm H		30	270	
600 appm H		12	162	1679
1500 appm H		12	405	
100 appm He	500	12	54	
	800	12	54	
300 appm H	500	12	81	
	800	12	81	
500 appm He	500	12	270	
	800	12	270	1350
1500 appm H	500	12	405	
	800	12	405	

Table 3b. Financial information (First year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Cyclotron irradiation	83950	67500	-	-	151450
-Microhardness-meter	10000	-	-	-	10000
-Computer, printer	5800	-	-	-	5800
EQUIPMENT TOTAL	99750	67500	-	-	167250
MATERIALS					
-Chemical reagents	-	-	200	-	200
-Photo-materials	-	-	500	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	100	100	800	100	1100
TRAVELS	-	-	-	-	-
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	10726	7501	8221	751	19799
TOTAL COST	117986	82511	9031	8261	217789

Table 4b. Financial information (Second year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	-	-	8400
-Support Staff	1500	1500	-	-	3000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	-	-	11400
EQUIPMENT	-	-	-	-	-
EQUIPMENT TOTAL	-	-	-	-	-
MATERIALS					
-Photo-materials	500	-	-	-	500
-Stationary	100	100	-	-	200
MATERIALS TOTAL	600	100	-	-	700
TRAVELS	10000	-	-	-	10000
GOVERNMENT TAXES	1710	1710	-	-	3420
OVERHEAD	1801	751	-	-	2552
TOTAL COST	19811	8261	-	-	28072

Table 5b. Summary cost of EXPERIMENT B.

BUDGET ITEM	FIRST YEAR	SECOND YEAR	TOTAL
PAYMENTS TO PARTICIPANTS	22800	11400	34200
EQUIPMENT	167250	-	167250
MATERIALS	1100	700	1800
TRAVELS	-	10000	10000
GOVERNMENT TAXES	6840	3420	10260
OVERHEAD	19799	2552	22351
TOTAL COST	217789	28072	245861

APPENDIX C

Table 1c. Technical Schedule.

Year	First quarter	Second quarter	Third quarter	Fourth quarter
First	TASK C1	TASK C2	TASK C3	TASK C3
Second	TASK C4	TASK C5	TASK C5	TASK C5
Third	TASK C6	TASK C6	TASK C7	TASK C8

Table 2c. Implantation parameters, number of samples and required cyclotron time.

<table>
<tr><th>Gaseous impurity concentration</th><th>Irradiation temperature, °C</th><th>Number of samples</th><th>Cyclotron time, hours</th><th></th><th></th></tr>
<tr><td>10 appm He</td><td rowspan="8">100</td><td>9</td><td>6</td><td rowspan="4">672</td><td rowspan="8">1950</td></tr>
<tr><td>100 appm He</td><td>96</td><td>288</td></tr>
<tr><td>200 appm He</td><td>9</td><td>108</td></tr>
<tr><td>500 appm He</td><td>9</td><td>270</td></tr>
<tr><td>30 appm H</td><td>9</td><td>9</td><td rowspan="4">1008</td></tr>
<tr><td>300 appm H</td><td>96</td><td>432</td></tr>
<tr><td>600 appm H</td><td>9</td><td>162</td></tr>
<tr><td>1500 appm H</td><td>9</td><td>405</td></tr>
<tr><td rowspan="2">100 appm He</td><td>500</td><td>9</td><td>54</td><td rowspan="4">270</td><td rowspan="4"></td></tr>
<tr><td>800</td><td>9</td><td>54</td></tr>
<tr><td rowspan="2">300 appm H</td><td>500</td><td>9</td><td>81</td></tr>
<tr><td>800</td><td>9</td><td>81</td></tr>
</table>

Table 3c. Concentration of helium and hydrogen atoms in samples for reactor irradiation, number of samples, neutron fluxes and number of reactor tests.

Concentration of helium and hydrogen	Neutron flux, $n/cm^2 s$				Number of tests
	$1x10^{16}$	$5x10^{16}$	$1x10^{17}$	$5x10^{17}$	
100 appm He 300 appm H 100 appm He + 300 appm H	12	12	12	12	48
10 appm He 30 appm H 10 appm He + 30 appm H 200 appm He 600 appm H 200 appm He + 600 appm H 500 appm He 1500 appm H 500 appm He + 1500 appm H $T_{implan.}$=500 °C 100 appm He 300 appm H 100 appm He + 300 appm H $T_{implan.}$=800 °C 100 appm He 300 appm H 100 appm He + 300 appm H	1	1	1	1	4

Table 4c. Financial information (First year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Cyclotron irradiation	500	33600	63900	-	98000
-Microhardness-meter	10000	-	-	-	10000
-Computer, printer	5800	-	-	-	5800
EQUIPMENT TOTAL	16300	33600	63900	-	113800
MATERIALS					
-Abrasives	200	-	-	-	200
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	1000	100	100	100	1300
TRAVELS	-	-	-	-	-
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	2471	4111	7141	751	14474
TOTAL COST	27181	45221	78551	8261	159214

Table 5c. Financial information (Second year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Reactor irradiation	96000	112000	-	-	208000
EQUIPMENT TOTAL	96000	112000	-	-	208000
MATERIALS					
-Abrasives	-	200	-	-	200
-Chemical reagents	-	200	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	600	500	100	100	1300
TRAVELS	-	-	10000	-	10000
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	10401	11991	1751	751	24894
TOTAL COST	114411	131901	19261	8261	273834

Table 6c. Financial information (Third year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT	-	-	-	-	-
EQUIPMENT TOTAL	-	-	-	-	-
MATERIALS					
-Abrasives	200	-	-	-	200
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	1000	100	100	100	1300
TRAVELS	-	-	10000	-	10000
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	841	751	1751	751	4094
TOTAL COST	9251	8261	19261	8261	45034

Table 5c. Summary cost of EXPERIMENT C.

BUDGET ITEM	FIRST YEAR	SECOND YEAR	THIRD YEAR	TOTAL
PAYMENTS TO PARTICIPANTS	22800	22800	22800	68400
EQUIPMENT	113800	208000	-	321800
MATERIALS	1300	1300	1300	3900
TRAVELS	-	10000	10000	20000
GOVERNMENT TAXES	6840	6840	6840	20520
OVERHEAD	14474	24894	4094	43462
TOTAL COST	159214	273834	45034	478082

APPENDIX D

Table 1d. Technical Schedule.

Year	First quarter	Second quarter	Third quarter	Fourth quarter
First	TASK D1	TASK D2	TASK D3	TASK D3
Second	TASK D4	TASK D5	TASK D5	TASK D6

Table 2d. Implantation parameters, number of samples and required cyclotron time.

Gaseous impurity concentration	Irradiation temperature, °C	Number of samples		Accelerator time, hours
10 appm He		36	0,4	
100 appm He		180	20	
200 appm He		36	8	
500 appm He		36	20	
1000 appm He		36	40	
	100			
30 appm H		36	0,6	
300 appm H		180	30	
600 appm H		36	12	241
1500 appm H		36	30	
3000 appm H		36	60	
100 appm He	500	36	4	
	800	36	4	
300 appm H	500	36	6	
	800	36	6	

Table 3d. Financial information (First year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Irradiation on UKP 2-1	4820	-	-	-	4820
-Computer, printer	5800	-	-	-	5800
EQUIPMENT TOTAL	10620	-	-	-	10620
MATERIALS					
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	800	100	100	100	1100
TRAVELS	-	-	-	- -	-
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	1883	751	751	751	4136
TOTAL COST	20713	8261	8261	8261	45496

Table 4d. Financial information (Second year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT	-	-	-	-	-
EQUIPMENT TOTAL	-	-	-	-	-
MATERIALS					
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	800	100	100	100	1100
TRAVELS	-	-	10000	-	10000
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	821	751	1751	751	4074
TOTAL COST	9031	8261	19261	8261	44814

Table 5d. Summary cost of EXPERIMENT D.

BUDGET ITEM	FIRST YEAR	SECOND YEAR	TOTAL
PAYMENTS TO PARTICIPANTS	22800	22800	45600
EQUIPMENT	10620	-	10620
MATERIALS	1100	1100	2200
TRAVELS	-	10000	10000
GOVERNMENT TAXES	6840	6840	13680
OVERHEAD	4136	4074	8210
TOTAL COST	45496	44814	90310

APPENDIX E

Table 1e. Technical Schedule.

Year	First quarter	Second quarter	Third quarter	Fourth quarter
First	TASK E1	TASK E2	TASK E3	TASK E4
Second	TASK E4	TASK E5	TASK E6	TASK E5

Table 2e. Implantation parameters, number of samples and required irradiation time.

Gaseous impurity concentration	Irradiation temperature, °C	Number of samples	Accelerator time, hours		
10 appm He		36	0.4		
100 appm He		36	4	44.4	
1000 appm He		36	40		
	100				104.4
30 appm H		36	0.6		
300 appm H		36	5.4	60	
3000 appm H		36	54		

Table 3e. Proton irradiation parameters.

Irradiation temperature, °C	Radiation damage, dpa	Number of samples	Accelerator time, hours		
	1	36	4		
500	5	36	20	174	
	30	36	150		
					348
	1	36	4		
800	5	36	20	174	
	30	36	150		

Table 4e. Financial information (First year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT					
-Implantation of gaseous impurities	2088	-	-	-	2088
-Proton irradiation	960	6000	-	-	6960
-Computer, printer	5800	-	-	-	5800
EQUIPMENT TOTAL	8848	6000	-	-	14848
MATERIALS					
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	800	100	100	100	1100
TRAVELS	- -	-	-	-	-
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	1705	1351	751	751	4558
TOTAL COST	18763	14861	8261	8261	50146

Table 5e. Financial information (Second year).

BUDGET ITEM	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER	TOTAL
PAYMENTS TO PARTICIPANTS					
-Technical Staff	4200	4200	4200	4200	16800
-Support Staff	1500	1500	1500	1500	6000
PAYMENTS TO PARTICIPANTS TOTAL	5700	5700	5700	5700	22800
EQUIPMENT	-	-	-	-	-
EQUIPMENT TOTAL	-	-	-	-	-
MATERIALS					
-Chemical reagents	200	-	-	-	200
-Photo-materials	500	-	-	-	500
-Stationary	100	100	100	100	400
MATERIALS TOTAL	800	100	100	100	1100
TRAVELS	-	-	10000	-	10000
GOVERNMENT TAXES	1710	1710	1710	1710	6840
OVERHEAD	821	751	1751	751	4074
TOTAL COST	9031	8261	19261	8261	44814

Table 6e. Summary cost of EXPERIMENT E.

BUDGET ITEM	FIRST YEAR	SECOND YEAR	TOTAL
PAYMENTS TO PARTICIPANTS	22800	22800	45600
EQUIPMENT	14848	-	14848
MATERIALS	1100	1100	2200
TRAVELS	-	10000	10000
GOVERNMENT TAXES	6840	6840	13680
OVERHEAD	4558	4074	8632
TOTAL COST	50146	44814	94960