JAEA-Review
2014-012

Proceedings of the 8th Specialist Meeting on Recycling of Irradiated Beryllium

October 28, 2013, Bariloche, Río Negro, Argentina

(Eds.) Roxana G. COCCO, Viviana ISHIDA, Kunihiko TSUCHIYA and Christopher K. DORN

Neutron Irradiation and Testing Reactor Center
Oarai Research and Development Center

March 2014

Japan Atomic Energy Agency

日本原子力研究開発機構

JAEA-Review

Proceedings of the 8th Specialist Meeting on Recycling of Irradiated Beryllium October 28, 2013, Bariloche, Río Negro, Argentina

(Eds.) Roxana G. COCCO[*1], Viviana ISHIDA[*1]
Kunihiko TSUCHIYA, Christopher K. DORN[*2]

Neutron Irradiation and Testing Reactor Center
Oarai Research and Development Center
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

(Received January 23, 2014)

This report summarizes the documents presented in the 8th Specialist Meeting on Recycling of Irradiated Beryllium, which was held on October 28, 2013, in Bariloche, Río Negro, Argentina, hosted by INVAP and CNEA (Comision Nacional de Energia Atomica). The objective of the meeting is to exchange the information of current status and future plan for beryllium study in the Research/Testing reactors, and to make a discussion of "How to cooperate". There were 20 participants from USA, Japan, Korea, Austria and Argentina.

In this meeting, information exchange of current status and future plan for beryllium study was carried out for the Research/Testing reactor fields, and evaluation results of beryllium materials were discussed based on new irradiated beryllium data such as swelling, deformation, gas release and so on. The subject of the used beryllium recycling was also discussed for the enforcement of demonstration recycling tests.

Keywords : Research/Testing Reactors, Beryllium, Reflector, Swelling, Deformation, Gas Release, Recycling

---

*1: INVAP S.E.
*2 : Materion Brush Inc.

「第８回照射済ベリリウムのリサイクルに関する専門家会議」講演資料集
2013 年 10 月 28 日、アルゼンチン　リオネグロ　バリローチェ

日本原子力研究開発機構
大洗研究開発センター　照射試験炉センター

(編) Roxana. G. Cocco[*1], Viviana. Ishida[*1], 土谷　邦彦, Christopher. K. Dorn[*2]

(2014 年 1 月 23 日受理)

本講演集は、INVAP と CNEA(アルゼンチン原子力委員会)が主催した「第８回照射済ベリリウムのリサイクルに関する専門家会議」に提出された発表資料をまとめたものである。本会議は、各国の試験研究炉で行われているベリリウム研究の現状と将来計画に関する情報交換及び照射済ベリリウムに係る今後の試験研究炉の協力について議論することを目的として、2013 年 10 月 28 日にアルゼンチンのバリローチェで開催された。会議には、米国、日本、韓国、オーストリア及びアルゼンチンの５カ国から 20 名が出席した。

本会議では、試験研究炉の分野におけるベリリウム研究の現状と将来計画に関する情報交換を行うとともに、照射されたベリリウムのスエリング、曲り、ガス放出などの新しいデータに基づいて評価結果を議論した。また、使用済ベリリウムのリサイクルの実証試験のための課題について議論した。

大洗研究開発センター　：〒311-1393　茨城県東茨城郡大洗町成田町 4002
＊１：INVAP S.E.
＊２：Materion Brush Inc.

Contents

目　次

1. Preface

As a structural material, beryllium (Be) is a light metal which has high tensile strength in comparison with aluminum. The surface of the Be is covered with a thin oxidation film by interacting with air like aluminum, and it is highly resistant to corrosion in dry gases. Beryllium's properties, such as high thermal conductivity, good mechanical properties at elevated-temperature and high melting point, make the material attractive for use in nuclear reactors. In particular, Be has been used as a reflector and/or moderator in a number of materials test reactors (MTRs). The key nuclear properties of Be are its low atomic number, low atomic weight, low parasitic capture cross-section for thermal neutrons, readiness to part with one of its own neutrons (n, 2n), and good neutron elastic scattering characteristics.

Reactors with beryllium exist in many places throughout the world, and a great deal of Be was used in MTRs from the beginning of development. The neutron environment causes mechanical property degradations for the Be. Lifetime of the Be components is mainly evaluated by the tensile strength change and/or the amount of deformation. In addition, the activation for the Be in nuclear reactors under neutron irradiation, which is caused mainly by (n, γ) and (n, p) reactions with impurities such as iron, nickel and nitrogen in the Be, should also be evaluated. Moreover, we should consider the tritium (^{3}H) production in beryllium by a well-known reaction sequence. Now, the used Be components are in each MTRs site, because it is difficult to reprocess irradiated Be due to high induced radioactivity and toxicity issues.

Thus, from viewpoints of the waste issue of beryllium reflectors and material modification, the lifetime extension and recycle of beryllium irradiated in MTR have been discussed. The first specialist meetings on beryllium study was held in Idaho Falls, USA in July 2007, and subsequently in Lisbon, Portugal (Dec. 2007), Oarai, Japan (Jul., 2008), Idaho Falls, USA (Oct. 2009), Řež, Czech Republic (Oct. 2010), Oarai, Japan (Dec. 2011) and Columbia, Missouri, USA (Oct. 2012). We have focused on the information exchange of current status and future plans for beryllium study in the Research/Testing reactors, and have been discussing the framework of "How to cooperate".

The 8th Specialist Meeting on Recycling of Irradiated Beryllium was held on 29, October 2013 in Bariloche, Argentina, hosted by INVAP and CNEA.

2. Summary

Industrial Challenge for Recycle of Beryllium Irradiated by Neutron with Advanced Fukushima Hot-Lab

H. Kawamura (JAEA, Japan)

For the decommissioning of Fukushima Daiichi Nuclear Station, "Radioactive material analysis and research facility" will be constructed by Japan Atomic Energy Agency (JAEA). As a part of the creation of new industries in Fukushima Prefecture using this new facility, JAEA proposes a project to recycle Be which are storage worldwide as waste. The Be recovery process will include removal of activated impurities, production of $BeCl_2$ by the reaction with the Cl_2 gas, Be powder production, Be rod and pebble production, which will be used in the ITER test blanket module. The Be pebble used in ITER can also be recycled using the this process. JAEA invited the international community to join to the Be recycle demonstration test which will start in 2014.

Summary of the 11th IEA Workshop on Beryllium Technology
C. K. Dorn (Materion Brush, U.S.A)

The founding partners of a Be Workshop (BeWS) were JAEA (Japan), INL(USA) and KIT(Germany); this workshop established for discussion on beryllium technology and hold the first unofficial BeWS in 1991. From 1993, this BeWS was held 11 times in different countries under the framework of the International Energy Agency (IEA) every two years. The last BeWS-11 was organized in Barcelona with the objective of this workshop is to disseminate results of research and technology development in areas relevant to Beryllium utilization in nuclear power systems, both fission and fusion. The highlights of the BeWS-11 were HIDOBE-01 PIE results, status on research on Beryllides and the implementation of the Mario-Delle-Donne Memorial Award for Excellence. The BeWS-12 will be jointly held by JAEA and National Fusion Research Institute (NFRI) in South Korea.

Status of Beryllium Design Study in INVAP
R. G. Cocco (INVAP S.E, Argentina)

INVAP has attempted to answer that which factor influences the lifespan of Be reflectors in order to establish the design criteria. It's study was focused in three issues: material behavior, fast neutron flux and mechanical design. Updated data are necessary for a better distortion prediction by a swelling. The inhomogeneous change in volume by the swelling due to a fast flux gradient though the material thickness is the responsible of Be reflector distortions and the associated stresses. Distortions and the associated stresses were study by a Finite Element Model (FEM) of Be reflector represented by prismatic bar. The study consisted of changing the dimension of the reflector bar in thickness, width and height under fast neutron irradiation conditions. The results showed that the design/geometry of reflector would have failure and lifespan. As a conclusion, for the lifespan extension purposes, it is important to consider the Be reflector as a component rather than material.

Beryllium Usage at the University of Missouri Research Reactor
L. P. Foyto (University of Missouri Research Reactor, U.S.A)

The University of Missouri Research Reactor (MURR) is a 10MW multidisciplinary research and education facility, which also provides a broad range of analytical and irradiation services. Based on the previous reflector cracking experience in 1981, Be reflector is replaced every 26,000MWds, equivalent to 8 years of operation the current operation factor of 90%. The Be reflectors were replaced in 1989, 1977 and 2006, and the next is scheduled in December 2013. Since there is no disposal site for irradiated Be in the USA, one irradiated Be is stored in the reactor pool and the other two are stored in dry casks, which are designed and constructed by MURR staff. The Be swelling has been measured, which shows good correlation with calculation results.

Status of Beryllium Irradiation Study in JAEA
K. Tsuchiya (JAEA, Japan)

The lifetime expansion of the Be frame used in JMTR has been carried out in JAEA. Three industrial grades of the beryllium metal such as S-200F (reference), S-65-H (isotropy) and I-220-H (isotropy and high-strength), were selected. In the out-of-pile test, the corrosion properties were evaluated in pure water. The presence of $Be(OH)_2$ as corrosion products was observed at the surface of Be, and the electric conductivity influenced the content of BeO in the Be metals. Irradiation test programs have been performed in JRR-3, WWR-K and JMTR. Irradiation tests were finished in JRR-3 and WWR-K, and PIEs were carried out with the irradiated Be in WWR-K. Irradiation test in JMTR will be carried out after re-start. As a part of the ISTC K-1566 Project, the experimental recycling tests of the irradiated Be in JMTR were carried out with the small test facility and purification rates of radioactive impurities were achieved an excellent values.

Status of Beryllium Study in KAERI
M. S. Cho (KAERI, Korea)

The Be reflectors have been used in Korean for research reactors: the Jordan Research and Training Reactor (JRTR) and Kijang Research Reactor (KJRR). The research on Be materials has been performed using three types of targets: S-65(HIP) and S-200-F(VHP) from Materion Brush, and EHP-56 (hot extrusion) of Kazakhstan. The out-of-pile tests consisted of microstructure observation, hardness test and photon irradiation test. The in-pile tests were performed in Hanaro research reactor. One of the capsules is under post irradiation examination, and the second capsule is under irradiation in the reactor.

Recent Activities in the MTR Field for Beryllium Reflectors
E. E. Vidal (Materion Brush, U.S.A)

The U.S.A government entered into a partnership with Materion Corporation initiating construction of Be "Pebbles Plant" in Elmore, Ohio, USA to ensure the production capacity of high purity Be to ensure the word demand. The current research reactor programs include: Advanced Test Reactor (ATR, USA), High Flux Isotope Reactor (HFIR, USA), Missouri University Research Reactor (MURR, USA), Japan Materials Testing Reactor (JMTR, Japan), High Flux Reactor (HFR, Netherlands), SCK-CEN Test Reactor (BR-2, Belgium), NESCA Test Reactor (SAFARI-1, South Africa), ANSTO Test Reactor (OPAL, Australia) and IPEN Test Reactor (IEA-RI, Brazil).

Beryllium Research in NGK and New Proposal for MTR Reflector Development
K. Nogiri (NGK, Japan)

NGK Insulators has been involved in the Be Business in not only in the nuclear fields but also in other industries. In the fusion, KGK´s BP-1 Be pebble is the reference material for the multiplier of the ITER project. In the fission field, the Be reflector frames have been manufactured to JMTR. The proposal for MTR is to coat the surface of the Be in order to reduce Tritium released to the coolant in the reactor. In cooperation with JAEA, coating specification was investigated, and aluminum coat has been selected to confirm a good adhesion to the beryllium surface. Neutron irradiation tests are planned as the next step.

Swelling and Thermal Effect on the Reflector Assembly
E. Fresquet (INVAP S.E, Argentina)

The most important effects caused by swelling in Be bars are distortion, strengthening and cracking. These several effects are increased by the effects of the temperature at power operation conditions. Then, the study of the Be reflector structural integrity by numerical methods is an essential tool for design. The results of structural integrity analysis on a Be reflector bar using the finite element method show the necessity to consider a cooling system to reduce the thermal effects at power operation, and then ensure limited distortion allowing a longer Be reflector utilization. These results contribute to the better understanding of distortion behavior and the generating stress under neutron irradiation for the design of reflector.

Tritium and Helium Release Properties for Different Grade of Beryllium Metals
K. Tsuchiya (JAEA, Japan)

Three types of industrial grade Be were prepared and irradiated in WWR-K at about 40˚C with fluences of 1.0×10^{20} to $4.0\times10^{20}/cm^2$. After the irradiation tests, post-irradiation examinations were carried out to measure the tritium and helium release properties using thermal desorption (TDS) methods. The X-ray diffraction measurement and SEM observation of the irradiated Be samples were carried out for the metallographic studies. Tritium release occurred in the range of 900 to 1200˚C, and Helium was difficult to release up to the melting point. The amounts of the released Helium and Tritium were in good agreement in all samples in comparison with the calculated values. The Helium and Tritium values were 483 ppm/g and 30 ppm-T/g, respectively. No effects of crystal structure of Be occurred up to $4.0\times10^{20}/cm^2$. The surface of the irradiated Be samples changed from polish to tarnish after irradiation. It seems that the corrosion and cohesion of BeO occurred in the surface of Be samples.

Discussion
All participants

(1) **Irradiation test for lifetime expansion**
Various properties of beryllium metals as reflectors of the Research Reactors (RRs) will be evaluated for the lifetime expansion. Especially, it is important for the lifetime expansion to evaluate strength and deformation of the irradiated beryllium. Deformation calculation method in INVAP and deformation measurement technique in MURR were attracted attention in this meeting. Adjustment of irradiation tests used in other RRs will be performed continually.

(2) **Strategy for Be recycle**
It is no problem for the storing space in ATR (U.S.A.). On the other hand, it will be a problem for operation of new RR in Korea but HANARO is not used the Be reflectors. It is necessary to consider the beryllium recycling of the used beryllium in the RR reflectors in future. The Be recycling technology is the RR common issues and it is necessary to construct as the cooperation study for Be recycling technique between the RRs groups and manufacturing makers such as Materion Brush and NGK. The program will be performed in JAEA, and conceptual design and cost analysis have been performed at the first stage.

(3) **Contribution of Be study to MTR Reflectors**
The IAEA Coordinated Research Project (CRP) on Material Property Data Base for Irradiated Core Structural Components will be established, and the first research coordination meeting will be held on November 18-22 in IAEA headquarters, Vienna, with 30 participants. The RR Section works to optimize research reactor availability and reliability through shared operating experience as well as the development and implementation of operational and maintenance plans, ageing management plans, training programmes and international peer reviews. This project will be performed for 3 years, and IAEA will propose the construction of database on beryllium.

3. Presentation Materials

3.1 Industrial Challenge for Recycle of Beryllium Irradiated by Neutron with Advanced Fukushima Hot-Lab

[Abstract]

Industrial Challenge for Recycle of Beryllium Irradiated by Neutron with Advanced Fukushima Hot-Lab

Hiroshi Kawamura[1]

[1] *Japan Atomic Energy Agency, Chiyoda, Tokyo, Japan*

The nuclear plant decommissioning safety research establishment was established in JAEA on April 1, 2013 based on the decision, and the examination toward construction of the research base facilities was started. The construction schedule was based on the revised Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 in June 27, 2013. These facilities will contribute to conduct the decommissioning of the power stations and to enhance the decommissioning technology. Furthermore, these facilities have the role as an international study center for post irradiation tests, human resources development on decommissioning and analyses techniques and challenges to new research issues by bringing together domestic and foreign wisdom.

As the viewpoints of challenges to new research issues, it is important for decommission of nuclear reactors to reprocess the nuclear structural materials such as stainless steel, zirconium alloy, beryllium, and so on. Especially, beryllium has been utilized as a moderator and/or reflector in a number of material testing reactors. In fact, the nuclear properties of beryllium are its low atomic number, low atomic weight, low parasitic capture cross section for thermal neutrons, readiness to part with one of its own neutrons (n, 2n), and good neutron elastic scattering characteristics. However, it is difficult to recycle the irradiated beryllium in the material testing reactors and its material has been kept in a reactor place. The part of irradiated beryllium had been buried as the radioactive wastes in the desert. At present, the radioisotopes such as ^{14}C, which is generated in the beryllium by neutron irradiation, are infected in underground water and it is social problem in USA. Thus, it is important problem to recycle the irradiated beryllium from the points of effective use of resources, reduction of radioactive waste and nuclear nonproliferation.

Up to now, research and development on beryllium recycling techniques have been performed by the small scale tests under JAEA original study and ISTC project. Basic properties such as tritium release and removal of radioactive impurities were evaluated from the results of R&D. However, it is necessary for the beryllium recycling establishment to develop the powder production, beryllium rod and pebble production, so on. These developing items are new technologies for the decommission, and consideration of the developing items is a absolute necessity for the design and construction of the new facilities.

In this presentation, status of beryllium recycling study and future plan for demonstration in the new facilities are introduced.

This is a blank page.

Industrial Challenge for Recycle of Beryllium irradiated by neutron with Advanced Fukushima Hot-Lab

Oct.28, 2013

Hiroshi Kawamura
Japan Atomic Energy Agency

Introduction

Concerning research and development (R&D) for the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station (called 1F,NPS), **85 billion yen** was financed to Japan Atomic Energy Agency (JAEA) to construct the research facilities mentioned above, etc. and to study with these facilities as a supplementary budget in 2012 by the Ministry of Economy, Trade and Industry in Japan (METI).

↓

In JAEA, "**Nuclear Plant Decommissioning Safety Research Establishment**" was founded for this project **on April 1, 2013.**

<Challenge of this research establishment>

As an essential research center for the decommissioning of 1F, following advanced research facilities will be constructed.

- Remote-controlled equipment and device development facility
- Radioactive material analysis and research facility

1

New Industry Creation in Fukushima Prefecture

Japanese government desire to revive Fukushima prefecture.

To create new industry with Radioactive Material Analysis and research facility (Hot Laboratory) which JAEA will be Constructed.

Beryllium Recycle Project → New Industry

2

Used Beryllium in Research and Materials Testing Reactor

Characteristic

- **International Regulated Material**
- **Specific Chemical Material (BeO)**
- **Tritium included Material**
- **Activated Material**

→ **Waste which handling is difficult and which is produced on and on.**

Amount of Storage of used beryllium

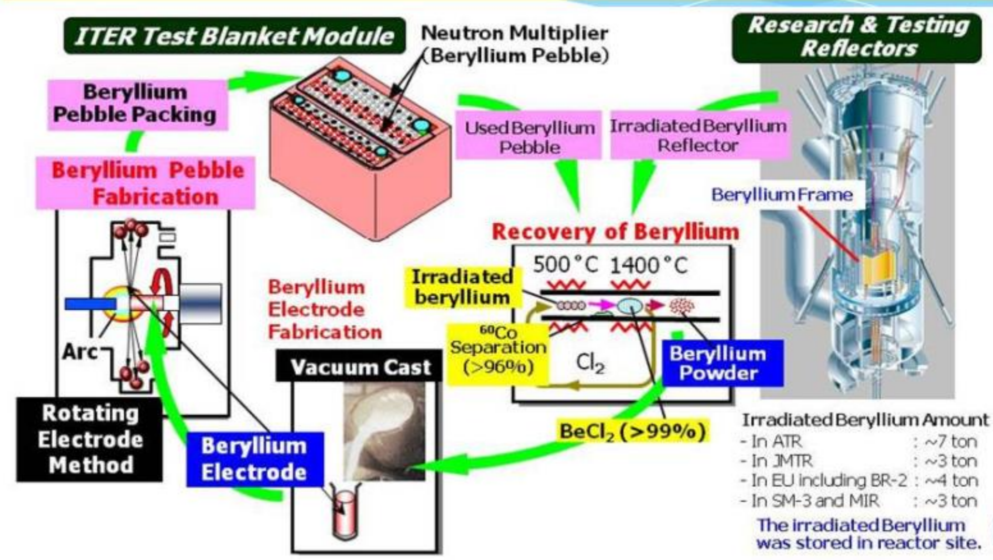
Japan : 3 ton
World : 30~40 ton

·In USA, the beryllium used at ATR, etc was buried in the desert. However, as the water pollution occurred by ^{14}C, buried beryllium was digged up and has been kept at surface place briefly.
·In EU, used beryllium has been kept in the pool generally.
·In Russia, there is the situation similar to EU.

3

Recycle Process of Used Beryllium

Development of irradiated beryllium treatment is expected worldwide.



4

Concrete Project Items on Beryllium Recycle

Technical establishment by JAEA original study and ISTC project

(1) Tritium release from irradiated beryllium
(2) $BeCl_2$ production by the reaction between used beryllium and Cl_2 gas ($BeCl_2$ becomes gas at about 500°C) *Removal of Activated Impurities (^{60}Co, etc.)*

Key development items for establishment of Be recycling technology

(1) Be powder production
- Thermal decomposition method (**Existing proposal, not success**)
- Electrolytic extraction method (**Existent technology, New Hot Trial**)
- Other method (**New proposal**)

(2) Be rod and pebble production
- Vacuum cast (**Existent technology, New Hot Trial**)
- Rotating electrode method (**Existent technology, New Hot Trial**)
- Other method (**New proposal**)

5

Proposal with new facility in Fukushima Prefecture

If other party has the interest on beryllium recycle project, please join the Demonstration Test Preparation which will be started from 2014 fiscal year.

Contents of Beryllium Recycle Demonstration Test with new facility

Treatment of Irradiated Beryllium Neutron Reflector of 100kg in new facility

6

Business Model of Beryllium Recycle

Reactor Owner

- To bear transportation fee and treatment fee of irradiated Beryllium used as neutron reflector etc.
- To abandon property right of used Beryllium

Beryllium Recycle Company (?)

- To treat used Beryllium and to recycle treated Beryllium
- To sell Beryllium pebble for fusion R&D (ITER)

Fusion Research Field

- To buy Beryllium pebble
- To bear transportation fee and treatment fee of irradiated Beryllium used as neutron multiplier.
- To abandon property right of used Beryllium

7

Framework Plan for International Cooperation on Beryllium Recycle

JAEA's Idea

Beryllium Powder Production
Player → JAEA, Others

Beryllium Rod production
Player → JAEA, Materion Brush, Others

Beryllium Pebble Production
Player → JAEA, NGK Insulators, Others

JAEA would like to hear from Be specialist concerning Beryllium Recycle Project.

8

Summary

For the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station, "Radioactive material analysis and research facility " will be constructed.

On the other hand, it is necessary to create new industry in Fukushima prefecture with Radioactive Material Analysis and research facility (Hot Laboratory).

JAEA will consider Beryllium Recycle as the effort for new industry creation. If necessary, JAEA will prepare all the equipment necessary for Beryllium Recycle Demonstration test with new facility mentioned above.

Please join the Demonstration Test Preparation which will be started from 2014 fiscal year.

9

This is a blank page.

3.2 Summary of the 11th IEA Workshop on Beryllium Technology

[Abstract]

Summary of the 11th IEA Workshop on Beryllium Technology

Christopher K. Dorn[1]

[1] *Materion Brush Inc., Brush Beryllium & Composites, Elmore, Ohio, U.S.A.*

In 1989, three scientists who were working in fusion energy research in different parts of the world decided that beryllium metal was an important material in their work, and they wanted to have a forum to share information about their work and learn about what others were doing. That decision resulted in the establishment of what would eventually become the bi-annual International Workshop on Beryllium Technology, complete with sponsorship and direction from the International Energy Agency (IEA).

The first official IEA Beryllium Workshop (BeWS) took place in 1993 in Karlsruhe, Germany, and ten more such events have been held to date. The most recent event, the BeWS-11, took place in Barcelona, Spain in September 2013 in conjunction with the 11th International Symposium on Fusion Nuclear Technology (ISFNT-11).

The BeWS-11 was particularly significant because it marked a return to the originally established schedule after an unfortunate and unexpected postponement of the BeWS-10 in 2011. The BeWS-11 also made use of a partnership between two organizations to handle the technical program and local arrangements and logistics at the workshop site. In this case, the Karlsruhe Institute of Technology (KIT) in Germany took care of the technical program, while CIEMAT and the Technical University of Catalonia handled the local arrangements in Spain. The partnership was both efficient and effective, and it is a model which will be used again in the future.

The technical sessions at the BeWS-11 featured the HIDOBE-01 Post-Irradiation Examination (PIE), Research on Beryllide Intermetallic Compounds, Beryllium for Fusion Applications, Beryllium for Fission Applications, Advanced Beryllium Production Technologies, and Modeling Techniques for Beryllium Materials.

Highlights of the technical program included the latest results of the ongoing HIDOBE-01 PIE, which gave new insights on microstructure versus gas release properties for beryllium pebbles (1mm-diameter mini-spheres) and the differences in behavior of pebble beds in free versus constrained states. The most important new research was in the field of beryllide intermetallic compounds, in which $TiBe_{12}$ can now be made in the form of pebbles, and the composition can be >90% of the desired formula thanks to an innovative post-fabrication homogenization technique. This latter work was so compelling that its principal scientist received a special award from the BeWS International Organizing Committee to recognize the achievement.

The future plans for the BeWS series in general and for the BeWS-12 in particular were also discussed.

This is a blank page.

MATERION

Summary of the 11th IEA Workshop on Beryllium Technology

Chris Dorn

Strategic Business Development

Materion Corporation

28 October 2013

1

Presentation Outline

MATERION

- Introduction
- History of the Beryllium Workshop
- Events Leading up to BeWS-11
- Organizing Committees
- Attendance
- Program Highlights
  - Keynote Speakers
  - Sessions Organized by Technical Subject
  - New Areas Not Previously Included
- BeYOND V Industrial Forum
  - Run by KBHF
  - Emphasizing Partnerships with Industry
- Planning for BeWS-12
- Summary & Conclusion

2

Introduction to the BeWS

MATERION

- Founding Partners
  - Dr. H. Kawamura, JAEA (Japan)
  - Dr. G. Longhurst, INL (U.S.A.)
  - Dr. M. Dalle-Donne, KIT (Germany)
- Purpose of the Beryllium Workshop
- Concept Developed 1989
- Unofficial First Workshop 1991
- International Energy Agency (IEA)

3

History of the IEA Beryllium Workshops

MATERION

- BeWS-11: 2013 in Barcelona, Spain
- BeWS-10: 2012 in Karlsruhe, Germany
- BeWS-9: 2009 in Almaty, Kazakhstan
- BeWS-8: 2007 in Lisbon, Portugal
- BeWS-7: 2005 in Santa Barbara, CA, U.S.A.
- BeWS-6: 2003 in Miyazaki, Japan
- BeWS-5: 2001 in Moscow, Russia
- BeWS-4: 1999 in Karlsruhe, Germany
- BeWS-3: 1997 in Mito, Japan
- BeWS-2: 1995 in Jackson Hole, WY, U.S.A.
- BeWS-1: 1993 in Karlsruhe, Germany

4

Leading up to BeWS-11 & Organization

MATERION

- Attendance at BeWS-9
- BeWS-10
  - Scheduled for 2011
  - Moved to 2012
- Int'l Organizing Committee
  - Challenges
  - Representatives
  - Changes Moving Forward
- Local Organizing Committee
  - Technical Program
  - Venue Selection
  - Logistics & Arrangements
- Getting BeWS Back on Track
  - BeWS-11 in 2013
  - Conjunction with ISFNT in Spain

BeWS-10 Karlsruhe Germany

10th IEA International Workshop on Beryllium Technology

5

BeWS-11 Attendance & Program

MATERION

Karlsruhe Institute of Technology

- Overall Attendance
- Plenary Session
  - Fusion for Energy (F4E)
  - Efremov Institute
  - Japan Atomic Energy Agency
  - Materion Brush Be & Composites
- Technical Sessions
  - HIDOBE-01 PIE
  - Research on Beryllides
  - Beryllium for Fusion
  - Beryllium for Fission
  - Advanced Beryllium Production Technologies
  - Modeling of Beryllium Materials

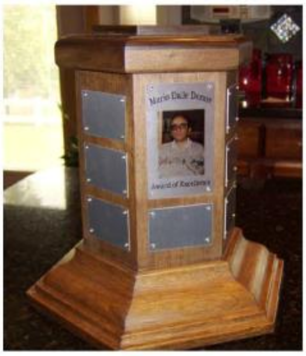
GOBIERNO DE ESPAÑA | MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

6

BeWS-11 Program Highlights

MATERION



- HIDOBE-01 PIE
  - New Results for Be Pebbles
  - Microstructure vs. Gas Release
  - Constrained vs. Free State
- Research on Beryllides
  - Fabrication of $TiBe_{12}$ Pebbles at IFERC in Japan (JAEA)
  - Developed Post-Fabrication Homogenization Technique
  - >90% Single Phase Now Possible
- Mario Dalle-Donne Memorial Award for Excellence
  - First Recipient at BeWS-11
  - Dr. Masaru Nakamichi of JAEA
  - Achievements in Beryllide Pebble Fabrication Development

7

Looking Forward to BeWS-12

MATERION

- Back on Schedule in 2013-2015
- BeWS-12 Plan
  - In Conjunction with ISFNT in Jeju Island, South Korea
  - September 2015
  - Run Jointly by JAEA & NFRI
- Int'l Organizing Committee
  - Diversify Technical Program
  - Encourage More Attendance from Other Beryllium Fields
  - Invite Keynote Speaker
  - Mario Dalle-Donne Award for Outstanding Contribution
- Vision for the Future
  - BeWS-13 in 2017
  - Possible Venues: Europe or North America

JAEA

NFRI

8

3.3 Status of Beryllium Design Study in INVAP

[Abstract]

Status of Beryllium Design Study in INVAP

Roxana G. Cocco[1]

[1] *INVAP S.E, Nuclear Projects Division, S.C Bariloche, Río Negro, Argentina*

Since 2010 INVAP has been working on modeling of Be reflectors assemblies and has participated in different international meetings. A summary of the performed works by INVAP is presented here.

INVAP has attempted to answer which the factors influence the lifespan of Be reflectors in order to establish the design criteria. The study it was focused in three issues: material behavior, fast neutron flux and mechanical design.

Material behavior: Beryllium is degraded by radiation damage, as a result of both displacement and transmutation. Transmutation produces Helium gas and swelling. Few low temperature swelling models are available. Three of them were used for distortion simulation behavior of a Be reflector prismatic bar: Gol´tsev and Serniaev equations both derived from Russian beryllium data, and a third more modern equation derived from bibliographic data recollected by Gelles for western material. The results of simulations using the equation derived from western material data were more consistent with distortions measurement on reactors, than the results derived from the application of swelling model for Russian material. Then, updated data are necessary for a better distortion prediction by swelling.

Fast neutron flux: Whereas the flux profile generated through the reflector thickness is a characteristic of the reflector material, the profile shape along the reflector assembly is characteristic of the core and this could have influence on the predicted distortions. However, its weight on calculation results showed to be negligible. The main factor that affects the reflector distortion is the variation in the flux trough the material thickness which is a beryllium characteristic and the swelling is proportional to fast neutron fluence. Thus, the face exposed to irradiation source, i.e. the highest fluence has larger volumetric strain. On the other hand, the opposite face has smaller volumetric change due to swelling. This inhomogeneous change in volume is the responsible of Be reflector distortions and the associated stresses.

Mechanical design: Geometry variation was analyzed on a simplified case of a Be reflector prismatic bar. Distortions and the associated stresses were study by Finite Element Modeling (FEM). The study consisted in varying the dimensions of the reflector bar in thickness, width and height subject to fast neutron irradiation conditions. The results showed that the distortion increases when the thickness and width diminish and the height increases. On other hand, the stresses increase with the thickness and width and the height have not major influence. This means that the mechanical design/geometry would have influence on fail mode of reflector and lifespan where large pieces tend to fail by cracking (like in ATR and MURR reactors) and svelte pieces tend to fail by distortion (like SAFARI I and JMTR reactors).

As a conclusion, a reasonable swelling model is available, it is understood how gradients of fast neutron flux generate the distortions on Be reflector and how the reflector geometry can drive to different fail modes. Then, with the lifespan extension purposes, it is important to take the reflector as a component rather than material.

This is a blank page.

8th Specialist Meeting on Recycling of Irradiated Beryllium

STATUS OF BERYLLIUM DESIGN STUDY in INVAP

Roxana G. Cocco

Mechanical Design Division: Nuclear components

INVAP S.E. – Argentina

INVAP

8th Specialist Meeting on Recycling of Irradiated Beryllium

Since 2010 INVAP has been working on modeling of Be reflectors assemblies and has participated in different meetings:

IAEA TM-40035. "Assessment of Core Structural Materials and Surveillance Programme of Research Reactors", Viena, Austria, 14-18 June, 2010

SAM/CONAMET 11. "Binational Congress on Metallurgy and Materials", Rosario, Argentina, 18-22 October, 2011

ISMTR-4. "4th International Symposium on Material Testing Reactors", Oarai, Japan, 5-9 December, 2011.

ISMTR-5. "5th International Symposium on Material Testing Reactors", Missouri, USA, 22-25 December, 2012.

INVAP

2013 - 8th Specialist Meeting on Recycling of Irradiated Beryllium

A summary of the performed works by INVAP will be presented

INVAP

Radiation effects on Be

Be is an excellent neutron moderator and reflector material and is used in numerous research reactors around the world.

However, the Be structure is altered during neutron irradiation by fast neutron promoting:

Swelling (He) → **Distortion Strengthening Cracking**

INVAP

Be Lifespan

For different reactors it has been adopted different strategies in order manage the problems associated to swelling: strengthening, cracking and distortion.

The lifespan of the Beryllium components, in fluence terms, typically vary between 1 and 6.4 x 10^{22} n/cm^2.

8th Specialist Meeting on Recycling of Irradiated Beryllium

Which are the factors that influence the lifespan?

Material behavior: Mechanical properties, Irradiation, properties, Irradiation damage (swelling model)

Core characteristics: power, fast neutron flux, neutron energy

Mechanical design: geometry, clamping mode, etc.

Distortions and stresses along the life of Beryllium assembly can be predicted by modeling.

8th Specialist Meeting on Recycling of Irradiated Beryllium

Generación de He

$^{9}Be + n \rightarrow 2\,^{4}He + 2n$ ($E_n > 2.7$ MeV)

$^{9}Be + n \rightarrow {}^{7}Li + {}^{3}H$ ($E_n > 10.5$ MeV)

$^{7}Li + n \rightarrow {}^{4}He + {}^{3}H + n$

$^{9}Be + n \rightarrow {}^{6}He + {}^{3}H$ ($E_n > 0.6$ MeV)

$^{6}He \rightarrow {}^{6}Li + \beta^{-} + \nu$

$^{6}Li + n \rightarrow {}^{4}He + {}^{3}H$

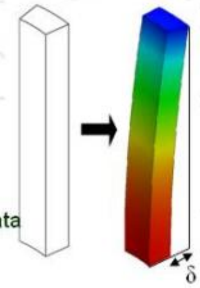
Material Behavior

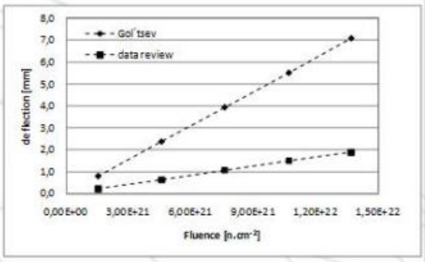
Yield Strength [Mpa]	*241*
Tensile Strength [Mpa]	*324*
Elastic Modulus [GPa]	*303*
Poisson Coefficient	*0,18*
Elongation at Failure [%]	*2*
S–200F alloy. Typical values extracted from Materion catalog	

$$\frac{\Delta V}{V}[\%] = 9,93x10^{-24}.(\varphi(x,y,z)t(seg))^{1,035}$$ Beebston

$$\frac{\Delta V}{V}[\%] = 8,20x10^{-23}.(\varphi(x,y,z)t(seg))$$ Gol'tsev

$$\frac{\Delta V}{V}[\%] \cong 3\frac{\Delta L}{L}[\%] = 2,0x10^{-23}.(\Phi)$$ Bibliographic data

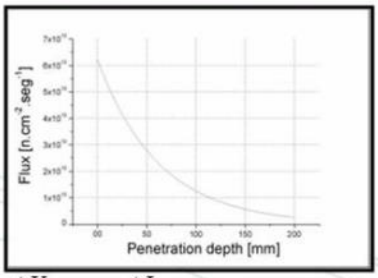




INVAP

8th Specialist Meeting on Recycling of Irradiated Beryllium

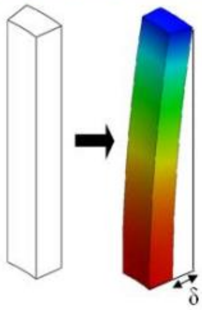
Flux profile through the thickness



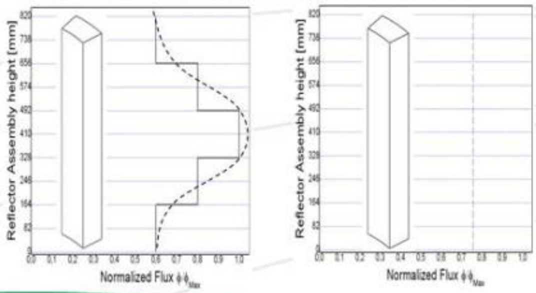
$$\frac{\Delta V}{V}[\%] \cong 3\frac{\Delta L}{L}[\%] = 2,0x10^{-23}.(\varphi t)$$

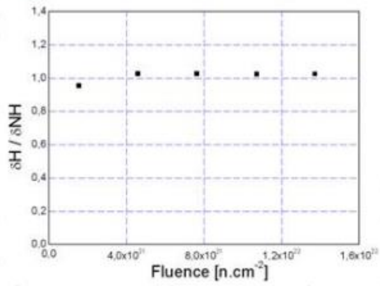
Fast neutron Flux

Reflector Bar distortion



Incident flux profile along assembly

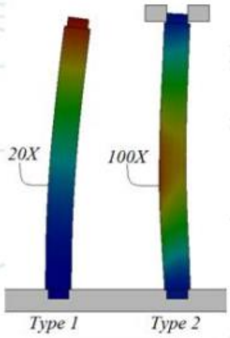


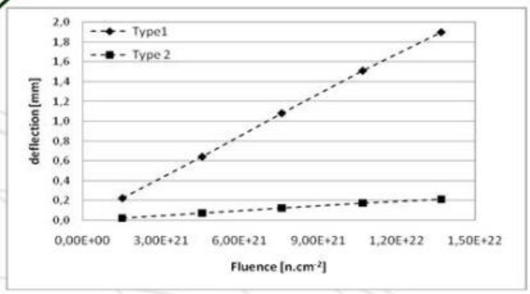


INVAP

Mechanical Design

Clamping mode





Maximum Stress [MPa]					
Fluence [$n.cm^{-2}$]	$1,52E^{+21}$	$4,57E^{+21}$	$7,61E^{+21}$	$1,07E^{+22}$	$1,37E^{+22}$
Type 1	8	26	43	61	82
Type 2	17	55	92	130	175

INVAP

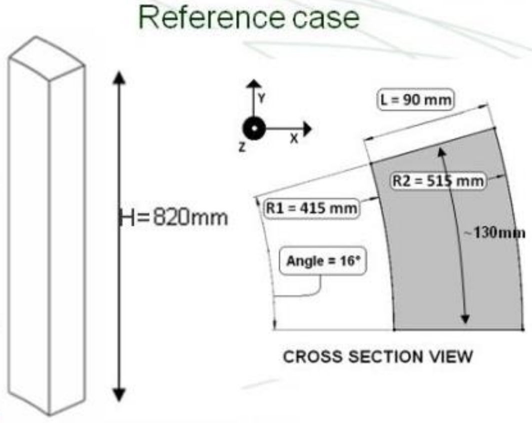
8th Specialist Meeting on Recycling of Irradiated Beryllium

Mechanical Design

Distortion increase
thickness ↓
width ↓
height ↑

Stresses increase
thickness ↑
width ↑
height not major influence

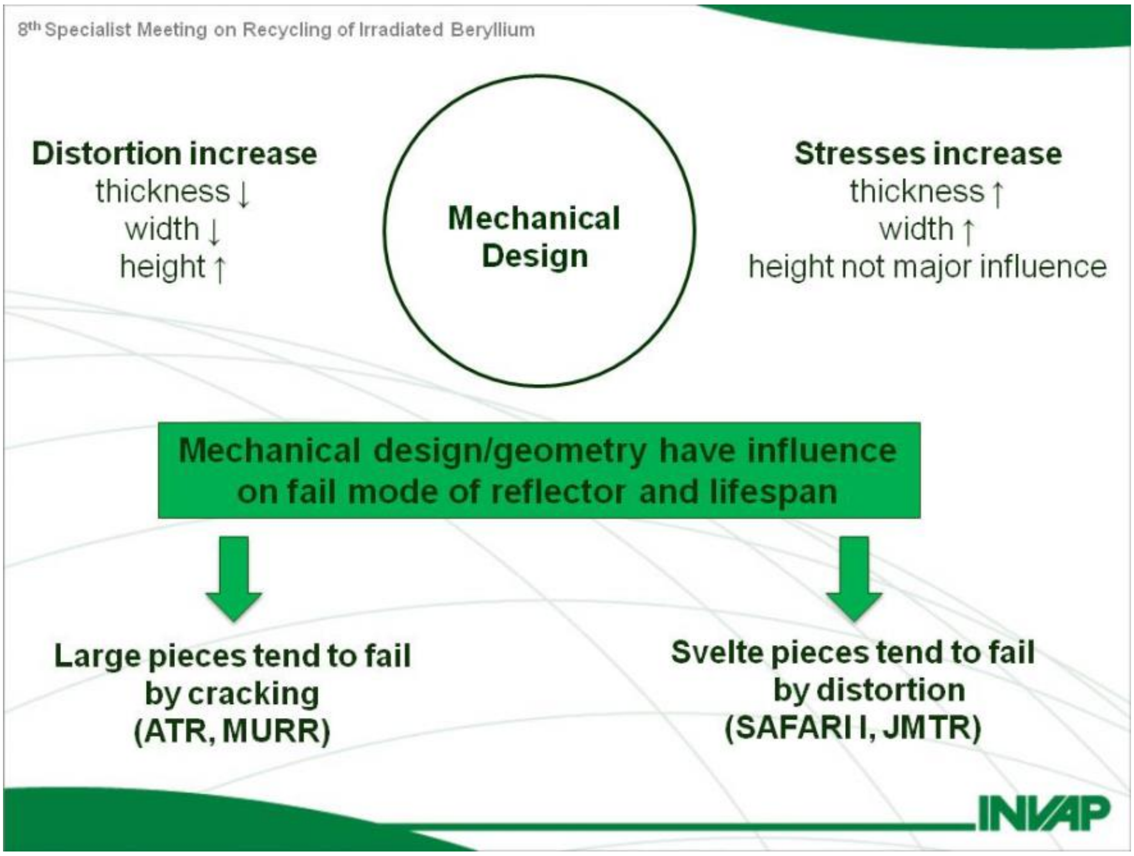
Reference case

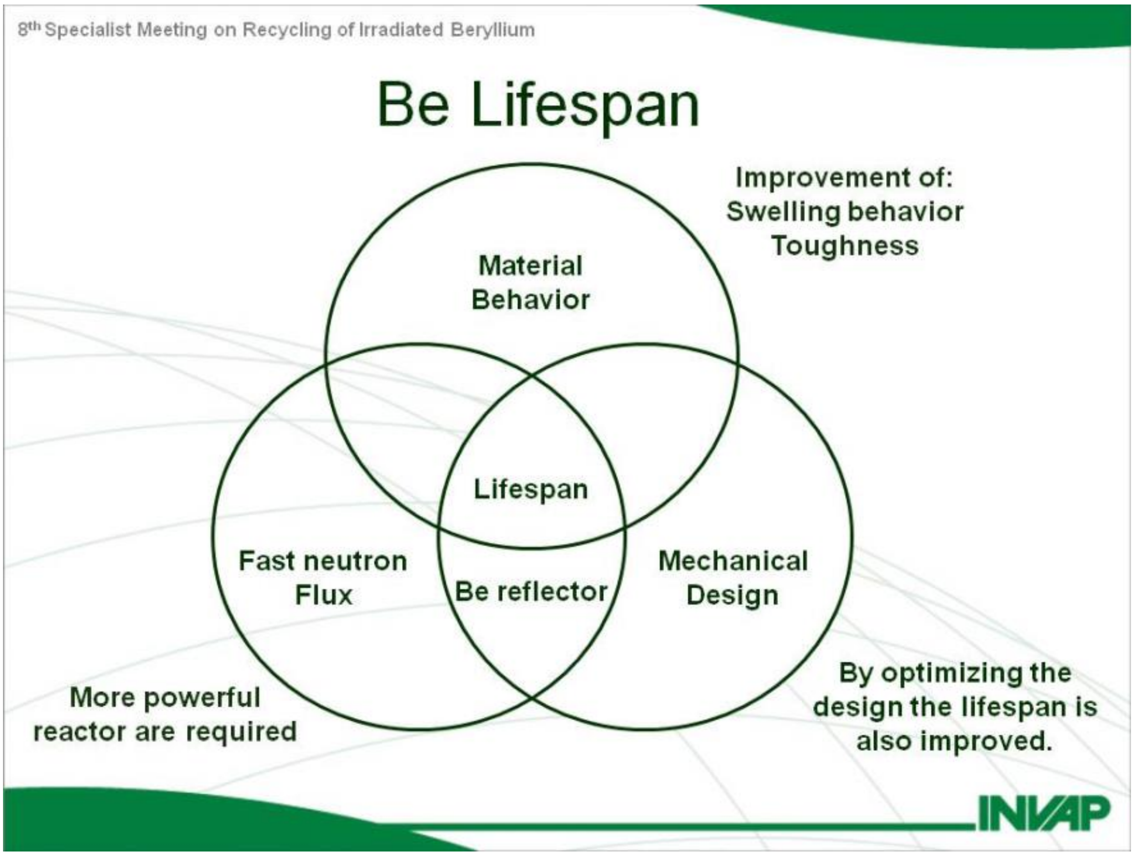


Geometry variation

Parameter	Variation			
L [mm]	30	**90**	150	180
H [mm]	205	275	420	**820**
Θ [°]	**16**	32	180	360

INVAP


8th Specialist Meeting on Recycling of Irradiated Beryllium
Distortion increase
thickness ↓
width ↓
height ↑
Mechanical Design
Stresses increase
thickness ↑
width ↑
height not major influence
Mechanical design/geometry have influence on fail mode of reflector and lifespan
Large pieces tend to fail by cracking (ATR, MURR)
Svelte pieces tend to fail by distortion (SAFARI I, JMTR)
INVAP


8th Specialist Meeting on Recycling of Irradiated Beryllium
Be Lifespan
Improvement of: Swelling behavior Toughness
Material Behavior
Lifespan
Fast neutron Flux
Be reflector
Mechanical Design
More powerful reactor are required
By optimizing the design the lifespan is also improved.
INVAP

Next step....

We have understood how swelling affect the Be reflector.

Now we are adding thermal effects and taking in account the cooling needs in the geometry.

Very preliminary results in a generic reflector assembly will be presented in next section.

INVAP

5th International Symposium on Material Testing Reactors 2012

INVAP

This is a blank page.

3.4 Beryllium Usage at the University of Missouri Research Reactor

[Abstract]

Beryllium Usage at the University of Missouri Research Reactor

L.P. Foyto[1], N.J. Peters[1], J.C. McKibben[1] and J.L. Saddler[1]

[1]*Reactor and Facilities Operations, University of Missouri-Columbia Research Reactor, 1513 Research Park Drive, Columbia, Missouri, 65211, U.S.A.*

In accordance with the mission of the Global Threat Reduction Initiative (GTRI) program of maintaining the current capabilities of research and test reactors after converting them from highly-enriched uranium (HEU) fuel to low-enriched uranium (LEU) U-10Mo monolithic fuel, studies must be performed to ensure that the reactor core performance will not be challenged in any way. While detailed work has been completed that predicts core neutronic and thermal-hydraulic behavior, the impact of a fuel conversion has not yet been studied to any level of detail for various critical components other than the reactor core for the University of Missouri Research Reactor (MURR), which is a 10 MW pressurized, light-water moderated and cooled, reflected (graphite and beryllium), heterogeneous, open pool-type design. In particular, there are limitations on the specialized beryllium sleeve which is replaced at 26,000 MWd of operation with HEU fuel operating at 10 MW. This is to avoid the eventual stress-fracture failure due to thermal stresses from gamma heating and swelling from gas production, in addition to the performance degradation seen as a corresponding loss in core reactivity due to lithium-6 poisoning and swelling. This replacement cycle that will change with LEU operations at 12 MW is being determined. Preliminary investigations using MURR MCNP models, coupled with ORIGEN depletion simulations to compare the HEU and LEU cores, have predicted differences in the gamma heating distribution, gas production rates and core reactivity changes concerning the beryllium as a function of megawatts days. Results from this work indicate that for an end-of-cycle beryllium reflector at MURR, the changes at the peak-flux region production going from the HEU to the LEU core are a 21.5% decrease in gamma heating and an 11% increase in gas swelling, respectively. Using the results reported here, a systematic approach to predict beryllium performance and failure point as a function of megawatt-days is being developed.

Beryllium Usage at the University of Missouri Research Reactor

Leslie P. Foyto
University of Missouri-Columbia Research Reactor Facility
Reactor and Facilities Operations
1513 Research Park Drive, Columbia, Missouri, 65211, U.S.A.

MURR Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

2

Presentation Overview

- MURR Basic Reactor Parameters and Operating Experience
- General Description of Beryllium Reflector
- Why the Beryllium Reflector is Periodically Replaced?
- Frequency of Replacement
- Beryllium Reflector Procurement
- Onsite Storage & Status of Disposal
- Swelling Measurements

MURR Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

3

Facility Overview

Location:

On the University of Missouri main campus in Columbia, Missouri, USA. (~200 km West of St. Louis)

History:

- First critical on October 13, 1966 (Licensed at 5 MW)
- Uprated and licensed at 10 MW in 1974
- Started ≥150 hours/week operation in September 1977
- Schedule for conversion to LEU fuel is July 2016

Purpose:

Multi-disciplinary research and education facility also providing a broad range of analytical and irradiation services.

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

4

Key Reactor Parameters

- MURR® is a pressurized, reflected, heterogeneous, open pool-type, which is light-water moderated and cooled.
  - Maximum power – 10 MW_{th}
  - Peak flux in center test hole – 6.0E14 n/cm^2-s
  - Core – 8 fuel assemblies (775 grams of U-235/assembly)
  - Control blades – 5 total: 4 Boral shim-safety, 1 SS regulating
  - Reflectors – beryllium and graphite
  - Forced primary coolant flow rate – 3,750 gpm (237 lps)
  - Forced pool coolant flow rate – 1,200 gpm (76 lps)
  - Primary coolant temps – 120 °F (49 °C) in, 136 °F (58 °C) out
  - Primary coolant system pressure – 85 psia (586 kPa)
  - Pool coolant temps – 100 °F (38 °C) in, 106 °F (41 °C) out
  - Beamports – three 4-inch (10 cm), three 6-inch (15 cm)

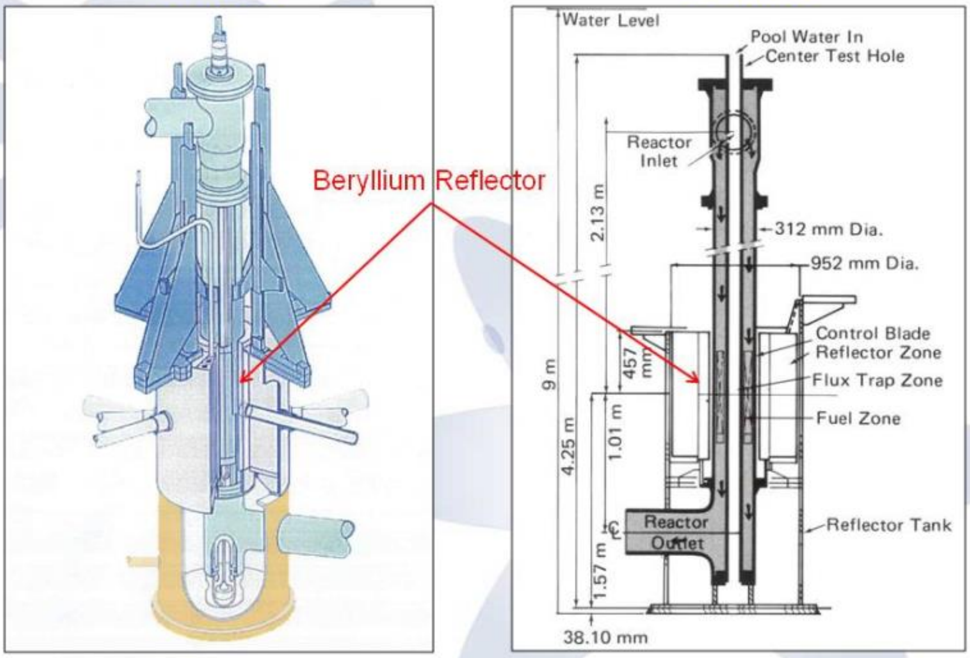
MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

5

Reactor Core Assembly 3D View

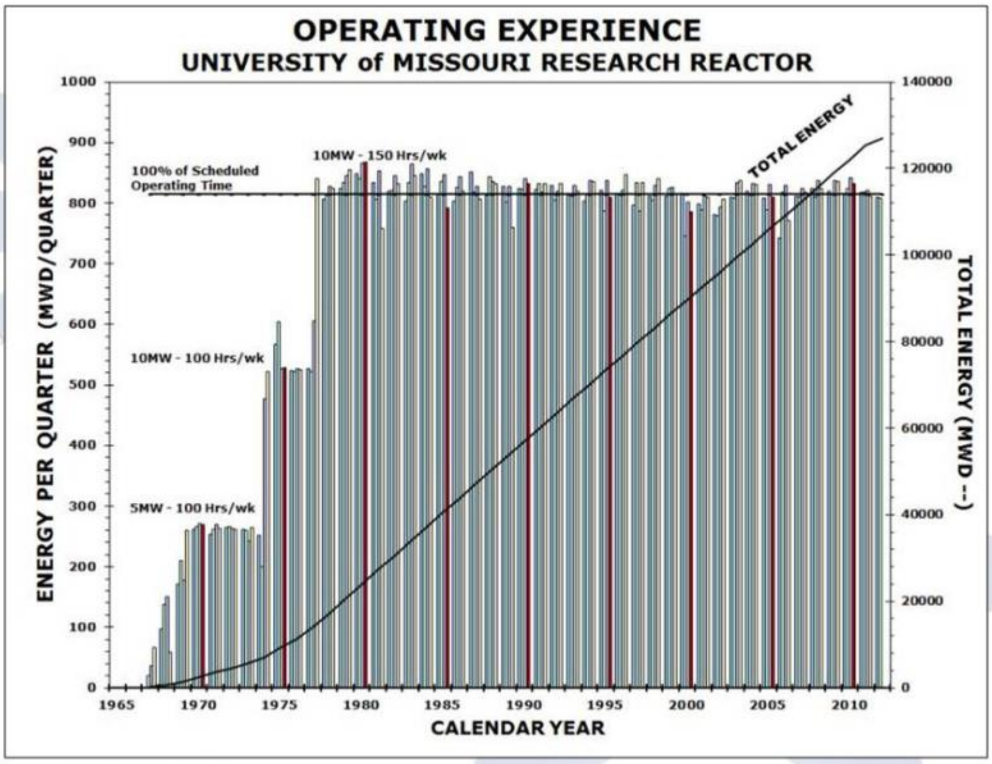
Reactor Core Assembly 2D View



MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

6

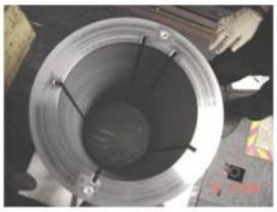


MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

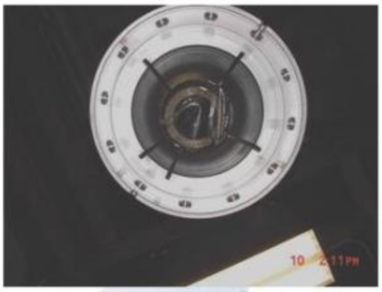
7

Beryllium Reflector - New



Specifications:

- 37 inches (94 cm) tall
- 9-inch (22.9 cm) Al skirt
- 19-inch (48.3 cm) OD
- 2.71 inches (6.9 cm) thick
- S-200FH Grade Beryllium
- 5 machined grooves for spacers



MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

8

Why is the Beryllium Reflector Periodically Replaced?

- Tensile stresses caused by (1) radiation induced swelling, and (2) radiation heating (Approximately 50/50).
- Three primary beryllium reactions:
  1. Be^9 (γ, n) Be^8
  2. Be^9 (n, 2n) Be^8
  3. Be^9 (n, α) He^6 $\quad n + Be^9 \rightarrow {}_2He^4 + {}_2He^6$

$${}_2He^6 \rightarrow {}_3Li^6 + \beta^- \qquad t_{1/2} = 0.8 \text{ seconds}$$
$$n + {}_3Li^6 \rightarrow {}_2He^4 + {}_1H^3$$
$${}_1H^3 \rightarrow {}_2He^3 + \beta^- \qquad t_{1/2} = 12.5 \text{ years}$$
$$n + {}_2He^3 \rightarrow {}_1H^3 + p$$

- Combined stresses [${}_1H^3$, ${}_2He^3$, and thermal] cause the combined expansion to reach the beryllium's yield point.

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

9

Frequency of Replacement

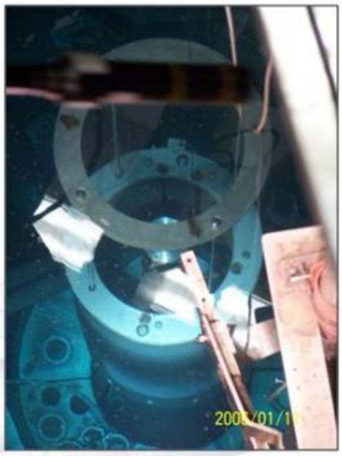
- The beryllium reflector is replaced every 26,000 MWds.
- This value is based on previous operating experience, with the first reflector cracking in place in 1981.
- Since 1977, the MURR has operated at 10 MW for 90% of the time. This equates to a replacement every 8 years - 1989, 1997 and 2006.
- Next scheduled replacement is December 2013.
- After next scheduled replacement, 3 irradiated beryllium reflectors will stored at MURR - ~1/2 ton.

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

10

Removal of Old Beryllium Reflector

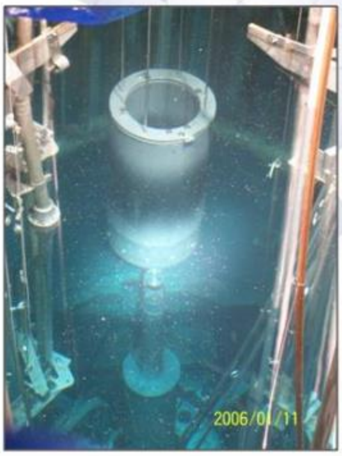


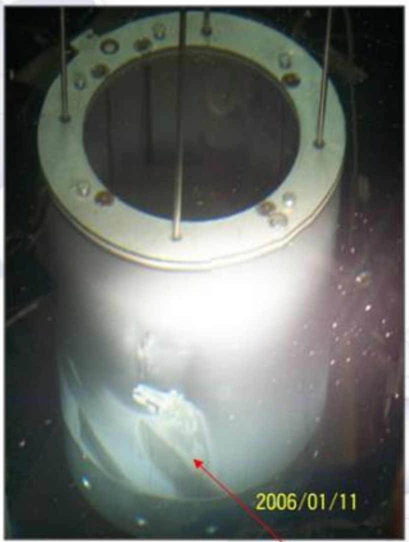
MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

11

Removal of Old Beryllium Reflector





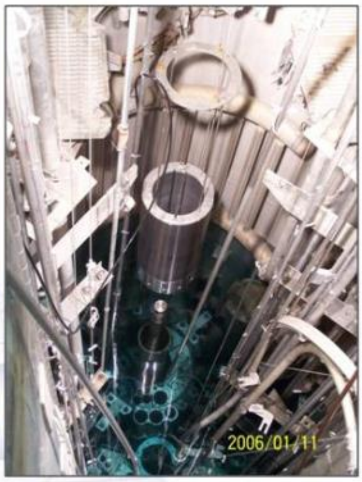
Beryllium horse

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

12

Installation of New Beryllium Reflector

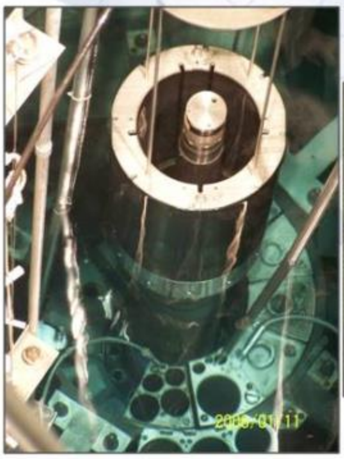
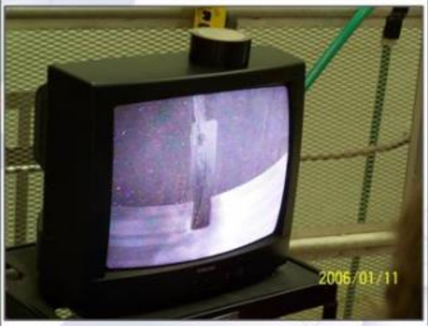


MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

13

Installation of New Beryllium Reflector

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

14

Beryllium Reflector Procurement

- Beryllium material from Materion Brush Beryllium and Composites – Formerly Brush Wellman Alloys
- S-200FH Grade Beryllium
- Beryllium reflector procured from AXSYS Technologies – General Dynamics Advanced Information Systems
- Next beryllium reflector has been procured and delivered

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

15

Onsite Storage & Status of Disposal

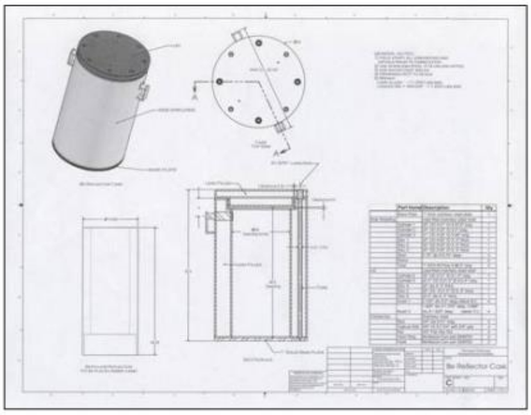
- One irradiated beryllium reflector had been stored in reactor pool – can not store 2 and must be removed before next beryllium replacement – completed.
- Two irradiated beryllium reflectors stored in dry casks (designed and constructed by MURR staff).
- Currently no disposal site for irradiated beryllium in the US.

MURR
Bringing quality nuclear research, education and service to a global community

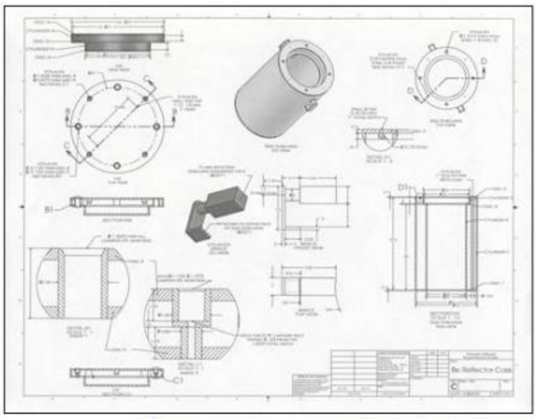
6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

16

Irradiated Beryllium Dry Cask Storage



- Design - entirely by MURR staff with shielding thicknesses based on activity and dose calculations, and historical data from 2 previous beryllium shipments
- Construction - entirely by MURR staff
- Materials - $12,000



- Design was kept simple without a lot bells and whistles
- Ability to either place it back in the reactor pool or the Co-60 pit

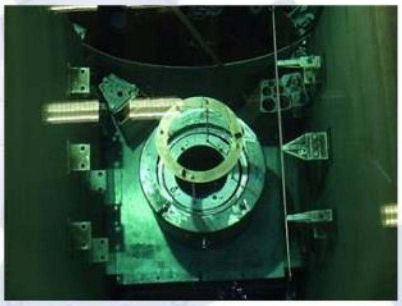
MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

17

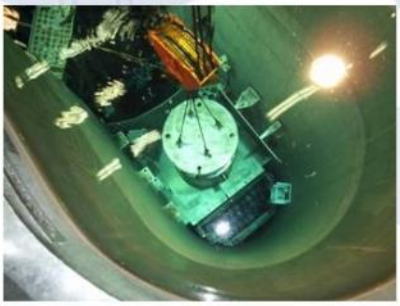
Loading of Irradiated Beryllium Dry Cask

Beryllium placed in the cask



Installing the lifting yoke

Placing the lid on the cask



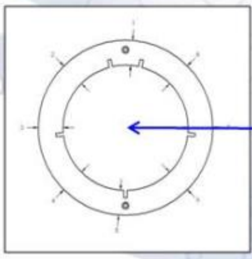
Removing the cask

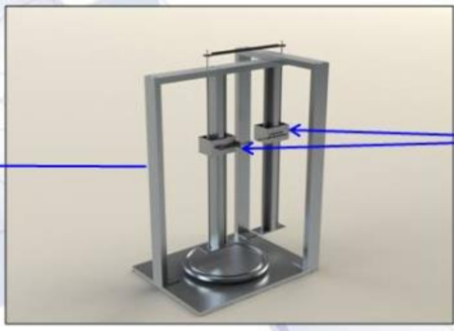
MURR
Bringing quality nuclear research, education and service to a global community

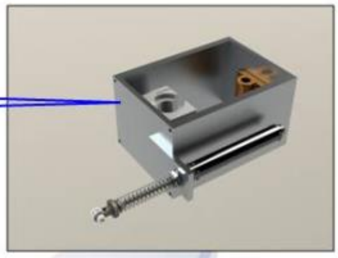
6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

18

Beryllium Swelling Measurement Equipment







- 8 radial locations.
- Data points were taken every 2 inches of downward travel.
- Measurements were then offset by 1inch.
- Data points were then taken every 2 inches of upward travel.
- This provided data points for every inch axially along the 8 radial locations.

Error Source	Tolerance
Beryllium Manufacturing Tolerance ID	0.0050
Beryllium Manufacturing Tolerance OD	0.0050
Potentiometer	0.0090
Roller Radial Runout	0.0010
Roller Diametrical Tolerance	0.0004
Roller Axle Diametrical Tolerance	0.0010
Roller Adapter Axle Hole Press Fit Tolerance	0.0014
Linear Carriage Hole Centerline Height	0.0012
Linear Rail Diametrical Tolerance	0.0010
Linear Rail Straightness Tolerance	0.0060
Rail Support Hole Centerline Height	0.0020
Total Stacked Tolerance:	0.033

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

19

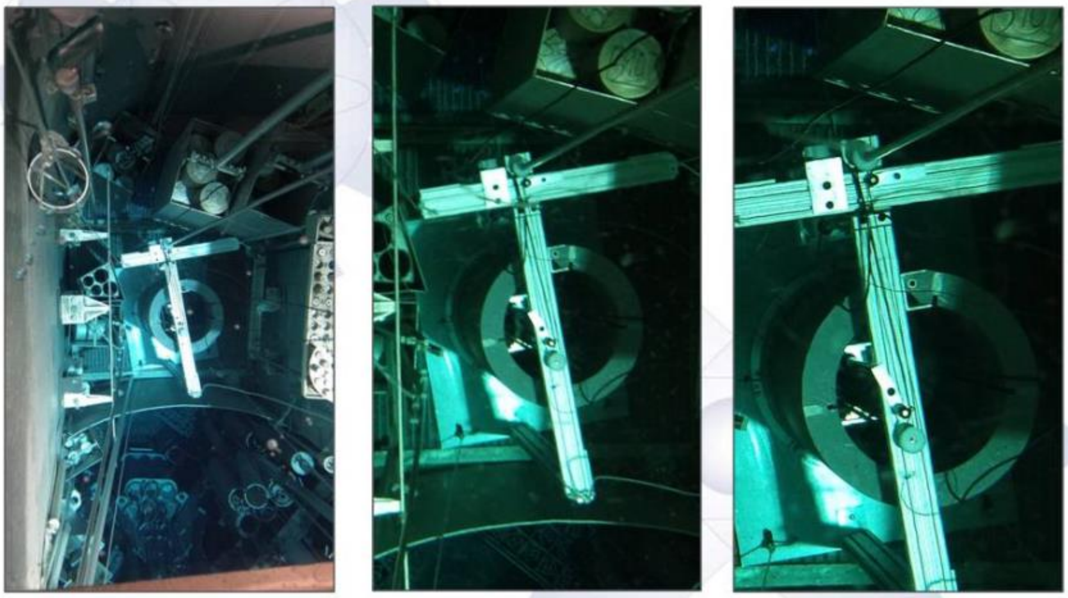
Measurements – New Beryllium

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

20

Measurements – Irradiated Beryllium

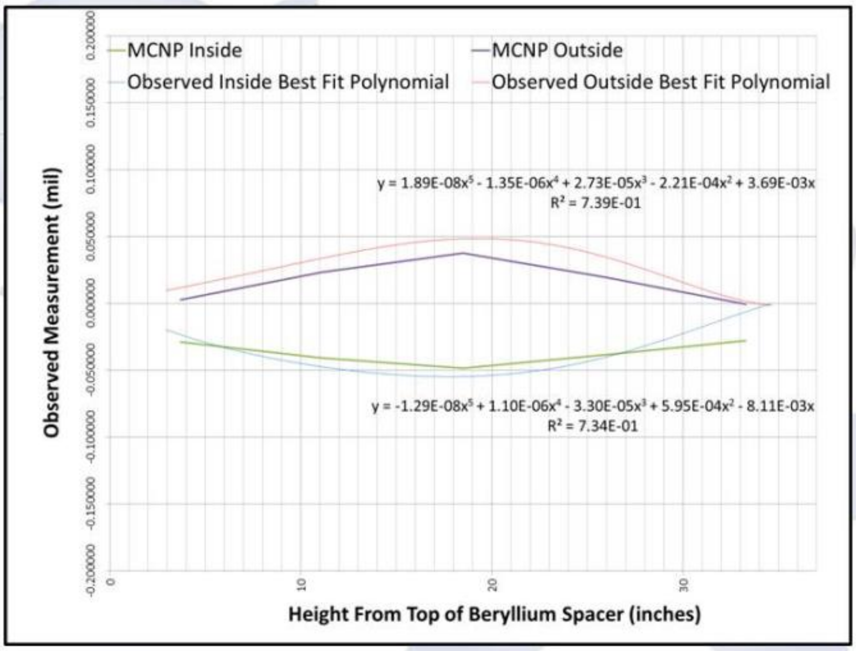


MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

21

Calculated & Measured Beryllium Swelling



MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

MURR
Bringing quality nuclear research, education and service to a global community

6th International Symposium on Material Testing Reactors
San Carlos de Bariloche, Argentina – October 28, 2013

3.5 Status of Beryllium Study in JAEA

[Abstract]

Status of Beryllium Study in JAEA

Kunihiko Tsuchiya[1]

[1] *Japan Atomic Energy Agency, Oarai, Ibaraki, Japan*

Beryllium has been used as a moderator and/or reflector in a number of materials testing reactors. The beryllium frames and reflector elements which have been used as a neutron reflector in the Japan Materials Testing Reactor (JMTR) at JAEA, have been fabricated from S-200F grade beryllium metal. The current operational lifetime for the beryllium frame in JMTR is five years, but the goal of the development program is to increase that service life to 15-20 years (180,000MWD). In order for that to happen, it will be necessary to consider fundamental changes to the frame design, starting with the choice of beryllium material grade.

Three grades of beryllium metal: S-200F, S-65-H, and I-220-H, were selected due to their differences in production method, impurity levels, mechanical properties, and grain size. The properties of these beryllium grades have been evaluated in out-pile tests. Mechanical properties such as tensile strength, hardness, and impact strength were measured, and the database of these beryllium grades has now been constructed.

In the area of chemical properties, corrosion tests were carried out under pure water at 50˚C for about 8000 h, and it was observed that the corrosion rate of I-220-H was lower than that of other beryllium grades. The weight change of S-200F was larger than that of I-220-H after the corrosion test. Ratio of electrical conductivity of S-200F was also larger than that of S-65-H and I-220-H. The conductivity of I-220-H showed almost no change. From these results, the corrosion properties were evaluated by the measurements of weight change and electrical conductivity and influenced by the content of BeO and grain size of each Be sample. Surface analysis for chemical combination of the beryllium grades was carried out by XPS under the research program at the University of Toyama.

The irradiation tests for each Be material grade have been carried out in JRR-3 and WWR-K, and the irradiation tests in the JMTR will begin at the time of the JMTR re-start. Especially, irradiation tests at WWR-K were carried out under the ISTC partner project between JAEA and INP-KNNC. Swelling and tritium release of the irradiated beryllium were evaluated.

Finally, beryllium recycling was studied under the ISTC regular project (ISTC K-1588). Project Leader was IAE NNC-RK in Kazakhstan, and Japan and EU were collaborated in this project. In this year, kg-scale demonstration test with used beryllium supplied from JAEA was carried out in IAE and evaluated the purification ratio of irradiated beryllium from the results of gamma spectrum before/after the tests.

In this meeting, status and future plans for the beryllium reflector development at JMTR are introduced, and discussion of the results will be also take place during the 6th ISMTR.

The 8th Specialist Meeting on Recycling of Irradiated Beryllium
Bariloche, Río Negro, Argentina (28th Oct., 2013)

Status of Beryllium Study in JAEA

K. TSUCHIYA

JAEA, 4002 Narita, Oarai, Higashiibaraki, Ibaraki, 311-1393, Japan

1. Introduction

Object for Beryllium Reflector of JMTR

Status of Beryllium Frame in JMTR

- Beryllium Grade : S-200F
- Frame Usage Period : about 5 years
  (av. 0.3×10^{26} /m^2 (E>1MeV), 36,000MWD)
- Period for Exchange : about 45 days*
- Used Be Frame : Storage in Canal

*: Actual working in reactor site

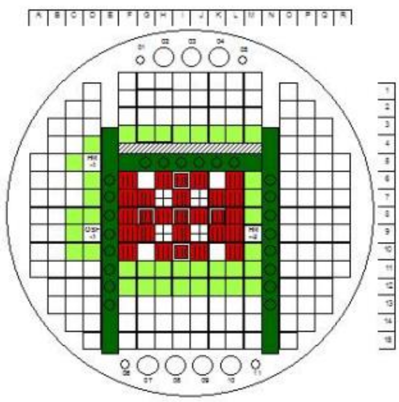
[Conditions]

- Thermal Power : 50MW
- Max. Fast Neutron Flux : 4×10^{18} /m^2/s
- Max. Thermal Neutron Flux : 4×10^{18} /m^2/s
- Max. Temperature : about 100°C
  (Temp. of cooling water : about 50°C)
- Operating Pressure : 1.5MPa
- Flow rate : 11m/s
- Cooling water (Light water) : pH5.5 – pH7.0

Improvement of Beryllium

- Exchange of Be frame : FY2019
- Beryllium Grade : New Grade
- Frame Usage Period : 15-20 years
  (av.1.5×10^{26} /m^2 (E>1MeV), 180,000MWD)

Core arrangement of JMTR



: Fuel element
: Control rod with fuel follower
: Beryllium reflector element
: Beryllium frame
: Aluminum reflector element

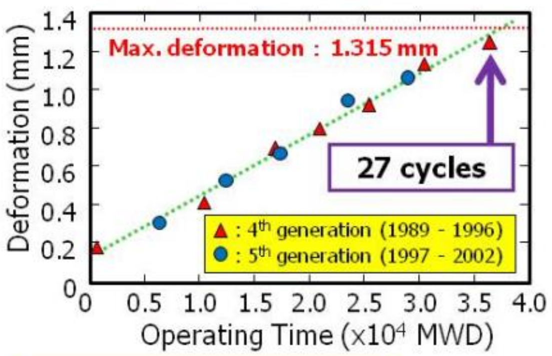
1

Results of Irradiated Beryllium in JMTR

Deformation of Beryllium Frame

JMTR operation : 165 cycles for 38 years
Replacement of Be frames : 6 times

Deformation Measurement

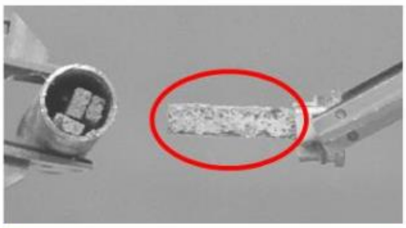


Deformation increased with increasing operation time for accumulation of helium.

Irradiation of Beryllium Samples

[Irradiation Conditions]

Cycle : 100 cycles
Temperature : about 50°C
Atmosphere : Cooling water

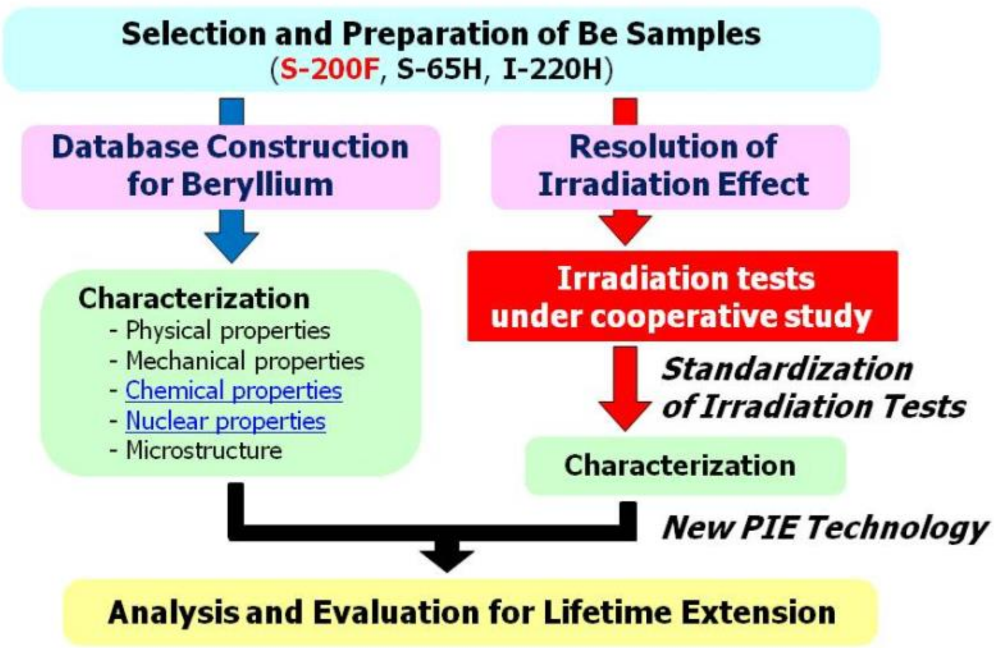


Corrosion of the beryllium surface resulted after a long period of irradiation.

- **Evaluation of mechanical properties**
- **Resolution of corrosion mechanism**

2

Test Flow for Lifetime Expansion



3

2. Material Selection and Chemical Properties

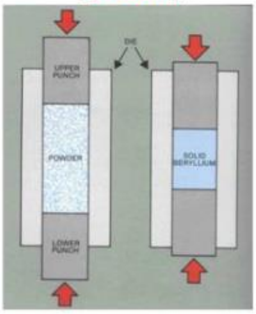
Material Selection for Lifetime Extension

[Target]
Lifetime of beryllium frame : 5 times (36,000MWd→180,000MWd)

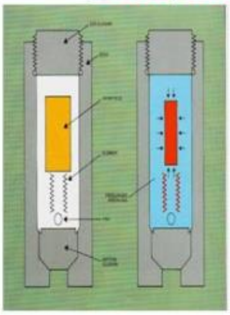
Production of beryllium metal ➡ Powder-Metallurgy

[Effect on properties of beryllium metal due to production method]
1) Purity (BeO content, etc.) and particle size distribution of Be powder
2) Production methods: VHP (Vacuum Hot Press), HIP (Hot Isostatic Pressing), etc.

VHP
Grade (S-200F)



HIP
Grade (S-65H, I-220H)

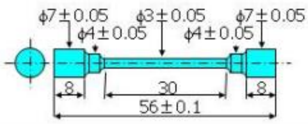
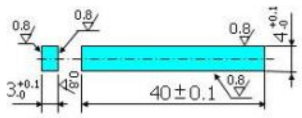
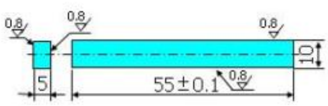
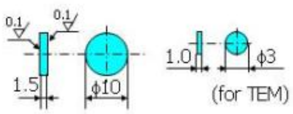
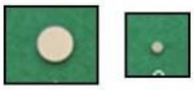


Advantages of HIP over VHP
1) Superior isotropy and density
2) Higher mechanical properties
3) Savings of Be powder
4) Potential to use near-net shape and reduce machining required

4

Preparation of Beryllium Specimens

[Materion Brush Beryllium & Composites, USA]

Name	Shape (Unit : mm)	Photograph	Fabrication Method
Tensile Specimens			Conventional Lathe Machining
Bending Specimens			Conventional Mill Machining
Impact Specimens			Conventional Mill Machining
Disk Specimens			Conventional Lathe Machining followed by Polishing of Surfaces

Fabrication experiences of small size specimens with S-200F, S-65H and I-220H for material testing.

5

Mechanical Properties of Beryllium

S-200F Beryllium (VHP) Reference
Down-Selection Process for Be Grades
- **Purity & Isotropy Combination : S-65H**
- **Strength & Isotropy Combination : I-220H**

Factor	Grade	Be Assay (%) min	Be Assay (%) typ	YS (MPa) min	YS (MPa) typ	UTS (MPa) min	UTS (MPa) typ	El (%) min	El (%) typ	GS (μm) max
Ref.	S-200F	98.5	99.1	241	260	324	380	2.0	3.0	20
Purity	S-65	99.2	99.4	206	230	289	386	3.0	5.2	20
Isotropy	S-65H	99.0	99.4	206	280	345	450	2.0	5.1	15
	I-70H	99.0	99.4	207	290	345	460	2.0	5.4	12
	O-30H	99.0	99.5	297	302	400	425	3.0	3.1	15
Strength	S-200FH	98.5	99.1	296	336	414	450	3.0	4.6	12
	I-220H	98.0	98.6	345	498	448	577	2.0	3.2	15

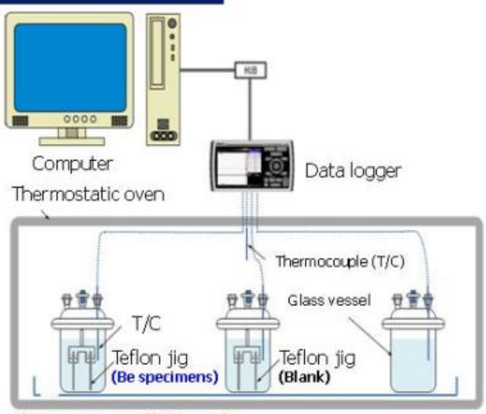
6

Corrosion Test of Beryllium in Pure Water

[Univ. of Toyama]

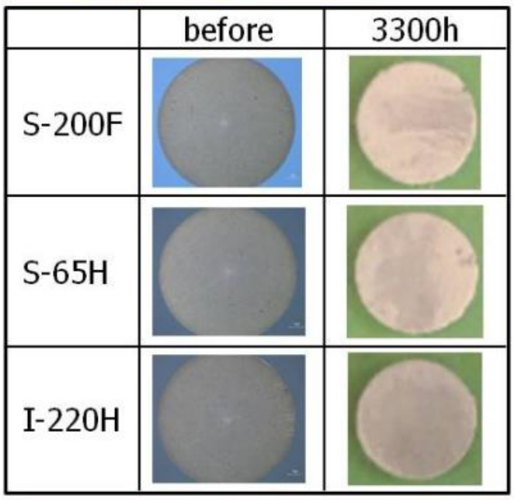
It is important to perform the characterization of the different grade beryllium for life time expansion evaluation and corrosion test of these beryllium samples were carried out under pure water.

Test Procedure



[Test Conditions]
Temperature : 50°C
Corrosion Time : 3300, 5200 and 8300h
Properties of Water :
1) Electric conductivity : <4μS/cm
2) pH5.5-7

Photograph of Specimens

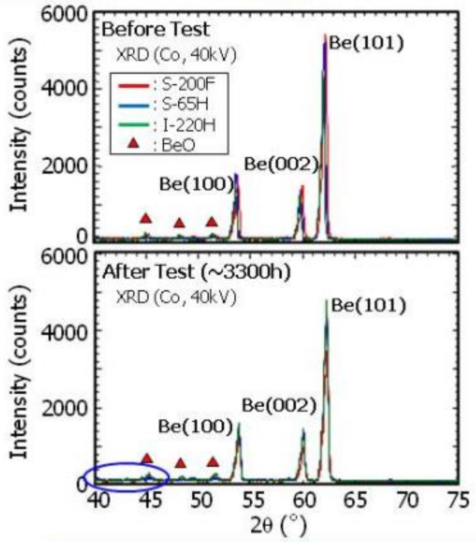


The white product was generated on the surface of each Be specimen.

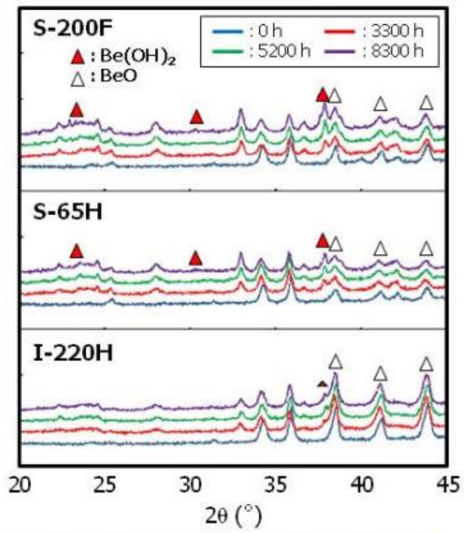
7

Characterization of Beryllium after Corrosion Tests

XRD Measurement (1)



XRD Measurement (2)

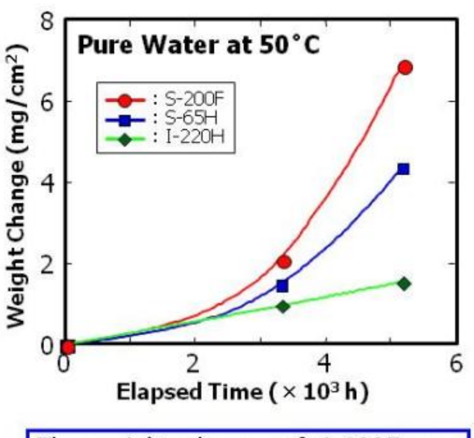


The peaks corresponding to BeO were almost the same intensity before/after the corrosion test from 40° to 75°.
Detail XRD measurements from 20° to 45°
: Appearance of the peaks corresponding to **$Be(OH)_2$**

8

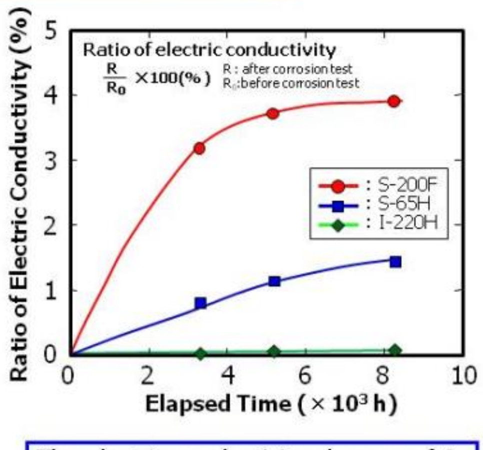
Corrosion Property of Be Samples in Pure Water

Weight change



The weight change of S-200F was larger than that of I-220H.

Electric conductivity



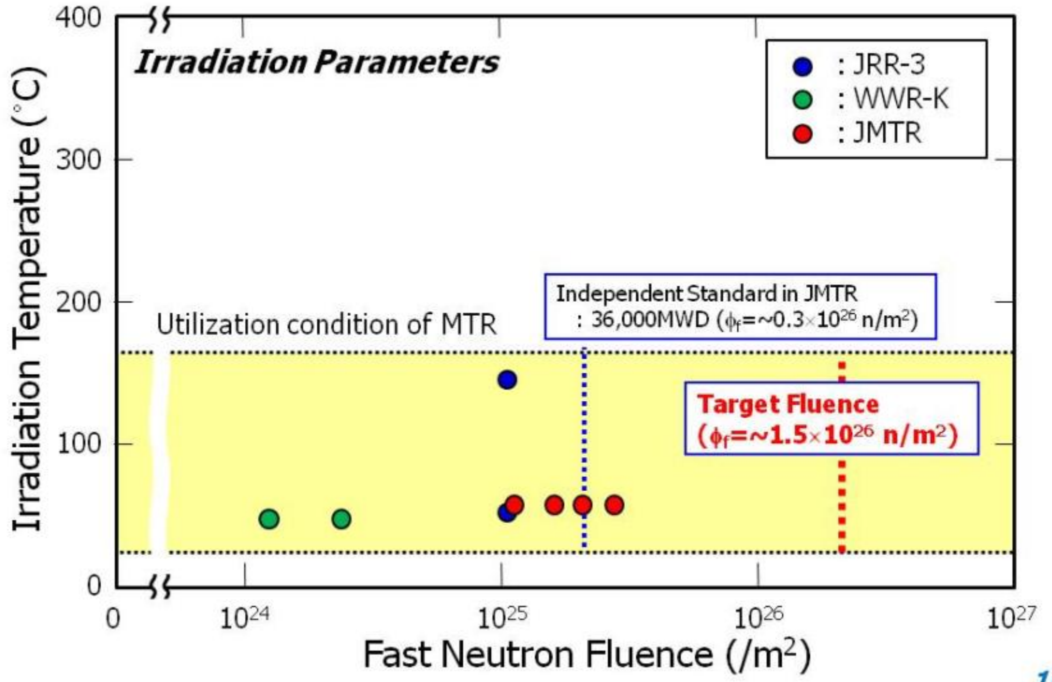
The electric conductivity change of S-200F was larger than that of I-220H.

Corrosion products : **$Be(OH)_2$**
Corrosion resistance of beryllium ➡ Effect of **content of BeO**

9

4. Irradiation Tests

Irradiation Parameters for Lifetime Extension



10

Change of Irradiation Conditions

	Test Name	Original Plan	Change Plan	Remarks
1	JRR-3 Irradiation Test	**Neutron Fluence** ϕ_f=1.5 x 10^{25} n/m^2 **Start of PIE** from June, 2011	**Neutron Fluence** ϕ_f=1.2 x 10^{25} n/m^2 **Start of PIE** from April, 2014	New Nuclear Regulation (No operation)
2	WWR-K Irradiation Test	**Neutron Fluence** ϕ_f=1.5 x 10^{24} n/m^2 **Start of PIE** from Jan., 2012	**Neutron Fluence** 1st : ϕ_f=1.5x10^{25} n/m^2 2nd : ϕ_f=4x10^{25} n/m^2 **Start of PIE** 1st : from Jan., 2012 2nd : from Jan., 2013	Completion of ISTC Project
3	JMTR Irradiation Test	**Start of Irradiation** from Oct., 2011	**Start of Irradiation** from next year	New Nuclear Regulation (No operation)

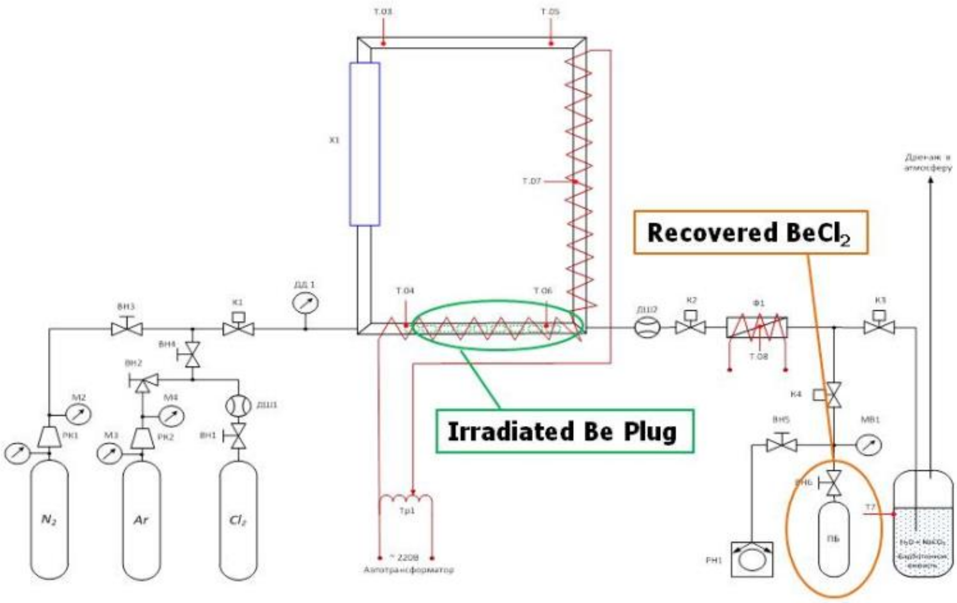
11

5. ISTC K-1566 Project (Be Recycling)

Experimental of Small Scale Tests

[IAE-NNC]

The small scale tests were carried out by the demonstration device with the irradiated beryllium samples.



12

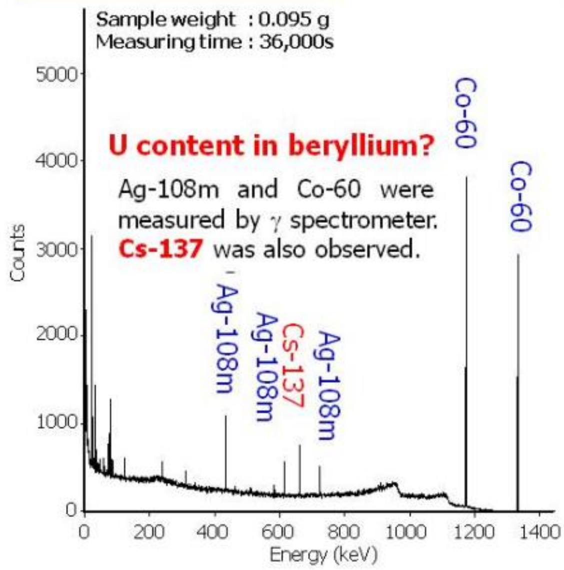
Results of γ Spectrum in Small Scale Tests

[IAE-NNC]

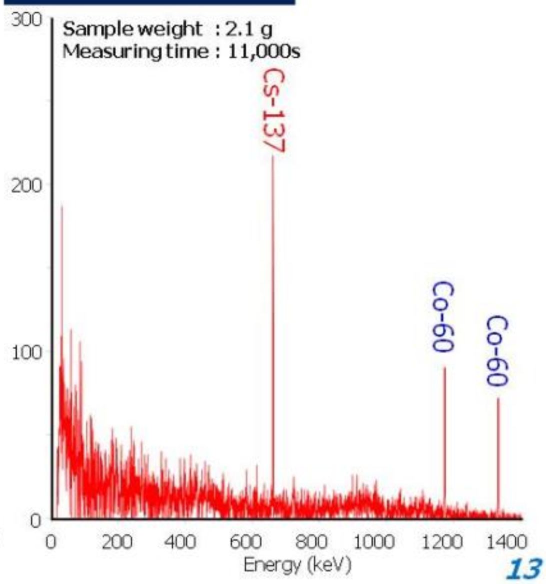
[Irradiated Be samples]

- Irradiation Period : 1968～1975 (1st Be frame)
- Cumulative Power : 24,017.4MWD
- Av. Thermal Neutron Flux : ~8.0×10^{13} n/cm²/s (50MW)
- Av. Fast Neutron Flux : ~7.5×10^{12} n/cm²/s (50MW)

Before small scale test



After small scale test



13

Evaluation of Purification in Small Scale Tests

[IAE-NNC]

		Amount of Be (g)	Activity (Bq)		
			Co-60	Cs-137	Ag-108m
(a) Activity evaluation in beryllium sample without purification					
1st Experiment	Total Irr. Be samples	**955.5**	**2.7×10^8**	**1.8×10^7**	**2.4×10^7**
	Reacted Be samples	**61.0**	**1.7×10^7**	**1.1×10^6**	**1.5×10^6**
2nd Experiment	Be ($BeCl_2$) samples before the 2nd experiment	**8.5**	**2.4×10^6**	**1.5×10^4**	**2.1×10^5**
	Be ($BeCl_2$) samples after the 2nd experiment	**2.1**	**6.0×10^5**	**3.7×10^3**	**5.2×10^4**
(b) Activity measurement in recovered sample					
Nuclide contents in the sample		**2.1**	**80±30**	**70±30**	**5**
(c) Evaluation of purification					
Purification degree (Removed ratio from irradiated Be)		-	**~7.5×10^3 (99.9999%)**	**~53 (99.98%)**	**~1.0×10^4 (99.9999%)**

: Experimental values   : Calculated values   : Evaluated values

14

6. Conclusion

Summary

Material Selection of Beryllium Grades as MTR Reflectors was discussed in the Be Specialist Meetings and the following items were decided:

- Selection of beryllium grades
  → Reference (S-200F), Isotropy (S-65H), Strength (I-220H)
- High-irradiation tests for lifetime extension
  → Performance of irradiation tests (JRR-3, WWR-K, JMTR)

Status of Be study

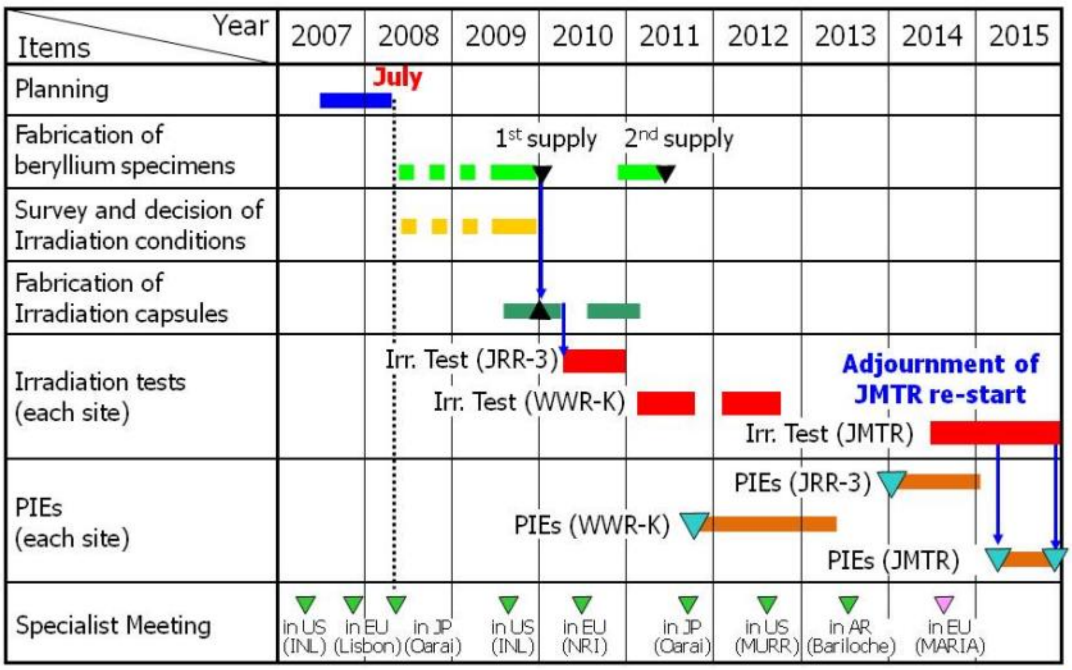
- Preparation of Beryllium Specimens for irradiation tests
- Irradiation tests in JRR-3 and WWR-K
- Preparation of irradiation test in JMTR
- Corrosion evaluation of Be specimens in out-of-pile test
- Completion of Small Scale Tests for Be Recycling (ISTC Project)

Future Plans

- Negotiation for conducting High-irradiation tests in each reactor

15

Research Schedule for Lifetime Expansion



16

3.6 Status of Beryllium Study in KAERI

[Abstract]

Status of Beryllium Study in KAERI

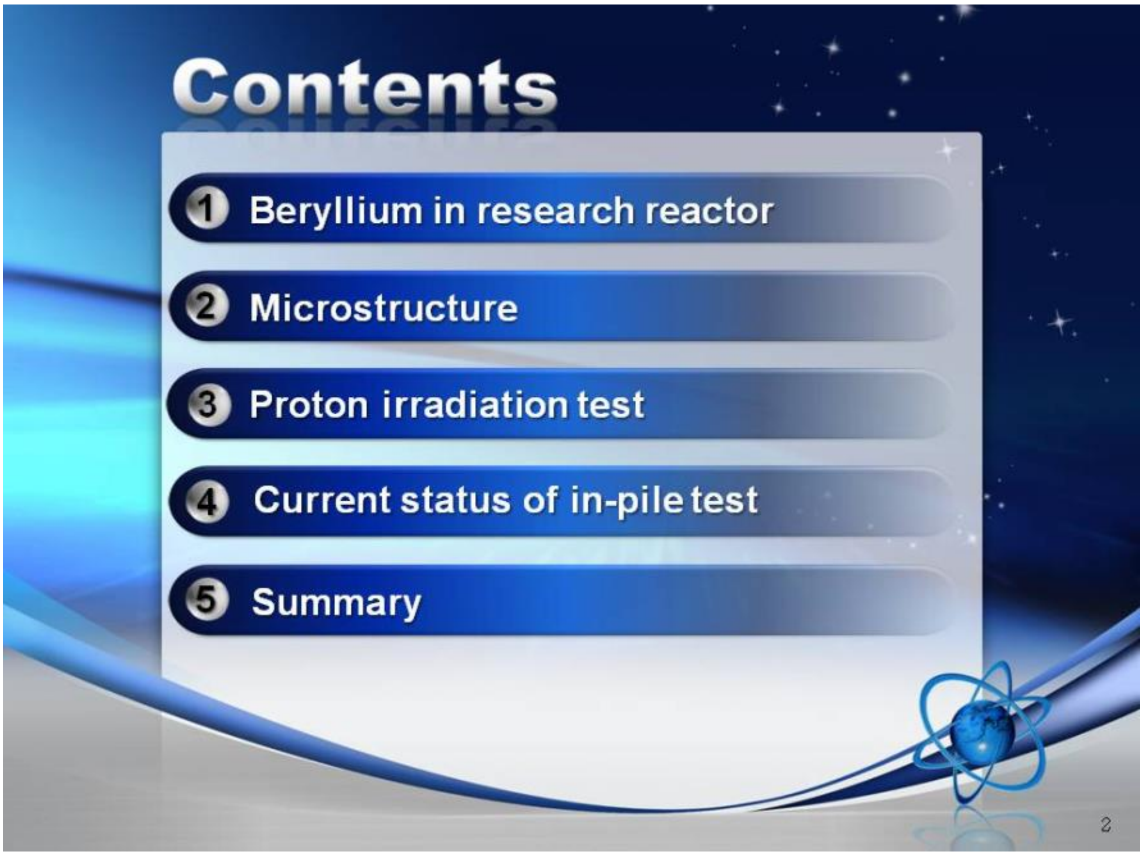
Man Soon Cho[1], Tae Kyu Kim[1]

[1] *Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*

The beryllium materials are being considered as a primary reflector in both the Jordan Research and Training Reactor (JRTR) and the Kijang Research Reactor (KJRR). In KAERI, the research on beryllium materials has been performed using three types of targets; S-65 (HIP) and S-200-F (VHP) from Materion (USA), and EHP-56 (hot extrusion) from Ulba Metallurgical Plant (Kazakhstan). The out-of-pile tests consisted in microstructure observation, hardness test and photon irradiation test. The microstructural observations using SEM/EBSD indicated that the VHP process was quite effective in producing a beryllium reflector block of randon orientation while the hot extrusion process produced strong anisotropic orientation. Microhardness test results indicated that the isotropic Vickers hardness value of about 1000 MPa for S-65 and S-200-F. The EHP-56 which was fabricated by hot extrusion revealed an anisotropy in microhardness for longitudinal and cross-sectional directions. For these beryllium materials, proton irradiation test has been also performed using gas ion irradiation machine of Korea Multi-Purpose Accelerator Complex. Protons were irradiated on a beryllium sample with the acceleration voltage of 120 keV and the fluence of 2.0 x 10^{18} ions/cm^2 at room temperature. The size of the irradiation damaged layer was estimated through a Monte Carlo simulation (SRIM2012 software) and a TEM. The damaged layer observed by TEM study was measured to be about 1 μm, and this size was coincident with the simulation result. The most severely damaged area was occurred at 600 nm in depth; tens-of-nanometer-sized voids were observed in this area. Multiple voids were observed in the entire damaged area, and they were preferentially distributed along with grain boundaries, and the interfaces between the matrix and the BeO particles. The voids were also distributed in the grains, showing that the distribution behavior of voids have been mainly determined by the grain orientation. As a result, it was found that the beryllium atoms could be easily dislocated through the proton irradiation while the basal plane was aligned along a direction perpendicular to the irradiation. The in-pile tests for the S-200-F and EHP-56 materials have been performed using HANARO (High Flux Advanced Neutron Application Reactor) in KAERI. The first capsule is under post irradiation examination and the second capsule is under irradiation in the reactor.

This is a blank page.


8th specialist Meeting on Recycling of Irradiated Beryllium
Oct. 28, 2013, Barilroche, Argentina
Status of Beryllium Study
in KAERI
Man Soon Cho/Tae Kyu Kim
KAERI Korea


Contents
1 Beryllium in research reactor
2 Microstructure
3 Proton irradiation test
4 Current status of in-pile test
5 Summary
2

Uses of Beryllium

Jordan Research and Training Reactor (JRTR)

- 5 MW
- Irbid, Jordan
- CP (Construction Permit) : August 15, 2013
- Under construction
- Primary reflector : beryllium

Kijang Research Reactor (KJRR)

- 20 MW
- Busan, Korea
- A kind exclusive for RI production
- used for RI production and NTD
- Under basic design
- Primary reflector : beryllium

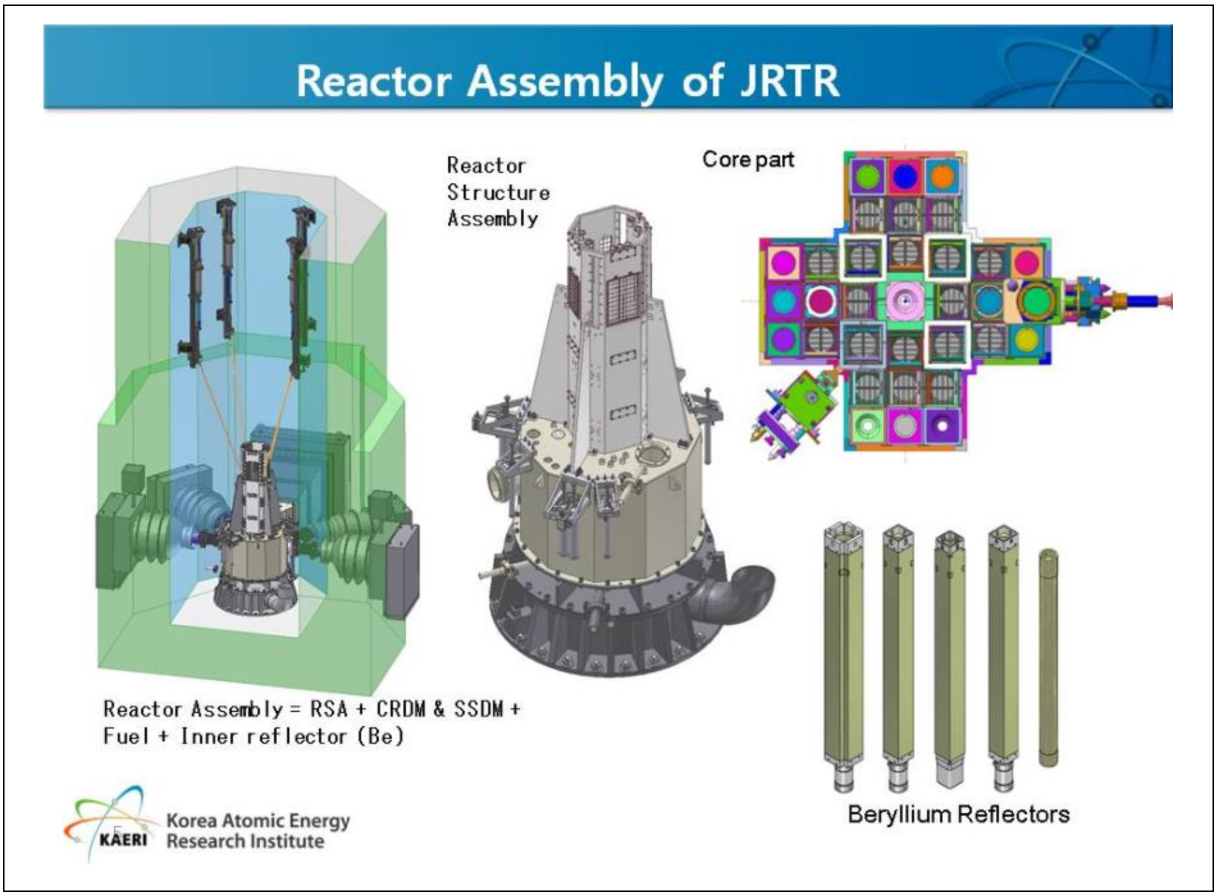
Korea Atomic Energy Research Institute

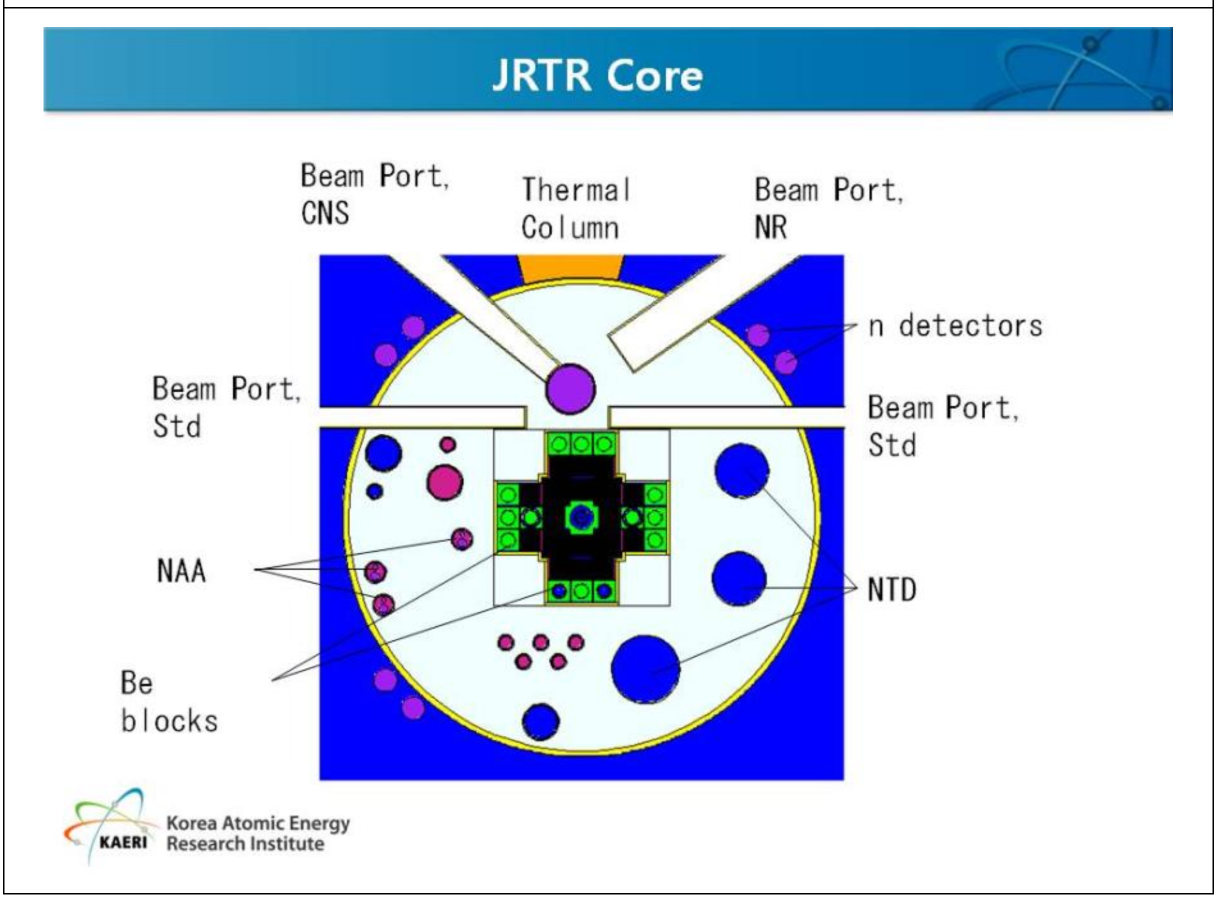
3

JRTR Specification

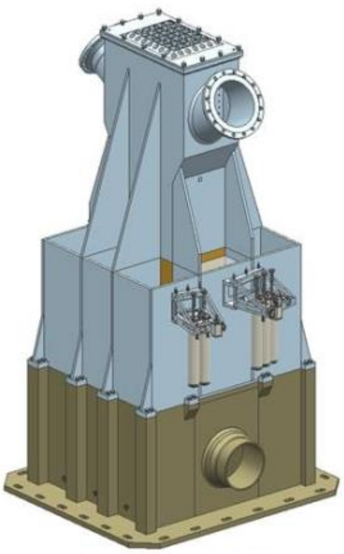
Reactor Type	Open-Tank-in-Pool
Thermal Power (MW)	5 (upgradable up to 10)
Max. Thermal Neutron Flux ($n/cm^2 \cdot s$)	1.5×10^{14} in the core (Central Trap) 0.4×10^{14} in the reflector region
Fuel Type & Material	Plate type; 19.75% enriched, U_3Si_2 in Al matrix
Fuel Loading	18 fuel assemblies, 7.0 kg of U^{235} (Equilibrium cycle)
Coolant/Moderator Cooling Method	H_2O Downward, forced convection flow
Reflector	Be and D_2O
Utilization	Multipurpose - neutron beam application (n. science, n. radiography, etc.) - neutron irradiation service (RI production, NAA, NTD, etc.) by utilizing - 4 beam ports (including 1 port reserved for cold neutron) - 1 thermal column - more than 22 vertical holes (including replaceable in-core holes)

Korea Atomic Energy Research Institute


Reactor Assembly of JRTR
Reactor Structure Assembly
Core part
Reactor Assembly = RSA + CRDM & SSDM + Fuel + Inner reflector (Be)
Beryllium Reflectors
KAERI Korea Atomic Energy Research Institute


JRTR Core
Beam Port, CNS
Thermal Column
Beam Port, NR
n detectors
Beam Port, Std
Beam Port, Std
NAA
NTD
Be blocks
KAERI Korea Atomic Energy Research Institute

Features of KJRR



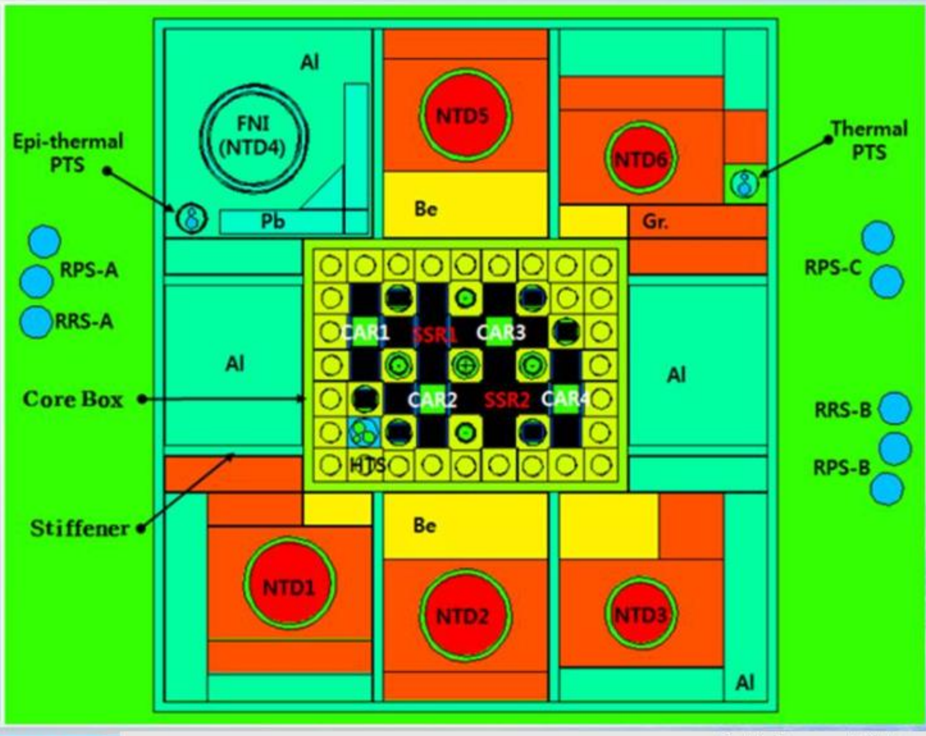
Overview of KJRR

Power	~20 MWth
Type	Open Tank in Pool type
Max. thermal neutron flux (n/cm^2s)	> $3.0x10^{14}$ (Central Trap)
Operation day	~300/year
Life time	50 year
LEU Fuel	U-7Mo plate type (U loading : 6.5, 8.0 g/cc)
LEU Target	UAlx plate type (2.6 g/cc)
Reflector	Be, Al, Gr, Pb
Coolant and flow direction in operation	H_2O, downward forced convection flow
Reactor building	Confinement
Decay heat cooling	Passive System
Robust Design, Aircraft Crash, 0.3g SSE, Digital I&C, Cyber Security, PSA of Internal & External Events (Earthquake, Fire, Flooding)	

KAERI Korea Atomic Energy Research Institute

7

Core Configuration of JRTR



http://www.kaeri.re.kr

Part II. Progress & Status 8

Research on Beryllium Materials

Target Beryllium Materials

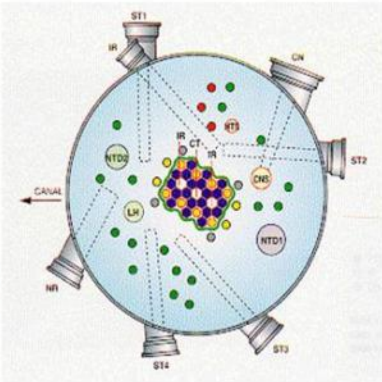
- Materion (USA) : S-65 (HIP), S-200-F (VHP)
- Ulba Metallurgical Plant (Kazakhstan) : EHP-56 (Hot Extrusion)

Out-of-pile Test

- Microstructural observation
- Hardness test
- Proton irradiation test

In-pile Test

- CT and IR2 in HANARO
- Max. flux : 2.1 x 10^{14} n/cm^2.sec(fast)
  4.39x10^{14} n/cm^2.sec (thermal)
- Target fluence: > 4 x 10^{21} n/cm^2 (E>0.18MeV)
- Irradiation temperature: < 70°C
  (RR operating conditions)

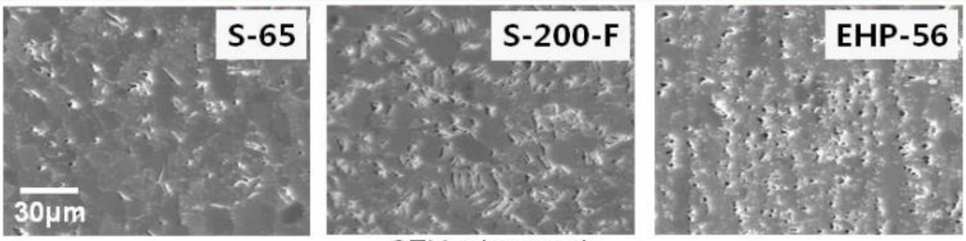


Korea Atomic Energy Research Institute

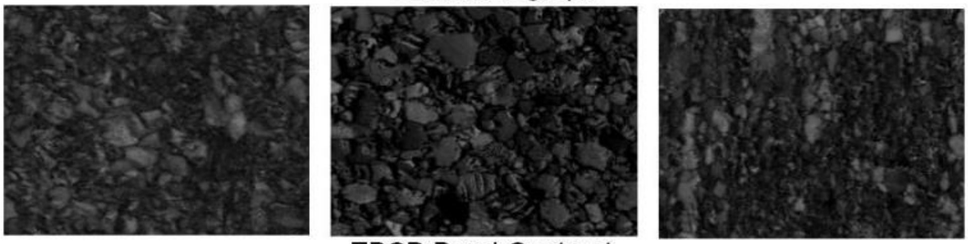
9

1. Out-of-pile test Microstructure

Out-of-pile test
Microstructures of Beryllium



SEM micrograph



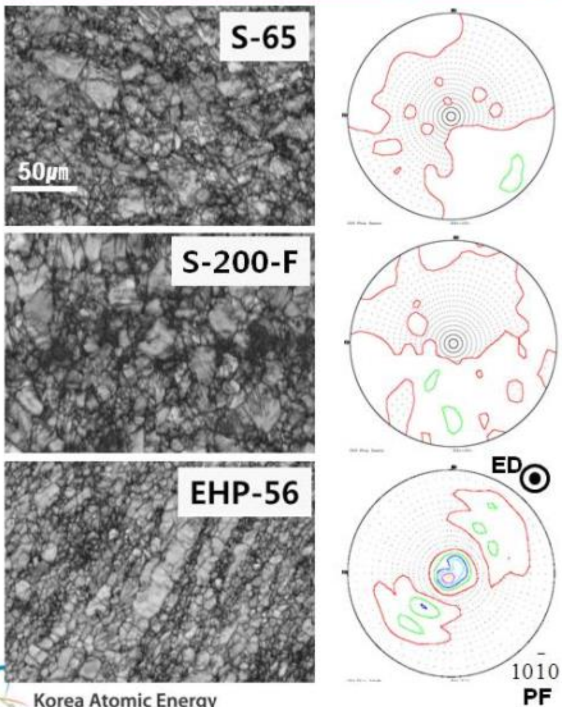
EBSD Band Contrast

Material	Be	BeO	Fe	C	Al	Si	Etc.
S-65, HIP	99.36	0.50	0.06	0.03	0.02	0.02	<0.01
S-200-F, VHP	98.50	1.20	0.10	0.10	0.05	0.03	<0.02
EHP-56, HE	98.30	1.30	0.20	0.12	0.03	0.04	<0.01

KAERI Korea Atomic Energy Research Institute

11

Out-of-pile test
Anisotropy of Beryllium



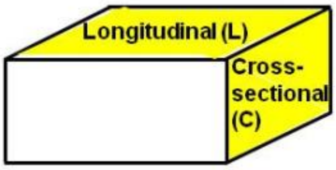
S-65 (HIP), S-200-F (VHP)
Isotropy

EHP-56 (Hot Extrusion)
Anisotropy
$<10\bar{1}0>$ **deformation texture**

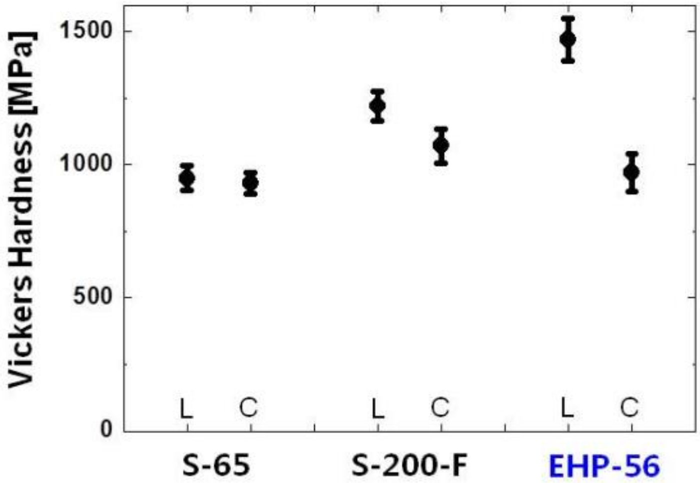
KAERI Korea Atomic Energy Research Institute

12

Out-of-pile test
Microhardness



Beryllium Block

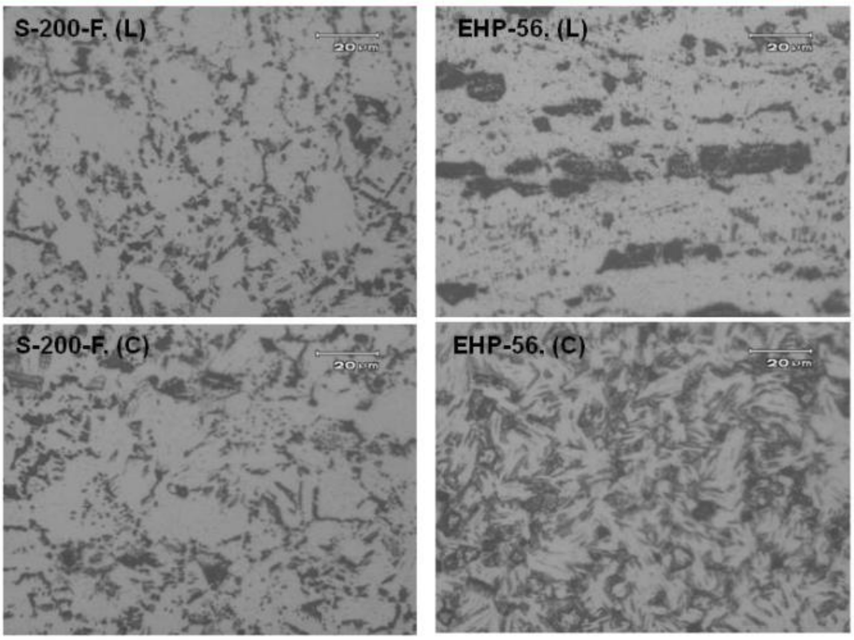


Hot extrusion : anisotropy in microhardness

Korea Atomic Energy Research Institute
KAERI

13

Out-of-pile test
Longitudinal & Cross-sectional Grain Shapes



Small grains but lower hardness in EHP-56, (c) ← $<10\bar{1}0>$ texture

Korea Atomic Energy Research Institute
KAERI

14

Out-of-pile test
Proton Irradiation Test

Out-of-pile test
Proton Irradiation Test of Beryllium

Korea Multi-Purpose Accelerator Complex, Gas ion irradiation machine

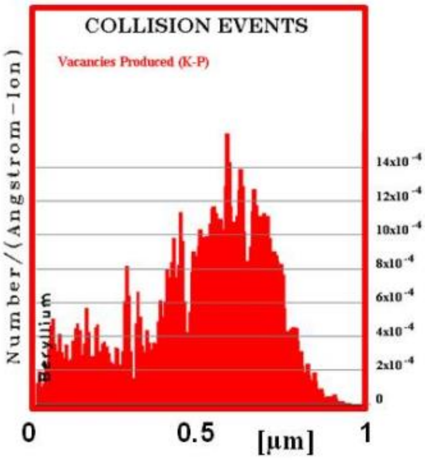
Acceleration Voltage : ~ 120 keV
Ions : H, He, N, Xe, etc
Beam current : 3 mA
Beam uniformity : ±20%
Implantation area : 20 cm diameter

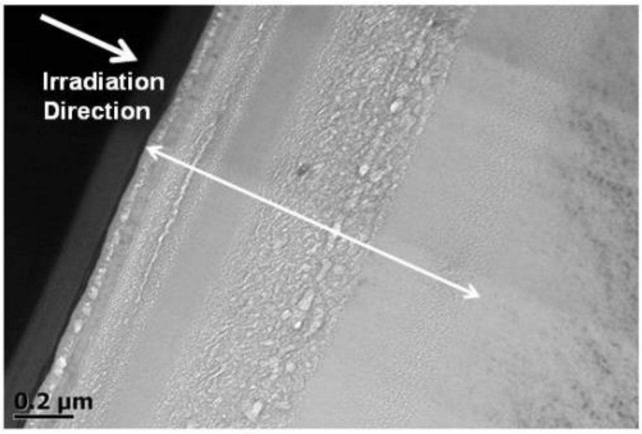
Korea Atomic Energy Research Institute (KAERI)

16

Out-of-pile test
Depth of Proton Damage Layer

Sample : 98.5% purity beryllium reflector material
Irradiation Condition : 120 keV, 4.0×10^{18}cm^{-2}



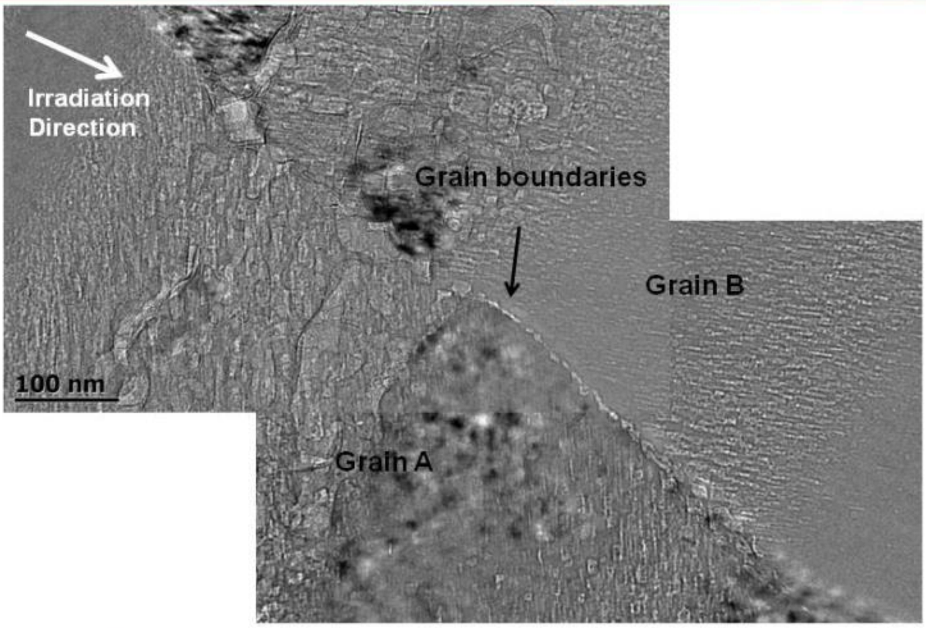


Damage layer : ~1 μm

Korea Atomic Energy Research Institute
KAERI

17

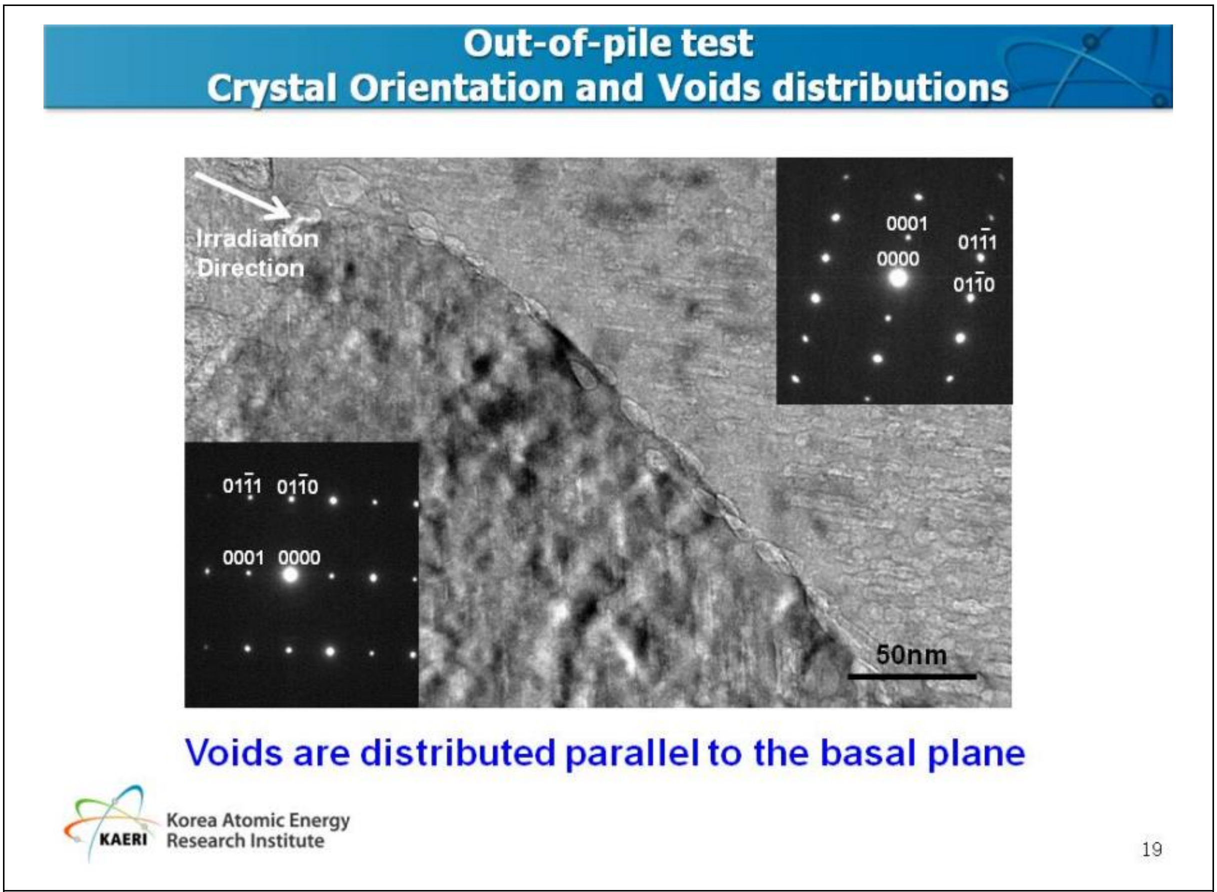
Out-of-pile test
Proton Radiation Damage on S-200-F

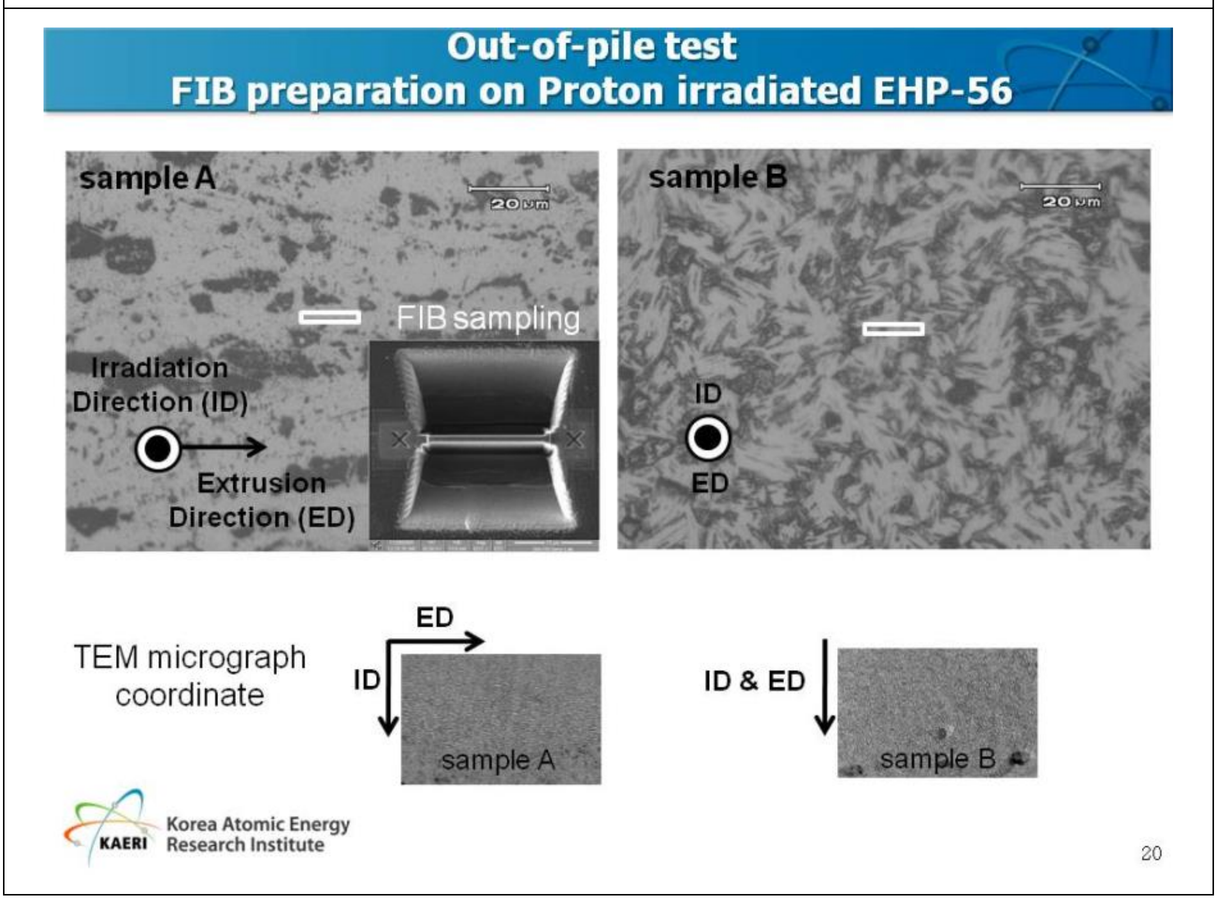


Directional voids are distributed regardless of irradiation direction

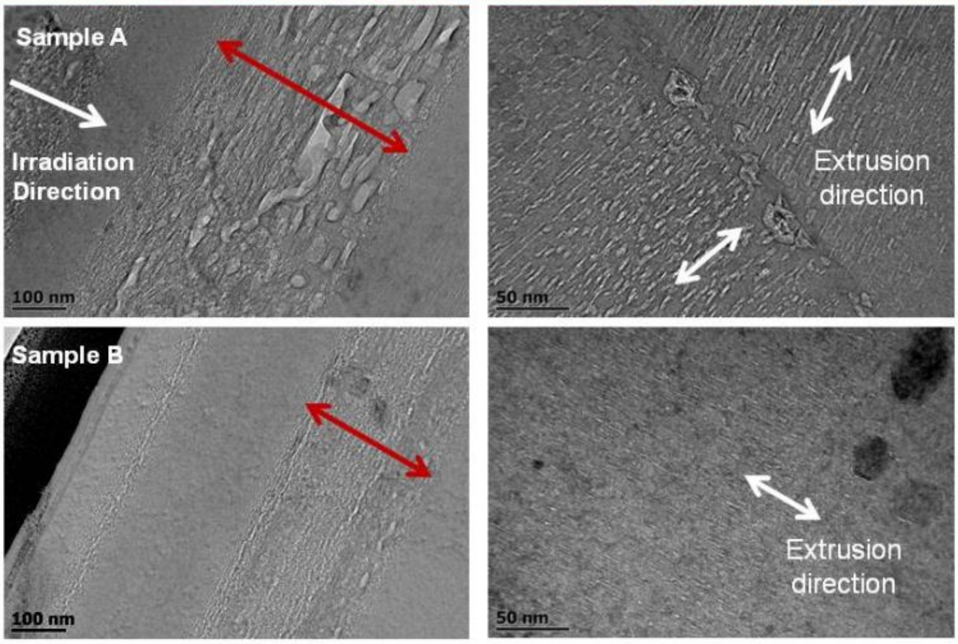
Korea Atomic Energy Research Institute
KAERI

18


Out-of-pile test
Crystal Orientation and Voids distributions
Irradiation Direction
0001
0000
$01\bar{1}1$
$01\bar{1}0$
$01\bar{1}1$ $01\bar{1}0$
0001 0000
50nm
Voids are distributed parallel to the basal plane
Korea Atomic Energy Research Institute
KAERI
19


Out-of-pile test
FIB preparation on Proton irradiated EHP-56
sample A
20 μm
FIB sampling
Irradiation Direction (ID)
Extrusion Direction (ED)
sample B
20 μm
ID
ED
TEM micrograph coordinate
ED
ID
sample A
ID & ED
sample B
Korea Atomic Energy Research Institute
KAERI
20

Out-of-pile test
Radiation Damage in EHP-56 (Anisotropy)



- More voids distribution along ED (// Basal plane)
- ED ⊥ Proton irradiation ➔ 1.5 times more dimensional change

KAERI Korea Atomic Energy Research Institute

In-pile test

In-pile test using HANARO

Research Reactor Materials

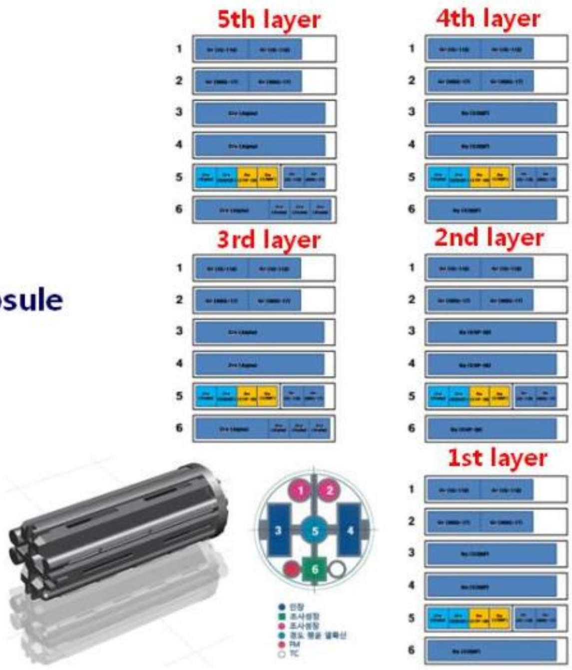
Materials	Test item	JRTR	KJRR
Graphite (IG110, NBG17)	Dimensional Change Thermal Diffusivity Hardness	Thermal column	2nd reflector Thermal column
Beryllium (S200F, EHP-56)	Tensile Properties Irradiation Growth Thermal Diffusivity Density, Hardness	Primary reflector	Primary reflector
Zircaloy-4	Tensile Properties Irradiation Growth Thermal Diffusivity Density Hardness	Heavy water vessel CAR Guide tube Beam tube	In core materials Structural components

Korea Atomic Energy Research Institute

23

Preparation of In-pile samples

- Preparation of test samples
  - Graphite
  - Beryllium
  - Zircaloy-4
- Design of irradiation test capsule
  - Tensile test
  - Irradiation growth
  - Hardness, microstructure
  - Thermal diffusivity and so on



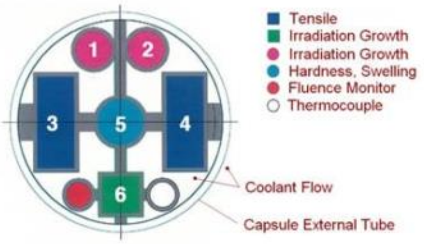
Design of irradiation capsule

Korea Atomic Energy Research Institute

24

Low temperature irradiation capsule

1. Research reactors operate at low temperatures. The reflector materials are required to be irradiated usually lower than 100℃(HANARO <50℃)
2. Standard capsules is operating at 250-400℃ in HANARO.
3. Low temperature irradiation capsule was developed and used for this purpose.
4. The main concept is the coolant to contact the specimen directly. So, coolant comes into the capsule and flows along the specimen

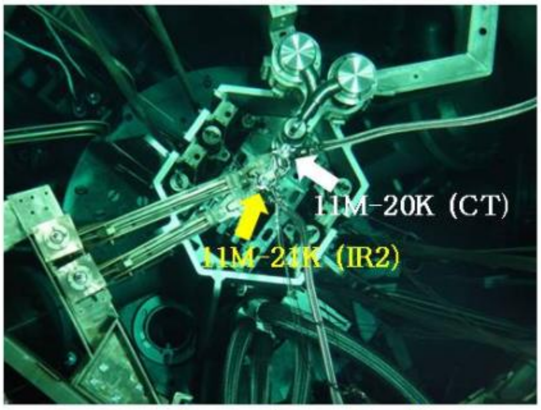


(L870 / Dia. 56mm)

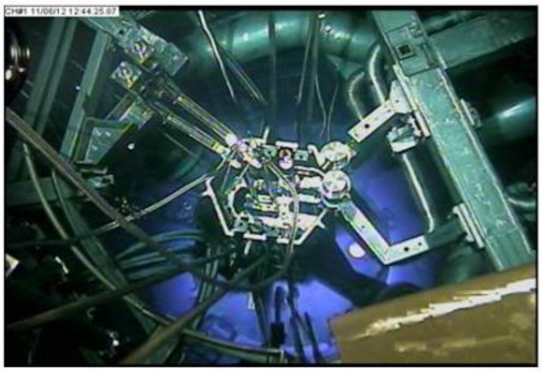
Korea Atomic Energy Research Institute

Irradiation test in HANARO

- Schematic of irradiation Capsule



Setting of capsules to irradiation holes in HANARO



Irradiation tests

Korea Atomic Energy Research Institute

26

Current status of in-pile test

1st capsule (11M-20K)

- Finished irradiation test (4 cycles in HANARO)
- Maximum fluence: ~2X10^{21} n/cm^2 (E>0.18MeV)
- Post Irradiation Examination

2nd capsule (11M-21K)

- Neutron irradiation
- Target : 8 cycles in HANARO
- Expected maximum fluence: ~4X10^{21} n/cm^2 (E>0.18MeV)

Korea Atomic Energy Research Institute KAERI

27

Summary

Beryllium reflector

- JRTR
- KJRR

Out-of-pile tests

- Proton radiation performance
- Microhardness, tensile test, microstructure

In-pile tests

- Irradiation tests at research reactor environment (<70^{o}C)
- 1st capsule : Post Irradiation Examination
- 2nd capsule : being irradiated in HANARO(will be finished in the end of this year)

Korea Atomic Energy Research Institute KAERI

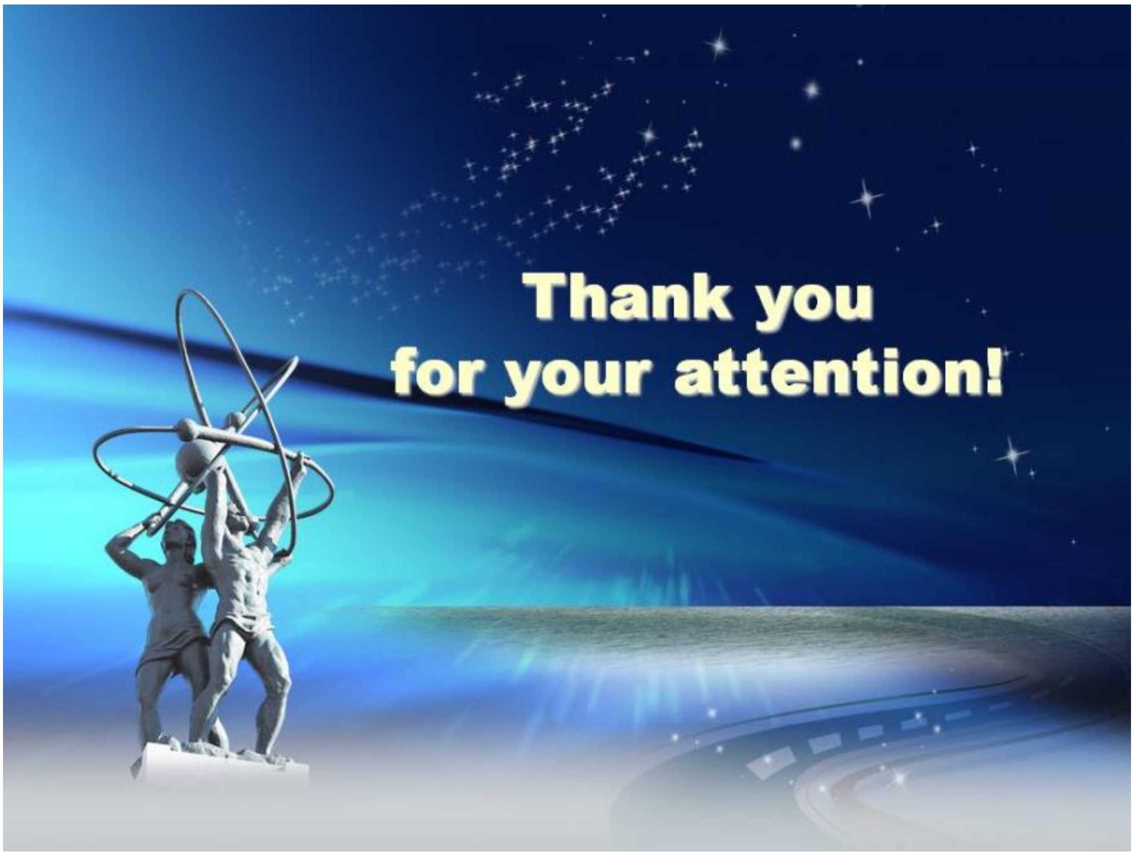
28

Acknowledgements

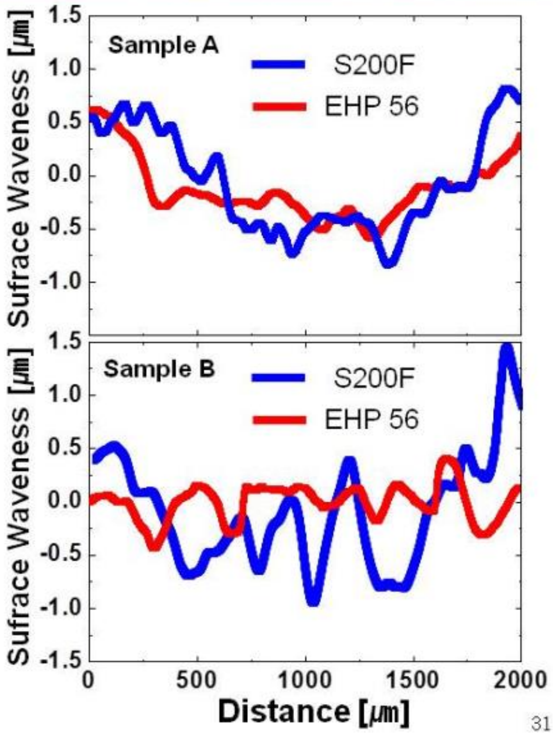
The beryllium samples in this work were supported by the Ulba Metallurgical Plant (Kazakhstan) and Materion (USA). We would like to express deep thanks to them.

KAERI Korea Atomic Energy Research Institute

29



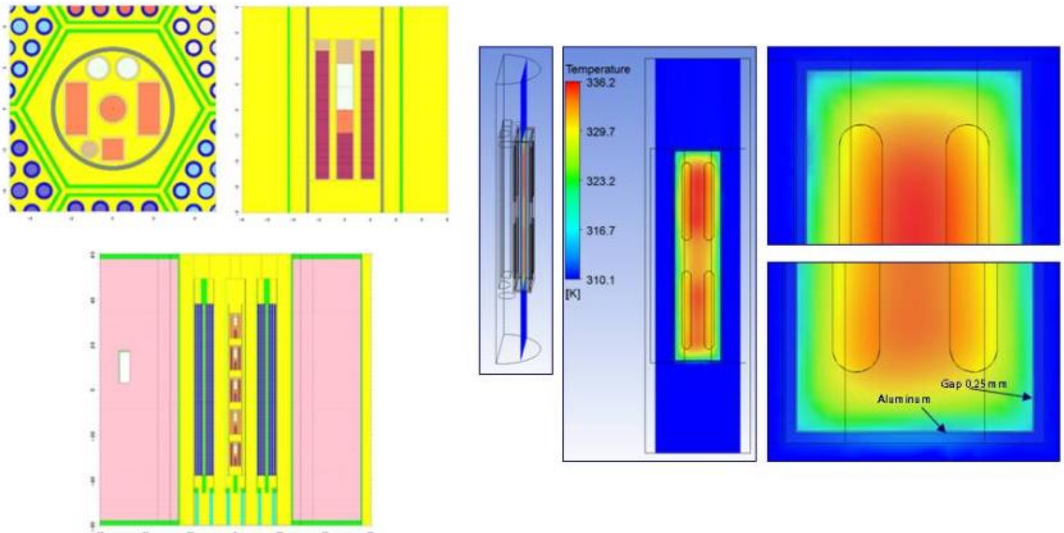
Out-of-pile test
Surface Waveness after Proton Irradiation



Korea Atomic Energy Research Institute
KAERI

31

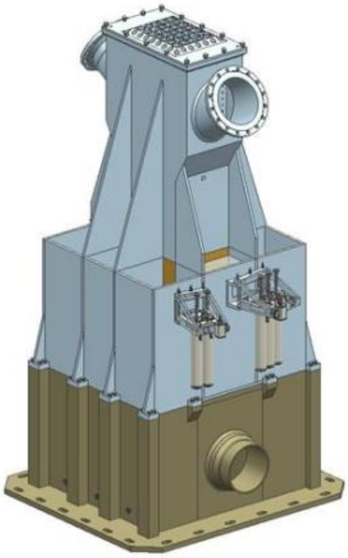
Estimation of irradiation temperature



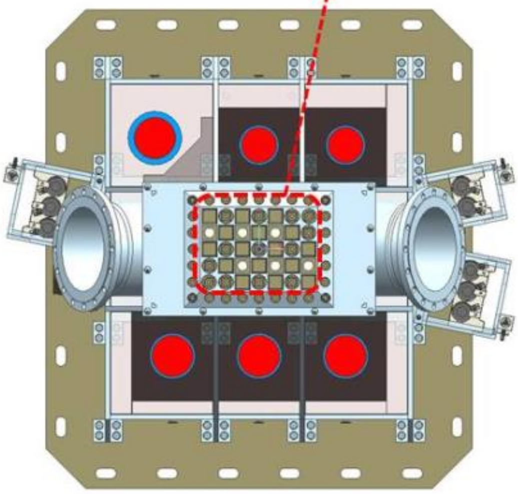
Korea Atomic Energy Research Institute
KAERI

32

Reflector in KJRR



Overview of KJRR

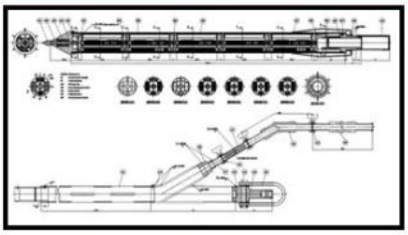


Core part

Korea Atomic Energy Research Institute

33

Design and fabrication of capsule



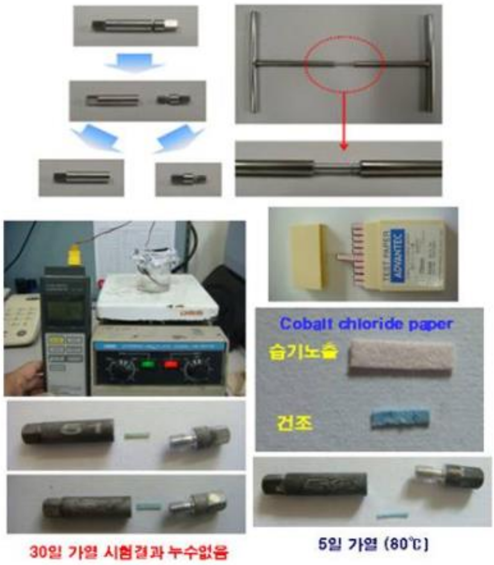
Design of capsule

Procedure of capsule fabrication

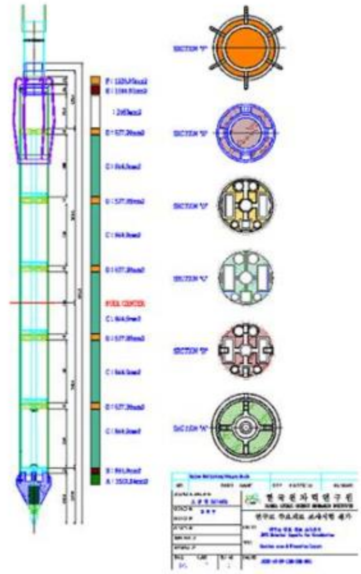
Korea Atomic Energy Research Institute

34

Safety test of capsule before irradiation



Design and fabrication of F/M

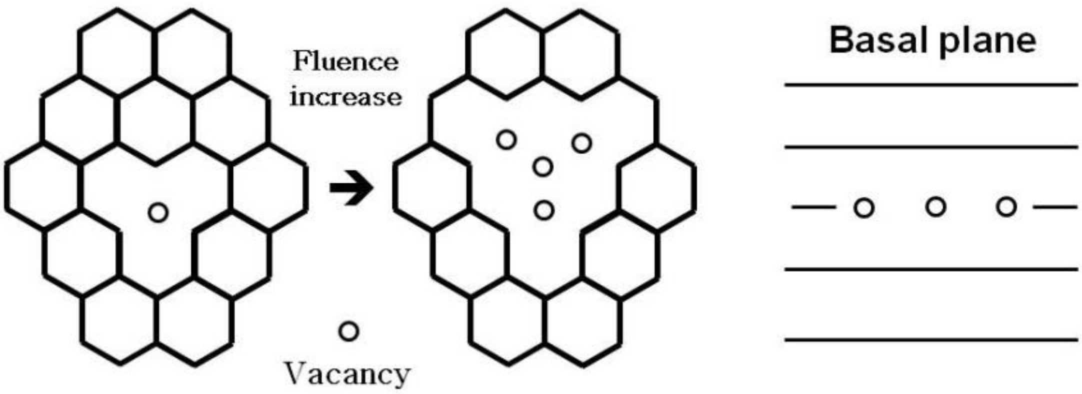


Soundness test of capsule

Korea Atomic Energy Research Institute
KAERI

35

Out-of-pile test
Radiation Damage in Hexagonal Structure



- Voids distribution along Basal plane
- Dimensional change along the normal direction of Basal plane

Korea Atomic Energy Research Institute
KAERI

36

3.7 Recent Activities in the MTR Field for Beryllium Reflectors

[Abstract]

Recent Activities in the MTR Field For Beryllium Reflectors

Edgar E. Vidal[1] and Christopher K. Dorn[2]

[1]Materion Brush Beryllium & Composites, 14710 W. Portage River So. Rd., Elmore, Ohio 43416 U.S.A.
[2]Materion Corporation, 6070 Parkland Blvd. Mayfield Heights, Ohio 44124-4191 U.S.A.

The nuclear properties of beryllium, combined with its low density, are attractive characteristics for neutron reflectors and moderators in the design of reactors. Beryllium's high scattering cross-section makes it effective in slowing neutron speed to a level required for efficient reactor operations under some required conditions. This ability classifies beryllium as one of the few good solid moderators available. As a reflector, beryllium acts to scatter leaked neutrons back into the reactor core. Neutrons are conserved because of beryllium's low thermal neutron capture cross-section. A review of the current status of beryllium utilization in MTRs around the world is presented. Materion has been producing beryllium for reflectors for more than 60 years and has continuously been updating its manufacturing technologies and capabilities to deliver a high quality product at the lowest cost possible.

Recent materials procurement and interests have come from reactors like JRTR, RJH and BR2. Because of the tsunami that lead to the Fukushima incident in 2011, the schedules at JAEA have been affected dramatically. Despite this upset, JAEA continues to be committed to the nuclear test reactor efforts and the use of beryllium as reflector material. Belgium’s nuclear research center SCK·CEN has now planned the refurbishment of the beryllium reflectors of BR2 which is one of the most powerful research reactors in the world. Progress has been made by KAERI in the design and construction of the Jordan Research and Training Reactor (JRTR) which will be an in-core beryllium reflected 5 MW reactor capable of being upgraded to 10 MW. Commissioning of the JRTR is expected to occur in 2015 and will utilize beryllium produced from Materion. KAERI is also designing and building a new reactor called the KJRR (Ki-Jang Research Reactor) which is a 20 MW system that uses beryllium and aluminum as the in-core reflector and is expected to be commissioned in 2017. KAERI has been irradiating samples of beryllium from Materion and Ulba Metallurgical in the Hanaro reactor. Materion continues to support the mayor players in the test reactor world by providing quality beryllium and engineering services.

MATERION

Beryllium Recycling Meeting:

Recent Activities in the MTR Field for Beryllium Reflectors

Christopher Dorn
Edgar Vidal

The 8th Specialist Meeting on Recycling of Irradiated Beryllium

Brush Beryllium & Composites

Materion Brush - Elmore, Ohio Facility

- The U.S.A. Government entered into a partnership with Materion Corporation initiating construction of the beryllium "Pebbles Plant" in Elmore, Ohio.
- Production capacity of high-purity beryllium metal to ensure world demand.
- The plant stands 73 feet tall, contains three levels, has a 51,045 sq. ft. footprint, and contains 124,358 total square feet of floor space.

MATERION

Brush Beryllium & Composites

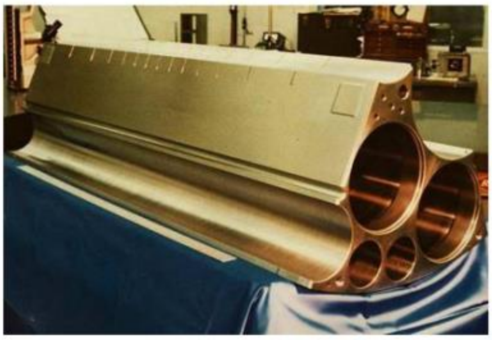
Current Research Reactor Programs

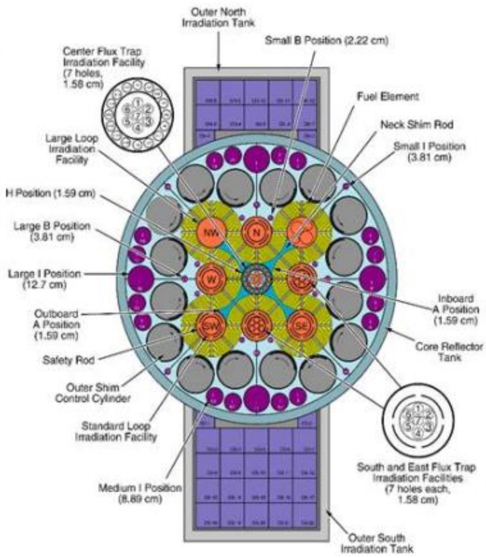
- ATR – Advanced Test Reactor (Idaho, U.S.A.)
- HFIR – High Flux Isotope Reactor (Tennessee, U.S.A.)
- MURR – Missouri University Research Reactor (U.S.A.)
- JMTR – Japan Materials Testing Reactor (Japan)
- JRR-3 – Japan Research Reactor (Japan)
- HFR – High Flux Reactor (Netherlands)
- BR2 – SCK-CEN Test Reactor (Belgium)
- SAFARI-1 – NECSA Test Reactor (South Africa)
- OPAL – ANSTO Test Reactor (Australia)
- IEA-R1 – IPEN Test Reactor (Brazil)

MATERION

Brush Beryllium & Composites

ATR – No new developments

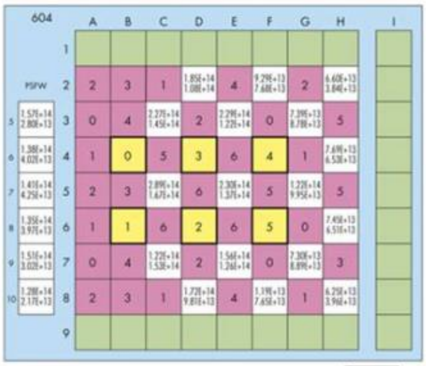




MATERION

Brush Beryllium & Composites

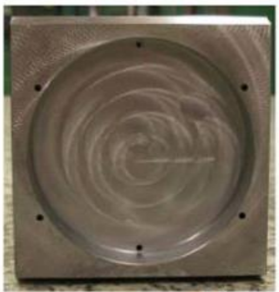
HFR Machined S-200F Beryllium Reflector Assemblies

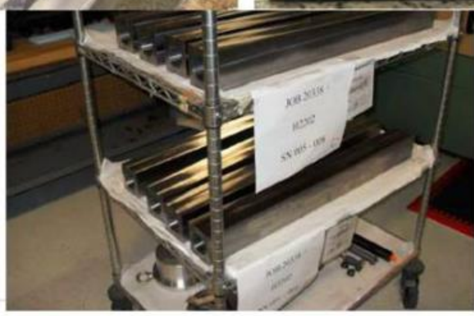


MATERION

Brush Beryllium & Composites

SAFARI-1 Machined S-65-H Beryllium Reflector Elements

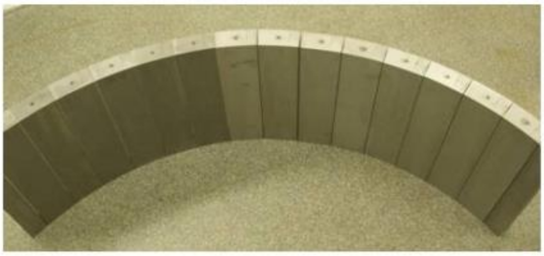




MATERION

Brush Beryllium & Composites

OPAL Machined S-200F Beryllium Filters

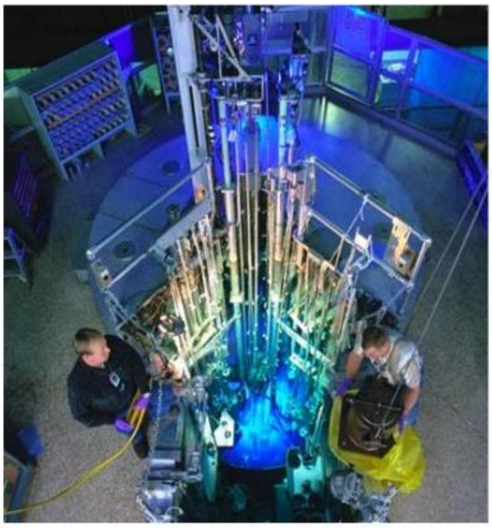


MATERION

Brush Beryllium & Composites

University of Missouri Research Reactor -

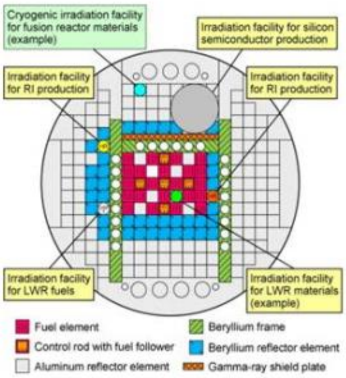
- Power Level: 10MWth
- Power Density, Core: 303 kW/liter, with peaking factor greater than 3
- Primary Coolant Operating Temperature, Outlet (T_h): 136° F
- Primary Coolant Operating Pressure: 80 psia
- Core, Fuel Type: Open pool PWR, HEU aluminide fuel
- LEU Conversion Feasibility Study: Currently underway
- Reflector: Beryllium and graphite
- Flux Trap, Peak: 6 x 1014 n/(cm2sec)
- License Status: 20-year renewal request submitted August 2006 (to extend to October 2026)

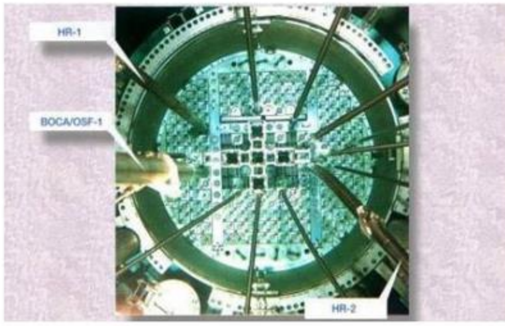


MATERION

Brush Beryllium & Composites

Japan Materials Test Reactor (JMTR) – 2014?



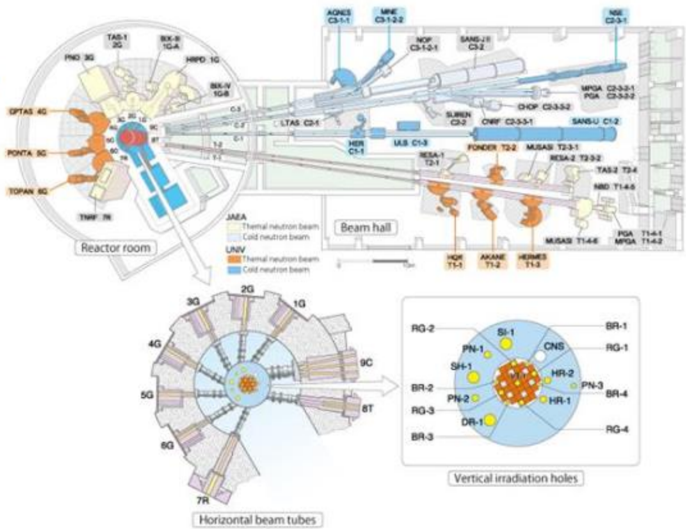


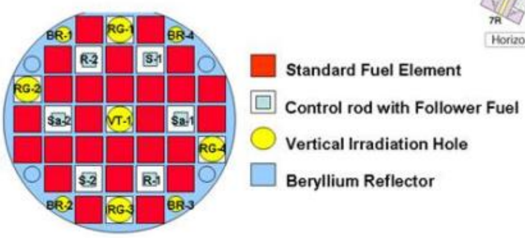
- A light water cooled tank type reactor with 50MW thermal power.
- From its first criticality in March 1968, the JMTR has been utilized for fuel/material irradiation examinations of LWRs, HTGR, fusion reactor as well as for RI productions under its transportation advantage that the JMTR and hot laboratory is connected by a canal.

MATERION

Brush Beryllium & Composites

JRR-3 - JAEA





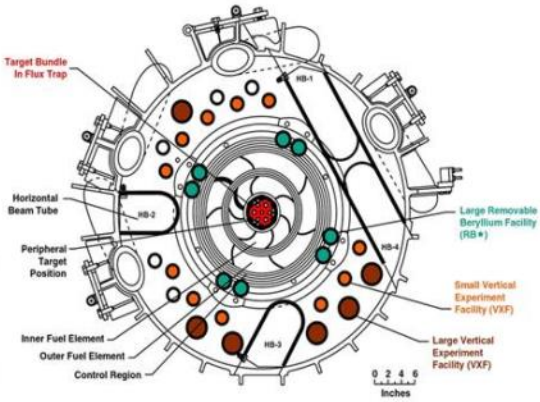
Courtesy of JAEA

MATERION

Brush Beryllium & Composites

High Flux Isotope Reactor (HFIR)

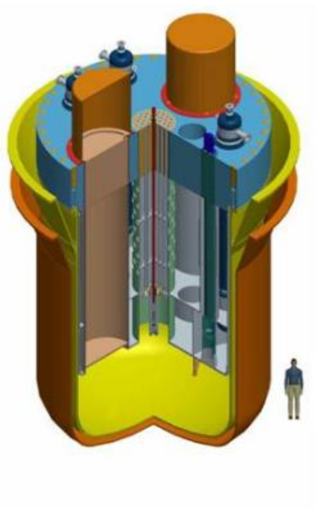
- HFIR is a beryllium-reflected, light-water-cooled and -moderated, flux-trap type reactor
- Uses highly enriched uranium-235 as the fuel. The image on the right is a cutaway of the reactor which shows the pressure vessel, its location in the reactor pool, and some of the experiment facilities.

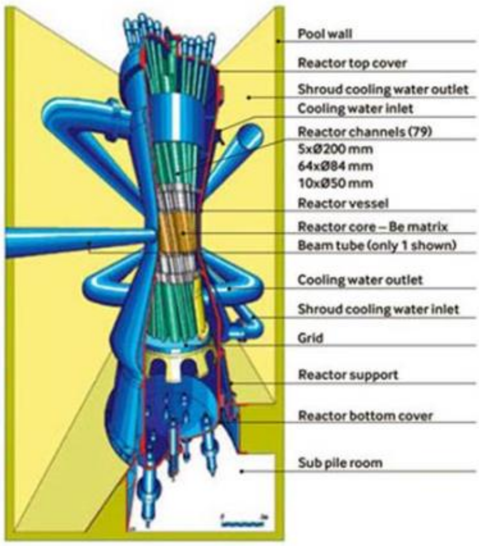


MATERION

Brush Beryllium & Composites

BR2 – SCK.CEN

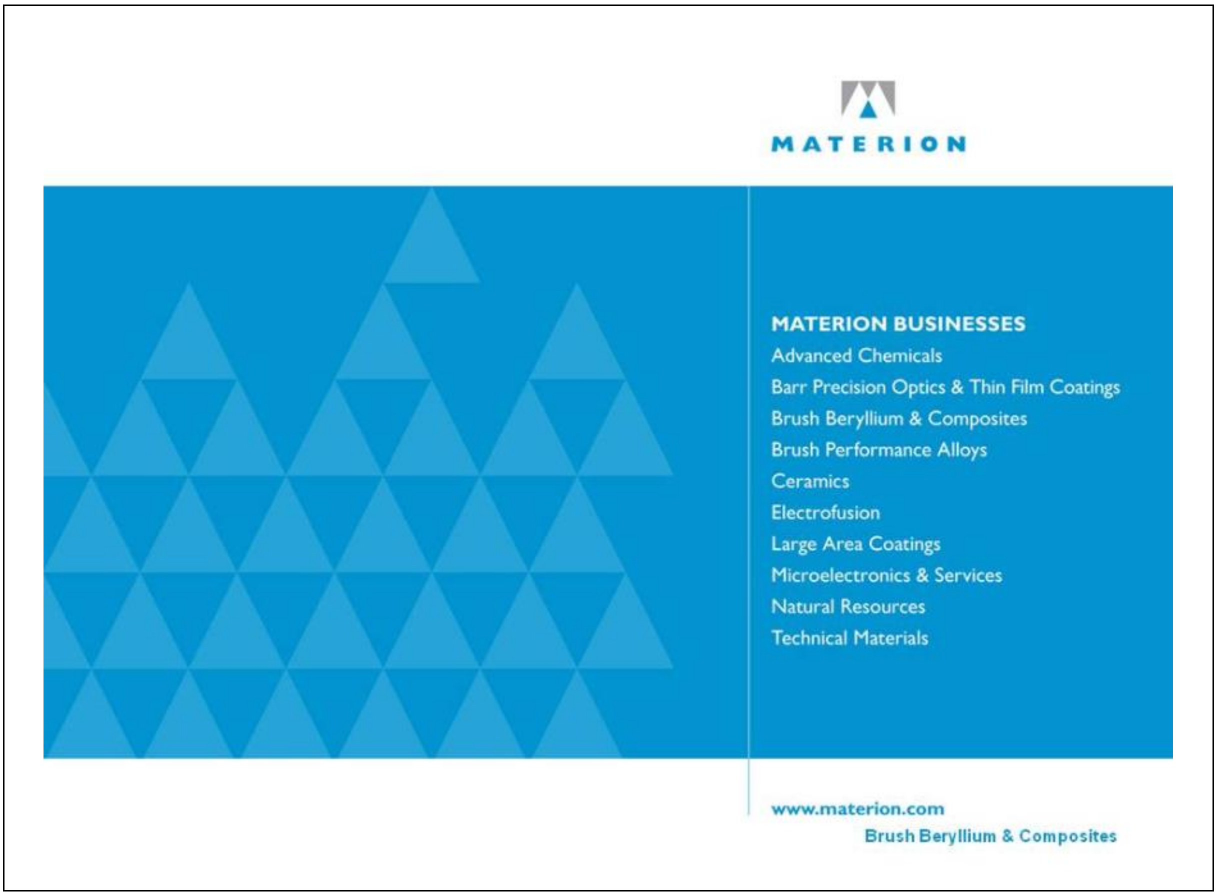




Courtesy of SCK.CEN

MATERION

Brush Beryllium & Composites


MATERION
MATERION BUSINESSES
Advanced Chemicals
Barr Precision Optics & Thin Film Coatings
Brush Beryllium & Composites
Brush Performance Alloys
Ceramics
Electrofusion
Large Area Coatings
Microelectronics & Services
Natural Resources
Technical Materials
www.materion.com
Brush Beryllium & Composites

3.8 Beryllium Research in NGK and New Proposal for MTR Reflector Development

[Abstract]

Beryllium Research in NGK and New Proposal for MTR Reflector Development

Keigo NOJIRI[1] **and Ryohei FUKATSU**[1]

[1] *NGK Insulators, ltd., Nagoya, Japan*

NGK Insulators is one of the world leading companies in the high performance ceramic industry. The new metal division in NGK is specialized in the high performance metal products as the result of expanding its business field in NGK. The division’s main products are various beryllium containing alloys and special parts made from the alloys. The pure beryllium applications are also important for the division. Beryllium metal is used various industrial and R&D scenes due to its unique and extremely excellent properties. In the nuclear field, NGK has two main applications with beryllium, the neutron multiplier for the fusion and the neutron reflector for the material test reactor.

The neutron multiplier is necessary in the concept of ITER project. The beryllium pebble multiplier is the reference material of the project. The ITER participating countries are evaluating the beryllium pebble, which is filled up in the test blanket module. The ITER organization has announced that the first plasma will be in 2020. It means that the beryllium pebble must be available before for preparing the test blanket module. NGK had developed the beryllium pebble fabrication technology as the rotating electrode method with JAEA. The pebble fabricated by this method has excellent sphere shape and narrow diameter distribution. NGK will continue developing to improve the productivity for preparing the big volume production.

The neutron reflector of NGK is used for the JMTR from the 1st generation installed in 1966 to the 7th generation which is ready to use actually. Some studies are going on for having the longer life of the reflector. NGK started a study with JAEA in a different view for preparing the longer time utilization of the reflector. Longer irradiation to the beryllium reflector releases more tritium into the cooling water. NGK tries to cover the reflector surface which touches the cooling water with aluminium layer to block the recoiled tritium in this layer. Some trials of the coating of aluminium by hot spraying are carried out. The evaluation including release of tritium will be planned.

The 8th Specialist Meeting on Recycling of Irradiated Beryllium

October 28, 2013, S.C. de Bariloche, Río Negro, Argentina

Beryllium Research in NGK and New Proposal for MTR Reflector Development

Ryohei Fukatsu, Keigo Nojiri

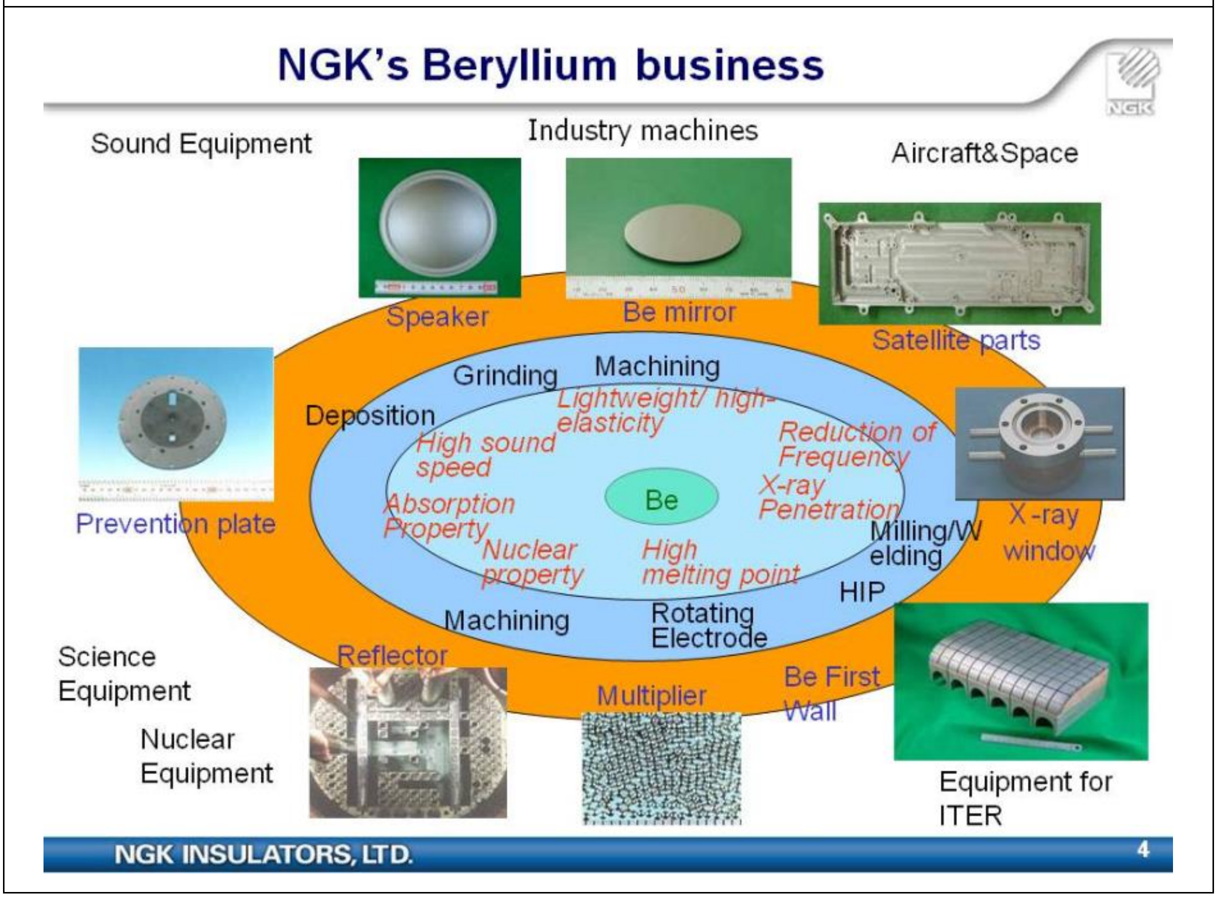
NGK Insulators, ltd
Aichi Japan

NGK INSULATORS, LTD. 1

Contents

NGK INSULATORS, LTD. 2

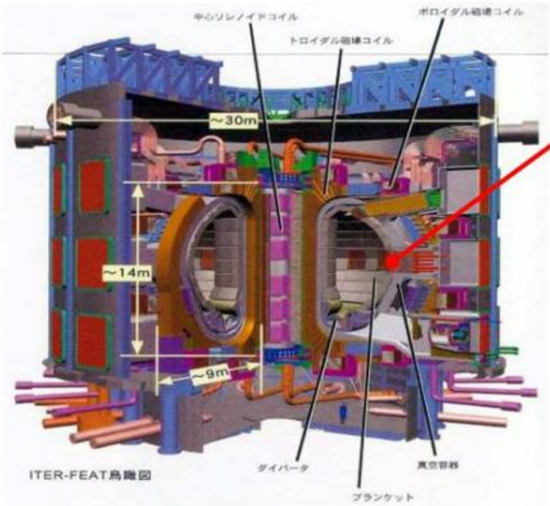

NGK Insulators, ltd
Company Name
NGK INSULATORS, LTD.
Date of Establishment
May 5, 1919
Paid-in Capital
69,849 Million Yen
Number of Employees
3,426 (non-consolidated)
13,159 (consolidated)
Consolidated Subsidiaries
54 companies
As of March 31, 2013
World Network
UK
Belgium
Poland
Germany
France
China
Japan
South Korea
Thailand
Indonesia
South Africa
Australia
Canada
USA
Mexico
Production Bases
Sales Offices
Main Products
Power Business
Ceramic Products Business
Electronics Business
NGK INSULATORS, LTD.
3


NGK's Beryllium business
Sound Equipment
Industry machines
Aircraft&Space
Speaker
Be mirror
Satellite parts
Grinding
Machining
Deposition
Lightweight/ high-elasticity
High sound speed
Reduction of Frequency
X-ray Penetration
Absorption Property
Be
Nuclear property
High melting point
Milling/Welding
HIP
Machining
Rotating Electrode
Prevention plate
X -ray window
Science Equipment
Nuclear Equipment
Reflector
Multiplier
Be First Wall
Equipment for ITER
NGK INSULATORS, LTD.
4

Beryllium Utilization in Nuclear Fields 1.Fusion Reactors

ITER will have the 1st plasma in 2020

➔ Test Blanket Module to prepare



TBM has;

- Li breeder
- Be Multiplier

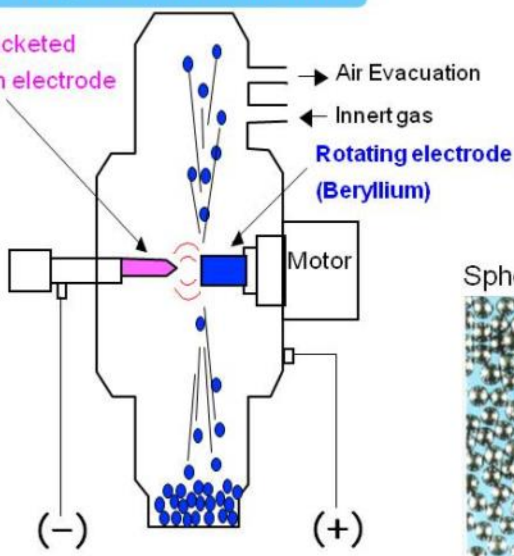
NGK's **BP1 pebble** is the reference material of the muliplier

NGK INSULATORS, LTD. 5

Beryllium Utilization in Nuclear Fields 1.Fusion Reactors

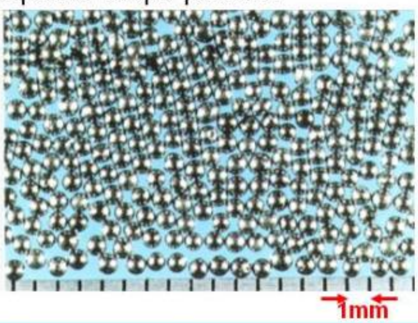
BP1 pebble

Rotating Electrode Method



Overview of Apparatus

Sphere shape pebbles

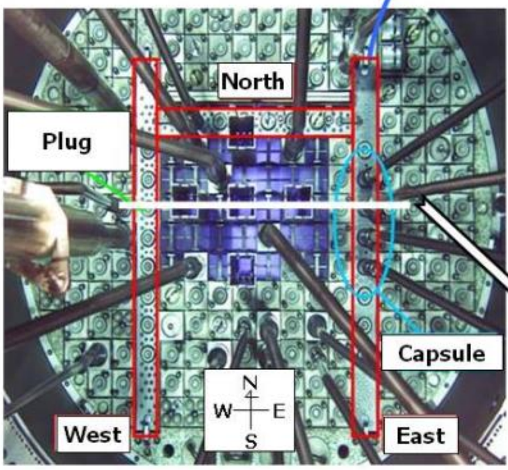


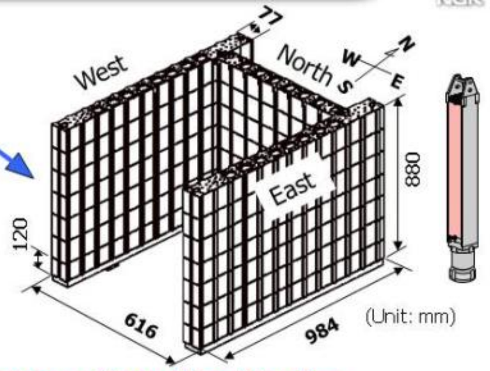
NGK INSULATORS, LTD. 6

Beryllium Utilization in Nuclear Fields 2. Reflector in MTR

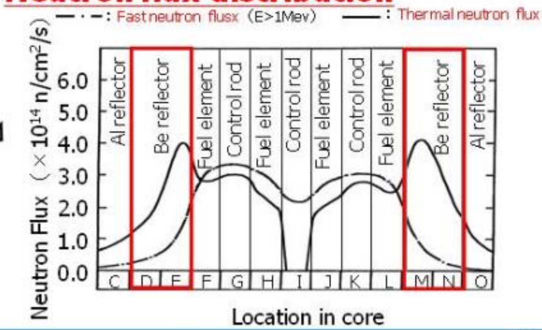
Be Reflector Frame

To enhance the neutron concentration in fuel area to irradiate the sample efficiently





Neutron flux distribution



Beryllium Utilization in Nuclear Fields 2. Reflector in MTR

Generation	Term	Cumulative power (MWd)	Neutron Fluence ($\times 10^{26} m^{-2}$)	Camber (mm)
1st	**1966-1974**	**~24,000**	**0.96**	**0.71**
2nd	**1975-1983**	**~28,000**	**1.12**	**0.84**
3rd	**1984-1987**	**~25,000**	**1.00**	**0.75**
4th	**1988-1995**	**~36,000**	**1.44**	**1.24**
5th	**1996-2002**	**~29,000**	**1.15**	**1.09**
6th	**2003-2007**	**~25,000**	**1.00**	**0.93**
7th	**Installed and waiting for the operation**			

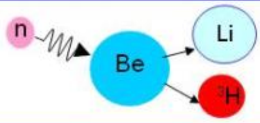
4th Generation - Design modification to improve lifetime

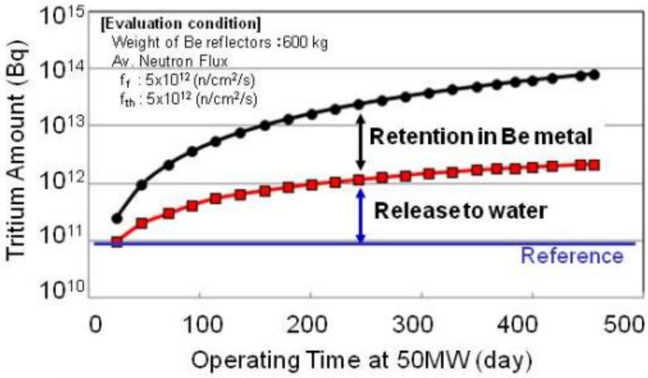
and 8th generation? ➡ Modification to study for easier management

Necessity of Tritium release reduction

Irradiation generates Tritium

$^{9}Be(n, \alpha)\ ^{6}He \rightarrow \beta$ decay
$\rightarrow\ ^{6}Li\ (n, \alpha)\ ^{3}H$





● : Tritium generation in total Be reflectors in JMTR

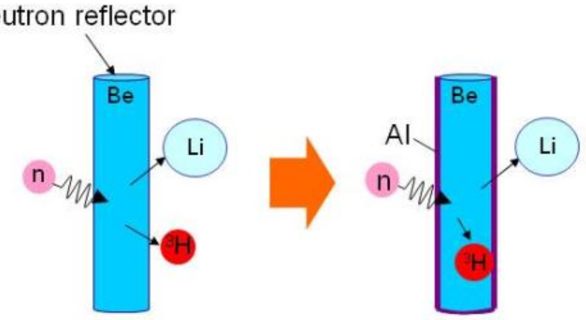
■ : Tritium amount in primary cooling water in JMTR

We need to reduce tritium release to cooling water.

NGK INSULATORS, LTD. 9

New Proposal for MTR: Reduce tritium release

Beryllium neutron reflector



How To Reduce ?

Coat the material on Beryllium surface

- Thickness > Recoiling distance
- Water proof
- Minimum thickness for the reflection performance

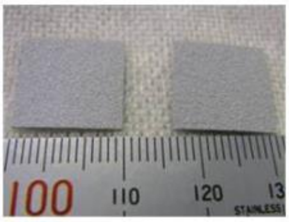
JAEA are planning to confirm this effects with us.

NGK INSULATORS, LTD. 10

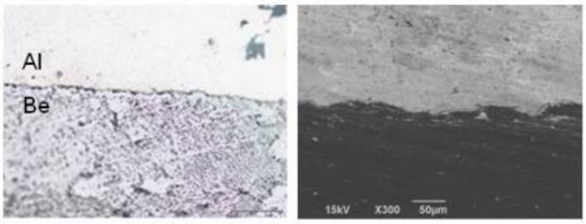
Results & Future Plan

1st STEP : Coat Aluminum on Beryllium surface

Supported by TOCALO



Aspect after spraying



Cross section (Left: Microscope, Right: SEM,BEI)

Good adhesion is confirmed

Future plan

2nd STEP : Neutron irradiation test

NGK INSULATORS, LTD. 11

Thank you for your attention

NGK INSULATORS, LTD. 12

3.9 Swelling and Thermal Effects on Beryllium on Reactor Assembly

[Abstract]

Swelling and Thermal Effects on Beryllium on Reactor Assembly

E. Fresquet[1], R. G. Cocco[1] and F. Francioni[2]

[1] Dept. of Mechanical Design: Nuclear Components, INVAP S.E,
S.C Bariloche, Río Negro, Argentina
[2] Dept. of Thermohidraulic: Nuclear Components, INVAP S.E,
S.C Bariloche, Río Negro, Argentina
rcocco@invap.com.ar

Beryllium is used in numerous research reactors to moderate neutron energy and to reflect neutrons back into the core, thus intensifying the thermal neutron flux. However, Beryllium is degraded by radiation damage, as a result of both displacement and transmutation. Transmutation produces Helium, which results in high levels of gas and swelling. The most important effects caused by swelling in Beryllium bars are distortion, strengthening and cracking. These several effects are increased by the effects of the temperature at power operation conditions. Because of this, the study of the Be reflector structural integrity by numerical methods is an essential tool to ensure an accurate behavior throughout its lifespan. It is the purpose of this paper to perform a structural integrity analysis on a hypothetical Beryllium reflector in order to study the distortion and state of stress associated to the variation in its geometry using the finite element method. Two sources of deformation were taken in account, swelling due to transmutation reaction and thermal expansion. The results obtained shows the dependence between the geometry, type of constraint and the necessity to consider a cooling system to reduce the thermal effects at power operation in order to ensure an limited distortion allowing a longer time operation. These results contribute to a better understanding of distortion behavior and the state of stress generated, which can be a useful tool during the design phase.

REFERENCES

[1] R. Cocco and P. Bejarano, “Beryllium Reflectors for Research Reactors”, INVAP SE, San Carlos de Bariloche, Río Negro, Argentina.
[2] R. Cocco and P. Bejarano, “reflector assemblies behavior in a MTR core according to FEM analysis”, INVAP SE, San Carlos de Bariloche, Río Negro, Argentina.
[3] R. Cocco, “Distortion of Beryllium Reflectors induced by Swelling”, INVAP SE, San Carlos de Bariloche, Río Negro, Argentina.

This is a blank page.

Swelling and Thermal Effects on Beryllium on Reactor Assembly .

E. Fresquet, R. Cocco, F. Francioni

INVAP S.E. – Argentina

ISMTR

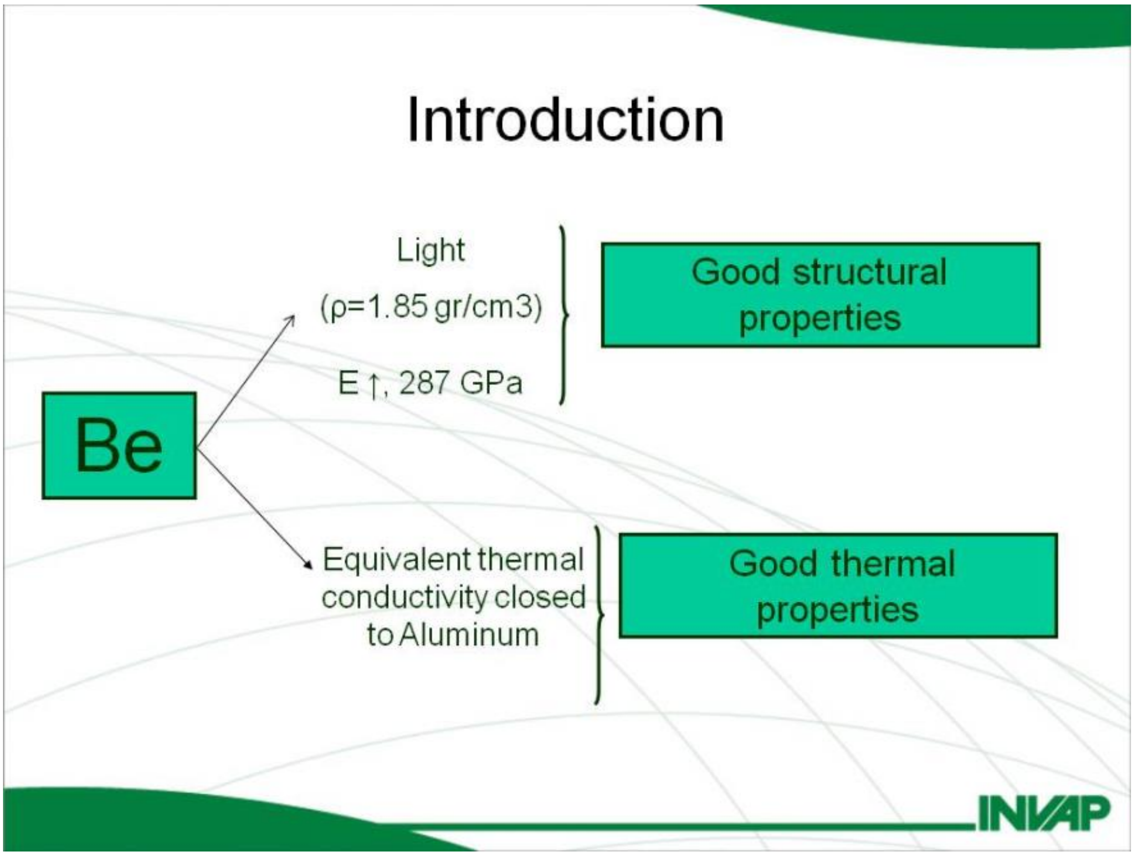
October - 2013

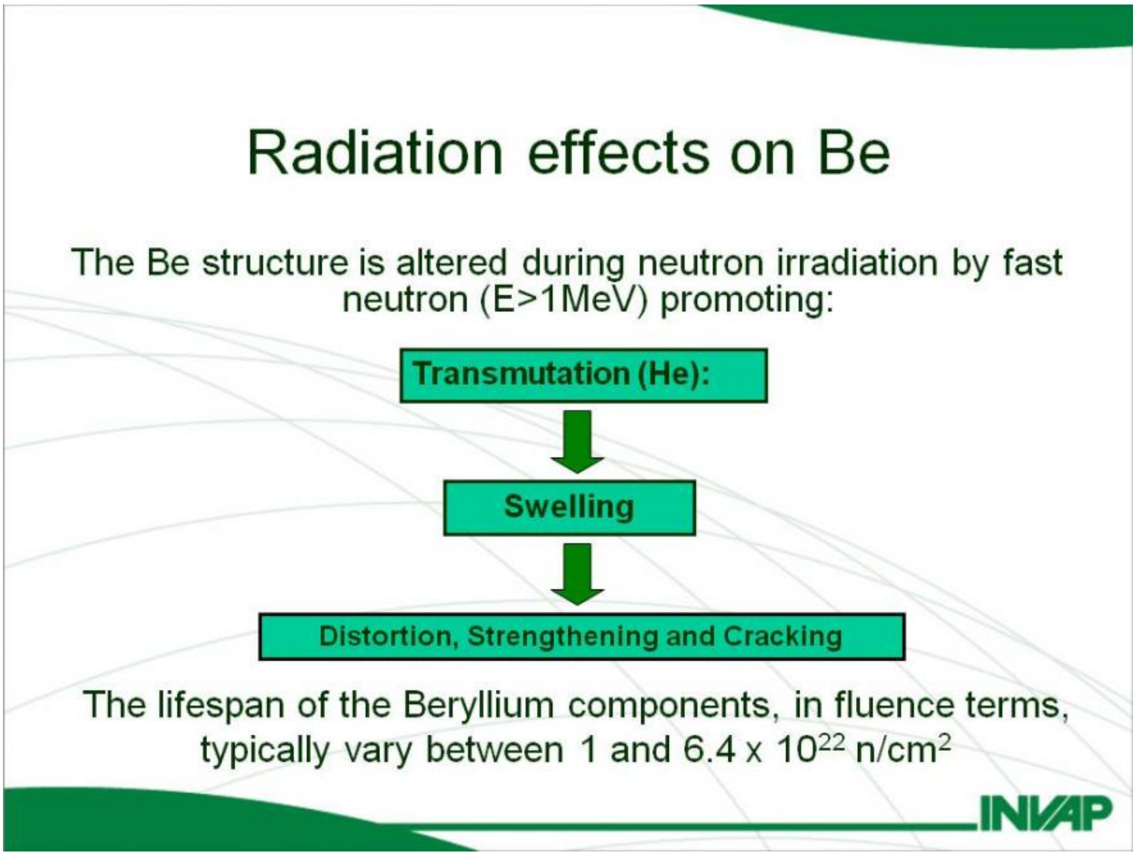
INVAP

Objetive

Analyze on a hypothetical Beryllium reflector bar, the distortions and state of stress associated to the variation in its geometry using finite element analysis (FEA)

INVAP

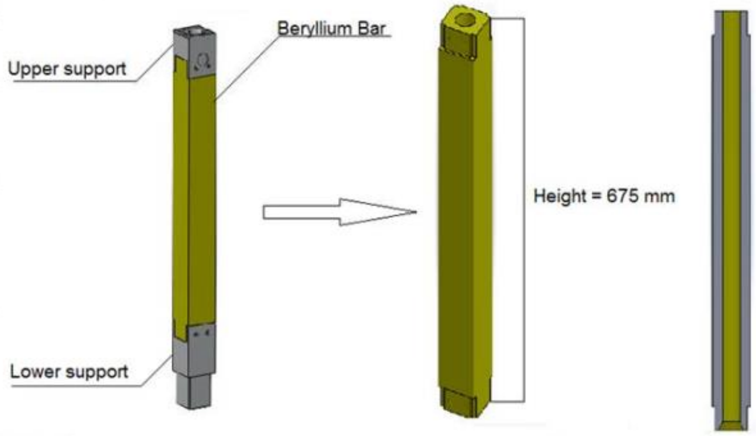

Introduction
Be
Light
(ρ=1.85 gr/cm3)
E ↑, 287 GPa
Good structural properties
Equivalent thermal conductivity closed to Aluminum
Good thermal properties
INVAP


Radiation effects on Be
The Be structure is altered during neutron irradiation by fast neutron (E>1MeV) promoting:
Transmutation (He):
Swelling
Distortion, Strengthening and Cracking
The lifespan of the Beryllium components, in fluence terms, typically vary between 1 and 6.4 x 10²² n/cm²
INVAP

3D Model

Geometry

The geometry of the beryllium considered in this case consist of a solid block 79,5 x 79,5 mm with a 40 mm diameter hole for cooling purpose.



INVAP

Beryllium Properties

Mechanical

Depends of the fabrications process

Yield Strength [Mpa]	*241*
Tensile Strength [Mpa]	*324*
Elastic Modulus [GPa]	*303*
Poisson Coefficient	*0,18*
Elongation at Failure [%]	*2*
S–200F alloy. Typical values extracted from Brush Wellman catalog	

Thermal

High Thermal Conductivity

(1,8E-05 C^-1)

INVAP

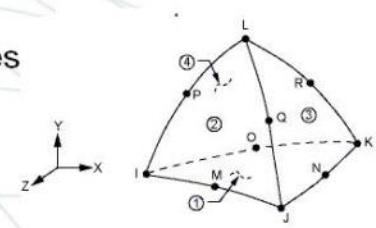
Hypothesis

- Linear Elastic (small displacement theory)
- Isotropic Material Behavior.
- Stress strengthening was not taken into account for this analysis.

INVAP

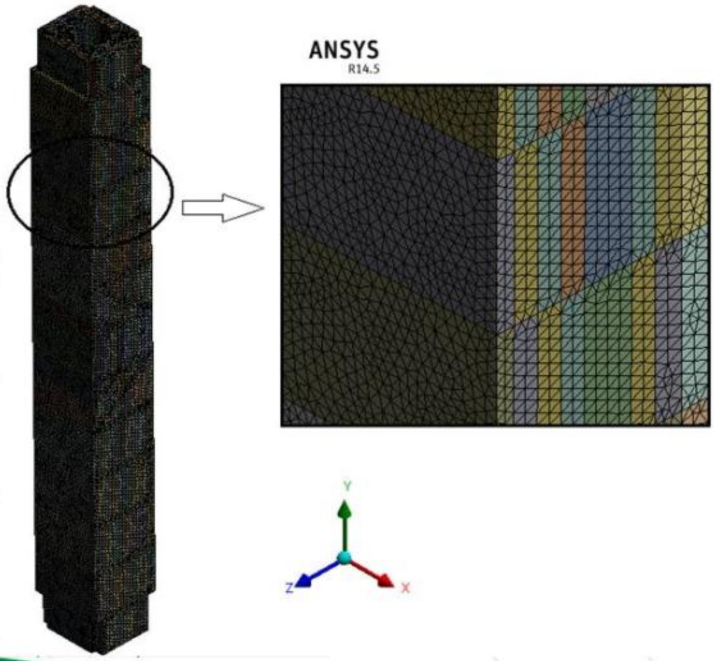
Finite Element Model

- All calculation were performed using commercial software ANSYS 14.5.
- Mesh Density: Elements: 581,962
  Nodes: 836,503
- Element Type:
  3D Solid tetrahedron with 10 nodes and 3 DOF per node.



INVAP

Finite Element Model



INVAP

Load Cases

- Step1: Variation of fast neutron fluence (dose).

- Step 2: Thermal exposure during power operation of the core reactor.

INVAP

Load Cases

- The swelling was estimated through a linear approximation fitted from bibliographic data:

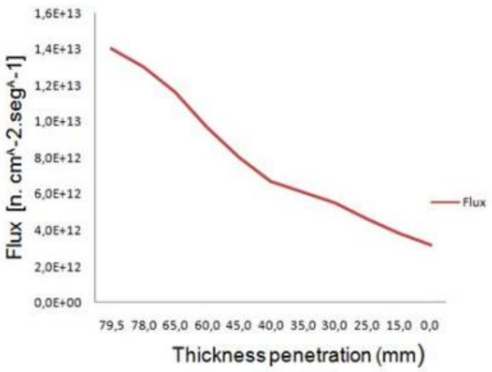
$$\frac{\Delta V}{V}[\%] \cong 3\frac{\Delta L}{L}[\%] = 2,0x10^{-23}.(\varphi.t)$$

Where, V: volume; L: length, Φ: fluence [n.cm^{-2}]

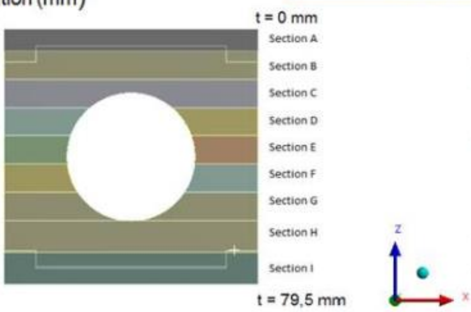
- The behavior was evaluated for fluence between $4,41x10^{20}$ and $1.16x10^{22}$ n.cm^{-2}

INVAP

Load Cases



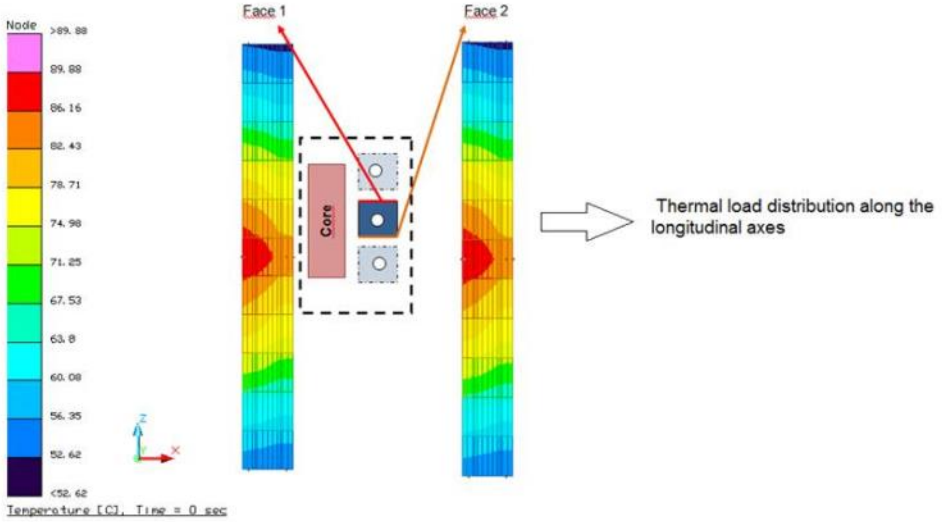
	T = 1 year	T = 5 years	T = 10 years	T = 23 years	
FLUENCE	4,41914E+20	2,20957E+21	4,41914E+21	1,0164E+22	
ΔT (°C) Introduced as a thermal load to represent the effect of the fax neutron flux	2,50	12,48	24,97	57,42	Section A
	2,32	11,60	23,19	53,34	Section B
	2,07	10,36	20,72	47,66	Section C
	1,72	8,60	17,20	39,56	Section D
	1,43	7,14	14,28	32,85	Section E
	1,19	5,93	11,86	27,28	Section F
	1,08	5,42	10,84	24,93	Section G
	0,98	4,91	9,82	22,58	Section H
	0,56	2,82	5,64	12,98	Section I
	Each ΔT is represented by a discrete block in the Beryllium bar				



INVAP

Load Cases

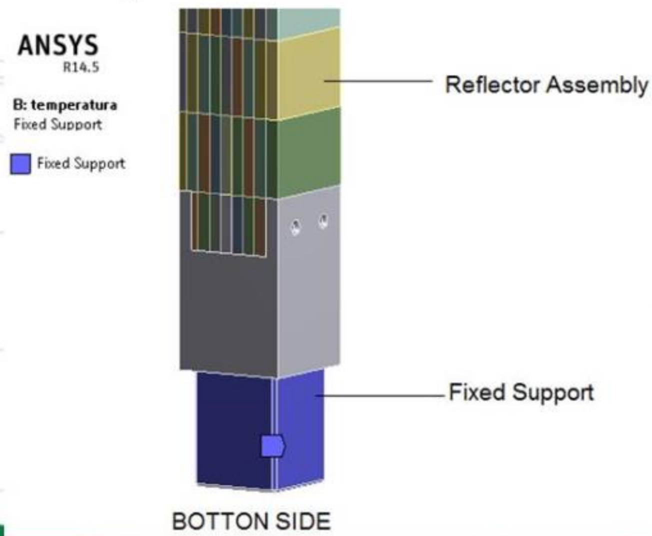
Thermal exposure during power operation of the core reactor.



INVAP

Cases of Study - Constraints

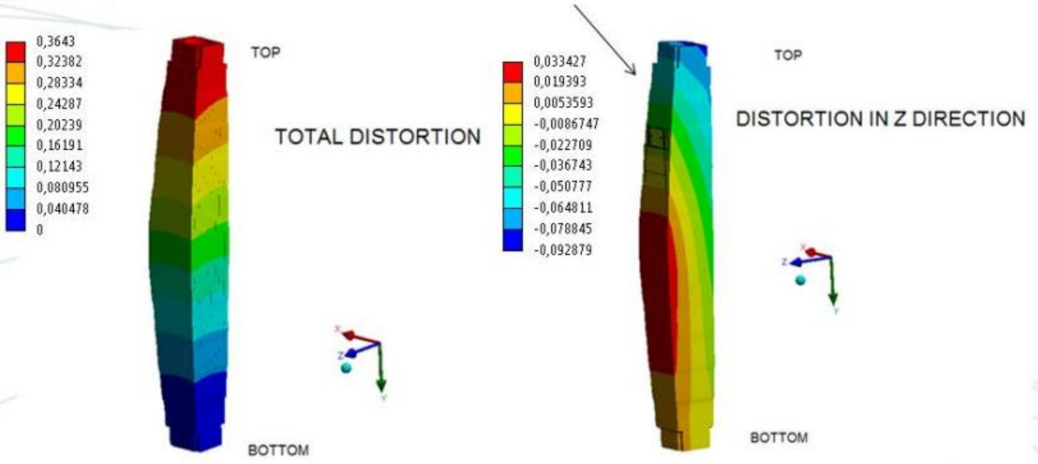
- Fixed support on the Botton
- Free end on the Top



INVAP

Results – Deformation

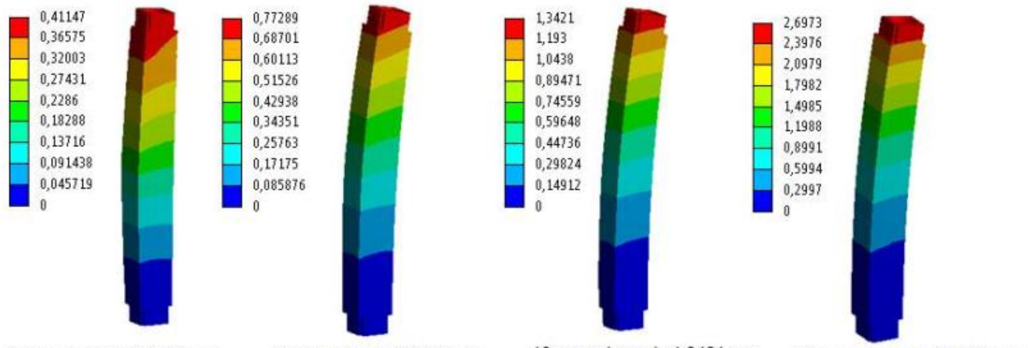
- Thermal exposure during power operation of the core reactor.
- The temperature distribution considered causes a located distortion at the middle of the bar tending to introduce a curvature in the z-direction.



INVAP

Results - Deformation

- Load Combination: Step 1 + Step 2 – Total Deformation

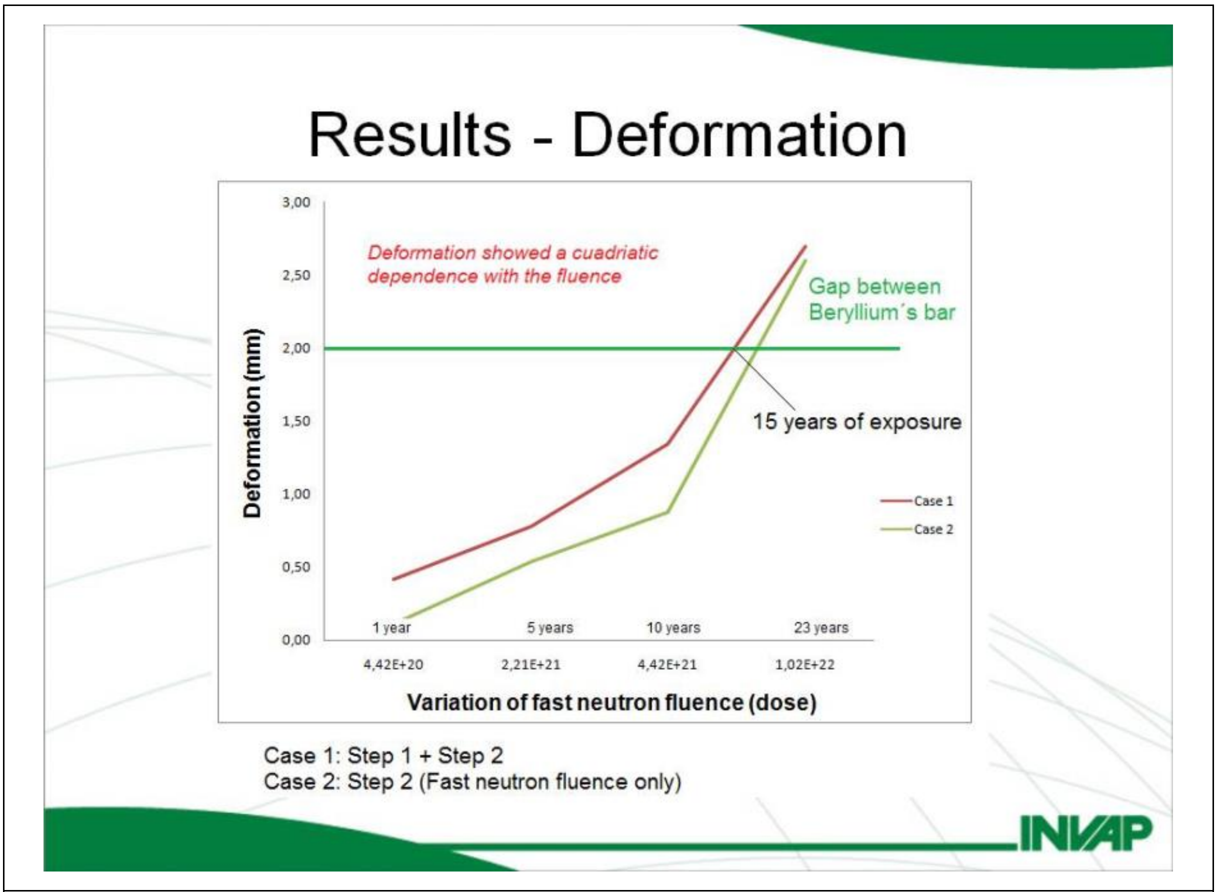


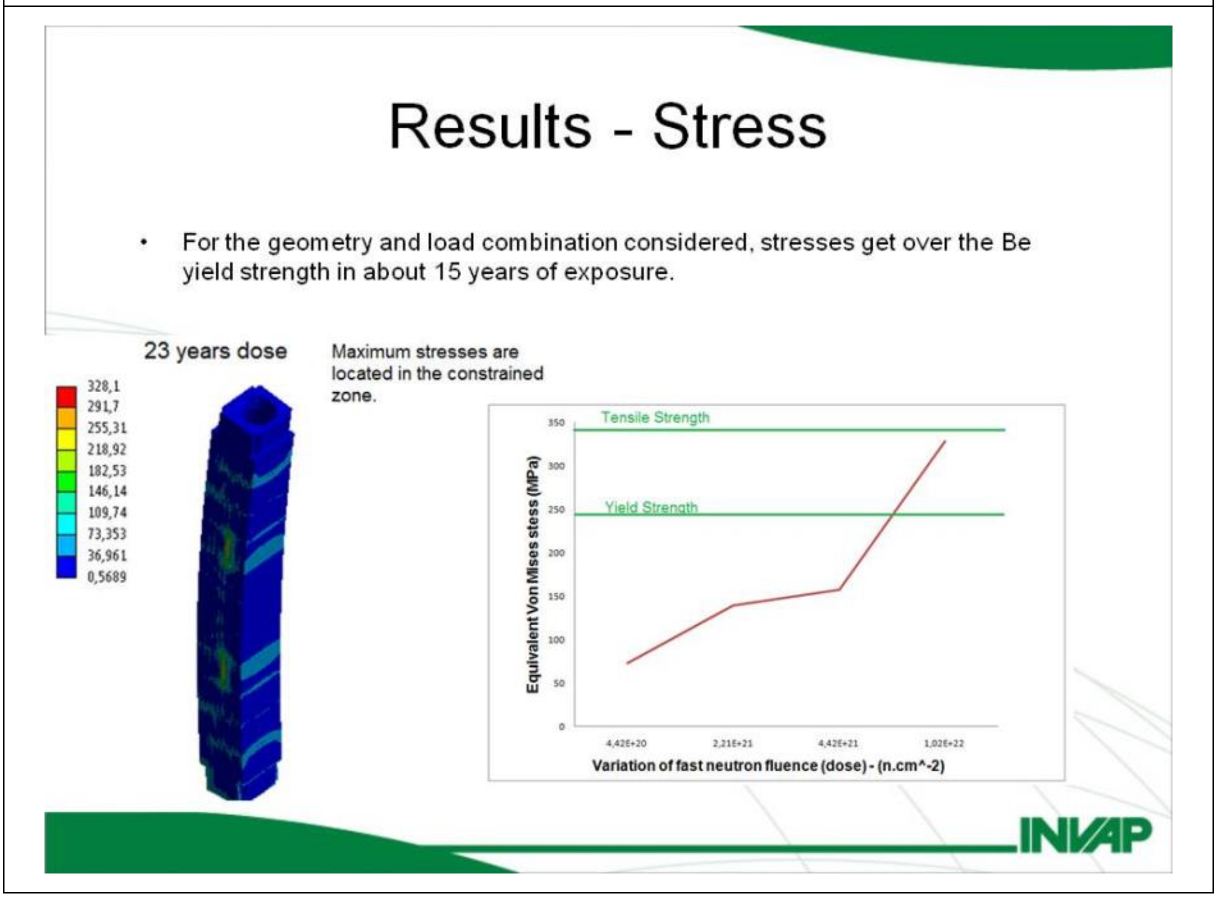
1 year dose; d= 0,4115 mm | 5 year dose; d= 0,7729 mm | 10 years dose; d= 1,3421 mm | 23 years dose; d= 2,6973 mm

LIFESPAN OF BERYLLIUM

- Displacement was calculated for 4 periods in years.
- Typical gap between RAs ≈ 2 mm

INVAP


Results - Deformation
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Deformation (mm)
Deformation showed a cuadriatic dependence with the fluence
Gap between Beryllium´s bar
15 years of exposure
Case 1
Case 2
1 year
5 years
10 years
23 years
4,42E+20
2,21E+21
4,42E+21
1,02E+22
Variation of fast neutron fluence (dose)
Case 1: Step 1 + Step 2
Case 2: Step 2 (Fast neutron fluence only)
INVAP


Results - Stress
• For the geometry and load combination considered, stresses get over the Be yield strength in about 15 years of exposure.
23 years dose
328,1
291,7
255,31
218,92
182,53
146,14
109,74
73,353
36,961
0,5689
Maximum stresses are located in the constrained zone.
Tensile Strength
Yield Strength
Equivalent Von Mises stess (MPa)
350
300
250
200
150
100
50
0
4,42E+20
2,21E+21
4,42E+21
1,02E+22
Variation of fast neutron fluence (dose) - (n.cm^-2)
INVAP

Conclusions

- For the geometry and loads considered it is possible to ensure the structural integrity for a 15 years of exposure without reach the yield strength as well as the typical gap of 2 mm between beryllium assemblies.
- The input of the temperature by power operation condition as a state of load has no relevance in total deformation for long time exposures to fast neutron flux. However for reduce time of exposure, it is the principal contribution to the total deformation.
- The state of stress generated depends on the type of constraint selected.
- It is necesary to consider in the design phase the introduction of a cooling system as the one presented in this geometry in order to reduce the thermal effects by power operation condition.

INVAP

INVAP

3.10 Tritium and Helium Release Properties for Different Grades of Beryllium Metals

[Abstract]

Tritium and Helium Release Properties for Different Grades of Beryllium Metals

Luydmila Chekushina[1], Daulet Dusambaev[1], Kunihiko Tsuchiya[2], Aset Shaimerdenov[1], Timur Kulsartov[3], Tomoaki Takeuchi[2] and Hiroshi Kawamura[2]

[1] *The Institute of Nuclear Physic, Almaty, Republic of Kazkhstan*
[2] *Japan Atomic Energy Agency, Oarai, Ibaraki, Japan*
[3] *The Institute of Atomic Energy, NNC,Kurchatov, Republic of Kazkhstan*

Beryllium's properties such as high thermal conductivity, good elevated-temperature mechanical properties for a light metal and high melting point make the material attractive for use in nuclear reactors. Reactors with beryllium (Be) exist in many places throughout the world, and a great deal of Be was used in materials testing reactors (MTR) from the beginning of atomic energy development. On the other hand, the activation issues for Be in nuclear reactors under neutron irradiation arise mainly via (n, γ) and (n, p) reactions with impurities such as iron, nickel and nitrogen in the Be. At the same time, tritium (^3H) is produced in beryllium by a well-known reaction sequence. Thus, it is difficult to reprocess irradiated Be because of high induced radioactivity. In this study, tritium and helium release properties from irradiated Be metals are evaluated for lifetime expansion of Be reflectors for MTR.

Three industrial Be grades such as S-200F, S-65-H and I-200-F were prepared as irradiation samples. These samples were subject to two-stage irradiation in one of the central irradiation channels of the WWR-K reactor. For the first stage of the 144-day irradiations, the fast neutron fluence (E>1MeV) was about 1.6×10^{24} m^{-2}. Then, three samples of each different Be grade where removed from the core and subject to study. The remaining three samples were irradiated in the second stage and total fast neutron fluence were achieved 4×10^{24} m^{-2} for 336 days in full power day of WWR-K. After the each stage irradiation test, microstructure observation and thermal desorption spectrometry (TDS) experiments were carried out with each irradiated beryllium grade.

The TDS experiments were carried out with three kinds of Be grades at the heating rates of 10, 20 and 40˚C/min. On a base of the obtained data, amounts of tritium and helium-4 (He-4) in the irradiated Be samples were evaluated. For all Be grades, amounts of He-4 and tritium were 25±3 and 1.3±0.3 ppm, respectively. The helium-3 (He-3) amount was found insignificant, comprising less than 0.02 ppm. Helium of each Be grade was released at the melting point of be sample or at the temperatures close to the melting point. On the other hand, two temperature regions of tritium release were observed at the low temperature (less than 700˚C) and the melting point. However, tritium release process of S-200F and other Be grades (S-65-H and I-220-H) was different. The irradiated S-200F was released about 90% at the less than 700˚C and about 50% of accumulated tritium was released in S-65-H and I-220-H at the melting point. It seems that tritium release from the irradiated Be was affected a process of re-crystallization of grain and re-crystallization speed of S-200F grade was much faster that of other Be grades. Moreover, accelerated re-crystallization of grains led to rapid release of gas bubbles with tritium.

The 8th Specialist Meeting on Recycling of Irradiated Beryllium
Bariloche, Río Negro, Argentina (28th Oct., 2013)

INSTITUTE OF NUCLEAR PHYSICS
of KAZAKHSTAN ATOMIC ENERGY COMMITTEE

Tritium and Helium Release Properties for Different Grades of Beryllium Metals

L. Chekushina[1], D. Dyussambaev[1], K. Tsuchiya[2], A. Shaimerdenov[1]
T. Kulsartov[3], T. Takeuchi[2], H. Kawamura[2]

1 : The Institute of Nuclear Physic (INP)
2 : Japan Atomic Energy Agency (JAEA)
3 : The Institute of Atomic Energy, NNC (IAE-NNC)

Objects

Beryllium has been utilized as a moderator and/or reflector in a number of material testing reactors. However, interaction on tritium and helium generated in the irradiated Be metal is not evident. Thus, it is necessary to evaluate the release properties of tritium and helium from the irradiated Be metal and microstructure change of the irradiated Be metal for lifetime expansion of Be reflectors for MTR.

In this study, tritium and helium release properties from irradiated Be metals were measured by the thermal desorption (TDS) method and metallographic studies of Be metal were carried out by the X-ray diffraction measurement and SEM observation.

This work was performed with support under the International Science and Technology Center (ISTC) partner project.

1

Nuclear Reaction of Beryllium

Reaction	Cross-section (barn)	Energy E_a	Half-time, $T_{1/2}$
${}^{9}_{4}Be + {}^{1}_{0}n \rightarrow 2\,{}^{4}_{2}He + 2\,{}^{1}_{0}n$	0.6	14 MeV	—
${}^{9}_{4}Be + {}^{1}_{0}n \rightarrow {}^{10}_{4}Be$	0.009	thermal	—
${}^{9}_{4}Be + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{6}_{2}He$	0.010 0.068	14.1MeV 5.0 MeV	—
${}^{6}_{2}He \xrightarrow{\beta^-} {}^{6}_{3}Li$	—	—	0.808 s
${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H$	940	thermal	—
${}^{3}_{1}H \xrightarrow{\beta^-} {}^{3}_{2}He$	—	—	12.3 y
${}^{3}_{2}He + {}^{1}_{0}n \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$	5327	thermal	—

2

Experimental Procedure

Preparation
a) Be samples
b) Irradiation containers

Calculation of irradiation field
a) Be samples
b) Irradiation containers

Neutron Irradiation (WWR-K)

PIEs of irradiated Be samples
(1) Measurements after irradiation
a) Aspect
b) Dimension
c) Weight
d) Hardness
(2) Measurements after cutting
a) Aspect & weight
b) SEM observation
c) XRD analysis
c) He/T release

WWR-K in INP

[Utilization of WWR-K]
- Material testing
- Isotope production
- Neutron physics

General Technical data of WWR-K

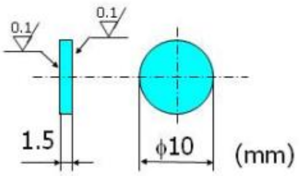
Reactor type	: Light water tank type
Thermal power	: 6MW
Flux (max.)	
Thermal	: 1.4×10^{14} n/cm^2/s
Fast	: 1.6×10^{13} n/cm^2/s
Moderator	: Light water
Coolant	: Light water
Control rod	: B_4C

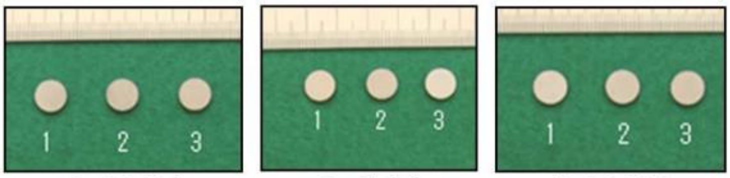
3

Preparation of Beryllium Samples

S-200F Beryllium (VHP) Reference
Down-Selection Process for Be Grades
– **Purity & Isotropy Combination : S-65H**
– **Strength & Isotropy Combination : I-220H**

Shape of Be samples





S-200F S-65H I-220H

Properties

Factor	Grade	GS (μm)	Elements (%)							
			Be	BeO	Al	Fe	Si	Ni	Ti	C
Reference	S-200F	10.3	**99.0**	**1.0**	0.05	0.12	0.03	0.01	0.01	0.06
Isotropy	S-65H	6.9	**99.4**	**0.7**	0.04	0.08	0.02	0.02	0.02	0.007
Isotropy	I-220H	5.6	**98.6**	**1.9**	0.01	0.06	0.02	0.02	0.02	0.03

(Fabricated by Materion Corporation)

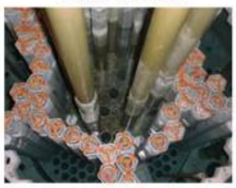
4

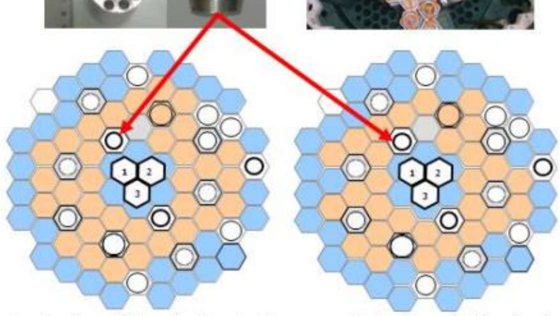
Irradiation Field in WWR-K

Irradiation Test

Be samples

WRR-K core





Beginning of irradiation test

End of irradiation test

: FA-1
: FA-2 with control rods
: Channel with shim rods
: LTA
: Beryllium
: Irradiation channel
: Displacer (hollow tube)

Calculation Result

(by 3D code MCU-REA)

Channel ID	Neutron flux density ($cm^{-2}\ s^{-1}$)	
	Thermal (En<0.4 eV)	Fast (En > 1.15MeV)
The beginning of irradiation test		
4 - 5	(1.4±0.1)E+14	(2.0±0.2)E+13
10 - 2	(4.4±0.4)E+13	(4.6±0.4)E+12
5 - 9	(5.9±0.1)E+13	(7.9±0.8)E+12
The end of irradiation test		
4 -5 (5.5cm above the bottom)	(1.0±0.1)E+14	(1.44±0.2)E+13
8-5 (center)	(1.85±0.1)E+14	(2.7±0.2)E+13
8-9 (center))	(7.9±0.1)E+13	(7.4±0.2)E+12

Dicision of irradiation conditions

1st irradiation test
$\phi_F = 1.5 \times 10^{20}\ /cm^2$
2nd irradiation test
$\phi_F = 4.0 \times 10^{20}\ /cm^2$
Irradiation Temperature
T = 40°C (coolant temp.)

5

PIEs of Irradiated Be Samples

PIE flow chart

Dismount of container

↓

Measurement Items
- a) Aspect
- b) Dimension
- c) Weight
- d) Hardness

↓

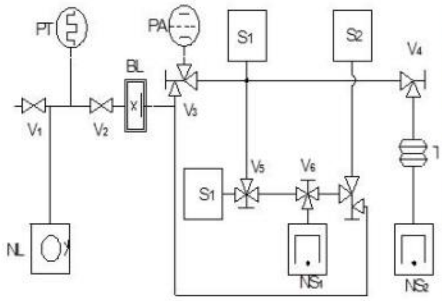
Cutting of Be samples

↓

Measurement Items
- a) Aspect & weight
- b) SEM observation
- c) XRD analysis
- c) He/T release

Experimental device

He/T release measurements were carried out with experimental installation VIKA.



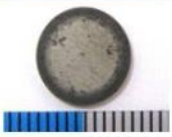
NL : Pump HBP-5 DM, NS : Pump NORD-100, NS2 : Magnet-discharge pump NORD-250,
BL : Nitrogen trap, PT : Thermocouple vacuum meter, PA : Ionization vacuum meter, CV : Work chamber,
V : Vacuum valve, S_1 : Omegatron-type sensor of the PMO-13 mass spectrometer EPDO-2.
S_2 : Quadruple mass spectrometer RGA-100

Items	Values
Range of work temperature	from 30 to 1500°C
Pressure in the chamber work volume at 1773 K	10^{-5} Pa
Inaccuracy of the temperature automate maintenance with respect to a specified one	±0.5°C
Range of the sample heating rate	from 2 to 50K/min

6

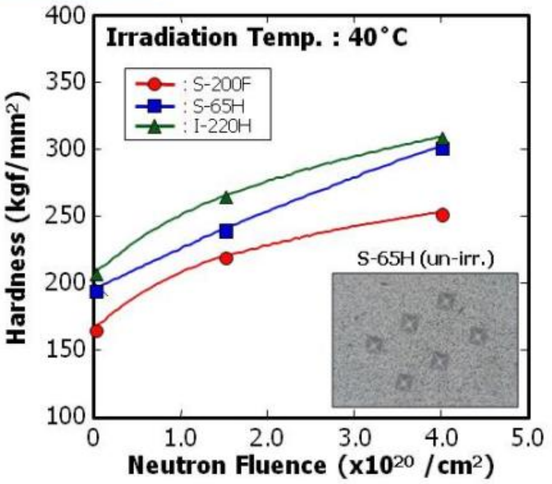
Results of PIEs (1)

Aspect

Fluence / Grade	1.5x10²⁰ /cm²	4.0x10²⁰ /cm²
S-200F		
S-65H		
I-220H		

Surface changes of irradiated Be occurred with increasing the neutron fluence.
(polished surface → tarnished surface)

Hardness

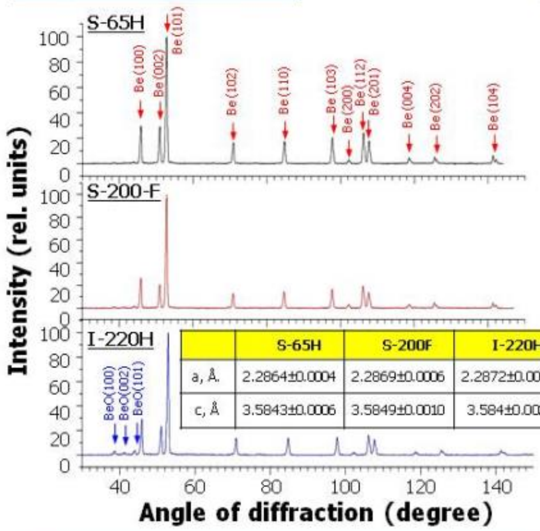


Hardness of irradiated Be was increased with increasing the neutron fluence.

7

Results of PIEs (2)

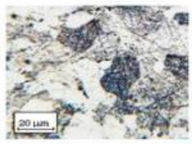
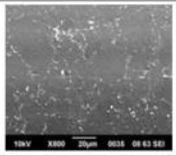
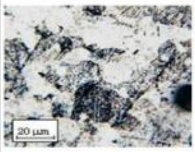
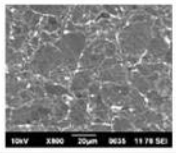
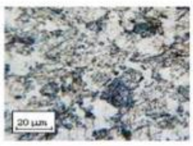
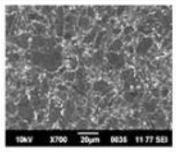
Crystal structure



	S-65H	S-200F	I-220H
a, Å	2.2864±0.0004	2.2869±0.0006	2.2872±0.0012
c, Å	3.5843±0.0006	3.5849±0.0010	3.584±0.002

- No change of crystal structure before/after neutron irradiation (Be, BeO)
- No differences in the lattice values

Observation and grain size

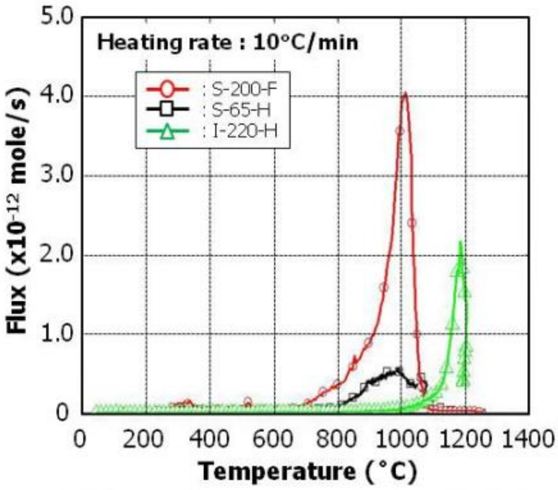
	Metallografic Observation	SEM Observation	Av. grain diameter
S-200F			15 μm
S-65H			11 μm
I-220H			7.9 μm

- Cohesion of BeO in grain boundaries

8

Results of PIEs (3)

Tritium release spectrum



Tritium release peaks : 900 to 1200°C
(I-220H : about 1150°C)

He/T release amounts

Sample	Sample ID (conditions)	Heating Rate (°C/min)	Tritium (ppm-T/g)	^{4}He (ppm/g)
S-65-H	*BS-1-1 (melted)*	20	27.3	436
	BS-1-2 (melted)	40	23.5	496
	BS-1-3 (melted)	10	22.4	551
S-200-F	*BS-2-1 (melted)*	10	27.8	481
	BS-2-2 (up to 1175°C)	20	28.0	80
	BS-2-3 (melted)	40	37.5	479
I-220-H	*BS-3-1 (melted)*	20	25.9	407
	BS-3-2 (up to 1200°C)	10	8.5	119
	BS-3-3 (melted)	40	42.6	532

Tritium release amount : 29.6ppm-T/g
Helium release amount : 483ppm/g
Helium release : more than M.P.
(Helium was difficult to release up to the M.P. (see the results of Be-2-2 and BS-3-2)).

9

Conclusions

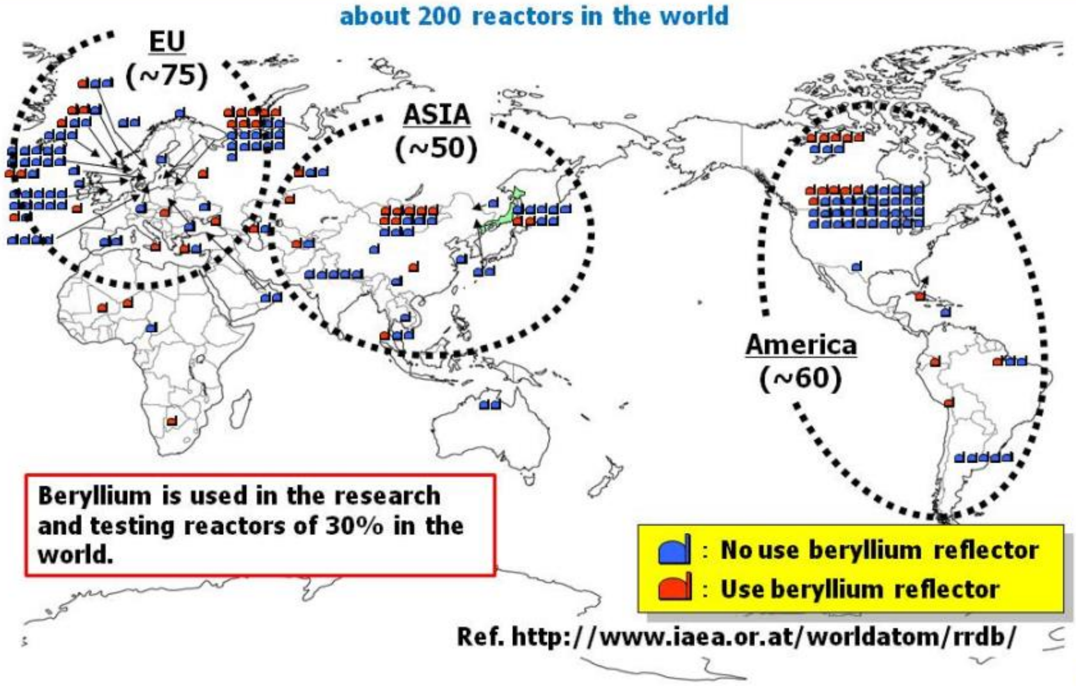
Three kinds of industrial Be grades such as S-200F, S-65H and I-220H were prepared and irradiated in WWR-K at about 40°C to fluences of 1.5×10^{20} and 4.0×10^{20} /cm^2. After irradiation tests, PIEs were carried out and the results of this study are given below.

(1) The surfaces of the irradiated Be samples changed from the polish to the tarnish after irradiation. It seems that the corrosion and cohesion of BeO occurred in the surface of Be samples. No effect of crystal structure of Be occurred up to 4.0×10^{20} /cm^2.
(2) The hardness of the irradiated Be samples increased with increasing the neutron fluence because of neutron irradiation embrittlement .
(3) Tritium (T_2) was released in the range from 900 to 1200°C and helium (^4He) was difficult to release up to the melting point. Amounts of ^4He and released T_2 were in good agreement for all irradiated Be samples, and He/T values were 483 ppm/g and 30 ppm-T/g, respectively.

10

Appendix

Research and Test Reactors in the World



A-1

Chemical compositions of coolant in WWR-K

Index Name	Index magnitude
pH at 25 °C	**5.0 to 6.5**
Specific Electric Conduction at 25 °C (mOhm/cm)	**4.0**
Hardness (mg·equiv./kg)	**< 3.0**
Ion Chloride Mass Concentration (mg/kg)	**< 50**
Aluminum Mass Concentration (mg/kg)	**< 50**
Iron Mass Concentration (mg/kg)	**< 50**
Copper Mass Concentration (mg/kg)	**< 10**
Fission Product Total Activity (Bq/kg)	**$< 2.5 \times 10^7$**

A-2

This is a blank page.

Appendix A　Program

The 8th Specialist Meeting on Recycling of Irradiated Beryllium
Monday, October 28, 2013
Hotel Edelweiss
San Carlos de Bariloche – Río Negro – Argentina

[Tentative Agenda]

Time	Topics	Presenter
14:00 - 14:05 (5 min)	**Opening on the 8th Meeting**	(INVAP)
14:05 - 14:25 (20 min)	**Special Lecture** Construction Plan of New Hot Laboratory for Convergence of the Fukushima Nuclear Plant Accident. (Tentative title)	H. Kawamura (JAEA)
14:25 - 14:40 (15 min)	**Report of BeWS-11 in Barcelona, Spain**	C. Dorn (Materion)
14:40 - 15:50	**Status of Beryllium Study (Utilization, Handling, Storage, Nuclear Calculation Property Evaluation, etc.) in Nuclear Fields in Each Country**	
(15 min)	Status of Beryllium design study in INVAP.	R. Cocco (INVAP)
(15 min)	Beryllium Usage at the University of Missouri-Columbia Research Reactor.	L. Foyto (MURR)
(15 min)	Status of Beryllium Study in JAEA.	K. Tsuchiya (JAEA)
(15 min)	Status of Beryllium Study in KAERI.	M. S. Cho (KAERI)
(10 min)	Discussion.	All Participants
15:50 - 16:10	**Coffee brake**	
16:10 - 16:50	**Status of Beryllium Study (Production, Property Evaluation, etc.) in Nuclear Fields**	
(15 min)	Recent activities in the MTR field for Be reflectors.	E. Vidal (Materion)
(15 min)	Beryllium Research in NGK and New Proposal for MTR Reflector Development.	K. Nojiri (NGK)
(10 min)	Discussion.	All Participants
16:50 - 17:30	**Evaluation of Irradiated Beryllium Grades as MTR Reflector**	
(15 min)	Swelling and Thermal Effect on Beryllium on a Reflector assembly.	E. Fresquet (INVAP)
(15 min)	Tritium and Helium Release Properties for Different Grades of Beryllium Metals.	K. Tsuchiya (INP-KZ)
(10 min)	Discussion.	All Participants
17:30 - 18:00 (30 min)	**Discussion Topics** (1) Irradiation Tests for Life time Expansion. (2) Strategy of Beryllium Recycle. (3) Contribution on Beryllium study for MTR Reflectors.	All Participants
18:00 - 18:10 (10 min)	**Summary in the 8th meeting and Next Meeting**	All Participants
18:10	**Adjourn**	

Appendix B　List of participants and Photograph

List of participants in the 8th Specialist Meeting on Recycling of Irradiated Beryllium

Name	Country	Institution
Leslie P. Foyto	U.S.A	University of Missouri Research Reactor (MURR)
Ralph A. Butler	U.S.A	University of Missouri Research Reactor (MURR)
Christopher K. Dorn	U.S.A	Materion Brush Inc.
Edgar Vidal	U.S.A	Materion Brush Inc.
Andrea Borio di Tigliole	Austria	International Atomic Energy Agency (IAEA)
Man Soon Cho	Korea	Korea Atomic Energy Research Institute (KAERI)
Kee Nam Choo	Korea	Korea Atomic Energy Research Institute (KAERI)
Hiroshi Kawamura	Japan	Japan Atomic Energy Agency (JAEA)
Kunihiko Tsuchiya	Japan	Japan Atomic Energy Agency (JAEA)
Tomoaki Takeuchi	Japan	Japan Atomic Energy Agency (JAEA)
Masayashu Ito	Japan	Japan Atomic Energy Agency (JAEA)
Keigo Nojiri	Japan	NGK Insulators, Ltd.
Masashi Shikata	Japan	Mitsubishi Heavy Industries Ltd.
Masakazu Tanase	Japan	Chiyoda Technol Corporation
Aníbal Blanco	Argentina	National Commission of Atomic Energy (CNEA)
Patricio M. dos Reis	Argentina	National Commission of Atomic Energy (CNEA)
Ezequiel Fresquet	Argentina	INVAP S. E.
Viviana Ishida	Argentina	INVAP S. E.
Roxana G. Cocco	Argentina	INVAP S. E
Fátima Francioni	Argentina	INVAP S. E

Photograph

Appendix C　Discussion Items from the 1st to 7th Meetings

Discussion Items in Specialist Meeting (1)

1st Meeting in INL (July 18, 2007)

1) Low Uranium Beryllium
- 30appm uranium impurity in typical beryllium material
  → Target values : about 1appm

2) Disposal of Irradiated Beryllium
- Storage of irradiated beryllium in MTR site
  → Investigation of amount of irradiated beryllium

3) Beryllium Strength
- Selection of Beryllium grades for lifetime expansion
  → Investigation of Beryllium grades

4) Recycling
- Kg-scale recycling test with dry procedure
  → Proposal in ISTC Project

5) Availability
- Beryllium utilization
  → 3 billets in ATR (Be grade : S-200F)
  → Beryllium frames in JMTR (Be grade : S-200F)

Discussion Items in Specialist Meeting (2)

2nd Meeting in Lisbon (December 7, 2007)

1) Beryllium Recycling Study
- Storage of irradiated beryllium in MTR site
  → ~7ton (ATR), ~3ton (JMTR), ~3.5ton (EU), ~3 ton (RF)
- Explanation of Beryllium recycling in ISTC Project
  → kg-scale recycling test in Kazakhstan

2) Material Selection of Beryllium Grades as MTR Reflector
- Properties and comparison of Beryllium grades
  → Reference (S-200F), Purity (S-65C), Isotropy (S-65H), Strength (I-220H)
- Proposal of High-irradiation tests for lifetime expansion
  → Proposal of international cooperation for irradiation tests
  → Proposal in ISTC project with SM-3

3) Other
- Establishment of International Committees
  → Consideration of framework in the meeting

Discussion Items in Specialist Meeting (3)

3rd Meeting in JAEA (July 18, 2008)

1) Beryllium Recycling Study
- Explanation of Beryllium recycling in ISTC Project
  → Not approve the work plan in ISTC Project, yet.

2) Material Selection of Beryllium Grades as MTR Reflector
- Selection of Beryllium grades
  → Reference (S-200F), Isotropy (S-65H), Strength (I-220H)
  → Investigation of irradiation specimens
- Proposal of High-irradiation tests for lifetime expansion
  → Selection of MTR for irradiation tests (JRR-3, ATR, SM-3)

3) Other
- Establishment of International Committees
  → Consideration of framework in the meeting

Discussion Items in Specialist Meeting (4)

4th Meeting in Idaho Falls (Oct. 1, 2009)

1) Status of Beryllium Recycling Study
- Status of Irradiated Beryllium Handling at ATR
  →Storing the used beryllium in the reactor canal
- Status of Irradiated Beryllium Recycling between JA & KZ
  →Recycle about one kilogram of irradiated beryllium supplied by JAEA to IAE-NNC.

2) Goals of Beryllium Recycling
- Is the need for the recycling of irradiated beryllium universal among test reactor facilities and their governing organizations?
- What should be the ultimate goal of a "recycling" program?
  →Discussion continually

3) Other
- Thoughts on Be Swelling & What Can Be Done About It

Discussion Items in Specialist Meeting (5)

5th Meeting in NRI (June 24, 2010)

1) Status of Beryllium Study

- Beryllium management in NRI
- R&D of beryllium in EU

→ Nuclear fusion reactor development

- Irradiation Test for lifetime expansion in KZ

2) Beryllium Recycling

- The BR2 will be shutdown in 2016 according to the MYRRHA plan and also the tritium lab will stop.
- Test result of beryllium processing by wet method (ISTC 3381)
- Transportation of irradiated beryllium from JPN to KZ (ISTC K-1566)

3) Other

Discussion Items in Specialist Meeting (6)

6th Meeting in Oarai (December 5, 2011)

1) Status of Beryllium Study

- Beryllium management in MURR and SAFARI
- R&D of beryllium in KAERI, JAEA and MBBe&C

2) Beryllium Recycling

- Status of recycling tests of irradiated beryllium in KZ (ISTC K-1566)

3) PIE Technology

- TEM Observation in NFD

4) Other

Discussion Items in Specialist Meeting (7)

7th Meeting in MURR (October 22, 2012)

1) Status of Beryllium Study
- Beryllium management in MURR and SAFARI
- R&D of beryllium in KAERI and JAEA
- Beryllium production and study in MBBe&C and NGK

2) Beryllium Recycling
- Status of recycling tests of irradiated beryllium in KZ (ISTC K-1566)

3) PIE Technology
- Characterization of Irradiated Beryllium in ATR, JAEA and KAERI

4) Other
- Evaluation method development of Deformation in INVAP

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度 (a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率 (b)	（数字の）　1	1
比透磁率 (b)	（数字の）　1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^{2}/m^2
周波数	ヘルツ (d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能 (f)	ベクレル (d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト (g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ sA$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ sA$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^9	ギガ	G	10^{-12}	ピコ	p
10^6	メガ	M	10^{-15}	フェムト	f
10^3	キロ	k	10^{-18}	アト	a
10^2	ヘクト	h	10^{-21}	ゼプト	z
10^1	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3\ kg$

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St\ =1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb\ =1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal\ =1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx = 1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G\ =1Mx\ cm^{-2}\ =10^{-4}T$
エルステッド (c)	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu\ =1\mu m=10^{-6}m$

（第8版，2006年改訂）