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Report of a Technical Evaluation Panel on the Use of Beryllium for ITER Plasma Facing Material and Blanket Breeder Material

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Report of a Technical Evaluation Panel on the Use of Beryllium for ITER Plasma Facing Material and Blanket Breeder Material

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CHAPTER 1. EXECUTIVE SUMMARY

1.1 BACKGROUND

Beryllium, because of its low atomic number and high thermal conductivity, is a candidate for both International Thermonuclear Experimental Reactor (ITER) first wall and divertor surfaces. Further, beryllium has a low activity in a nuclear environment and is a neutron multiplier which will be needed for tritium self sufficiency. Potential disadvantages are beryllium's relatively low maximum operating temperature, possibly high sputtering losses and its health and environmental maintenance requirements. These disadvantages in all probability can be dealt with in all phases of ITER construction and operation with the appropriate investment and development funds. An actively cooled copper substructure is intended to be the primary heat removal path.

1.2 FINDINGS AND RECOMMENDATIONS

Recommended grades of beryllium for ITER components, other than the Breeder Blanket, have been divided into those available today and those most promising to be developed during the Engineering Design Activity (EDA). These are S-65C* in various product forms, rolled ingot (MSC-100**) or powder sheet (SR-200') and spherical powder (for plasma spraying). By the end of the EDA process (~1998) plasma sprayed powder is projected to be the principal form of beryllium required, based upon the anticipated success of plasma spray deposition process development. A beryllium grade with 10% isotropic ductility is not a realistic production material.

The timetable for the developments needed in beryllium technology and testing, especially neutron exposure and testing of qualified ITER components, i. e., *well characterized beryllium sub-components produced by scaleable processes*, seems unduly compressed. While some development work may continue beyond the EDA, the risk of a short time frame program is that either poorly qualified material will be tested or that promising developmental processes requiring more time may be abandoned.

It is recommended that \$229M be devoted to the development and qualification of beryllium for the various ITER components during the EDA period. This is substantially in excess of money being currently devoted to ITER. Detailed development plans based on the established panel priorities should be formulated and implemented over as near a time frame as is practicable.

The recommended distribution of the funds devoted to the fabrication technology of beryllium components for ITER is 50% for plasma spray technology, 30% for brazing technology, 10% for roll bonding technology and the remaining 10% to be devoted to other methods such as friction welding, hot isostatic pressing (HIP) bonding and electroplating. The relatively larger investment in plasma spray technology is in recognition of both its early state of development and future promise for ITER components.

* Brush-Wellman product designation

** Manufacturing Science Corporation product designation

1.2.1 SUPPLY

The supply of beryllium for ITER is adequate. A good physical and mechanical property data base for ambient and moderate temperature exists for most commercial grades of beryllium produced in the US. Production capacity for wrought forms of beryllium is adequate. Should plasma spray technology be ultimately proved feasible, using spherical [atomized] powder, supply of such powder may become an issue. This is because commercial atomizing capacity is currently very limited. The data base for high density plasma sprayed beryllium for ITER is virtually non-existent. Plasma spray process optimization and scale up must be a high priority ITER goal if such a process is to be useful.

1.2.2 RADIATION EFFECTS

The response of beryllium to a moderate neutron energy radiation environment such as in thermal fission reactors is generally well understood. Much of the specific data is for older grades of beryllium rather than for the more modern grades (S-65C, HIPed, etc.). No radiation exposure effects data exists for plasma sprayed material. The high neutron energy of ITER raises questions concerning the applicability of much of the existing data.

General radiation effects on beryllium properties are reduced ductility and subsequent swelling due to helium and tritium generation. Additional experimental data on material irradiated at ITER service temperatures is vitally needed. Some S-200 material has been irradiated but not yet evaluated. Some initial data should be collected to address the differing effects of high energy neutrons compared to thermal neutron effects already studied. The need for a Fusion Neutron Source should be determined based on the available data and theoretical models. Irradiation effects on the beryllium/copper alloy joint/compliant layer integrity must also be determined.

1.2.3 TRITIUM

Tritium breeding rates in beryllium will be much higher in a fusion spectrum with a strong 14MeV component than in a fission spectrum that is strongly thermalized. The amount of bred tritium that remains in the beryllium will be strongly influenced by factors such as operating temperature, surface oxide films, surface roughness, micro-cracking, and porosity. The details of how tritium re-emerges to the plasma must be established to predict accumulated tritium inventory and safe operating procedures. Tritium and other radionuclides may be released in an accident in which beryllium is oxidized by leaking coolant or air ingress.

1.2.4 EROSION

It is predicted that 100-1000 disruptions will completely erode the beryllium armor, depending on whether or not the melt layer is lost. It is also predicted that 25 full-power (1000s) shots will completely erode the beryllium in the dump target region of the divertor due to sputtering. The magnitude of these estimates emphasizes the critical need for in-situ repair techniques.

1.2.5 HEALTH AND SAFETY

Health and safety procedures for the use of beryllium in an industrial environment have been well established. These consist principally of controlling and monitoring airborne beryllium particulate material. The principal hazard of beryllium is the inhalation of such 'aerosols' leading to Chronic Beryllium Disease (CBD). CBD is diagnosed by blood and tissue studies and is currently thought to be an allergic reaction in about 2% of the population. Currently under final stages of development is a 'real time' monitor for beryllium aerosols. This development should be completed and the instrument be made available for use in ITER development, construction and operation.

1.2.6 MANUFACTURING

The materials and process issues relating to the fabrication of a layered beryllium/copper alloy structure have been analyzed and prioritized based on many performance, data base and experience factors. Of the manufacturing methods considered for joining beryllium to a copper alloy substrate, brazing was considered the most mature, but still in need of development and evaluation for ITER. Brazing alloys must be selected to be compatible with the ITER nuclear environment. Plasma spray deposition of beryllium directly onto a copper alloy substrate, although in an early stage of development, was deemed to be the most promising future fabrication and repair technique. Consequently it is recommended that the majority of development funding be applied to these two processes. Of the other processes reviewed, roll bonding was assigned sufficient importance to receive funding. The other processes evaluated were found to be of lesser importance but should not be eliminated.

A critical feature of the current ITER design is the beryllium to copper alloy bond. The mechanical and thermal integrity of this bond must be assured for reliable ITER performance, whatever process is used to produce the desired beryllium layer. Because of the complex and inter-related materials, manufacturing and design issues, it is strongly recommended that a concurrent engineering design approach be implemented.

Mechanical constraint arising between beryllium and copper during ITER service may require a compliant layer to relieve thermal stresses. This must be determined in the very near term, since it will have a significant effect on the development work required.

CHAPTER 2. RECOMMENDATIONS FOR PROJECT MANAGEMENT

1. The design effort on ITER should be integrated more carefully with material and fabrication specialists.
2. The designers, materials, and fabrication specialists should pick the two most promising manufacturing routes for the divertor components and first wall.
3. The research and development activities should be directed to support the selected fabrication routes.
4. Both the “low pressure plasma-arc transfer process” and the “high velocity inert gas atmosphere process” for plasma spraying of Be should be supported through the most appropriate R&D phase.
5. The development of inspection and quality assurance methods should be an integral part of the fabrication methods development program.
6. The program for developing fabrication and inspection methods for ITER hardware should have input from the remote maintenance and repair activities.
7. DOE should be urged to convert the Oak Ridge National Laboratory Y-12 Be Complex to an unclassified User Facility to minimize the cost of building another expensive facility for producing the ITER components. A large part of the cost of such a facility is air handling, permitting, et al., for Be handling.
8. Since Fusion Energy is supporting several programs under the SBIR program, these activities should be better integrated with the overall Be ITER components program.
9. Due to the fluid nature of the ITER design and the multiplicity of the development programs, systematic review of these activities should be conducted on a continuing basis by a panel of materials and fabrication specialists.
10. Should spherical powder be the preferred feed material for plasma spray deposition, an adequate supply facility must be assembled.

CHAPTER 3. CONCLUSIONS

The format for these conclusions is presented as answers to specific questions addressed to the Technical Evaluation Panel.

3.1 What are the potential costs of developing beryllium for ITER?

The panel estimated that it would take \$229M to develop beryllium for ITER during the Engineering Design Activity (EDA) period.

3.2 Is it possible to validate beryllium in time for ITER construction?

Only partial validation of beryllium for ITER construction is currently possible. Limitations on the budget and time available for R&D on beryllium restrict the amount of data that can be gathered. Other needs such as joining, compliant layer development and evaluation, irradiation effects, etc., suggest that either increased funds or added time with current funding rates will be needed to qualify the various forms of beryllium needed for successful ITER construction and operation. In addition, increased emphasis by the JCT and other Home Teams on tungsten and carbon fiber composites (CFCs) as alternative plasma facing materials will further dilute the funds available for development of beryllium. This will further reduce the chance of validating Be in time for ITER construction. ITER Joint Central Team is planning for additional R&D on plasma facing components during the construction phase. This increases the likelihood of validation. Materials development/validation priorities will need to be developed with significant materials community input.

3.3 What is the state of our database for mechanical properties?

For mechanical properties at room temperature, the database for industrial beryllium grades is generally complete. However, at elevated temperatures (up to 600°C operating temperature), the database is incomplete, especially with respect to thermal fatigue, creep, and fracture properties. For plasma sprayed beryllium with high density (e.g., >95% as-sprayed), the database is essentially non-existent. With regards to the prospect of developing a new grade of beryllium with isotropic ductility greater than 6% at room temperature (so-called "ductile beryllium"), the panel concluded that this was highly unlikely in a commercially feasible product form.

3.4 How well are the thermo-mechanical fatigue properties of beryllium understood and how do they affect the performance of Be in ITER?

The thermo-mechanical fatigue properties of beryllium are poorly understood due to a lack of data on fatigue crack initiation, growth, creep, and fracture toughness at elevated temperatures (up to 600°C) on modern grades (e.g., S-65C, plasma sprayed dense Be). Fatigue behavior of beryllium at room temperature is understood. However, most data are for older and/or different grades than planned for ITER. Experimental high heat flux tests using one-sided heating of beryllium samples by rastered electron beams or ion beams heat sources can yield significant new data specific to ITER conditions which depend on heat load, number of cycles, sample geometry, and degree of constraint. Both lateral, vertical, and curved cracks have been observed, which can lead to reduced heat conduction.

3.5 Considering the state of the post irradiation database on beryllium, what additional irradiations and testing (irradiated and unirradiated) are required during and after the EDA?

Additional irradiations, at ITER-relevant temperatures (up to 600°C), are needed on modern grades of beryllium (e.g., S-65C and plasma sprayed). Measurements of the thermal conductivity, strength, ductility, swelling, and thermal fatigue behavior are critically needed. With the recent shutdown of the last operating fast flux fission reactor in the US (i.e., Fast Flux Test Reactor), beryllium samples will need to be provided to fast reactors in Europe and Russia. The need for a 14MeV neutron source was highlighted by the panel. Testing in thermal fission reactors with modified neutron spectra can also yield valuable data.

3.6 What additional data are needed to determine, a) the tritium retention in irradiated and eroded and redeposited beryllium, and b) tritium solubility and transport in beryllium neutron multipliers?

Key data needs in the area of tritium interactions include (1) tritium solubility, diffusivity, and trapping data in beryllium and its oxide and carbide, (2) surface modification effects associated with plasma exposure, (3) tritium trapping and release characteristics as a function of damage state, temperature, surface conditions, and impurity content, and (4) better information on tritium recycle characteristics. These data need to be measured on the recommended grades of beryllium, S-65C and plasma sprayed material, including neutron irradiated material, at relevant temperatures up to 600°C. It is essential to maintain the experimental capabilities for beryllium operation at the Plasma Interactions with Surfaces and Components Experimental System (PISCES) and Tritium Plasma Experiment (TPE) plasma test facilities at the University of California at San Diego (UCSD) and Los Alamos National Laboratories (LANL), respectively.

3.7 Will the anticipated tritium inventory present a safety problem?

The panel estimated that the ITER tritium inventory in the beryllium plasma facing components may amount to several kilograms. This inventory, if released during a thermal excursion followed by a failure of the vacuum containment boundary, would pose a significant safety threat to persons located at the site boundary. The tritium inventory is primarily tied up at neutron-induced trapping sites in the bulk material, though it will be very difficult to release at low temperatures. It should be noted that tritium inventory will be similar or slightly less for tungsten and is likely to be much greater for carbon-based materials.

3.8 What R&D needs to be done to allow maintenance of eroded beryllium plasma facing components to be carried out?

An industrial firm engaged in plasma spraying (Electro-Plasma, Inc.) estimated that it would take \$32M and 10 years to fully develop plasma sprayed beryllium for fabrication and on-site repair capabilities. Use of the Oak Ridge National Laboratory Y-12 facility would likely reduce this cost (accelerate the development time). Critical research objectives are: maximizing thermal conductivity, and improving deposit efficiency, coating uniformity, and coating adhesion. A three-year R&D effort is recommended in the following areas: classified literature review, powder evaluations, torch design, process modeling, process diagnostics, spray trials, characterization and performance, surface preparation, NDE, scale-up for manufacture of ITER components, and development of robotic maintenance methods.

3.9 Is the plasma spray technology adequate or could it be available in time for ITER?

Although the state of the art produces deposits adequate for specialized applications such as the divertor gas box liner and first wall, the present deposit efficiency and robotics are inadequate for some ITER needs. With extremely low funding anticipated at Los Alamos National Laboratories to conduct the needed plasma spray development work, it may not be possible to scale up this technology in time for ITER construction.

3.10 What is required to develop beryllium and associated joining techniques to remove up to 5 MW/m² under ITER conditions?

The panel estimated that it would take \$28M during the EDA to develop both a deposited beryllium and techniques for joining of beryllium to copper alloys. The panel recommends that 50% of these funds be devoted to plasma spray technology, 30% for brazing, 10% for roll bonding, and the remaining 10% to other methods, such as friction welding, HIP bonding, electroplating, and explosion bonding. The relatively larger investment in plasma spray technology is in recognition of both its early state of development and future promise for ITER components. Critical joining issues include: (1) use of a compliant layer (such as AlBeMet™, an aluminum/beryllium alloy) to relieve differential thermal stresses, (2) use of diffusion barriers to prevent brittle beryllium/copper intermetallic phases from forming, (3) effect of joining temperatures on strength of substrate copper alloy, (4) effects of hydrogen at the interface, (5) neutron effects, (6) repair techniques, and (7) reliable NDE techniques.

3.11 Are there low activation joining materials that can be used or developed?

The panel identified the braze alloy combination of aluminum-12% silicon as a highly desirable, low activation replacement for the standard silver-copper braze alloys. Also, methods for directly bonding beryllium to copper alloys with no interface materials were identified: explosion bonding, HIPing, friction welding, plasma spraying. However, formation of brittle beryllium/copper intermetallic phases is a concern with direct bonding that may require the use of a diffusion barrier, such as aluminum, silicon, or germanium. Formation of the radioisotope Al-26 is a concern for waste disposal because of its very long half-life. Other materials used in ITER will dominate the radioactivity produced.

3.12 What inspection techniques need to be developed to assure reliability of the joints?

A variety of techniques exist for non-destructive evaluation (NDE) of beryllium joints, including: X-ray, ultrasonic, laser ultrasonic, infrared imaging, eddy current, dye penetrant, magnetic particle, acoustic emission, and laser holography. Infrared 2-D thermal imaging is considered the most promising technique for detecting unbonded regions over large areas. For non-destructive measurement of plasma sprayed beryllium coating thickness, the "DXT" (distance x thickness) radiation gauging technique based on X-ray attenuation is recommended.

3.13 What are the limiting factors on the use of beryllium in a) the ITER PFC/Blanket environment, and b) a fusion reactor environment?

The most serious limiting factors on the use of beryllium for both ITER and a fusion reactor are: (1) plasma erosion from sputtering and loss of the disruption melt layer, (2) unknown reliability of beryllium joints, (3) tritium inventory buildup, and (4) loss of ductility from neutron irradiation.

The thermal conductivity of beryllium limits the armor tile thickness to 5-10mm at heat fluxes of 5-10MW/m². The allowable operating surface temperature of Be is about 600° C. The brittleness of beryllium prevents its use as a primary structural element or pressure boundary inside of the vacuum vessel. The low atomic weight results in high physical sputtering rates, as well as poor protection of the copper heat sink from runaway electron impact.

The toxicity of beryllium particulate is not considered a large safety hazard when compared to the large quantities of tritium and activated impurities in the Be.

3.14 What are the safety and compatibility issues related to the choice of coolant and coolant structural materials associated with the use of beryllium?

At elevated temperatures (on the order of 800°C), beryllium reacts exothermically with water to form beryllium oxide and hydrogen gas. The reaction rates are greater for porous beryllium and porous plasma sprayed beryllium than for 100% dense material. In a mixed system with carbon, water will react with hot beryllium carbide and release acetylene. Safety concerns are the buildup of explosive quantities of hydrogen or acetylene gas during a water leak. A good understanding of the temperature vs time history of the beryllium during a leak is essential to accurate modeling of the gas evolution. Good thermal conduction paths from the plasma facing components to the cryostat or other heat sinks will be important in minimizing the gas production. Mobilization of toxic beryllium oxide particulate formed from water reactions is also a safety issue. Reactions of beryllium with helium gas or liquid lithium coolants are not considered to be a safety issue.

3.15 Do these [safety] issues restrict the choice of materials and/or coolants?

Helium gas is the preferred coolant over water with regards to chemical reactions with beryllium PFC's. However, computer simulations of the temperature cooldown, and simultaneous hydrogen generation during a water ingress accident in ITER indicate that explosive quantities of hydrogen may not be generated. In this case, water would be an acceptable coolant from the safety perspective. However, more data is needed on the oxidation rates of various forms of beryllium, especially plasma sprayed beryllium. Also, validated models of the transient temperature response during accidents are needed. It should be noted that hydrogen gas will also be generated during water reactions with hot graphite or tungsten PFC's.

3.16 What are the issues regarding health physics, blood tests, and gene tests for beryllium?

The toxic health effects of beryllium exposure are generally well understood. A small fraction, from 1-5%, of exposed individuals are sensitive to beryllium. Recent development of the Blood Lymphocyte Transformation Test (BLTT) has permitted the identification of those individuals who have actually become sensitized to beryllium. Reliable identification *a priori* of individuals who may become sensitized is not yet possible. Development of a real-time (or very short-time), portable beryllium air concentration monitor should be actively pursued.

3.17 What are the possible interactions between beryllium and high-Z first wall materials (tungsten or molybdenum)?

It is very likely that due to disruption melting or ablation and sputtering erosion, a first wall made of both beryllium and high-Z coatings will become intermixed. Beryllium with surface deposits of tungsten or molybdenum will react to form intermetallic compounds that have a higher melting point than Be. MoBe_{22} melts at 1300°C, MoBe_{12} melts at 1690°C, WBe_{22} melts at 1500°C, and WBe_{12} melts at about 1750°C. These beryllide compounds generally have a significantly lower thermal conductivity than beryllium. On the other hand, tungsten or molybdenum with deposits of beryllium will form compounds that begin melting at their eutectic temperatures: 2100°C for Be on W (WBe_2), and 1870°C for Be on Mo (MoBe_2). In general, the properties of these compounds are not known.

CHAPTER 4. INTRODUCTION

On May 2, 1994, Marvin Cohen, Plasma Technology Section, ITER, and Technology Division, Office of Fusion Research, Office of Energy Research, Department of Energy, formed a Technical Evaluation Panel for the Use of Beryllium as Plasma Facing Components and Blanket Components in the International Thermonuclear Experimental Reactor (ITER) project; the Charter for the panel was presented in his letter (Appendix I) along with the panel members.

At the first meeting in Pleasanton, California, he added to the Charter (Appendix II) and two Panel members were added (Jim Hanafey, Lawrence Livermore National Laboratory and Glen Longhurst, Idaho National Engineering Laboratory) (Appendix III).

The Panel has held five meetings and the Agendas and Attendees are presented in Appendices IV, V, VI, VII, and VIII. Prior to completing this report, the Panel released the following reports: **Be Properties** (see Chapter 6, this report), **Mechanical Alloying** (Appendix IX), **Be HIPed Components** (Appendix X), and **Interaction of Be with Mo or W** (Appendix XI).

CHAPTER 5. WHY BERYLLIUM?

Beryllium is the present reference plasma-facing material for ITER, based on a combination of plasma, safety, and design considerations¹⁻⁴. Low atomic number materials have led to significant improvements in plasma performance in present day tokamaks, and beryllium offers some significant improvements over carbon-based materials for most plasma-interactive component applications in the ITER environment.

The Joint European Torus (JET) has been operated with both graphite and beryllium as the plasma-facing materials. With beryllium, the strong oxygen gettering has led to negligible oxygen content, leading to reduced erosion. The presence of beryllium in JET has also led to remarkable improvements in off-normal disruption behavior. No density limit disruptions have been observed, and MHD triggered disruptions are less violent compared to graphite. The time scales for these disruptions to develop are longer, and the current decay times are an order of magnitude lower, leading to lower disruption-induced electromagnetic loads. The production of runaway electrons is also significantly reduced for beryllium, due to the lower radiation losses leading to a hotter plasma with lower loop voltage.

Beryllium has some distinct technological advantages over carbon-based materials. Based on a very limited database, it appears that beryllium suffers significantly less thermal conductivity degradation with neutron irradiation. The interaction of beryllium with tritium is also significantly weaker than that of carbon, leading to potentially reduced tritium inventory. Beryllium does not form a stable hydride above 300°C, so there is no trapping of tritium in co-deposited layers after sputtering. Beryllium also offers the attractive possibility of *in situ* repair by plasma spraying. (Carbon cannot be plasma sprayed because it cannot be melted.) An ITER R&D Program is currently underway to explore issues such as bond strength of beryllium to copper alloy substructure, mechanical properties, and thermal conductivity of the deposited layers.

Tungsten is considered as the only real alternative material to beryllium for plasma-facing material applications in the divertor. Tungsten has a significantly lower hydrogen isotope sputtering erosion than beryllium at low incident energy. Tungsten can also be plasma sprayed. However, there are serious concerns over the compatibility of tungsten with the plasma. The use of tungsten or other high atomic number materials will have to be proven to be viable in present diverted tokamak experiments, such as C-Mod and ASDEX-U, with high auxiliary heating power.

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1. W. B. Gauster and the ITER Joint Central Team, *J. Nucl. Mater.* 212-215. pp.3-10, 1994.
2. ITER Design Option Development, TAC-3, September 1993.
3. Detail of the ITER Outline Design Report, TAC-4, January 1994.
4. ITER R&D Program for TAC5, April 1994.

CHAPTER 6. DESIGN REQUIREMENTS OF THE ITER DIVERTOR

6.1 INTRODUCTION

To find a solution for the ITER divertor is one of the most challenging problems in the ITER EDA. The physics concept must allow acceptable divertor component lifetimes and feasible engineering solutions. Consequently, a robust and flexible engineering design compatible with reasonable maintenance times under remote handling must be developed. Because ITER is the first quasi steady state (long pulse) high power, high neutron flux fusion machine the requirements for the plasma facing components in the divertor are unmatched in any presently existing device. A solution for the ITER divertor is only found if all requirements can be met simultaneously inside a sufficiently large operating window. This chapter summarizes the requirements for the ITER divertor.

6.2 ITER DIVERTOR GENERAL REQUIREMENTS

- The ITER divertor has to exhaust the major part (60% - 80%) of the alpha particle power ($P_\alpha \sim 300\text{MW}$ nominally, but $P_\alpha \sim 600\text{MW}$ at the beta limit).
- The power loads would be 40MW/m^2 to 60MW/m^2 on divertor target plates perpendicular to the magnetic surfaces. Reduction by poloidal tilting of the targets is limited by alignment and space considerations to a factor of 3, giving $\sim 15\text{-}20\text{MW/m}^2$.
- Further reduction of the target power load could be obtained by volumetric losses (e.g. impurity radiation) in the whole divertor chamber, but requires that the total plasma pressure drops by a factor 10 along field lines ("Dynamic Gas Target").
- For the Dynamic Gas Target regime, neutral-plasma interaction in the whole divertor is necessary which can be either obtained in an open divertor configuration (present experiments) or in a wide gas box divertor (physics R&D needed).
- A baffle for neutrals designed for a neutral density (pressure) reduction of 10^4 is needed between the divertor and the main plasma chamber (because of density control, H-mode CX sputtering, impurity retention).
- A transparent wall close to the divertor plasma is required inside the Divertor gas box in order to facilitate efficient momentum removal (physics R&D needed).
- Transient high recycling phases (~ 10 sec) depositing $\sim 15\text{-}20\text{MW/m}^2$ on the energy dump targets will occur causing evaporation and surface melting (Be, W) of the PFC. It is essential that in these phases the joint between the cladding material and the heat sink material does not break and that the heat sink material is not weakened by the accompanied temperature rise ($\Delta T \sim 400^\circ\text{C}$ in the water film).
- The divertor must also withstand giant ELMs and disruptions. The latter deposit up to $\sim 140\text{MJ/m}^2$ on the target plates within 0.1 to 3ms, causing evaporation and surface melting (for metals).
- To achieve acceptable lifetimes (> 100 disruptions) the cladding on the high heat flux components must be as thick as possible (e.g. 1cm Be or W, 3cm C), reducing the steady state heat removal capability (e.g. to $\sim 5\text{MW/m}^2$).
- Regular giant ELMs ($\sim 10\text{MJ/m}$, ~ 100 per discharge) are not acceptable because the resulting target lifetime would be < 50 discharges.
- The divertor component lifetime will also be determined by erosion due to plasma ions and CX-neutrals. The lifetime is maximized if the cladding is as thick as allowed by the predicted steady state power load (e.g. $< 1\text{cm}$ Be or W, $< 3\text{cm}$ C) and if the sputtering threshold including self (+

chemical) sputtering is higher than the particle energy. High Z favored (e.g., W), however, the compatibility of W with good plasma operation needs to be demonstrated.

- The ITER divertor plasma has to entrain target produced and recycling impurities (Ne, Ar,... seeding to enhance radiation), and in particular He. This requires a flow of plasma ions along the SOL towards the target large enough to balance the thermal force.
- The divertor has to withstand the electromagnetic forces during disruptions, in particular, halo current forces
(~ 100 tons downward force and up to 50 tons radial force).
- To reduce the halo current loads to the above values and avoid arcs between adjacent cassettes and between the divertor and the vessel, a defined current path (earth straps ?) is essential.
- The engineering design and choice of material has to take account of the changes in the material properties, such as thermal conductivity (high heat flux components) and mechanical strength (mechanical structure), under neutron irradiation(1MWym²).
- The Divertor components have to provide sufficient neutron shielding (shielding factor ~100) for the vessel and the coils.
- Shut down times longer than 6 month for repair/maintenance of in-vessel components must be avoided in order to obtain reasonable availability for the machine. Therefore maintenance times are needed in the order of <4 months for all in-vessel components.

6.3 DIVERTOR BAFFLE ENGINEERING REQUIREMENTS

The Baffle must provide efficient baffling of the neutral gas in the divertor chamber; prevent the plasma from direct interaction with the transparent side-walls of the divertor channel (leading edges) and act as a limiter for the plasma during transition from limiter to divertor plasmas and during vertical displacement events.

Table 6.1 Input Parameters for Engineering Design

Heat load, MW/m ²	minimum average maximum average peak (up to 10 s)	0.3 5 15	Thermal stresses evaluated for whole range of heat loads. First wall structure must not disintegrate, cooling system for 5 MW/m ²
Neutron load, MW/m ²		0.6	Average
Helium generation in the SS of manifold, appm		0.8	For 3·10 ⁴ pulses (1 MWa/m ² average neutron fluence on the first wall)
Neutron damage in copper, dpa		6.7	
Cooling water:	outlet pressure, MPa inlet temperature, °C pressure drop, MPa water velocity at inlet, m/s	2 130 0.2 5	To avoid boiling at the outlet In order not to exceed the 4.5 MW pumping power
Electromagnetic loads	inboard, MPa outboard, MPa	1.5 1	Pushing or pulling
Allowable leak rate, atm cc/s		1.2·10 ⁻⁷	For inboard and outboard baffles
Allowable total gaps between baffle modules, m ²		0.003	By-pass neutrals leaks should not affect the control over pumping
Toroidal electrical resistance of the first wall, μW		200	Fits with the blanket resistance. Electrical contacts between the baffles and earth straps to divertor cassettes by brazing or mechanical fixation of copper strips
Replacement time, months		<4	Four handling ports in operation

6.4 DIVERTOR CASSETTE ENGINEERING REQUIREMENTS

The entire cassette assembly must be capable of withstanding the thermal loads from the plasma and from the neutron flux, as well as the mechanical loads generated by the electro-magnetic forces and the coolant pressure, and have sufficient conductance to pump the helium ash. The input parameters for the engineering design are listed in Table 6.2.

Table 6.2 Input Parameters for Engineering Design (Divertor)

Total Surface Heat Flux	240 MW	Based on 80% of the total alpha
Total Nuclear Heating	80 MW	
Av. Surface Heat Flux	1 MW/m ²	For Dynamic Gas Divertor
Peak Surface Heat Flux		
Dump, Dome & Wing	5 MW/m ²	
Gas Box Liner	1 MW/m ²	
Peak Transient Surface Heat Flux	<20 MW/m ² for <10s	With 10mm Be local surface melting will occur but there must be no detachment of the Be armor from Cu
Peak Nuclear Heating	0.5 W/cm ³	On the Dome
Disruption Load	10 -140 MJ/m ² 0.1- 3.0 ms	Including ELM's
CHF of Heat Sink	20 MW/m ²	Hypervapotron/Swirl Tube
Toroidal Resistance	> 100μ ²	
Electro- magnetic loads		
Vertical upwards	0.2 MN/cassette	
Vertical	1 MN/cassette	
Downwards	0.5 MN/cassette	
Radial	0.1 MN/cassette	
Toroidal		
Armor Materials		
Dome	Be or W	Optional CFC in a relatively small area of high power flux on the Dump Targets/Vertical Targets
Wings	Be or W	
Dump /Vertical Target	Be	
Bake-out Temperature	300°C - 350°C	
Heat Sink Material	CuCrZr / DS Cu	
Structure Material	316LN	
Coolant	water	All high heat flux elements are fed in parallel off the manifolds in the cassette body.
Inlet Temperature	~150°C	
Inlet Pressure	20 bar	
Mass Flow Rate	6 - 10 tonnes/s	High Dp (>1 bar) through high heat flux elements avoids two-phase flow instabilities
Pressure Drop	~2 bar	
Pumping Power	2 MW	
Alignment of Dome & Dump Target	2mm	maximum step between adjacent cassettes
Divertor Replacement Time	< 4 months	
Pumping / Conductance	1.5x10 ⁶ l/s at 0.1Pa	8% He fraction
Maximum Leak Rate	< 1x10 ⁻⁷ atm cc/s	

6.5 ENGINEERING DESIGN OF THE BAFFLE

Neutral density reduction of 10^4 between divertor and main plasma is realized by Toroidal Limiter/ Baffle modules attached to the lower part of the blanket (Figure 6.1). These modules form a toroidally continuous high heat flux component following the 6cm flux surface (outside the separatrix) above the X-point for about 1.4m of poloidal length.

6.5.1 THE BASIC CONFIGURATION

The basic options for the baffle, as of the writing date, consists of 72 outboard baffles and 48 inboard baffles. Measured poloidally along the first wall, the length is 1.4m for the inboard and 1.9m for the outboard. The weight of one (inboard or outboard) unit is about 4.5 tons. The baffles are fixed on a strong back plate, to which the blanket modules are attached. The back plate carries toroidal rails along which the baffles can slide from the area of one of four remote handling ports to the final position (maximum 45°) around the machine axis.

Cooling water supply for the baffles will be provided through the blanket for the inboard baffles and through the divertor piping ports for the outboard ones. The pipes are routed through one of four inboard blanket modules or four divertor piping ports through the "service" baffle module, and go toroidally in both directions through 9 outboard or 6 inboard baffles. The inboard pipe is 150mm ID, the outboard pipe is 250mm ID. The inboard pipe is integrated with the blanket first wall cooling 80mm ID (needs to be increased to 170mm ID). The reduction in shield performance leads to about 30% local heat deposition rate in the TF coil.

Hot spots with an expected 5MW/m^2 heat load can be cooled by water flowing in these channels with 10m/s velocity, but due to uncertainties in ITER operation it is expedient to also mill transverse teeth at the copper side of the channels thus applying a hypervapotron scheme, which allows enhancing the critical heat flux up to 20MW/m^2 . The first wall is covered with 10mm thick beryllium tiles fixed by brazing (or continuous Be plate with castellations). The body of the baffle is a self-supporting structure made of plates and ribs welded together and to the first wall steel plate, providing appropriate shielding and coolant flow arrangement.

The coolant pipes are conveyed in a hole through the baffle. They enter the body at one point where the water is branched to the baffle. The pipe has a series of convolutions which makes it flexible and allows for adjustment with the pipe nozzle of the next block.

6.6 ENGINEERING DESIGN OF THE DIVERTOR CASSETTES

The divertor gas box consists of 96 divertor cassettes mounted on toroidal rails (Fig. 6.1). Each cassette is 5m long, 2m high and 0.3 - 0.8m wide, and weighs more than 15 tonnes. The cassettes are manufactured in two halves, each consisting of a water-cooled stainless steel structure with Be-clad CuCrZr surfaces towards the plasma side accepting a power load of up to 1MW/m^2 . The transparent wall is realized by wing-like Be or W clad water cooled CuCrZr structures designed to accept 5MW/m^2 steady state heat load.

6.6.1 CASSETTE COMPONENTS

A design using cassettes has been chosen for the following reasons:

- _ minimizing of installation and replacement times (same operations are repeated 96 times)
- _ incorporation of neutron shielding to protect the vessel
- _ neutron damaged coolant pipes are replaced with the cassette
- _ the cassette option gives a more flexible approach to incorporating different divertor designs since the support structure can be changed to support radically different plasma facing components.

An important feature of the design is the modular nature of the components, where beryllium (or tungsten) clad high heat flux elements are manufactured and fully tested prior to being installed onto the support structure towards the end of the manufacturing cycle. This also means that other designs of plasma facing components can be accommodated into the basic divertor support structure relatively late in the program.

6.6.2 CASSETTE BODY

The cassette body is fabricated in two toroidally symmetric halves. The inside of each half is a stainless steel plate or casting (inner) and this is clad with stainless steel sheet on the surfaces not facing the plasma and a cooled copper skin bonded to a stainless steel substrate on the surfaces that will face the plasma. Only the outer skin has to meet UHV requirements.

Between the two half cassettes an alumina coated insulation plate is inserted which has the purpose of increasing the toroidal resistance of the assembled divertor ($>100\mu\text{W}$) and is cooled by conduction to the two halves of the cassette. The side wall cladding of the inner is only attached along the edges to the cassette body, so that when pressurized (20 bar) in the machine the side walls of each cassette will deform slightly and press against the side walls of neighboring cassettes.

Figure 6.1 ITER Divertor Showing the Gas Box Concept

A part of these toroidal loads gives a radial reaction which is transferred to the location pins in the support rails. Advantages of this design are that a single cassette item is installed that will make the toroidal electrical connection, and it can accommodate some thermal distortion or swelling.

6.6.3 DUMP TARGETS AND DOME PROTECTION

Hypervapotron copper alloy plates clad with 10mm thick beryllium are being considered for the high heat flux elements such as the dome and dump targets. A water temperature of around 150°C maintains adequate ductility of the beryllium at the copper interface. Using coolant parameters that give a critical heat flux $>20\text{MW/m}^2$ should ensure that in the event of unexpectedly high thermal transients detaching the cladding, the copper skin which forms the vacuum-water boundary will not be breached. Coolant manifolds are integrated into the plates, leaving only the feed and return as vacuum tight connections to be made during the final assembly onto the support structure. In the case of failure of a plate during final assembly or during initial operation of ITER, the modular approach of the design allows a cassette to be refurbished by the replacement of a single component.

6.6.4 TRANSPARENT WALL OR WINGS

The transparent wall is constructed of 60mm thick vane shaped copper plates that are cooled through small channels running close to the surface. With this geometry the thermal gradient is concentrated into the region between the surface and the coolant channels and the overall thermal distortion of the plate is kept to a minimum. Where the thermal load is highest at the tip of the vane nearest to the divertor channel a larger diameter hole is used in order to give sufficient flow for the bulk temperature of the coolant to remain subcooled. A twisted tape is inserted into this hole at the tip of the vane to increase the critical heat flux.

6.6.5 ALIGNMENT

Shine-through flux strikes the dump targets at a glancing angle (as low as 2°). Targets on adjacent cassettes must be aligned accurately with respect to one another and angled slightly so as to avoid presenting leading edges to the SOL when account is taken of a flux angle, a 10mm gap between adjacent dump or dome targets and a poloidal misalignment between adjacent cassettes of 2mm. Angling the target in this way contributes to the increase in peaking factor which relates the maximum peak load to that which would be incident on a toroidally continuous flat plate. In order to maintain the relative alignment of adjacent targets/domes the cassettes are installed in the vessel on two toroidally continuous rails, that are final machined in vessel using measurements taken with a computer assisted theodolite.

CHAPTER 7. BERYLLIUM SUPPLY AND UNIRRADIATED PHYSICAL/MECHANICAL PROPERTY DATABASE

This chapter is structured to first give basic information about supply, production processes and process terminology. With that background, sample cost information and unirradiated property characterization needs are summarized.

7.1 BERYLLIUM SUPPLY

7.1.1 WORLDWIDE SUPPLY

Table 7.1 shows an estimate of the known world reserves of beryllium with the exception of the former USSR and the Peoples Republic of China. There are an estimated 485,500 metric tons of beryllium in known reserves¹. Projected need for construction of ITER for beryllium is approximately 17 metric tons for first wall, divertor and ICRH and RF antennas, and 187 metric tons for the breeder blanket. Known world reserves can easily satisfy these projected needs.

Known beryllium reserves are large, but the full extent of other reserves are largely unknown. This is because beryllium has traditionally been used for low volume, highly specialized applications, principally aerospace, and known reserves have been sufficient to satisfy those modest needs. In addition there are the unknown size of reserves in the former USSR and in the Peoples Republic of China, and reserves around the world which have not yet been evaluated due to lack of economic demand.

7.1.2 BRUSH WELLMAN SUPPLY AND PRODUCTION CAPACITY

Commercial production capacity data will focus on the production capacity of Brush Wellman, Inc. in the U.S.A, which was until very recently, the only commercial producer of beryllium. With the disbanding of the U.S.S.R., more facilities have become commercially available, but their full capabilities and economic viability are unknown at this point.

Brush Wellman has a peak production capacity of 181 metric tons per year. This is over ten times the projected needs for construction of ITER plasma facing components, first wall, ICRH and RF antennas. Production of beryllium for the breeder blanket would take slightly over a year, depending on the form finally chosen for the blanket. Brush Wellman beryllium reserves are expected to last 46 years at the above production rate, which represents known company reserves of 8,346 metric tons. There are significant uncharted company reserves; economic demand has not been great enough to justify their full exploration.

Table 7.1 Estimated Worldwide Beryllium Supply (except for Russian Federation and China)

	Tons of Be
North and South America	344,000
Europe	4,000
Africa	103,000
India and Afghanistan	26,500
Australia	7,900
TOTAL	485,400

Note: This estimate is not exhaustive for those regions shown. There has not been economic incentive to produce an exhaustive survey.

Source: B.I. Kogan, K.A. Kapustinya, G.A. Topunova, *Beryllium*, Report LN302-88, USSR Ministry of Geology, Nauka Publishing, Moscow, 1975

7.2 SUMMARY OF BERYLLIUM PRODUCTION AND TERMS

7.2.1 OVERALL PRODUCTION DESCRIPTION

Beryllium is produced from bertrandite ($\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$) and beryl ($3\text{BeO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$) ores²⁻⁵. A combination of chemical and mechanical methods are dictated for beryllium extraction due to its very strong affinity for oxygen. Beryl ore must go through a series of high temperature thermal decomposition steps to prepare it for processing. Heat treatment at temperatures as high as 1700°C followed by a water quench is used to break down the complex beryl structure, followed by another thermal decomposition step at 1000°C. Ball milling is then used to prepare the processed beryl ore for leaching. Sulfuric acid leaching at 325°C is used to dissolve beryllium from the processed beryl ore. By contrast, only sulfuric acid leaching at 95°C is needed to extract beryllium from bertrandite ore.

Once beryllium is in solution it is concentrated by solvent extraction and then precipitated as beryllium carbonate. A second hydrolysis step at 160°C is used to precipitate the beryllium as beryllium hydroxide.

Beryllium hydroxide, lime and ammonium bifluoride solution are combined to produce ammonium beryllium fluoride (ABF) salt in aqueous solution. The ABF salt solution is then chemically treated to remove impurities such as iron, lead, manganese and zinc. Vacuum evaporation and a centrifugal separation step produce ABF salt. The salt is decomposed to ammonium fluoride gas and molten beryllium fluoride at 700-900°C in a continuous induction furnace. Solid beryllium fluoride is reduced with magnesium metal to molten beryllium and magnesium fluoride. Upon cooling, a solidified cake of beryllium, magnesium fluoride and unreacted

beryllium fluoride is formed. The solid cake is crushed in a hammer mill and leached with water to remove the beryllium fluoride and most of the magnesium fluoride. A density separation step is used to separate the beryllium from the residual magnesium fluoride. The beryllium is in the form of spherical pebbles at this point.

Beryllium pebbles are processed by vacuum melting to eliminate impurities⁴⁻⁵. Molten beryllium is poured into a graphite mold under vacuum and solidified. The graphite mold reacts with the molten beryllium to form a beryllium carbide skin on the outer surface of the ingot. This carbon rich skin is removed using a lathe.

The beryllium ingot must be processed by either the powder metallurgy (PM) process or by extensive rolling to reduce the grain size and obtain the desired mechanical properties. The powder metallurgy route has the advantage of producing fine grain size without generating very large texturing in the final product. Texturing results in highly anisotropic properties. In the PM process⁴ the ingot is reduced to chips by an engine lathe with a seventeen tool cutter. These chips are too large to manufacture a useful product, so they are sent through one of several powdermaking operations: attrition milling, impact grinding, or ball mill grinding.

The type of powdermaking process used has a significant effect on beryllium properties^{2,4-5}. In attrition milling, beryllium chips are ground into powder between a fixed, grooved beryllium plate and a rotating grooved beryllium plate. Attrition milling produces plate-like particles that tend to align preferentially during die loading, resulting in anisotropic mechanical properties. Impact grinding consists of suspending beryllium chips in a stream of high velocity gas and colliding those chips against a solid beryllium target. The blocky particles produced by impact grinding result in a less textured microstructure and more uniform properties in all directions. Ball mill grinding produces extremely fine particles which in turn produce an extremely fine grained microstructure. The largest volume of beryllium is made using impact ground powder.

Spherical beryllium powder has been made by inert gas atomization⁶⁻⁷ and centrifugal atomization⁸. Both processes involve break up and rapid cooling of a molten metal stream to form powder. This type of powder has only been made in limited quantities.

Beryllium powder must be consolidated to form useful products. Powder consolidation can occur by all the conventional powder metallurgy consolidation techniques including vacuum hot pressing (VHP), cold die pressing and sintering, hot isostatic pressing (HIP), cold isostatic pressing (CIP) and HIP, cold isostatic pressing (CIP) and sintering, cold isostatic pressing (CIP) and extrusion, and so on. Vacuum hot pressing and CIP/HIP are the most widely used consolidation routes.

Like other metals, beryllium can be machined and formed by a wide variety of techniques. It has the general machining characteristics of chilled grey cast iron or heat treated aluminum castings⁹. Beryllium can be rolled, extruded, forged, stamped, jogged, and drawn to produce bars, tubes, sheet, plate, wire and other forms¹⁰.

7.2.2 GLOSSARY OF PROCESSING TERMS

This section is meant to provide the reader with those few processing terms which can quickly convey information about anisotropy of properties and product purity. Beryllium is primarily made by powder metallurgy methods to provide strength in bulk forms, but much of the early characterization work has been done on ingot metallurgy material. A section on powder metallurgy terms will be followed by a section on ingot metallurgy.

1. Powder Metallurgy

a. Grinding Production of most Be powder begins with chipping of a beryllium ingot. The chips are then ground using one of three grinding methods.

1. Attrition Milling Chips are ground into powder between a fixed, grooved beryllium plate and a rotating, grooved beryllium plate. Plate-like particles are produced which tend to align preferentially during powder consolidation steps, resulting in anisotropic mechanical properties. This technique is becoming obsolete.

2. Impact Grinding Beryllium chips are suspended in a stream of high velocity gas and then directed at a solid beryllium target. The blocky particles produced by the impact result in a less textured microstructure and more uniform properties in all directions than attrition milling. The largest volume of beryllium is made using impact ground powder.

3. Ball Mill Grinding Ball mill grinding produces extremely fine particles which in turn produce an extremely fine grained microstructure in the final product. This expensive and time consuming method is used to obtain resistance to mechanical distortion in precision guidance components.

b. Atomization Inert gas atomization produces spherical beryllium powder particles in contrast to the angular or blocky particles produced by grinding. Atomized spherical powder (ASP) generally has less than half as much BeO as the other beryllium powders. This technology has only recently been successfully applied to beryllium.

c. Powder Consolidation The method of powder consolidation has a strong effect on anisotropy of mechanical properties. Cold compaction of powder is either done by cold pressing (CP) or cold isostatic pressing (CIP). Vacuum hot pressing (VHP) and hot isostatic pressing (HIP) are the two most widely used hot consolidation techniques, although sintering and powder extrusion are also performed. Plasma spraying of beryllium to form deposits on substrates is presently being developed.

1. Cold Pressing (CP) Powder is fed into a steel die and then uniaxially pressed from the top and bottom. The cold pressed or green powder billet then goes to one of the hot consolidation processes, usually sintering. Cold pressing tends to yield anisotropic mechanical properties.

2. Cold Isostatic Pressing (CIP) Powder is fed into flexible rubber bags which are sealed and lowered into a water filled pressure vessel. Pressure is applied simultaneously from all directions (isostatically). The CIP billet then goes to one of the hot consolidation processes, usually hot isostatic pressing (HIP), sintering or extrusion. Products produced with a CIP step tend to have more isotropic mechanical properties than products produced with a cold pressing step.

3. Vacuum Hot Pressing (VHP) Powder is poured into a vertical cylindrical die. Pressure is then applied from rams at the top and bottom of the die under temperature and vacuum. Mechanical properties are anisotropic; mechanical properties measured parallel to the pressing direction (longitudinal) are generally lower than properties measured perpendicular to the pressing direction (transverse).

4. Hot Isostatic Pressing (HIP) Loose powder or a cold isostatically pressed (CIP) powder billet are placed in a steel can which is welded shut after degassing at elevated temperature. The sealed can is then placed into a pressure vessel where it is heated and then pressed from all directions simultaneously (isostatically) by argon gas. Simple shapes made by hot isostatic pressing have minimal anisotropy in mechanical properties. Complex near net shapes can be made by this technique.

5. Sintering (S) A cold pressed (CP) or cold isostatically pressed (CIP) billet is placed in a furnace and heated under vacuum. Diffusion of beryllium atoms produces bonding. Sintered products have a coarser grain structure than HIP products and have more anisotropy in mechanical properties.

6. Extrusion Billets made by cold pressing (CP) or cold isostatically pressing (CIP) are generally used as input stock, although extrusion of loose powder has been done. The feedstock is put in a cylindrical steel can, and degassed at elevated temperatures. The can is then welded shut and heated in a furnace. The hot can is then pushed through a die by a ram. Extruded products have anisotropic properties; the properties in the ram direction (longitudinal) differ from those in material perpendicular to the ram direction (transverse).

7. Plasma Spraying This description covers a wide range of processes which spray molten or semi-molten beryllium droplets onto a substrate where they solidify into a partially dense deposit.

2. Ingot Metallurgy

a. Cast This covers any process where molten beryllium is poured into a mold and solidified by liquid heat transfer or solid heat transfer. Cast beryllium generally has very coarse grain size and a different distribution of BeO compared to powder metallurgy beryllium. The strength and ductility of cast beryllium is much lower than powder metallurgy beryllium but can be improved by cold working and hot working it to a fine grain size. Rolling is at present the only practical method to produce a fine grain size in cast beryllium. The most pure forms of beryllium are prepared by casting and zone refining techniques.

b. Ingot Sheet This is beryllium sheet produced from cast beryllium by rolling. It is notable for low BeO content and more ductility in the out of plane direction than powder metallurgy sheet.

3. Refining Processes Beryllium can be refined using the same techniques as other metals, but zone refining and vacuum distillation are currently used the most.

a. Zone Refining A bar of beryllium is placed in a device where the furnace moves axially along it. A very small molten zone is formed at one end of the furnace and impurities are driven into the liquid by thermodynamic forces. Very high purity beryllium with very large grain size is produced. There is not a commercial scale facility for beryllium zone refining.

b. Vacuum Distillation Beryllium is vaporized and separated from impurities by fractional condensation. A high purity, coarse grained product is produced.

7.2.3 SUMMARY OF COMMERCIAL GRADES

Since much of the post 1979 property characterization has been for commercial grades, a brief summary of them is given below by name, nominal chemical composition and nominal tensile properties. Although beryllium is used in relatively small quantities compared to steel or aluminum, specific grades have been tailored for the major aerospace applications: structural, guidance instruments and optics. Grain size, impurity content, anisotropy and BeO content are the principal differences between these grades.

The properties and degree of characterization vary depending on the needs of the applications:

Structural grades (S-65C, S-200F, S-200E) are processed to provide the highest strength. They are the most versatile grades and are the most well characterized. Note that S-65C is the reference material in ITER for plasma facing component and first wall applications.

Instrument grades (I-220B, I-400A, I-70A) are optimized to provide the least distortion in aerospace guidance instruments. They are optimized to provide the best precision elastic limit (PEL), which is the maximum stress which can be applied before one microinch of plastic strain is made.

Optical grades (O-50, I-70A, I-220B) are optimized for reflectivity, thermal expansion and polishing characteristics. The principal application is in satellite mirrors, although there are some terrestrial mirror applications where weight and infrared reflectivity are important.

Chemical composition and nominal room temperature tensile properties for commercially available beryllium grades are discussed in the section on reasonable values of room temperature physical and mechanical properties. Specific values for each grade are shown in Appendix I.

7.2.4 SAMPLE BERYLLIUM COSTS

Any material cost is a function of the following variables:

- a. Volume
- b. Number of Processing Steps
- c. Complexity of Product Shape
- d. Grade
- e. Tolerances

Beryllium is a specialty material which has found most of its use in weight critical aerospace applications. These applications are generally custom by nature and consist of 1 - 50 piece lots. The volume of beryllium which could be used in ITER will have a significant effect on overall costs. Examples of Brush Wellman cost estimates for the projected needs discussed are shown in Tables 7.2 through 7.5. Note that specific product shapes and processing steps are assumed for these cost estimates.

As shown by comparing Table 7.2 and Table 7.4, complex pieces such as the divertor module will cost much more than the simpler blanket modules on a per weight basis.

The cost of beryllium is high on a per unit weight basis compared to commodity metals such as aluminum. However, if one is covering a surface, one kg of Be goes further than any other structural metal due to its low density, particularly compared to tungsten. Table 7.6 compares the cost of covering the first wall with tungsten sheet versus the cost of using Be sheet. Three mm thick sheet is assumed. Beryllium would be 64% of the cost of tungsten.

Table 7.2 Cost Estimate for Beryllium in Breeder Blanket

Material	\$510/kg
- S200F Powder	
- 70% yield	
Fabrication	\$ 81/kg
- Load/CIP/EXT/MACH/FORM	
Tooling - Expendable	\$ 11/kg
- Cans/Bags/Etc.	
Quality Control	\$ 15/kg
- Etch and Visual	
- Inspect per Fixture (Go/No Go)	
TOTAL	\$627/kg
Fixed Tooling	\$ 4.2M
- Machine Tools - E,H &S	
- Fixtures (Mach.,Load,Form)	
- Flattening Press	

Based on a 1993 design for Be modules in a molten metal breeder blanket. This assumes curved Be sections which are 11 m x 2 cm x 4 cm.

Table 7.3 Brush Wellman Cost Estimates for Bumper Limiter Modules

Material	\$535/kg
- S65C Powder Yielded Price	
- 70% yield	
Fabrication	\$ 64/kg
- Load/CIP/EXT/MACH	
Tooling - Expendable	\$ 22/kg
- Cans/Bags/Tool Bits/Etc.	
Quality Control	\$ 10/kg
- X-ray input powder	
- Etch and Visual	
- Inspect per Fixture (Go/No Go)	
TOTAL	\$631/kg
Fixed Tooling	\$ 2.1M
- Machine Tools - E,H &S	
- Fixtures (Mach.,Load)	

Based on a 1993 design which is very similar to current design: segments with saddle shaped curve on one side. Overall dimensions are 250 mm x 94 mm x 20 mm.

Table 7.4 Cost Estimates for Straight Beryllium Tube Divertors

Material	\$565/kg
- S65C Powder Yielded Price	
- 60% yield	
Fabrication	\$260/kg
- Load/CIP/EXT/MACH	
- Can/HIP Bond	
Tooling - Expendable	\$ 55/kg
- Cans/Bags/Tool Bits/Etc.	
Quality Control	\$ 20/kg
- X-ray input powder	
- Etch and Visual	
- Inspect per Fixture (Go/No Go)	
TOTAL	\$900/kg
Fixed Tooling	\$ 5.1M
- Machine Tools - E,H &S	
- Fixtures (Mach.,Load)	

Based on a 1993 design: 4mm o.d. x 4mm wall x 1000mm

Table 7.5 Brush Wellman Cost Estimates for Various Stock Product Forms.

A. -38 + 10 mm SPHERICAL Be POWDER	\$352/kg
- for Be Plasma Spraying	
B. 1/16 in. dia. Be WIRE	\$5,690/kg
- for Be Plasma Spraying	
C. 3 mm THICK SHEET CUT	\$1,200/kg
from HIPed Be BLOCK	
- S-200FH	
- 3 mm x 240 mm x 450 mm	
* If Slurry Saw Initiative succeeds, cost could drop to \$800 /kg	
D. 3 mm THICK PM SHEET	\$1,300/kg
- SR200	
E. 3 mm THICK Be INGOT SHEET	Price Not Available
- MSC price	
F. 1 - 2 mm Be SPHERES	\$ 670 /kg
- for Breeder Blanket	

NO FINISH MACHINING INCLUDED IN ABOVE COSTS

Table 7.6 Cost Comparison of Be Sheet and Tungsten Sheet

	Density (kg/m ³)	\$ /kg	\$ /m ²
Be ¹	1,850	1,200	6,660
W ²	19,300	180	10,422

¹ Sheet cut from S-200FH block

² WS2 99.95% pure W plate

NOTES:

The cost of beryllium is high on a per unit weight basis compared to commodity metals such as aluminum. However, if one is covering a surface, one kg of Be goes further than any other structural metal due to its low density. The cost of 3mm thick sheet is compared.

7.3 REASONABLE BERYLLIUM PROPERTIES

The purpose of this section is to provide the fusion community with an overview of reasonable properties which can be expected from commercial beryllium.

7.3.1 BACKGROUND

There is continuing confusion in the fusion community as to what levels of mechanical properties can be realistically achieved for beryllium using standard methods of metal property development. There were some references in the late 70's to a beryllium which had 10% elongation in three orthogonal directions* at room temperature, so-called "ductile beryllium". A wealth of scientific data shows this to be improbable. Early work in the 60's and 70's was able to achieve ductility increases in beryllium products from 1% min (2% typical) to the current 3% min (4-5% typical) by a combination of lower oxide content, finer grain size and impurity control. Such improvements, unfortunately, have their limits since they are essentially second order effects rather than fundamental solid state changes. Selected beryllium products with 4% min. ductility may be available in the near term (at added expense) from current products. Further substantial increases in room temperature isotropic ductility are unlikely in a commercially feasible product form; i.e., it is unlikely that so-called ductile beryllium can ever be produced.

It is considered a critical task of this forum to provide realistic beryllium mechanical property values for use by ITER tokamak designers. As with most metals, beryllium mechanical properties are a function of texturing, degree of mechanical work, grain size and composition; beryllium, having hexagonal close packed structure, is especially sensitive to texture effects. This document provides ranges of properties which reflect changes in those critical variables. Beryllium properties are also influenced by processing, and general trends are given.

Finally, certain constraints are outlined which must always be used when designing with a commercial material.

* For example: V. Ivanov et.al., Phys, Met. Metall., 47(2), pp. 169-173 (1977)

7.3.2 EFFECT OF TEXTURING

Beryllium with isotropic mechanical properties can be produced by hot isostatic pressing. As will be described below, the unit cell crystal structure inherently limits the magnitude of these isotropic properties. Property values beyond those limits are achieved by texturing in limited product directions at the expense of properties in other directions.

The anisotropy of beryllium properties with crystallographic direction is well documented. A single crystal of beryllium will have very different mechanical properties depending on which crystallographic direction is tested. Ductility of beryllium single crystal is virtually zero parallel to the crystallographic "c" axis. The limiting factor, therefore, in beryllium ductility is the ease of cleavage of the basal plane in the hcp structure. Stresses perpendicular to the basal planes are not reduced by slip and cause cleavage.

Polycrystalline beryllium with fine grain size masks some of the anisotropy depending on how randomly the single crystal grains are oriented; there is an averaging effect. If the grains have a tendency to align their crystallographic planes with each other, the bulk sample is said to be textured. Degree of texturing varies from zero (random distribution of crystallographic axes) to 100%, as shown in Figure 7.1.

Figure 7.1 also shows the effect of texturing on anisotropy in percent elongation. The randomly oriented crystals in the block form (most closely realized by HIP products) give relatively low but uniform average percent elongation in three orthogonal directions. The moderately textured ingot sheet gives higher elongation in the two in-plane directions, but a decreased percent elongation in the through thickness direction. Highly textured powder metallurgy sheet with virtually all basal planes parallel to the sheet surface shows even higher elongation in the two in-plane directions, but zero elongation in the through thickness direction.

7.3.3 REASONABLE PHYSICAL AND MECHANICAL PROPERTY VALUES FOR BERYLLIUM AT ROOM TEMPERATURE

Table 7.7 lists reasonable physical properties for beryllium.

Table 7.8 lists the range in mechanical properties for different product forms as a function of degree of texture. The ranges represent the span from the lowest minimum guaranteed (specified) value for that product family to highest typical production value for that product family. For example, under VHP products, the lowest UTS value is the minimum specified for S-200F grade beryllium and the highest value is the typical value for S-65C grade beryllium. This gives the fusion community a realistic range with which to compare other values encountered. If quoted a UTS of 350 MPa for VHP material, the fusion scientist can see that it is above the manufacturer guaranteed minimum, but still below a typical value which can be obtained with conventional technology. If given a percent elongation of 10%, the fusion scientist knows that it must be for an anisotropic product which most likely has less than 1% elongation in an orthogonal direction.

A list of manufacturer's specifications for chemical composition and room temperature mechanical properties of commercial beryllium grades is given in Table 7.13.

Figure 7.1 Example of the Effect of Texture and Degree of Preferred Orientation on Tensile Elongation of Beryllium Hot Isostatically Pressed (HIP) Block, Rolled Ingot Sheet, and Rolled Powder Sheet

7.3.4 PROPERTY IMPROVEMENT RESEARCH

Much of ITER Task T-1 is devoted to improving Be properties, especially room temperature ductility. However, it is critical that the scientists performing this task be aware of the great amount of previous research conducted in this area. Excellent reference articles which consider property improvement based on fundamental principles are found in the two volume 1979 publication entitled *Beryllium Science and Technology*. In particular, the properties of high purity (100 ppm total impurities) beryllium and single crystal beryllium are summarized.

The crux of this research is that in order to dramatically increase the percent elongation of beryllium, stresses causing basal plane cleavage must be relieved by non-basal slip or cross slip of basal dislocations. Interatomic bonding is not changed by thermomechanical processing and the many conventional alloying techniques have failed to improve ductility.

The benefits of the improvements described above have already been realized and further substantial ductility increases are highly unlikely.

Table 7.7 Baseline Physical Properties

	Value	Reference
Melting Temperature	1289°C	11
Boiling Temperature	2470°C	11
Heat of Fusion	1132 kJ/kg	11
Heat of Vaporization	24,930 kJ/kg	12
Density	1848 kg/m ³	13
Electrical Resistivity	$\approx 4 \times 10^{-8}$ W-m	14
Thermal Conductivity	204 W/m-K	15
Coefficient of Thermal Expansion	11.5×10^{-6} /degree K	16
Vapor Pressure	$\log P \text{ (atm)} = 6.186 + 1.454 \times 10^{-4}T - 1.6734 \times 10^{-4}T^2$	17

Table 7.8 Reasonable Mechanical Property Values for Different Beryllium Product Forms at Room Temperature

	Ultimate Tensile Strength (MPa)	Yield Strength (Mpa)	Elongation (%)
ISOTROPIC HIP Block	352-606	257-634	2.4 - 5.1
Highly Textured Sheet			
Powder Metallurgy Sheet ¹			
- In Plane	483	345	10
- Through Thickness (out-of-plane)	-	-	< 1
Ingot Metallurgy Sheet ²			
- In Plane	276	138	3
- Through Thickness (out-of-plane)	-	-	< 1
Strongly Textured Extrusions³			
-Longitudinal (Extrusion Direction)	745	345	10
- Transverse (perpendicular to Extrusion Direction)	434	372	0.6
Moderately Textured VHP Block			
- Longitudinal	241-372	172-346	2 - 4.0
- Transverse	241-397	172-251	2 - 6.0

NOTE: Values represent range in properties for various grades from manufacturer guaranteed minimum to typical production values. Materials producers will only guarantee minimum specified properties; they will NOT guarantee typical or mean values.

¹ Limited by basal plane cleavage

² Guaranteed Minimum values only

³ Typical values only

7.3.5 CLASSIFICATION SYSTEM FOR BERYLLIUM GRADES

The fusion community is faced with interfacing Western beryllium grade nomenclature with the disparate nomenclature of Russian Federation and Kazakhstan beryllium. There are constraints on data for the *ITER Design Data Book*. Trade names cannot be used, and data must be accepted by the international members of the review board. There are, however, process and compositional categories which must be used to describe

any metal to put its properties in perspective. We suggest the categories in Table 7.9. An example of usage is shown in Table 7.10.

Although this list may seem to lend an inordinate emphasis to details of processing, it is necessary because beryllium is a low volume (about 50 tons/yr) specialty material. It is made many different ways depending on the specific application, and data in the literature can be from any of these ways, particularly data prior to 1970. For example, although most of the aerospace grades are made by vacuum hot pressing powder, the most cost effective way to produce the belt limiter tiles for JET was a Cold Die Press (CDP) and Vacuum Sinter (VS) process. This latter approach saved JET money because it is a near net shape process.

Table 7.9. Suggested Categories for Beryllium in the *Materials Handbook for Fusion Energy Systems* and the *ITER Design Data Book*

Wt% Be	
Wt% BeO	(BeO has a large effect on thermal and high temperature properties)
Form	Block, plate, sheet, tube, etc.
Major Production Process	Powder metallurgy or ingot metallurgy
Powder Production Process	Comminution, Atomization, Rotating Electrode Process
Powder Metallurgy Comminution Process	Impact Grinding, Attrition Milling, Ball Milling
Powder Metallurgy Consolidation Process	1- Cold Isostatic Pressing (CIP) 2- Hot Isostatic Pressing (HIP) 3- Cold Die Pressing (CDP) 4- Vacuum Sintering (VS) 5- Direct Extrusion (DE) 6- Direct Rolling

Table 7.10 Example of Description of Beryllium Grades Based on Proposed Categories

Grade	wt% Be	wt% BeO		Major Production Form	Powder Production Process	P/M Comminution Process	P/M Consolidation Process
S-200F	98.5 ¹	1.5 ¹	Block	P/M	Comminution	Impact Grinding	VHP ²
JET ³ (S-65C)	99.0 ³	1.0 ³	Tile	P/M	Comminution	Impact Grinding	CDP/VS/HIP ⁴

¹ Manufacturer Specification.

² Vacuum Hot Pressing

³ Specification for Belt Limiter Tiles

⁴ Cold Die Pressing (CDP) followed by Vacuum Sintering (VS) and Hot Isostatic Pressing (HIP)

7.4 BERYLLIUM MECHANICAL PROPERTY CHARACTERIZATION NEEDS, COSTS AND TIMETABLE

The panel was charged with determination of the minimum critical characterization needs for use of existing grades of beryllium in ITER applications. Recommendations were based on a review of existing databases.

7.4.1 SCOPE OF PROPERTY REVIEW

A review was made of beryllium properties at temperatures of interest for principal Be applications in plasma facing components and the breeder blanket. The temperatures of interest span the range from room temperature to 600°C for steady state applications, and up to the melting point of beryllium for plasma disruption events. There is a wealth of data from the 1950's and 1960's for large characterization programs investigating materials for use in nuclear fission reactors and *The Reactor Handbook*¹⁸ is a good summary of this data on obsolete grades. However, there have been significant product and process improvements in the subsequent 30 years. The current range of available beryllium products have not had a similar characterization program. While there is a large and recent database for room temperature property data, there is considerably smaller and less extensive database for properties of current commercial products at the higher temperatures. Beryllium block was a focus for the property review because there has been a significant amount of characterization since Pinto¹³ and because block is being seriously considered for a number of tokamak applications. Plasma sprayed beryllium was also emphasized because the ITER community is interested in plasma spraying capabilities for in-situ repair and original manufacture of complex shapes. Other product forms are made in relatively low volumes and have not had a significant amount of characterization since the review by Pinto¹³.

7.4.2 SUMMARY OF UNIRRADIATED PROPERTY CHARACTERIZATION NEEDS FOR PFC APPLICATIONS

This discussion focuses on the temperature range of interest for plasma facing component applications. This has variously been described as room temperature to 600°C and as room temperature to the melting point. Other conditions such as strain rate will need to be specified, particularly for tensile properties, creep, and fatigue. Both powder sheet and ingot sheet have adequate databases for basic properties and will only be mentioned in critical areas.

Thermal conductivity is broadly defined but needs to be more specifically defined for VHP grades and best available plasma sprayed beryllium.

CTE of block grades needs to be accurately measured over the whole temperature range of interest for fusion applications. Measurement of CTE for both VHP and HIP grades would be beneficial and is definitely needed for plasma sprayed beryllium. Measurements would have to be made for the longitudinal and transverse directions of the VHP material.

Electrical resistivity of block materials needs to be measured over the whole temperature range of interest for fusion applications. This needs to be done for grades with different impurity levels and plasma sprayed beryllium. Measurements should be made for the longitudinal and transverse directions of the VHP material.

The temperature dependence of elastic modulus is described with a few data points. Additional data points may be needed on either S-65C or a HIP grade.

Shear modulus needs to be measured as a function of temperature for modern beryllium grades.

There is significant scatter in room temperature Poisson's Ratio and no temperature dependence of this property. Thorough and precise characterization is needed in general, although it is not known how important this property is to the fusion materials community.

There has been some call in the fusion community for precision stress versus strain curves for temperatures up to 1200°C. If needed, characterization of several grades with different BeO contents would be most useful, but characterization of S-65C and plasma sprayed beryllium is needed as a minimum. Strain rates relevant to fusion would have to be specified. Measurements would have to be made for the longitudinal and transverse directions of the VHP material.

Although there is sufficient data to see the trends of tensile properties with temperature, there is not complete coverage of the temperature range for all modern grades. There is a good data set for ingot sheet, and a good framework for S-65C grade. It would be useful to obtain more data for S-65C grade, since it is the baseline beryllium material. Measurements would have to be made for the longitudinal and transverse directions of the VHP material. However all the above data is for aerospace relevant strain rates. A complete characterization program using strain rates relevant to fusion may be desirable. Characterization of plasma sprayed beryllium is definitely needed, and characterization of HIP grades may be very useful.

There is a lack of systematic creep data and high temperature fatigue data for all beryllium grades presently in production. This may be one of the most critical deficiencies in the database, since beryllium will be subjected to thermal cycles and has a design steady state operating temperature of 600°C. This data would be invaluable in modeling and extrapolating from high heat flux data. Data is needed on S-65C and plasma sprayed beryllium. Measurements would have to be made for the longitudinal and transverse directions of the VHP material. Characterization of a HIP grade, ingot sheet and powder sheet would be useful in exploring different options in severe use areas. The sheet grade data may be useful in assessing the possibilities of laminated sheet composites.

A complete set of data is needed on the temperature dependence of fracture toughness, particularly for S-65C data which suggests that beryllium made by HIP from atomized spherical powder has higher fracture toughness than beryllium made from impact ground powder, and it would be useful to gather more data. It is not possible to generate valid K_{IC} for sheet, but K_Q values may be of some use to the designers.

Table 7.11 lists the variables which would need to be considered for each of the properties discussed.

Table 7.12 lists the bare minimum of critical characterization which is needed. The tests are given in rough order of descending priority. **The minimum characterization program would need \$786K.** As discussed, characterization in various categories could be beneficially doubled or tripled beyond this to give the fusion designers more flexibility in severe use applications. Baseline needs were seen as characterization of S-65C and plasma sprayed Be products. A minimum characterization of three replicates at six different temperatures was assumed for plasma sprayed beryllium, for 18 tests per property. This number was doubled to 36 for S-65C to account for the anisotropy in the longitudinal and transverse directions. The above needs are based on the categories in the IAEA Fusion Materials handbook and do not represent all characterization which may be useful to the designer. For example, crack propagation kinetic data (da/dN curves) have been suggested.

This characterization matrix is by no means an exhaustive list. There have also been interesting proposals for use of Be sheet laminates in severe thermal cycling applications. This idea rests on the hypothesis that placing the plane of highest ductility perpendicular to the surface will minimize thermal fatigue cracking, and would be interesting to test. Adding such characterization to the matrix in Table 7.12 can be easily accomplished by multiplying the given value by the percentage increase in test number, as the cost will be roughly linear with number. As it stands, Table 7.12 represents a critical minimum of data.

Excepting creep and high temperature fatigue testing, the above tests could be accomplished in one year. Creep and high temperature fatigue testing would require approximately two years.

Table 7.11 Variables for Property Measurements
Suggested Characterization Matrix
(Unirradiated Properties)

	Temp.	Strain Rate	Appl. Load	Freq. (Hz)	No. of Cycles	Be Grades
Creep	X	X	X			X ²
Fatigue ¹	X	X	X	X	X	X
Poisson's ratio	X					
Thermal Conductivity	X					X
Elastic Modulus	X					
CTE	X					X
Fracture Toughness	X					X
Precision Stress vs. Strain	X	X				X
Electrical Resistivity	X					X
Ultimate Tensile Strength	X	X				X
Yield Strength	X	X				X
Elongation (%)	X	X				X

¹ Might want to run in vacuum to minimize environmental effects

² Must characterize properties for a minimum of 2 grades: S-65C and Plasma Sprayed Deposits. Consider HIP grades, including HIPed atomized spherical powder.

Table 7.12 Minimum Number of Beryllium Characterization Tests and Estimated Costs

**Suggested Characterization Matrix:
(Unirradiated Properties)**

	No. of Tests ¹	Total ²
Elevated Temperature Fatigue	180	\$300k
Creep	90	\$120k
Poisson's ratio	36	\$ 36k
Thermal Conductivity	36	\$ 22k
Elastic Modulus	36	\$ 30k
CTE	54	\$ 33k
Fracture Toughness	45	\$150k
Precision Stress vs. Strain	18	\$ 50k
Electrical Resistivity	18	\$ 15k
UTS	54	\$ 30k
YS	54	included in UTS
% elong.	54	included in UTS

Note: Ranked in decreasing order of importance

¹ Baseline no. of tests: 6 temperature. x 3 rep./temp. x 2 grades = 36; 2 grades = S-65C and Plasma Sprayed Be (This is a minimum. L and T directions must be characterized for VHP material, bringing the minimum to 36 + 18 = 54. Characterization of HIP grades and HIP spherical powder is desirable.)

² Rough Estimate which includes machining samples, \$/test and applicable set up charge. Does not include engineering support, final evaluation and report.

Table 7.13 Manufacturer Specifications for Chemical Composition and Room Temperature Tensile Properties of Commercially Available Structural Beryllium Grades

(Typical mechanical property values are higher than specifications.)

CHEMICAL COMPOSITION

	S-65B/S-65C ¹	S-200E ²	S-200F ¹	S-200F-H ³	S-200F-C ⁴
Be, min %	99.0	98.0	98.5	98.5	98.5
BeO, max %	1.0	2.0	1.5	1.5	1.5
Al, max ppm	600	1600	1000	1000	1000
C, max ppm	1000	1500	1500	1500	1500
Fe, max ppm	800	1800	1300	1300	1300
Mg, max ppm	600	800	800	800	800
Si, max ppm	600	800	600	600	600
Other, max ppm	400	400	400	400	400

SPECIFICATIONS FOR TENSILE PROPERTIES AT ROOM TEMPERATURE

	S-65B/S-65C ¹	S-200E ²	S-200F ¹	S-200F-H ³	S-200F-C ⁴
Ultimate Tensile Strength (MPa), min	290	276	324	414	262
Typical - L	372	NA	372	441	317
- T	397	NA	393	414	262
0.2% Offset Yield Strength (MPa), min	207	207	241	297	172
Typical - L	251	NA	255	345	207
- T	251	NA	241	345	172
% Elongation, min	3.0	1.0	2.0	3.0	2.0
Typical - L	3.8	NA	4.0	4.9	4.1
- T	6.0	NA	6.0	4.9	4.1

¹ Impact Ground Powder, Vacuum Hot Pressed (VHP) grade. S-65B and S-65C differ only in inspection specifications

² Attrition Ground Powder, Vacuum Hot Pressed (VHP) grade

³ Impact Ground Powder, Hot Isostatically Pressed (HIP) grade

⁴ Impact Ground Powder, Cold Pressed (CP) and Sintered (S) grade

NA = not available

Table 7.14 Manufacturer Specifications for Chemical Composition and Room Temperature Tensile Properties of Commercially Available Beryllium Sheet Grades

(Typical mechanical property values are higher than specifications.)

CHEMICAL COMPOSITION

	MSC-100 ¹	SR-200 ²
Be, min %	99.5	98.0
BeO, max %	< 100 ppm	2.0
Al, max ppm	1000	1600
C, max ppm	1000	1500
Fe, max ppm	1500	1800
Mg, max ppm	NA	800
Si, max ppm	1000	800
Other, max ppm	100	400

SPECIFICATIONS FOR TENSILE PROPERTIES AT ROOM TEMPERATURE

	MSC-100 ¹	SR-200 ²
Ultimate Tensile Strength (MPa), min	276	483
0.2% Offset Yield Strength (MPa), min	138	345
% Elongation ³ , min	3.0	10.0

¹ Fully annealed ingot sheet

² Impact Ground Powder, Vacuum Hot Pressed (VHP) grade

³ Elongation in the plane of the sheet. Out-of-plane elongation is significantly lower (<1%).

NA = not available

Table 7.15 Manufacturer Specifications for Chemical Composition and Room Temperature Tensile Properties of Commercially Available Instrument and Optical Beryllium Grades

(Typical mechanical property values are higher than specifications.)

CHEMICAL COMPOSITION

	I-70 ¹	I-70-H ²	I-220-H ²	I-250 ²	I-400 ³	O-50 ²
Be, min %	99.0	99.0	98.0	97.0	94.0	99.0
BeO, max %	0.7	0.7	2.2	2.5	4.25 min.	0.5
Al, max ppm	700	700	1000	1000	1600	700
C, max ppm	700	700	1500	1500	2500	700
Fe, max ppm	1000	1000	1500	1500	2500	1000
Mg, max ppm	700	700	800	600	800	700
Si, max ppm	700	700	800	600	800	700
Other, max ppm	400	400	400	400	100	400

SPECIFICATIONS FOR TENSILE PROPERTIES AT ROOM TEMPERATURE

	I-70 ¹	I-70-H ²	I-220-H ²	I-250 ²	I-400 ³	O-50 ²
Ultimate Tensile Strength (MPa), min	241	345	448	517	345	241
Typical - L	NA	503	634	606	NA	NA
- T	NA	490	634	606	NA	NA
0.2% Offset Yield Strength (MPa), min	172	207	345	448	NS	172
Typical - L	NA	338	542	524	NA	NA
- T	NA	338	542	524	NA	NA
% Elongation, min	2.0	2.0	2.0	1.5	NS	2
Typical - L	NA	5.1	3.7	3.0	NA	NA
- T	NA	5.1	3.7	3.0	NA	NA
Microyield Strength ⁴ (MPa)	12	21	41	69	62	NS

¹ Impact Ground Powder, Vacuum Hot Pressed (VHP) grade

² Impact Ground Powder, Hot Isostatically Pressed (HIP) grade

³ Ball Milled Powder, Vacuum Hot Pressed (VHP) grade

⁴ Stress required to produce first 2.5×10^{-2} mm (1×10^{-6} inch) of permanent strain

NS = no specification

NA = not available

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CHAPTER 8. EFFECTS OF IRRADIATION ON BERYLLIUM PROPERTIES

When beryllium is subjected to irradiation by neutrons, several material property changes are known to take place. Helium and some tritium are produced resulting in swelling and embrittlement. Activation of beryllium is minor, but impurity activation may be significant. The degree and nature of the effects of neutron irradiation will vary with the material purity and fabrication history, the location (neutron energy spectrum), and operating conditions. The three areas of ITER considered here are the divertor, the first wall, and in a breeding blanket. In this chapter we examine the available information on these processes and consider actions needed to fill in the gaps.

8.1 RADIATION EFFECTS - CURRENT KNOWLEDGE

High energy neutrons impinging on beryllium generate structural defects and material transmutations. Displacement damage leads to point defect clustering, irradiation hardening, and embrittlement. Transmutations produce helium and lithium (which eventually becomes tritium) leading to high levels of gas-driven swelling and embrittlement. These processes are dependent on neutron energy spectrum, on temperature, and on material form and history.

Two reaction chains produce He. The first,

(1)

is the (n,2n) neutron multiplication reaction for which beryllium is used in breeding blanket designs. It has an effective threshold of 2.7MeV incident neutron energy and a cross section of about 500mb. The second chain,

(2)

results in two helium atoms and a tritium atom for each beryllium transmuted. The energy threshold is lower, about 1.4MeV, and the cross section for the first stage (n, α) peaks at about 100mb.

Experimental data have been gathered on a variety of material grades. However, the irradiation conditions have been either at low temperature over a range of neutron fluences from low to high fluences, or to only low fluences at higher temperatures. Most of the data reported are from thermal fission reactors, with relatively little coming from fast-flux reactors. Measurements have mostly been made on older grades of beryllium. Not many data are for modern hot-isostatically-pressed (HIP) or rolled vacuum-melted products. None are for plasma-sprayed beryllium. When considering data available on irradiated material properties, it is important to rely on information for modern commercial grades. Often older material had high BeO content, high impurities, and unknown microalloying. Processing used to produce samples varied widely, and there is a significant correlation between processing history and irradiation effects.

8.1.1 SWELLING

In an excellent review on radiation effects on beryllium, Gelles and collaborators¹ noted that there are three regimes of swelling response to damage and helium production in beryllium irradiated at low temperatures (40-80°C): (1) the point defects accumulate, but the helium remains essentially immobile; (2) the point defects coalesce, and the helium moves; and (3) gas-driven swelling takes place. Correlations have been developed that show swelling is linearly dependent on fluence,² non-linearly dependent on fluence,³ and related to fluence and temperature in rather complex ways.^{4,5} At low temperatures, helium is relatively immobile and remains dispersed in the beryllium, almost as if it were in solid solution. Swelling is typically of order 1% for fluences of order 10^{22} n/cm². At higher temperatures of 400-600°C, defects coalesce, and bubbles nucleate at damage sites from the migrating helium. Swelling is of order 10%. At temperatures above 600°C, helium bubbles grow markedly. Swelling may reach 25-40%. As bubbles exceed a critical size, interconnected porosity develops, and helium is released along with tritium in what is termed breakaway swelling.^{6,7}

These results are for material irradiated at low temperatures and then subjected to thermal anneals. Relatively few data are available for material irradiated at higher temperatures. In one report by Rich, Walters, and Barnes,⁸ beryllium irradiated at temperatures of 280-480°C showed no initial swelling after a fast neutron fluence of about 3×10^{21} n/cm², though microscopic examination revealed the presence of relatively large (50-Å diameter) helium bubbles before any annealing was performed.

It may be possible to minimize swelling by adding a dispersed bubble nucleating material, such as finely dispersed oxide. The concept is based on the belief that if the tiny helium bubbles become pinned by local defects before they can coalesce into larger ones, the small bubble radius, combined with interfacial surface tension, will keep the gas pressure higher and thus reduce volume changes.

8.1.2 MECHANICAL PROPERTIES

Studies on strength and ductility changes due to irradiation have shown that irradiation temperature affects response. At low irradiation temperatures, strength increase due to irradiation is most evident, whereas at high temperatures (near 650°C) embrittlement can take place without significant strength increase. The general trend for variation of strength with fluence following low temperature irradiation is for the strength to begin to increase at fluences of about 10^{19} n/cm² ($E > 1$ MeV), to saturate as ductility approaches zero (about 1.5×10^{22} n/cm²), and then to decrease with further fluence. Strength increases up to 4-5 times unirradiated values have been observed. A similar effect is seen for irradiation effects on ductility. Irradiation makes the material more brittle. In measurements made on cold pressed and sintered powder-metallurgy product with densities from 80% to 97% of theoretical density, irradiated at about 75°C to a fluence of 2.6×10^{21} n/cm² in a thermal fission reactor, strengths increased and ductilities decreased following irradiation, both by a factor of 4-5.⁹ Hardness generally correlates with strength.¹⁰ Irradiated materials have increased hardness, but fracture toughness is reduced by irradiation.

8.1.3 THERMAL PROPERTIES

Not much information is available on the effects of neutron irradiation on thermal conductivity. A single (Russian, V. Barabash) paper shows little effect, but there is a very limited data base. In theory, widely spaced large helium bubbles should have little effect, since most thermal conduction is done by electrons whose paths the bubbles would not significantly interrupt.

8.2 ITER DESIGN ASSESSMENT

As presently planned, beryllium is contemplated for use in the ITER divertor, on the plasma-facing first wall of the shield structure, and as a neutron multiplier in blanket test modules, or possibly in a tritium breeding blanket if that concept returns to vogue. Here are addressed issues regarding those applications, particularly in light of neutron irradiation effects.

8.2.1 DIVERTOR

The present divertor concept considers use of beryllium in the divertor mainly on the energy dump plates at the bottom of the divertor channels, on the dome in the private flux region, and for the baffles at the top of the divertor channels (see Figure 6.1). The most serious concerns for beryllium in the divertor relate to thermal conductivity, especially that of the joint between the beryllium and the substrate, and erosion, which is caused by plasma interactions. At the energy dump plates, particularly, ion or hot neutral atom fluxes could be quite high, depending on the degree to which the gas quenching concept is successful in extinguishing the plasma in the divertor channels. If the plasma quenching by recirculating cool gas is successful, the highest loads will be near the top of the channel, near where the quench front resides. Erosion rates have been calculated in that region as from 50-150 cm/burn-yr (0.6-1.7mm/hr).¹¹ Heat loads will probably be at least 0.5MW/m^2 and may be as high as 5MW/m^2 , and ion bombarding fluxes may be of order $10^{22}\text{ion/m}^2\text{s}$ at bombarding energies of 50-500eV.¹²

With a fusion neutron wall loading of 1MW/m^2 , corresponding to a flux of $4.4 \times 10^{13}\text{n/cm}^2\text{-s}$, it would take months of continuous operation to reach a fast neutron flux of even 10^{21}n/cm^2 . An estimate of the buildup of 14MeV fluence on ITER divertor components over a 20-year estimated operating life is shown in Figure 8-1. One tenth of the total fluence of 3MW-yr/m^2 ($4.2 \times 10^{21}\text{n/cm}^2$) is expected at an increasing rate in the first ten years. The balance is assumed to be received at a rate increasing more slowly in the second ten years. Irradiation effects in the beryllium could be expected to begin to appear in only a few weeks of operation. It is not known yet with exactness what the total fast fluence in the neutron spectrum would be before strengthening effects saturate. Shown in Figure 8-1 is the fast fluence ($E > 1\text{MeV}$) at which strength saturates at low-temperature in a thermal fission spectrum. Different operating temperatures, irradiation rates and material structures are known to influence the changes in properties due to irradiation. It is possible to see strengthening with little embrittlement and vice versa.

Figure 8.1 Estimated 14MeV Neutron Buildup Estimated on ITER Divertor Components

Erosion will make it necessary to frequently replace divertor beryllium. In eroded areas, beryllium will not be in the machine long enough to receive a significant neutron irradiation dose that would alter its mechanical properties. If plasma-spraying is used as the beryllium replacement mechanism, beryllium in low erosion areas may be used for many replacement cycles. Because of the long range of high-energy neutrons, and the substantial scattering as the neutrons become thermalized and absorbed, such residual beryllium could receive a substantial irradiation dose over the lifetime of a divertor cassette. However, since that beryllium is not load-bearing, the main concerns for neutron irradiation effects would be swelling that may change its physical dimensions, hardening that would reduce its ability to handle thermal stresses, and a reduction in thermal conductivity that may appear as a consequence of helium generation and the associated structural defects. The effectiveness of the mechanical and thermal bond that secures such beryllium to the substrate material may degrade with neutron fluence as well.

8.2.2 FIRST WALL

The lower portion of the plasma-facing first wall is presently considered to function as a toroidal limiter as well as a divertor baffle to restrict the flow of neutral gas into the main plasma chamber. It, too, would be a high-heat flux component, similar to the surfaces mentioned previously in the divertor section. What was said there applies to the toroidal limiter as well.

The balance of the first wall will be of significantly lower particle loading, and heat loading will be lower as well. It is likely that the plasma-facing material would remain through the DT burning phase and thus sustain damage up to about 5 dpa or 10^{22} n/cm². We expect first wall beryllium to survive many more operating cycles than would that in the divertor; thus, somewhat different issues arise. Significant questions that must be asked include:

What will be the response (e.g., swelling, embrittlement, loss of thermal conductivity) of the material actually selected for use to the neutrons considering that (1) Be composition (impurities and structure) to be used in ITER has probably never been evaluated in any neutron spectrum, (2) the neutron energy spectrum at the first wall will be different from any heretofore available, and (3) loadings will be cyclic rather than more or less continuous ones used in testing?

How will the joining method be influenced by the neutrons? If brazed, will the braze activate, lose strength, lose conductivity, or otherwise degrade? If plasma-sprayed, will the bond between the substrate and the beryllium remain viable. Will differences in swelling result in bond failure? Will the mechanical shocks incident to removal and replacement of the various components result in joint separations of the beryllium?

How will the helium-laden and damaged material withstand the thermal shocks and temperature gradients required as a first-wall plasma-facing material? Will thermal stresses increase because of reduced thermal conductivity? If they do, and if ductility is lower, will this mean that beryllium flakes or chunks may be expected to come off at unexpected times late in the machine life?

8.2.3 BLANKET

At the present time, the ITER EDA design calls for a shield that does not breed tritium. Hence there is no need for neutron multiplication, and no beryllium is planned. There will be test modules that have representative blanket segments installed for evaluation. Conceptual Design Activity (CDA) designs featured beryllium as a neutron multiplier to enhance the amount of tritium produced. Such utilization of beryllium did not make use of it as a structural material. Rather, it was present as balls or cubes within constraints.

The main questions regarding beryllium in this application relate to swelling and mechanical properties. Heat transfer through the beryllium was a key concern in one design.¹³ If the material embrittles and swells significantly, and if because of the mechanical constraints significant loadings develop, it may fracture and become compacted in localized regions. That would alter heat transfer significantly and degrade performance. Tritium retention would also be a concern.

8.3 CRITICAL EXPERIMENTS

Once the beryllium material composition(s), including manufacturing method and preparation technique, have been determined, it will be important to conduct neutron irradiations on samples of these materials. Test specimens should also include representative joints. Irradiations should be carried out in a fast-flux fission reactor if one is available that will house the needed volume. Consideration should be given to tailoring the neutron energy spectrum if a thermal fission reactor is used to make it more representative of that expected in the ITER environment. Irradiations should be conducted to fluences of at least 10^{22} n/cm² at temperatures typical of those to be seen in ITER service. This may be in the vicinity of 450°C for plasma-facing applications. Post-irradiation examination and testing should evaluate swelling, changes in hardness and strength, loss of ductility, and retained gases including tritium.

Samples of S-200E grade beryllium with densities from 80-100% of theoretical have already been irradiated in FFTF and in EBR-II to fluences in excess of those considered minimum. Irradiation has been at temperatures from 375°C to 525°C. Even though these may differ slightly in composition and manufacturing history from beryllium used in particular ITER applications, evaluating these specimens for changes to properties caused by exposure to neutrons will be extremely valuable in contributing to the solution of the issues raised previously in this chapter.

8.4 NEEDED TEST FACILITIES

As of this writing, the Fast Flux Test Facility (FFTF) at PNL has been shut down, apparently permanently. The Experimental Breeder Reactor II (EBR-II) is also down. Only foreign fast-flux reactors will be available for neutron irradiations. Three thermal fission reactors are available in the U.S., the Advanced Test Reactor (ATR) at the INEL, the High Flux Reactor (HFIR) at ORNL, and the High Flux Breeder Reactor (HFBR) at BNL. The Missouri University Research Reactor (MURR) could also be considered. Table 8.1 compares the capabilities of these facilities. Russian reactor space is also readily available at very competitive rates, but we have not included information on those reactors here.

Other facilities may be used to obtain neutron irradiation. One under current consideration is a Fusion Neutron Source, similar in concept to the Fusion Materials Irradiation Test (FMIT) facility, planned at one time for HEDL. In this concept, a flowing stream of molten lithium or lithium-bearing salt is impacted by a beam of high-energy deuterons, producing high-energy neutrons over a small volume. The main challenges to this facility now are its high construction cost and the small volume (few cm³) available where neutron fluxes are high.

8.5 COST AND SCHEDULE

8.5.1 HFIR EXPERIMENTS

A program of irradiation and testing of beryllium is being planned at ORNL for the HFIR reactor.¹⁴ Tests planned will investigate swelling and changes in thermal conductivity, elastic modulus, strength, and elongation. TEM disks will also be irradiated. Material types include LANL plasma-sprayed, Brush Wellman S65-C, Max Planck zone-refined (Brush Wellman), and KBI 'P-0' high purity beryllium. Assuming two irradiation iterations, two fluence levels, and two irradiation temperatures (8 total irradiations in two campaigns), the estimated cost, exclusive of investigators' time, materials, or fabrication costs is estimated at \$1.7M.

A separate program looking at monolithic beryllium that would include 12 irradiations, testing for swelling, strength, elastic modulus, elongation, thermal conductivity, creep, fatigue strength, and fracture toughness is estimated to cost \$3.7M, again exclusive of investigators' time, materials, and fabrication costs.

The irradiations, followed by suitable cool-down time, will take nominally one year for each cycle, and two cycles are proposed. Total elapsed time for these series will be 5-7 years, depending on the degree of concurrence in the testing of the first series and designing of the second. Personnel costs for investigators and fabrication are estimated to add \$2M over the period of the tests. Hence a total program cost for the planned HFIR irradiation program of \$7.1M is estimated.

Table 8.1 U. S. Fission Reactor Specifications

Reactor	Power (MW)	Thermal Flux (n/cm ² /s)	Fast Flux (n/cm ² /s)	Expt. Size (cm)
EBR-II (Idaho) [Shutdown]	62.5	-	2×10^{15}	7.4 dia x 36 (multiple)
FFTF (Washington) [Shutdown]	400	-	4.6×10^{15}	7 dia x 91 (2) 11 dia x 91 (8)
ATR (Idaho) [High availability]	250	1×10^{15} 4.3×10^{14} 4.6×10^{14} 5.8×10^{14} 2.5×10^{14} 3.9×10^{13} 7.7×10^{13} 1.9×10^{14}	1.5×10^{15} 3.8×10^{14} 5.3×10^{14} 1.9×10^{14} 3.7×10^{13} 3×10^{12} 3×10^{12} 7×10^{12}	7.6 dia x 122 (9) 1.6 dia x 122 (24) 1.6 dia x 122 (4) 2.2 dia x 122 (8) 3.8 dia x 122 (4) 12.7 dia x 122 (4) 8.2 dia x 122 (16) 3.8 dia x 122 (4)
HFIR (Tennessee) [Available]	100	9×10^{14} 2×10^{14} 1.5×10^{14}	1.3×10^{15}	13 dia x 51 1.3 dia x 51 (8) 3.8 dia x 51 (11) 7 dia x 51 (2)
HFBR (New York) [Available]	40	5.5×10^{14}	2.0×10^{14}	2.4 dia x 7.6 (multiple)
MURR (Missouri) [Limited availability]	10	4.6×10^{14}	3.5×10^{13}	3.8 dia x 75 (3)

Note: Use of foreign reactors, while possible, is not considered here.¹⁵

8.5.2 ATR EXPERIMENTS

Further irradiations are needed to fully develop the material. For comparison in estimating irradiation costs in ATR, an estimate was made for costs of irradiating several hundred beryllium spheres (1-3mm dia) in ATR in a temperature-controlled loop. Costs for designing the irradiation loop and conducting the irradiation were between \$2M and \$3M. Estimated additional costs for conducting post-irradiation testing looking only at swelling and mechanical properties (strength and elastic modulus) were approximately \$400K. This program was estimated to take 3 years to conduct.

A main advantage of the ATR is the very large test volumes available. Those volumes, combined with the high flux, makes it useful in irradiating larger, more complex pieces than would be practical elsewhere. Nominal cost for one of the large flux trap locations would be of order \$3-5M/yr, not including researchers time or the cost of special loop equipment. Irradiations to 10^{22} n/cm² can be achieved in less than half a year of operating time or approximately half a year of elapsed time. It is difficult to know exactly which subcomponents and special samples will require irradiation. Assuming three irradiation

cycles in a flux trap, costs (including labor) may run in the \$10-30M range over 3-5 years to obtain basic data on key components and structures.

8.5.3 PREVIOUSLY IRRADIATED MATERIAL

Approximately 80 specimens already irradiated in FFTF and EBR-II could be made available for testing changes in mechanical properties due to neutron irradiation. Estimated costs for retrieval of the FFTF specimens are \$120K¹⁶. Samples in EBR-II may be retrieved under existing program funding. Costs to prepare the test facilities for making the measurements and actually conducting the tests are estimated at approximately \$200K. Tests could be completed in six months.

8.5.4 THE REAL NEED

The experiments planned in HIFR and proposed for previously irradiated samples are not really sufficient to give the data base needed for reliable design, fabrication, and use of beryllium in ITER's radiation environment. It is difficult to say just how much would be needed, but it is several times the quantities mentioned here. Ten times as much testing as considered here could easily be needed to get the kind of data needed for licensing of a commercial facility, but ITER may get by with less than that because it is experimental. It is not beyond reality to think that more than \$50M and 5-8 years would be needed to develop basic information needed for design reliability in ITER if only existing fission reactors were used.

Costs for the Fusion Neutron Source are not yet known, but numbers of the same order, i.e. several tens of millions of dollars and a decade or so in time, seem realistic.

8.6 RECOMMENDATIONS

8.6.1 NEAR TERM ACTIONS

At the very least, a program for conducting testing on the previously irradiated beryllium should be pursued. This would cost less than \$500K and would provide important information that is not presently available. It will not give all the answers, but it will enable much more informed design decisions to be made in the near term. This work could be done within a year.

8.6.2 FOLLOWUP PROGRAMS

A more extensive program of irradiation and testing should be pursued. This should begin with the program planned at ORNL for irradiation in HFIR, possibly accelerated beyond present plans. Additionally, a rather extensive program to qualify joints and complex shapes should be considered for the ATR where test volumes available are larger. These programs are summarized in Table 8.2.

Table 8.2 Possible Neutron Irradiation Facility Requirements

Facility	Activity	Duration (yr)	Cost \$M/yr
HFIR	Monolithic and composite samples* for swelling, strength, elastic modulus, elongation, thermal conductivity, creep, fatigue strength, fracture toughness, etc.	5-7	1-1.5
ATR	Composite specimens* and complex components for post-irradiation functional qualification.	4-8	3-8

*Includes samples of optimized plasma-spray product.

If no funding limitations existed, it would be very important to proceed with the Fusion Neutron Source to provide basic information on the swelling and changes in mechanical properties on small samples of representative materials in the high neutron energy spectrum it would produce. Costs would be in the hundreds of millions of dollars.

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CHAPTER 9. TRITIUM ISSUES

The interaction of tritium with beryllium used for plasma-facing components for ITER is significant from several perspectives. The most important of these is the tritium inventory that may develop in plasma-facing components. This inventory may amount to several kilograms. If that inventory is released during a thermal excursion, it would pose a significant safety threat for persons located at the site boundary. We do not yet possess enough information on tritium plasma interactions with beryllium to make reliable estimates of what these inventories will be. There are also substantive issues for plasma physicists related to the rate of recycling of hydrogen isotopes to the plasma from beryllium at the first wall and their influence on plasma control and stability. Another concern is an economic one. To the extent the beryllium captures tritium impinging on the wall, it represents an unusable reservoir for the fuel. If the beryllium captures 5kg of tritium as one estimate indicated,¹ the cost of this inventory would be in excess of \$60M at today's prices. On the other hand, tritium will be bred in the beryllium. A machine that has 15m³ of beryllium may generate approximately 6kg if taken to a neutron fluence of 10²²n/cm² based on fission reactor irradiation data.² Again, the value of this tritium is not trivial. In all of these areas, there is little information available on which to base a design for ITER. Billone, Dalle Donne, and Macaulay-Newcombe³ have presented a comprehensive review of the current understanding of many of these matters. The experimental work done is comparatively sparse, and more needs to be done.

9.1 TRITIUM BREEDING

This is perhaps the area where most is known relative to the tritium-beryllium topic. The breeding reaction chain is

(1)

where the first step is the rate controlling one. It has an effective threshold neutron energy of about 1.4MeV. For that reason, tritium breeding rates in beryllium will be much higher in a fusion spectrum with a strong 14MeV component than in a fission spectrum that is strongly thermalized. Computer codes are used with libraries of neutron interaction cross sections to estimate gas production rates. However, these codes have been found to give results different by up to factors of two from experimental observations for helium generation,³ and similar lack of precision may be anticipated with tritium production as well.

Because the inventory of tritium bred in plasma-facing beryllium may be on the same order as that due to ion implantation, it will be reasonably important to have a good estimate of what this inventory will be. The amount of bred tritium that remains in the beryllium will be strongly influenced by the structural integrity of the beryllium and the temperature at which it is operating. Experimental data⁴ suggest most of it tends to reside in helium bubbles or clusters. Some seems to become bound up in oxide inclusions or coatings. Under conditions that allow the helium to escape, the tritium escapes with it. Experiments performed by Baldwin and Billone⁵ found that in less dense beryllium (20% porosity), less helium and tritium were retained in the irradiated samples than for fully dense material irradiated under similar conditions. The ANFIBE code, developed by Dalle Donne and co-workers,⁶ has been quite successful in modeling the retention and release of tritium bred by neutrons.

9.2 PLASMA INTERACTIONS

When plasma ions and neutrals strike the first wall or divertor surface, most of them are implanted into the surface and re-emitted through the process of recombination to the plasma. Some become trapped in defects and bubbles, and some permeate through the beryllium into the substrate and eventually into coolant channels. Some fundamental questions remain regarding details of this process. One area that is particularly significant is the detailed mechanics of how the tritium re-emerges to the plasma, since that tends to dominate all the other effects. Surface contamination retards recombination and causes inventories and permeation rates to be larger. It is not known how clean the beryllium surface will be during ITER plasma operation. Experiments performed by Anderl and co-workers⁷ showed that it may be possible to erode the surface contamination fast enough to keep the beryllium surface relatively clean.

Those experiments revealed that the beryllium surface became highly textured, as shown in Figure 9.1. It is not known if such pitting will be observed in ITER as well. If it is, then recycling of tritium to the plasma will be significantly accelerated, and permeation and inventories will be reduced.

Figure 9.1 Surface of Beryllium Test Sample Exposed to 1.5-keV D^{3+} Ions

Successful modeling of the plasma-interactive processes, necessary to pre-operational safety evaluations of the tritium source term, require better understanding of the detailed processes controlling tritium recycling than is presently available. For example, most experimental data reported in the literature appears to be strongly influenced by surface oxide films. However, important properties such as diffusivity of hydrogen isotopes through BeO or even the effective solubility of hydrogen isotopes in BeO are not well understood. Even the existence of hydrogen isotopes solubility in metallic beryllium is being doubted. Codes such as TMAP4⁸ and DIFFUSE⁹ have been written to model these processes, but at present, the uncertainties in the values of key parameters make *a priori* prediction of tritium inventories and fluxes highly imprecise.

9.3 SAFETY AND ACCIDENT CONSEQUENCES

There are two major safety concerns with regard to tritium in ITER beryllium. One is the inventory of tritium that may become trapped in the first wall or the divertor. If the beryllium undergoes a temperature transient, such as in the event of a loss of coolant event or a plasma disruption, tritium may be released into the vacuum vessel. Depending on the integrity of the barriers to the release of that tritium, it may get into the building housing the ITER machine or even outside and escape to the environment. A significant question in that regard is the degree to which tritium emerging from beryllium will become oxidized. Tritiated water (HTO) is approximately 25,000 times more hazardous to humans than is elemental tritium gas. The second concern is tritium that may pass through the first wall structures and into the water coolant. That water will probably be otherwise contaminated with radioactive material as activation products from the structures cooled make their way into the coolant stream. Those activation products can be removed by fairly simple means, but HTO behaves physically and chemically as ordinary water does, and it is costly to remove when mixed with large volumes of H₂O. Some similar issues are expected for C or W plasma-facing materials.

9.4 ITER DESIGN ASSESSMENT

The above concerns are inherent in the use of beryllium as a plasma-facing material in a tokamak. There is little in the design of ITER that has shown much potential for mitigating or exacerbating those concerns. Success of the gas divertor that will reduce heat loads is a key factor, however. Two design possibilities may make a difference. Using beryllium that has a relatively high degree of interconnected porosity should substantially reduce the inventory of tritium that will build up from tritium breeding in the beryllium. It will probably have unfavorable heat transfer characteristics, however, and for that reason probably will not be used. Be with interconnected porosity could be used on first wall where the heat flux is lower. Plasma sprayed Be is being considered for use on the first wall also. Taking advantage of, or even promoting the production of surface texturing will enhance recycle of tritium to the plasma and thus reduce inventories. In regions where beryllium clad surfaces are near the coolant temperature, large inventory buildups will arise; whereas near the plasma-facing surface, where temperatures will be close to 600°C, little or no tritium should be retained as inventory in the beryllium.

9.5 CRITICAL EXPERIMENTS

Key data needs in the area of tritium interactions include (1) tritium solubility, diffusivity, and trapping data in beryllium and its oxide, (2) surface modification effects associated with plasma exposure, (3) tritium trapping and release characteristics as a function of damage state, temperature, surface conditions, and impurity content, and (4) better information on tritium recycle characteristics. These data will be needed for the exact material to be used on ITER. Since they will vary substantially with material form,

composition, and fabrication history, it will be important for researchers to have well characterized samples of both plasma-sprayed and the reference S-65C grades.

Facilities currently in use to study the interaction of hydrogen isotopes with beryllium, especially processes related to plasma interactions, include Plasma Interactive Surface Component Experimental Station (PISCES), the Tritium Plasma Experiment (TPE), and other supporting laboratory facilities.

9.5.1 PISCES

The PISCES facility was constructed at UCLA to investigate and characterize the behavior of materials under plasma bombardment. That will contribute to the development of materials for plasma-facing components. A second objective is to investigate and understand the behavior of plasmas interacting with surfaces with the hope of developing techniques to control the plasma flow and heat fluxes to surfaces.¹⁰ Upgraded to the PISCES-B facility, it has been the primary off-line (non-tokamak) plasma-surface interactions research facility, operating at UCLA since 1989. In 1991, the heat removal efficiency in the plasma generator was modified so an increased heat load could be handled to sustain high-density, steady-state plasmas. It is now capable of deuterium flux deposition experiments simulating the 1000-sec discharge cycles planned for ITER. It has also been surrounded by a specially filtered enclosure intended to facilitate safe use of beryllium as a target material in experiments. Plans are in place to move the facility to UCSD in December of 1994.¹¹

TRITIUM PLASMA EXPERIMENT

The TPE is in many ways similar to PISCES. The plasma source was manufactured by the same vendor, and initially the general configuration was similar to that of PISCES. TPE was assembled at Sandia National Laboratories (SNL), Livermore, CA with the important distinction that it was designed to operate with tritium plasmas, not just deuterium. With the closure of the SNL Tritium Research Laboratory to tritium operations, the facility was moved to the Tritium Systems Test Assembly (TSTA) at LANL. It is now in the process of being assembled in a specially constructed glovebox that will allow it to be used with tritium there. Procedures for using beryllium are also being developed.

The target holder is being designed and built by McDonnell Douglas Aerospace (MDA) as part of its ITER PFC support work. Installation of the facility is being overseen by SNLL, but operation will be by the staff at TSTA with assistance from SNLL, MDA, and INEL.

The main purpose of experimental work to be done on TPE is measurements of tritium permeation and recycling at levels so low that they must be detected using the radioactive nature of the tritium. One of these is permeation of tritium into coolant streams. Another will examine trapping effects of tritium deep in the beryllium layer.¹²

Figure 9.2 The Tritium Plasma Experiment as Configured at SNLL

9.5.2 SUPPORTING EXPERIMENTS

Other experimental capabilities exist at Sandia National Laboratories in Albuquerque and Livermore, at the INEL, and other places such as universities. These are referred to here as supporting experiments, though experimental apparatus such as those at Sandia National Laboratories Albuquerque facility are larger than either the PISCES or the TPE facilities. These typically have ion implantation capability to investigate plasma-surface interaction issues. This can usually be done on time scales and at costs that make it useful to explore certain aspects of an experiment design by trying it before committing to that feature in the more expensive testing.

9.6 NEW FACILITIES

The movement of PISCES to UCSD is one of convenience rather than necessity. Presumably, only the building specific material will need replacement. When the TPE returns to operation, it should be capable of investigating all of the issues relating to plasma interaction with beryllium. Supporting experimental facilities are largely intact. No specific needs for additional supporting facilities except some added diagnostics have been identified for these issues except, possibly, that it may be useful to conduct retention and permeation measurements on samples of neutron irradiated material. In that case, some gamma shielding would be needed.

9.7 COSTS AND SCHEDULE

Approximately \$1M was spent upgrading the PISCES facility to its present state of readiness for beryllium use. Approximately the same costs will be spent in making the move to UCSD. That will probably take a year to accomplish. Experiments planned on PISCES to answer critical erosion problems will cost approximately \$500K/yr. Surface erosion and texturing studies needed on PISCES are estimated to continue for 5-7 years.

The TPE will be ready to operate in 1994. Costs to bring it to the operational state are approximately \$250K. More diagnostics will add approximately \$80K. Experiments conducted in TPE will take approximately 5 years to provide the needed answers with an estimated funding requirement of \$600K/yr.

Costs for Tritium interaction research are summarized in Table 9.1.

Table 9.1 Anticipated Costs for Tritium Interaction Research

Facility	Activity	Estimated Costs (\$M)					
		<u>95</u>	<u>96</u>	<u>97</u>	<u>98</u>	<u>99</u>	<u>00</u>
PISCES	Relocate to UCSD	1.0					
PISCES	Erosion and recycling studies		0.5	0.5	0.5	0.5	0.5
TPE	Permeation, retention & release experiments	0.6	0.6	0.6	0.6	0.6	
Laboratory Facilities	Supporting experiments to TPE and PISCES	0.25	0.25	0.25	0.25	0.25	
TOTALS		1.85	1.35	1.35	1.35	1.35	0.5

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CHAPTER 10. BERYLLIUM HEALTH AND SAFETY

One of the concerns with regard to safety associated with using beryllium in the ITER machine is the potential health risks. In this chapter those health risks are discussed along with monitoring needed to help mitigate those health risks.

10.1 HEALTH EFFECTS OF BERYLLIUM

The main toxic effect of beryllium on humans is a granulomatous condition often called berylliosis. A small fraction, estimated to be from 1-5%, of exposed individuals is sensitive to beryllium. When beryllium is present in air as suspended particles, usually less than 10 μ m in size, breathing will result in the deposition of the beryllium particles in the lungs. Larger particles tend not to make it into the alveoli but are trapped in convolutions of the airway.¹ When beryllium particles lodge in body tissues of sensitive individuals, the beryllium appears to complex with a protein that is perceived as an antigen and is attacked by the immune system. The allergic response varies in intensity from mildly elevated levels of T-lymphocytes to the deposition of copious quantities of granulomatous or fibrous material in an attempt to isolate the intrusion. Other possible symptoms include coughing, chest tightness, fatigue, anorexia and weight loss. Chronic beryllium disease results in death for about 3-10% of sensitive people who have the disease. If left untreated, up to 35% of cases result in increasing pulmonary dysfunction, respiratory failure, and right-heart failure.²

Beside lung injury, beryllium can cause problems in the skin and other organs through effects on cellular immunity and by direct chemical toxic effects, mainly from fluorides. Beryllium disease can come from essentially all chemical forms of beryllium such as oxide fumes or respirable dusts of salts, oxides, or metals, or splinters.³ In ITER one expects to see respirable dust of the metal, carbide, oxide, and possibly nitride. There may also be flakes of sputtered metal or even shards from fractured components.

Reliable *a priori* determination of sensitivity to beryllium is not yet possible. There are some indications that susceptibility may involve a genetic link, but no beryllium specificity has been documented. There appears to be no correlation of beryllium disease with smoking or allergy histories, gender or race. Sensitization to beryllium occurs when the body develops antibodies in response to the presence of beryllium in the body. These antibodies are responsible for the development of the symptomatic granulomas. Sensitization can be detected by *in-vitro* blood tests. The most reliable of these is the Blood Lymphocyte Transformation (or proliferation) Test (BLTT) in which blood T-lymphocytes multiply and become active in the presence of beryllium. Determining sensitivity by *in-vivo* methods such as patch testing with beryllium salts is generally discouraged because of the potential for exacerbating any existing disease.^{2,4,5} It can cause sensitization where none previously existed.

The BLTT involves exposing the T lymphocytes from a blood sample, exposing them to a beryllium salt solution of different concentrations for different lengths of time, and observing the rate at which the lymphocytes multiply or proliferate. A high rate indicates that the individual is sensitive to beryllium, or that an individual's immune system has learned to recognize beryllium as an undesirable atom, and has prepared itself to respond to its presence in the body.

A study has been underway at the Rocky Flats Plant for several years which has as its objective the application of the BLTT to all current and former workers who may have been exposed to beryllium during the course of their employment at Rocky Flats. (A similar study has recently begun at the Oak Ridge Y-12 Plant.) In the Rocky Flats study some 5000 persons have now been given this test, and one hundred instances of sensitivity to beryllium have been identified. This number corresponds to the previous estimate that some two percent of the human population is sensitive to beryllium, and may,

therefore, be at risk for developing chronic beryllium disease, which is caused by inhalation of beryllium particulate into the lungs. In a sensitive individual, over a several year time period, granulomas may develop in the lungs as the immune system proceeds to isolate the beryllium that is there. The presence of these granulomas as determined by a lung tissue biopsy, along with a sensitive BLTT result, is now thought to constitute a clear diagnosis of chronic beryllium disease.

It is clear that the BLTT alone does not always indicate disease. Of the 100 positive tests so far, 56 do not have confirmed disease, and 44 do. Of the 44 confirmed cases, there are ten that do not yet have any symptoms of the disease, of which the most significant is shortness of breath. Much more testing, over several years, will be needed in order to determine whether or not the 56 individuals classed as "sensitive" by the test could be categorized as "false positives" who never develop the disease, and to determine whether treatment is effective in preventing the development of symptoms in the ten who have no symptoms now. Some important information is lacking regarding the incidence of "false negatives" in BLTT testing. There is no incentive for an individual who tests negative to proceed with a lung tissue biopsy to see whether or not disease is present. Several years more of repeat testing of this large population would be necessary in order to determine whether anyone who previously tested negative changes to positive, and/or develops disease.

Since the Rocky Flats testing is categorized as a study, more work remains to determine whether the BLTT is a useful screening test for beryllium workers. It would be helpful to be able to use such a test to determine which individuals should not be subjected to additional health risk by working with beryllium. Recent genetic research has revealed that 30 of 31 individuals with known chronic beryllium disease have a specific genetic marker. However, this same marker is found in 30 percent of the human population, a far greater proportion than the two percent who are sensitive to beryllium. Work is continuing to further study genetic material in order to determine other markers that might correlate more closely with both disease and beryllium sensitivity. In the meantime, it is still necessary to apply the specified exposure limits for airborne beryllium to all workers.

10.2 BERYLLIUM MONITORING

When working in the vicinity of respirable beryllium, the key parameter in limiting risk is the beryllium air concentration. Limits have been established by various regulatory agencies including OSHA and various state governments for allowable suspensions of beryllium and its compounds in air. A current technological challenge is the rapid measurement of those concentrations. A standard method used in estimating air concentrations experienced by workers is a lapel monitor. There are two problems with this method. One is that it only gives next-day results. The other is that the collection of a large particle that would probably never be inhaled will give an unrealistically large concentration indication. There is a need for an accurate, real-time concentration monitor.

Work in the U.S. on direct monitoring of air in the workplace in order to determine beryllium concentration in real time, or near real time has been performed at Los Alamos and at Oak Ridge, though work at Oak Ridge has stopped. Both techniques may prove to be useful, and the Los Alamos developed portable Laser Induced Breakdown Spectroscopy (LIBS) instrument is very nearly ready for extensive testing in beryllium processing facilities. Several different tests must be performed in order to determine the usefulness of the LIBS instrument. Parallel sampling by conventional methods will be performed in order to determine how the LIBS results correspond to those obtained by prolonged airflow through a filter. The LIBS instrument will be used to sample beryllium processing equipment in order to determine locations requiring better engineering controls to minimize release of airborne beryllium. Finally, some testing will be required in order to establish whether or not the LIBS instrument can be used as an "alarm", warning the workers that airborne beryllium concentrations have exceeded a particular trigger level.

10.3 SAFE BERYLLIUM LEVELS

It is not clear what safe exposure levels to airborne beryllium are for all individuals in the workplace. Regulatory limits and guidelines vary widely. An early standard for safe air concentration occupational exposure to beryllium and beryllium compounds set by the U.S. Atomic Energy Commission in 1949 was $2\mu\text{g}/\text{m}^3$ for an 8-hour time weighted average with $25\mu\text{g}/\text{m}^3$ peak exposure. The U.K. Health and Safety Executive publication EH 40/88 recommended the same $2\mu\text{g}/\text{m}^3$ limit, but the higher peak exposure limit is not now accepted there. The U.S. Environmental Protection Agency restricts beryllium emitted into the open environment by industries to an amount that would give not more than $0.01\mu\text{g}/\text{m}^3$. The current U.S. Federal Regulation stemming from OSHA (1989), 29 CFR 1910, has a time-weighted average personnel exposure limit of $2\mu\text{g}/\text{m}^3$ for beryllium and its compounds and a short-term exposure level of $5\mu\text{g}/\text{m}^3$ (30 min). The National Institute for Occupational Safety and Health (NIOSH) recommends an occupational exposure limit of $0.5\mu\text{g}/\text{m}^3$. The American Council of Government Industrial Hygienists recommends a time-weighted average threshold limit value (TLV) of $2\mu\text{g}/\text{m}^3$. Many states have regulations more restrictive than these.

Guidelines for surface contamination of beryllium are less well defined. The main hazard perceived is that an activity or person may cause the surface beryllium to become levitated or an aerosol. Though there is little danger for most individuals from casual touching of beryllium or its compounds, contamination of a wound or slivers in sensitized individuals may exhibit a response. The limit for surface contamination recommended in the U.K. by the Health and Safety Executive⁶ is $100\mu\text{g}/\text{m}^2$. At Los Alamos, the standard for initiating cleanup actions for surface contamination is $25\mu\text{g}/\text{ft}^2$ ($269\mu\text{g}/\text{m}^2$). Observations of more than $200\mu\text{g}/\text{ft}^2$ require a wet cleanup.⁷ At the Idaho National Engineering Laboratory, decontamination from beryllium cannot be declared until surface smears register less than $100\text{ng}/100\text{ cm}^2$.

There are indications that even these low levels may not be low enough to prevent beryllium disease for all persons. This comes from diagnoses of chronic beryllium disease in persons with very minimal exposures. The disease has also been diagnosed among workers at beryllium facilities where the NIOSH standards are adhered to, who do not work directly with the material such as secretaries, security guards, laundry workers, and among "dust disturbers" such as electricians, custodial personnel, and ventilation maintenance workers.²

10.4 BERYLLIUM CONCENTRATION MEASUREMENT

10.4.1 STANDARD DIAGNOSTIC TECHNIQUES

The most commonly used and most reliable method for determining levels of beryllium in air involves pumping air through a filter disk at a known rate for a predetermined period. Then the filter is analyzed. In one method, it is dissolved with hydrochloric or perchloric acid, and the solution is fed to an induction coupled plasma for atomic absorption spectroscopy. There are variations in the details of methods used, but invariably the process takes several hours to complete, and the routine expectation of environmental hygienists is that results will not be available till at least the next shift, possibly not until the next day.

Detection limits using this technique can be as low as 500ng with the use of electrothermal atomization. At Los Alamos, detection at $10\text{ng}/\text{filter}$ with electrothermal atomization and $130\text{ng}/\text{filter}$ with flame atomization is routine.⁸

Stationary samplers are installed at key locations in manufacturing facilities to monitor beryllium air concentrations. By sampling for 8 hours, the 8-hour average criterion is satisfied. Sampling in this way

is far from trivial. One major U.S. beryllium plant keeps two persons fully employed making such measurements. In cases where there may be particular hazard for inhalation, the NIOSH recommended technique is to use a lapel monitor. This is essentially a small portable version of the same measurement system with the air pump operated by power from batteries carried in a strap-on pack. The filter is worn clipped to the worker's lapel or other suitable location near the face. It will then give a reading that closely approximates the concentrations the worker encountered during his/her work activity. Surface contamination is usually monitored in a similar way, taking a moistened filter paper or more standard "swipe" sampling disk used for measuring radioactive surface contaminants. It is then processed as the air-monitoring samples are. There is controversy over the reproducibility of wipe samples and whether there is strong direct correlation between surface contamination and human health risks.

A significant limitation of such methods is that they are historical in nature. That is, they can be used only to measure conditions as they were when the samples were taken, and then usually only over relatively long periods. As noted earlier, this may be hours or days prior to the time the information is available. There has not been the routine capability to make measurements that may be used in on-the-job process decisions. There is a strong need for development of a monitor that can determine within minutes the concentration of beryllium in workplace air.

10.4.2 EXPERIMENTAL TECHNIQUES

Several efforts have been undertaken to develop more rapid methods for determining beryllium air concentrations. Some of these are still in progress while others have been discontinued.

ORNL

One of these development thrusts was led by Miller and Fisher at the Oak Ridge National Laboratory, though their work has been suspended. Their approach is based on conventional luminescence in an automated analyzer. Beryllium present in a liquid (introduced by bubbling) is dissolved with morin ($C_{15}H_{10}O_7$ 2',3,4',5,7-pentahydroxy-flavone), Triton X-100® (a non-ionic surfactant), and a buffer (hexamethylenetetramine). This solution is then illuminated with sinusoidally modulated laser light. A phase-modulated emission spectrum is obtained from which information on the beryllium concentration is extracted with a fluorometer.

A key factor in the success of the method is the ability to distinguish between beryllium and aluminum. Although the conventional (steady-state) method of measurement showed a selectivity for beryllium of 1000:1 over aluminum, one expects typical samples to have about 50,000 times as much aluminum as beryllium present. Hence, steady-state measurements may not be accurate and the phase-modulated measurements were pursued.

The measurement sensitivity of this approach is 200pg or less of beryllium. That represents the beryllium in only 400cm^3 of air at the NIOSH criteria level of $0.5\mu\text{g}/\text{m}^3$. Further, because it operates by chemical solution, it has the advantage of measuring very small particles ($< 2\mu\text{m}$), not just those caught in the filter disks using the conventional method. This may be important in light of concern over the health effects of the smaller particles.

Work done using this approach concentrated on the physical chemistry of detection. A logical next step would be to assemble a portable instrument that could be used in field trials, comparing results of such measurements with those of the more proven techniques. As indicated earlier, work on this approach is not now active due to funding limitations. Variants on this scheme that have been reported include immobilizing the morin on a medium such as a filter disk, ion-exchange resin, or silica gel.^{9,10} Presumably, that would improve portability over the wet chemistry application originally envisioned.

LANL

Another approach for making real-time measurements of beryllium air concentration is one whose development has been led by Cremers at Los Alamos National Laboratory.⁸ This technique makes use of a laser induced breakdown (LIB) spark to reduce beryllium, elemental or in compounds, to atoms and excite them, many going to the excited singly ionized state. A spectrometer tuned to the 313.042/313.107-nm doublet is then used for detection.

The application of the technique to a portable monitor is realized by either direct ionization of beryllium in a small air-sampling volume or by sparking the surface of a filter paper segment through which air has been passed for an arbitrary period. The latter provides a physical concentration of the beryllium suspended in the air, and, therefore, gives greater sensitivity. By firing the laser at a 10Hz repetition rate, the spectral sampling generates sufficient data for reasonable statistics. Approximately 3-5 minutes is used in analysis of the spectral data by a built-in computer that also controls the machine. The filter paper is a band on a rotatable spindle with multiple sampling stations, so the filter only requires changing after half a dozen or so measurement sequences.

The method is somewhat sensitive to beryllium particle size. Smaller particles give a stronger signal for the same amount of beryllium than do larger ones. Presumably this is linked to the efficiency of coupling the laser energy to the beryllium (greater surface area per unit mass) and the completeness of the ionization.

The detection threshold using the present instrument parameters with a signal-to-noise ratio of 6 is 0.45ng/cm^2 on the exposed area of the filter. Hence, for a 37mm diameter filter disk with an air pumping rate of 2L/min, the required air pumping time for detection at the $0.5\mu\text{g/m}^3$ NIOSH concentration limit would be 23 minutes. Increasing the pumping speed to 40L/min would reduce that time to just over one minute.

The key to portability has been the availability of small lasers with which to induce the sparks. Total instrument volume/mass is largely driven by the power supplies available. At the present time, a unit the size of a suitcase and a bit too heavy for true one-person portability has been assembled and some preliminary tests have been performed. The laser power supply occupies about half of the assembly volume and contributes substantially more than half to the weight. These systems are solid-state. They may be better suited for surveys to determine relative concentration levels because of comparatively high detection thresholds and inherent sensitivity variation with particle size and so on. They should be very useful, compared with the wet chemical approach described previously, for field measurements where speed and portability are important. Much more information about this approach may be found in Refs. 8 and 1.

Work is in progress to reduce the size further to something approximately brief-case size. In one variant being developed, the spectrophotometer, control, and power supply are in a small, typewriter-sized case. The laser head and detection optics are on a flexible cord. The optical signal from the laser head is carried to the spectrophotometer over an optical fiber. The case size for this configuration is mainly determined by the size of the commercial notebook computer used to control the system and display the results. Because the spectrophotometer can be used to detect a variety of emissions, these instruments are in use to detect lead and other contaminants in paint and soils. They are not suitable for isotopic determination, but they can detect the presence of H_2 . A patent for this approach was awarded approximately 8 years ago, and the technology is presently under consideration for commercialization by at least one vendor.

10.5 ITER DESIGN ASSESSMENT

Present plans call for no human access to the vacuum vessel once plasma operations have begun. Further, any items taken from the torus will be considered radioactive and so must be housed in hot cells, gloveboxes, or equivalent. During construction, it will be important during and after the installation of the beryllium to know rapidly what beryllium air concentrations are. Once construction is complete and operations have started, a process that may pose significant threat of personnel exposure to beryllium will be adding feed stock to the plasma spray process, wherever that is conducted. There will be the need to determine levels of airborne beryllium and beryllium compounds before any personnel access is granted to areas where this is done. Such a device should be sufficiently small and mobile that it can be used with ease in the chambers and passages available for access to the plasma-spray machine.

10.6 CRITICAL RESEARCH

It will be important to have available an instrument system that can give real-time or very short-time indications of beryllium air concentration. Current measurement techniques may be used to determine what levels were at the time of the measurement, but those levels may have changed considerably between the time the measurements were taken and the time the work in the vicinity is to be done. Further, the costs associated with waiting for the measurement results to come back must be considered. More than likely, there will be some wait time for short-lived radioisotopes to decay, so the costs directly attributed to waiting for beryllium measurements may be diminished. The greater concern is with concentration levels that may fluctuate substantially during the work and which present standard measurement techniques could not detect.

Work being done at Los Alamos National Laboratory to develop a real-time, portable beryllium air concentration monitor should be pursued. The approach of using laser-induced breakdown to ionize and excite the beryllium atoms, either in air directly or on the surface of a concentrating filter is making excellent progress in portability, but it may suffer from sensitivity and stability limitations. That would make it less useful for absolute beryllium concentration determination, but it would still be very useful for coarse surveying and relative measurements.

It would be a great advantage to ITER to have a truly portable, reliable instrument available that would be capable of making measurements down to concentrations of interest (at least one order of magnitude below the prescribed limit) in times that are short compared with a standard work shift. Funds should be made available to continue development to the point of commercialization for such an instrument. Additionally, work should continue to seek for ways of identifying sensitive individuals and thus make possible the avoidance of exposure to beryllium.

The effort required to complete development of the instrument to the point where it could be used in the ITER application will be approximately \$500K and take about two years. This activity is presently being pursued under weapons program funding at Los Alamos, so direct ITER funding will not be necessary. However, strong statement of need and justification to continue from ITER will be useful.

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CHAPTER 11. BERYLLIUM-COOLANT INTERACTIONS AND SAFETY

Present ITER designs do not call for beryllium to be in direct contact with coolants, mainly because beryllium will not be used as a structural material. In the event that coolants escape into the vacuum vessel during an accident, then ITER safety may be influenced by the consequences of chemical reactions between coolants and the beryllium. Three coolants have been considered for ITER: water, helium, and liquid metals--probably lithium. Of these, water is the one with the greatest hazard potential. Helium is non-reactive, and if lithium spills, a lithium fire would be much more hazardous than an interaction with beryllium. Beryllium reactions with air are also of concern because of the potential of air-ingress events.

11.1 SAFETY CONCERNS

11.1.1 WATER

The hazards from chemical interactions between beryllium and water lie in three main areas. One is the generation of hydrogen from the reaction

This hydrogen, if generated in sufficient quantity, is subject to detonation or deflagration, which could cause pressures in the vacuum vessel to rupture it. Another reaction that may be significant is

Acetylene produced would also be flammable. It is not yet known how much Be_2C will be in ITER.

A related concern is that heat generated by beryllium oxidation may cause temperatures to rise, contributing to the release of activation products and tritium from the heated structures.

A third concern is the production of BeO , which probably would be powdery and quite respirable, making it a substantially greater health hazard than its parent solid metal.

At room temperatures, unless water is notably acidic or basic, reactions between beryllium and water are not a problem. In the Advanced Test Reactor (ATR), for example, the beryllium reflector structure functions for years with no evidence of corrosion. Likewise, after the beryllium is removed from the reactor core and placed in a storage canal, it remains for years with no corrosion evident. It must be assumed that water chemistry in ITER will be as tightly controlled as it is in ATR. Hence, beryllium and water will not be a problem at ambient temperatures.

At elevated temperatures, however, experiments have shown that reactions with steam may be quite vigorous, even self-sustaining.^{1,2} Several factors influence the rate at which reactions with steam take place. Most significant of these is the porosity, or more particularly, the specific surface area of the material. Specimen geometry and fabrication technique have also been found to have an effect. With porosity, the greater the porosity, the lower the temperature at which self-sustaining reactions take place. This is shown in Figure 11.1 where data for fully dense,² several porous (87-90% density),³ and plasma-sprayed beryllium⁴ are shown. Reaction rates are given in terms of liters of H_2 produced per square meter of exposed area per second. The break point in the data for fully dense beryllium at 900°C is associated

with the restricted permeation of oxygen through the BeO at temperatures lower than 900°C. Plasma-sprayed beryllium is the most reactive of all the samples tested. This is due to its high porosity and relatively poor adhesion between beryllium grains (splats).

Figure 11.1 Current Data from Porous (97-90% dense) Beryllium (2), Dense Beryllium (2,3), and Plasma-Sprayed Beryllium (4)

11.1.2 OTHER COOLANTS

Helium, being inert, has no reaction with beryllium. However, in real systems it is unreasonable to think that there will not be some oxygen impurity in the helium. At elevated temperatures (>600°C) this may be expected to react with beryllium. That reaction will be very slow and should have no significant consequences. No hydrogen would be produced.

A spill of liquid lithium may result in some dissolution of beryllium into the molten lithium, but that would have no significant safety impact. It may result in the need to replace the beryllium, but that would probably be done for other reasons anyway. There are no known solid compounds of lithium in beryllium.⁵ The most significant hazard would be that due to lithium fires. Discussion of that hazard is outside the scope of this report.

11.2 ITER DESIGN ASSESSMENT

Water is the most probable coolant for beryllium clad surfaces, but the water will not contact the beryllium directly in routine operations situations. Water is used for its efficiency in heat removal and the need to keep beryllium surface temperatures low (600-700°C). The key to safety in this regard is to build into the design good thermal conduction paths through the structure from the beryllium clad surfaces to the cryostat or other heat sink. Studies have shown that if there is good heat transfer to carry away activation product decay heat, then temperatures reached in a loss of coolant accident will be maintained below those at which self-sustained oxidation takes place.⁶ The temperature that may be withstood before a self-sustaining reaction takes place is reduced by interconnected porosity. Good heat transfer should minimize that reaction, as shown in Figure 11.1. Also, if the incoming water coolant is present in sufficient quantity (i.e., a very massive break) and if it enters as a subcooled liquid, the vaporization enthalpy may remove a large amount of heat from the beryllium and its supporting structures and thus preclude rapid oxidation of the beryllium. A more likely event would be the flashing to vapor as the coolant leaves its pressurized conduits and enters the vacuum chamber.

11.3 CRITICAL EXPERIMENTS NEEDED

Because of uncertainties in the degree to which the actual ITER design will be able to carry away the heat of activation products during an accident where cooling is lost, it will be important to better understand vulnerabilities of ITER beryllium to severe oxidation reactions. This includes not only smooth beryllium but material that has been surface textured as it may be by plasma ions, by thermal cycling, or by disruptions. Specifically, this includes repeating with air the tests conducted thus far with steam. Also it will be important to have measurements on the actual material planned for use in ITER plasma-facing structures, especially if it is plasma-sprayed. Further there is the question of whether the porosity induced by helium build-up, especially in dense beryllium operated at 350-500°C will result in high oxidation rates and low threshold temperatures for strong reactions, characteristic of porous beryllium. That objective may be partly met by conducting measurements on material that has already been irradiated in FFTF or EBR-II to fluences of 10^{22} n/cm² at temperatures representative of those in service and comparing those results with those from similar tests on unirradiated specimens. Beryllium samples that have been irradiated include 28 samples (80%, 85%, 95%, and 100% dense) irradiated in FFTF at 370-550°C to $1-5 \times 10^{22}$ n/cm² ($E > 1$ MeV) - awaiting disencapsulation (no funds have been made available), and 36 samples (80%, 85%, 95%, and 100% dense) irradiated in EBR-II at 425-525°C that will be removed from the reactor in August 1994. Equipment is ready to conduct tests - only funding is needed.

11.4 COST AND SCHEDULE

Repeating with air tests already done with steam will take approximately \$170K and 9-12 months. Tests conducted on irradiated specimens would not be so many, because the number of irradiated samples available is limited. Those can be done in existing facilities as well. Costs would be approximately \$200K, and they could be done within about six months. Because the same facility would be used for all tests, this time would be incremental to that for the air exposure tests just mentioned. Tests on plasma-sprayed samples have been planned, and some have been funded. They have not yet been done because samples have not been available. These will probably warrant repeating once the final production process is established. Costs for those added tests would be approximately \$170, and the tests would take 9-12 months for unirradiated material. Tests of irradiated plasma-sprayed material will be similar to those for the powder-metallurgy material.

The total program will depend on the materials actually used. For planning purposes the series listed in Table 11.1 should be considered. Times listed are serial because the same VAPOR facility will be used for all tests.

Table 11.1 Testing Series to Evaluate Beryllium-Coolant Interactions

Test Series	Duration	Cost (\$K)
Repeat in air tests already completed with steam.	9 mo	170
Tests of BeC specimens in steam	6 mo	100
Tests of plasma-sprayed beryllium in steam.	9 mo	170
Tests of plasma-sprayed beryllium in air.	9 mo	170
Tests of irradiated powder-metallurgy beryllium in steam.	6 mo	200
Tests of irradiated power-metallurgy beryllium in air.	6 mo	200
Tests of irradiated plasma-sprayed beryllium in steam.	6 mo	200
Tests of irradiated plasma-sprayed beryllium in air.	<u>6 mo</u>	<u>200</u>
TOTALS	60 mo	1,410

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CHAPTER 12. THERMAL AND MECHANICAL TESTS

12.1 INTRODUCTION

ITER plasma facing components (PFC) will be subjected to high heat fluxes ranging from 1-10MW/m² for times ranging from 10-1000s. Peak divertor heat fluxes are 5MW/m² for 1000 seconds. Off-normal loads up to 10MW/m² may occur for up to 10 seconds from ELM's, which may result in melting of the beryllium armor. The PFC's should be capable of withstanding neutron irradiation, thermal shock, electromagnetic forces from disruption eddy currents or halo currents, runaway electrons, and seismic loads. The required fatigue life is 10⁴ cycles and 5dpa neutron dose. For all PFCs, the minimum beryllium temperature between plasma shots is 150°C, with occasional baking cycles up to 350°C. Water is considered the reference coolant, with helium gas as the backup choice.

Critical issues for beryllium are closely tied with the issues for the entire plasma facing component, since they are strongly bonded together. These issues are divided into two major categories, thermal-hydraulic and thermo-mechanical effects.

12.2 THERMAL-HYDRAULIC ISSUES

1. Thermal response under steady-state loads.
2. Burnout safety margin (e.g., Critical Heat Flux limits)
3. Flow instabilities and flow-induced vibrations in parallel cooling channels
4. Pressure drop and pumping power requirements
5. Thermal response to accident conditions, LOFA (loss-of-flow-accident), LOCA, etc.

12.3 THERMO-MECHANICAL ISSUES

6. Thermal fatigue stress cycling in the bulk beryllium tile.
7. Thermal fatigue stress cycling of the Be-Cu bond joint.
8. Thermally induced deflections, e.g., bowing
9. Structural response to accident conditions, e.g., LOFA, LOCA, earthquake
10. Thermal creep response, deformation, creep rupture, creep-fatigue interactions
11. Thermal fatigue from periodic 350°C baking cycles.

The same set of issues apply for components with intentionally placed defects at the bond joint, and/or defects on the surface or interior of the beryllium or copper structure.

Likewise, these issues are of concern for components which have been repaired with in-situ or ex-situ repair techniques.

Because of the long ITER pulse length, 1000s, it is practically impossible to perform the required 10,000 thermal fatigue cycles (this would take approximately 1 year, working regular 8-hour days, of operation of the high heat flux test facility for a single sample). Therefore, it may be necessary to perform accelerated lifetime testing in order to capture the effects of creep and creep-fatigue interactions. Use of computer modeling will be required to support such accelerated lifetime tests.

Thermo-mechanical tests also need to be performed on neutron irradiated components in a hot cell facility, because the beryllium or the joint will most likely be embrittled by helium gas bubbles and displacement damage (dpa). Neutron induced swelling and creep will also have a degrading effect on the component lifetime, especially from differential swelling induced stresses in the beryllium and copper. Transmutation of elements at the bond joint (such as silver brazes, for example) must be considered.

Simultaneous effects need to be studied due to possible damaging **synergistic** behaviors. Examples include:

1. Simultaneous steady-state high heat flux loading plus disruption thermal shock
2. Simultaneous steady-state high heat flux loading plus disruption mechanical shock, from eddy current or halo current forces.
3. Simultaneous steady-state high heat flux loading plus earthquake seismic loads.
4. All of the above on neutron irradiated components.
5. All of the above on intentionally flawed components.
6. All of the above on repaired components.
7. Sudden exposure of a high heat flux-loaded sample to hot water or steam shock.

12.4 R&D OBJECTIVES

The objectives here update the original list of objectives from the JCT by including specific objectives related to both a reference design (as yet unspecified) with water cooling and an alternative design with helium cooling. It is presumed that a decision to carry forth a single design will be made sometime during Stage II.

12.4.1 HEAT TRANSFER TESTS

These tests will measure the performance of cooling medium (water and helium gas) with high heat flux (1-10MW/m²) under a variety of conditions. Specific objectives include:

- detailed measurements of heat transfer coefficients around the inner circumference of water-cooled channels for several values of heat load, pressure velocity, and inlet temperature,
- comparisons with finite element model predictions
- measurements of Critical Heat Flux at several values of pressure, temperature, velocity,
- geometric effects that simulate manufacturing defects such as voids in joining and defects from operation such as cracks that alter heat transfer,
- influence of turbulence promoters (twisted tape, hypervapotron, fins, etc.)
- LOCA, LOFA tests
- Flow instabilities in parallel cooling channels
- detection of boiling induced noise, and precursor signals to CHF/burnout
- performance figures of merit (heat transfer efficiency vs. pumping power/pressure)

12.4.2 HIGH HEAT FLUX TESTS

These tests will measure the performance of beryllium-clad test elements with a maximum heated length of 80cm exposed to 10^4 thermal cycles of 3s duration at 5MW/m^2 . For beryllium samples, the surface temperature of the Be will be maintained above 150°C (coolant temperature $> 150^\circ\text{C}$) between power cycles. Samples with and without intentional flaws will be tested. Samples that have been repaired with either *in-situ* or *ex-situ* techniques will be tested. Specific objectives include:

- Adequate diagnostics, including but not limited to (i) infrared thermography of surface temperature with observation of entire sample, (ii) thermocouple arrays to measure the temperature gradients through the heat sink and the temperature drop across any interfaces, (iii) thermocouple probes to measure coolant temperature before and after the heated length, (iv) flowmeter, (v) measurements of pressure at inlet and outlet of the heated length, (vi) strain gauges on the armor and heat sink, (vii) gross deflections/bowing of the sample, and (viii) in-situ visual inspection of cracks with a borescope.
- Definition and design of the test set-up including the coolant loop.
- Procurement and commissioning of the test set-up.
- Provision of test specifications.
- Manpower and auxiliaries to carry out tests.
- Reports of measurements.
- Evaluation of measurements, for example, comparison of results with modeling using standard finite element codes (e.g., ANSYS or ABAQUS) capable of thermomechanical analysis with plastic strain.

12.4.3 NEUTRON IRRADIATIONS

The irradiations and subsequent testing of irradiated samples will be the basis for extrapolating the performance of divertor test elements as neutron radiation affects the properties of the materials in the divertor. Materials and representative small-scale samples of divertor elements shall be irradiated to 5dpa ($E > 1\text{MeV}$) at 450°C . This is a problematic area since it will not be possible within a reasonable cost to irradiate large test elements, with ITER-like distributions of stress and temperature, for post-irradiation testing. The strategy will be to utilize small samples of single materials to determine the effects of irradiation on materials properties and to augment these tests with irradiations of duplex samples (e.g., armor and heat sink) in which there is an attempt to reproduce critical factors such as the temperature and stress distribution. The effects of irradiation on medium and large scale multi-channel test elements will have to be extrapolated by incorporating the results from post-irradiation materials and high heat flux tests into the modeling of performance of the test elements.

12.5 POST-IRRADIATION HIGH HEAT FLUX TESTS

These tests will measure the performance of small scale divertor test elements subjected to neutron irradiation and exposed to 2×10^3 thermal cycles of 30s duration at 5MW/m^2 . For beryllium samples, the surface temperature of the Be will be maintained above 150°C (coolant temperature $> 150^\circ\text{C}$) between power cycles. Specific objectives include:

- Adequate diagnostics, including (i) infrared thermography of surface temperature with observation of entire sample, (ii) thermocouple arrays to measure the temperature gradients through the heat sink, (iii) thermocouple probes to measure coolant temperature before and after the heated length, (iv) flowmeter, (v) measurements of pressure at inlet and outlet of the heated length, (vi) strain gauges on the armor and heat sink, (vii) gross deflections/bowing of the sample, and (viii) in-situ visual inspection of cracks with a borescope.
- Definition and design of the test set-up including the coolant loop.
- Procurement and commissioning of the test set-up.
- Provision of test specifications.

- Manpower and auxiliaries to carry out tests.
- Reports of measurements.
- Evaluation of measurements, for example, comparison of results with modeling using standard finite element codes (e.g., ANSYS or ABAQUS) capable of thermomechanical analysis with plastic strain.

12.5.1 MECHANICAL TESTS

These tests will simulate the response of divertor tests elements to various force histories. Test specifications shall be developed in conjunction with the JCT based on design data on the anticipated operating history of the ITER divertor, including disruption eddy current forces, halo current forces, and seismic loads.

12.5.2 POST-IRRADIATION MECHANICAL TESTS

These tests will simulate the response of small scale irradiated divertor tests elements to various force histories. Test specifications shall be developed in conjunction with the JCT based on design data on the anticipated operating history of the ITER divertor, including disruption eddy current forces, halo current forces, and seismic loads.

12.5.3 THERMAL SHOCK TESTS

This test program will evaluate the performance limits of divertor tests elements with respect to thermal shock generated by plasma disruptions and/or runaway electrons. Test specifications shall be developed in conjunction with the JCT based on design data on the anticipated operating history of the ITER divertor.

12.5.4 POST-IRRADIATION THERMAL SHOCK TESTS

This test program will evaluate the performance limits of small scale irradiated divertor tests elements with respect to thermal shock from plasma disruptions and/or runaway electrons. Test specifications shall be developed in conjunction with the JCT based on design data on the anticipated operating history of the ITER divertor.

12.5.5 BAKE CYCLE JOINT RELIABILITY TESTS

This test program will evaluate the effect of periodic baking cycles on the reliability of various joints used in the divertor (e.g.; Be/Cu, Be/SS; Cu/SS; Be/other; SS/SS). Testing shall consist of 100 cycles from RT to 350°C.

12.5.6 SYNERGISTIC TESTS

This test program will evaluate the effect of simultaneous steady-state high heat flux cycling and combined disruption thermal shock loads, and/or mechanical loads. Test specifications shall be developed in conjunction with the JCT based on design data on the anticipated operating history of the ITER divertor.

12.6 EXISTING DATABASE ON BERYLLIUM THERMAL FATIGUE AND JOINT FAILURES

The existing database on beryllium thermal fatigue and joint failures is rather sparse. Early work done in the 1980's involved short pulse (1-10 second) high heat flux cycling of inertially cooled (i.e. not bonded to a water-cooled heat sink), unirradiated, S-65C, bulk beryllium (for ISX-B and JET limiter tiles). Here, it was found that cyclic plastic strains on the order of 0.2-0.6% were sufficient to induce microcracking of the heated beryllium surface in as few as 25 cycles. The initiation, growth, curvature, and final arrest of the cracks depended strongly on the geometry, heat flux level, and pulse length. In some cases, deep cracks (e.g., tears) developed in a few thousand cycles to depths of 2-3cm. Crack arrest was also observed. These samples also

displayed evidence of so-called "lateral" cracks, which grew parallel to the heated surface starting at free edge corners. These lateral cracks are especially damaging, since they effectively reduce the thermal conductivity through the armor tile, and lead to overheating of the surface (with possible melting). During cooldown, cycling of the beryllium below 150-200°C into its so-called "brittle" regime is believed by JET personnel to increase fatigue damage. This is one reason the ITER inlet water temperature is set at 150°C. This issue will be an important subject to study during the EDA.

With regards to high heat flux testing of beryllium bonded to copper actively-cooled PFCs, the database is even smaller. Most of the work has been done at JET on their neutral beam test stand. Samples consisted of 2-3mm thick beryllium tiles (typically 6 x 6mm), silver-brazed to a CuCrZr hypervapotron heat sink. A variety of brazes were used, including CuSi18Ti (BAG-18), InCuSi1, and InCuSi1-ABA. Both vacuum furnace and induction brazing methods were used. Early thermal cycling tests showed poor performance of the furnace brazed BAG-18 mockups, with bondline fractures in the Be/Cu intermetallic layer occurring after a few hundred cycles at heat fluxes around 10MW/m². Later, with improvements in the brazing methods, samples survived over 1000 cycles at 12MW/m² with no damage. Ultimate failure was observed at higher heat fluxes (16-18MW/m²).

High heat flux thermal cycling tests were performed recently on a Russian Federation divertor mockup with diffusion bonded beryllium to copper at the Sandia electron beam test system (EBTS). Beryllium tile thickness was 5mm. A wide variation in fatigue lifetime was observed, ranging from complete tile detachment after a few cycles, to partial debonding after 9000 cycles, both at 5MW/m² steady-state heat flux. Another tile failed at 10MW/m² after less than 100 cycles, and a fourth tile failed (again, debonded) after 6000 cycles at 5MW/m². The large variation in cycles-to-failure was attributed to the formation of a brittle beryllium-copper intermetallic phase (Be₂Cu) during the high temperature diffusion bonding process (no diffusion barrier was used). However, examination of the bulk beryllium showed no evidence of microcracking, even after 9000 cycles at 5MW/m². This is an encouraging result, especially since room temperature water was used for cooling the sample, meaning that each cycle the sample cooled down below its ductile-to-brittle transition temperature. These test results are in good agreement with similar tests performed in Russia on similar samples.

High heat flux tests were also performed on a diffusion bonded S-65C beryllium monoblock with OFHC copper tube. Early fatigue failures (< 100 cycles) were observed at 5MW/m². This joint used silver as a diffusion barrier, but oxidation of the silver interface was suspected as a possible cause of the poor performance.

The existing database on disruption thermal shock effects on beryllium is sparse (about 3 points). Some evidence exists for the formation of very small microcracks at the heated surface after 10MJ/m² heat pulses of 0.1ms duration on samples of S-65C beryllium irradiated in PLADIS at the University of New Mexico.

No thermal cycling or thermal shock tests have been performed on neutron irradiated beryllium.

No synergistic tests have been performed on beryllium (except for the use of beryllium limiter tiles in existing tokamaks, ISX-B and JET).

In summary, the following conclusions can be drawn from the existing database regarding the limitations on beryllium use in ITER:

1. At 5MW/m² surface heat flux, and 5mm thick beryllium tiles bonded to copper, bulk cracking does not appear to be a problem for unirradiated material.
2. Diffusion bonding beryllium directly to copper produces a wide variation in bond fatigue strength, from a few cycles to over 9000 cycles at 5MW/m², resulting in very poor reliability.

3. Beryllium tiles, 2-3mm thick, brazed to copper with silver-based alloys have withstood over 1000 cycles at 12MW/m², without failure (which exceeds the design peak heat flux of 5MW/m² by more than a factor of 2). However, silver braze alloys are unacceptable in the ITER neutron environment due to cadmium transmutation and high radioactivity.
4. The database on thermal fatigue performance of alternate methods of bonding is non-existent (silver-less brazes, e.g., aluminum-silicon, roll bonding, plasma spraying, friction welding, electroplating, explosion bonding, etc.).
5. The minimization of brittle beryllium/metal intermetallic layers appears to be an important step in improving thermal fatigue lifetimes of bonded duplex structures.
6. No database exists on the thermal fatigue performance of neutron irradiated beryllium or beryllium/copper bonded duplex structures.
7. No database exists on thermal fatigue performance of emerging beryllium materials (plasma sprayed beryllium, beryllium carbide composites, carbon-fiber reinforced beryllium composites, beryllium/aluminum alloys, etc.).

12.7 LIMITING FACTORS ON THE USE OF BERYLLIUM IN ITER

With respect to high heat flux thermal cycling and mechanical loads, the key uncertainties regarding the use of beryllium are:

1. Will the heat transfer of the coolant system be sufficient to cool the beryllium armor to stay below acceptable limits (500-700°C), and with an adequate safety margin against CHF burnout?
2. Will the cyclic thermal stress or mechanical stresses from eddy current forces, etc. at the bond interface lead to bondline failure, partial delamination, or complete detachment? Loss of adequate cooling of the armor tile would lead to overheating and eventual melting, causing unacceptable erosion and/or impurity generation into the plasma core.
3. Will the cyclic thermal stress or mechanical stresses from eddy current forces, etc. inside the bulk beryllium armor lead to fatigue crack initiation and growth? So-called vertical cracks (e.g. perpendicular to the bondline), may not pose a hazard to the plasma facing component because the good heat flow is not affected. However, lateral cracking will increase the thermal resistance, and possibly lead to overheating and eventual melting, causing unacceptable erosion and/or impurity generation into the plasma core.
4. Will neutron induced loss-of-ductility and embrittlement of the bulk beryllium lead to premature fatigue cracking under thermal cycling and/or mechanical loads? If so, how fast will this happen?
5. Will neutron induced swelling and irradiation creep cause excessive deformations, and/or differential swelling stresses, leading to unacceptable cracking and premature failure?
6. Will periodic baking cycles (to 350°C) lead to joint failures?
7. Will simultaneous steady heat loads plus disruption thermal shock or mechanical loads cause premature failure of the Be/Cu bond joint, or cracking of the Be armor?

12.8 ADDITIONAL DATA REQUIRED

An extensive program of testing will be required to answer the questions posed in the previous sections. The following sections describe a test plan for generating this data.

12.8.1 SUBTASK T-2.1 MANUFACTURE DIVERTOR TEST ELEMENTS

The US Home Team will manufacture 10 divertor test elements in accordance with sketches supplied by the JCT. The joining technology for beryllium armor will be developed in Task T-1. In advance of the start of this subtask, guide-lines for a QA plan for manufacturing will be including in the initial development of Task T-2 via Subtask T-2.2. Detailed manufacturing specifications will be developed in accordance with appropriate quality control and quality assurance procedures. Within the US Industrial Partners working with Sandia, McDonnell Douglas will lead in manufacturing of water-cooled test elements, General Atomics will lead in manufacturing of helium-cooled test elements, and Rocketdyne will be responsible for the beryllium joining technology. This subtask will be coordinated with other parties manufacturing Divertor Test Elements.

Total Cost:	\$2M
Facilities:	Existing facilities
Collaborations:	RF, EC, J

12.8.2 SUBTASK T-2.2 DEVELOPMENT AND COORDINATION, QUALITY ASSURANCE

The US Home Team will develop a test program for validation tests on divertor test elements that includes (1) a Quality Assurance (QA) Plan that covers materials, fabrication of samples, test procedures and analysis and reporting of test data and guidelines for manufacturing of divertor test elements, (2) test program specifications that cover materials, designs for test rigs, test procedures and procurement of materials and fabrication of samples, and (3) a database assessment of the unirradiated and irradiated properties of materials necessary to perform appropriate design analysis and analyses of test results. The planning and initial implementation will be done during the first year, after which coordination and oversight of QA for US activities in Task T-2 will continue in this subtask. The database assessment will draw upon other tasks (e.g., data on beryllium from T-1). The US Home Team will work closely with the other parties to share information and, as much as possible, develop a common approach for planning and QA.

Total Cost:	\$1M
Facilities:	Existing facilities
Collaborations:	RF, EC, J

12.8.3 SUBTASK T-2.3 HEAT TRANSFER TESTS

The US Home Team will fabricate samples and perform heat transfer tests with high heat flux ($1\text{--}10\text{MW/m}^2$) under a variety of conditions. Preliminary testing (Stage I) will be done on both single channel water-cooled samples and single channel helium-cooled samples. Both types of testing can be done at Sandia's Plasma Materials Test Facility (PMTF). Helium tests will use an upgraded helium flow loop on the 30kW e-beam facility in PMTF. The major effort will be in providing baseline data, with subcooled boiling water flow, from which heat transfer coefficients and Critical Heat Flux values may be deduced for the configuration(s) of interest for ITER and the basic operating parameters for normal operation. Most tests will be on single channel samples. Some tests with multiple channel samples will be performed to study flow instabilities caused by boiling. During Stage II, the testing (on small samples) will be extended to cover flow regimes important for analyses of accidents and off-normal operation (hot spots, imperfections such as voids in joints,

asymmetric flow in parallel channels, low flow, etc.). Stage I will include tests on the influence of geometry on internally finned tubes in helium-cooled samples and evaluations of heat transfer efficiency versus pumping power. If a design with helium cooling is carried into Stage II, tests on flow instabilities in helium-cooled multiple channel samples will also be done. Thermal-hydraulic analysis will be done to support the design of tests and the evaluation of test results. Testing and analysis will be coordinated with the overall Quality Assurance for T-2. The US Home Team will work closely with the other parties to share information and, as much as possible, develop a common approach for planning and QA.

Total Cost:	\$0.5M
Facilities:	Existing facilities
Collaborations:	RF, EC, J

12.8.4 SUBTASK T-2.4 HIGH HEAT FLUX TESTS

The US Home Team will fabricate and perform preliminary high-heat flux (HHF) tests on small samples and will perform HHF tests on four divertor test elements in an existing facility. The divertor test elements will have a heated length of 200mm and be exposed to 10^4 thermal cycles of 30s duration at MW/m². For beryllium samples, the surface temperature of the Be will be maintained above 150°C (coolant temperature > 150°C) between power cycles. Preliminary testing (Stage I) will be done on both single channel water-cooled samples and single channel helium-cooled samples. Both types of testing can be done at Sandia's Plasma Materials Test Facility (PMTF). Helium tests will use an upgraded helium flow loop on the 30kW e-beam facility in PMTF. Some preliminary tests with multiple channel samples will also be performed to study thermal fatigue under heat loading that is non-uniform from channel to channel. During Stage II, the testing (on small samples) will be extended to cover heat loads important for analyses of accidents and off-normal operation (hot spots, imperfections such as voids in joints, asymmetric flow in parallel channels, low flow, etc.) and thermal fatigue testing of armor replacements representing in-situ repair. Studies of synergistic effects from plasma disruptions and thermal fatigue are covered in Subtask T-2.6. If a helium-cooled design is carried into Stage II, then, in preparation for HHF tests on divertor test elements beginning in 1996, the helium flow loop will be expanded and coupled to Sandia's large e-beam facility. Thermomechanical and thermal-hydraulic analysis will be done to support the design of the tests and the evaluation of the tests results. Testing and analysis will be coordinated with the overall Quality Assurance for T-2. The US Home Team will work closely with the other parties to share information and, as much as possible, develop a common approach for planning and QA.

Total Cost:	\$4.5M
Facilities:	Convert existing facilities to beryllium operations (\$1M)

12.8.5 SUBTASK T-2.5 MECHANICAL TESTS

The US Home Team may rely on other parties for mechanical testing. The expected activities include fabrication and perform preliminary mechanical tests on small and medium sized samples, including testing to failure, and non-destructive mechanical (vibration) tests on divertor test elements. The US will perform some mechanical analyses and may request non-destructive mechanical tests of US-manufactured divertor test elements by another ITER party. Beryllium-compatible test facilities exist at a wide variety of US companies and national laboratories, i.e. Rockwell, Lockheed, Rocky Flats, ORNL, LANL, LLNL, INEL, etc. However, additional costs will be incurred in the long-term (e.g., lifetime) health monitoring a new set of "beryllium workers".

Total Cost:	\$2M
Facilities:	Convert existing facilities to beryllium operations (\$0.5M)

12.8.6 SUBTASK T-2.6 THERMAL SHOCK TESTS

The US Home Team will fabricate small samples and perform thermal shock tests and also expects to continue the existing bilateral collaboration with Russia on experiments in the US and Russia with plasma guns and to negotiate further collaborations on larger tests to be done at Russian facilities. The US activity will include tests on the anticipated synergistic effects of thermal fatigue and thermal shock. For these tests, a 200kJ plasma gun will be installed on the 30kW e-beam at Sandia National Laboratories. Thermomechanical analysis will be done to support the design of the tests and the evaluation of the tests results. Testing and analysis will be coordinated with the overall Quality Assurance for T-2. The US Home Team will work closely with the other parties to share information and, as much as possible, develop a common approach for planning and QA.

Total Cost: \$2.5M

Facilities: Upgrade EBTS with 200 kJ disruption gun (\$1.5M)

12.8.7 SUBTASK T-2.7 BAKE CYCLE JOINT RELIABILITY TESTS

The PMTF EB-1200 facility could perform these tests.

Total Cost: \$0.5M

Facilities: Existing facilities, with upgrades for beryllium operations (n.c.)

12.8.8 SUBTASK T-2.8 NEUTRON IRRADIATIONS OF DUPLEX SAMPLES

Small samples of various duplex structures (e.g. Be/Cu with plasma sprayed, diffusion bonded or brazed joint) will be prepared for irradiation tests. Beryllium (from T-1) will be the armor. Heat sinks will likely include dispersion strengthened copper, V5Cr5Ti (a vanadium alloy) and a stainless steel. Duplex samples representing joints of armor/substrate and joints in the heat sink piping will be included. Irradiations at 400°C to fluences of 1,3 and 5dpa. A detailed test matrix will be developed with the JCT. The US Home Team will fabricate, encapsulate these samples for irradiations and transport the samples and containers to the reactor(s), and, after the irradiations, will retrieve the irradiation capsules, clean, sort, identify samples at ORNL and ship samples to the appropriate sites for post-irradiation testing. Within the neutron irradiation activity for Subtask T-2, "archive" samples will be maintained for comparison with irradiated samples. The inventory of samples will also include samples for pre- and post-irradiation characterization of microstructures as well as control samples to be exchanged with other parties who are performing irradiations (e.g. Russia BOR-60 Reactor) and post-irradiation testing. The US Home Team will work closely with the other Parties to coordinate the exchange of samples and to share information and, as much as possible, develop a common approach for planning and QA. This task should be closely coordinated with the irradiations of bulk pieces of beryllium, as described in the earlier chapter of this report on neutron effects on beryllium.

Total Cost: \$0.5M

Facilities: Existing facilities

12.8.9 SUBTASK T-2.9 POST-IRRADIATION HIGH HEAT FLUX TESTS

The US Home Team will perform high heat flux (HHF) tests on irradiated samples supplied via Subtask T-2.8. The tests parameters will be similar to those for unirradiated samples. About one fourth of the samples will receive the full lifetime exposure of 10^4 thermal cycles of 30s duration at 5MW/m^2 . To reduce cost, other samples will be exposed to 1000 cycles. For beryllium samples, the surface temperature of the Be will be maintained above 150°C (coolant temperature $>150^\circ\text{C}$) between power cycles. In preparation for the post-irradiation HHF tests, a hot cell electron beam facility will be prepared by outfitting existing hot cell space at Sandia with an existing 40kW electron beam. The US proposal is put forth due to the continuing denial of an operating license for the hot cell e-beam at KFA Jülich; if the facility at Jülich does become available, the US would prefer a collaboration using that facility. Collaboration with other parties on the preparation of specimens and evaluation of results is desired. JAERI has plans to install an e-beam test facility in a hot cell in Japan. Testing and analysis will be coordinated with the overall Quality Assurance for T-2.

Total Cost: \$4.5M

Facilities: Upgrade e-beam for hot cell and beryllium operations (\$2M)

12.8.10 SUBTASK T-2.10 POST-IRRADIATION MECHANICAL TESTS

The US Home Team will perform mechanical tests on irradiated samples supplied via Subtask T-2.8. These tests will include measurements of basic mechanical properties, including yield and ultimate stresses, tensile ductility and creep, of both "archive" (unirradiated) and irradiated samples. (Note: these tests differ from the vibration tests performed in the Subtask T-2.5 Mechanical Testing.) Collaboration with other parties on the preparation of specimens and evaluation of results is desired. Testing and analysis will be coordinated with the overall Quality Assurance for T-2.

Total Cost: \$2M

Facilities: Upgrades for beryllium operations in a hot cell (\$0.5M)

12.8.11 SUBTASK T-2.11 POST-IRRADIATION THERMAL SHOCK TESTS

The US Home Team will perform thermal shock tests in conjunction with HHF tests (Subtask T-2.9) on irradiated samples supplied via Subtask T-2.8. In preparation for the post-irradiation thermal shock tests, the hot cell electron beam facility proposed for Subtask T-2.10 will be expanded to include a 200MJ plasma gun. The US proposal is put forth due to the continuing denial of an operating license for the hot cell e-beam at KFA Jülich; if the facility at Jülich does become available, the US would prefer a collaboration using that facility. Collaboration with other parties on the preparation of specimens and evaluation of results is desired. Testing and analysis will be coordinated with the overall Quality Assurance for T-2.

Total Cost: \$2M

Facilities: Add 200 kJ disruption gun to e-beam in a hot cell (\$1.5M)

12.9 ADDITIONAL FACILITIES REQUIRED

Upgrades of existing facilities, and new facilities will be required to perform these tests.

1. Convert e-beam and ion-beam HHF test facilities to beryllium operations	\$1.0M
2. Convert mechanical test facilities to beryllium operations	\$0.5M
3. Add 200kJ disruption gun to e-beam test system	\$1.5M
4. Upgrade e-beam system for hot cell and beryllium operations	\$2.0M
5. Convert mechanical test facilities to hot cell and beryllium operations	\$0.5M
6. Add 200kJ disruption gun to hot cell e-beam test system & beryllium operations	<u>\$1.5M</u>
Total Cost	\$7.0M

12.10 VALIDATE IN TIME FOR ITER?

If the R&D plan as laid out in this chapter is fully funded, then there will sufficient information to validate the PFC design for ITER. Without the facilities upgrades for beryllium operation, and hot cell operation, it will be impossible to generate most of the required data.

12.11 TASKS, FACILITIES, AND COSTS

Costs for the R&D tasks are summarized in Table 12.1.

Table 12.1 Cost Summary, R&D Tasks & Upgrades

ITER EDA		
Task	Description	Cost (5 yr)
1	Manufacture of PFC test elements	\$2.0M
2	Development, coordination, quality assurance (QA)	\$1.0M
3	Heat transfer tests	\$0.5M
4	High heat flux tests	\$3.5M
5	Mechanical tests	\$1.5M
6	Thermal shock tests	\$1.0M
7	Baking cycle joint reliability tests	\$0.5M
8	Neutron Irradiations	\$0.5M
9	Post-irradiation high heat flux tests	\$2.5M
10	Post-irradiation mechanical tests	\$1.5M
11	Post-irradiation thermal shock tests	\$0.5M
12	Upgrades to experimental facilities	<u>\$7.0M</u>
	Total	\$22M

This cost estimate is for a 5 year ITER EDA. It is almost a factor of 2 higher than the current total amount of ITER IUA credits (\$12M) which have been allocated to R&D in this area, for all four ITER parties.

The US Home Team is spending an estimated \$1.6M/year on high heat flux and thermal shock testing. If the required R&D shown in Table 12.1 would be shared equally among the four parties, then the yearly rate would be $22/(5*4) = \$1.1\text{M/yr}$. This is less than what the US is currently spending on this task. It is not clear, however, that the other three ITER parties are spending at the same rate as the US.

CHAPTER 13. PLASMA EROSION OF BERYLLIUM

13.1 SPUTTERING EROSION

13.1.1 INTRODUCTION

It is widely recognized that power and particle control in the divertor region is a critical issue, affecting the plasma cleanliness as well as wall lifetime of a magnetic fusion reactor. In the case of the open-geometry divertor designed during the ITER conceptual design activity (CDA), the divertor plate is subjected to severe conditions of steady-state DT-plasma bombardment at fluxes above 10^{19} ions/cm²-s at energies around 100eV, corresponding to heat fluxes on the order of 10MW/m². This energy is above the minimum threshold energy required to sputter beryllium.

In the ITER engineering design activity (EDA), several innovative divertor concepts are being investigated to resolve the divertor plate erosion and heat load issues. Among those concepts, the dissipative divertor concept appears to be promising, supported by recent modeling and experimental data. In a dissipative divertor configuration, the peak power flux is reduced to 5MW/m² by intense neutral gas recycling and/or by impurity induced radiation. At the divertor plate, the plasma is essentially extinguished (electron temperature < 1eV), however, the charge-exchange flux and energy to the sidewalls are significant.

The plasma at the dissipative divertor sidewall-boundary (EDA) differs from the conventional high recycling plate-boundary plasma (CDA) in at least two respects: (1) the plasma density at the boundary is much lower (10 X), but may have a high local gradient, and (2) the magnetic field angle is likely to be more tangential. This may adversely affect the transport of sputtered impurities (e.g., Be). Typical plasma parameters are $T_e = T_i = 15\text{-}60\text{eV}$, and electron density = $10^{18}\text{-}10^{20}$ m⁻³ at the sheath. Hydrogen flux = $10^{21}\text{-}10^{22}$ /m²-s, and helium flux is about 10% of the hydrogen flux.

Redeposition of sputtered beryllium occurs when the sputtered atom, after being ejected from the wall, is ionized by the incoming electron and/or ions fluxes (i.e. electron impact ionization), and then travels along magnetic field lines to a location downstream from the point of origin. If the plasma density and temperature near the wall is high, then the mean-free-path (mfp) for redeposition is small, on the order of millimeters. This results in high redeposition rates, and lower net erosion rates. However, for cold plasma conditions and grazing angle of magnetic field (typical of the ITER EDA dissipative divertor design), then the sputtered Be atom can travel many tens of centimeters away from the point of birth, leading to low redeposition rates, and high net erosion rates.

13.1.2 R&D OBJECTIVES

- Understand the major physical processes during sputtering and redeposition simulation experiments (PISCES-B, TPE, ion beam sputtering).
- Perform accurate modeling of different sputtering/redeposition simulation experiments (PISCES-B, TPE)
- Define critical parameters and data needed to simulate ITER sputtering/redeposition.

- Perform simulation experiments on beryllium (PISCES-B, TPE).
- Recommend, design, and evaluate sputtering erosion experiments on existing tokamaks (DIII-D, TEXTOR, etc) relevant to ITER conditions.
- Perform modeling of erosion experiments on existing tokamaks (DIII-D, TEXTOR, etc).
- Evaluate ITER first wall and divertor sputtering erosion lifetime.

13.1.3 EXISTING DATABASE AND COMPUTER MODELS

The existing database on sputtering erosion of beryllium is quite small, and is primarily limited to monoenergetic ion beam irradiations by the Max Planck IPP [Roth, et. al] at normal angle of incidence with protons, deuterons, and alphas. Only recently have they performed experiments with beryllium self-sputtering, and at oblique angle of incidence (e.g. less than 90°). The formation of a beryllium oxide layer, which is difficult to remove, complicates accurate measurements of commercially pure Be sputtering. PISCES-B at UCLA has recently begun sputtering experiments of beryllium, but not in a regime where redeposition occurs. Problems with carbon contamination of the PISCES-B experiments have been reported, leading to lower measured erosion rates than theoretical calculations would predict. No data on the sputtering of beryllium at grazing angles of incidence have been reported. No data on the sputtering of redeposited Be, or of plasma sprayed beryllium, exist.

Computer models have been developed by the national laboratories (ANL, PPPL, Univ. Ill), which include most of the important physics effects. This set of codes includes WBC, REDEP, DEGAS, and VFTRIM. WBC is a monte Carlo code which computes the sputtering, Lorentz force motion, impurity-plasma collisions, Bohm diffusion, and detailed impurity transport at/near a sidewall point. It provides input to REDEP, a large-scale erosion/redeposition code. DEGAS is another Monte Carlo code which computes the charge exchange flux to the sidewalls. VFTRIM calculates the sputtering coefficients for REDEP, and includes energy and angle-resolved rough-surface wall reflection coefficients in a fractal methodology.

Initial experiments on the DIMES sample probe (graphite) in DIII-D have shown relatively good agreement between the calculated erosion/redeposition of carbon (calculated by Brooks, ANL), and the measured net erosion profile.

Computer modeling of both the plasma edge parameters, and of erosion/redeposition processes are generally considered to be highly speculative. These calculations are intended to provide only general trends, and to highlight critical issues.

13.1.4 LIMITING FACTORS ON THE USE OF BERYLLIUM IN ITER

Recent REDEP computer analyses by Jeff Brooks at Argonne National Laboratories point to several limiting factors on the use of beryllium for ITER plasma facing components. It is important to remember that, in general, computer modeling of both the plasma edge parameters, and of erosion/redeposition processes are generally considered to be highly speculative. These calculations are intended to provide only general trends, and to highlight critical issues. Jeff's conclusions are listed here:

- Erosion analysis has been initiated for dissipative divertors using coupled computer codes applied to a conceptual model and PPPL plasma solution.

- Runaway self-sputtering at the sidewall is a potential problem. This may set an upper limit on acceptable boundary [plasma] temperature. The limit may be worse (lower) for the low-Z materials due to the oblique incidence of the redeposited ions.
- Redeposition fractions for the sidewall are lower than for a conventional divertor plate due to a lower boundary electron density and more tangential poloidal field geometry.
- Calculated erosion rates for beryllium appear [to be] very high. A 5mm thick Be coating, for example, could be eroded in as few as 25 burn pulses (1000s pulses), even assuming no-runaway sputtering situation.
- Vanadium erosion is an order of magnitude lower than beryllium, all other things being equal. Tungsten erosion is potentially 2-4 orders of magnitude lower.
- Sputtered atoms of vanadium and tungsten appear likely to be confined to the near-boundary region and so would not affect the bulk of the divertor plasma. This is true of lithium and beryllium under most, but not all of the conditions surveyed.

The calculated sputtering erosion lifetime of the sidewalls is unacceptably low, only 25 shots. When combined with disruption erosion rates as high as 50 microns per disruption, it is clear that the present divertor design is unacceptable with respect to beryllium erosion.

Assuming a 50% duty cycle, the beryllium surface would be completely eroded in about one day. Then, assuming it takes three months (probably would be much longer) to *in-situ* plasma spray re-coat the surface back to 5mm, this would give an overall duty cycle less than 1%, which is unacceptably low for the technology phase of ITER.

Since all of the beryllium which is eroding inside of the vacuum vessel is redepositing somewhere, the buildup of thick layers of may also be a limiting factor for ITER.

Use of tungsten and beryllium simultaneously for PFC coatings raise the question of beryllium sputtering by tungsten, which could produce very high erosion rates.

13.1.5 ADDITIONAL DATA REQUIRED

More experiments and computer modeling are required to fully understand sputtering/redeposition erosion of beryllium inside of a tokamak. A key component is the validation of the coupled computer codes. J. Brooks listed five critical issues that need to be addressed:

Issue #1:

Dissipative divertor feasibility and plasma parameters at boundary-particle fluxes, sheath potential, magnetic field geometry, etc. Validation of computer models.

What is needed #1:

Crash modeling program (2-D fluid, kinetic code analysis), and an accelerated experimental program on tokamaks and simulators. Erosion/redeposition experiments on existing tokamaks (DIII-D, Alcator C-Mod, JET, etc.) with beryllium samples in dissipative divertor locations, including sidewalls, using DIMES type sample exchange mechanism. Erosion/redeposition experiments on plasma simulators, such as PISCES-B and TPE, at ITER-relevant parameters.

Estimated cost = \$10M\$

Issue #2:

Beryllium self-sputtering coefficients at oblique incidence (10-300eV, at 50°, are these greater than unity?

What is needed #2:

Experimental data (e.g., ion beam experiments, PISCES-B type data), coupled with sputtering code analyses.

Estimated cost = \$1.2M (only 2 years)

Issue #3:

Beryllium sputtering coefficients: D, T, He at very low energy and oblique incidence (5-50eV, 60°).

What is needed #3:

Experimental data (e.g., ion beam experiments, PISCES-B type data), coupled with sputtering code analyses.

Estimated cost = \$1.2M (only 2 years)

Issue #4:

Properties of thick redeposited Be films (thermal, mechanical, sputtering).

What is needed #4:

Experimental data on thick redeposited Be surfaces.

Estimated cost = \$2M

Issue #5:

Divertor and First Wall erosion lifetime predictions for ITER.

What is needed #5:

All data above, plus an accelerated, integrated modeling effort (e.g. with sheath, sputtering, and impurity transport codes).

Estimated cost = \$2M

13.1.6 ADDITIONAL FACILITIES REQUIRED

Upgrades of existing sputtering simulation facilities (such as PISCES-B) will be required to achieve ITER-relevant parameters. Estimated cost of upgrading PISCES-B, or an equivalent device, is \$10M.

Since no simulation facility can fully duplicate the tokamak environment, some in-situ tokamak experiments will be required (even though these tokamaks still do not fully simulate ITER conditions). Upgrades to DIII-D, Alcator C-Mod, JT-60, Tore Supra, etc. would be required to handle beryllium operations (JET already uses beryllium). Estimated cost is \$2M.

The total cost of facilities upgrades and /or new facilities is \$12M.

13.1.7 VALIDATE IN TIME FOR ITER?

The best computer model predictions that exist today predict a sputtering erosion lifetime of the ITER divertor equal to 25 full power shots, although with an extremely high uncertainty factor. This represents a completely unacceptably high erosion rate. No changes in the grade of beryllium will substantially change this answer. Only changes in the divertor geometry and tokamak physics have the potential to alleviate or eliminate this problem.

A dedicated R&D program is needed to improve our understanding of this problem, and select new divertor plasma physics regimes or divertor designs which reduce the erosion rates of beryllium by at least two orders of magnitude. With the present funding rates, it will be impossible to validate this R&D task in time for ITER.

13.1.8 TASKS, FACILITIES, AND COSTS

The R&D tasks are summarized in Table 13.1.

Table 13.1 Erosion Studies

ITER EDA

Task	Description	Cost
1	Modeling program, integrated with tokamak experiments	\$10M
2	Be self-sputtering coefficients at oblique angles	\$1.2M
3	Be sputtering coefficients (D,T, He) at oblique angles	\$1.2M
4	Properties of thick redeposited Be films	\$2M
5	Divertor, FW erosion lifetime predictions	\$2M
6	Experimental upgrades	\$12M
	Total	\$28.4M

This cost estimate is for a 5 year ITER EDA. It is roughly a factor of 6 higher than the current total amount of ITER IUA credits (\$4.9M) which have been allocated to R&D in this area, for all four ITER parties.

The US Home Team is spending an estimated \$1.3M/year on sputtering erosion tests of beryllium, including non-Be tests on tokamaks. If the required R&D would be shared equally among the four parties, then the yearly rate would be $28.4/(5 \text{ years} \times 4 \text{ ITER parties}) = \$1.4\text{M}/\text{yr}$. This is almost exactly what the US is currently spending on this task. It is not clear, however, that the other three ITER parties are spending at the same rate as the US.

13.2 DISRUPTION EROSION

13.2.1 INTRODUCTION

Intense deposition of energy during the thermal quench phase of a plasma disruption can cause severe surface erosion of beryllium-clad plasma facing components. Energy fluxes may be as high as 100-200MJ/m², with deposition pulse lengths of 0.1-3ms. The mix of particle type, (electron, deuteron, triton, alpha) and their energies are unknown. Neither the heated area is well known (which affects the heat flux), nor is the location of the heat flux (inner first wall, divertor dome, fins, dump plate, baffle, etc.).

Runaway electrons, which can be formed under certain conditions during the current quench phase of a plasma disruption, can be accelerated up to very high energies, 10-100MeV (possibly 300MeV in the ITER-CDA), and can cause very localized damage (melting) of both the beryllium, and the underlying copper heat sink, because of the deep penetration at these high energies. Sufficient energy can easily be generated for the runaway electrons to penetrate the low-Z beryllium, and melt the copper heat sink, leading to a water leak. A recent failure (e.g., water leak) of a the Tore Supra Phase-III water-cooled outboard pumped limiter has been attributed to a single runaway electron impact event, where the pyrolytic graphite tiles were essentially undamaged, but the underlying copper tube was melted. However, runaway electrons may be less severe with the use of beryllium, as compared to carbon, based on JET results.

Use of beryllium in JET (as compared to carbon) reduced both the severity and frequency of disruptions, because of its low-Z and spectral radiation characteristics. However, they were not completely eliminated. It must be presumed that ITER will have some number of disruptions, some minor, and some major. For this reason, it will be important to predict the exact amount of beryllium eroded by melting and ablation. The exact number, size, etc. will be debated among the physicists during the EDA, and, hence, the erosion lifetime will remain highly uncertain. Also, the threat to melting of the copper heat sink from runaway electrons needs to be studied and quantified, so that possible design changes can be implemented which mitigate the effects.

13.2.2 R&D OBJECTIVES

- Understand the major physical processes during both ITER disruptions and simulation experiments.
- Perform accurate modeling of different disruption simulation experiments (laser, electron beam, plasma gun, etc.)
- Define critical parameters and data needed to simulate ITER disruptions.
- Perform simulation experiments on beryllium.
- Recommend, design, and evaluate disruption experiments on existing tokamaks (DIII-D, TEXTOR, etc.) relevant to ITER conditions.

- Perform modeling of runaway electron generation, impact, and damage.
- Perform critical experiments on existing tokamaks (DIII-D, TEXTOR, Tore-Supra, etc.) with runaway electrons.
- Evaluate ITER first wall and divertor disruption lifetime.

13.2.3 EXISTING DATABASE

The existing database on disruption erosion of beryllium is quite small. A total of three data points exist for plasma gun (PLADIS) simulations. No data points exist for laser or e-beam simulations. PLADIS (PLAsma DISruption facility) is a coaxial plasma gun located at the University of New Mexico, which operates in the deflagration mode. These results show that at energy densities of 10-17 MJ/m² and 0.1 ms pulse length, the beryllium erosion is 8-22 microns (as measured by mass loss), and 35-50 microns (as measured by surface profilometry). It was observed visually that beryllium had splashed off the sample surface, presumably due to a high pressure of the incoming high velocity plasma.

Computer models have been developed which include three stages: (1) plasma-surface interaction, (2) plasma-vapor interaction, and (3) radiation transport. 2-D effects, and effects of low-angle magnetic field have been recently added to the A*THERMAL-S code, developed at Argonne National Laboratory. For similar conditions that were done in the PLADIS facility (10 MJ/m², 0.1 ms) described above, this code predicts an ablated thickness = 4 microns and a melt layer thickness = 40 microns. When compared with the experimental results, good agreement is found when the entire melt layer is assumed to be lost.

Although beryllium was used extensively inside of JET both as a thin coating, and as thick limiter tiles, no measurements of disruption erosion thickness has been published. However, there is clear evidence of melting and migration of melted layers of limiter tiles.

13.2.4 LIMITING FACTORS ON THE USE OF BERYLLIUM IN ITER

A. Hassanein at ANL has predicted using the A*THERMAL-S code the maximum allowed number of disruptions for a 5 mm thick beryllium armor tile, with 10 keV ions, 0.1 ms pulse length, and 5 Tesla magnetic field at 2° angle of incidence, as a function of incident plasma energy up to 100 MJ/m². Assuming that the melt layer is completely lost due to plasma pressure or electromagnetic forces, then the maximum allowed number of disruptions in ITER is 100. If the melt layer is not lost, then the number of disruptions increases to around 1000, an order of magnitude increase. These very low numbers of allowed disruptions illustrate the severe nature of this problem, and place strict requirements on the active control of disruptions.

As the beryllium tile becomes thinner from disruption or sputtering erosion, the temperature rise at the back of the tile (e.g. the braze interface) just after the disruption is over (due to the pulse of heat conducting through the tile) may become sufficiently large so as to melt the braze layer, especially if aluminum/silicon braze is used (melting point = 600°C). This may become a serious problem for tile thicknesses around 1 mm.

Even more severe is the problem of runaway electrons. Calculations performed during the ITER CDA showed that a single runaway electron event caused by a disruption had the potential to melt the copper heat sink, leading to a massive water leak. In theory, this could happen during any single given disruption. Beryllium, by virtue of the fact it is low-Z and transparent to high energy electrons, provides no protection to the copper heat sink from these events. On the other hand, tungsten, because of its high-Z, would provide excellent protection to the copper, at the expense of sacrificial melting itself.

13.2.5 ADDITIONAL DATA REQUIRED

More experiments are required using disruption simulators for beryllium. Effects of initial sample temperature, magnetic field, pulse length, energy flux, particle energy, and particle type are required. Measurements of the behavior of the melt layer motion are required. Effects of neutron-generated helium gas bubbles need to be studied. Additional plasma diagnostics are required to better characterize the incoming plasma blob, as well as the temperature, density, and size of the generated vapor shield cloud above the ablated surface. Better sample diagnostics are required, including: ultra-fast temperature pyrometry and pressure pulse measurements. Disruption simulations are needed comparing the erosion of bulk beryllium, vs re-deposited beryllium, vs plasma sprayed beryllium coatings. Experiments on neutron-embrittled beryllium are required to study the thermal shock effects.

Experiments *in-situ* in existing tokamaks with beryllium samples are urgently needed, because *ex-situ* simulations do not include all of the relevant effect simultaneously. Sample exchange stations, such as the DIMES probe on DIII-D, are ideally suited for such an experiment.

Detailed studies are required on beryllium armor tiles exposed to disruptions in JET.

Improved computer models are required to better simulate the disruption erosion. Such improvements include (1) vapor effects, turbulence and instabilities, (2) magnetic fields, edge effects, (3) vapor-plasma mixing zone effects, including impurities, and (4) melt layer loss, instabilities, and runoff or transport.

13.2.6 ADDITIONAL FACILITIES REQUIRED

Upgrades of existing disruption simulation facilities (such as PLADIS) will be required to achieve ITER-relevant parameters. An increase in the stored energy capacity at PLADIS will be needed to achieve 100MJ/m² energy density. Additional electronics is needed to provide pulse lengths an order of magnitude longer than 0.1ms (very difficult for coaxial plasma guns). Additional diagnostics are required for both the plasma gun and sample. Additional safety features are needed for safe beryllium operations. Estimated cost of upgrading PLADIS is \$1.0M.

Disruption testing of neutron irradiated beryllium samples in a hot cell facility has not been discussed, and no costs are available, although it could be as high as \$1.0M.

Conversion of the Russian Federation plasma disruption simulators, such as 2MK-200 or VIKA, to safe beryllium operations would be extremely useful, since some of their machines operate in a high magnetic field. Estimated cost is \$1.0M.

Addition of a 200kJ plasma disruption gun to the existing electron beam test facility at Sandia (EBTS), to provide simultaneous steady-state high heat flux temperature and stress profiles along with pulsed plasma disruption is required to study synergistic effects. Estimated cost of this upgrade is \$1.5M.

No experimental facilities have been identified for the study of runaway electrons, with the exception of Tokamaks. Additional funding is required for tokamak studies, including special diagnostic equipment, estimated at \$2M.

The total cost of facilities upgrades and /or new facilities is \$6.5M.

13.2.7 VALIDATE IN TIME FOR ITER?

Sufficient data exists today to state that from 100-1000 disruptions in ITER will completely erode the protective beryllium armor surfaces, depending on whether or not the melt layer is lost. No changes in the type of beryllium, or of the mechanical design, will affect this answer. Only changes in the tokamak physics, or in the day-to-day operation, have the potential to alleviate or eliminate this problem.

Without the required experimental upgrades described above, it will be impossible to study the effects of neutron irradiation, magnetic fields, or synergistic effects in time to affect the selection of beryllium for ITER.

13.2.8 TASKS, FACILITIES, AND COSTS

The R&D tasks are summarized in Table 13.2.

Table 13.2 Disruption Studies

ITER EDA

Task	Description	Cost (5 yrs)
1	Plasma disruption simulation experiments	\$2M
2	Computer model code development and validation	\$1M
3	Tokamak disruption erosion experiments	\$1M
4	Runaway electron computer modeling	\$0.5M
5	Runaway electron experiments on tokamaks	\$2M
6	Upgrade experimental facilities (non-tokamak)	<u>\$6.5M</u>
	Total	\$13M

This cost estimate is for a 5 year ITER EDA.

It is roughly a factor of 3 higher than the current total amount of ITER IUA credits (\$3.9M) which have been allocated to R&D in this area.

These costs can be compared to what the US Home Team is currently spending on a yearly basis in the area of disruption simulation (including non-Be tests in tokamaks). This present spending rate is 0.4M\$/year (ref. K. Wilson, SNL). An additional \$0.2M/year would need to be added to the present US funding in this area to bring it up to the required level, based on an equal share with the other parties.

CHAPTER 14. RECOMMENDED BERYLLIUM GRADES FOR ITER PLASMA FACING COMPONENTS

This chapter discusses the critical issues and panel recommendations for selection of Be materials in ITER applications. Issues and recommendations are broken down by application area in the divertor, first wall and breeder blanket. General recommendations are shown in Table 14.1. Discussion of these recommendations are found below.

14.1 DIVERTOR COMPONENTS

The divertor is broken down into five areas: fin, dome, baffle, dump plate and gas box liner.

14.2 FIN, DOME AND BAFFLE

The divertor fins are designed for a 5MW/m² heat flux, and are directly exposed to the plasma. In general S-65C is specified for those conditions based on low oxide content, low metallic impurities, and microalloying to achieve superior ductility at elevated temperatures. This general grade has been used in JET. S-65C is a vacuum hot pressed grade with anisotropic properties. Use of this VHP grade may be advantageous if the 6% typical elongation in the transverse direction can be used by designers to minimize thermal fatigue cracking. If isotropic properties are important, then S-65H, the HIP version of S-65C, should be considered. S-65C would be used as small machined tiles brazed on to these structures. Note that beryllium products from other sources may be used if acceptable properties and composition are demonstrated.

Plasma sprayed beryllium has many fabrication advantages for the fin and dome structures. Bonding of beryllium block or sheet to curved surfaces is very labor intensive. Plasma spraying of beryllium onto curved surfaces is much simpler. In addition, beryllium plasma spraying is an extremely attractive option for in-situ repair. At this time, considerable development of the Be plasma spray process is needed to obtain acceptable thermal conductivity and mechanical properties for the deposited beryllium. This may be a stronger option at the end of the EDA (>1998). Plasma sprayed beryllium would use low BeO, low impurity spherical powder, produced by any one of several powder processes including inert gas atomization and centrifugal atomization.

The baffle has similar requirements to the fin and dome, but its simpler geometry allows fabrication using slab or sheet. Isotropic properties may be useful here. With sufficient development of roll bonding or HIP of slab to Cu over the term of the EDA, S-65H may provide advantages to the designer.

S-65C is the recommendation for ITER as the best commercially available option in 1994 for dome, fin, and baffle. Plasma spraying of spherical beryllium powder is considered the best option after the end of EDA for fin and dome. S-65H slab is considered the best option after the end of EDA for baffle.

14.3 DUMP PLATE

This application may have the most severe conditions associated with it, particularly in terms of high heat flux. High heat flux can produce great cyclic stresses perpendicular to the plasma facing surface. One hypothesis is that beryllium service life under these cyclic stresses can be maximized by using beryllium having the highest possible ductility perpendicular to the surface. Rolled beryllium sheet made from either powder or ingot has high in-plane ductility due to texturing. Powder sheet can have 10-12%

elongation in-plane at room temperature. If sheets could be stacked on edge and bonded together, the resulting structure would have the highest possible percent elongation perpendicular to the plasma facing surface. Heiple (Met. Trans., vol. 3, April 1972, pp. 807-812) demonstrated in 1972 that a laminated beryllium sheet structure could be made using conventional HIP technology. Although unproven on the commercial scale it is expected that minimal development would be needed to obtain a structure with acceptable properties for this application. Either SR-200 sheet made from beryllium powder or MSC-100 sheet made from beryllium ingot could be used in such a laminated sheet structure.

In the long term, successful development of Be plasma spraying may provide acceptable Be properties and ease of manufacture. Maximum fracture toughness is achieved for 95% dense beryllium (Be Science and Technology). This means that near term developments in plasma spraying may provide an acceptable material for the dump plate. Thermal conductivity requirements need to be further defined.

14.4 BOX LINER

The low (1MW/m^2) heat flux expected for this application means that plasma sprayed beryllium may be acceptable after only modest development. The advantage of plasma sprayed beryllium is again ease of Be layer fabrication on a curved surface.

14.5 FIRST WALL

Plasma sprayed beryllium is the first choice here based on similar considerations for use in the gas box liner. With lower design heat fluxes ($<1\text{MW/m}^2$), the requirement for deposit thermal conductivity is not as great as in other applications, and even currently available plasma sprayed beryllium may be acceptable. However, excellent adhesion will be required, particularly in the event that eddy current forces cause flexing of the first wall. In addition, ease of repair is a substantial advantage.

14.6 BREEDER BLANKET

This application has minimal requirements for mechanical properties or chemical purity. The least expensive Be grade is chosen. However, there are two rival blanket designs, one requiring block material and one requiring pebbles 1mm in diameter. Although current breeder blanket research is focused on pebble, the production method does not allow control of size distribution, and spherical beryllium made by conventional shotting technology is specified. The panel recommends S-200F block or S-200F shot.

Table 14.1 Beryllium Grade for Various Components

Be Grade	Today's Choice	Most Promising End of EDA > 1998
1. Fin	S-65C 4/6% typical elongation "C" VHP 5/5% typical elongation "H" HIP	Spherical powder
2. Dome	S-65C	Spherical powder
3. Baffle	S-65C	S-65H (slab) 1 x 1 m ²
4. Dump plate	SR-200 MSC-100 sheet	Spherical powder
5. Box liner	Spherical powder	Spherical powder
6. First wall	Spherical powder	Spherical powder
7. Breeder	S-200F block or pebbles	S-200F block or pebbles

CHAPTER 15. PROPOSED MANUFACTURING METHODS TO PRODUCE BERYLLIUM PARTS FOR ITER

15.1 INTRODUCTION

Manufacturing methods to produce beryllium parts for ITER were considered in terms of both large scale initial fabrication and in-situ repair requirements. For the initial fabrication, manufacturing methods must be scalable to yield parts with very large surface areas. The processes must be amenable to real-time controls to insure that consistent quality can be achieved throughout the part.

Joining the beryllium panels to the copper cooling units which are in turn joined to the structural steel components is a key technical problem for ITER applications...Developing a basic process which is amenable to production methods in a reproducible manner will be difficult. Since the early 1960's, joining beryllium to itself and to other metals has been done for unique singular applications and for small and large scale production; however, there has been negligible study or need of joining beryllium to copper, and especially age hardenable copper base alloys. The beryllium joining processes which have been developed and improved upon over the past thirty years for other applications do provide a good foundation for the ITER beryllium to copper joining problem.

In-situ repair of damaged beryllium armor material demands that the repair process allows either 1) replacement of individual beryllium armor pieces by detaching them from a copper or other high conductivity substructure and substituting new pieces, or 2) redepositing additional beryllium onto the eroded or disruption damaged beryllium armor surface. Both of these processes must be capable of being robotized since personnel access to the first wall and plasma facing components will not be feasible due to high radiation levels that are expected after ITER operation.

The initial fabrication and the in-situ repair methods may not necessarily be the same process. Because of the large area of the first wall, for example, a lower cost and complexity fabrication method can be used for initial assembly. Subsequent repair and refurbishment will be necessary only at limited area locations, and so a more complex procedure could be employed.

15.2 REVIEW OF MANUFACTURING PROCESSES

15.2.1 WELDING

Powder origin beryllium has been welded to itself using a filler metal and the following processes:^{1-8, 12-16, 19, 29-32}

- Metal Inert Gas (Al/Si filler)
- Pressure Inert Gas Metal Arc (Al/Si filler)
- Electron Beam with preplaced shim (Al/Si filler)
- Electron Beam with cold wire feed (Al/Si filler)
- Electron Beam with PVD Aluminum

Powder origin beryllium has been welded to aluminum using electron beam processes.

Powder origin beryllium has been welded to itself without filler alloys (autogenous welding) using both electron beam and laser welding processes.

Ingot beryllium has been welded autogenously using both electron beam and laser welding processes.

Some of these processes were developed in the 1960's and some are recent developments. The welding processes developed in the 1960's have not undergone fundamental changes, however, there have been many improvements and the welds of today are of much higher quality. All of these processes have been used in singular applications, and many have been used in production. Because of the geometry of the ITER application, welding may not be the best approach. However, it has been found that for successful welding of beryllium there are many factors in the beryllium material which should be controlled (e.g., restrictions on certain impurities, necessary controls on mechanical properties, restrictions on maximum grain size, special controls on the quality, need for preheat).³² Many of these variables discovered in the welding developments apply to other processes of joining beryllium, and these variables should be included in any beryllium to copper ITER joining efforts.

15.2.2 BRAZING AND SOLID STATE DIFFUSION

Beryllium has been brazed to itself and to a variety of other alloys using many different intermediate alloys.^{8-13, 17, 18, 21, 22, 25-28, 30, 31, 36} Beryllium to beryllium solid state diffusion has also been done. Following is a representative summary:

Join Beryllium to	Braze Material	Temperature (°C)
Beryllium	none	800-1000
Beryllium	Al/Ge	425
Beryllium	Al/Si	580
Beryllium	Al	680
Beryllium	10Sn/30Cu/60Ag	650
Beryllium	28Cu/72Ag	800
Beryllium	Ni	800
Beryllium	Cu	885
Beryllium	Ag	900
Copper	28Cu/72Ag	800
Monel	28Cu/72Ag	800
Monel	10Sn/30Cu/60Ag	650
Uranium (D38)	Ag	900
Uranium alloy	Ag	900
304 SS	28Cu/72Ag	800
304 SS	Al/Ag	580
316 SS	28Cu/72Ag	800
Tantalum	Ag	900
W/Ni/Fe	Ag	900

Some of the above bonding procedures are simple and some are complicated. There are also some unpublished proprietary brazing procedures in addition to those listed. Using some of these procedures, beryllium to beryllium bond strengths exceeding 345MPa (50 ksi) have been achieved. We recognize that the lowest temperature brazes may be too low for the ITER applications, the highest temperature brazes may present practical problems, while those containing silver are not favored for other reasons. The essential point is that there are many ways that beryllium can be brazed to other metals, and while copper is not a common application, there is a good base of information to utilize.

Beryllium and copper have been solid state bonded by W. D. Ludeman in 1969.⁸ This work was a basic study on the importance of surface preparation and oxide film participation in the bonding process. Brush Wellman Inc. has used hot isostatic pressing (HIP) to bond beryllium to other materials. The experience

is not extensive, and surface preparation would be a key concern. If solid state bonding is successful, it does lend itself to production quantities and reproducibility.

15.2.3 FRICTION WELDING

Friction welding is a good method of joining alloys that differ significantly in melting temperature or metallurgical properties. The low joining temperature is favorable to the alloys being joined and the subsequent service temperatures, in that the friction welding process usually minimizes the formation of intermetallic phases. The feasibility could be quickly established, as the geometry used in friction welding lends itself to simple tensile tests. If reasonably high strengths are obtained on laboratory size specimens, then the ensuing effort could be directed to the practicalities of scaling up to ITER size coupons, developing the inspection methods and understanding the metallurgical aspects and the accompanying limitations of the weld. There is a friction welding development currently in progress at Sandia National Laboratories. Mechanical properties have not yet been determined. Because of the configuration of the copper alloy parts, friction welding would probably have to be an intermediate junction, with a subsequent copper to copper alloy joint required. Friction welds 10cm to 15cm in diameter are routinely made, and there are a few machines that can make friction welds up to 50cm in diameter. Using 2000m² as a rough estimate of the area of the first wall and divertor, this would require some where between 15,000 and 128,000 tiles containing the friction weld. While many manufacturing steps could be automated, friction welding may present some scale up problems.

15.2.4 ELECTROPLATING

Beryllium has been joined to itself by electroplating. Dini and Johnson reported at the American Electroplaters' Society Light Metals Symposium in Toronto (June 1975) the development of using both copper and nickel to create joints between two pieces of beryllium.^{33,35} Tensile tests of the bonds resulted in failure in the base beryllium material and failure strengths exceeding 320MPa (46ksi). In unpublished work, Los Alamos National Laboratories reported joining beryllium to beryllium using copper electroplating and achieving shear strengths of about 250MPa (36ksi). The low joining temperature of the electroplating process is favorable to the alloys being joined and the subsequent service temperatures. While the geometry used in these studies are not amenable to the ITER applications, the basic concept may be suitable. For example, copper could be electroplated on to the beryllium tiles, and then this new copper interface be joined to the copper cooling units using more conventional copper to copper joining techniques.

15.2.5 ROLL BONDING

Copper and copper alloys are roll bonded to many materials on a production scale including stainless steel. Roll bonding of beryllium has not been done. The high reduction in thickness needed for roll bonding at room temperature and the low ductility of beryllium may necessitate roll bonding at high temperatures, preferably in the beryllium annealing temperature range (700°C - 1000°C). However, there is a possibility that moderate temperature (400°C) roll bonding experiments using only 10-15% reduction may prove valuable. The reactivity of beryllium may make preparation and maintaining the cleanliness of the large surfaces during the roll bonding difficult. The rolling process may develop a stronger crystallographic texture in the beryllium than desirable. The differences in thermal expansion of the copper and beryllium combined with the high rolling temperatures may cause distortion upon cooling. A compliant layer may be effective in ameliorating this potential problem. There also may be a problem with the high bonding temperature and maintaining the strength of the copper alloy. If roll bonding is successful, it would have a major advantage in scaling up to the sizes needed for the ITER applications.

15.2.6 PLASMA SPRAYING

The plasma spray process is accomplished by means of a plasma gun in which an arc is struck between concentric electrodes, in the annulus of which a gas is flowing. The plasma temperature can approach 10,000-20,000°C and powder is injected into the plasma flame either inside the gun itself, or just downstream from the gun. The solid powder particles are melted in the plasma flame and are deposited on a substrate located some distance downstream from the plasma gun. The plasma spray process is widely used for coating of critical gas turbine engine components such as turbine blades, and for forming free standing shapes of various metallic and ceramic materials.

An excellent review of past experience with plasma-spraying of beryllium is contained in the report "U.S. Design Support Study for the ITER Divertor", ITER/US/93/IV-PF-3 (October 1993). Current effort is also presented, and the remaining technical issues are indicated as optimization of spray parameters to achieve the desired deposit properties, and the uncertainties regarding the bonding of plasma-sprayed deposits to various substrates and to beryllium surfaces. The latter issue is central to the utility of plasma spraying as an in-situ beryllium surface repair technique.

Information submitted to the committee by a major industrial firm engaged in plasma-spraying (Electro-Plasma, Inc.) indicated that the cost to perform the R&D scaleup and process demonstration of plasma spraying of beryllium could cost up to \$32M and require about ten years to accomplish. This assumed that the scaleup would be accomplished in three steps: 1) an experimental facility using a model material such as Al_2O_3 ; 2) a production facility that would fabricate required components; and 3) an on-site repair facility. These tasks were estimated to require: 1) \$8M and 36 months; 2) \$12M and 48 months, making no use of the facility developed in 1); and 3) \$12M and 48 months.

It has been suggested to the committee that existing beryllium plasma spray facilities at the Y-12 plant could be utilized for process scaleup and ITER component manufacture. Close coordination with the effort to develop remote maintenance procedures would be maintained since this effort is being performed by Oak Ridge National Laboratory. It was estimated that from one to two years would be required to convert the existing facility to an open operation. No cost estimate was given, but the committee believes that this option could represent significant cost and time savings over the three tasks proposed above by Electro-Plasma, Inc.

Current effort at the LANL BATS facility to optimize the vacuum plasma spray process should continue, with research results sufficient to guide future scale-up of the process. Critical research areas should be emphasized such as maximizing thermal conductivity, improving deposit efficiency, coating uniformity and coating adhesion to the underlying material. Research should be conducted using current state-of-the-art plasma-spraying technology, and the approach used should be scalable for future production operations. Samples for physical property measurements should be taken from optimized material, and minimum use should be made of samples that do not represent the best material that could be made, given more time for material optimization.

A three year R&D effort is recommended, in order to evaluate options for plasma spray processing, and to develop selected options for eventual scale-up. A detailed program is described for the first year, and the subsequent years will proceed to complete the objective of having an optimized process ready for implementation. LANL and Y-12 will work closely together to accomplish the tasks, as follows:

- **First Year:**

1. Classified Literature Review and Assessment. Both Y-12 and LANL will conduct this review of information which has not been generally available before in order to identify those aspects of past work that can contribute to the current effort. (\$20K)
2. Powder Evaluations. Different beryllium powder grades and morphologies will be assessed as to their performance in the plasma spray operation, and a set of specifications will be developed for chemical composition, size and size distribution and required morphology. (\$200K)
3. Torch Design. The requirements for optimized torch performance will result in design modifications for operation under low pressure or atmospheric pressure conditions. This will involve differences in anode and cathode configuration, gas injection, powder injection and nozzle geometry, each of which may be iterated before optimum performance is realized. (\$500K)
4. Process Modeling. Huge savings in experimental effort might be realized through process model development which will guide the selection of specific experimental conditions. Topics such as gas dynamics, plasma-particle interactions and impact kinetics will be addressed. (\$200K)
5. Process Diagnostics. Application of techniques for determining particle temperature and velocity will provide important input to process control parameters. Also, in-process application of real time deposit thickness measurement will be helpful to optimize processing. (\$400K)
6. Beryllium Spray Trials. Both atmospheric and low pressure plasma spray methods must be evaluated through actual operational trials. (\$500K)
7. Characterization and Performance: The thermal conductivities and microstructures of optimized coatings must be measured, and the results used to determine directions for further development and scale up. (\$100K)
8. Surface Preparation. Methods of surface preparation such as transferred arc and inert gas pellet cleaning will be evaluated. (\$80K)
9. NDE. Methods of non-destructive inspection suitable both for in-process measurements, and post-spraying inspection of plasma sprayed coatings will be investigated. (\$250K)

Total effort for first year = \$2,250K Capital equipment = \$500K

- **Second and Third Years**

Similar tasks will be continued, and the emphasis will shift to those issues involving scale-up for manufacture of ITER components and for the development of repair methods suitable for application with robotic equipment. Costs for each year will be similar to the first year costs, or approximately \$2,500K per year.

15.2.7 EXPLOSIVE BONDING

Explosive bonding has been used on a commercial basis for 2-3 decades to bond dissimilar metals. The low ductility of beryllium would not appear to favor this bonding process; however, there has been some success on other low ductility metals. As for some of the other bonding processes, explosive bonding

could provide a transition layer, with unalloyed copper bonded to the beryllium and then the beryllium/copper sandwich brazed to the copper alloy using a conventional relatively low temperature copper to copper alloy braze material. Northwest Technologies Inc. is committed to trying a limited development program with their own funding. Brush Wellman is supplying them with commercial S200E sheet material, and Lawrence Livermore National Laboratory is providing them with "CIP-HIP" beryllium sheet which has unusually high ductility combined with high strength. The latter sheet, while no longer available, could be made on a commercial scale if there was a market for it.

15.2.8 ORGANIC ADHESIVES

Organic adhesives have been used successfully. The temperature requirements and the radioactive environment eliminate this procedure for ITER.^{20, 23, 24}

15.2.9 MECHANICAL JOINING

Mechanical joints have been used to join beryllium to beryllium. The heat transfer requirements and the low fracture toughness of beryllium do not favor this approach for ITER.^{12, 20}

15.3 SPECIFIC TECHNICAL CONCERNS FOR THE ITER APPLICATION

In solid state diffusion it is usually necessary to have very flat surfaces which can readily mate. By applying pressure and high temperatures, surface imperfections can be overcome. However, (a) the difference in thermal expansions of the beryllium and the copper alloy (b) the possible high pressures that may be needed, (c) the high temperatures needed may harm the copper alloy mechanical properties, and (d) the relatively large surface area to be bonded militates against beryllium to copper solid state diffusion, unless a compliant layer is incorporated into the solid state process.

The large surface area to be covered and related large number of tiles needed to cover the wall and divertor may militate against friction welding.

Surface preparation and cleaning is an essential step in every joining operation. The fundamentals are well known, but the exact procedures for every new situation must be determined.

If an intermediate material is used in the joining process - either in a brazing process or an otherwise solid state diffusion process, the temperature of bonding and the kind of intermediate material are very important. The operating temperature is in the 400°C range, so for strength and durability, the temperature of joining should be above approximately 500°C. The coefficients of thermal expansion of copper and beryllium are different (11.4 vs. $17.6 \times 10^{-6}/^{\circ}\text{C}$). So the joining temperature should not be too high, as there will be significant thermal stresses in the finished part.

Intermetallic phases may degrade the bond. In the beryllium - copper system and for most of the intermediate joining/brazing materials, there are many intermetallic phases and compounds. These phases can be created in the joining operation and at the operating temperatures. Not all intermetallic phases are harmful, and even harmful (brittle) phases can be tolerated in small amounts.

By judicious placement of layers of some intermediate brazing materials and precise time and temperature control, some undesirable intermetallic phases can be avoided. The effects of these many variables must be determined experimentally.

The reported copper alloy of choice is an age hardenable alloy with chromium and zirconium additions ("Elbrodur-G"). The age hardening temperatures are in the 400-500°C temperature range. If the joining temperatures are in this range or higher, the desired mechanical properties of the copper alloy cooling units may be severely compromised. The design requirements of these copper cooling units have to be coordinated with the methods of joining to the beryllium.

In a parallel manner, the beryllium-copper units should be considered as a unit with the proposed steel structural frame work planned to support the beryllium-copper units. It is quite possible that the copper alloy - steel joining method may not be compatible with the copper alloy - beryllium joining method.

15.4 RECOMMENDATIONS FOR MANUFACTURING METHODS

15.4.1 BASIC REQUIREMENTS OF THE COPPER COOLING UNITS

The design requirements of the copper alloy cooling units have to be integrated with all beryllium to copper cooling unit joining processes, especially the mechanical properties. It is difficult to continue joining studies until the mechanical property requirements of the copper cooling units are clearly defined.

15.4.2 REQUIREMENTS OF THE BERYLLIUM/COPPER ALLOY/STEEL UNITS

There should be integration of the properties of the beryllium/copper/alloy/steel cooling unit with the process to be used to join this unit to the supporting steel frame work. The development of an incompatible beryllium/ copper alloy joining process can easily be developed in ignorance of the other design requirements and developments.

15.4.3 COMPLIANT LAYER

The need for a compliant layer between the beryllium and the copper alloy must be established. This has a major effect on the approaches to bond the beryllium and copper alloy, as some joining processes are amenable to an intermediate compliant while other joining processes cannot easily or not at all accommodate a compliant layer.

15.4.4 BRAZING

The long history, the technical data base and the adaptability to production methods favor brazing as one of the primary joining methods to support. A decision on feasibility could be reached within one calendar year with a 4 person effort at an estimated cost of \$1M. Full prototype development would be an additional two calendar years at a 4 person level of effort at an estimated cost of \$2M.

15.4.5 PLASMA SPRAYING

Plasma spraying may be feasible in repairing operational first wall damage and as a method of initial construction. It is important to establish early in development the adherence of plasma sprayed beryllium to both the age hardenable copper alloy and damaged beryllium layers. It is recommended that research in this area be included in the current program.

15.4.6 ROLL BONDING

If high temperatures and large deformations are needed to achieve adequate bonding, roll bonding of beryllium and the age hardenable copper alloy may be difficult. However, (a) if the deformation is in the 10-20% reduction in thickness, (b) if the temperature can be kept to the 400-500°C range, and (c) possibly incorporating a compliant layer, roll bonding could be successful. Roll bonding would have substantial advantages in ease of fabrication and scaling up to production quantities. Because of the potentially large pay off, we recommend that a small effort be directed to study the feasibility of roll bonding. A decision on feasibility could be reached within one year with a 2 person effort at an estimated cost of \$500K. Full prototype development would be an additional two calendar years at a 3 person level of effort at an estimated cost of \$1.5M.

15.4.7 SOLID STATE BONDING

The large area militates against bonding without an intermediate liquid layer. Keeping in mind the temperature restrictions, balanced by the advantages of hot isostatic pressing and using an intermediate liquid or solid state layer to aid bonding, this approach is worthy of consideration. A decision on feasibility could be reached within one year with a 2 person effort at an estimated cost of \$500K. Full prototype development would be an additional two calendar years at a 4 person level of effort at an estimated cost of \$2M.

15.4.8 FRICTION WELDING

Friction welding is attractive as it may avoid undesirable intermetallic phases during fabrication, and the resulting microstructure would probably be more amenable to the high temperatures of operation. It does have the disadvantage of probably acting as an intermediate step and therefore needing a second bonding operation. If feasible, proper tooling could be developed for efficient production of thousands of units needed for ITER. A decision on feasibility could be reached within six calendar months with a 2 person effort at an estimated cost of \$250K. Full prototype development would be an additional two calendar years at a 4 person level of effort at an estimated cost of \$2M.

15.4.9 ELECTROPLATING

Electroplating would involve a two step process, and may not be the most efficient production method. However as a backup process, it would be useful to demonstrate the feasibility and the cost may not be high. A decision on feasibility could be reached within six calendar months with a 1 person effort at an estimated cost of \$125K. Full prototype development may be an additional two calendar years at a 4 person level of effort at an estimated cost of \$2M.

15.4.10 EXPLOSIVE BONDING

The feasibility of explosive bonding may be determined in a limited study that is in progress and not dependent on ITER funding. We recommend that any ITER related effort be held in abeyance until the results of this independent study is complete.

15.4.11 WELDING

The proposed geometry of the beryllium and copper cooling unit is not amenable to the conventional fusion welding processes. This approach should not be pursued. It should be noted that the material requirements for weldable grades of beryllium is applicable to many of the recommended processes for joining beryllium to a copper alloy. It may be necessary to include these additional requirements in the beryllium material specification.

15.4.12 ORGANIC ADHESIVES

Operational requirements eliminate this process.

15.4.13 MECHANICAL JOINTS

Operational requirements eliminate this process.

15.5 SUMMARY

Following is an attempt to quantify the advantages and disadvantages of the many possible joining processes. The definitions of the markers are:

- + Information and/or experience is available, or if the process works (which may not be known), then this feature would be an advantage for the ITER application.
- 0 In the framework of this analysis, this feature compares in a neutral manner to the other processes.
- Not a desirable characteristic, or has a undesirable effect.
- NA Not apply.
- ? Not known.

Beryllium to Copper Joints	Braze	HIP Solid State Bond	Plasma Spray	Friction Weld & Braze	Electro-plate & Braze	Explosive Bond	Roll Bond	Be Evaporation (PVD)
Experiment Base	+	-	-	-	-	-	-	-
No Silver	+	+	+	+	+	+	+	+
Al/Be Layer	+	+	0	?	0	?	0	0
Al-Si	+	+	NA	NA	NA	NA	NA	NA
Bond Strength @ 300°C	0	0	0	+	0	+	?	?
Compliant Layer	+	+	+	-	+	+	+	+
Scale-Up?	+	0	+	-	+	0	+	-
Capacity	+	0	+	0	0	-	+	-
NDE	0	0	0	+	0	0	0	0
Effect on Copper alloy	-	-	0	-	-	+	0	0
Cost	0	-	0	-	0	+	+	-
Cu-SS Comp.	-	-	+	-	-	+	+	0
Remote Repair	-	-	+	-	-	-	-	+
In-situ Repair	-	-	+	-	-	-	-	+

Note that, except for the brazing process, it is not known if any of these joining processes will be suitable for the ITER application. Hence, many of the advantages (+) may not be realized without a serious development effort.

We recommend the following priority in resource allocation.

50%	Plasma Spraying
30%	Brazing
10%	Roll Bonding
10%	Other Processes.

15.6 NON-DESTRUCTIVE EVALUATION OF BE COMPONENTS

15.6.1 INTRODUCTION

Designing structures and components for inspectability is critical to extending the life of structures. Incorporating NDE into process control helps prevent defects and saves substantial money, reduces manufacturing time, and minimizes scrap. Implementing NDE during operation allows cost effective maintenance and reduces unnecessary down time. NDE detects defects before catastrophic failures cause very expensive repairs. Finally NDE allows components to be retired for cause rather than simply replaced based on speculation.

Nondestructive evaluation techniques and facilities need to be developed early so that construction components can be inspected. Advanced materials and new construction techniques such as plasma sprayed Be coatings, require research and development in NDE methods to satisfy inspection requirements. Prototype inspection systems should be assembled to assess the limitations of the inspections and demonstrate the inspection capabilities of various techniques. Production inspection facilities must be designed and assembled soon if inspection capabilities are to be available during construction of ITER.

Nondestructive evaluation (NDE) helps the development of new materials by allowing the material scientists to better understand the properties of these materials. Advanced materials and new construction techniques such as plasma sprayed Be coatings, require research and development in NDE methods to satisfy inspection requirements. Be composites may behave very differently from pure Be when traditional NDE methods are applied.

15.6.2 NDE METHODS

Several nondestructive evaluation techniques are applicable to construction inspection. If ITER is designed for inspectability, then during construction there should be adequate access to the components and structures to allow x-ray, ultrasonic, and infrared evaluations to be routinely conducted. Laser ultrasonics could provide real time feed back for the plasma sprayer to control thickness, porosity, and adhesion during deposition of the Be. After the coating is applied infrared imaging could provide a global assessment of the coating integrity.

Thickness determination - Radiation gaging methods have been used quite successfully in Y-12 for in-process measurement and control of thickness. It is a non-contact technique ideally suited to automation, including use of robotic positioning. For measuring beryllium on copper, a one-sided measurement would be practical. One approach would utilize a radiation source to excite 8keV K-shell Cu X-rays. The attenuation of these X-rays by the beryllium can provide a sensitive measure of beryllium thickness. The development approach would involve utilizing a computer model to optimize source selection and geometric configuration of the probe. The measurement would then be refined and experimentally verified in the laboratory before designing the automated inspection instrument.

Density - It should be noted that the radiation gaging measurement described above would actually measure the areal mass (or density times thickness) of the beryllium. One way to determine density, then, is to independently measure the thickness. However, such two part measurements are difficult to perform accurately. Measuring small variations in density of a near full density product is unlikely to be successful. An approach which is more likely to be successful is to characterize the process sufficiently to understand and control parameters necessary to maintain the desired density. Monitoring the density of coupons sprayed during the production spraying process and comparing the nondestructive measurement

of related characteristics with laboratory measurement of density and porosity provide a continuing check that process control is being maintained.

Porosity - Radiography is the first method of choice for nondestructively inspecting for porosity.

However, for beryllium on copper and steel, only very large porosity would be detectable. An alternate approach to conventional radiography would be autoradiography after neutron activation of the underlying copper. Copper has a reasonable absorption cross section and produces two isotopes each with short half-lives. Copper⁶⁴ (12.5 hour) half-life decays by positron/electron capture/beta/gamma and emits Ni x rays. Copper⁶⁶ (5.1 minutes) half-life decays by beta/gamma. A film is placed against the beryllium layer to obtain an autoradiograph.

This is an area where comparison/correlation with destructive measurements is very important. The relationship between porosity detected by autoradiography, porosimeter measurements on samples, radiographs of sectioned samples, and density measurement on samples can provide the basis for a rigorous quality control program.

Residual Stress - The basis for understanding and controlling residual stresses should be characterization of the process using destructive methods such as hole-drilling. X-ray diffraction should be evaluated for determining residual stresses in the plasma-sprayed structure. Portable devices suitable for robotic manipulation can be assembled if the method proves useful. The development of the nondestructive x-ray diffraction method should be carried out in conjunction with a program of characterization of samples using a destructive method such as hole-drilling.

Cracking - Eddy current and dye penetrant methods should be evaluated if cracks perpendicular to the surface are anticipated. Dye penetrant is the easiest to apply and is the most sensitive method for detection of surface breaking cracks. Even if the final product cannot be exposed to the penetrant materials, it would be prudent to utilize penetrant testing during process development to determine if cracks are a problem. Microscopy methods can be used to characterize cracks, but dye penetrant is the method of choice for the initial locating of a crack. Based on locating a crack with dye penetrant, the non-contact method of eddy current inspection should be evaluated to determine if the crack signal is sufficient for automated inspection.

Bond Integrity - A rigorous program of mechanically testing for bond strength to characterize bond integrity versus process parameters is essential. Nondestructive methods for inspecting for bond integrity can be useful for detecting unbonds. Successful detection of weak bonds has been rare. In fact, tight contact is usually undistinguishable from bonding. Ultrasonic inspection of plasma-sprayed beryllium is expected to be especially challenging. Ultrasonic methods should be evaluated to determine if there is hope for a practical test, but significant resources should not be devoted to developing unproven methods unless significant promise is demonstrated. Limitations of ultrasonics are described in more detail below. Thermal testing is the most promising approach to NDE for unbonds. An approach to thermal testing is described at the end of this section.

Ultrasonic inspection of plasma-sprayed structures has been utilized in Y-12. The structures were rather porous and had to be inspected using a through transmission immersion technique in freon. The structures had to be soaked for approximately 30 minutes until they came into equilibrium before inspection to obtain a stable signal. Delaminations were easily detected although the attenuation was rather high. It would be difficult to inspect the beryllium-copper bond in through transmission if the inspection is to be in-situ. This would then require a pulse-echo or pitch-catch inspection. Beryllium has a high velocity which makes it difficult to resolve near surface defects in a pulse-echo inspection. Solid beryllium metal is difficult to inspect using angled beam inspections because of the high velocity of the metal. The angle of the refracted beam is too shallow to allow detection. A plasma-sprayed structure may be quite anisotropic and this may also affect the direction of the refracted signal. In a pulse-echo inspection, the attenuation of the plasma-sprayed beryllium metal is an important consideration. Porous

material will make the bond inspection more difficult. To develop an ultrasonic inspection, it is necessary to empirically relate the type of structure being fabricated. The empirical determination of bond integrity with ultrasonic evaluation requires coupon studies.

Laser ultrasound methods are suggested as a potential method of inspecting the structure without couplant. In general, laser generated ultrasound is an order of magnitude less sensitive than a pie to crystal generated sound. With the potential high attenuation in the sprayed beryllium coating, it will be difficult to detect reflections from the bond line. Sometimes, electromagnetic acoustic transducers (EMATs) are used for detection, but EMATs are in general narrow bandwidth (long pulses) and could not resolve the layer thickness. Squirter inspection systems might be more appropriate, but if water cannot be used, another couplant will be required. Freon is no longer environmentally acceptable.

The provision for water cooling in the structure design allows for a straightforward approach to thermal NDE for unbonds. Heat can be applied to the back side of the plasma-sprayed beryllium using hot water in the channels provided for cooling. The copper layer acts as heat sink to create a uniform elevated temperature behind the beryllium. Thermal imaging of the beryllium surface should detect unbonded areas as cool spots on the surface of the beryllium. The thermal imaging camera could easily be robotically manipulated to facilitate inspection. The development program should include modeling of the heat flows to guide an experimental design for determining optimum heating/inspection protocols, minimum detectable unbond size, emissivity variation effects and compensation, and detail design for an inspection device.

Nondestructive testing development and application should be part of an integrated approach to process and product characterization, measurement and control. Y-12 Development Division has experience in all of the NDE and other measurement and characterization methods mentioned in this paper, and in applying them is an integrated approach to supporting process development and assuring product quality.

15.7 RECOMMENDATIONS

Nondestructive evaluation capabilities should be established at the ITER construction site to support all phases of construction. Radiation based inspections, ultrasonic, infrared, eddy current, penetrant, magnetic particle, acoustic emission are examples of capabilities which will benefit the construction process. As the design is finalized the appropriate NDE technologies will become evident. NDE experts should be part of the design team to ensure that adequate inspection capabilities are available when construction begins (.2 FTE per year for NDE person to help design for inspectability, full construction NDE facility should be included in the construction funding).

As new materials emerge for ITER components, nondestructive evaluation can aid the acceptance process. NDE will provide information as to the applicability of the materials in the ITER environments. For example, nondestructive evaluation can provide quantitative damage assessment for irradiated specimens. NDE experience obtained during the new material's development will expedite the implementation of appropriate technologies for construction and life cycle determination.

Nondestructive evaluation should be considered as a tool to aid the material scientists as they develop new materials and processes. NDE will measure properties and provide quantitative information about the new materials. Performing NDE will save the process development program much time and money by quickly and inexpensively assessing the quality of new materials. If the new material development program entails accelerated aging studies, NDE can quantify the amount of damage sustained.

In-situ inspection of the Be wall can be accomplished with two NDE techniques: infrared imaging to inspect large areas with low resolution and ultrasonic inspection for more precise defect location and sizing. Infrared cameras could be incorporated into the maintenance robot which would point the camera

at the wall and provide temperature maps. These images will indicate suspect areas which would be investigated further with ultrasonics. A laser ultrasonic system would be attached to the robot and noncontact ultrasonics would measure the Be thickness and Be/Cu bond quality.

A dedicated divertor cassette nondestructive evaluation station should be established at the ITER site. This facility will allow quick and accurate assessment of divertor damage so that effective repairs can be performed. This NDE facility would include a dedicated infrared imaging system and an ultrasonic scanner designed to inspect divertors. Other NDE methods such as x-ray and eddy current may be needed to completely evaluate the divertor.

Infrared and laser based ultrasonic inspection systems should be designed to be incorporated into the internal inspection and maintenance robotic system. As an attachment for the robot, the NDE sensors will measure Be wall thickness and adhesion both globally and locally.

A dedicated nondestructive evaluation facility should be designed and fabricated to evaluate the Be walls on the divertor cassettes when they are removed for repair. This automated facility would quickly assess the damage and ensure the integrity of the repairs. Several NDE methods should be evaluated to determine the optimal configuration to completely inspect the divertors (funding should be included in the construction budget).

15.8 SCALEUP OF MANUFACTURING METHODS

In a project of this complexity and risk, it will not be possible to assume that potential vendors will perform the necessary manufacturing development work at their own expense, providing samples for test to other participants. Substantial resources must therefore be directed toward development and scaleup R&D for candidate manufacturing processes.

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CHAPTER 16. EMERGING BERYLLIUM MATERIALS

16.1 BERYLLIUM-ALUMINUM ALLOYS

Beryllium-aluminum (Be-Al) alloys offer increased ductility and toughness over beryllium metal. Recently the production of Be-Al alloys has been reactivated after a long period of inactivity between the 1970's to 1990's. Current investigations by Brush Wellman, Inc. have shown that the properties of today's material are similar to that of the 1970's Be-38w/oAl alloy (known as Lockalloy in the 1970's). These alloys received much interest in the National Aerospace Plane Program and recently found commercial applications. Brush Wellman, Inc. has several commercially available grades of Be-Al alloys (AlBeMet alloys) e.g., Be-38w/oAl, Be-50w/oAl.

These Be-Al alloys are recommended as candidate compliant layer materials to accommodate the differential thermal strains between the beryllium and copper alloy substrate. These alloys are low neutron activation.

16.2 BERYLLIUM-CARBIDE FIBER REINFORCED BERYLLIUM COMPOSITE

Beryllium-carbide (Be_2C) fiber reinforced beryllium composite potentially offers a plasma facing material that could withstand thermal shocks from the plasma without losing its shape. Beryllium plasma facing components exposed to disruptions and other off-normal effects can lose their shape and integrity by local melting. Peacock, Haws, and Pick² have shown this composite can be produced with two routes. The first uses a woven carbon cloth converted to the Be_2C fibers and infiltrated with molten Be with assistance of a wetting agent (i.e., silicon). The second route has three dimensional structure, again with Be as the matrix but with random Be_2C fibers produced by hot pressing a mixture of Be powder with 6mm Be_2C fibers; no wetting agent was used. The measured thermal conductivity of less than 100W/mk is too low to be useful divertor plate armor.

Also, severe chemical reactions of Be_2C and hot water or steam will evolve acetylene gas.

16.3 CARBON FIBER REINFORCED BERYLLIUM COMPOSITE

Carbon fiber reinforced beryllium composite offers another fiber reinforced composite that could provide the structure stability to resist the thermal shocks from the plasma. Trester, Chen, Elsner, Mazdinyasni, Sevier and Dombrowski³ used an electrophoretic Be particle infiltration process to incorporate beryllium into a preform of carbon fibers. The carbon fibers are coated with a proprietary coating to prevent reaction with Be to form Be_2C at high consolidation temperatures. The preform is surrounded with Be powder, encapsulated, and hot isostatic pressed for final consolidation. This system depends on the integrity of the fiber coating to prevent the fiber/matrix reaction. A large effort will be required to develop a reliable coating system and then be scaled up to produce the quantities required.

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CHAPTER 17. PROPOSED INSPECTION AND MAINTENANCE TECHNIQUES FOR BERYLLIUM COMPONENTS AND COATINGS

17.1 INTRODUCTION

Plasma facing components (PFCs) such as the blanket/shield mounted plasma limiters and the divertor vanes have yet to be tested under reactor relevant conditions, and these are not yet well defined. Therefore, all such components are susceptible to unforeseen damage which includes sputtering erosion and redeposition, disruption erosion or melting, and possible destruction of the beryllium components or coatings. Inspection techniques suitable for defining the extent of damage, repair methods for correcting the damage, and follow-up inspection methods to confirm the repair must, therefore, be developed. It is important that these methods be capable of being performed over a relatively short time period in order to minimize reactor downtime.

17.2 INSPECTION TECHNIQUES

From the very earliest use of deuterium and tritium in the ITER, the entire device will become sufficiently activated such that the radioactivity will preclude direct human access. It is estimated that radiation levels within the vacuum vessel at shutdown could reach 3×10^6 Rads per hour. This will place severe constraints on the systems that will be expected to operate in this environment. Optical and infrared imaging systems will thus be required to be relatively insensitive to this radiation environment. Two types of in-vessel inspection systems are planned for monitoring the condition of components within the vacuum vessel. These include a video based system for visual inspection and a metrology system for 3D position mapping. While these systems are still under development, it is expected that the ability to map first wall surfaces to within a millimeter or so will be realized.

Suspect areas that are identified by such imaging systems would be further characterized by ultrasonic methods, including both contact type and laser systems. Eddy current devices might also be used. Another method for measuring the density or thickness of coatings is called the "Density-Time-Thickness" method, or the "DXT" method. This technique is based on x-ray or gamma ray absorption/scattering phenomena, and in other production situations involves placing a source behind the surface being coated. The ITER structure will not permit this method to be used, and so a backscattering method will have to be developed in which both the source of radiation and the detector are outside the plasma facing surface. In this case, it may be possible to excite a characteristic X-radiation in the backing layer (copper), and the absorption of this radiation by the coating can be measured. Suitably well characterized standards would be used to relate the in-situ measurements to coating thickness and density. It is clear that substantial work will be necessary in order to validate such inspection methods for use within the ITER plasma chamber.

While in-situ inspection of divertor components would be preferred, an alternative, since the divertor cassette will probably be designed to be removed from the vacuum vessel, would be to develop a specialized station for inspection and repair of divertor components. It is not clear at this point whether or not individual divertor components such as vanes or bumpers could be removed for repair or replacement.

17.3 MAINTENANCE OF IN-VESSEL COMPONENTS

In the current ITER design, first wall components will be maintained with a remote handling (RH) system consisting of a transporter (either a boom or a railed vehicle) equipped with a dextrous manipulator and onboard viewing systems. The RH system will be stored outside of the cryostat, and will reach the

vacuum vessel through extensions penetrating the cryostat wall, which will allow the magnet coils to remain at cryogenic temperature. The RH will enter the vacuum vessel through two of the main horizontal ports, and will use the other two main horizontal ports for component transfer. All in-vessel RH operations will be performed inside containment and under an inert gas atmosphere. Design details of the RH system are currently under development.

The in-vessel RH system will utilize special end effectors and tooling to maintain PFCs. It will be desirable to repair eroded or damaged sections by some method that can apply new material in-situ. This limits the possible methods for beryllium surfaces to some form of thermal spraying or evaporation deposition. While reliability and time efficiency are the primary factors in determining repair techniques and procedures, the atmosphere that might be required for such deposition techniques may not be compatible with the remote handling system. As presently conceived, the ITER RH systems are not vacuum compatible, and to develop vacuum compatible systems would require considerable additional time and expense. This is due to the fact that the friction and wear of sliding surfaces, and design of bearings, is much more difficult to deal with for a vacuum environment. However, since the inert atmosphere in the vacuum vessel will have to be extremely dry so as not to leave behind a moisture film that will require a bake-out step in order to remove, it is difficult to imagine how this environment could be very different from a vacuum, from the perspective of anticipated friction concerns.

The possibility that the RH system will have to be designed as though it will have to operate in a vacuum opens up all of the deposition methods mentioned earlier as possible repair techniques. Other aspects of each deposition method will then have to be considered before an optimum choice can be made. The suitability of an evaporated deposit may depend on the substrate surface being heated to a temperature of 700°C, and such localized heating could lead to undesired conditions elsewhere in the article to be repaired. Similar complications could be associated with low pressure or atmospheric pressure plasma spray methods. A wire-arc spray technique would depend on the economical and practical availability of beryllium wire in the lengths and diameters required. All repair methods will have to consider the possibility that not all of the beryllium will adhere to the area being repaired. This will require that some method be devised for the capture and removal of such excess material. Finally, some method such as the DXT technique mentioned earlier will need to be developed for monitoring of the progress of the repair process.

If divertor cassettes are to be removed from the vacuum vessel for inspection and repair, most of the considerations that apply to remote in-vessel repair will not be applicable. It should be relatively straightforward to apply methods similar to those used to manufacture the components in order to repair damaged beryllium surfaces. Replacement of individual divertor components, as mentioned earlier, may be possible, as well.

17.4 COST AND SCHEDULE

All previous estimates will be useless if a vacuum-compatible RH system is deemed to be necessary for successful operation in a dry inert gas environment. Consultations with appropriate experts will be required.

CHAPTER 18. TIME TABLE AND CAPITAL COSTS

18.1 TIME TABLE FOR BERYLLIUM DEVELOPMENT

The complicated process for developing beryllium for use in ITER will take a considerable amount of time to complete. Estimates for the duration of each major development were compiled by various panel members. Those estimates have been assembled into an overall time table (see Table 18.1). As can be seen from this table the development is expected to last well beyond the ITER EDA phase. One would expect this to be the case because scale-up of processes to full production would not normally be done until a decision was made to proceed with construction of the ITER device. In addition, irradiation of the component designs delivered at the end of the EDA would have to be conducted after the EDA but before construction is completed. It is also possible that additional design and fabrication technique changes will be made early in the construction phase.

18.2 ESTIMATED CAPITAL COSTS

From the time schedule shown in section 18.1 and the detailed technical estimates contained in earlier chapters, total estimated costs broken down by year were compiled. These estimates were broken down into labor and facilities upgrades. A summary of the cost estimate is shown in Table 18.2. It should be noted that these costs extend beyond the ITER EDA phase. The column labeled ITER credits is the panel's best estimate of the ITER EDA phase R&D cost estimate. The column US program is the estimated US portion of the EDA R&D cost. The other ITER partners (Japan, European Union, and Russia). For these reasons, one should not make a direct comparison between the estimated costs and the ITER EDA numbers.

Table 18.1 Time Table for Beryllium Development

BERYLLIUM DEVELOPMENT FOR ITER

Table 18.2 Estimated Capital Costs

Chapt	Title	94	95	96	97	98	Labor/Svcs Costs M\$	Fac Up - Grd M\$	Total R&D M\$	ITER Credit	US Prgm
7	Properties						0		0		
8	n-effects		4	6.5	6.5	6.5	23.5		23.5		
9	Tritium		1.85	1.35	1.35	1.35	5.9	1	6.9		
10	Health/Safety						0		0		
11	Coolant/Safety		0.2	0.2	0.2	0.3	0.9		0.9		
12	Thermal Cycling	1.5	6	4	3	2	16.5	4.5	21	12	
13	Disruption Erosion	0.5	6	3	2	1	12.5	6	18.5	3.9	2
13	Sputtering Erosion	1.4	11	8	6	2	28.4	12	40.4	4.9	6.5
14	Be Grades						0		0		
15	Joining	5	10	10	3		28		28		
15	NDE		0.5	1	2		3.5		3.5		
15	Manufacturing	5	10	31	26	14	86		86		
15	Quality Control						0		0		
16	New Materials						0		0		
17	Repair & Maintenance						0		0		
	Total	13.4	49.6	65.1	50.1	27.2	205.2	23.5	228.7	20.8	8.5

CHAPTER 19. THE IMPORTANCE OF INTEGRATING MATERIALS AND MANUFACTURING PERSONNEL WITH DESIGNERS

19.1 INTRODUCTION

This chapter discusses a number of illustrative examples from a recent large development program and from industrial practices that emphasize the importance of a close working relationship between system designers, materials, and manufacturing specialists.

19.2 EXPERIENCE FROM NATIONAL AEROSPACE PLANE PROGRAM

In 1984, the United States embarked on a very challenging effort to develop the National Aerospace Plane (NASP).¹ This was to be a vehicle that would reach orbit with only one stage, and the propulsion system was to be air-breathing. It was originally assumed that all of the necessary materials to construct such a vehicle would be available "off-the-shelf", and development work would be necessary in selected areas. Most of the work was envisioned to be associated with the vehicle design for operation at very high Mach numbers (greater than 20) and with the development of suitable propulsion systems. The schedule was extremely aggressive, with a manned flight vehicle to begin construction in about 1993 (then later delayed to 1995). About \$150M over three years was spent on materials development, and some seven or eight million dollars was spent on beryllium and beryllium alloys. Work continued throughout the period on beryllium reinforced with carbon or silicon carbide fibers. The best success was achieved using SCS-6 silicon carbide fibers in a Be-38Al matrix.

As the designs evolved, the requirements for the materials of construction were refined. In order to accelerate the materials development to meet the program schedules, the five contractors formed a materials augmentation program in March 1998 with the intent to develop and scale-up the necessary materials and processes (known as the Materials Consortium Program).² Eventually, designers reduced their interest in beryllium unless something could be done to improve the cryogenic toughness. This led to a revitalization of interest in beryllium-aluminum alloys, and some new and interesting materials and processes were developed.

Progress in hypersonic design and materials and processes (M&P) was a concern and coupled with funding issues in the outyears ultimately led to a decision to abandon the goal of a manned flight vehicle. The NASP program was redirected to focus on development of the engines, and on mounting a flight demonstration of the propulsion system.

The NASP experience is recounted here because several members of the panel were closely involved in the NASP materials work, and we believe that there can be some important lessons learned from that program that can be applied to ITER. The simplest statement of the most important lesson is that materials, processing and design teams must be in close and constant interaction as early as possible during the design of a complex machine. Had sufficient consultations been held at the outset of NASP, it would have become apparent that materials limitations existed, and the early years of the effort could have been much more intensely focused on materials developments that were needed in order to meet the design requirements. As the materials and processes matured, design properties became available to support detailed design. Because of the necessary times required in materials and process development, it is not possible to develop materials along with a design, and expect to achieve success.

19.3 EXPERIENCE FROM JET ENGINE DESIGN

One is reminded of a time at one of the jet engine companies when the designers and the materials people sat down together and negotiated a set of materials properties, not yet achieved, on which the next design improvements would be based, for components to be tested some three to five years in the future. Both sets of specialists then went away to work independently--the designers on the actual designs, the M&P people on new alloy formulations or processes aimed at making a material with the negotiated property set. In most cases, the materials properties had already been achieved in laboratory scale specimens, so the basic formulations were known, and the main problems had to do with scaling up the processing while maintaining the small scale properties. At least one new turbine disk alloy and one new blade alloy were developed this way, and both were eventually used in the company's jet engines.

19.4 COMMENTS ON CONCURRENT ENGINEERING

Implementation of concurrent engineering is highly recommended. A number of experiments on beryllium components for ITER have already been performed without the benefit of close collaboration with materials and processes specialists, and we find, as expected, that the results are difficult to interpret, lacking detailed characterization of the beryllium material, its properties, the process used to fabricate it, non-destructive evaluation of the material and any joints used in the component fabrication, and similar information absences. We are at the very early stages of developing new ways of plasma spraying beryllium, and are discovering the importance of additional process variables with every new spraying trial. This is not the time to be making careful measurements of thermal conductivity of plasma sprayed specimens and basing design choices of joining method, cooling technique, etc. on the results that are in hand. The process has yet to be optimized, and so, until it is, all measurements of physical and mechanical properties should only be considered in the context of material and process optimization. They should not have any influence on the design. Rather, the design activity should work with the materials, processes, and manufacturing in order to influence the design to insure fabricability. Eventually it will become clear what combination of materials properties can be achieved using a particular process, or processes, and then a realistic design can be set down.

In the meantime, some benchmarks can be established using a suitable quality beryllium that is presently available in large quantities from the beryllium supplier. This activity should also involve close collaboration between materials, manufacturing and design communities so that well characterized materials and processes are used to fabricate test components. Interpretation of the test results should also involve the same sort of collaboration.

Some important issues involved in the utility of beryllium for ITER should be resolved by a joint materials, processes, and manufacturing, and design team effort. In particular, erosion effects and the consequences of disruptions on beryllium components are particularly thorny problems.

In general, we believe that the program should include a materials, process, and manufacturing perspective. It is, therefore, recommended that a forum be established that will bring together on a regular and frequent basis key members of design teams and materials, process, and manufacturing specialists. This forum will provide the means by which early consideration can be given to materials property issues, changing design requirements and materials fabrication options. Resolution of these issues at early times will help to avoid unpleasant surprises later on, when it may become evident that a particular design option cannot be fabricated within the time and funds available.

19.5 REFERENCES

1. R. Bathelemy, "The National Aero-Space Plane Program," presented at the AIAA National Aero-Space Plane Conference, AIAA-89-5001, July 20-21, 1989, Dayton, OH.
2. T. Ronald, "Materials Challenges for NASP," presented at AIAA First National Aero-Space Plane Conference, AIAA-89-5010, July 20-21, 1989, Dayton, OH.

APPENDICES

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APPENDIX I

MAY 02 1994

Dr. William Manly
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Dear Dr. Manly:

Thank you for agreeing to serve on the Technical Evaluation Panel for the Use of Beryllium as Plasma Facing Components and Blanket Components in the International Thermonuclear Experimental Reactor (ITER) project. The charter for the panel is enclosed with this letter. The members of the panel are:

Dr. William Manly, Oak Ridge National Laboratory, Chairman
Dr. David Dombrowski, Brush Wellman
Dr. Loren Jacobson, Los Alamos National Laboratory
Dr. Gil London, Naval Air Warfare Center
Dr. Robert Watson, Sandia National Laboratories
Dr. James Yuen, Rockwell International

This technical evaluation is very important to the Department of Energy. I would like to have the first meeting of the panel May 24-25, 1994, at the Doubletree Inn in Pleasanton, CA. It is very important that the panel complete its work by early July. Dr. Michael Ulrickson at Sandia National Laboratories will be sending you details on local arrangements for the first meeting.

Sincerely,

A handwritten signature in dark ink, appearing to read "Marvin Cohen", is positioned above the typed name.

Marvin Cohen
Plasma Technologies Section
ITER and Technology Division
Office of Fusion Research
Office Of Energy Research

TECHNICAL EVALUATION OF THE TECHNOLOGY OF BERYLLIUM FOR USE AS A PLASMA FACING AND BLANKET MATERIAL IN FUSION REACTORS

This panel is convened to produce an evaluation of the technology of beryllium relevant to the use of beryllium both as a plasma facing material and a blanket neutron multiplier in a fusion reactor. This evaluation should be completed by July 1, 1994. The evaluation should include the current state of beryllium technology for both of the uses discussed above and identify the steps needed and costs anticipated to be ready to use beryllium in ITER in 1999. The panel should also address the specific designs put forward by the ITER Joint Central Team (JCT). The possible utility of beryllium in a demonstration fusion power plant in 2025 should also be addressed.

Beryllium is the primary choice for the plasma facing material (PFM) for the International Thermonuclear Experimental Reactor (ITER) divertor and first wall, as well as a possible candidate for a blanket neutron multiplier. However, the mechanical properties database for beryllium (both before and after irradiation) is incomplete. Beryllium is a candidate for the plasma facing material because of its low atomic number, low retention of hydrogen isotopes, very low residual radioactivity, and oxygen gettering capability. As a plasma facing material beryllium must be joined to a cooled heat sink because of its relatively low melting point. The grade of beryllium to be used, together with the heat-sink-joining technique, will have a significant impact on the realization of its potential for use in ITER.

This assessment should be planned in detail by the Assessment Committee, in consultation with the DoE Program Manager and key ITER U.S. Home Team members (K. Wilson, M. Ulrickson, and R. Mattas). Activities could include a workshop to develop wide input from the materials research and development, design, production, fabrication and other segments of industry that would be involved in successfully utilizing beryllium in ITER.

CHARTER

The following questions should be addressed:

- 1) What are the potential costs of developing beryllium for ITER?
- 2) Is it possible to validate beryllium in time for ITER construction? What is the state of our database for mechanical properties? How well are the thermo-mechanical fatigue properties of beryllium understood and how do they affect the performance of Be in ITER? Considering the state of the post irradiation database on beryllium, what additional irradiations and testing (irradiated and unirradiated) are required both during and after the Engineering Design Activity (EDA)? What additional data are needed to determine, a) the tritium retention in irradiated and eroded and redeposited beryllium, and b) tritium solubility and transport in

beryllium neutron multipliers? Will the anticipated tritium inventory present a safety problem?

- 3) What R&D needs to be done to allow maintenance of eroded beryllium plasma facing components to be carried out? Is the technology adequate or could it be available in time for ITER?
- 4) What is required to develop beryllium and associated joining techniques to remove up to 5 MW/m² under ITER conditions? Are there low activation joining materials that can be used or developed? What inspection techniques need to be developed to assure reliability of the joints?
- 5) What are the limiting factors on the use of beryllium in a)the ITER PFC/Blanket environment, b)a fusion reactor environment?
- 6) What are the safety and compatibility issues related to the choice of coolant and coolant structural materials associated with the use of beryllium? Do these issues restrict the choice of materials and/or coolants?

The panel should take account of the previous use of beryllium in the Joint European Torus (JET), as well as other fusion devices (such as ISX-B).

The product of this activity should be a written technical evaluation that answers the questions posed here, and/or other relevant questions that may be developed by the panel. This Assessment should identify the tasks, major facilities, and costs needed. Estimates of schedules are also requested. The panel should feel free to address other pertinent considerations not included in this charter. The report should be submitted by July 1, 1994.

APPENDIX II

COHEN'S ADDITION TO CHARTER

1. Maintainability of Be Surface Erosion and Sputtering
2. Timetable/Cost for Manufacturing Program
Timetable for R&D Dollars -- EDA and Beyond
3. Joining Be
4. Health Physics -- Blood Tests, Gene Tests
5. Design/Materials People/Engineering Better Interplay

APPENDIX III

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

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APPENDIX IV

BERYLLIUM PANEL MEETING

Triple Crown Room
Hilton Hotel, Pleasanton, California
May 24-25, 1994

Tuesday, May 24, 1994

INTRODUCTION.....Marvin Cohen, DOE

ITER REQUIREMENTS.....Michael Ulrickson, SNL

NEUTRON IRRADIATION EFFECTS ON BERYLLIUM.....David Gelles, PNL

BREAK

BERYLLIUM ATTACHMENT TO Cu.....Ben Odegard, SNL

BLANKET/NEUTRON MULTIPLIER ISSUES.....Mike Billone, ANL

LANL Be POWDER EXPERIENCE.....Loren Jacobson, LANL

SAFETY ISSUES FOR Be IN ITER.....Glen Longhurst, LMIT

HIGH TEMPERATURE PROPERTIES.....Jim Hanafee, LLNL

ITER TASK T-1: DEVELOPMENT OF DUCTILE Be AND
A STUDY OF MANUFACTURING AND JOINING TECHNIQUES.....Robert Watson, SNL

HIGH HEAT FLUX TESTING CAPABILITIES AT SNL.....Robert Watson, SNL

ALTERNATE FORMS OF Be.....Dave Dombrowski, Brush Wellman

Wednesday, May 25, 1994

1. What needs to be covered that was not presented.
2. Subjects need additional input from Agenda of first meeting.
3. Additional members for panel.
4. Examine Charter. What was left off Agenda plus Cohen's additions.
5. Industry members working on Be - Design, et al. Should they be heard?
6. Choose future meeting dates.
7. How to parcel out subjects and responsibility for writing report.
8. What are most important problems to be understood.
9. What property data - mechanical and physical - exist and how to present it to designer.
10. Development projects - dollars, timetable for Be development.

First Beryllium Panel Meeting
Pleasanton, California
May 24-25, 1994

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APPENDIX V

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Sheraton Old Town, Albuquerque, New Mexico

Panel Meeting, June 7-8, 1994

Agenda - June 7

7:30 - 8:00 AM	Continental Breakfast.....	Turquoise Room
8:00 - 8:15	Introduction and Meeting Objectives.....	Ken Wilson, SNL
8:15 - 8:30	ITER PFC and Blanket Design Requirements.....	Ken Wilson, SNL
8:30 - 9:00	ITER R&D Plans and Funding for Be R&D.....	Ken Wilson, SNL
9:00 - 9:30	Disruption Erosion Experiments at UNM.....	John Gahl, UNM
9:30 - 10:00	Remote Maintenance of Divertor Components.....	Ken Wilson, SNL
10:00 - 10:30	Coffee Break	
10:30 - 11:00	Beryllium Carbide Composites for JET.....	Dave Dombrowski, BW
11:00 - 11:30	Beryllium Metal Matrix Composites.....	Paul Trester, GA
11:30 - 12:00	Neutron Irradiation Experiments at INEL.....	Glen Longhurst, LMIT
12:00 - 12:45 PM	Lunch	
12:45 - 1:00	Beryllium Brazing Plan.....	Chuck Cadden, SNL
1:00 - 1:15	Beryllium Friction Welding - Recent Results.....	Ben Odegard, SNL
1:15 - 1:30	Non-Destructive Evaluation of Be/Cu Joints.....	Satish Nair, Karta
1:30 - 2:00	Beryllium Joining Development.....	Bob Watson, SNL
2:00 - 2:30	Beryllium High Heat Flux Experiments.....	Dennis Youchison, SNL
2:30 - 3:00	Be/Al Alloy Joining for NASP Heat Exchangers.....	Steve Robinson, SNL
3:00 - 3:30	Coffee Break	
3:30 - 4:00	Be Volatility and Oxidation Experiments.....	Glen Longhurst, LMIT
4:00 - 4:30	Activation/Waste Disposal/Recycling of Be.....	Glen Longhurst, LMIT
4:30 - 5:00	Ion Beam Experiments with Be.....	Bill Wampler/Barney Doyle, SNL
5:00 - 5:30	Tritium Experiments with Beryllium.....	Ken Wilson, SNL

Agenda - June 8

7:30 - 8:00 AM	Continental Breakfast.....	Turquoise Room
8:00 - 8:30	IAEA Review of Thermal and Mechanical Properties.....	Dave Dombrowski, BW
8:30 - 9:00	Beryllium Supply, Manufacturing, and Costs.....	Dave Dombrowski, BW
9:00 - 9:30	Industrial Perspective on Be Development.....	Jerry Wille, MDA
9:30 - 10:00	Beryllium Alloy Development for NSP.....	Gil London, NAWC
10:00 - 10:30	Coffee Break	
10:30 - 10:45	LANL Gleeble Tests.....	Jake Jacobson, LANL
10:45 - 12:00	Panel Discussions	
12:00 - 1:00 PM	Lunch	
1:00 - 2:00	Panel Discussions	
2:00 - 4:00	Sandia Laboratories Tour:	
	Plasma Materials Test Facility.....	Dennis Youchison, SNL
	Ion Beam Test Facility.....	Barney Doyle, SNL

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Sheraton Old Town, Albuquerque, New Mexico
Panel Meeting, June 7-8, 1994

Attendance

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APPENDIX VI

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Sheraton Cleveland City Centre Hotel, Cleveland, Ohio

Panel Meeting, July 13-14, 1994

Agenda

Wednesday, July 13

7:30 - 8:00 AM	Continental Breakfast
8:00 - 8:15	Introduction of Panel and Mission.....W. D. Manly (ORNL)
8:15 - 8:45	Be Erosion/Redeposition Modeling.....J. Brooks (ANL)
8:45 - 9:15	Disruption Erosion Modeling.....A. Hassanein (ANL)
9:15 - 9:45	Be Erosion/Redeposition Experiments.....Y. Hirooka (UCSD)
9:45 - 10:15	Be Outgassing Experiments.....D. Cowgill (ANL)
10:15 - 10:45	Coffee Break
10:45 - 11:15	Panel Summary of Erosion/Redeposition Costs, Timetable, and Critical Issues
11:15 - 11:45	Be High Temperature Properties.....S. Abeln (RF)
12:00 - 12:45 PM	Lunch
12:45 - 1:15	Plasma Sprayed Be Experiments.....R. Castro (LANL)
1:15 - 1:45	Requirements for Scale-Up of Plasma Spraying.....A. Sickinger (EPI) E. Muehlberger (EPI)
1:45 - 2:15	Panel Discussion of Plasma Spraying Costs, Timetable, and Critical Issues
2:15 - 2:45	Summary of Be Bonding and Joining.....J. Hanafee (LLNL)
2:45 - 3:15	Coffee Break
3:15 - 3:45	Review of ITER Garching JCT Meeting, Discussion of Joining Issues, and Status of E-Beam Hot Cell.....M. Ulrickson (SNL)
3:45 - 4:15	Panel Discussion of Be Bonding and Joining Costs, Timetable, and Critical Issues
4:15 - 5:15	Panel Discussion of Direction
6:30	Dinner at Shooters in Cleveland Flats District

Thursday, July 14

7:30 - 8:00 AM	Continental Breakfast
8:00 - 8:30	Non-Destructive Evaluation Issues.....G. Thomas (LLNL)
8:30 - 9:00	Panel Summary of NDE Costs, Timetable, and Critical Issues
9:00 - 9:30	Hot Cell Creep, Fracture Toughness and Fatigue Testing.....D. Gelles (PNL)
9:30 - 10:00	Panel Discussion of Ivanov Recipe for Ductile Be, Mechanical Alloying, and Be Sheet Laminate
10:00 - 10:30	Coffee Break
10:30 - 11:00	Panel Discussion of Interaction Between Design, Materials and Processes or Summary of Unirradiated Mechanical Property Costs, Timetable, and Critical Issues or Summary of Tritium Retention and Safety Research Costs, Timetable, and Critical Issues
11:00 - 11:30	Panel Summary of High Heat Flux Testing Costs, Timetable, and Critical Issues
11:30 - 12:00 PM	Be Neutron Irradiation Experiments at ORNL.....L. Snead (ORNL)
12:00 - 12:45	Lunch
12:45 - 1:15	Panel Summary of Be Irradiated Properties Costs, Timetable, and Critical Issues
1:15 - 1:45	Schedule, Agenda, and Meeting Place for July 28-29 Meeting
2:00	Adjourn

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Sheraton Cleveland City Centre Hotel, Cleveland, Ohio

Panel Meeting, July 13-14, 1994

Attendance

Steve Abeln	Los Alamos National Laboratory	505-667-2357
Jeff Brooks	Argonne National Laboratory	708-252-4830
Jere Brophy	Brush Wellman, Inc.	216-486-4200
Richard Castro	Los Alamos National Laboratory	505-667-5191
Don Cowgill	Sandia National Laboratories	510-294-2146
Dave Dombrowski	Brush Wellman, Inc.	216-383-4007
David Gelles	Pacific Northwest Laboratory	509-376-3141
Jim Hanafee	Lawrence Livermore National Laboratory	510-422-6928
Ahmed Hassanein	Argonne National Laboratory	708-252-5889
Yoshi Hirooka	University of California-San Diego	310-825-6476
Loren Jacobson	Los Alamos National Laboratory	505-667-5151
David Krus	Brush Wellman, Inc.	216-486-4200
Kris Lauraitis	Lockheed Missiles & Space	415-424-3956
Gil London	Naval Air Warfare Center	215-441-3191
Glen Longhurst	Lockheed Martin Idaho Technologies	208-426-9950
Bill Manly	Oak Ridge National Laboratory	615-574-2556
Jim Marder	Brush Wellman, Inc.	216-486-4200
Erich Muehlberger	Electro Plasma, Inc.	714-863-1834
Albert Sickinger	Electro Plasma, Inc.	714-863-1834
Lance Snead	Oak Ridge National Laboratory	615-574-9942
Graham Thomas	Lawrence Livermore National Laboratory	510-422-7325
Mike Ulrickson	Sandia National Laboratories	505-845-3020
Bob Watson	Sandia National Laboratories	505-845-3139
Jim Yuen	Rockwell International	818-586-2820

APPENDIX VII

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Manly Conference Center, Kingston, Tennessee

Panel Meeting, July 28-29, 1994

Agenda

Outlining the Various Chapters of Be Report.....	D. E. Dombrowski
Beryllium Plasma Spray Experience of Union Carbide Corporation Speedway.....	C. F. Leitten
Y-12 Beryllium Complex.....	R. D. Seals
Remote Maintenance of ITER PFCs and Issues Regarding Use of Beryllium.....	J. N. Herndon
Developing the Panel's Position on Important Issues in Report.....	Panel
Writing and Discussing Various Chapters of Report.....	Panel

TECHYNICAL EVALUATION FOR THE USE OF BERYLLIUM

Manly Conference Center, Kingston, Tennessee

Panel Meeting, July 28-29, 1994

Attendance

Dave Dombrowski	Brush Wellman, Inc.	216-383-4007
Jim Hanafee	Lawrence Livermore National Laboratory	510-422-6928
J. N. Herndon	Oak Ridge National Laboratory	615-574-7065
Loren Jacobson	Los Alamos National Laboratories	505-667-5151
C. F. Leitten	Oak Ridge National Laboratory	615-574-0729
Gil London	Naval Air Warfare Center	215-441-3191
Glen Longhurst	Lockheed Martin Idaho Technologies	208-526-9950
Bill Manly	Oak Ridge National Laboratory	615-574-2556
R. Seals	Oak Ridge National Laboratory	615-574-0936
Bob Watson	Sandia National Laboratories	505-845-3139
Ken Wilson	Sandia National Laboratories	510-294-2497
Jim Yuen	Rockwell International	818-586-2820

APPENDIX VIII

TECHNICAL EVALUATION FOR THE USE OF BERYLLIUM

Sandia National Laboratories, Albuquerque, NM

Panel Meeting, August 10-11, 1994

Agenda

Discussions of Update on ITER Divertor Design and Divertor Requirements.....Mike Ulrickson

All time was spent writing and discussing various chapters of the Beryllium Report.

Attendance

Dave Dombrowski	Brush Wellman, Inc.	216-383-4007
Jim Hanafee	Lawrence Livermore National Laboratory	510-422-6928
Loren Jacobson	Los Alamos National Laboratories	505-667-5151
Gil London	Naval Air Warfare Center	215-441-3191
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APPENDIX IX

Technical Evaluation Panel for Use of Beryllium as PFC Components and Breeder Blanket Components in ITER

TO: Jim Hanafee, Loren Jacobson, Gil London, Glen Longhurst, Bill Manly, Bob Watson, Jim Yuen

FROM: Dave Dombrowski

SUBJECT: Comments on Mechanical Alloying of Beryllium

cc: Mike Ulrickson, Ken Wilson, J. Marder, J. Brophy

This memo provides general comments on the proposals made in Annex B of The TAC-4 Divertor Design Report. The literature on beryllium mechanical alloying has been briefly reviewed and discussions were conducted with those acquainted with mechanical alloying of nickel based superalloys.

Description of Mechanical Alloying

Mechanical alloying is high energy dry milling process of mixtures of two or more types of powder. The process can be performed with either attritors or ball mills. Alloying of two metal powders occurs by a combination of particle fracture and welding. Alloying of a metal and an extremely fine brittle phase such as an oxide occurs by entrapment of the brittle phase during the particle fracture and welding of the metal phase. In general, the critical factors are process control additives and atmosphere control. Process control agents prevent excessive welding of the metal phases to themselves, the ball charge, the attritor or ball mill tank, and attritor impellers¹.

Control of Atmosphere

The atmosphere must be very closely controlled in mechanical alloying in general. Atmospheric control is even more critical for beryllium than most metals due to its reactive nature. Beryllium has one of the strongest tendencies to form an oxide of all the metals, and excessive oxide interferes with the welding portion of the process. Oxygen must be kept at extremely low levels, the ratio of hydrogen to water vapor partial pressures (P_{H_2}/P_{H_2O}) must be very high, and the ratio of carbon monoxide to carbon dioxide (P_{CO}/P_{CO_2}) must be kept very high. Considering the large amount of gases adsorbed to container walls without a container bake out, this is not a trivial requirement.

What is the consequence of poor atmosphere control on beryllium properties? Beryllium metal is commercially ground by impact grinding and by ball mill. Ball mill grinding is done in air and produces a very fine particle size distribution and consequent increase in strength. However, this beryllium (I-400 grade) has a high BeO content and has little or no ductility.

Development of Process Control Additives

Process control agents prevent excessive welding of the metal phases to themselves, the ball charge, the attritor or ball mill tank, and attritor impellers¹.

Those intimately involved with the invention of mechanical alloying at INCO state that development of the proper process control additives is the major barrier to success. This has been time consuming for other alloy systems. It is expected to be even more time consuming for beryllium because beryllium reacts with all forms of carbon and many of the known process control additives are carbon based.

Relative Stability of Be₂C and BeO

Annex B of The TAC-4 Divertor Design Report proposes that Be₂C dispersoids may under mechanical alloying reduce BeO impurities to Be. Although there is little thermodynamic data on Be₂C, one can estimate room temperature free energy from room temperature enthalpy and entropy values given by Okamoto and Tanner².

For the reaction:

At 298 K: $\text{DG}^\circ_{\text{R}} = 3(0) + (-94.3) - (-29.2) - 2(-131.4) = 197.7 \text{ kcal/mole}$

$$\text{DG}^\circ_{\text{R}} > 0$$

Since the free energy of reaction is greater than zero, the reaction cannot occur. Since the free energy of reaction is dominated by the large BeO and CO₂ free energy values, it is unlikely that temperature increases of less than many hundred degrees will change the free energy of reaction. Be₂C will not reduce BeO impurities to Be.

The final issue is the stability of fine Be₂C particles. Atmosphere control will be crucial in the manufacture and processing of Be₂C because it reacts with water and water vapor. Bulk carbide may take several months of ambient atmosphere exposure before significant degradation, but the extremely fine carbide particles needed for mechanical alloying will have a very high surface to volume ratio and can be expected to react much more quickly.

Beryllium metal is commercially ground by impact grinding and by ball mill. Ball mill grinding is done in air and produces a very fine particle size distribution and consequent increase in strength. However, this beryllium (I-400 grade) has a high BeO content and has little or no ductility.

Summary

1. Development of process control additives for beryllium is a potentially long term project.
2. Control of atmosphere to protect Be surfaces during mechanical alloying is important to ductility and is not trivial to achieve.
3. Be₂C will not reduce BeO impurities to Be.
4. Extremely fine (submicron) Be₂C dispersoids will react very quickly with water and humidity.

REFERENCES

1. J.S. Benjamin, M.J. Bomford, Met. Trans. A, Vol. 8A, August, 1977, pp. 1301-1305
2. H. Okamoto and L. Tanner, "The Be-C (Beryllium-Carbon) System", in *Phase Diagrams of Binary Beryllium Alloys*, eds., H. Okamoto and L. Tanner, ASM, Metals Park, OH, 1987, p. 32

APPENDIX X

Technical Evaluation Panel for Use of Beryllium as PFC Components and Breeder Blanket Components in ITER

TO: Jim Hanafee, Loren Jacobson, Gil London, Glen Longhurst, Bill Manly, Bob Watson, Jim Yuen

FROM: Dave Dombrowski

SUBJECT: Comments on Recent Proposals for HIP Manufacture of First Wall and Blanket

cc: Mike Ulrickson, Ken Wilson, J. Marder, J. Brophy

Two presentations were made at the July 18-20, 1994, ITER Blanket Working Group Technical Meeting, in Garching, Germany, on use of HIP to manufacture the First Wall of ITER. Our preliminary comments on these proposals are found in this memo. These comments are given as background to the panel for use in the final report of the panel.

I. Comments on "First Wall Manufacturing By Hot Isostatic Pressing" by J. Collen and R. Tegman

J. Collen is with Studsvik Ecosafe, and Ragnar Tegman is with IVF. Their proposal is summarized on page 7 of their presentation. It consists of the simultaneous consolidation of three metal powder layers with 316L tubes. The three powder layers are Be powder on top of Cu powder on top of 316L powder. The 316L tubes are shown in the Cu powder layer.

The following issues are raised with respect to this proposal:

1. Compatibility of three consolidation temperatures for the three different powders.
 - a. Formation of Be-Cu intermetallics
 - b. Formation of Be-Cu eutectic
 - c. Producing maximum ductility in consolidated Be
2. Preservation of alignment and/or position of the 316L tubes to any precision.
3. Preservation of flat interfaces.
4. Availability of Cu-Cr-Zr or Cu-Be-Ni powders

The authors have shown an example of manufacturing a composite part from copper powder and stainless steel powder but have not demonstrated manufacture of a composite part from either Be powder and Cu alloy powder or Be powder and Cu alloy powder and stainless steel powder. The difficulty with manufacture of parts from Be powder and Cu powder is achievement of maximum beryllium properties, especially percent elongation. HIP temperatures above 750°C are required for reasonable Be properties and temperatures below 700°C are required to minimize formation of brittle Be-Cu intermetallics. These conflicting requirements were demonstrated in HIP of Be powder to solid CuCrZr, and to solid Glidcop® by Brush Wellman under contract to JET. Significant formation of beryllides degraded bend test performance of such bonds. Further, unlike the pure Cu case proposed by Collen and Tegman, the use of a Cu alloy such as CuCrZr produces a complicated non-planar structure of precipitates and lamellae. As expected, primary fracture and secondary fracture occurs in the

precipitate rich bands. If achieving reasonable beryllium percent elongation is difficult with HIP of Be powder to solid Cu, it is unlikely to achieve reasonable properties by HIP of Be powder to Cu powder, or by simultaneous HIP of Be powder to Cu powder and Cu powder to stainless powder.

The most successful bonding of Be to Be¹ and of Be to Cu² used silver as a diffusion barrier. The use of a diffusion barrier or compliant layer between Be and Cu powder layers is problematic.

There is general concern over preservation of cooling tube alignment during HIP. Those experienced in the art know how difficult it is to account for asymmetric forces from HIP can weld corners and therefore how difficult it is to maintain cooling tube position. Sensitivity of heat transfer performance to tube position must be determined by the designers.

Although a flat interface can be maintained for powder to solid bonding, it is unlikely that a flat interface can be maintained in powder to powder consolidation and bonding. The importance of flat interfaces to uniform heat transfer and mechanical properties is yet to be determined. Repair of the first wall may be difficult if the interface layers are not flat.

Finally, although this proposal assumes pure Cu powder, a Cu alloy will actually be used. The availability of specialty Cu alloys in appropriate powder form is unknown. Solid CuCrZr is difficult to obtain at this time, and it is unlikely that there is a capability for CuCrZr powder. Cu-Be-Ni is a second candidate alloy, and it is not available in powder form.

In summary, the potential problems with this approach may require a very large amount of development work or be may be intractable.

II. Comments on "HIP Processing of ITER FW/Blanket" by F. Moret (CEA/CEREM)

This proposal is summarized on pages 9 and 10 of their presentation. Stainless steel powder is initially HIPed against the cooling tubes (Cu or SS?). Dispersion strengthened (DS) Cu and Be plates are then simultaneously HIP'd to the stainless steel and tube part.

The Moret proposal avoids many of the powder based problems of the Collen and Tegman proposal. However, the important issues of Be-Cu bonding which underlie all bonding approaches are still applicable. The simultaneous bonding of solid Be to solid Cu and solid Cu to solid stainless steel also needs closer inspection for compatibility of temperature windows and possibility of achieving acceptable bond properties.

III. Summary

These proposals do not address the generic issues of Be to Cu bonding and compound those problems with a more complicated material system and use of powder. There are in addition questions about preserving part alignment for the proposal based entirely on powder.

IV. References

1. D.L. Olson, A.L. Liby, *Beryllium Science and Technology*, vol. 2, eds., D. Floyd and J. Lowe, Plenum Press, NY, 1979, p. 282, 286
2. H. Altmann et. al, 15th IEEE Symposium on Fusion Engineering, Hyannis, MA, Oct. 11-15, 1993

APPENDIX XI

Interaction of Beryllium with Tungsten and Molybdenum

The binary phase diagrams of beryllium with tungsten and molybdenum are similar in that both have compounds with stoichiometry MBe_{22} and MBe_{12} , at 4.3 and 7.7 atomic percent refractory metal. The melting points of these compounds are above that of beryllium, with MoBe_{22} at 1300°C, MoBe_{12} at about 1690°C, and WBe_{22} at about 1500°C and WBe_{12} at about 1750°C. The properties of these compounds have not been studied, but the high melting points of the MBe_{12} compositions suggest that they are quite stable. The solubility range of these compounds is quite narrow. The solubility of beryllium in tungsten about 3 atomic % in the range of 1000 to 1300°C and reaches a maximum of 5 atomic % at a temperature of 2100°C, the eutectic temperature between tungsten and the compound WBe_2 . The properties of such solid solutions are not known. It has been reported that an alloy of low melting point is formed when beryllium is deposited on a tungsten filament at 1230°C, but the composition and structure of this phase was not determined, and so it was not included in the assessed phase diagram. The solubility limit of beryllium in molybdenum is very low, about 0.9 atomic % at a temperature of 1870°C, the eutectic temperature between molybdenum and the compound MoBe_2 .

The main interactions can be summarized as follows: beryllium with deposits of tungsten or molybdenum will react to form intermetallic compounds that have a higher melting point than beryllium. The beryllide intermetallic compounds generally have significantly lower thermal conductivity than beryllium. These compounds are also quite brittle and have low electrical conductivity.¹ Tungsten or molybdenum with deposits of beryllium will begin melting at the respective eutectic temperatures of 2100°C and 1870°C, respectively. This represents a significant reduction in melting points of the pure metals, which are 3422°C and 2623°C.² Should beryllium deposit on tungsten or molybdenum, operating at very high temperatures (near their melting points), significant low melting liquid would form. This would limit the maximum operating temperature of such components. As an aside, we point out that the volatility of the oxides of tungsten and molybdenum could also pose a problem if these metals are used as ITER plasma facing components. It would also be expected that the sputtering of beryllium by high atomic number elements would be more severe than the sputtering by the low Z atoms such as hydrogen isotopes and helium.

-
1. Stonehouse, A. J., "Beryllides," *Encyclopedia of Chemical Technology*, John Wiley and Sons, New York, 1971, pp 73-80.
 2. Okamoto, H. and Tanner, L., *Phase Diagrams of Binary Beryllium Alloys*, ASM International, Metals Park, Ohio (1987).

APPENDIX XII

ACRONYMS

ABF	Ammonium Beryllium Fluoride
ANL	Argonne National Laboratory
ASP	Atomized Spherical Powder
ATR	Advanced Test Reactor
BATS	Beryllium Atomization and Thermal Spray facility
BLTT	Blood Lymphocyte Transformation Test
BMI	Battelle Memorial Institute (Battelle Northwest Laboratory)
BNL	Brookhaven National Laboratory
BW	Brush Wellman, Inc.
CBD	Chronic Beryllium Disease
CDA	Conceptual Design Activity
CDP	Cold Die Press
CEA	Commissariat a L'Energie Atomique (French Atomic Energy Commission)
CEREM	Centre d'Etudes et de Recherches sur les Materiaux
CFC	Carbon Fiber Composites
CHF	Critical Heat Flux
CIP	Cold Isostatic Pressing
CP	Cold Pressing
CTE	Coefficient of Thermal Expansion
CX	Charge Exchange)
DIII-D	Doublet III-D tokamak
DIFFUSE	tritium transport code
DIMES	Divertor Material Exposure System
DOE	Department of Energy
dpa	displacements per atom
DT	Deuterium-Tritium
DXT	Distance times Thickness
EB-1200	Electron-Beam 1200 watts
EBR-II	Experimental Breeder Reactor II
EBTS	Electron Beam Test System
EC	European Community
EDA	Engineering Design Activity
ELM	Edge Localized Mode
EMATS	Electromagnetic Acoustic Transducers
EPI	Electro Plasma, Inc.
FFTF	Fast Flux Test Facility
FMIT	Fusion Materials Irradiation Tests
FW	First Wall
GA	General Atomics
hcp	hexagonal close-packed
HEDL	Hanford Engineering Development Laboratory (Washington)
HFBR	High Flux Breeder Reactor
HFIR	High Flux Irradiation Reactor
HIP	Hot Isostatic Pressing
HTO	tritiated water
IAEA	International Atomic Energy Agency (Vienna, Austria)
ICRH	Ion Cyclotron Resonance Heating
INCO	International Nickle Company

INEL	Idaho National Engineering Laboratory (also LMIT)
ISX-B	Impurity Studies Experiment (tokamak at ORNL)
ITER	International Thermonuclear Experimental Reactor
IUA	ITER Unit Account (1 IUA = \$1000 [1989])
IVF	Institut Verkadsteknisk Forskning (Swedish institute)
J	Japan
JAERI	Japanese Atomic Energy Research Institute
JCT	Joint Central Team
JET	Joint European Torus
KFA Juelich	Kernforschungsanlage Juelich
LANL	Los Alamos National Laboratory
LIB	Laser Induced Breakdown
LIBS	Laser Induced Breakdown Spectroscopy
LLNL	Lawrence Livermore National Laboratory
LMIT	Lockheed Martin Idaho Technologies (also INEL)
LMS	Lockheed Missiles and Space
LOCA	Loss of Coolant Accident
LOFA	Loss of Flow Accident
M&P	Materials and Processes
MD	McDonnell-Douglas
MDA	McDonnell-Douglas Aerospace
mfp	mean-free-path
MHD	Magnetohydrodynamic
MPa	Megapascal
MSC	Materials Science Corporation
MURR	Missouri University Research Reactor
NASP	National Aerospace Plane
NAWC	Naval Air Warfare Center
NDE	Non-Destructive Evaluation
NIOSH	National Institute for Occupational Safety and Health
OFHC	Oxygen Free High Conductivity Copper
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PEL	Precision Elastic Limit
PFC	Plasma Facing Component
PISCES	Plasma Interactions with Surfaces and Components Experimental System
PLADIS	Plasma Disruption Simulator
PM	Powder Metallurgy
PMTF	Plasma Materials Test Facility
PNL	Pacific Northwest Laboratory
PPPL	Princeton Plasma Physics Laboratory
PVD	Physical Vapor Deposition
QA	Quality Assurance
R&D	Research and Development
RF	1. Russian Federation 2. Rocky Flats 3. Radio Frequency
RH	Remote Handling
RI	Rockwell International
S	Sintering
SBIR	Small Business Innovative Research
SNL	Sandia National Laboratories
SNLA	Sandia National Laboratories in Albuquerque
SNLL	Sandia National Laboratories in Livermore
SOL	Scrape-Off Layer
SS	Stainless Steel

TAC-4	Technical Advisory Committee, Report 4
TEM	Transmission Electron Microscopy
TEXTOR	tokamak in Juelich, Germany
TLV	Threshold Limit Value
TPE	Tritium Plasma Experiment
TSTA	Tritium Systems Test Assembly
UCLA	University of California at Los Angeles
UCSD	University of California at San Diego
UNM	University of New Mexico
UTS	Ultimate Tensile Strength
VAPOR	air/steam reaction facility at INEL
VHP	Vacuum Hot Pressing
VIKA	plasma disruption facility in Russia
VS	Vacuum Sinter
YS	Yield Strength

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