|  |  |  |
| --- | --- | --- |
| **Report IDM reference No.** |  | **Version: see IDM** |

Final Report

on Deliverable

MAT-1.3.1-T005-D001 - Structural Design Crtieria Development – Brazed Joints

|  |  |  |  |
| --- | --- | --- | --- |
|  | | **Deliverable-ID**[[1]](#footnote-1) | *MAT-1.3.1-T5-D1* |
| **Work Package** | *WPMAT* | **Date** | *31st Oct. 2016* |
| **Project Leader** | *Michael Rieth* | | |
|  | | | |
| **TS Title** | Structural Design Criteria Development: Brazed Joints | | |
| **TS Ref. No.** | *MAT-1.3.1-T005* | **TS IDM-link** | *[2N4SGZ](https://idm.euro-fusion.org/?uid=2N4SGZ&action=get_document)* |
| **Task Owner** | Jason Hess | | |
| **RU(s)** | *CCFE* | | |

|  |  |
| --- | --- |
| **Report Review & Approval** | |
| **IDM role** | **Name(s)** |
| **Author** | J. Hess |
| **Co-author(s)** |  |
| **Reviewer(s)** | *Mike Gorley* |
| **PMU Reviewer** | *Eberhard Diegele, Matti Oron-Carl* |
| **Approver** | *Michael Rieth* |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| X | Study / Assessment |  | Procurement / Commissioning of Hardware |  | Industry |

|  |  |  |  |
| --- | --- | --- | --- |
|  | Use of Facility |  | Other *{please specify}* |

|  |
| --- |
| **Executive Summary** |
| The following report summarises the state of brazed joints in fusion technology and the assessment of the most relevant design code, the SDC-IC. It is concluded that brazing technology is insufficiently understood and that the SDC-IC is inadequate for a design by analysis approach.  It is recommended that a particular joint configuration be chosen for detailed development and testing. This should be in a critical region like the tungsten-copper divertor armour-heatsink joint. Large scale testing should be carried out to develop material property handbook and allowable stress data for each joint type. Further work is needed to assess whether brazed joints can be accurately modelled or if they should be represented in analysis by knock-down factors as in SDC-IC. |

|  |
| --- |
| **Comments** (shortcomings, deviations, etc.) |
| *Although the objectives for this task were completed, the vastness of the subject has been highlighted and not all aspects can be covered. Despite already decreasing the scope of this task from assessing all joining techniques to focussing solely on brazing; further prioritisation should be carried out going forward.* |

**Table of Contents**

[Abbreviations 2](#_Toc468693986)

[Introduction 3](#_Toc468693987)

[Work on Objectives 4](#_Toc468693988)

[I. List the potential braze specifications for armour to structural joints 4](#_Toc468693989)

[II. Identify relevant damage mechanisms to joints 5](#_Toc468693990)

[III. Identify associated gaps in design rules and materials data 6](#_Toc468693991)

[IV. Propose and design rule development and validation programme 7](#_Toc468693992)

[Creation of Experimental Curves 7](#_Toc468693993)

[Study of Joint Stress State 7](#_Toc468693994)

[Development of Joints 8](#_Toc468693995)

[Further Work 9](#_Toc468693996)

[Brazed Joint Issues 9](#_Toc468693997)

[Other Sources of Information 10](#_Toc468693998)

[Recommendations 12](#_Toc468693999)

[Fabrication 12](#_Toc468694000)

[Testing 12](#_Toc468694001)

[Analysis 12](#_Toc468694002)

[References 13](#_Toc468694003)

# Abbreviations

|  |  |
| --- | --- |
| CTE | Coefficient of Thermal Expansion |
| DBA | Design By Analysis |
| DBE | Design By Experiment |
| DEMO | Demonstration Power Plant |
| PFC | Plasma Facing Component |
| SDC-IC | Structural Design Criteria for In-Vessel Components |

# Introduction

DEMO in-vessel joints present unique challenges as regions of high stress concentrations and potential failure. There are numerous available joining techniques that have been studied in some measure for use in fusion reactors. However, a report by R. Bamber[1] prioritised the development of brazed joints, as these are relatively poorly understood and are likely to be applied in critical areas of high neutron and heat fluxes. Therefore, this report will focus on brazing; particularly, PFCs with dissimilar material joints.

The objectives are as follows:

* 1. List the potential braze specifications for armour to structural joints
  2. Identify relevant damage mechanisms to brazed joints
  3. Identify associated gaps in design rules and materials data
  4. Propose and design rule development and validation programme

The ultimate goal is to produce Design By Analysis (DBA) rules for use on joints. Whether or not this is practical is currently uncertain. This report will act as a stepping stone towards this goal; providing insight from literature and an assessment of the current design rules; the SDC-IC.

It is important to understand the requirements of the future designers of brazed components. They will likely need the following:

* A complete understanding of brazing or the confidence that the braze operator fully understands the process. Ideally no experimentation should be needed and a high quality of final braze, with known properties, can be assumed by the designer. Thus making selection of joint specifications trivial.
* A set of design rules and codes which are built from the ground up with joints in mind, supported by experience and experimentation.
* Complete materials property and allowable stress data for all relevant materials available for selection by a designer to be used in analytical validation of a component.

This work has included the following:

* A literature review of brazing technology in the fusion industry.
* Review of other design codes and brazing related standards.
* Familiarisation with analysis techniques (SDC-IC) and software (ANSYS).
* Assessment of the SDC-IC DBA procedure using ANSYS.

# Work on Objectives

## I. List the potential braze specifications for armour to structural joints

Table 1 lists the fusion related brazed joints that are reported in the literature. These are generally joints for PFCs; in particular, the divertor region. This list is not exhaustive; a few studies have been selected from the recent literature based on relevance.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parent Materials** | **Filler Materials** | **Test** | **Pass/Fail** | **Reference** |
|
| 316LN - CuCrZr | Ni Bal - 14Cr - 10P - 0.05Si - 0.03C - 0.01B | SEM - Microstructural | No intermetallics | [2] |
| W(Mono) - Ta - Eurofer | Ti bal - 22.5Cr - 7.5V - 3Be | Thermocycling - 30 cycles - 750°C | Pass | [3] |
| Fe Bal - 18Ta - 8Ge - 2Si - 2Pd - 3.5B |
| W - Cu(OFHC) | 80Au - Cu20 | XRD & FEA | N/A | [4][5] |
| W - W | 80Au - 19Cu - 1Fe | Nano-indentation | No increase in hardness | [6] |
| W - Eurofer |
| W - Cu(OFHC) |
| W - SS316L |
| Ti - Cu(OFHC) | 72Ag - 28Cu | Thermal Autofrettage - XRD & FEA | Pass | [7] |
| W(Mono) - 50FE/50Ni - Steel | Ni Bal -15Cr - 4Mo - 4Fe - (0.5–1.0)V - 7.5Si -1.5B | Thermocycling - 100 cycles - 700°C | Pass | [8] |
| W 2CeO2 - 50FE/50Ni - Steel | Fail |
| W 1La2O3 - Eurofer | Ni Bal - 19Cr - 10.1Si - 0.003B - 0.06C - 0.02P | Bending & Charpy | Failed easily at low temperatures | [9] |
| W - Cu(OFHC) | 9.5Ni - 52.5Cu - 38Mn | Thermocycling - 2000 cycles - 5MWm-2 | Pass | [10] |
| Shear Strength | Failed at lower bonding pressures | [11] |
| Be - CuCrZr | Cu Bal - 12Sn - 9In - 2Ni - 0.4Mn - 0.4Cr - 0.5P | Neutron irradiation (4.9 x 1014 cm-2s-1) and thermocycling 1000 cycles - 8MWm-2 | Pass | [12] |
| Be - Cu |
| CFC - CuCrZr | Ti-based | Neutron irradiation (0.35 dpa) + Thermocycling - 1000 cycles - 15MWm-2 | Pass | [13] |
| Be - CuCr-Zr | InCuSil | Neutron irradiation (0.35 dpa) + Thermocycling - 1000 cycles - 9.5MWm-2 + Shear Strength | Pass thermocycling + Loss of shear strength after irradiation |
| W - W | Ni Bal - 16Co - 5Fe - 4Si - 4B - 0.4Cr | Shear Strength | Failure at 235MPa cracks in W | [14] |
| Eurofer - Eurofer | Failure at 230MPa cracks in interlayer |
| W - CuCrZr | 75Cu - 25Mn | Thermocycling - 1000 cycles - 11.7MWm-2 | Pass | [15] |
| W - Cu | 45Ti - 30Zr - 15Cu - 10Ni | Shear Strength | 16.6MPa | [16] |
| W - 70W/30Cu - Cu | 119.8MPa |
| W - (OFHC) - Mo - Cu | 140.8MPa |

**Table 1. A selection of brazed joint specifications and testing results for PFC experiments in the literature.**

Table 1 shows a relatively small selection of the fusion relevant brazed joints from the literature. It demonstrates the distinct lack of standardisation for testing methodology and the lack of a single defined candidate for PFC joint configuration. Clearly more focus on a particular joint configuration is needed as the parent-filler material combinations are too numerous to fully develop them all.

## II. Identify relevant damage mechanisms to joints

Table 2 contains the damage mechanisms listed for analysis in the SDC-IC[17], plus the additional ‘Compound Damage’ group. These are dependent upon the environment in which the joint is applied; and thus, all of the mechanisms are potentially relevant to brazed joints. Therefore, table 2 uses a case study of divertor monoblocks to assess the damage mechanisms; and ranks each of them on their relevance; as agreed with Mike Fursdon (WPMAT & WPDIV):

* 1 – Irrelevant
* 2 – Seemingly irrelevant but cannot be ruled out
* 3 – Unknown
* 4 – Seemingly relevant but dependent upon conditions
* 5 – Relevant

|  |  |
| --- | --- |
| **Damage Mechanism** | **Relevant Divertor Monoblock Designs?** |
| **M-Type Damage** | |
| **Ductile Damage Modes:** |  |
| Immediate Plastic Collapse | **2** – Stresses would not be high enough in a monoblock. |
| Immediate Plastic Instability | **2** – Significant dimensional changes are unlikely. |
| **Non-Ductile Damage Modes:** |  |
| Immediate Plastic Flow Localisation | **3** – Small areas of high plastic deformation may occur. |
| Immediate Local Fracture Due to Exhaustion of Ductility | **4** – Cracks appear away from defects after manufacture. |
| Fast Fracture (Ductile and Brittle Tearing) | **4** – Initiation/propagation of cracks from a flawed braze. |
| Thermal Creep | **5** – Covered in literature. |
| **C-Type Damage** | |
| Ratcheting (Progressive Deformation) | **2** – Fatigue is dominant (J. Gardiner - ratcheting). |
| Fatigue (Time Independent and Dependent) | **5** – Extensively covered in literature. |
| Buckling (Load/Strain-Controlled and Time-Dependent) | **2** – Unlikely to be of concern for this component. |
| **Environmental Damage** | |
| **Irradiation Effects:** |  |
| Irradiation-Induced Creep | **5** – Limited irradiation data unsurprisingly points to degradation of joints. However, logic alone suggests that this is a vital damage mechanism. |
| Irradiation-Induced Swelling |
| Irradiation-Induced Changes in Material Properties |
| Corrosion and Erosion | **4** – Dependent on whether joints are exposed. |
| Multilayer Effects (i.e. Delamination) | **5** – A vague damage mechanism, but relevant here. |
| **Compound Damage** | |
| Stress Corrosion Cracking | **3** – Dependent on environment. |
| Creep Fatigue | **4** – Creep is not the dominant fatigue mechanism. |

**Table 2. Rating the relevance of different damage mechanisms with regards to divertor monoblocks.**

Analysis using the SDC-IC procedure can only suggest that a damage mechanism is not relevant by judging reserve factors from the results of an analysis. Study of the literature can only show what others’ have worked on and works best to confirm the relevance rather than dismiss it. No definitive answer will be known without extensive testing; which does not exist for many of these damage mechanisms.

## III. Identify associated gaps in design rules and materials data

This study has been focussed around the existing brazed joint design code in the SDC-IC. Experience in use of ANSYS was developed whilst analysing very simple geometries with the SDC-IC analysis procedure. The following points are the author’s evaluation of the code’s suitability to assess DEMO in-vessel components:

* There are numerous holes in Appendix A[18] Data, such as allowable stresses and properties for many key materials, which are required to carry out the SDC-IC analysis procedure. Furthermore, there is no data at all on interlayer materials should an analyst choose to model this layer. The full analysis cannot be carried out on most of the materials of interest due to these holes.
* Seemingly arbitrary knockdown factors leading to unknown and potentially unsubstantiated conservatism. In some cases (particularly for plastic analysis) it is suggested that these knockdown factor must be found through experimentation.
* There is very little mention in the SDC-IC on how to create the model to best represent a brazed joint:
  + 2D or 3D modelling?
  + Mesh refinement?
  + Representation of braze layer, if at all?
* There is little mention of modelling the stress state around the materials interface, which is much studied in the literature and remains a key issue for brazed joints. There is a section ‘IC 5201 Abrupt changes in mechanical properties at brazed joints’ which directs the analyst back to welding rules for the equivalent section. Unfortunately this section is only relevant to particular types of welded joint and cannot be applied to brazing.
* Analytical singularities are a real issue in measuring these stress states around the joint as they can misrepresent the residual stress in the critical region adjacent to the interface. The SDC-IC doesn’t approach this subject.
* Section ‘IC 5011 Design Requirements’ lists four design rules which are adapted slightly from the welding section IC 4011. Each of these rules initially seems agreeable and has a good basis. However, an adaption from welding rules does not seem to describe the brazed joints well. An example is:
  + ‘***d) Brazed joints in high fluence zones should be avoided.***’
  + Although this seems like a sensible rule, most in-vessel components will experience high neutron fluence and many of the current designs for PFCs which use brazed joints are in the very highest fluence regions in the first wall.

‘IC 5000 Rules for Brazed Joints’ is a new section for version 3 of the SDC-IC, and seems to be adapted from existing rules for welding. These rules are based upon years of experience and testing, but brazed dissimilar material joints present unique stress states so any adapted rules warrant further substantiation. Should the above points be addressed and the code fully substantiated with experimental testing, then the current structure may be suitable for brazed joint DBA rules.

## IV. Propose and design rule development and validation programme

This report has been unable to rule out the use of an adapted SDC-IC or any of the damage mechanisms that are used in its analysis procedure. However, the next step towards DBA rules can be suggested with the work that has been carried out.

### Creation of Experimental Curves

A large amount of experimental data is needed to build curves which are the basis for analysis design codes[19][20][21]. This information can be used to derive allowable stresses, joint knockdown factors and materials data whilst increasing the expertise in joint fabrication and behaviour. The tests that should be a priority are the following:

* Thermal and mechanical fatigue tests to determine S-N curves. Carry out in shear and tension for mechanical testing as brazed joints may be weaker in shear.
* Tensile testing at varying temperatures for determination of M-type damage mechanism. Carry out tests in tension and shear.
* Accelerated or extrapolated creep testing. Accelerated creep may not be representative as creep mechanism changes at different temperatures.

Neutron irradiated samples for the above tests would be desirable. However, irradiation time in experimental reactors with sufficient neutron fluence is costly. With no irradiation campaign guaranteed it must be assumed that the data may come from surveillance of DEMO samples. The implications of this must be considered in greater detail than in this report. An assessment of this risk should be included in the 2017 deliverable, along with an argument for the neutron irradiation of key joints.

### Study of Joint Stress State

Gaining an understanding of the complex stress state around the joint, and its evolution throughout service, is the focus of many analytical studies[2][4][22][23]. It is described in more detail later in this report; for now it suffices to say that high residual stresses are caused by mismatch of parent material CTEs following solidification of the braze layer after the joint fabrication heat cycle. Unique stress-states appear in each material and can dictate the failure of the joint. Therefore, it is necessary to study this feature in more detail:

* Modelling – the Hot-Spot Stress technique:
  + This has been identified in the literature[23][24] as a technique to measure residual stresses in weld toes where analytical singularities exist; as they do at the dissimilar material interface in brazed joints.
  + It has been successfully applied to brazed joints in this study and is also detailed later in the report.
  + This appears to be a promising method, but experimental measurements of residual stress are required to validate this technique.
* Experimental – Measurement of residual stresses:
  + Typically XRD has been used to measure residual stresses in the literature[2][7].
  + Mixed results have been obtained with this method. There is the issue of poor penetration of the X-rays into materials and the need to cut up the joint to carry out the test which can affect the stress state.
  + Neutron diffraction could provide far greater penetration into samples and thus reveal greater detail of the stress state in the entire joint.

If the stress state of these joints can be better understood, and furthermore, accurately modelled, then the life of the joint could be easier to predict, forming the basis of a DBA technique. If the stress state is too complex to accurately predict, any experiments that are carried out in the attempt to understand it may yield some knockdown factors to apply to analysis which have a stronger experimental basis than those given in the SDC-IC.

### Development of Joints

As is partially demonstrated in table 1, there is currently no single joint configuration for each component type. This is largely due to the selection of filler material, as parent material combinations for in-vessel components are better defined. The following are currently the most likely candidates for DEMO PFC material joints:

* Armour (W) – Heat sink (Cu/CuCrZr)
* Armour (W) – Structural (Eurofer/CuCrZr)
* Heat sink (Cu/CuCrZr) – Structural (Eurofer/CuCrZr)

The large variation in joint configurations in the literature is mostly due to the use of different filler materials. The most common filler used in divertor-like joints is Cu80Au20, with good results reported in the literature[4,5,6]. However, there are still many other possible candidates that deserve more attention. Thus it is proposed that this is followed up in the 2017 deliverable report with a section on the exact joint configuration to be pursued, including filler material.

Although there are many joints that should be fully assessed it would be necessary to initially focus on just one. This should reduce number of samples needed for creating the experimental curves and studying the stress state of joints, thus reducing the workload and cost of the programme and allowing comprehensive testing. Furthermore it will act as a trial run and inform the design of testing campaigns for future joints.

# Further Work

This section is a summary of work that was not fully related to the main objectives but is important enough to mention:

## Brazed Joint Issues

* Stress state:
  + The mismatch of CTEs in dissimilar material joints cause a complex residual stress state following manufacture and may evolve throughout the lifetime of the component subjected to thermal and mechanical loads as well as high neutron fluence.
  + It is affected by:
    - Mismatch of material properties following manufacture.
    - Primary creep may also play a role.
    - Plastic deformation on cooling.
    - Nature of materials – i.e. brittle/ductile.
  + The braze layer can experience hydrostatic stresses which effectively strengthen the joint as dislocations movement is impeded. There is also suggestion that this leads to greater strength in tension than in shear.
  + Different studies show failure in different locations within the joint. It is more common to see failure in the brittle material (tungsten) due a tensile stress field, whereas the ductile material (i.e. copper) experiences compressive stresses. It is also common for failure within the interlayer.
  + Failure is dominated by crack propagation.
  + There are two arguments about the way to deal with stress states with regards to future code development:
    - Understanding of the behaviour of this stress state so it can be effectively modelled is essential if new joints are to be designed using DBA and not DBE.
    - Understanding of the stress state is difficult and analysis may be even more so. The stress state for each joint type should be deduced experimentally and relevant knockdown factors applied to the analysis.
  + Practical solutions to the residual stresses have been studied:
    - Autofrettage – inducing plastic strain in the joint, and thus releasing some residual stress via lowering the temperature of the joint to cryogenic temperatures.
    - Interlayers – a third parent material in the middle of the joint between filler materials in the form of a thin plate or foil which bridges the gap in CTE between the primary two parent materials.
* Microstructural:
  + Migration of elements between layers – there is a suggestion that allowing diffusion of parent and filler elements may be beneficial in particular joints[10], other joint setups could be degraded by the formation of brittle intermetallic phases[3][5][6].
  + Directionality in the grain texture – the interlayer is usually around <100μm in thickness. Without the necessary number of grains to average out their orientation, properties of this layer could be anisotropic[2].
* Analytical singularities:
  + The aforementioned residual stresses in brazed joints are also present in analytical models. However, they become stress singularities at the free surface edge of the joint. These unconverged stresses make it very difficult to accurately predict the stress state in what is a key region of the joint.
  + Analytical work to understand and reduce the strength of these singularities[25]. It has been shown that:
    - FGM brazed layer reduces the strength of the singularity.
    - A larger braze layer also reduces the strength.
    - Filleting of one of the parent materials, so that there is one shared node at the free edge, eliminates the singularity.
    - Although these techniques affect the singularities they do not guarantee accurate predictions of the joint stress state and, if applied, may not be representative of the joint geometry.
  + Another way to understand the stresses at the joint is to use a method typically used to understand stresses at a weld toe; the hot spot stress technique:
    - Extrapolation of the stress near the joint as the stress raises, but before the singularity.
    - Relies on mesh refinement, sampling distance and extrapolation type; which makes this another approximation technique like linearization.
    - Work has been carried out to assess this method for use with the free surface edge at the braze interface.
  + Different joint element types were investigated :
    - The braze layer can be represented in a number of ways:
      * Solid elements – possibly the most representative way model the stress state in a brazed joint. However, high refinement of mesh is needed around material interface which makes modelling impractical.
      * Membrane – membrane elements are in place of the braze layer greatly reducing the element count, but represent the stress state poorly.
      * Cohesive elements – good for modelling delamination at material interfaces. However, this is not always the region of failure in a brazed joint.
* Irradiation data:
  + There is relatively little literature available on the irradiation of brazed joints. The work that does exist focuses on the transmutation of elements in the joints. For example:
  + Transmutation
    - Common filler material elements Au and Ag transmute to Zn and Cd which have low vapour pressure and can cause cryo-pump poisoning[26].
    - The amount of Cd transmuted from Au may not conform to low activation rules[27] as might the existence of certain Ag isotopes.
    - Another product, Hg, has also been shown to degrade the joint[27].
  + One older study[28] showed that a dissimilar material joint with Au-Ni braze filler failed only in the parent material at low temperatures, but failed in the braze layer at all temperatures in irradiated samples (n fluence – 6 x 1020cm-2).
  + Due to the lack of comprehensive literature available for irradiated materials, it is likely that a surveillance campaign will be carried out in DEMO to assess irradiation effects.

## Other Sources of Information

* Standards:
  + ‘BS EN 14324:2004, Brazing - Guidance on the application of brazed joints’[29] is an extremely useful resource in the understanding of brazed joint manufacture and design. There is information on materials selection, surface finish, heat treatment, inspectability and brazing gap change at temperature. There are also diagrams that list recommended designs for application of filler material and high/low stress configurations that the SDC-IC references.
  + Other EN, ISO and BSI standards have not yielded anywhere near as much useful information as BS EN 14324. Comparison of equivalent welding codes showed the level of vagueness and lack of knowledge that went into making the brazing standards.
* Other codes:
  + The RCC-MRx Nuclear Design Code is the basis of the SDC-IC. It contains no dedicated section for analysis of brazed joints. Between two sections that mention brazing; ‘RB 4370 MECHANICAL ASSEMBLIES - BRAZED ASSEMBLIES’[19] and ‘RF 7300 BRAZED ASSEMBLIES’[20] there is limited information, all which can be found in EN, ISO and BSI standards.
  + The ASME III Code also mentions brazing, but the information is even more limited than in the RCC-MRx and there is again, no specific section by analysis of brazed joints[21].
* Industry:
  + The Welding Institute (TWI)[24] is a consultancy and research organisation which the UKAEA is a member of. Contact was made via phone with the duty engineer and information was provided regarding the ‘hot-spot stress’ analysis technique.
  + ANSYS engineering analysis software was used in this work to assess the SDC-IC, brazed joints, hot-spot stress technique and an exhaustion of ductility technique. Contact was made with the ANSYS technical support team who advised on methods with which to model a brazed layer. Information regarding cohesive elements was obtained from this source.
  + Special Techniques Group, UKAEA, have extensive practical experience in joining techniques such as brazing.
  + Potential industry contacts that have not been approached are STFC as is the aerospace industry in general.

# Recommendations

### Fabrication

There is an obvious lack of information on brazed joints throughout the available literature and other resources when compared to a more mature technology such as welding. Should this not be the case, the recommendation would be to begin a testing campaign to validate, augment or replace current deign codes. However, more research is needed into different joint configurations and their manufacture:

* Focus on parent materials relevant to PFCs (tungsten, copper and Eurofer).
* Review available filler material options in the literature.
* Create brazed samples with chosen filler and parent material combinations, with the aim of obtaining consistently reliable wetting of joint.
  + SEM and nanoindenter tests may be needed to assess the quality of the braze layer and any microstructural changes.
* Samples for testing programme to be created as per relevant standards.

### Testing

Samples will be required for the following tests:

* X-ray or neutron diffraction to study residual stresses at the joint.
* Creation of experimental curves:
  + Thermal and mechanical cycling tests to assess fatigue
  + Tensile and shear monotonic tests.
  + Extrapolated 100,000 hour creep testing
* Furthermore, it is necessary to define failure criteria for joints:
  + - Initiation
    - Propagation
    - Delamination
* Production of 5/10 year plan over the next year to properly define testing plan.
  + Phase 1 – Guineapig braze
  + Phase 2 – Other brazes

### Analysis

* Study of stress state:
  + Further investigation of Hot-Spot technique.
* New analysis techniques also under development in EDDI for individual damage mechanisms should be awaited upon and each should consider joint design given that it is often an issue. The philosophy of ‘the less joints the better’ has been suggested.
* How to best model a brazed joint:
  + Elements types
  + Geometry
  + Where does the ‘joint region’ become the parent material and vice versa?

# References

[1] Joint Rule Gap Analysis & Development Proposal, R. Bamber, 2014, EDDI-1.3.1-02, EFDA D 2MDR76

[2] The metallurgy, mechanics, modelling and assessment of dissimilar material brazed joints, N. R. Hamilton, 2013, Journal of Nuclear Materials Vol 432 Pg 42-51

[3] Development of brazing foils to join monocrystalline tungsten alloys with ODS-EUROFER steel, B. A. Kalin et al, 2007, Journal of Nuclear Materials Vol 367-370 Pg 1218-1222

[4] Residual Stress Generation in Tungsten-Copper Brazed Joint Using Brazing Alloy, D. Easton et al, IEEE 26th Symposium on Fusion Engineering

[5] Interfacial metallurgy study of brazed joints between tungsten and fusion related materials for divertor design, Y. Zhang et al, 2014, Journal of Nuclear Materials Vol 454 Pg 207-216

[6] Brazing development and interfacial metallurgy study of tungsten and copper joints with eutectic gold copper brazing alloy, D. Easton et al, 2015, Fusion Engineering and Design Vol 98-99 Pg 1956-1959

[7] Thermal Autofrettage of Dissimilar Material Brazed Joints, N. Hamilton et al, 2015, Materials and Design Vol 67 Pg 405-412

[8] Development of rapidly quenched brazing foils to join tungsten alloys with ferritic steel, B. A. Kalin, 2004, Journal of Nuclear Materials Vol 329-333 Pg 1544-1548

[9] Mechanical characterization and modeling of brazed EUROFER-tungsten-joints, T. Chehtov et al, 2007, Journal of Nuclear Materials Vol 367-370 1228-1232

[10] High heat flux test of tungsten brazed mock-ups developed for KSTAR divertor, J. H. Song et al, 2016, Fusion Engineering and Design Vol 109-111 Pg 78-81

[11] Toward tungsten plasma-facing components in KSTAR: Research on plasma-metal wall interaction, S. H. Hong et al, 2015, Fusion Science and Technology Vol 68 Pg 36-43

[12] High heat flux performance of neutron irradiated plasma facing components, M. Rodig et al, 2002, Journal of Nuclear Materials Vol 307-311 Pg 53-59

[13] Neutron-irradiation effects on high heat flux components – examination of plasma-facing materials and their joints, M. Rodig et al, 2000, Journal of Nuclear Materials Vol 283-287 Pg 1161-1165

[14] Joining of HHF materials applying electroplating technology, W. Krauss et al, 2014, Fusion Engineering and Design Vol 8-9 Pg 1213-1218

[15] Tungsten joining with copper alloy and its high heat load performance, X. Liu et al, 2014, Journal of Nuclear Materials Vol 455 Pg 382-386

[16] Mechanical characterization and modeling of brazed tungsten and CuCrZr alloy using stress relief interlayers, D. Qu et al, 2014, Journal of Nuclear Materials Vol 455 Pg 130-133

[17] Structural Design Criteria for In-Vessel Components (SDC-IC), 2012, Version 3

[18] SDC-IC Appendix A, Materials Design Limit Data, 2012, Version 3.2

[19] RCC-MRx Code - Afcen – Subsection B Class N1Rx Reactor Components its Auxiliary Systems and Supports - Section RB 4730 MECHANICAL ASSEMBLIES - BRAZED ASSEMBLIES

[20] RCC-MRx Code - Afcen - Tome 5 Manufacturing Operations (Other than Welding) - Section RF 7300 BRAZED ASSEMBLIES

[21] ASME III Code, ARTICLE NB-3000 DESIGN, NB-3671.6 Brazed and Soldered Joints

[22] Proposed Rules for Joints with Interlayers in Fusion Reactor Containments, R. Bamber et al

[23] The challenges in predicting the fatigue life of dissimiliar brazed joints and initial finite element results for a tungsten to EUROFER97 steel brazed joint, 2011, N. R. Hamilton et al, Fusion Engineering and Design 86 (2011) 1642-1645

[24] Website accessed 23.09.2016 http://www.twi-global.com/technical-knowledge/published-papers/recommended-hot-spot-stress-design-s-n-curves-for-fatigue-assessment-of-fpsos-june-2001/

[25] A Study of Joints between Dissimilar Materials with a View to Fatigue Performance in Fusion Reactor Applications, M. B. Olsson-Robbie, 2016, Thesis, University of Strathclyde

[26] Overview of fabrication and joining of plasma facing and high heat flux materials for ITER, M. Merola et al, 2002, Journal of Nuclear Materials 307-311 (2002) 1524-1532

[27] Brazed dispersion strengthened copper: the effect of neutron irradiation and transmutation on bond integrity, D. J. Edwards, 1999, Effects of Radiation on Materials: 1th International Symposium, ASTM STP 1325

[28] Properties of TZM and Nuclear Behaviour of TZM Brazements, A. Semeniuk & G. R. Brady, 1974, Welding Research Supplement 459-s

[29] BS EN 14324:2004, Brazing - Guidance on the application of brazed joints

1. One *Deliverable Report* shall be submitted for each deliverable e.g. Study Report, Commissioning Report, Final Assessment Report, Technical Acceptance Report, Procurement Report, etc. [↑](#footnote-ref-1)